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Radiological Protection Aspects of Imaging in Radiotherapy

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**CONTENTS**

[Abstract 4](#_Toc179824862)

[MAIN POINTS 6](#_Toc179824863)

[EXECUTIVE SUMMARY 7](#_Toc179824864)

[1. INTRODUCTION 11](#_Toc179824865)

[1.1. Background 11](#_Toc179824866)

[1.2. Risks of radiation effects 14](#_Toc179824867)

[1.3. Techniques used for imaging in radiotherapy 17](#_Toc179824868)

[1.4. The use of imaging pre- and post- radiation therapy 19](#_Toc179824869)

[1.5. Doses from imaging procedures in radiation therapy 20](#_Toc179824870)

[1.6. Justification and optimisation of imaging procedures in radiotherapy 22](#_Toc179824871)

[1.7. Taking account of doses from imaging in treatment plans 24](#_Toc179824872)

[1.8. The development of artificial intelligence applications in radiotherapy. 24](#_Toc179824873)

[1.9. ICRP reports on radiotherapy, imaging, justification and optimisation 25](#_Toc179824874)

[2. RADIOTHERAPY TREATMENT PLANNING AND DELIVERY 27](#_Toc179824875)

[2.1. External beam radiation therapy 27](#_Toc179824876)

[2.2. Brachytherapy 29](#_Toc179824877)

[2.3. The role of imaging in radiotherapy 30](#_Toc179824878)

[3. CLINICAL JUSTIFICATION FOR IMAGING IN RADIOTHERAPY 34](#_Toc179824879)

[3.1. Clinical benefits of imaging 34](#_Toc179824880)

[3.2. Key factors in considerations for justification 35](#_Toc179824881)

[3.3. Considerations for specific clinical scenarios 35](#_Toc179824882)

[3.4. Existing recommendations and practice guidelines 39](#_Toc179824883)

[4. THE PROCESS OF OPTIMISATION OF IMAGING 40](#_Toc179824884)

[4.1. Choices to be made for imaging 40](#_Toc179824885)

[4.2. Selection and use of imaging equipment 41](#_Toc179824886)

[4.3. Strategies for implementing optimisation of imaging 42](#_Toc179824887)

[4.4. Development of optimisation of radiological protection for imaging 48](#_Toc179824888)

[5. EVALUATION AND MANAGEMENT OF DOSES FROM IMAGING 51](#_Toc179824889)

[5.1. Dosimetric quantities and dose distributions from imaging procedures 51](#_Toc179824890)

[5.2. Dose levels from imaging 53](#_Toc179824891)

[5.3. Estimation of imaging doses for incorporation into treatment plans 56](#_Toc179824892)

[5.4. Uncertainties in dose assessment and prediction of radiation effects 59](#_Toc179824893)

[6. IMAGING FOR TREATMENT PLANNING 62](#_Toc179824894)

[6.1. Objectives of imaging prior to treatment 62](#_Toc179824895)

[6.2. Technologies for imaging prior to treatment 65](#_Toc179824896)

[6.3. The impact of AI on image analysis 70](#_Toc179824897)

[7. IMAGING DURING THE TREATMENT CYCLE 74](#_Toc179824898)

[7.1. Objectives of imaging during therapy delivery 74](#_Toc179824899)

[7.2. Imaging for adaptive radiotherapy 77](#_Toc179824900)

[7.3. Imaging technologies and frequencies used during therapy delivery 79](#_Toc179824901)

[8. IMAGING FOR BRACHYTHERAPY 84](#_Toc179824902)

[8.1. Use of ionising and non-ionising imaging modalities in brachytherapy 84](#_Toc179824903)

[8.2. The purpose of imaging in brachytherapy (justification) 85](#_Toc179824904)

[8.3. Techniques of dose reduction and optimisation 89](#_Toc179824905)

[9. PAEDIATRIC IMAGING IN RADIOTHERAPY 92](#_Toc179824906)

[9.1. Factors affecting choices in paediatric oncology 92](#_Toc179824907)

[9.2. Imaging in paediatric radiation oncology 93](#_Toc179824908)

[9.3. Medical considerations for imaging during paediatric radiation therapy 95](#_Toc179824909)

[9.4. Technical considerations for paediatric radiation oncology imaging 99](#_Toc179824910)

[10. THE IMAGING EQUIPMENT LIFE CYCLE, QUALITY ASSURANCE AND AUDITS 102](#_Toc179824911)

[10.1. The imaging equipment life cycle 102](#_Toc179824912)

[10.2. Quality assurance programme of imaging equipment 105](#_Toc179824913)

[10.3. Reviews and audits 109](#_Toc179824914)

[11. AVOIDANCE OF ERRORS ORIGINATING FROM IMAGING IN RADIOTHERAPY 114](#_Toc179824915)

[11.1. Terminology used for unintended and accidental medical exposures 114](#_Toc179824916)

[11.2. Errors resulting from imaging during plan preparation 115](#_Toc179824917)

[11.3. Errors resulting from imaging during the treatment 119](#_Toc179824918)

[11.4. Promotion of good practice in imaging in radiotherapy 120](#_Toc179824919)

[12. EDUCATION AND ONGOING TRAINING OF RADIOTHERAPY STAFF 122](#_Toc179824920)

[12.1. Importance of education and training in radiotherapy 122](#_Toc179824921)

[12.2. Competence-based training 124](#_Toc179824922)

[12.3. Development of inter-professional communication and team culture 129](#_Toc179824923)

[13. RECOMMENDATIONS TO IMPROVE RADIOLOGICAL PROTECTION FOR IMAGING IN RADIOTHERAPY 132](#_Toc179824924)

[13.1. Health professionals involved in radiotherapy processes 132](#_Toc179824925)

[13.2. Equipment vendors and software developers 133](#_Toc179824926)

[13.3. Regulators and professional bodies 133](#_Toc179824927)

[REFERENCES 135](#_Toc179824928)

[ANNEX A. IMAGING TECHNIQUES USED IN RADIATION THERAPY 157](#_Toc179824929)

[A.1. Treatment planning 157](#_Toc179824930)

[A.2. Patient positioning, verification and replanning 158](#_Toc179824931)

[A.3. References 161](#_Toc179824932)

[ANNEX B. KV CONE BEAM CT DOSIMETRY 162](#_Toc179824933)

[B.1. Computed tomography dosimetry 162](#_Toc179824934)

[B.2. Standard dosimetry methods applied to Cone Beam CT 164](#_Toc179824935)

[B.3. Practical methods for measurement of CBCT patient doses for surveys 166](#_Toc179824936)

[B.4. References 170](#_Toc179824937)

[ANNEX C. Errors in treatment involving the application of imaging 171](#_Toc179824938)

[C.1. Examples of treatment errors linked to imaging 171](#_Toc179824939)

[C.2. Errors from imaging during plan preparation 171](#_Toc179824940)

[C.3. Errors in matching to the plan during treatment 173](#_Toc179824941)

[C.4. Errors due to differences in patient positioning 176](#_Toc179824942)

[C.5. References 177](#_Toc179824943)

[ABBREVIATIONS 179](#_Toc179824944)

[GLOSSARY 183](#_Toc179824945)

[ACKNOWLEDGEMENTS 188](#_Toc179824946)

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**RADIOLOGICAL PROTECTION ASPECTS OF IMAGING IN RADIOTHERAPY**

ICRP PUBLICATION XXX

Approved by the Commission in MMMMM 20XX

**Abstract**

**–**Dramatic improvements in delivery of patient radiation therapy enable radiation treatment fields to be conformed to any shape of tumour, a trend that began in the latter stages of the twentieth century. External beam radiotherapy linear accelerators (linacs) can potentially limit irradiation induced cell death to the tumour and spare surrounding normal tissue. However, this can only be achieved if the patient is in a position on the treatment couch that corresponds precisely to the treatment plan. This can often only be accomplished through imaging at many, if not all, of the fractions in which treatment is delivered. This process is often referred to as image guided radiation therapy (IGRT). Treatments are given to patients on the basis of clinically approved radiation distributions calculated on planning computers using computed tomography (CT) x-ray images. When the patient is set-up for treatment, further images, planar or cone-beam CT, are taken and compared to the planning images. The comparison ensures that differences in patient position, patient anatomy and tumour location between the planning images and those taken on the day of treatment, are clinically insignificant. Image guidance enables changes in patient anatomy to be monitored and modifications made to treatment plans daily. Imaging during treatment planning and delivery can also be used to account for motion, with the recording of multiple images through breathing or other motion cycles. However, increased x-ray imaging exposes patients to radiation doses that carry a risk of inducing second primary cancers in tissues surrounding the target volume. This is important because of improvement in long term patient survival with the success of modern therapies and is crucial for paediatric patients. Therefore, reductions in treatment margins and alignment errors that can be realised from IGRT need to be balanced against detriments from higher doses from more frequent imaging. Less effort has been put into optimisation of imaging doses in radiotherapy as they are much lower than those from therapeutic radiation, but imaging irradiates more normal tissues than the treatment beams and the frequency of scanning is much higher than in diagnostic radiology. This report considers all aspects of optimisation for imaging, starting with options available for both planning and delivery, including alternatives using non-ionising radiations, and the frequency with which imaging is carried out during treatment. The optimisation of radiological protection requires teams comprising radiation oncologists, therapy radiographers / radiation technologists and medical physicists and vendors to work together on improving imaging protocols. Consulting colleagues from Diagnostic Radiology departments can be beneficial for reducing dose and improving image quality. Considerable progress has been made in optimisation of radiological protection for diagnostic imaging, based on surveys of patient doses, but few radiotherapy centres record imaging doses. The awareness of imaging doses needs to be raised, and improvements made in the display of the dose quantities on imaging equipment in radiotherapy to allow calibration and assessment to be performed more readily. Recommendations are included for users, managers, equipment vendors, professional bodies and regulators to facilitate improvements in the application and optimisation of imaging in radiotherapy.

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*Keywords:* Radiotherapy, Image guided radiotherapy, Optimisation, External beam radiotherapy, Brachytherapy.

MAIN POINTS

Developments in radiotherapy techniques during the twenty-first century allow treatments to be planned with dose distributions conformed to the shapes of tumour targets with high precision. Imaging of the region surrounding the tumour target is required at regular intervals throughout treatment to achieve a similar accuracy in treatment delivery.

High dose margins around tumour volumes are used in radiotherapy planning to account for uncertainty in target delineation, anatomical changes, organ movement and patient set-up. The treatment margins can be reduced to spare normal tissue through use of imaging, but significant cumulative doses to large volumes of normal tissue from imaging will contribute to the risks of second primary cancers, especially for paediatric patients.

High quality imaging is required to delineate the target for planning radiotherapy treatments and to verify alignments during treatment delivery. Radiological protection should be optimised for the whole process to achieve the image quality levels required while minimising doses to the patients including the use of non-ionising radiation techniques with special attention being paid to paediatric patients.

Imaging allows patient morphology and physiology to be assessed throughout treatment so that techniques can be adapted for changes in patient anatomy from day to day and used to account for motion. However, the techniques require the acquisition of multiple images leading to an increase in imaging dose to the patient.

Imaging optimisation teams comprising radiation oncologists, therapy radiographers / radiation technologists and medical physicists trained in diagnostic radiology skills, should be set up to develop protocols that provide images of a quality that is adequate for verifying alignments, with optimised radiological protection, at a frequency adjusted to balance the detriments from additional imaging doses against those from alignment errors.

Staff knowledge of doses from imaging needs to be improved and imaging dose levels should be audited regularly to facilitate optimisation of radiological protection. To aid in accomplishing this, vendors are recommended; 1) to include imaging dose quantities on displays for imaging equipment that can be audited by radiotherapy departments; 2) to include imaging dose calculation tools in treatment planning systems.

EXECUTIVE SUMMARY

1. There have been tremendous improvements in localisation of target volumes for the treatment of cancer with radiation therapy during the last few decades. In external beam radiotherapy, the development of multi-leaf collimators (MLCs) allows treatment beams to be conformed to the outlines of tumours. Sophisticated computer planning systems can design treatment plans employing MLC shaped beams from multiple directions to provide an intensity modulated distribution of radiation dose delivered to tumours. Using charged particles such as protons and carbon ions, steep dose gradients can be achieved around the boundaries of the target volumes, thereby minimising the exposure of normal tissues adjacent to the treatment site and this is particularly important for treatment of the smaller bodies of paediatric patients. However, improvements in treatment outcomes will only be achieved if the radiation can be delivered to the patient on the treatment couch with a similar accuracy to the approved treatment plan. Imaging is therefore necessary not only for planning the treatments, but also at the time they are delivered.
2. The imaging during treatment is referred to as image guided radiation therapy (IGRT) and permits normal tissue doses to be reduced through better localisation of therapeutic beams. The image guidance is indispensable if full advantage is to be taken of the potential improvements in treatment delivery. Imaging during treatment should enable more precise treatments that spare more sensitive normal tissues and improve safety. It may also allow some patients to receive treatments that might otherwise not have been considered feasible. Imaging at the time of treatment also enables plans to be adapted to take account of anatomical changes that may occur in patients during the treatment which can involve twenty or more fractions (inter-fraction). It also allows movement of the target, such as that linked to breathing for tumours of the lung, to be considered (intra-fraction).
3. In the majority of centres, imaging at the time of treatment is carried out with diagnostic kilovoltage (kV) x-ray facilities combined with linear accelerator treatment units. The megavoltage (MV) x-ray treatment beam can also be used although the image quality is much poorer and dose levels are significantly higher. kV imaging systems can acquire 2D planar radiographs but are more frequently used to capture 3D volumetric images using cone beam computed tomography (CBCT). These techniques expose not only the tumour target but surrounding normal tissues to additional radiation. There may often be a lack of awareness of this additional radiation exposure among those planning and carrying out treatments. Although the dose levels are far lower than those of the therapeutic radiation, since they may be repeated at twenty or more fractions during a radiotherapy treatment, they are not negligible, and inevitably carry a potential risk of inducing cancer and other diseases such as cardiac events in surrounding tissues. There are other techniques available which use non-ionising radiation. Magnetic resonance imaging (MRI) is more expensive but is becoming available in some high-income countries. Ultrasound and surface guided optical imaging also provide alternatives for limited types of treatment. However, CBCT is the technique most widely available and is the predominant one in use throughout the world.
4. Obtaining an image of the patient with the target volume at the time of treatment reduces uncertainty in the position of the tumour, so that tighter margins can be set for the boundary of the radiation field surrounding the target. Increasing the frequency of imaging and adjustment, e.g. imaging at every treatment fraction, allows uncertainties in the dose margins to be reduced. However, the advantages of reducing the target margin to decrease the potentially high exposure of normal tissue adjacent to the tumour need to be balanced against reducing the lower dose from imaging that affects normal tissues within the whole imaging field.
5. Because of the rapid growth in IGRT the development of guidance on when it is appropriate to carry out imaging and on optimisation of radiological protection for imaging techniques has been limited. Moreover, many radiotherapy centres do not have medical physicists with expertise in diagnostic imaging who can advise on strategies to achieve optimisation of radiological protection in imaging. As such, patient dosimetry, dose auditing and imaging optimisation techniques should be an integral part of the training and education of therapy medical physicists. More medical physicists trained in diagnostic radiology skills including patient dosimetry, dose audit and optimisation techniques are needed in radiotherapy departments. Optimisation starts at the time equipment is introduced into a radiotherapy department, and if physics expertise in diagnostic imaging is limited, assistance should be sought from medical physics colleagues in diagnostic radiology for commissioning and setting up appropriate quality assurance (QA) programmes including measurements of imaging dose parameters. Optimisation teams comprising radiation oncologists, therapy radiographers / radiation technologists (RTTs), medical physicist(s) with experience in optimising imaging protocols and vendors should be set up for imaging. Each member of the team has unique skills that will contribute to the development and improvement of the protocols. They can work together in optimising protocols for each type of procedure.
6. One of the issues to be tackled in achieving optimisation of radiological protection is that information on doses that patients receive in terms of measurable quantities is often limited, but without this information optimisation is impossible. In the diagnostic use of x-ray imaging, there are programmes in place for surveying doses to patients, comparing dose levels in different facilities, and setting diagnostic reference levels based on national or regional comparisons that provide standards against which comparisons of dose levels can be made. A similar approach is recommended here for imaging in radiotherapy but called dose reference level, using the same abbreviation DRL but with a subscript, namely DRLRT. Departments are encouraged to carry out audits of imaging doses and generate typical vales for doses within their departments for comparison with national DRLRTs (ICRP, 2017), and so to identify whether their doses are high and implement changes to bring them into line with standard practice where appropriate.
7. There are a few examples of surveys of imaging doses in radiotherapy, but the practice is not widespread. The surveys that have been carried out show that there are wide ranges in the doses from CT scans used both in treatment planning and imaging during treatment among radiotherapy centres. Information from surveys of imaging doses, together with assessment of image quality, and information on clinical requirements should feed into the review and improvement of clinical protocols for imaging. This applies to both planning exposures and those undertaken at the time of treatment. One barrier that is restricting dose audit is the lack of accurate displays of measurable dose quantities on CBCT systems. Equipment vendors are encouraged to provide useful patient imaging dose information that users can calibrate and employ for future patient dose surveys.
8. As mentioned earlier imaging allows patient, target and organ motion to be taken into account, which otherwise can be a significant problem, leading to the unplanned radiation delivery, potentially compromising the treatment. However, imaging to characterise motion requires the acquisition of multiple images which can again lead to an increase in imaging dose to the patient. Particular attention should be paid to techniques and protocols for motion management and adaptive radiotherapy in which changes in patient anatomy from day to day are taken into account.
9. Medical imaging is also essential in brachytherapy, a type of treatment employing radioactive sources that have to be cautiously positioned within or in the vicinity of the aimed target (tumour). These enable localised high doses to be delivered to a small volume, but accurate positioning is crucial and requires careful planning based on imaging. Several different imaging modalities may be used, depending on the tumour site, the applicator design, the complexity of the treatment and clinical practice. Imaging is integrated into the workflow throughout the treatment to support clinical decision-making and facilitate the implant.
10. Optimisation of radiological protection in protocols is particularly important for paediatric patients for whom there are greater risks from radiation exposure and sensitivity to positioning accuracy. Radiation oncologists and other groups involved in the treatment of paediatric patients need to be reminded that imaging exposes healthy tissues to repeated diagnostic quality x-rays. Treatment and imaging techniques adapted to the treatment and imaging of paediatric patients are slowly emerging, but the number of paediatric patients is relatively small. There are options such as reducing the field of view, making sure appropriate exposure factors are used, employing iterative reconstruction for CT, and use of non-ionising imaging tools such as MRI and optical surface guidance which show promise. But at present there is little consensus about best practices and more discussion is required, together with the development of more guidelines.
11. Another factor that should be considered is the contribution that doses from imaging make to the dose received by organs at risk (OARs), but this is rarely considered outside some paediatric hospitals. This may be of particular importance in regions where the doses to the OARs are close to tolerance values. Moves to document these doses should be encouraged, and the possibility of including them in the treatment prescription in the future be considered. Many modern treatment planning systems (TPSs) have the capability to calculate MV imaging doses and to implement them into treatment plans. However, they do not have the ability to calculate kV imaging doses, so additional calculation processes would need to be implemented into TPSs to make this a possibility. Therefore, imaging QA protocols should be developed and reviewed more regularly to ensure dosimetric consistency which may affect any incorporation into treatment dose.
12. This report provides an overview of the radiological protection aspects relating to use of imaging during both the planning and treatment delivery. It develops ideas relating to the promotion of awareness of doses to normal tissues from imaging undertaken as part of radiotherapy. It includes recommendations on the training of staff, the establishment of practices to provide information on imaging doses, including the survey and audit of doses to provide information that can feed into the improvement of protocols to optimise radiological protection. The report also includes consideration of the life cycle of the imaging equipment, optimising imaging protocols during commissioning with the involvement of medical physicists with expertise in imaging, establishing QA programmes required to ensure performance is maintained, and putting in place procedures to reduce errors in treatment that may arise when images and patient data are not interpreted correctly. Appropriate record keeping for QA programmes will inform and drive forward cyclical improvement and ensure that corporate knowledge is maintained. Analysis of this data informs the justification process, ensuring the benefit from exposure always outweighs the risk associated with imaging dose. The setting up of optimisation teams for imaging comprising radiation oncologists, RTTs and medical physicists who can undertake regular review and improvement of imaging protocols will help to support this process and is strongly encouraged.

# INTRODUCTION

1. **Key points in this section:**

Successful delivery of precision radiotherapy treatments requires planning images with anatomical references or fiducial markers, and repetition of imaging to guide treatment delivery with facilities integrated into therapy equipment.

Radiological imaging to guide radiation treatments will carry a risk of induction of second primary cancers. The frequency at which imaging is justified depends on a delicate balance between the accuracy of treatment delivery and the additional dose from imaging.

Improvements in sparing of normal tissue through better localisation of therapeutic beams should be offset against the additional radiation doses from imaging to surrounding organs and tissues that will contribute to risks of second primary cancers.

Margins around the target and critical structures are used in radiotherapy planning to account for uncertainty in target delineation, anatomical changes, patient set-up and delivery. Image guidance can reduce the uncertainties and may enable smaller margins to be used with less irradiation of normal tissues.

The object of optimisation of radiological protection for imaging exposures is to identify the level of image quality that is adequate for performing and verifying patient setup. This involves adjusting the dose level and frequency of imaging to balance radiation detriments against those from patient deviations.

Doses from x-ray imaging exposures are measured in terms of quantities based on air kerma. Surveys of these quantities and comparisons of median dose values with dose reference levels (DRLRTs) for imaging in radiotherapy will help to promote standardisation of imaging practices and encourage optimisation.

Imaging protocols from vendors provide a starting point from which optimised protocols can be developed. Imaging parameters should be adapted to specific tasks with lower exposure factors for smaller patients, especially paediatric patients.

Doses from megavoltage (MV) imaging could be calculated by treatment planning systems (TPSs) but are only starting to be included in treatment plans in most centres, while dose distributions from kilovoltage (kV) imaging can only be derived using specialist research tools at present.

## Background

1. Almost since the discovery of x-rays and radioactive materials at the end of the nineteenth century radiation has been regarded as a potential means through which diseased cells could be killed. Early treatments involved irradiation of surface lesions, but as the potential of radiation therapy became apparent, medical doctors sought ways to irradiate tumour tissue deep within the body. Early radiation treatments used brachytherapy, a method through which sealed radioactive sources are positioned on or in the body. Brachytherapy still plays an essential role in the treatment of cervical cancer patients, while treatment with external radiation beams has now become the primary modality for radiotherapy. Technical advances have led to the production of machines which can reliably produce MV radiation beams with the penetration required to treat masses within the body and because it is non-invasive management of cancer patients within the clinical workflow is easier.
2. The incidence of cancer worldwide is predicted to increase from 18.7 million in 2018 to more than 29 million by 2040 (Ferlay et al., 2019; WHO, 2020). Radiation therapy or radiotherapy (RT) is currently one of the most widely used treatment options for cancer throughout the world with radiation being the indicated method of treatment for about 50 % of cancer patients (Atun et al., 2015). Having reasonable knowledge about the location of the tumour is essential for performing any such treatment, so imaging has always been a vital component for radiation therapy techniques.
3. External beam radiotherapy can treat tumours at depth using overlapping radiation beams delivered from different directions that enable higher doses to the target tissues to be achieved while sparing the surrounding healthy tissue. Treatment machines have high intensity, high energy radiation sources mounted on gantries that allow movement around the body of the patient. The most common sources are now electron linear accelerators (linacs) which deliver dose rates around ~ 4-20 Gy min-1 predominantly with bremsstrahlung generated photon beams. High activity radioactive sources such as 60Co are used for specialised equipment, such as the Elekta Gammaknife ®, and are still employed as conventional treatment units in some parts of the world.
4. In the 21st century, therapies with charged particles such as protons have begun to play an important role. These deposit energy with a narrow range in depth (also known as the ‘Bragg peak’) as the particles approach the end of their track through the body, and this can help to minimise exposure of other normal tissues. Neutrons are used occasionally for specialised treatments such as boron neutron capture therapy (BNCT). However, neutrons are also produced as a byproduct through (γ, n) interactions within linacs by photons with energies > 10 MV. The main consideration for neutrons within radiotherapy is regarding the radiation protection of the patient and staff in high energy x-ray and particle radiation treatments. For the majority of external beam treatments, the tumour is positioned near the gantry isocentre, and the source is rotated around the body to irradiate the target from several angles or through a continuous arc.
5. Images recorded prior to the treatment are used to outline the shape of the target and organs at risk (OARs), and define their position within the body, and from these a treatment plan is developed. Sometimes, on-table adaptive therapy can be accomplished, especially with linacs guided by high quality volumetric imaging such as cone beam CT (CBCT) or magnetic resonance imaging (MRI).These techniques are used in improving the delivery of radiation therapy that can help in reducing premature mortality through improved treatment, thereby promoting health and well-being, one of the goals for sustainable development (Rühm et al. 2023).
6. Treatments during most of the latter half of the twentieth century were delivered by largely rectangular beams and utilising manufactured blocks to shape the fields. The accuracy in positioning of the treatment field at that time was the order of 5-15 mm relative to the target. Treatment plans were based on plain x-rays or computed tomography (CT) scans acquired several days before the start of the therapy. Simulation images were taken of the patient on a linac ‘simulator’ to confirm that the planned treatment could be delivered to the patient. A few simulation images recorded for setting up the treatment, and portal images with the therapy beam were taken at the start of treatment as part of the verification process and at certain stages during treatment to confirm beam position in relation to the tumour (Fig.1.1). An important advance in radiation therapy was the introduction of multi-leaf collimators (MLCs) in the 1990s, which consist of motorised high density tungsten alloy leaves that can be moved in order to conform the irradiation field to the shape of the tumour target. Combining MLCs with the delivery of radiation from different directions under the control of a computer provided an ability to limit irradiation more effectively to the tumour while sparing surrounding normal tissue in conformal radiotherapy. These developments utilise the three-dimensional (3-D) patient images obtained from CT scanning that are fed into 3-D computerised Treatment Planning Systems (TPSs).
7. Imaging is used before treatment is commenced in the planning (pre-treatment), during treatment delivery for verification and adaptation, and post treatment for response assessment and evaluation. The term image guided radiation therapy (IGRT) has been used extensively to describe the use of imaging in radiotherapy (Mundt and Roeske, 2011), but application of the term has varied between regions and publications. In this publication, reference will be made to imaging prior to treatment for assessment and planning, and during treatment for verification and adaptation carried out in the treatment room (Korreman et al., 2010).
8. Systematic errors made during preparation of the treatment plan will be propagated through the treatment process but can be reduced by imaging at a few fractions (van Herk, 2004). Random errors occur in the positioning of patients at each fraction. Trying to position patients consistently to the nearest mm, and even sub mm for treatment of brain lesions, is almost impossible in most clinical situations without confirmation from additional imaging. If a patient is imaged immediately before treatment is administered, then corrections can be applied before treatment delivery and errors reduced to a minimum. Imaging can also be employed during treatment delivery to ensure that the position of the tumour target does not move with respect to the intended treatment position due to involuntary patient or internal organ motion and in new systems the MLC can potentially even track the target motion. The treatments can also be gated so that the radiation beam is only switched on when the target is in the correct position, this being judged from surrogate markers indicating breathing motion of the chest wall or abdomen.
9. Technology has developed rapidly in the last three decades as depicted in Fig. 1.1. The improvements in technology shown in the figure columns 1 and 3 provide extra degrees of freedom in radiation delivery, enabling the radiation field to be tailored ever more precisely to the shape of the tumour, enhancing the potential effectiveness of treatments and improving clinical outcomes (De Neve et al, 2012). However, these improvements can only be realised if the treatment delivery to the patient is performed with high spatial accuracy. Therefore, imaging is indispensable to the success of modern complex radiotherapy treatment not only in producing the initial plan, but also ensuring that the patient is in the position in which the dose distribution will be delivered to the correct tissues.
10. Thus, imaging is essential both for planning radiation treatment and during the treatment, to achieve the precision and accuracy of delivery needed with the tighter treatment margins required for conformal radiotherapy and proton therapy. The methods used include extensions such as intensity modulated radiation therapy (IMRT) in which the MLC leaves move during beam delivery to create complex 3-D dose distributions as the beam is moved around the patient and stereotactic body radiotherapy (SBRT) where high doses of radiation are delivered from many angles with less fractionation to be more biologically effective (Dawson and Sharpe, 2006). The dose delivered to the target might also be increased with the hope of a higher probability of cure for the cancer, without a significant increase in dose to the surrounding healthy tissues. It is also worth noting that treatments with a larger dose per fraction for fewer fractions, have less opportunity for correction if misalignment occurs, thus strengthening the case for imaging at every fraction. Therefore, accurate imaging not only enables hypofractionation and SBRT, but is essential for safe SBRT.

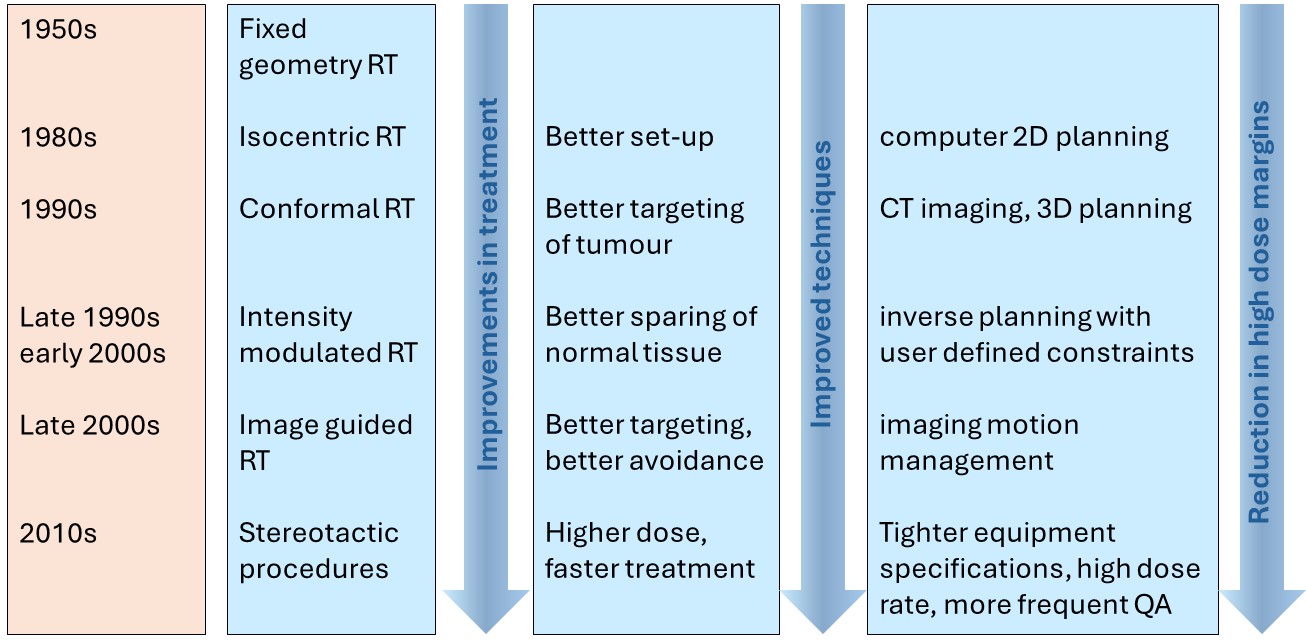


Fig.1.1. Developments in radiation technology during the latter half of the 20th and early 21st centuries and the impacts on radiotherapy treatment and changes in treatment planning.

## Risks of radiation effects

1. Adverse health effects of radiation can be classified into two general categories: Tissue reactions and stochastic effects. Tissue reactions, also termed “deterministic effects”, are functional tissue reactions that develop following radiation exposure. Stochastic effects are the induction of cancer in exposed individuals due to mutation of somatic cells, as well as potential heritable disease in their offspring (including cancer) due to mutations in reproductive cells.

### Early and Late tissue and organ reactions

1. The appearance of tissue reactions is often characterised by a threshold dose above which radiation damage to a population of cells in a given tissue needs to be sustained before damage is expressed clinically. In general, tissue reactions occur in the dose regions of radiation treatment with doses of a magnitude considerably larger than imaging doses and are not a large part of this analysis. However, imaging does allow for more precise treatments that can lead to reduced tissue reactions or dose escalation while maintaining the same level in risk of tissue reactions potentially leading to increased tumour control.
2. An important exception to the high dose tissue reactions is the reproductive system that can be affected by relatively low doses of radiation. The estimates of threshold doses in males and females for acute, fractionated/protracted, and chronic exposures have been unchanged since recommended by ICRP in the early 1980s (ICRP, 1984). The testicular tissue, especially the germinal epithelium lining, has a high sensitivity to ionising radiation. Transient infertility occurs after doses <1 Gy. However, fertility recovers from surviving stem cells, even after doses up to 4 Gy, provided that enough spermatogonia stem cells survive to repopulate the seminiferous tubules. The human oocytes are highly sensitive to radiation-induced apoptosis, with an estimated LD50 of <2 Gy for the destruction of primordial follicles. The resulting radiation-induced infertility occurs more often in older women due to the decline in oocyte population with age (Wo and Viswanathan, 2009).
3. Another organ sensitive to radiation is the lens of the eye, in which opacities appear in the crystalline structure of the lens. These evolve from aberrant differentiation of lens epithelial cells damaged by radiation. *Publication 118* concluded that the threshold for development of lens opacities with a 1 % risk of occurrence was 500 mGy (ICRP, 2012). The latest epidemiologic and radiobiological evidence suggests that although early effects at higher doses are tissue reactions, late onset cataractogenesis at lower doses might have a stochastic component with effects developing decades after radiation exposure (Hamada et al., 2020; Richardson et al., 2020).
4. Radiation exposure of the heart and circulatory system is known to present increased risks of cardiovascular disease and diseases of the circulatory system (ICRP, 2012). Doses of several Gy from radiotherapy treatments of the thorax increase risks of cardiovascular disease (Darby et al., 2013; van Nimwegen et al., 2016; Taylor et al., 2017; Banfill et al., 2020; Shrestha et al, 2021; Errahmani et al., 2022) and patients treated for head and neck cancers show evidence of higher incidences of cerebrovascular disease (Huang et al., 2019; van Aken et al., 2021). There is also evidence of excess risks of heart disease and cerebrovascular disease among Japanese atomic bomb survivors (Shimizu et al., 2010) and in studies of nuclear industry workers (Gillies et al., 2017). However, there is considerable heterogeneity in results from epidemiological studies and uncertainty about the dose threshold for the effects, which make potential risks difficult to predict. Nevertheless, results from a meta-analysis by Little et al. (2023) imply that risks of cardiovascular disease may be present at dose levels that result from medical imaging.

### Stochastic effects

#### Linear No-Threshold model

1. In 2007, ICRP (ICRP, 2007b) re-iterated that a linear dose–response relationship (linear no-threshold model or LNT) should be assumed for the induction of cancer and heritable effects, according to which an increment in dose induces a proportional increment in risk even at low doses. NCRP made a similar recommendation (NCRP, 2018a) and subsequently released a commentary following review of the epidemiological studies of cancer and genetic effects from low dose/dose rate irradiation, stating that the LNT model should be maintained as the basis for the purpose of radiological protection. Further supportive evidence has come from a study of leukaemia in patients having diagnostic CT scans (de Basea Gomez et al., 2023).

#### Risk of Cancer

1. Epidemiological and experimental studies provide evidence of radiation risk of cancer incidence at doses of about 100 mSv or less. Based on the epidemiological data available at the time, ICRP (ICRP, 2007b) had calculated a detriment adjusted, sex averaged, nominal risk coefficient for cancer incidence of 5.5% Sv-1 for the whole population, and 4.1% Sv-1 for adult workers. The most recent report from UNSCEAR (UNSCEAR, 2019) estimated the risks of solid cancer mortality after acute and protracted exposure from various epidemiological studies. These included the Life Span Study cohort, which comprised survivors exposed through the atomic bombs detonated over Japan in 1945 (Cullings et al., 2017), and cancer incidence and mortality studies of radiation workers from nine countries covering nuclear power plant workers, uranium processing workers, x-ray technicians, emergency workers, and individuals from the public exposed to high levels of natural background radiation. Radiation worker studies are biased towards adult males, but the Life Span Study is on a population of all ages and both sexes. It shows that risks are generally greater for children and adolescents, and lower for those over 60-70 years of age, primarily because their expected life span is shorter. Epidemiological data derived predominantly from the Life Span Study group are used to estimate risks of cancer by extrapolating the dose-effect data down to the lower dose levels used in medical imaging (ICRP, 2005c, 2007b, 2021).
2. Most individuals from the radiation worker cohorts received doses <100 mSv, but individual studies do not have the statistical power to detect true radiogenic risk, so it has only been possible to demonstrate risks at these dose levels through combining data from a number of countries. Nevertheless, evidence is emerging from recent reviews of epidemiological data that doses below 100 mSv are associated with cancer risks (Lubin et al., 2017; Little et al.; 2018; Hauptmann et al., 2020; Little et al., 2022; Rühm et al., 2022). For most worker studies and the Life Span Study, the estimated excess relative risk (ERR) values are within a range from 0 to 0.7 per Gy. There is also evidence of an association between malignancy and doses from CT scans of children to dose levels below 100 mGy (Pearce et al., 2012; de Basea Gomez et al., 2023).
3. Doses to organs surrounding the tumour target from single imaging procedures undertaken prior to treatments vary from around 1 mGy for radiographic images to a few mGy for kV cone beam CT up to 30-50 mGy for MV portal images (Ding and Munro, 2013; Siiskonen et al., 2024). However, imaging may be used at every treatment fraction and this repeated radiological imaging can deliver 10s or 100s mGy to these organs. This combines with the low dose wash from modern radiotherapy techniques increasing the risk of induction of further cancers. More information on dose levels is given in subsections 1.5 and 5.2 of this report. It is important to note that radiation risks for cancer patients can differ as they are on balance older than the general population but on the other hand may carry genetic features that make them more susceptible to cancer induction.
4. Second primary cancer risk due to radiation has also been demonstrated in many cancer patients with age being an important confounding factor (Suit et al., 2007). This makes paediatric patients particularly vulnerable (Harbron et al., 2014). A relatively well studied group are also breast cancer patients, where groups of patients with and without radiotherapy can be compared and both second lung cancer and contralateral breast cancer resulting from radiotherapy have been documented (Darby et al., 2005; Stovall et al., 2008).

#### Heritable effects in human populations

1. Studies of children from parents exposed to radiation (atomic bombs, accidental, environmental or medical) have been conducted over many decades using a wide range of endpoints and reported weak or no evidence of excess in heritable genetic changes (Signorello et al., 2012; Winther and Olsen, 2012; NCRP, 2013). Most notably, no effects have been found in the first generation children of atomic-bomb survivors (Otake and Schull, 1990; Grant et al., 2015). Therefore, heritable genetic effects have not been demonstrated for either cancer or noncancer endpoints in human studies. The current estimates of heritable risk are based on radiation-induced mutations from animal studies where transgenerational effects are clearly observable. For the purposes of incorporating heritable risk into the overall risk from ionising radiation, heritable risk is calculated for continuous low dose-rate exposures over two generations. The present heritable risk estimate, developed by ICRP (2007b) and UNSCEAR (2001) essentially using the same methods, was estimated to be ~ 0.2 % Sv-1.

## Techniques used for imaging in radiotherapy

1. The majority of radiotherapy treatments require information on tumour and critical organ locations from a CT scan acquired during planning with the patient in the treatment position. However, conventional simulators, which are diagnostic x-ray machines mounted on rotating gantries to replicate the geometry of the treatment machine, were the mainstay of radiotherapy in the past and are still in regular use in some parts of the world. More advanced centres may use them for imaging simple cases, where fast turnaround is essential, monitoring motion using fluoroscopy, or assessing brachytherapy treatments in low resourced settings. Positron emission tomography (PET) may also be used in treatment planning, most often using the marker fluorodeoxyglucose (FDG) labelled with 18F, which due to its uptake in metabolically active tissue enables the target to be identified more readily (Somer et al., 2012; ICRP, 2024c). PET images are normally recorded together with a CT scan which can be used for planning by itself or a fusion of the PET–CT with dedicated planning CT scans can enable more accurate localisation of tumours. Magnetic resonance imaging (MRI) simulators are becoming widely used in some countries. In most circumstances MRI scans are fused with CT scans for the purposes of planning but newer workflows also use ‘synthetic CTs’ that have been generated directly from MRI scans (Annex A.1, sections 1.8, 6.2.3 and 6.3). The use of dual energy CT is becoming an important addition to the armoury, especially for particle therapy. The various occasions in the patient pathway in which imaging is used in radiotherapy are illustrated in Fig. 1.2.
2. When a patient is being set up for treatment, the target location may be verified using a range of methods for multi-directional imaging (e.g. kilovoltage [kV] or megavoltage [MV] planar imaging or CT, MRI) (Murphy et al., 2007; AAPM, 2009; Simpson et al., 2010) or ultrasound (Western et al., 2015) and optical imaging (Li, 2022). As MRI and optical imaging do not use ionising radiation, they are frequently also used to monitor patient position in real time during the delivery (this is less frequently the case with ultrasound for practicality reasons). The patient position verification images are often viewed online by the RTT and a radiation oncologist (online or offline after the treatment has been delivered) to verify that the treatment requirements are met. Successful delivery of a treatment requires planning images, with tumour position identified with respect to anatomical references or fiducial markers, used where tumour contrast or bony anatomy is insufficient for localisation. These references must be located within the field being imaged for positioning the patient during the course of treatment. Therefore, the imaging field is generally considerably larger than the high dose treatment field. The cumulative doses from these imaging procedures are not recorded routinely, because methods for estimating doses to individual patients are limited (Zhou et al., 2018).

A diagram of a process

Description automatically generated with medium confidence Fig. 1.2. Illustration of the categories of imaging and the different modalities used in radiotherapy. The more recent developments are related to inclusion of functional imaging into treatment planning and the explicit allowance for motion in the planning and delivery process. (MRI magnetic resonance imaging, PET positron emission tomography, EPI electronic portal imaging with MV beam, CINE acquisition of multiple images of the same anatomy over time, US ultrasound)

1. **MV portal images** with radiation emitted by the treatment source, have been used for many years to indicate the location of beam isocentres and field outlines (Court et al., 2008) on a patient’s anatomy. Most linacs are equipped with an electronic portal imaging device (EPID) to perform this registration. The irradiation field required to cover the target and bony landmarks may require irradiation of a large volume of normal tissue, covering a considerably greater area than the treatment field. The source and detector may also be rotated around the body to collect image data from multiple angles to acquire MV cone beam CT (CBCT) scans providing sectional images of the patient. However, the contrast given by MV x-rays for soft tissues is poor and the absorbed doses delivered to tissues are the order of tens or even hundreds of mGy, which is substantially greater than those from other imaging techniques (Stock et al 2011, Ding and Munro 2013). A variation on the theme of MV CT imaging is fan beam MVCT used in helical tomotherapy (DeMarco et al., 2019; Yartsev et al., 2007). The reduction in volume imaged at any one time leads to better image quality and reduced radiation dose. MV imaging may be used during the treatment beam on time, to provide real-time monitoring of structures inside the treatment field. Due to the low soft tissue contrast, this is primarily relevant in cases of implanted fiducial markers or very visible structures such as the patient surface or the lung-chest wall border (Lin et al., 2013; Vasina et al., 2022; Nielsen et al., 2023).
2. **kV imaging** facilities are incorporated into modern linacs with integrated imagers based on large area planar detectors to acquire digital kV radiographs or CBCT scans (ICRP, 2015). Planar kV imaging is the technique that delivers the lowest dose, and the use of orthogonal kV images may be sufficient for treatment sites such as the head and neck or spine, which can use bony anatomy for localisation. Planar images or CBCT scans provide the potential for the patient’s position and the radiation beams to be adjusted to correct errors in alignment and may be performed at each fraction (Lei and Wu, 2010). Absorbed doses to sensitive organs are tens of mGy per CBCT scan (Ding and Coffey, 2009; Zhang et al., 2015b), but doses to children and smaller adults could be 2-3 times higher if exposure factors are not adjusted (Deng et al., 2012; Alaei and Spezi, 2015; Wall et al, 2018). Current models allow image acquisition over a limited arc (e.g. 200-210) for some treatment modes, enabling doses to sensitive organs such as the eyes in head scans to be minimised at the cost of a limited 3D field of view. Using larger detectors with higher efficiency such as Varian Hypersight, half-fan/full-trajectory mode can be replaced by full-fan/half-trajectory mode, reducing projection numbers and imaging dose without sacrificing image quality and field of view (FOV). Spotlight mode is also used for low dose imaging which provides a smaller volume of 3D anatomies. In Spotlight mode the field of view in the axial plane is restricted using collimation and half gantry rotation with the resulting image showing anatomy around the centre of rotation only. Patient contours are not visible and the CT number are not accurate (Ding et al., 2010; Ordóñez-Sanz et al., 2021).
3. **Magnetic resonance imaging** (MRI) systems integrated into linacs are now available (Liney et al., 2018), offering an alternative without the use of ionising radiation. These are much more expensive than CBCT and the number in use in most countries is small because of the limitation of price, time and complexity, but the market share is expected to increase (de Mol van Otterloo et al., 2021). However, at the present time x-ray imaging is the dominant method used and the trade-off between therapeutic advantages and additional radiation doses from imaging needs to be considered.
4. **Optical surface imaging** systems (Freislederer et al., 2020) provide another non-radiographic imaging option for performing patient set-up and intra fraction motion monitoring from the live tracking of changes in position of the patient surface (skin). Optical surface guidance is based on projection of a light pattern onto the patient’s skin which is monitored using video cameras and allows assessment of set-up based on a large area of the patient’s body as opposed to skin markers.
5. **Ultrasound** has reasonable soft tissue contrast and is useful for pelvic and abdominal imaging. However, the pressure required to provide good image quality may deform the anatomy of interest and is operator dependent. Ultrasound can be used in brachytherapy to monitor applicator position.

## The use of imaging pre- and post- radiation therapy

1. All equipment within a facility needs a common co-ordinate system which is integrated across all therapy and imaging equipment. The match between the simulated location of a tumour and the image measurement at the time of treatment may be determined manually or through automated image analysis software or a combination of both. A correction is then applied for any discrepancy through repositioning the patient or reshaping of the treatment beam. This should ensure that the plan fits the anatomy as precisely as possible and enable the tumour to be treated more effectively. Imaging frequency will depend on the mobility of the anatomy, but in general increasing the frequency of imaging and correction enables uncertainties in the margins of irradiated normal tissue surrounding the tumour to be reduced. Thus, the treatment is delivered according to the plan approved by the radiation oncologist, but at the cost of additional radiation dose from imaging. More frequent imaging may not be justified according to therapeutic efficacy if adjustments to the treatment position based on the images are rarely required (ICRP, 2024a).
2. When “dynamic imaging” is used in treatment of tumours in regions of the body such as the lung and abdomen, it provides information on internal motion due to for instance respiration, which can often be clinically significant, and other internal motion such as that caused by bladder and rectal filling. The different physiological processes that have to be considered occur over varying time scales and result in different types of motion. Margins to take account of tumour motion due to respiration or other factors have in the past been based on historical population data or at times assessed prior to treatment using multiple CT studies.
3. A more modern approach is to assess patient motion during treatment planning and respiratory gated CT acquisition (4DCT) has become the most common method to assess breathing motion for treatment planning. A 4DCT scan typically uses an external surrogate like a pressure sensitive belt, a marker on the chest wall or optical surface imaging to associate CT projections to phases of the breathing cycle. As typically 8 or 10 phases are reconstructed, the dose for 4DCT is usually higher to maintain acceptable image quality. Treatment planning is either based on a composite scan that combines the target volumes in each phase of the breathing cycle into a larger ‘internal target volume’, a mid-ventilation approach in which probabilistic margins are used in the mean position during the breathing cycle, or one or a few phases are utilised for a gated delivery. Other options for breathing motion management are breath hold delivery, abdominal compression, direct tumour tracking and mechanical ventilation. Motion management for breathing can be monitored also through time resolved imaging at time of treatment delivery using gated or 4D CBCT or fluoroscopic imaging using the integrated kV imagers. Motion management in delivery can include the breath hold techniques mentioned above as well as gated delivery or more recently motion adaptive therapy where the MLC leaves move to follow the target motion. Bladder and rectal filling are slower and commonly are only assessed at the start of the dose delivery for each fraction.
4. Brachytherapy treatments with high dose rate afterloading units, or insertion of radioactive source seeds, use ultrasound, MRI, CT or fluoroscopy to guide surgical applicator insertions and doses from the latter two can be considerable (ICRP, 2005a, 2005b). Fluoroscopy is usually done with systems having the x-ray tube and image receptor mounted on a C-arm gantry, and the exposure factors are adjusted automatically to match the attenuation of the patient (ICRP, 2010).

## Doses from imaging procedures in radiation therapy

1. Imaging provides additional accuracy in localisation of tumour volumes at the time of treatment, but there is a balance to be achieved. As explained in section 1.2.2, ionising radiation is known to cause second primary cancer and the risk extends down to low dose levels (ICRP, 2005c, 2007b, 2012). Therefore, improvements in sparing of normal healthy tissue through better localisation of therapeutic beams should be offset against the additional radiation doses to surrounding organs and tissues from imaging. There is evidence that doses delivered from CT scans used for medical imaging do have an associated risk of cancer (Pearce et al., 2012; ICRP, 2021; Foucault et al., 2022; Hauptmann et al., 2023; de Basea Gomez et al., 2023). This stochastic risk is a concern, because of the large volumes of tissue imaged (compared to treatment), the need to repeat CT imaging, often daily and potentially even multiple times per fraction and the fact that cancer patients survive longer with modern treatments. Moreover, at the present time, most imaging systems incorporated into linacs do not have the automatic exposure controls used in diagnostic equipment. Since diagnostic energy x-rays are mainly absorbed superficially, they will add proportionately more dose to superficial tissues (ICRP, 2000b).
2. A common historical assumption has been that as the doses from imaging are much smaller than the large therapeutic doses delivered to tumours and the surrounding tissues along the beam path as it transits the patient, little effort needs to be put into reducing imaging doses. However, changes in patterns of imaging, from 2-D to 3-D, with more frequent exposures, creates a potential for more significant cumulative doses to large volumes of normal tissue surrounding the tumour, and this has become a cause for concern. Moreover, while radiotherapy treatment doses are targeted at the tumour, the doses from concomitant imaging are deposited across much larger volumes within the patient. There have been reports of mean absorbed doses between 800 mGy and 2.7 Gy to critical organs such as the brain, lungs, and bone marrow in some patients, from repetitive imaging procedures performed without settings being adjusted for individual patients (Zhou et al., 2015). Although doses from imaging are not generally at this level, doses from typical CBCT scans can deliver up to 120 mGy to some organs and tissues, and this would be significant if they were repeated at each fraction (Deng et al., 2014). Moreover, cancer patients may potentially have a higher genetic risk of tumour induction and may receive many more imaging procedures during investigation of their disease and follow-up after treatment.
3. There are fundamental differences in the radiation doses that are received from the diagnostic x-rays used for imaging and the high energy therapeutic photon beams from linacs. Lower energy diagnostic x-rays are more highly attenuated within tissue, so absorbed doses within the superficial tissues are high, but there is a steep decline in dose deposition with depth. In addition to this, dose deposition in bone is higher in kV radiation due to increased photoelectric interactions. This makes the direct measurement and quantification of doses difficult and complicated. In the diagnostic energy range, radiation levels are commonly measured with air filled ionisation chambers and the accepted method of quantification is in terms of air kerma. The air kerma, defined as the sum of kinetic energy of all charged particles per unit mass through the interaction of the ionising radiation with molecules of air, is closely related to the ionisation effect that damages tissue and to absorbed dose per unit mass in tissue.
4. The quantities that are measured for radiography record the amount of radiation entering the body. These are the air kerma incident on the skin, the entrance surface air kerma (ESAK) which includes back-scatter of radiation from deeper tissues (providing a measure of skin dose) and the kerma-area product (KAP, *P*KA), which is a product of the incident air kerma and the area of the x-ray beam, thus providing a measure of all the radiation entering the body.
5. CT scans irradiate the body or head from multiple directions, and the dose quantities measured are an attempt to derive an approximate value for absorbed doses to organs within the body. The volume averaged CT dose index (CTDIvol, *C*vol) provides a measurement of air kerma related to the average dose within head or body phantoms of standard sizes (ICRP, 2007a, 2024a). Size specific dose estimates are being developed that make adjustments for the size of the patient’s body. Values for the CTDIvol are multiplied by the length of a CT scan in order to provide a measure related to the total dose from the scan, which is called the dose length product (DLP, *PKL*) (see Annex B.1). Surveys of these dose quantities are used in making comparisons with diagnostic reference levels and between centres in diagnostic radiology. However, due to the width of the x-ray field used for CBCT, the concept of CTDI and its measurement in a 150 mm long phantom requires modification for use with radiation therapy. This will be discussed in more depth in section 10.3.
6. Thus, the dose quantities used for measurement of imaging procedures are different from ones used in radiotherapy. Monte Carlo simulations are the only method currently available to accurately compute absorbed doses from imaging to individual organs and tissues (see section 5.2). It is only these absorbed doses which can be compared with those to organs adjacent to the treatment volume from radiation therapy. The effective dose is a whole body dose derived from the summation of doses to organs throughout the body for a reference phantom, weighted according to the risk of stochastic effects (ICRP, 2021). This can be used as an overall assessment of dose related to the risk of stochastic effects (ICRP, 2007b; Murphy et al., 2007; ICRP, 2021). Calculations can be useful in assessing the impact of steps in optimisation, but comparisons with doses from treatment using effective dose are not generally appropriate as this will include the dose to the tissue being treated and those to surrounding tissues exposed to therapeutic dose levels.

## Justification and optimisation of imaging procedures in radiotherapy

1. The principles of radiological protection, justification and optimisation are applied to all medical exposures (ICRP, 2007b). Justification for the use of a radiation technique involves a generic judgement of whether the procedure will improve diagnosis or treatment of the exposed individual that lies with the healthcare professional group, while responsibility for the justification on the use on a particular patient lies with the relevant radiological medical practitioners taking all relevant information on the individual into account. Optimisation of a justified therapeutic procedure involves delivery of the prescribed dose to the tumour and planning the protection of healthy tissue outside the target volume and this includes the appropriate use of radiation for imaging.
2. Imaging during radiation therapy enables radiation field margins surrounding a tumour to be reduced in highly conformal treatments and minimising doses to adjacent tissues from the treatment beam. This should improve the ability to treat each patient’s tumour while limiting the toxicity to other tissues, but all decisions must take account of the ethical dimension to provide the best treatment available for each patient (ICRP, 2024a). The purpose of imaging during the treatment cycle is to verify the accuracy of alignment of the treatment beam in relation to a targeted tumour at the time of treatment. There are four aspects that need to be considered in justification and optimisation of the imaging process.

* ***The imaging modalities used*:** There are significant differences in what available imaging techniques can offer in terms of the amount of information provided and the dose level, so decisions are required about optimum choices for different types of treatment.
* ***The frequency of imaging*:** Increasing the number of images taken will reduce alignment errors, although as the frequency is increased the significance of any adjustments is likely to diminish. When a misalignment error is identified through imaging the patient may be moved to correct this and, in some cases, imaging may be repeated.
* ***Image quality*:** The level of detail in images needed to perform and verify alignments with bony structures for some treatments may be lower than that required for diagnosis for some treatments. The balance between image quality and dose should be adjusted to provide an image quality appropriate for clinical use with the minimum dose.
* ***The volume of tissue imaged*:** The sizes of the fields to be imaged to achieve the required accuracy of target positioning should be restricted to the minimum. This will not only reduce dose but also improve image quality as the amount of scattered radiation is reduced. However, attention should be paid to ensure that the appropriate markers are visible on the images, as this can be a source of treatment errors (see sections 11.2 and 11.3).

1. The imaging modality to be used and the frequency with which imaging is performed should be justified prior to the procedure. The object of optimisation is to identify the level of image quality and the size of the field that are adequate for performing and verifying alignments and adjust the frequency of imaging to balance detriments from additional imaging doses against those from alignment errors. The aim is to achieve the best balance for the benefit of each patient’s well-being (ICRP, 2024a).
2. Practices vary between radiotherapy centres in the imaging modalities used, the frequency of imaging, and the level of optimisation undertaken (Siiskonen et al., 2017, 2024; Wood et al.; 2018, 2024; IRSN, 2020; Martin et al., 2021). Surveys of patient doses from specific types of diagnostic radiology procedure, recorded in terms of the measurable quantities described in section 1.5, are used to identify procedures or establishments for which patient doses are high. Similar surveys performed in multiple centres can be used for comparing radiotherapy imaging doses and establishing national dose reference levels (DRLRTs) based on the 75th percentile of the distribution. This helps to promote standardisation of imaging practices and encourage optimisation through peer comparison (Wood et al., 2018, 2024; Zalokar et al., 2020). Typical values of doses for individual facilities, which equate to the median doses for examinations of the same type of groups of patients, can be used to provide a reference for standardisation and are compared with national or regional DRLRTs to assess performance (ICRP, 2017). Guidance on organising and running dose surveys and setting DRLRTs is discussed in section 10.3.
3. There have been numerous improvements and new features incorporated into diagnostic imaging equipment in the last decade (ICRP, 2024b) and it is important that these are employed and utilised effectively for imaging in radiotherapy where applicable. This requires the education of radiation oncologists about the dose levels from different imaging techniques and their contribution to the overall doses to patients. In addition, therapy radiographers / radiation technologists (RTTs), dosimetrists and medical physicists need to be educated in optimisation techniques for imaging. It requires radiotherapy centre management with guidance from the imaging professionals to acquire equipment with appropriate dose optimisation tools and engage with and encourage vendors to provide them.
4. Imaging parameters should be adapted to the specific task. Lower exposure factors may be suitable for smaller patients, especially paediatric patients who have a higher risk of developing cancer in the future. On the other hand, a higher dose protocol may be the appropriate choice for very large patients with complex presentations. Tumours that have higher contrast, such as bone and lung tumours, can be imaged satisfactorily with significantly lower doses. However, many centres use protocols provided by equipment manufacturers, which are often not optimal in terms of radiological protection, and training of radiotherapy staff often does not include awareness about techniques for optimisation of imaging dose. Imaging protocols from vendors provide a starting point from which optimised protocols can be developed. Image acquisition parameters should be adapted to specific tasks for individual patients both for treatment planning exposures and those during treatments, as they are in diagnostic radiology with lower exposure factors for smaller patients, especially paediatric patients (Zhang et al., 2015a; Wood et al., 2018, 2024).
5. Limiting the size of the field being imaged will reduce the volume of tissue exposed and may allow irradiation of some sensitive organs to be avoided altogether (Ding, et al., 2018; Martin and Abuhaimed, 2022). Although a range of field sizes may be available, standard fields are used frequently for CBCT scans on most patients and this results in more organs being exposed in smaller patients. Use of radio-opaque markers to identify the location of soft-tissue targets, which would otherwise not be visible, can facilitate reductions in fields of view by avoiding the need to include bony markers (Siiskonen et al., 2017, 2024).
6. The direct exposure of certain organs should be avoided. For example, a careful selection of imaging beam incidence directions, or limiting exposure from certain angles in CBCT will minimise doses to the eyes or breasts, while consistent use of bow-tie filters for CBCT will result in better image quality and lower doses (Ding and Munro, 2013).
7. Moving towards agreed requirements and standards for different treatments might assist in improving imaging practices, and sharing experiences between centres would encourage optimisation. National surveys of patient doses from imaging are being carried out (Siiskonen et al., 2017, 2024; Wood et al., 2018, 2024) and other initiatives in which radiation oncology centres might participate to optimise their work should be encouraged. These could ultimately lead to establishment of DRLRTs for common imaging tasks that might provide guidance on appropriate dose levels and alternative approaches.

## Taking account of doses from imaging in treatment plans

1. The doses from MV imaging can be calculated by TPSs assuming the beams are commissioned, although their inclusion varies considerably between centres. However, these planning systems do not currently have the capability to compute doses from kV imaging, for which the distributions are very different. Therefore, at the present time doses received both by target organs and surrounding tissues from imaging are seldom taken into account in treatment planning (Ding and Coffey, 2008; Ding et al., 2018; IRSN, 2020). Inclusion of kV imaging doses would require not only modifications to TPSs, but also measurements characterising imaging beams to be included in planning systems (see section 5.3).
2. Imaging doses must also be seen in the context of doses from leakage and scatter from the treatment beams, which are often not well characterised or calculated by planning systems Taylor and Kron 2011). The provision of more dose information would enable informed decision-making on the selection of imaging protocols by ensuring clinicians have more awareness of doses being delivered by imaging. It could also provide the potential for imaging doses to organs at risk (OARs) and target organs to be accounted for in planning the delivery of treatment. A conservative starting point would be to ignore imaging dose for the target and take full account for OARs. The analysis of normal tissue complications including stochastic effects is providing clinical complication probability data, which can be used together with tumour response results in optimising radiation treatments. Better dose assessments, taking account of all the radiation delivered, should facilitate these developments and lead to steady improvements in optimisation of treatment delivery.

## The development of artificial intelligence applications in radiotherapy.

1. Artificial Intelligence (AI) is a subject of intense research in all fields of medical sciences, with particular progress being made in the field of medical image analysis. AI will undoubtedly play an important role in radiotherapy treatment and image analysis in the future, and applications are already in clinical use both in the shape of commercial products and “home-grown” solutions (Huynh et al., 2020).
2. It is highly likely that AI in the future will have the potential to be used substantially in efforts to minimise imaging dose to the patient, however such methods are still in development and this promise is not yet fulfilled. It is beyond the scope of this report to give an in-depth account of the progresses in AI development in radiotherapy, but it will be an important field to cover in the context of radiation protection in radiotherapy (as well as in other fields) in the near future. Here, we will only briefly introduce some of the developments that are currently of particular interest.
3. Deep learning based on convolutional neural networks is a sub-field of AI which is particularly well conditioned for image processing tasks, such as registration and segmentation of medical images, as well as prediction of radiation dose. The neural networks learn image features in a spatial hierarchy through forward and back propagation through multiple hidden layers. In the training process, a large number of network parameters are optimised to minimise the difference between output estimation and input images with an annotated ground truth. The field is in fast development and a variety of network architectures are emerging suitable for different processing tasks (Zhou et al., 2021).
4. Generative AI, using for instance adversarial networks is one of the more promising approaches enabling for instance synthetic CT images to be generated based on CBCT or MRI images. This development has potential to facilitate significant reduction of imaging dose during the radiotherapy course, as MR and low-dose imaging can be employed to generate synthetic CT images (see sections 6.2.3 and 6.3).
5. More shallow machine learning techniques can potentially be used to automate quality assurance (QA) procedures, minimising the need for patient specific QA and optimising quality assurance schedules to auto-detect errors (El Naqa et al., 2019).
6. Taking a broad look at the potential impact, AI is taking on roles in image acquisition, reconstruction, registration, segmentation, as well as error detection, QA procedures and many other processes. Deep learning-based image reconstruction (DLIR) algorithms are being used to reduce imaging noise, enabling high quality images to be reconstructed from lower dose CT acquisitions and to remove artefacts from items such as dental fillings that can affect calculated dose distributions in treatment plans (ICRP, 2024b). The removal of artefacts in CBCT images is likely to be important for improving image quality in patient localisation and setup in the future (Griner et al., 2020; Dong et al., 2021). DLIR techniques can also enable synthetic CT images to be generated from MR images with the potential to avoid CT planning exposures altogether (Owrangi et al., 2018; Peng et al., 2020; Lerner et al., 2021).
7. Artificial intelligence is already used through image segmentation of organs at risk and target volumes for auto-contouring and has the potential to make real-time predictions of patient organ doses from CBCT examinations (Isaksson et al., 2023). AI is likely to play an increasingly role in adaptive radiotherapy, to take account of changes in patient anatomy from day to day, not only in deciding on adaptation strategies and guiding decision making during each treatment fraction, but also acting as a support tool in predicting likely anatomical changes over the course of a treatment. AI can also aid in the improvement of image guidance practices, for example through retrospective analysis of registration between planning and pretreatment CBCT scans (Luximon et al., 2024).
8. AI advancing the clinical radiotherapy workflow, but models generally appear as black boxes to the users, so commissioning, implementation and QA procedures are essential to ensure proper and accurate operation (Vandewinckele et al., 2020). Any AI application must undergo robust validation and testing during commissioning. This will involve a training/validation phase using large image datasets to tune the model to the clinical need. All centres will need to carry out testing to provide independent evaluation of the performance and investigate the robustness of the model using image datasets for the type of patients to which the model will be applied in the clinic. Development of an understanding about operation and testing of the tools will require guidelines from professional bodies such as the recent guideline from ESTRO and AAPM (Hurkmans et al., 2024), as well as extensive input from AI vendors.

## ICRP reports on radiotherapy, imaging, justification and optimisation

1. Protection of the patient in radiotherapy was first considered by ICRP in *Publication 44* (ICRP, 1984) and this had been preceded by a document considering the patient in diagnostic radiology (ICRP, 1982). Concern about the serious consequences from accidents in radiotherapy saw publications relating to the prevention of such events in external beam therapies (ICRP, 2000c, 2009b) and brachytherapy (ICRP, 2005a). Other publications have focussed on radiation protection for specific types of therapy such as implanted seeds for treatment of prostate cancer (ICRP, 2005b) and ion beam therapy (ICRP, 2014). However, none of these considered the use of imaging in detail, which has expanded enormously within the recent decades. During this time the many developments in radiological imaging for diagnosis, have spawned a series of publications that have included practical methodologies for optimisation to address the needs arising from the new technologies. The imaging modalities considered include digital radiography (ICRP, 2004), fluoroscopically guided interventions (FGIs) with reports addressing the avoidance of radiation injuries (ICRP, 2000b) and the use of FGIs by specialties outside the imaging department (ICRP, 2010), CT (ICRP, 2007a), and cone beam CT (ICRP, 2015), as well as the specific needs in paediatric imaging (ICRP, 2013). *Publication 135* provides guidance on use of the diagnostic reference level tool in optimisation (ICRP, 2017). Publication 154 deals specifically with approaches to optimisation of radiation protection in digital radiology (ICRP, 2023) and *Publication 1xx* updates the recommendations on practical techniques involved in optimisation contained in earlier reports for all radiology modalities (ICRP, 2024b). Radiological protection aspects involved in PET/CT imaging are discussed in *Publication 1xx* (ICRP, 2024c).
2. The present publication provides guidance on radiological protection aspects in the use of imaging in radiotherapy during both planning stages and treatment. Guidance is included for users on optimisation of protocols for exposures carried out prior to treatment, including PET/CT procedures and treatment planning exposures. Choices of imaging modality options during treatment; planar kV x-ray radiographs, CBCT, and MRI, and optimal use of CBCT including 4D methodologies, are considered, as well as the level of optimisation that is appropriate. The frequency at which imaging is justified with the delicate balance between the accuracy of treatment delivery is discussed. The need to initiate surveys of imaging dose to establish DRLRT values as standards against which dose comparisons can be made is considered. These will assist in the identification of imaging protocols where further optimisation is required.
3. The report also examines the need for more information on assessment of organ and tissue doses relating to imaging for communication to radiation oncologists and possible inclusion in the planning process. The development of software for evaluating doses to organs being imaged is reviewed and consideration given to how facilities could improve results on absorbed doses to organs outside the target volume from imaging. Studies undertaken to determine the feasibility of inclusion of imaging dose in treatment prescription in the light of developing technologies are examined and advice provided on the future direction of this development for users and equipment manufacturers. The introduction of image guidance and the rapidly evolving imaging technologies have led to substantially greater accuracy and precision of radiation treatment delivery, and optimisation of radiological protection for related imaging should enable clinical outcomes of treatments to be as good as possible.

# RADIOTHERAPY TREATMENT PLANNING AND DELIVERY

1. **Key points in this section:**

The advent of motorised multi-leaf collimators (MLCs), intensity modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT) coupled with advanced treatment planning software (TPS) improved the precision of radiation treatment delivery but requires imaging to guide and verify treatment location.

Targeting accuracy is critical for the success of Stereotactic Radiation Therapy treatments for which any geometric miss can result in failure and local recurrence or could lead to severe adverse effects.

Proton therapy deposits dose in tissue over a narrow range of depths, enabling lower doses to be given to healthy tissue before and after the tumour target and this deposition pattern is advantageous for treatment of paediatric patients.

High dose rate (HDR) after-loader implants in brachytherapy can be accurately localised on volumetric imaging. This allows precise treatment plans, which detail the relationship of the implant's location to the target volume and adjacent OARs to be created.

CT is the most common imaging modality used for treatment planning and dose calculation, as it is free of distortion and provides a linear relationship between the tissue mass and electron densities required by dose calculation algorithms.

Imaging provides comprehensive 3D anatomical data with modalities like CT, CBCT, magnetic resonance imaging (MRI) or ultrasound providing direct visualisation of the targets and organs at risk (OARs) and has led to improved precision and accuracy of radiation delivery.

Dose margins for radiotherapy delivery are used to account for uncertainty in target delineation, anatomical changes, microscopic extension, patient set-up and delivery. The choice of imaging modality and technique determines the size of margins.

## External beam radiation therapy

1. The main modality for generating therapeutic radiation is External Beam Radiation Therapy (EBRT). Radiation treatments are delivered with collimated bremsstrahlung photons generated by linear accelerators (linacs) with energies ranging from 3 MeV to over 20 MeV or 60Co radioactive sources emitting gamma-rays with energies of 1.17 MeV and 1.33 MeV . Linacs are by far the preferred modality for EBRT and most can also deliver electron beam therapy. The advantage of linacs over radioactive sources is the delivery of constant dose rates versus source decay and additional national security and radiation safety concerns. In addition, linacs can deliver higher energy photons than radioactive sources, which increases penetration and reduces skin dose.
2. 60Co treatment units can be cheaper and less complex to operate than linacs and provide an attractive solution for low to middle income countries (LMICs). EBRT can also be delivered with protons, other charged particles or neutrons. It should be noted that a number of manufacturers have developed cheaper, single energy linacs, which are easier to maintain than multi-energy linacs.

### Linac based 3D conformal radiation therapy (3DCRT)

1. For a long time teletherapy consisted of 2D delivery techniques employing large radiation treatment fields delineated on radiographic films. The invention of computed tomography (CT) coupled with technological advances in beam shaping devices lead to the development of 3-D conformal radiation therapy (3DCRT) (Fraass, 1995). The 3D volumetric information on patient anatomy obtained with a CT scan allows the direct visualisation and contouring of the targets and OARs (ICRU, 1994).
2. The advent of motorised multi-leaf collimators (MLCs) and treatment planning software (TPS) improved the precision of radiation treatment delivery. The use of MLCs and TPSs allowed smaller treatment fields, reducing toxicity and opened up the possibility of escalating dose to improve tumour control rates.

### Intensity modulated radiation therapy and volumetric modulated arc therapy

1. While uniform fluence is delivered for all beams in 3DCRT, intensity modulated radiation therapy (IMRT) generates non-uniform beam intensities to achieve the desired therapeutic dose distribution. The intensity modulation is achieved by the motion of computer-controlled MLCs along with other optimisable parameters such as dose rates, gantry and collimator angles, etc. to define a series of apertures that result in non-uniform beam intensity profiles. Volumetric Modulated Arc Therapy (VMAT) allows additional degrees of freedom for beam fluence modulation through delivering radiation while the gantry and MLCs are in motion. In both IMRT and VMAT, the beam apertures and fluence profiles are determined through inverse planning by the TPS, which employs user-defined dose constraints for the target and dose limitation objectives for OARs.
2. With respect to 3DCRT, IMRT techniques enhance the conformity of treatments delivery. They enable the treatment of targets with complex shapes located near to OARs, while allowing for steep dose gradients at boundaries between targets and OARs.

### Stereotactic radiosurgery (SRS)/stereotactic body radiotherapy (SBRT)

1. Stereotactic radiosurgery (SRS) aims to deliver an ablative dose to a single or multiple tumours of the central nervous system (CNS) in a one to five fraction treatment course (Fanous et al., 2019). SRS treatments are delivered with MV linac beams or a Gamma Knife, which contains 201 60Co sources. The collimated beams from these sources are precisely directed at the tumour target. Linac based intracranial SRS typically uses non-coplanar static beams or arcs with fields defined by collimator cones or MLCs. The concept of SRS is extended to extracranial targets in SBRT making use of advanced image guidance and motion management. Targeting accuracy is critical for the success of precision radiotherapy treatments as any geometric miss will likely result in treatment failure and local recurrence or could lead to severe adverse effects.

### Hadron therapy

1. Hadron therapy was pioneered at Berkeley, CA where patients were first treated with fast neutrons in 1938 (Lawrence et al., 1936) and protons in 1954 (Tobias et al., 1958). There are now more than a hundred facilities worldwide equipped to provide particle therapy (IAEA, 2021b), the majority delivering protons. The ranges of protons in tissue increase with their initial energies. Protons’ energy deposition in matter is initially low, rising gradually until it reaches the end of the proton range, where it peaks sharply at the Bragg peak, followed by an abrupt drop to zero (ICRP, 2014). This allows for dose deposition in tissue over a narrow range of depths, which is determined by the proton energy. This dose deposition pattern is particularly advantageous for paediatric patients, as their small size leaves less physical separation between the tumour and OARs, making the transition from tumour dose to low dose more challenging. Minimising the risks of second radiation-induced primary malignancies is also crucial in these cases. The same principle applies for adult patients where tumours are localised in the vicinity of radiosensitive structures. A small number of centres in the world offer carbon ion therapy, which uses ionised carbon atoms to take advantage of their sharper Bragg peak and higher radio-biological effectiveness (RBE) when interacting in tissue (Mohamad et al., 2018). Neutron therapy combined with boron (Malouff et al., 2021), has also been utilised given its high radiobiological effectiveness. Due to the importance of accurate range determination of hadrons, imaging at the time of treatment is increasingly considered essential to not only verify the anatomy but also the radiological depth.

## Brachytherapy

### Brachytherapy sources

1. Brachytherapy uses sealed radioactive sources to deliver radiation treatment inside or near tumours. The dose distributions are heterogeneous, created by steep dose gradients due to the proximity of the treated tissue to the sources, which allows for the sparing of surrounding healthy tissue. Table 2.1 lists the common radionuclides currently used for brachytherapy. Many brachytherapy sources contain radionuclides encapsulated in small seeds or encoded plaques which be used individually, in strands, or welded at the end of a wire and introduced remotely.

Table 2.1. List of isotopes currently used clinically for brachytherapy treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Isotope | Mean energy (keV) | Half-life(T1/2) | Uses | Implant type |
| 137Cs | 662 | 30.05 y | LDR | Temporary |
| 125I | 35 | 59.39 d | LDR | Permanent |
| 192Ir | 372 | 73.83 d | LDR / PDR / HDR | Temporary |
| 103Pd | 137 | 16.991 d | LDR | Permanent |
| 131Cs | 30 | 9.689 d | LDR | Permanent |
| 60Co | 1253 | 5.27 y | HDR | Temporary |
| 106Ru | 3.54 | 373.59 d | HDR | Temporary |

### Brachytherapy delivery types

1. Brachytherapy can be delivered as intracavitary, interstitial, intraluminal, intravascular or as surface therapy. Surface brachytherapy treatments are used to treat superficial skin lesions or tumour resection sites in an intra operative RT setting (Fulkerson et al., 2020; Conejo et al., 2021). Eye brachytherapy through 106Ru plaques is used effectively for localised, precision treatment of uveal melanoma, offering significant tumour control with minimal impact on surrounding healthy tissues (Tarmann et al., 2015; Jiang et al., 2020). Intracavitary brachytherapy is used for the treatment of multiple cancers such as gynaecological, bronchus and oesophageal lesions (Lettmaier and Strnad, 2014; Stewart et al., 2016; Skowronek and Zwierzchowski, 2017; Holschneider et al., 2019). Endovascular brachytherapy delivers a high localised dose to prevent the restenosis of arteries for patients with stents (Gowda et al., 2004). Interstitial brachytherapy treatments are delivered through needles or catheters implanted in the patients’ tissues.
2. Seed sources may be placed inside the body as permanent implants using pre-loaded needles, delivering treatments at a low dose rate to minimise the development of late tissue effects. Alternatively, they can be temporarily placed in shells or plaques, available in various shapes such as circular, notched, or horseshoe, tailored to the size and location. Temporary implant sources are after-loaded in catheters or intra-cavitary applicators inserted in the treatment area beforehand. Brachytherapy treatments can be delivered with Low Dose Rate (LDR) 0.2-2 Gy h-1, Pulsed Dose Rate (PDR) 2-12 Gy h-1, or High Dose Rate (HDR) > 12 Gy h-1 (ICRU, 1985). LDR is typically delivered with sealed radioactive sources that may be placed manually or remotely with needles or intraluminal devices (Gibbons, 2020). HDR brachytherapy is delivered with a single high activity (~ 370 GBq) source welded at the end of a wire in a remote after-loader and moved under computer control remote to a series of dwell positions (Strohmaier and Zwierzchowski, 2011). PDR brachytherapy employs a lower activity source (~ 37 GBq) to deliver periodic treatment ‘pulses’ over 10 to 30 min every ~ hour (Balgobind et al., 2015) mimicking the traditional LDR treatment use of which is declining. Use of remote after-loaders limits radiation exposure to treatment staff, however, the high activity of HDR sources requires the use of specially shielded rooms.

### Treatment sites

1. The main brachytherapy treatment sites include gynaecological, prostate, breast and superficial skin cancers. High Dose Rate (HDR) brachytherapy delivered with a high activity 192Ir or 60Co source remains the most effective and widely used treatment for managing cervical cancer patients (Banerjee and Kamrava, 2014; Holschneider et al., 2019; Harkenrider et al., 2015). It is also used for prostate cancer, either as monotherapy for primary or recurrent tumours or as a boost after EBRT (McLaughlin and Narayana, 2020). Permanent LDR implants are delivered with 125I or 103Pd seeds (Stish et al., 2018) HDR brachytherapy is a commonly used treatment method delivered in different fractionation schedules, either in single or multiple applicator insertion sessions. This technique is utilised across various types of cancer, including gynaecological and breast cancers, as well as in areas like the head and neck, lungs and oesophagus.

## The role of imaging in radiotherapy

### The roles of imaging before, during and after treatment

1. Imaging has become an integral part of modern radiation therapy. The roles of the various modalities during clinical evaluation, planning, treatment and follow-up of patients for external beam radiotherapy are illustrated in Fig. 2.1. The clinical evaluation involves diagnosis and tumour staging to inform the decision about the therapy to be prescribed. Imaging modalities employed in this crucial initial step are not listed as they are not specific to radiotherapy.

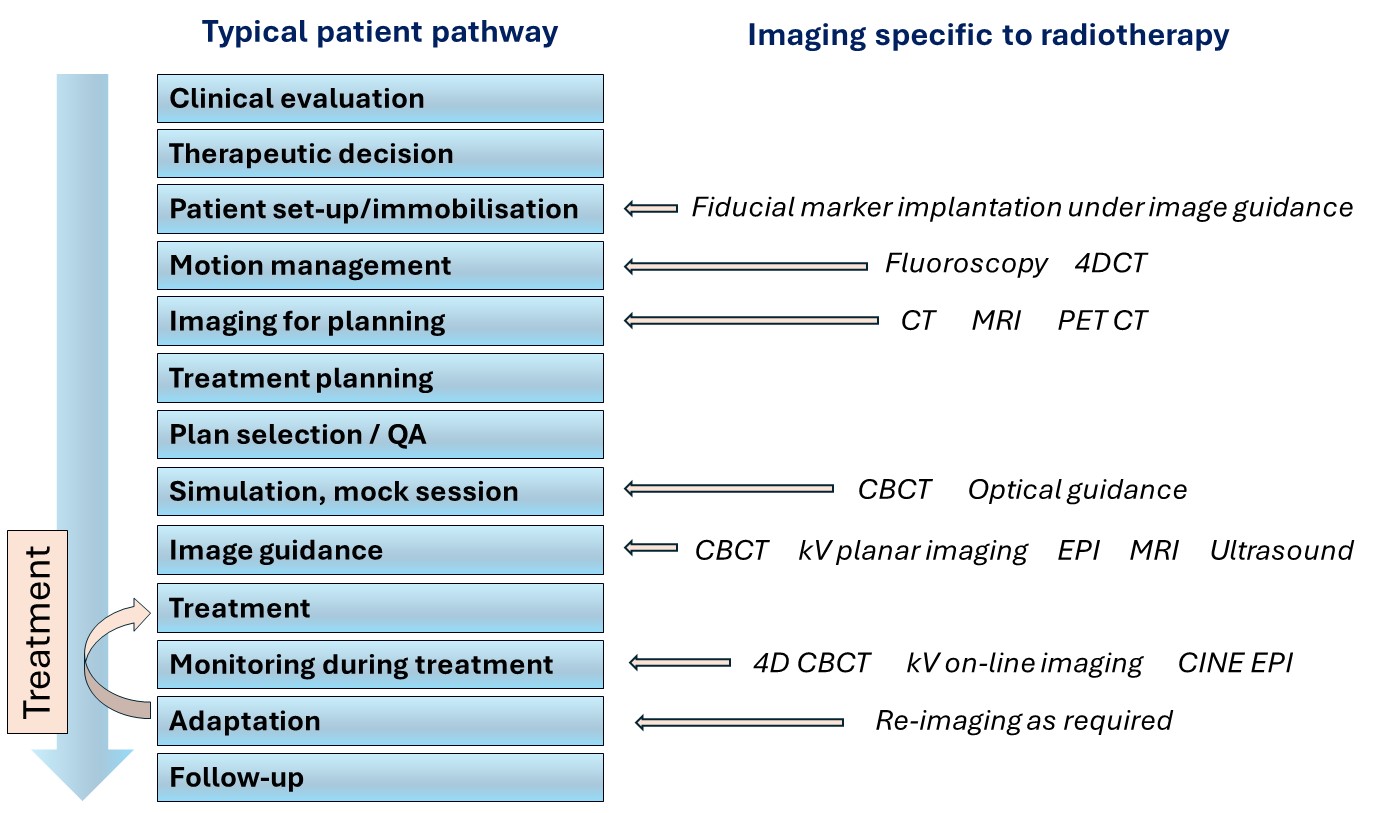


Fig. 2.1. A typical pathway that patient management will follow for external beam RT showing the steps where imaging is introduced specifically for the purpose of RT delivery. The figure has been adapted from IAEA (2008a) and demonstrates the cyclical nature of the multi-fraction treatment process in an adaptive setting.

1. Imaging has significantly enhanced the precision and accuracy of radiation delivery. The range of imaging modalities has expanded from the use of 2D radiographic films to 3-D image sets encompassing multi-modalities, each providing different and complimentary information useful for patient care. Additionally, imaging is the cornerstone of adaptive radiation therapy where treatment plans are modified according to internal anatomical changes monitored throughout the radiation treatment course.
2. The role of imaging in radiation therapy goes beyond the traditional CT simulation required for treatment planning and patient positioning prior to treatment delivery. Magnetic resonance imaging (MRI) provides additional anatomical information and offers better soft tissue contrast than CT. Positron emission tomography (PET) and PET-CT modalities can identify areas of metabolic activity and are routinely used to localise nodal targets in various sites, including head and neck, mediastinum, and pelvis, as well as to detect bone metastases. Single photon emission CT (SPECT), kV and MV cone beam CT (CBCT) and ultrasound are all part of the array of techniques employed by the multi-disciplinary imaging team to improve the efficacy of radiation therapy treatments. Similarly to Fig. 2.1, Fig. 2.2 shows the role of imaging during a representative brachytherapy treatment workflow, where a greater use is made of ultrasound in the assessment and monitoring of treatment.

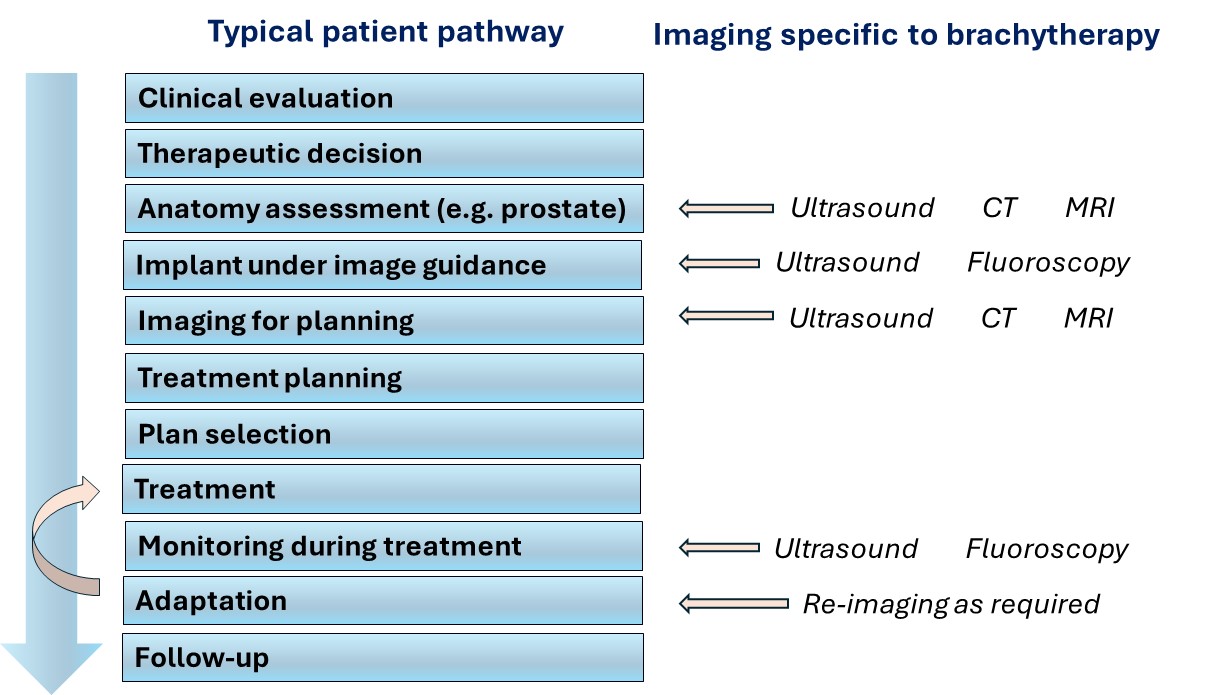


Fig.2.2. A typical pathway patient management will follow for brachytherapy showing the steps where imaging is introduced. US ultrasound, MRI magnetic resonance imaging. The image has been adapted from IAEA (2008a).

### Defining dose margins

1. Dose margins are used in radiotherapy to account for uncertainty in target delineation, anatomical changes, microscopic extension, patient set-up and delivery. The choice of a specific imaging modality and technique is important to determine the size of margins for radiotherapy delivery. The International Commission on Radiation Units and Measurements (ICRU) distinguishes between margins that account for different uncertainties as shown in Fig. 2.3 (ICRU, 2000, 2008):
2. **Clinical margins** that acknowledge that microscopic tumours may be present in parts of the tissue surrounding the gross tumour volume (GTV) even if this is not discernible in diagnostic procedures. This clinical target volume (CTV) is based on clinical judgement.
3. **Internal margin**s which account for deformation, differences in organ filling, and organ motion during treatment. Volumetric image guidance allows assessment of organ deformation and filling, and motion management requires real-time information. Motion management is discussed in more detail in the next section.
4. **Set-up margins** account for any geometric displacement between the isocentre in treatment planning and delivery. These differences would be detected by two orthogonal x-ray images, surface imaging techniques or any volumetric imaging modality.
5. Fig. 2.3 illustrates the approach to margins suggested by the ICRU. The target for treatment that can be clearly identified from palpation, clinical investigation or imaging (the Gross Tumour Volume, GTV) is expanded to guide the actual delivery to ensure that, within an acceptable probability, the identified target is within the high dose region. In general, this leads to two expansions: a) the inclusion of tissues that are likely to contain tumour cells (the Clinical Target Volume, CTV) and b) an allowance for all uncertainties that can affect targeting.

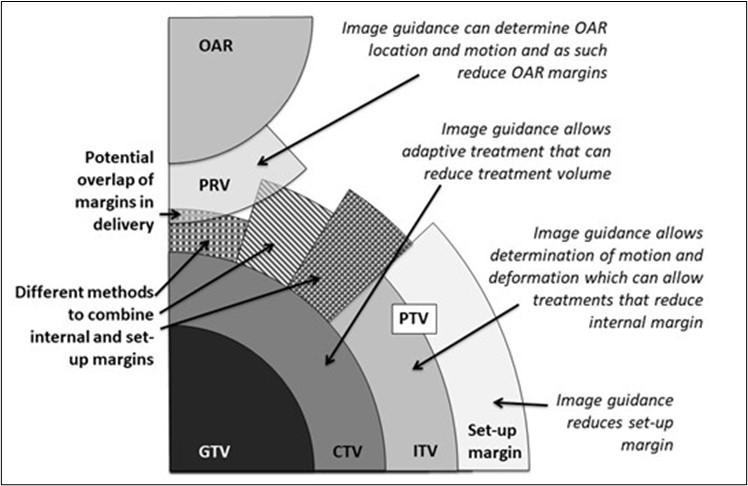


Fig. 2.3. Illustration of the volumes proposed by the ICRU for guiding radiotherapy treatment planning. GTV = Gross Tumour Volume; CTV = Clinical Target Volume; ITV = Internal Target Volume; PTV = Planning Target Volume; OAR = Organ at Risk; PRV = Planning Organ at Risk Volume. The impact of image guidance is illustrated. (T Kron, Peter MacCallum Cancer Centre, Melbourne, Australia, adapted from ICRU, 2008, permission being sought).

1. Larger setup margins increase the probability that the target is covered by radiation, as they account for all treatment delivery uncertainties. The size of the margin is a balance: while larger margins ensure the tumour is covered by radiation under all circumstances, they also increase the volume of normal tissue in the high dose region, raising the risk of toxicity. The larger radiation fields required to treat the greater volume encompassed by large margins increases the volume irradiated via the beam path (up and downstream from the target) and the scattered radiation, which increases the lower doses in more distant parts of the patient’s anatomy. This makes margins an important consideration for radiation safety. Image guidance can reduce uncertainties, potentially resulting in smaller margins and less normal tissue irradiation.
2. As clinical practice evolves to deliver larger doses per fraction and per treatment course, normal tissue tolerance increasingly limits the dose that can be safely delivered to a target. The concept of margins, and even that of OAR is being extended to normal tissues. The selection of the image guidance approach will depend not only on the technique and image quality but also on the information regarding the margins to be applied. This is illustrated in Fig. 2.3 which also lists selected impacts of image guidance on margins.

# CLINICAL JUSTIFICATION FOR IMAGING IN RADIOTHERAPY

1. **Key points in this section:**

The decision to use additional radiological imaging, which increases the patient’s radiation exposure, must be justified by the anticipated clinical benefit.

Key considerations include the imaging modality, the feasibility of visualising critical anatomical structures, the ability to make necessary adjustments, and the associated risks and potential benefits.

Adaptive radiotherapy requires a larger number of high-quality images to make and verify adaptations. This need must be carefully weighed against the clinical justification of the imaging protocol and practical considerations

The frequency of imaging may depend on patient type, treatment site, disease entity, available resources and the treatment protocol. Any deviation from a predefined imaging protocol for an individual patient should be clinically justified.

Justification of the frequency of imaging for a type of treatment requires input from radiation oncologists, therapy radiographers/radiation technologists (RTTs) and medical physicists.

Recommendations from national societies and official bodies, based on practice surveys, offer specific guidance on general imaging strategies and for particular clinical sites and scenarios, with regular updates.

## Clinical benefits of imaging

1. High quality imaging for planning and treatment guidance have enabled the pursuit of answers to a wide range of questions in radiation therapy, such as those concerning dose escalation, target volume reduction, and the treatment of targets with complex geometry.
2. A 2012 literature review (Bujold et al., 2012) addressed these issues in three important questions about image guidance in radiotherapy: Whether image guidance (a) improved tumour control, (b) reduced toxicity and/or (c) lead to the treatment of patients who would otherwise not have received radiation therapy.
3. With this in mind, image guidance involves a balance between benefit and risk, and it is useful to look at the benefits from the clinical perspective as listed below.

* Improved treatment accuracy enables an increase in tumour dose with potential for better tumour control.
* Irradiation of smaller volumes through reduced margins enables a potential reduction in risk of complications.
* More accurate and potentially faster treatments could improve access to radiation therapy, similar to introducing a new indication for treatment. Enhanced accuracy and targeting may also enable new therapeutic applications.
* Provision of data can be used to determine the appropriateness of delivering treatment. This becomes a consideration for instance when the patient anatomy has changed so much that treating the patient might now be inappropriate.

1. On a population basis, the accumulation of imaging information for large groups of patients, can be used to develop imaging and treatment practices. Specific imaging protocols used over longer periods of time may be linked with information from record-and-verify systems with numbers from actual usage, and potentially even with outcome data, to inform the establishment of future imaging protocols.
2. With the increasing use of adaptive radiotherapy an increased number of images will be required, to not only decide on the adaptation but also to verify it. Often these images will be acquired with a high quality to be adequate for deformable image registration, dose accumulation and tracking, and rapid replanning. From the radiologic protection viewpoint, this should be carefully balanced with the clinical justification of the imaging protocol, as well as with key factors of practical considerations.

## Key factors in considerations for justification

1. To consider the place of imaging in clinical practice, some key factors should be analysed, answering relevant questions to establish an institutional standardised guideline. The decision to use any added radiological imaging, which will result in additional radiation exposure to the patient, must be balanced by the clinical benefit foreseen. The key factors that should be incorporated into good clinical practice, based on clinical guidelines and reflecting evidence are:

* **Resources** - Which imaging modality is available and accessible for the patient considering the available time and staff?
* **Feasibility 1** – How well will the additional imaging visualise and define key anatomical structures, such as the target and organs at risk (OARs)?
* **Feasibility 2** - Is the imaging modality compatible with all other aspects of the treatment (e.g. MR compatibility)?
* **Operationality** - Can mitigating or adjustment measures be performed in adequate time if indicated by the imaging?
* **Risks** – What are the potential benefits to the patient compared to the potential risks when selecting a specific imaging modality and frequency? Have the uncertainties and limitations been identified and evaluated?

1. Justification requires input from radiation oncologists, therapy radiographers/radiation technologists (RTTs) and medical physicists and should be given for:
2. The imaging modalities to be used.
3. The frequency at which imaging is required for the treatment with the caveat that imaging only be used when necessary.

## Considerations for specific clinical scenarios

1. Image guidance has been implemented for a wide range of disease sites, including the brain, head and neck, lung, thorax, mediastinum, breast, chest wall, liver, pancreas, and prostate, along with pelvic tumours, gynaecologic tumours, and paraspinal, spinal, and craniospinal sites. The frequency of imaging has been studied for some but not all clinical scenarios and may be driven by the patient type, treatment location, and disease entity, as well as by human and local departmental resources, reimbursement considerations, and the treatment protocol. Deviation from the predefined imaging protocol for an individual patient should necessitate a clinical justification.
2. Decision points for imaging strategies in clinical practice include the choice of optimal imaging modality, the frequency of use and the relevant tolerances. Some examples of considerations for generic clinical scenarios are given in Table 3.1. Volumetric imaging may include CBCT, in-room CT or more recently MRI, whereas low dose imaging will most often consist of orthogonal kV or MV images.
3. In each clinical site, specific considerations regarding the potential clinical benefit, expected dose magnitudes, the nature of the setup and anatomical variations, required image quality, and patient specific factors etc, will form the basis for decisions on the choice of predefined imaging protocol and potential deviations from it. In addition, the types of imaging modalities available and the intended treatment delivery technology can significantly affect the choice of imaging strategy. Examples of specific considerations for a range of clinical sites are given in the following sub-sections.

Table 3.1. Considerations when making decisions about image guidance

|  |  |
| --- | --- |
| Scenario | Suggested imaging approach |
| High accuracy requirements (e.g. SBRT/SRS) | Volumetric imaging prior to delivery, consider post-treatment imaging to assess impact of intrafraction motion |
| High risk treatment (e.g. proximity to sensitive structures) | Volumetric imaging prior to delivery, also intrafraction monitoring in cases of motion |
| Paediatric radiotherapy | Low dose imaging (if appropriate), consider frequency necessary |
| Systematic difference between planning and treatment expected (e.g. weight loss) | Frequency of imaging balanced with the magnitude of errors expected and the requirement for margin reduction |
| Random variations expected between fractions (e.g. bladder filling, intestinal motion) | Consider high frequency of imaging balanced with the magnitude of errors expected |
| Significant intrafraction motion expected (breathing) | frequent imaging during delivery or use of surrogate markers to monitor motion and link to imaging prior to delivery. |

SBRT – stereotactic body radiation therapy, SRS stereotactic radiosurgery

### Brain

1. For treatment in the brain, bony anatomy setup is usually adequate as there is little risk of soft tissue variation over the treatment course. Exceptions include monitoring of treatment response in order to potentially adapt or change the treatment prescription.
2. Brain radiosurgery is an example of a scenario in which toxicity has been attributed to large PTV margins (Jhaveri et al., 2018). The transition of radiosurgery single-fraction treatments from frame-based treatments, in which the patient was immobilised, to frameless treatments has been enabled by image guidance. It has allowed more patients to receive the benefit of that modality, facilitating treatments without a mobilisation device not only for the brain but for multiple other sites throughout the body.

### Head and Neck

1. Marked anatomical changes are known to happen during radiotherapy of head and neck cancers, giving justification for frequent imaging during treatment (Bobic et al., 2023; Noble et al., 2019). The most prevalent anatomical changes include weight loss, swelling, filling of cavities, flex and shoulder movement, and tumour and/or nodal volume regression. The soft-tissue contrast is low in the head and neck region, and the effects of anatomical changes on target coverage will require volumetric imaging. In addition, even the gross variations in patient outline and bony anatomy will be geometrically complex, and thus difficult to discern accurately in 2D images (Kearney et al., 2020). Therefore, CBCT scanning (or in-room CT scanning) is performed on a daily basis in many clinics, with the dual aim of accurate localisation and assessment of anatomical changes for potential treatment adaptation.
2. Normal tissue toxicity is a major concern in head and neck cancer radiotherapy and is a limiting factor for delivering adequate dose to the target. Margin reduction is therefore desirable, providing additional justification for frequent imaging during treatment. In several studies, reduced toxicity and improved outcome has indeed been demonstrated with use of image-guided radiotherapy in head and neck cancer (Navran et al., 2019; Håkansson et al., 2023).

### Thorax

1. In the thorax region, the respiratory cycle causes movement of organs and potentially also the target during irradiation. Depending on the treatment strategy (encompassing margins ≈ internal target volume [ITV], gating, breath-hold or tumour tracking), this may require some level of real-time imaging capable of resolving the motion of relevant structures (Korreman, 2015). Motion imaging prior to beam-on may be achieved with on-board fluoroscopy or 4D-CBCT. While fluoroscopy may be adequate to measure the magnitude of motion of a tumour in the lungs, soft tissue visibility of for instance the abdominal wall or centrally located tumours will require volumetric imaging. Also, 3D imaging is required in order to resolve more complex motion trajectories beyond just magnitude.
2. Imaging of bony anatomy in the thorax region is difficult to use for localisation (owing to difficulty in correctly distinguish level of ribs and vertebrae longitudinally) and does not give information regarding motion of soft tissue. However, for soft tissue imaging in the lungs, the contrast is high and low-dose imaging could be considered.
3. Image guidance has been shown to enable successful adaptive radiotherapy in lung cancer with improved outcome (Møller et al., 2022), and even to enable safe dose escalation in lung tumours (Møller et al., 2017; Schytte et al., 2024).

### Breast

1. For breast cancer, margin reduction and/or dose escalation is typically not the desired objective of image guidance, rather the accuracy provided by imaging aims to increase accuracy in targeting and maintaining low doses to organs at risk. In particular, for patients with left-sided breast cancer, lung inflation through respiratory gating or deep inspiration breath-hold is a standard technique which has been shown to reduce doses to the heart and lungs (Lu et al., 2022). Imaging may be required to ensure reproducibility of the level of lung inflation on a daily basis. Given the high visibility of the patient surface and the chest wall, orthogonal 2D-2D imaging may be adequate for the purpose using either kV-kV or kV-MV (with the MV image visualising the outer contour of the patient’s body). Similarly, optical surface guidance can help to verify the position of the patient and monitor intrafraction motion without using ionising radiation (Li, 2022).
2. The use of lung inflation using deep inspiration breath hold (DIBH) during treatment enables inclusion on the internal mammary nodes in the treatment target for high-risk patients for whom this has been shown to increase overall survival (Thorsen et al., 2022), without compromising the strict constraints on the dose to the heart (Nissen and Appelt, 2013).
3. In addition, imaging of the tangential MV treatment beam may be used to verify the locations of the heart, the chest wall and the outer patient contour throughout gating/breath-hold treatment (Kron et al., 2022; Vasina et al., 2022) with no extra dose to the patient.

### Gastro-intestinal cancers

1. In a large real-world data set investigating effects of image guidance, it was demonstrated that residual setup errors that resulted in the beam being closer to the heart correlated with increased heart toxicity in patients with oesophageal cancer (Johnson-Hart et al., 2020). This effect was also shown for lung cancer patients in the same study, indicating the importance of image guidance for assessing the effect of treatment in the vicinity of critical organs at risk.
2. For some cancer sites in the upper abdomen (e.g. liver and pancreas), respiratory gating or breath-hold may be employed as a means to reduce treatment margins and increase the accuracy of treatment in particular when SBRT is used (Sharma et al., 2022; Shouman et al., 2024).

### Genito-urinary cancers

1. In the pelvic region, anatomy is highly variable due to the irregular and unpredictable nature of bowel and bladder filling over time. This makes imaging crucial for achieving high accuracy in treatment delivery. As most variation happens in soft tissue, volumetric imaging with soft tissue contrast will most often be warranted, and in many clinics CBCT or in-room CT is used on a daily basis (Webster et al., 2020). To control bladder volume also ultrasound may be a suitable choice using a bladder scanner prior to radiotherapy to assess the consistency of bladder filling on the day (Smith et al., 2022).
2. Controlling the bladder volume is also highly desirable to reduce margins in bladder cancer. Daily CBCT can be used for this also enabling a type of adaptive radiotherapy where the most suitable plan for the patient’s bladder filling is selected based on imaging (Murthy et al., 2011; Huddart et al., 2021). This ‘plan of the day’ approach can reduce margins and therefore potentially reduce integral patient dose despite the additional imaging (Kron et al., 2010).
3. For prostate cancer, the primary objective of image guidance is to reduce margins (with potential for dose escalation) (Wang et al., 2023), and a technique to minimise radiation dose is to implant gold seeds which can be localised in 2D-2D orthogonal kV images with high accuracy (Logadottir et al., 2011). While this avoids the need for CBCT, the downside is that it is an invasive procedure and soft tissue surrounding the prostate is not visible.
4. For cancers of the female reproductive system where marker placement is not used and the primary objective is to limit toxicity, volumetric imaging with soft tissue contrast is warranted to verify daily anatomy, for localisation and potential adaptation of treatment (Eng et al., 2013; Guberina et al., 2023).

### Pregnant patients

1. In the case of pregnant patients requiring radiotherapy, the clinical justification for using image-guided radiotherapy must be carefully evaluated due to the potential risks to the developing fetus. Image guidance is particularly advantageous for ensuring precise dose delivery, improved tumour targeting while minimising radiation exposure to healthy tissue. This is crucial for pregnant patients to mitigate radiation risks to the fetus, such as malformations, growth retardation, or neurocognitive impairments, which may arise if radiation doses exceed established safety thresholds (AAPM, 1995; NCRP, 2013; ICRP, 2000a).
2. The use of volumetric imaging modalities such as cone-beam CT (CBCT) allows for improved localisation of the target, but the additional imaging dose must be accounted for, especially given the vulnerability of the fetus to ionising radiation. Optimised low-dose imaging techniques and appropriate fetal shielding are essential to reduce out-of-field radiation (Wong et al., 2023).
3. A multidisciplinary approach involving radiation oncologists, medical physicists, and obstetricians is essential to monitor and manage fetal dose throughout the treatment course. While no dose is the ideal every effort should be made to ensure the fetal dose remains below the established threshold of 0.1 Gy (Michalet et al., 2022). When these precautions are taken, image guidance can be justified as it enables effective treatment while safeguarding fetal health.

## Existing recommendations and practice guidelines

1. Surveys of practices have been carried out and recommendations published by a number of national societies and official bodies. Specific recommendations of imaging strategies of a general nature as well as for various specific clinical sites and scenarios can be found in such documents, often with regular updates, following the development of practices and possibilities.
2. In Europe, some ESTRO-ACROP guidelines include evidence-based recommendations for use of imaging (https://www.estro.org/Science/Guidelines), and the National Radiotherapy Trials Quality Assurance Group (UK) reviews specific protocols for clinical trials (https://rttrialsqa.org.uk/).
3. The American College of Radiology (https://www.acr.org/Clinical-Resources/ACR-Appropriateness-Criteria) and American Society of Radiation Oncology (https://www.astro.org/patient-care-and-research/clinical-practice-statements/image-guided-radiation-therapy) (Luh et al., 2020), as well as The Royal Australian and New Zealand College of Radiologists have issued recommendations for image guided radiotherapy.
4. As there may be existing guidelines and recommendations for specific protocols, clinical sites and scenarios, considerations regarding choice of imaging strategy in a specific situation may be relevant.

# THE PROCESS OF OPTIMISATION OF IMAGING

1. **Key points in this section:**

Radiotherapy staff should be aware that the volume of tissue imaged for planning and verification of radiotherapy is often considerably larger than the treatment volume and may include critical structures.

Opportunities for optimisation of patient imaging should be considered when planning the acquisition of new imaging equipment.

Optimisation of exposure factors and the volume of tissue to be imaged for a particular clinical task requires input from radiation oncologists, RTTs and medical physicists.

More medical physicists trained in radiology imaging skills related to patient dosimetry and optimisation techniques are needed in radiotherapy departments. If expertise in imaging is limited, assistance should be sought from medical physics colleagues in diagnostic radiology.

Optimisation teams for imaging should be set up comprising radiation oncologists, RTTs and medical physicists to optimise protocols for each type of procedure.

Requirements for routine quality control (QC) on imaging equipment, audits of patient doses, and continual feedback of information into optimisation of imaging protocols should be included as part of quality management systems.

Regulators and governments can encourage optimisation through inclusion of requirements for QC of imaging equipment, audit of patient imaging doses and setting of DRLRTs in regulations and monitoring through inspections.

Professional organisations can play a role in development and improvement of optimisation processes and techniques by issuing professional recommendations and good practice guidelines

## Choices to be made for imaging

1. All radiotherapy staff should be aware that the volume of tissue imaged during planning and verification of radiotherapy is often considerably larger than the treatment volume and may include critical structures. Since imaging may be performed at many fractions, all exposures should be justified and techniques optimised to minimise doses to adjacent organs and tissues.
2. The full implementation of justification and optimisation for radiological protection, when imaging is used in radiotherapy, requires a consistent approach that is applied routinely for all treatments. Justification should be given for:
3. The imaging modalities to be used
4. The frequency at which imaging is required for the treatment with the caveat that imaging only be used when necessary
5. There are at least two components of imaging for any treatment for which decisions have to be made about optimisation of radiological protection that can be for a population group or an individual patient:
6. The volume of the region to be imaged
7. Exposure factors and reconstruction parameters required to achieve the appropriate level of image quality for the specific clinical task.
8. All these decisions will potentially affect the RT dose margins that can be used and as such impact the treatment related dose received by the patient. There need to be systems in place to facilitate consistent and validated choices for all of these. While selecting the imaging modality is ultimately the responsibility of the treating radiation oncologist, each component benefits greatly from inputs provided by all professionals involved in the treatment process: radiation oncologists on the medical needs and condition of the patient, therapy radiographers and radiation technologists (RTTs), on the practical aspects and clinical usefulness, medical physicists on the implications for dose, image quality and RT treatment optimisation. In the justification, the choice of imaging modality for individual patients may be limited by the equipment available, but the frequency of imaging will require input from all professionals. Although the frequency of imaging should be part of the justification, this may also be adjusted further for optimisation of radiological protection during the course of treatment.

## Selection and use of imaging equipment

1. The choice of imaging modality to use as part of any treatment will depend on availability of that modality and will be decided initially through the radiotherapy centre’s planning process and resources. There should be a systematic approach to the acquisition, deployment, maintenance, quality control (QC), and repair of imaging equipment, and how this can best be provided with the funds available. The development of an equipment specification, including requirements for maintenance, optimisation facilities, and training for staff, followed by its procurement require management to work with radiation oncologists, RTTs and medical physicists (ICRP, 2023). Opportunities for optimisation of patient imaging should be considered when planning the acquisition of new imaging equipment. Medical physicists will carry out extensive acceptance testing on the treatment delivery systems and imaging equipment and will establish continual programmes of QC testing to identify any components outside tolerances (Section 10).
2. Ideally a representative of the vendor (usually an applications specialist) should set up clinical imaging protocols for different treatments sites in collaboration with radiotherapy staff. These protocols should be evaluated (and modified as applicable) during the commissioning phase. As vendor staff may want to prioritise image quality, lower dose settings for specific imaging protocols should be investigated at this stage, and protocols should be checked for consistency with other imaging equipment. An example is the use of planning CT, where all treatment plans for a particular treatment scenario within the department should be performed with a similar protocol for each CT scanner, as far as possible. Other important groups of imaging equipment emerging in radiotherapy departments are multimodality imaging such as PET/CT where considerations should be given to utilising the CT component for treatment planning instead of acquiring another scan and DECT/spectral CT especially for particle therapy where the type of equipment (dual-layer detector, kV switching, orthogonal sources) should be considered.
3. In addition to new equipment, new IGRT processes such as 4D cone beam CT, breath-hold, gating, triggered imaging, etc. all involve modification that affect doses to the patient from imaging and all will need to go through a commissioning phase. There will also be periodic equipment upgrades and the purpose and impact of such upgrades must be understood by users for both planning CT systems and CBCT for treatment delivery as they might require additional staff training and further acceptance testing and commissioning. Upgrades in treatment planning software or radiation oncology information systems may involve changes in imaging protocols, which can be associated with increases in field sizes or exposure factors (Abuhaimed et al., 2018) or have the potential to affect CT number calibration. Performance should be monitored after such upgrades to confirm that any changes in dose and image quality are acceptable.

## Strategies for implementing optimisation of imaging

1. Several factors have to be considered in developing a programme to achieve optimisation of radiological protection for the imaging aspects of radiotherapy. The goals and development steps can be described in terms of three components (Samei et al., 2018; ICRP, 2023).

* Professional collaboration (section 4.3.1)
* Scientific expertise and methodology (section 4.3.2)
* Organisational processes and documentation (section 4.3.3)

1. RT departments that are in the early stages of implementing a programme of optimisation of the radiological protection aspects of imaging for guidance of radiation treatment should develop a strategy to take them forward. In addition to consideration of imaging dose and quality, the potential impact of any inaccuracy in the CT number (HU)-electron density calibration should be checked carefully, as this is critical for determining the dose calculation. RT department staff should be well equipped with the generic skills required from their general work in RT that involves introducing new treatment techniques. This experience can be applied to the new domain of imaging.
2. However, many departments will not have the radiation detectors, test objects, phantoms and software applications suitable for measurements of the performance of imaging devices. Hence, radiotherapy centres in different parts of the world will vary in the levels of optimisation they have in place and the components in which they need to take steps to improve their practices. Since the implementation of optimisation will be a gradual process that cannot be achieved expeditiously, various stages are identified here to stimulate radiotherapy centres to consider the operation of processes within their own departments and these are set out in Table 4.1.
3. The developments can be considered as building on the arrangements within the service. They should start with a review of current practices, followed by addressing deficiencies in optimisation of radiological protection through improvements in imaging protocols, leading eventually to a process where this optimisation becomes routine and occurs continuously. The stages in the process are set out in more detail in Table 4.2 and might involve taking on staff with new skills, expanding roles of existing staff through training, introducing additional elements to the service, and monitoring improvements to the performance.

Table 4.1. The development of optimisation capacity through the addition of new or improved procedures, expansion of staff roles and responsibilities, and monitoring of performance with the goal of establishing, improving and refining imaging protocols.

|  |  |  |  |
| --- | --- | --- | --- |
| Domain | Common starting point | Useful intermediate steps | Suggested goal |
| Scientific expertise and methodology | Basic life cycle management of equipment with regular maintenance  Acceptance testing and commissioning following established guidelines | Routine QC testing of imaging performance  QC testing of imaging equipment includes measurement of quantities related to patient dose | Comprehensive needs analysis and QA program  Preventative maintenance, regular audits and reporting to multidisciplinary team |
|  | Medical physicists in department have limited expertise in imaging physics | Occasional consultation with imaging professional(s) from another department or centre | Medical physicist(s) within department trained in imaging physics |
|  | Use of imaging protocols set up by vendor  Performing IGRT without imaging dose management | Adjustment of vendor protocols to optimise radiological protection  Evidence based preparation of imaging protocols | Best practice protocols based on literature, evidence and discussion with imaging professionals  Protocols with optimisation of radiological protection for individual patients  Comprehensive set of paediatric protocols available |
|  | Routine testing of imaging functionality and adequacy | Periodic surveys of patient doses from imaging to identify procedures for which optimisation may be required | Regular assessment of patient doses from imaging with audit against standards such as DRLRTs as these are established |
| Professional collaboration | Professionals work in isolation and perform roles independently | Formation of multidisciplinary teams comprising RTTs, oncologists and medical physicists to review imaging protocols  Image quality level requirements for different applications agreed by teams  Imaging teams optimise protocols for selected procedures | Systematic collaboration between professionals in imaging teams  Clear links between imaging professionals with recognised roles |

*(continued on next page)*

Table 4.1. *(continued)*

|  |  |  |  |
| --- | --- | --- | --- |
| Domain | Common starting point | Useful intermediate steps | Suggested goal |
| Practical operation | Limited feedback of results on imaging performance from equipment tests  Limited test instruments and phantoms for testing imaging equipment available | Regular feedback of information on imaging and dose performance by medical physicists | Multidisciplinary teams regularly review and optimise protocols  Establish expected values for DRLRTs at commissioning for verifiable imaging quality on reference phantom (section 10.3) |
|  | Treatment prescription and justification of imaging exposures without consideration of imaging dose | Radiation oncologists have information on imaging dose from patient dose surveys | Imaging dose is taken into consideration where needed and practical (section 5.3) |
| Organisational processes | Vendor based imaging protocols used | Requirement for periodic review and adjustment of protocols for selected cases (e.g. paediatrics) | Continual review of protocols by multi-disciplinary teams based on image quality requirements and dose |
|  | Objective of equipment performance to achieve regulatory compliance | Development of QA system with inclusion of imaging dose | Systems for dose audits and consideration of imaging dose for individual patients |
|  |  | Determine median values of patient doses for different imaging procedures in radiotherapy for future comparison with national DRLRTs (see section 10.3) | System for regular review and updating of local DRLRTs derived from national values |
|  | Limited documentation of procedures relating to imaging | Systematic documentation of requirements for imaging exposures | Documentation of imaging dose in files for individual patients and reporting to institution |

Table 4.2. Questions to pose in assessing level of optimisation of imaging, actions to address deficiencies and the aim of procedures

|  |  |  |
| --- | --- | --- |
| Questions to ask in review of current practices to identify areas where optimisation is possible | Actions to take to encourage optimisation of imaging protocols. | The procedures that should be put in place as optimisation of imaging protocols evolves |
| Does the facility have sufficient allocation of medical physicist support for radiological imaging to carry out and evaluate results from imaging performance tests and patient dosimetry? | Review medical physics support for imaging and address to ensure that services of a physicist with diagnostic imaging training is available to assist in addressing any deficiencies | Patient dose surveys undertaken regularly, documented and results audited against agreed standards, e.g. DRLRTs (see Section 10.3). |
| Do different staff groups work closely together as a team or operate independently within their professional roles? | Create multi-disciplinary teams of radiation oncologists, RTTs, and medical physicists with responsibility for optimisation of imaging protocols for different types of treatment. | Results from equipment performance tests used in interpreting results from dose surveys. |
| Do staff have the necessary expertise in radiological imaging to optimise radiological protection based on results of the tests? | Ensure that deficiencies in staff expertise and training in imaging that have been identified are addressed. | Imaging protocols reviewed regularly by multidisciplinary teams and optimised taking account of results from dose audits and performance tests. |
| Is QC testing of x-ray imaging equipment sufficient to provide the information on image quality and dose performance required for optimisation of radiological protection? | Extend performance testing of imaging equipment, so that it not only confirms performance is maintained by comparison against baseline values, but feeds into the development and review of imaging protocols. | Imaging parameters adapted to optimise radiological protection for requirements of individual patients |
| Have exposure factors for imaging, which may have been based on historical practices or vendor recommendations initially, been reviewed and adapted to take optimisation of radiological protection into account? | Initiate surveys of patient doses from imaging to establish current dose levels.  Provide results of patient dose surveys to the optimisation teams and use them to evaluate and optimise radiological protection. | All aspects relating to optimisation of imaging equipment controlled through quality management system. |
| Do the exposure factors and reconstruction parameters achieve the appropriate level of image quality for specific clinical tasks? | All members of optimisation team feed into assessment of appropriateness of image quality.  Include requirements for tests on imaging equipment in quality management system. | Collaboration between the vendor and clinical users, to develop knowledge and techniques for imaging dose optimisation to improve commercial systems as quickly as practicable. |

1. Evaluating arrangements that are in place can guide staff in decisions about actions they need to take to promote optimisation. The next steps in the improvement process will depend on the level of technical performance for the imaging equipment, linked to the resources available in terms of professional expertise, technical optimisation tools, and the organisational infrastructure.

### Professional collaboration

1. It is crucial that all staff recognise that it is necessary and appropriate to move along a path towards fully optimised radiological protection for imaging. The argument that might be put forward by some that because doses from imaging are much smaller than therapy ones, there is little point in reducing them, needs to be addressed through education highlighting issues such as the imaging volume that is often considerably larger than the treatment volume and may include critical structures.
2. In some countries the various tasks that contribute to optimisation can be undertaken by different categories of professionals independently with limited communication. For example, equipment testing can be done by medical physics personnel, clinical images are evaluated by radiation oncologists and clinicians, and RTTs have responsibility for operating the equipment. If there is limited communication between these groups about the imaging undertaken, effective optimisation cannot take place.
3. Progression along a path to optimisation requires a move from traditional, often hierarchical, organisational cultures to more multidisciplinary ones with jointly organised tasks, and establishment of multi-disciplinary teams for imaging, with appropriate coverage for all types of treatment. IAEA (2019) provides information on staffing requirements for IGRT. The relationship should be built on mutual respect of professional roles and competence to ensure continuing improvement.
4. Close collaboration with professionals from other disciplines such as radiology and nuclear medicine can be helpful. Collaboration with vendors and manufacturers is also important, as some imaging systems employed in radiation therapy might lack user friendly optimisation facilities and are potentially prone to being set to deliver higher doses. Through collaboration between the vendor and clinical users, knowledge and techniques can be developed for optimisation of radiological protection for imaging and used in improving commercial systems.
5. The practical changes that should occur as the multidisciplinary approach to imaging evolves are set out in Table 4.1. Radiotherapy departments should be able to identify the level to which a collaborative approach is implemented in their departments and decide how this might be improved and progressed. The approach should be systematic in that all operations are planned and can be described as processes, with duties and responsibilities clearly assigned. Hospital management plays a key role in providing the organisational structure and staffing of the service and support to ensure adequate training of staff. Allocation of resources is required to enable the teams to work effectively in routine practice and support continuous improvement.

### Scientific expertise and methodology

1. The extent to which optimisation can be taken forward depends on many different aspects. The practical tasks that might be implemented to achieve the various levels of performance in optimisation will depend on the imaging facilities, human resources, access to funding and tools, and radiological and scientific expertise available.
2. Appropriate instruments and test tools need to be available for measuring imaging equipment performance. The medical physicists and RTTs performing the tests must have the necessary expertise to interpret the results from measurements carried out on the complex imaging equipment currently in use (AAPM, 2019a; ICRP, 2023).
3. Therapy medical physicists need to extend their expertise in techniques for optimisation of diagnostic imaging and carrying out surveys of patient doses to improve their understanding of dose levels and optimisation for imaging within radiotherapy departments. The objectives, the dosimetry quantities, and the expertise in image quality evaluation required for imaging are different from those in radiotherapy. Therefore, it is important that there are medical physicists within radiotherapy departments trained in imaging skills, including patient dosimetry, dose audit and optimisation techniques, or that diagnostic radiology physicists assist in the evaluation, testing and optimisation of imaging equipment. Medical physicists should undertake surveys of patient doses from imaging for a range of clinical protocols and analyse and evaluate the results through dose audit (Section 10.3).
4. Clinicians and RTTs need to develop a better understanding of the dose quantities relevant to imaging and to learn about differences in dose between imaging techniques. These developments in professional knowledge and skills can be achieved through additional education and training, linked with methods of improvement through self-evaluation. One approach might be to train multidisciplinary groups of local professionals in optimisation requirements through visits to national/international centres. Another option that might be applied over a wider area would be to set up a national team of experts to visit some centres to optimise protocols, using results from the dose surveys. A ‘train the trainers’ approach could be considered in order to cascade the training through the workforce. Factors involved in the intermediate stage of the progression to full optimisation are described in Table 4.1.
5. At the present time, radiotherapy departments in many parts of the world do not have the necessary tools, teams, nor expertise to fully embrace optimisation of imaging dose and take it forward to the same endpoint, because of the restricted technical infrastructure and limited availability of multi-professional expertise. Therefore, decisions on the appropriate steps to be taken next by each department will depend on the tools and expertise that are available currently.
6. The vendors’ clinical/application specialists should be trained in low dose techniques so that they can assist clinicians, medical physicists and RTTs in the development of low dose practices. This is appropriate for specialists providing advice both on-site and at helpdesks via telephone.

### Organisational processes and documentation

1. In order to ensure that optimisation of imaging protocols becomes a routine activity in a radiotherapy department, the requirements should be enshrined as part of the quality management system to ensure that optimisation is undertaken in a systematic manner. All the contributory processes should be included and documented. This should aid the bringing of activities such as practical performance testing, patient dose audits, and in the future audit of patient imaging doses against dose reference levels (DRLRTs) (section 10.3), into the regular review and optimisation of imaging protocols and adaptation to individual patients. Documentation of the results of patient dose audits and communication of the outcomes to prescribing clinicians is essential. It is only through surveys of patient doses that true doses delivered in practice can be assessed (Ding et al., 2018).
2. The processes start with the initial arrangement of needs analysis, establishing equipment requirements and the procurement process. They cover every aspect of the imaging service that relates to optimisation, including development of protocols, performance testing of equipment, surveying of patient doses, and carrying through the audit and analyses of results to determine optimisation requirements. Radiological protection and image quality should be optimised as soon as any new techniques are introduced.
3. Radiotherapy centres should have a policy for user training that is part of the Quality Management Programme. Initial user training will normally be provided by the applications specialist before the equipment is put into clinical use. Training of staff unable to attend the initial sessions, and others joining the department subsequently should be delivered through a cascade process. Staff should be provided with refresher training throughout the life of the equipment. Members of the image optimisation teams should also receive update training explaining the influence that new technical facilities on imaging equipment have on patient dose and image quality, and how they can be utilised.

## Development of optimisation of radiological protection for imaging

### Initial steps in implementation

1. Some of the practical steps that should be taken to initiate optimisation of radiological protection for imaging in radiotherapy are listed here:

* Provide education and training to medical physics, RTTs and oncology staff in relevant aspects of radiological imaging science, technology, and practice through targeted courses and on-site training in experienced departments.
* Set up optimisation teams comprising RTTs, radiation oncologists, and medical physicists, led by a medical physicist to review imaging protocols with the aim of identifying where effort is required.
* Purchase appropriate equipment for measuring performance of x-ray imaging equipment in terms of dose and image quality or obtain the services of an external organisation that can provide these services, as appropriate.
* Set up links with professionals in other radiotherapy centres, especially for medical physicists with limited experience in radiological imaging, to mentor and exchange ideas.
* Ensure that the QA programme includes performance test measurement of image quality and dose for all imaging equipment and initiate surveys of patient doses from imaging for the main types of procedure carried out.

1. The initiation of the optimisation processes for imaging is just the first stage. The development and improvement will require continual sharing of experiences in optimisation techniques with regular review of imaging protocols by the optimisation team with adjustments made based on experience, and results of performance tests and patient dose surveys. Improvement will be a gradual process, so radiotherapy departments should decide on the priorities to achieve optimisation for their situation, based on the stage in the development process, their equipment, tools available, level of staff expertise, and their patient cohort. Through proper management of the processes contributing to optimisation of imaging, the optimal frequencies, levels of image quality, and exposure factors should be decided for every patient at all stages of their treatment.

### Practices in optimisation of radiological protection for imaging

1. The clinical use of x-ray imaging equipment requires careful consideration of positioning strategies and the optimisation of acquisition protocols. The management of doses delivered to the patient should focus on their incorporation in treatment plans and patient records in order to limit their impact on OAR with respect to risks of early and late effects to ionising radiation exposure.
2. The doses from imaging depend on a variety of factors including the imaging modalities and the region of the patient’s anatomy being imaged. In order to optimise radiation protection in the imaging process and the technology used, actions are required both within individual radiotherapy centres and at national level. The clinical staff should be familiar with the magnitude, if not values of imaging doses of each imaging modality and protocols in use for radiotherapy
3. Optimisation of radiological protection for imaging of each patient should be based on:

* Selection of the imaging modality and protocol that yields the required clinical information at the lowest radiation dose possible (e.g. planar vs cone beam CT imaging for verification purposes).
* Reduction of the doses received by the most radiosensitive organs in the body section being imaged (e.g. by suitable choice of angles of incidence for static imaging beams, adjustment of the collimation to focus on the volume of interest, implementation of automated tube current modulation techniques for CBCT acquisition).
* Adaptation of acquisition parameters according to patient morphology, the volume to be treated and the required image quality (tube voltage, tube current and/or exposure time).

1. To help optimising radiological protection, actions to promote agreed standards for imaging at national or regional levels should be carried out to:

* Improve knowledge of the doses delivered by different types of imaging systems amongst all radiotherapy professionals by carrying out surveys of patient doses in terms of measurable dose quantities.
* Establish acceptable dose levels for different techniques as national or regional DRLRTs in terms of measurable dose quantities.

1. Technological developments will enable reductions in the doses from imaging. For example, carrying out a 3D reconstruction from a partial arc-acquisition for kV-CBCT allows for reduction in doses to particular organs, and can minimise the dose to the lens of the eye by avoiding direct irradiation (Ding et al., 2018). Partial arcs also offer the advantage of faster acquisitions and may reduce motion induced artefacts commonly observed in kV-CBCT images, although partial arc trajectories will result in reduced fields of view. AI technology may also be helpful for reducing the imaging dose without compromising image quality (Zhu et al., 2018).
2. However, reduced doses and numbers of projections may result in poorer image quality that could compromises the clinical intent of imaging; hence, all the advantages and disadvantages of techniques need to be evaluated. This should be done with consideration of the whole of the patient pathway as it should be recognised that higher dose imaging protocols may achieve a net dose saving to the patient if improved image quality delivers better target localisation and accuracy of the treatment. It is also the case that in some circumstances, relatively high dose or high frequency protocols are the only option for the imaging technique being used to achieve a specific clinical goal e.g. four dimensional cone beam CT, or triggered imaging.
3. Many different choices are available for medical physicists regarding the selection of the imaging technique and acquisition parameters, and as a result, doses delivered during IGRT vary significantly depending on individual practices (Siiskonen et al., 2017, 2024). Hence, the knowledge of dose levels needs to be improved and characterised through indicators common to the different imaging systems. Further considerations are discussed in section 10.3.
4. Repeated imaging for patients with pacemakers and other implanted electrical devices should be considered in the context of radiation dose.

### Roles of regulators and professional organisations roles in promotion of optimisation of radiological protection for imaging

1. Countries will need to promote optimisation of radiological protection for imaging in RT at a national level in order to encourage RT centres to fully embrace and implement the development. This is likely to involve promoting national surveys of patient imaging doses in radiotherapy. Results can be used to identify broad needs for optimisation across the country and may be applied in establishing DRLRTs that could be used in identifying hospitals where more optimisation is required (section 10.3).
2. Professional organisations can all play a role in the development and improvement of the processes and techniques by issuing professional recommendations and good practice guidelines.
3. Regulators and governments can encourage the developments through inclusion of requirements to monitor procedures for QC of imaging equipment, audit of patient imaging doses and setting of DRLRTs both in the regulation and through periodic on-site inspections.

# EVALUATION AND MANAGEMENT OF DOSES FROM IMAGING

1. **Key points in this section:**

A range of dosimetric quantities are used currently in planning and imaging over the course of radiotherapy treatment. A knowledge of patient dose in terms of measurable quantities such as the CTDIvol and DLP for CT, or KAP is the first step in the process of optimisation of radiological protection for imaging.

A cone beam dose index (CBDI) is proposed to allow practical dosimetry measurements linked to patient doses to be made for CBCT equipment.

The increasing use of repeated image acquisition during treatment of a patient can give significant additional doses to healthy organs and tissues within a large volume of tissue surrounding the target volume. Knowledge of doses from imaging needs to be improved and provided to physicians, medical physicists and RTTs.

The distribution of dose within the patient’s anatomy depends on body habitus, the mode of acquisition (planar or CT imaging) and the energy of the x-ray beam. Absorbed doses to organs and tissues should be considered when accounting for doses from imaging at the treatment planning stage.

Many modern TPSs have the capability to calculate MV imaging dose using model-based dose calculation algorithms and to implement them into treatment plans. Vendors are encouraged to implement additional calculation processes into treatment plans to allow kV imaging doses to be taken into account.

## Dosimetric quantities and dose distributions from imaging procedures

1. A knowledge of patient dose from imaging in terms of measurable quantities such as the CTDIvol and DLP for CT, or kerma-area product (KAP) and air kerma at the patient entrance surface and for radiography and fluoroscopy, is the first step in the process of optimisation of doses from imaging (Annex B.1). In addition, use of a cone beam dose index (CBDI) is proposed for practical dosimetry measurements on CBCT equipment for assessment of patient dose levels (section 10.3, Annex B.2). These quantities are not direct measures of tissue doses, but absorbed doses to tissues can be derived through the application of Monte Carlo simulations combined with whole body computational human phantoms. When reporting tissue doses from imaging doses in the radiotherapy context, care needs to be taken to identify whether effective dose or absorbed dose to an organ is being described.
2. It is impractical to compare or attempt to sum the measurable dose quantities resulting from imaging modalities due to the different dosimetric quantities employed (Annex B, Table B.1) and the differences in dose distribution (Murphy et al., 2007). The mode of image acquisition and the energy of the beam have a major impact on the distribution of dose. For example, for the same median dose delivered to an organ with a kV imaging system, the dose distribution may be very different between a 2D or 3D modality. The doses from 3D imaging are relatively uniform whereas in planar imaging the maximum dose is located in the skin on the source side and decreases with the depth by a factor of 100 to 1000 between the entry and exit of the beam from the patient (Murphy et al., 2007) (see Fig. 5.1).

A collage of images of a brain

Description automatically generated

Fig. 5.1. Dose distribution in the pelvis for one of a pair of 6 MV portal images (left), a kV-CBCT (middle), and one from a pair of orthogonal kV radiographs (right) (adapted from Ding and Munro, 2013 with permission from Elsevier).

1. AAPM Task Group (TG) 75 (Murphy et al., 2007) and TG 158 (Kry et al., 2017) initially explored the possibility of converting the imaging doses into effective dose (ICRP, 2021). However, in 2018, the AAPM TG 180 (Ding et al., 2018) moved away from the individualised calculation of modified effective doses and proposed the use of the mean absorbed doses to individual organs and tissues so that risks could be put into perspective compared with normal treatment planning requirements.
2. As specified in *Publication 147* (ICRP, 2021), effective dose is intended for use as a protection quantity and, although it can be used as an approximate assessment of an unintended exposure, it is not recommended for detailed retrospective investigations of individual exposure and corresponding risk. In radiotherapy the use of organ absorbed doses allows for a more direct comparison with treatment doses, and it is anticipated with the evolution of TPSs that dose estimation for healthy organs and tissues may ultimately be accounted for within the TPS software. However, effective dose could play a role in the comparison of doses from different imaging techniques. Size-specific effective dose could also potentially be useful in the optimisation of imaging procedures for patients of varying stature (Martin et al., 2020; Martin and Abuhaimed, 2022).
3. Although absorbed dose could be used for comparing doses from imaging with those from treatment, converting measurable imaging dose quantities into organ- or tissue-specific absorbed dose involves complex calculations, which means this information is not readily available when imaging is undertaken. If radiation protection for medical imaging used in radiotherapy is to be optimised, operators need to be aware of dose levels delivered in terms of the dose quantities displayed on the treatment unit and be familiar with the dose levels that are appropriate for different imaging tasks. Currently this information can only be obtained from surveys of imaging doses to real patients. The methods used for carrying out dose surveys, setting standard dose reference levels against which comparison of dose can be made, and the approach to optimisation that is used in radiology will be covered in section 10.3.

## Dose levels from imaging

### Radiotherapy planning CT scans

1. CT is integral at the planning stage to accurately delineate the locations and volumes of the treatment target and OARs and provide the electron or physical density information necessary for the dose calculation in the TPS. Image quality must be sufficient to achieve these goals, whilst keeping doses as low as reasonably achievable.
2. Radiotherapy planning CT scans have some requirements that may limit the options for dose optimisation and/or impact image quality when compared with diagnostic scans. For example, the tube kV is mainly fixed to minimise uncertainty in CT number, recorded in Hounsfield Units (HU), which can affect dose calculation, and the use of large bore CT scanners with increased x-ray tube to detector distances may affect image quality (Wood et al., 2018).
3. *Publication 112* (ICRP, 2009b) highlighted the growing importance of imaging in the treatment planning process. The publication provides the example use of 4D CT where each slice is potentially replaced by ten slices acquired at different phases of the respiratory cycle. It concluded that the additional exposure from imaging needs to be assessed.
4. A survey among UK radiotherapy departments, which focused on dose indices from radiotherapy planning CT scans for adults, highlighted a wide range of CTDIvol and DLP among CT scan protocols, with a variation by a factor of up to 18 for some scan types (Wood et al., 2018). A second survey of imaging during treatment based on the cone beam dose index (CBDI) has shown a similar spread in imaging doses (Wood et al., 2024). These surveys have demonstrated that there is scope to optimise CT and CBCT scan protocols in radiotherapy and have proposed the introduction of the concept of dose reference levels, similar to the diagnostic reference levels (DRLs) used in diagnostic imaging. The ICRP supports this approach but recommends that to avoid confusion the abbreviation should include the subscript RT (DRLRT). A recommendation about the development of DRLRTs for treatment planning CT scans has also been proposed by researchers at IRSN (IRSN, 2020) (see also section 10.3).

### Imaging devices available on treatment machines

1. General characterisation of absorbed doses from the different imaging modalities available on radiotherapy machines is not trivial. It depends on the imaging modality (conventional accelerators are provided with the possibility of performing portal images [2D-MV), planar images (2D-kV), or tomographic images (kV-CBCT)], the method of evaluation (e.g. Monte Carlo simulation or direct dose measurement in phantoms), the dosimetric quantities used [e.g. Cone beam dose index (CBDI), CTDIvol, DLP, KAP] and the parameters on the imaging systems. For example, there will be differences in imaging doses when comparing CBCT dose from a centre that uses default protocols provided by the vendor for all imaging with CBCT dose from centres where the default protocols may have been adjusted for different patient sizes (Siiskonen et al., 2024).
2. The D50, which indicates the dose received by 50 % of the given organ, for different imaging modalities are compared in Table 5.1. MV portal imaging techniques, which provide a more even distribution across the tissue (Fig. 5.1), record significantly higher values than kV imaging. Studies show that MV portal imaging delivers higher organ absorbed doses, as well as providing poorer image quality (Ding and Munro, 2013; Alaei and Spezi, 2015; Siiskonen et al., 2017, 2024). However, this may be the only imaging option on older linacs in many countries (Martin et al., 2021).

Table 5.1. Comparison of imaging doses (D50 in mGy derived from the DVHs) delivered to sensitive organs for different imaging modalities and the tumour locations for different beam parameters for the imaging procedures (Ding and Munro, 2013). An example of the corresponding dose distributions is reproduced in Fig. 5.1 for the pelvis.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Treatment site | Considered organ | 2D-6MV imaging (a pair of portal images) (mGy) | 3D-kV imaging  (kV-CBCT) (mGy) | 2D-kV imaging (a pair of orthogonal kV radiographs, AP or PA, and RL radiographs) (mGy) |
| Head | Eyes | 43-48 | 0.4  acquisition of projections on 200° (around the back of the head) | 1.2 (AP and RL radiographs)  0.08-0.17 (PA and RL radiographs) |
| Brain stem | 37 | 1.6 | 0.3 |
| Thorax | Heart | 35 | 2 | 0.7 |
| Right lung | 38 | 2.7 | 1.2 |
| Pelvis | Prostate, bladder, rectum | 30 | 9 | 1 |

1. A recent study, conducted in Finland on prostate cancer patients in nine radiotherapy centres, showed that if kV CBCT imaging is done at every fraction, the cumulative mean doses are 184 - 530 mGy (prostate), 107 - 218 mGy (rectum), 72 - 233 mGy (bladder) and 250 - 690 mGy (femoral head), for a 20-fraction treatment. These doses are nearly doubled in case of 39 fraction treatments, reaching then a maximum dose for the prostate of 1034 mGy and 1346 mGy for the femoral heads (Siiskonen et al., 2024).
2. Furthermore, it is necessary to consider not only the dose per imaging, but also the imaging frequency (Siiskonen et al., 2024). It is important to remember that in the context in which verification imaging is used, there is the potential for not only significant numbers of exposures from daily imaging regimes, but there is also the potential for repeated imaging if issues are identified that require repositioning of the patient. This can result in significantly higher levels of absorbed doses when compared with those resulting from just a single exposure. However, this is also one of the key justifications for the use of x-ray imaging in the verification of patient setup to ensure the high dose treatment is delivered to the correct structures.
3. It is also possible that for patients with image acquisition during the treatment (e.g. CyberKnife ® radiosurgery device [Accuray, USA]), there can be several tens of images per session (Moeckli et al., 2020). However, the order of magnitude of effective doses resulting from imaging for CyberKnife ®, based on kV planar images, is similar to kV-CBCT-based image guidance, for a single treatment fraction (Moeckli et al., 2020).
4. MV 3D imaging is available on some Siemens accelerators (discontinued in 2014), Varian’s Halcyon, and helical delivery accelerators: Tomotherapy® and Radixact® from Accuray. The doses delivered from this modality are between 6 and 12 mGy MU-1 per acquisition for conventional Siemens accelerators, with the number of MU used varying from 2 to 15 (Ding et al., 2018). Doses to surrounding organs are given in Table 5.2. For the MV-CBCT in Halcyon, Malajovich et al. (2019) estimated the additional doses to organs for images acquired in the low dose setting (5 MU) for various treatment sites (head and neck, left breast and pelvis) from a single MV-CBCT acquisitions, and found that the highest tissue doses were in the range of 20-70 mGy. It should be noted that although TPSs can calculate the MV imaging dose correctly, errors may occur during the integration with treatment dose as a result of couch shifts during IGRT (Huang et al., 2019). For Tomotherapy®, the doses were 8-25 mGy per acquisition (measured in the centre of the Accuray reference phantom of 30 cm diameter for different acquisition protocols) (Ding et al., 2018). However, thorough calculations of dose distributions should be performed as the imaging doses cannot be fully quantified through single measurements in phantoms.

Table 5.2. Typical organ doses for images taken with MV EPID portal imaging for pairs of orthogonal setup fields in terms of the D50 or minimum dose delivered to 50 % of the organ. Values for the average organ doses delivered by MV cone beam CT (CBCT). Adapted from Ding et al. (2018).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Treatment site | Organ considered | D50 for 6 MV planar pair with 2 MU/field (mGy) | D50 for 2 MV planar pair with 1 MU/field (mGy) | Average dose for 6 MV CBCT (mGy MU-1) |
| Brain | Brain | 20-50 | 10-20 | 9 |
|  | Brainstem | 30-40 | 10-20 | - |
|  | Chiasm | 30-50 | 12-20 | - |
|  | Eyes | 30-50 | 13-20 | 11.4 |
|  | Optic nerves | 30-50 | 10-20 | - |
|  | Pituitary | 20-50 | 10-20 | - |
| Thorax | Aorta | 20-40 | 10-20 | - |
|  | Lungs | 10-45 | 5-20 | 8.3 |
|  | Oesophagus | 25-35 | - | - |
|  | Kidney | 20-30 | - | - |
|  | Heart | 30-45 | 10-15 | 8.6 |
|  | Liver | 10-45 | - | - |
|  | Spinal Cord | 20-30 | 5-10 | 5.9 |
| Pelvis | Bladder | 20-35 | 10-15 | - |
|  | Bowel | 20-40 | 10-15 | - |
|  | Femoral heads | 25-35 | 8-15 | 8 |
|  | Prostate | 25-35 | 9-11 | - |
|  | Rectum | 20-40 | 8-10 | - |

1. Through the introduction of new imaging technologies, the kV CBCT doses are expected to decrease while improving or keeping the same image quality (Kawahara et al., 2016; Robar et al., 2024; Siiskonen et al., 2024). However, some kV CBCT acquisition modes can require the delivery of slightly increased doses for the use of kV CBCT images for radiotherapy planning which creates possibilities for adaptive radiotherapy and an optimised workflow (Bogowicz et al., 2024; Lustermans et al., 2024). In addition, moves towards hypofractionation for some treatment sites will have an influence on imaging dose reduction (Siiskonen et al., 2024).

## Estimation of imaging doses for incorporation into treatment plans

1. Ding et al. (2018) noted that according to the data available in the literature imaging dose is generally less than 5 % of the therapeutic target dose, except for some imaging procedures that use MV beams, particularly MV-CBCT. However, although this may be true for the target volume, the dose delivered to surrounding tissues and OARs has to be considered independently as imaging dose is not conformed to the target volume in the same way as the treatment.
2. The report of the AAPM TG 180 (Ding et al., 2018) suggests two methods for calculating doses in organs and tissues due to imaging.

* “Nonpatient-specific” method: in most cases, it is possible to estimate the dose due to the imaging received by the organs of interest for a given acquisition protocol from tabulated values (Ding et al., 2018) and from other publications. This may be enough to inform the radiation oncologist and help the choice of the imaging procedure according to the treatment performed, assess the doses to OARs and know whether these doses should be taken into account when adapting the treatment plan.
* “Patient-specific” method: Imaging dose distributions can be calculated and take into account the patient’s morphology by calculations done on the patient CT images via Monte Carlo simulations or from analytical calculation models available in the TPS. However, to date, if Monte Carlo methods are available for MV beams in commercial TPSs, they are not commercially available for kV beams. Regarding model-based methods, some improvements seem to be required in commercial TPSs for kV beams, particularly with regards to the dose calculation to bone.

### Inclusion of MV imaging dose in planning software

1. There are different dose calculation algorithms available for MV imaging: model-based calculation and Monte Carlo radiation transport. Model-based algorithms (Ahnesjö and Aspradakis, 1999), built into commercial TPSs, have long been used in radiotherapy planning for MV treatment beams. Therefore, it is possible to extend the dose calculation algorithms to MV imaging procedures. A number of commercial TPSs also provide the capability of Monte Carlo dose calculation for MV imaging and incorporating the results into treatment plans. Commissioning of the beam by a medical physicist is required.
2. The general method to implement MV imaging dose into treatment plans, called treatment plan compensation or treatment plan optimisation, is as follows. The objective of radiotherapy is usually to ensure uniform target coverage with maximum dose while sparing the normal tissues surrounding tumours. The objective of the treatment plan optimisation would be the same as that of radiotherapy itself while considering additional imaging doses. Imaging dose distribution is usually fixed by the imaging protocol so that treatment plans should be adjusted and optimised to satisfy the criteria of target dose distribution and the dose constraints of OARs. During the optimisation process, the MU planned for the treatment without accounting for imaging dose is reduced and then the reduced amount of MU is added to the imaging dose. This will allow the overall target mean dose to be the same as that prescribed in the treatment plan without the additional dose from imaging. As the dose is given at a slightly different time and dose rate, radiobiological effectiveness may need to be considered. The integration of imaging and treatment dose should also be performed carefully to consider inconsistent imaging and treatment isocentres (Huang et al., 2019).
3. The feasibility of implementing MV CBCT doses in treatment planning systems was demonstrated successfully by Morin et al. (2007) and Miften et al. (2007) for head and neck and prostate cancer patients. Their methods accounted for daily MV CBCT dose by either reducing the total treatment dose to compensate for imaging dose (Morin et al., 2007) or accounting directly for imaging exposure during IMRT plan optimisation. More recently, Li et al. (2018) calculated and measured MV and 3D MV CBCT doses on targets and OARs from an anthropomorphic thorax phantom. They showed that the sum of imaging and treatment dose distributions were accurately calculated by the treatment planning system to be within 0.5 %. Bell et al. (2018) employed TPS calculations to evaluate the impact of imaging dose and treatment positioning errors on target coverage, OARs doses and normal tissue complication probability (NTCP). They concluded that 3D MV imaging doses were non negligible and that target coverage, OAR sparing and NTCP could worsen due to potential positioning errors.

### Inclusion of kV CBCT dose in planning software

1. Commercial TPSs, designed to calculate MV dose distributions, cannot be used directly for the calculation of kV imaging dose. Prerequisites include the modelling of the x-ray source and the implementation of dose calculation algorithms for low energy kV x-rays physics. Two successfully implemented kV imaging dose calculation methods involve model-based estimation and Monte Carlo techniques. Currently, few systems can calculate these doses, but future developments may allow their inclusion in treatment plans if deemed appropriate.

#### Model based kV CBCT does estimation

1. Existing TPSs commissioned for MV treatment beams can also be modified for kV energy ranges and used for kV imaging dose calculations (Alaei et al., 1999, 2000, 2001; Dzierma et al., 2014). Although the method provides kV imaging dose distribution with sufficient accuracy for soft tissues, the dosimetric error for skeletal dose can be up to 300 % due to lack of accounting for the photoelectric effect (Pawlowski and Ding, 2011, 2014). Alaei et al. (2014) described an approach where they retrospectively calculated dose distribution from kV CBCT to ten head and neck cancer patients and ten pelvis cancer patients. They performed treatment plan optimisation with a kV imaging beam commissioned in a TPS. They observed an average reduction of 4 % in the monitor unit in treatment plans after adding kV CBCT imaging dose.

#### Monte Carlo simulation of kV CBCT x-ray sources

1. Monte Carlo radiation transport techniques, which have been widely used in studies of medical radiation, can be used to estimate kV imaging dose. Currently no commercial TPSs allow Monte Carlo-based dose calculation for kV beams so that the dose calculation must be conducted in-house.
2. Different Monte Carlo radiation transport codes have been used to simulate kV CBCT devices including EGSnrc/BEAMnrc (Kawrakow and Rogers, 2003), PCXMC (Wood et al., 2015), MCNP (Werner, 2017), and GATE (Jan et al., 2011). The components that are simulated within the Monte Carlo codes include x-ray source, beam collimators, bow tie filter, and treatment table. To simulate the x-ray source, the following parameters must be obtained from device manuals or vendors: focal spot size, incident electron angle, target design, beam filtration systems, incident electron energy. Key geometry parameters such as source-to-isocentre distance and source-to-detector distance are also required to accurately simulate kV imaging procedures.
3. Several kV CBCT systems have been simulated using Monte Carlo methods to date.

* The Monte Carlo simulation of the On-board imager (OBI) system (Varian Medical Systems, Palo Alto, CA) has been reported by many authors (Wen et al., 2007; DeMarco et al., 2008; Ding and Coffey, 2009; Deng et al., 2012; McMillan et al., 2013; Abuhaimed et al., 2014, 2015, 2018; Poirier and Tambasco, 2016; Son et al., 2017). The OBI system has two types of bow-tie filters available: full bow tie (for full-fan mode imaging) and half bow tie (for half-fan mode imaging). Different bow tie filters are used depending on the size of image acquisition volume.
* The XI system, installed on Varian Truebeam linacs, was simulated to estimate organ doses from pelvic CBCT scans (Gilling and Ali, 2022). Its kV beam delivery system provides a 0.89 mm titanium beam hardening foil in addition to full fan and half fan bowtie filters.
* The x-ray volume imaging (XVI) system (Elekta, Crawley, UK), which has been simulated using Monte Carlo methods by several authors (Chow et al., 2008; Spezi et al., 2008; Downes et al., 2009). The Elekta XVI system uses two filtration cassettes: F0 blank filter and F1 bowtie filter. The F1 filter is used to deliver a lower skin dose. The system also has the collimator cassette identified by Small, Medium, or Large, depending on the size of the volume included in the image acquisition.

1. The Monte Carlo simulation of kV CBCT devices is combined with a digital patient anatomy to calculate organ absorbed doses. In most studies on patient-specific dose calculations, patient CT images were used with segmentation of major organs of interest. Other studies evaluated general dose delivered to standard human anatomy models, called computational human phantoms: ICRP adult male and female phantoms (Abuhaimed et al., 2018), paediatric and adult XCAT phantoms (Norris et al., 2014), and GSF phantom series (Petoussi-Henss et al., 2002). Although this approach based on computational human phantoms may not provide patient-specific organ doses, it eliminates the need for time-consuming manual or automatic organ segmentations and takes advantage of a large number of pre-contoured organs and tissues for dose calculations. Some pre-defined tissues (e.g., gastro intestines with radiosensitive layers and detailed skeletal structures) in computational human phantoms, which are not easy to segment from patient CT images, can assist accurate dose calculations for sophisticated organ and tissue structures. The Commission has reported a series of paediatric (ICRP, 2020a) and adult (ICRP, 2009a) reference computational human phantoms as well as the same series of phantoms in surface format (ICRP, 2020b). The surface-based phantoms also allow for the systematic adjustment of the outer body contours so that a library of body size-dependent computational human phantoms (Geyer et al., 2014) can be created for more accurate dose calculation by implementing patient body sizes.
2. Monte Carlo dose calculation methods were also used to directly estimate kV CBCT imaging dose which was then implemented into treatment plans. Chow et al. (2008) calculated kV CBCT organ dose using BEAMnrc simulation for five prostate cancer patients treated with IMRT and evaluated the impact of the imaging dose on the IMRT plans. They found that dose volume histograms (DVHs) vary only slightly with the added imaging dose with the exception of femoral heads for which dose increased by 5 % due to the imaging doses. They concluded that the implementation of kV CBCT does not make a significant change in the total dose distribution in the prostate IMRT sessions. To reduce dose calculation time, Boissonnat et al. (2020) created virtual source models (i.e., phase space files) by using Monte Carlo radiation transport of x-ray tube and used them to calculate patient doses. By using pre-calculated virtual source models, they reported a reduction in calculation time by a factor of 2.8.
3. Since the dose from kV CBCT is relatively small and the calculation process is not straightforward compared with MV CBCT, pre-calculated dose tables could eventually be used to roughly estimate kV CBCT dose. These may then be incorporated into treatment planning dose as an alternative to model-based methods and Monte Carlo dose calculations. This look-up-table approach may be enough for the purpose with the accuracy within ±20 % (Nelson and Ding, 2014; Ding et al., 2018) until the availability of a more accurate full dose calculation method.

#### Organ dose prediction for kV CBCT using artificial intelligence

1. Recent works proposed an artificial intelligence (AI)-based method for organ dose prediction for thorax kV CBCT acquisitions. Tsironi et al (2024) evaluated the efficacy of AI algorithms by comparing dose predictions with the actual doses derived from Monte Carlo simulations, considered as the ground truth. The authors concluded that AI models can make real-time predictions of the organ doses for patients undergoing CBCT thorax examinations: AI predicted doses were in close agreement with those calculated using Monte Carlo simulations, with a maximum discrepancy between the 2 models of 21 % for lungs

## Uncertainties in dose assessment and prediction of radiation effects

1. Improvements in the delivery of radiation therapy treatments, in which imaging has been an important component, have been considerable in recent decades. This should allow more accurate forecasts of outcomes in the future, but uncertainties in delivery remain and imaging plays a vital part in reducing these (Tudor et al., 2020). The dose levels used for treatment are high and are calculated in commercial TPSs with accuracies depending on the treatment scenario. In homogeneous tissues the standard deviation in dose calculation is of the order of ±2 %-3 %; however, in complex small and dynamic fields and in the presence of tissue inhomogeneities it can exceed 5 %. The prediction of dose levels in surrounding normal tissues that are associated with the radiation treatment are more uncertain as they are not the focus of the planning software and doses to these tissues are orders of magnitude less than the dose delivered to the target.
2. The doses to surrounding tissues are made up not only from the primary beam before it enters and after it leaves the tumour, but also radiation scattered within the patient, radiation scattered from the collimator and within the treatment head and leakage radiation that penetrates through the accelerator head shielding (Kry et al., 2017). Patient scatter is the dominant source close to the treated volume, but at greater distances (greater than ~20 cm) head leakage becomes the main source of exposure. Photon doses decline approximately in an exponential way with distance from the field edge, although with IMRT there will be some dependence on the specific treatment plan. In high gradient regions at the margins of the treatment field, a small difference in optimisation of the plan can substantially impact doses delivered to nearby tissues. The dose from outside the treatment field depends on the size of the treatment field and imaging plays a vital part in minimising this.
3. When considering the potential impact of imaging, it is the dose levels from the treatment in these normal tissues outside the target volume that need to be considered and compared with the doses from imaging. They are often portrayed in the form of dose volume histograms as in Fig. 5.1, which shows the distributions of doses to tissues within particular organs or portions of anatomy resulting from portal imaging with the treatment beam and kV imaging. Uncertainties in doses to these surrounding soft tissue organs from the radiation treatment depend on the radiation quality, the dose calculation algorithm and the distance from the treatment field and are likely to be of the order of ±10 %-50 %.
4. Organ doses from cone beam imaging are calculated using Monte Carlo simulations and values can be represented in various ways. Detailed evaluations of the mean cumulative doses to a few organs in a selection of patients using a standard phantom have been made by Siiskonen et al., (2024). This study showed that doses to the rectum and bladder from imaging preformed at every fraction for treatment of the prostate would be up to 200 mGy - 300 mGy, while that to the femoral head might be 400 mGy – 800 mGy. The statistical uncertainty in mean doses to organs and tissues lying entirely within the imaging beam in these studies are the order of ±1 %-2 %, but when account is taken of conversions from in-phantom air kerma measurements, corrections for table attenuation and backscatter, and use of a reference phantom, the overall uncertainties are of the order of ±6 %-10 %. This represents uncertainties in detailed research applied to a limited number of patients and few studies of this type have yet been published.
5. A number of studies have calculated mean organ and tissue doses from CBCT for reference phantoms (Norris et al., 2014; Abuhaimed et al., 2018). Here the uncertainties in doses for organs lying within the imaging field in particular phantoms may be of the order of ±10 %, but uncertainties in doses to organs and tissues lying partially within an imaging field can be of the order of ±20 %-50 % as they are dependent on the positioning of the field boundary. The positions of the rapid declines in dose within the dose volume histograms in Fig 5.1 will change with the position of the boundaries. This illustrates the wide range of doses that occur within many organs and tissues and the critical importance of the positions of radiation field boundaries. Comparisons of the 50 % values for organ doses from different imaging options, representing the dose received by 50 % of the given organ, are given in Table 5.1 (Ding and Munro, 2013). Dose values in all these studies are likely to contain uncertainties of the order of ±20 % or more for most organs and tissues. Uncertainties in doses to red bone marrow are likely to be higher because of incomplete knowledge of the distribution of red bone marrow.
6. The examples of organ and tissue doses from imaging in radiotherapy given in this report are limited because few studies have been carried out. The overall uncertainty of imaging doses in radiotherapy departments across the world cannot be predicted until more data on measurable dose quantities are available (Martin et al., 2021) with studies linking these to organ and tissue doses. The overall impact of optimisation of imaging for radiotherapy is difficult to predict because of these dose uncertainties. It involves reducing the dose to normal tissues from the imaging component but this may be similar to that from scatter from the treatment beam for some treatments and in other cases it is likely to be much less.
7. The purpose of optimisation of radiological protection is to reduce the dose from imaging without affecting the clinical need, namely inhibiting verification of the correct patient position for treatment. For this it is not the doses to organs and tissues that are used, as these are complex to calculate, but surrogate quantities such as the wide beam CT dose index and the cone beam dose index discussed in section 10.3 and Annex B. The accuracy of these quantities, which can be compared between centres involves obtaining calibrations for kV x-ray beams used for imaging and the traceability of such calibrations to national or international standards, as well as the consistency of practices in performing measurements and is of the order ±20 %. However, at the present time most radiotherapy centres around the world do not have access to suitable instruments and phantoms, so the numbers of centres making such measurements is limited (Martin et al., 2021). Without any knowledge of these dose levels, which will be the case if no evaluations of patient dose are carried out, the uncertainties could potentially be of the order of 100 % or more.
8. The measurable quantities are not linked directly to doses received by tissues but do give an indication of dose performance. The dosimetry quantity approved by the IEC for display on cone beam CT equipment in radiotherapy is the wide beam CTDI (CTDIw,IEC, see Annex B) (IEC, 2016). Although it is recommended that this quantity should be displayed on CBCT imaging equipment, this is not the case at the present time. Therefore, a different quantity, the cone beam dose index, is proposed here for initial measurements, as it is easier to measure so that programmes of patient dose surveys can be initiated (Amer et al., 2007; Abuhaimed et al., 2015). Links with the CTDIw,IEC, which should be displayed on imaging equipment in the future, and to doses to exposed organs and tissues will need be established.
9. The final stage for assessing the benefits of optimisation of radiological protection for imaging is evaluating the cancer risk and risks of tissue reactions. For this, results from epidemiological studies are used and most of these are based on very different population groups with different exposure routes, which is problematic. The recent summary of findings in the meta-analysis of the risk of second primary cancers in patients treated with radiotherapy by UNSCEAR found that the excess relative risks per unit dose for seven second primary cancer sites were generally lower than the risks reported in other radiation epidemiological studies (UNSCEAR, 2024). Between 5 % and 15 % of cancer survivors may develop a second primary cancer but the committee considers that only a small proportion are attributable to radiation. Therefore, this presents the largest uncertainty.
10. The aim of imaging is to improve the accuracy of treatment delivery, which has obvious benefits, but when this involves fine tuning treatment delivery by reducing the size of the high dose margin, evaluation of the impact and determining uncertainties in any reduction in risk of cancer and lowering of the risk of short term tissue reactions is almost impossible to quantify. It also has an additional risk in that reduction of the margin to the extent that there is a danger of underdosing tissue on the periphery of the tumour could increase the risk of tumour recurrence. The imaging performed must be able to provide information for enabling the best diagnostic decision to be made.
11. The final outcome in image guided radiotherapy should be an improvement in patients’ qualities of life, conditions and survivals. The effectiveness of radiotherapy treatment from previous decades in improving survival can be evaluated in these terms, but it will be many years before this can be done for the changes in treatment delivery and additional imaging that are being made at this point in time. Nevertheless, the advancement of radiation therapy including image guidance is a major advance that is already showing evidence of better outcomes (De Neve et al, 2012; Jaffray 2012).

# IMAGING FOR TREATMENT PLANNING

1. **Key points in this section:**

The quality of images, in terms of the reproduction of clinically important structures, obtained during pre-treatment imaging procedures should not be compromised at the expense of reducing the radiation exposure.

Optimisation of radiological protection during pre-treatment imaging requires use of appropriate imaging techniques and exposure parameters that vary with the imaging modality. Understanding the impact of different settings on patient dose, image quality and treatment planning dose calculations is important.

Image processing and reconstruction software may contribute to the optimisation process, but care must be taken to ensure image quality remains suitable for the clinical task. Artefacts must not be introduced through inappropriate imaging dose levels and image processing settings.

Optimisation of CT/CBCT for simulation requires the accuracy and uniformity of CT number in Hounsfield Units (HU) to be evaluated where images are used for treatment planning. The correct HU to electron density curve for the acquired imaging must be selected by the Treatment Planning System for dose calculations.

Organ motion tracking with 4DCT typically delivers higher radiation doses compared with 3D scans. The use of 4DCT for simulation should be justified only for specific clinical indications.

## Objectives of imaging prior to treatment

1. The primary role of imaging prior to treatment planning is to localise the treatment volume and organs-at-risk (OARs) accurately. This information is then used to determine the best treatment approach and calculate the precise radiation dose distribution to be delivered to the tumour and surrounding tissues.
2. Radiotherapy simulation most often uses ionising radiation based imaging techniques, though alternative options such as MRI are becoming more widely available in routine clinical practice. This means that the patients receive an extraneous radiation dose that is in addition to the prescribed therapeutic radiation dose. Although the magnitude of these exposures for treatment planning is much lower than the treatment dose, the radiation field is larger and includes more adjacent structures, so the principles of radiological protection i.e., justification and optimisation should be upheld. However, it is important to remember that image quality, in terms of the reproduction of clinically important structures, must not be diminished through reduction of the radiation exposure to the point where this will jeopardise the accuracy of radiotherapy delivery (ICRP, 1982a, 1982b).
3. This section introduces the main modalities for imaging prior to treatment, including brief technical descriptions and recommendations for dose and image quality optimisation (where appropriate).

### Consideration of margins and robust planning

1. Current dose calculation methods rely on the accurate determination of tissue densities and inhomogeneity within the internal patient anatomy. CT is the most common imaging modality used for treatment planning and dose calculation, as it provides a clear relationship between the CT numbers measured for specific tissue types within the patient and the electron density required by dose calculation algorithms (Gibbons, 2016).
2. Some treatment modalities do not rely on CT density information for dose calculation. For example, dose calculation algorithms for brachytherapy are based on the AAPM TG-43 formalism that assigns water properties to tissue (Rivard et al., 2004). This allows for fast dose calculation, and the development of MRI based treatment planning for brachytherapy is relatively straight forward (Harkenrider et al., 2015). The generation of synthetic CT from MRI for dose calculation is an active area of research as it would help to reduce imaging dose for RT patients, whilst also providing improved soft tissue contrast for tumour and OARs delineation (Owrangi et al., 2018) (section 6.2.3). Successful approaches utilise machine learning to generate anatomic atlases and assign attenuation coefficient values based on specific MRI contours (Farjam et al., 2019).
3. In addition to allowing the visualisation of internal anatomy for radiotherapy planning, CT allows tumour and organ motion to be assessed and potentially managed during treatment delivery. Four-dimensional CT (4DCT) is routinely applied in thoracic and upper abdominal cases to quantify and assess the effect of the respiratory cycle on the position of the tumour and critical organs (Rosu and Hugo, 2012; Nelson et al., 2010) (section 6.1.2). Other physiological internal variations might lead to changes in tumour position, size and shape, such as variable filling of the bladder and rectum, heartbeat, and swallowing. These are accounted for by the definition of an internal margin delineated as the internal target volume (ITV) prior to adding a PTV margin (ICRU, 1999; Murem et al., 2003; Boda-Heggemann et al., 2021) (see section 2.3.2). The main limitation of CT for target delineation is its low soft tissue contrast. The resulting inter-observer variability in tumour contour delineation has been studied and is well documented for a multitude of clinical locations (Joskowicz et al., 2019; van der Veen et al., 2019). Moreover, the lack of functional information from CT imaging prevents the detection of small groups of cancer cells separate from the gross tumour volume.

### Imaging for motion management prior to treatment

1. Organ movement or motion is one of the major challenges in the planning and delivery of radiotherapy (see section 7.1.2). During imaging for simulation, organ motion can introduce artefacts into images which will consequently affect the accuracy of structure delineation and CT number values for dose calculations. Suitable immobilisation or setup devices for the treatment site must be used to minimise any patient movement that can degrade image quality or compromise treatment outcomes; for example, to prevent the patient changing position on the couch during both imaging and treatment. However, other types of involuntary movement cannot be eliminated completely, so several CT simulation strategies have been used to account for these, with particular emphasis on respiratory motion. The main CT simulation techniques for motion management are slow CT, breath-hold CT, gated CT, and 4DCT.
2. **The slow CT** **method** involves acquisition of scans using a slow gantry rotation speed (~ 4 seconds per slice) and/or low pitch values to capture tumour motion during each slice acquisition. This method allows acquisition of the entire trajectory of tumour motion on the CT image set with the patient breathing freely. The disadvantage of this technique arises from the difficulty in accurately defining the exact shape and size of the tumour as well as the surrounding structures on the CT images due to motion blurring (Chinneck et al., 2010). With regards to the radiation exposure, the slow CT technique should be used with care as imaging dose may be higher compared with the conventional scanning technique.
3. **Breath-hold CT** simulation involves acquisition of images when the patient is holding their breath at specific phases of the respiratory cycle, implemented either under voluntary regulation of breath by the patient or with mechanical aid. This method can be used to capture tumour positions at both inhalation and exhalation breathing stages, but with the expense of doubling the radiation exposure. The non-reproduceable respiratory magnitude of inhalation and exhalation is another limitation of this method. Additional radiation exposure to the patient can result if an additional free breathing CT scan is acquired for dose calculation. Another option for the breath-hold method is to scan and subsequently treat the patient at a specific phase of the respiratory cycle. The radiation exposure for imaging using this method can be the same as the free breathing scan; however, it is not uncommon to acquire multiple CT scans, including a free breathing scan, as an alternative treatment planning image set.
4. **Gated CT** acquires CT images when the patient is in a certain phase of the respiratory cycle similar to the breath-hold method. However, it does not require the patient to hold their breath at certain phases of the respiratory cycle. The patient is allowed to breathe freely and an external respiratory signal triggers the CT scanner to start scanning when the surrogate marker reaches a pre-set part of the respiratory cycle. Although the image acquisition time can be four to five times longer depending on the duty cycle, the radiation exposure associated with this method may be similar to the free-breathing CT scanning (Moorrees and Bezak, 2012).
5. **4DCT** is the most popular method to account for organ motion during CT simulation. This allows the acquisition of the entire breathing cycle rather than one phase. The CT scanning is performed at a much lower pitch or with continuous scan in axial mode at one couch position, resulting in the acquisition of many more images per unit length of the patient (Keall et al., 2004). The image data are collected simultaneously with the respiration signal based on an external surrogate or respiratory measuring device, with a variety of devices currently being offered by different vendors. All images acquired in a similar respiratory phase will be ‘binned’ together for treatment planning. The choice of the number of ‘bins’ for planning is a trade-off between quality of image sets, as well as radiation exposure to patients.
6. In terms of radiation exposure, 4DCT doses will be higher than the standard 3D free breathing scan, whilst an increased number of bins may require higher radiation exposure to ensure images are of sufficient quality for each phase of the breathing cycle. A 2018 survey of doses from CT simulation in the UK showed that 4D methods give doses that are approximately a factor of three to four higher when compared with the 3D technique (Wood et al., 2018). The same survey also showed that some centres reduced doses delivered during lung 4D scans by minimising scan length, where supplementary data were available from 3D scanning of the extended anatomy. Although the dose received is much lower than the therapeutic dose (e.g. several tens of mGy in comparison with 40 to 70 Gy to the lungs in thoracic radiotherapy), steps should be taken to optimise radiation exposure from 4DCT scans as much as is practicable, as more tissues surrounding the tumour are irradiated. The benefit of the 4DCT technique is that it can ensure a highly targeted therapeutic dose is delivered to the tumour while minimising the dose to normal structures, but the use of 4DCT for simulation should be justified with care.
7. The method for optimising radiation exposure during 4DCT is similar to that for a conventional CT scan, which is in general dependent on the choice of scanning parameters as described in section 6.2.2. 4DCT rescans should be avoided where possible to minimise patient dose, though these may be necessary where unsuitable scan conditions or irregular patient breathing patterns lead to unacceptable image quality. The number of rescans can be reduced through the identification of unsuitable patients via a 4DCT QA protocol and by having a good mechanism for ensuring stable respiration of a patient through patient education and respiratory training, coaching or audio visual (AV) assisting devices (Matsuzaki et al., 2013).

## Technologies for imaging prior to treatment

### Conventional simulator

1. A conventional simulator is primarily used to determine the treatment field geometries based on 2-D x-ray radiographs with a system that mimics the geometry and mechanical movements of a C-type rotating gantry linac. It is used in two modes: radiographic and fluoroscopic. Optimisation of radiological protection can be implemented by applying appropriate imaging parameters and technique (ICRP, 2024b).
2. ***Tube potential (kV), current and exposure time (mAs)***: Use appropriate exposure factors that take into account the size of the patient and clinical intent. Pre-sets of tube parameters are usually available but may require further optimisation.
3. ***Automatic exposure control (AEC)***: AEC systems, where available, aim to provide an acceptable and consistent image quality regardless of patient-centric factors such as size and density, by adjusting the kV and/or mAs. Optimisation of settings related to this may be appropriate in some cases.
4. ***Collimation***: Limiting collimation to only the volumes of interest (including target and OARs) minimises radiation exposure to the patient and improves image quality (as scattered radiation increases with the size of the exposed field).
5. ***Anti-scatter grids***: Grids can be used to reduce scattered radiation, which would otherwise reduce image contrast at the potential expense of increased patient exposure. These may not be appropriate for small children (where scatter is much reduced).
6. ***Image processing***: Image processing can enhance image presentation, but care should be taken to avoid ‘over-correction’ that can impact the accuracy of treatment planning (e.g. modify the original size of a lesion to be treated) (ICRP, 2004).
7. Simulators may also be capable of CBCT imaging. In addition to the previous recommendations, operators ought to understand the scanning geometries and modes available and use them appropriately for the intended body site. Appropriate collimation, use of filters and number of projections are important in acquiring high-quality CBCT images with optimum radiation exposure. In addition, the accuracy and uniformity in terms of CT number (HU) has to be evaluated if CBCT images are used for treatment planning dose calculations and limitations such as scatter artefacts, short scan range and limited field of view (FOV) need to be considered.

### CT Simulation

1. Conventional simulators have been replaced by computed tomography (CT) simulators as the standard method of tumour and normal tissue localisation in many countries for both radical and palliative radiotherapy treatments (Martin et al., 2021).

#### CT acquisition parameters

1. The purpose of CT simulation is to collect three/four dimensional information on patient position and landmarks and acquire images of a sufficient quality that enables accurate structure delineation (by humans or auto contouring systems) with the patient in the treatment position. Oral and/or intravenous (IV) contrast can be administered to patients in order to help with the delineation of tumours or OARs.
2. In addition, the correlation between the CT number (HU) and electron density allows accurate dosimetry in the treatment planning system. For this purpose, usually a fixed tube potential (kV) is used (and automated adjustment ought to be disabled and locked). This is different from the practice in diagnostic CT scanning, where many combinations of tube parameters (including kV) may be used depending on patient size and contrast use.
3. Different CT scanner systems may have different energy spectra, even where the tube potential is set the same, so this should be accommodated in the calibration of the CT number-electron density curve and robust systems put in place to ensure the correct one is used in the TPS. In addition, any upgrade or major maintenance performed on the CT scanner, especially involving the x-ray tube, may impact the CT number-electron density curve. Therefore, CT number calibration should be checked and consistency with the TPS confirmed after such events.
4. It is prudent to use appropriate exposure factors and scanning techniques to optimise both dose and image quality. However, a UK survey of dose indices from CT simulation revealed that similar procedures on CT scanners in different centres varied by up to a factor of 18 (Wood et al., 2018). The results from this survey show evidence that there is considerable scope for optimisation of CT simulation imaging protocols as a number of centres have taken steps to reduce doses whilst maintaining appropriate clinical outcomes, with other centres still use vendor default protocols.
5. ICRP has previously published reports on managing doses for both single-detector and multidetector CT scanners, and most recommendations in these reports are relevant for CT scanning for simulation (ICRP, 2000d, 2007a, 2024a). However, there are other considerations to be taken into account when optimising radiological protection for patients from simulation. The trade-off between radiation exposure and image quality for structure delineation, including automated and AI based systems, and the impact of CT number accuracy on radiotherapy dose calculation must be considered. The following points should be considered in the optimisation of CT simulation protocols.
6. ***Tube potential***: Tube potential affects the CT number of the CT images generated, which impacts the correlation with electron density that is used for dose calculation in the TPS (Kearns and McJury, 2007; Skrzyński et al., 2010). For this reason, a single fixed tube potential is often used for CT simulation, with 120 kV being the most common. However, 120 kV may not be suitable for producing optimal image quality for paediatric imaging or large patients. Therefore, where the TPS allows more than one CT number to electron density calibration curve, the use of 80 kV and 140 kV may be considered. In this case, CT number to electron density curves for planning should be generated and calibrated using phantoms of appropriate sizes. In addition, robust systems are of utmost importance to ensure the correct electron density curve is selected for dose calculation (ASN, 2019).
7. ***Tube current***: In general, increased tube current is associated with reduced image noise (all other parameters being equal) and therefore increased image quality, at the expense of higher radiation doses to patients (Lira et al., 2015). It should be remembered that it is the tube current × time (mAs) that determines the dose level. In modern CT scanners, automatic tube current modulation (ATCM) varies tube current to accommodate differences in attenuation due to patient anatomy, shape and size, with the aim of maintaining a similar (but not necessarily identical) level of image quality throughout a scan and for different patients (ICRP, 2024b). Hence, ATCM is recommended for CT scanning during simulation. As CT vendors have different methods of implementation, it is essential for users to understand the operation of their system at the commissioning stage and ensure that they understand the parameters that influence it when configuring protocols. Inappropriate setting of the ATCM may lead to significant increases in radiation exposure or reductions in image quality (Martin and Sookpeng, 2016), or inaccurate dose calculation (ASN, 2019). Changes in CT number are minimal when varying tube current, either manually or by automatic modulation during scanning (Bissonnette et al., 2012; Khan et al., 2016; Davis et al., 2018).
8. ***Tube rotation time***: For a given tube current, the dose to patients and total scan time will be directly proportional to tube rotation time; for this reason, it is often preferable to keep this to a minimum. However, it should be noted that due to the upper tube current limit on CT scanners (either the fundamental limits of the scanner hardware or user defined limits for individual protocols), there may be cases where the ATCM system can reach maximum values with no scope to increase exposure further. In the case of larger patients, this may compromise clinical image quality. Increasing tube rotation time enables higher total exposures to be delivered in such cases. The opposite may be true for smaller patients with lower tube current limits.
9. ***Scan range and field of view***: Scan range defines the start and the end of the region to be imaged and is usually determined after a scan projection radiograph has been acquired. The acquisition field of view (FOV) determines the acquisition geometry and maximum size of the reconstructed image. An increase in scan range and acquisition FOV will increase the radiation dose (all other factors being equal). For this reason, scan range should be kept to the area required for treatment planning and accurate dose calculation (to ensure enough scattering for dose calculation at the edge of the irradiation field), whilst the appropriate acquisition FOV (e.g. small or large) should be used for the anatomical region provided it does not impact on the CT number calibration. The whole volume of some parallel OARs should be scanned in order to calculate dose-volume metrics to reduce the risk of complication, such as V20Gy and mean dose for lungs; incomplete scanning may result in repeated imaging that increases patient exposure. The FOV should be selected so that it encompasses the complete region including patient immobilisation devices so that structure delineation and dose calculation are not compromised. Any objects outside the FOV may lead to errors in dose delivery if they are in the path of the treatment beam, because their images were not used for calculating the dose attenuation and scattering during treatment planning. The reconstructed FOV may be less than or equal to the size of the acquisition FOV. In this case, patient dose is not impacted by any changes to this parameter, but the impact on clinical image quality (for example, image noise and spatial resolution) should be considered (Davis et al., 2018).
10. ***Beam collimation and image slice thickness***: Beam collimation is a product of the number of data channels in the z-axis multiplied by the effective detector row thickness. In general, the choice of beam collimation for scanning depends on the desired reconstructed CT slice thickness, with smaller collimations required for reconstructing narrower slices. However, smaller beam collimations also result in relatively poor geometric efficiency which increases patient dose (Hamberg et al. 2003). The choice of reconstructed or image slice thickness is an important factor influencing the delineation of targets and normal structures for planning. It has been shown that thinner slices produce more accurate volume assessment (Prionas et al., 2010; Wang et al., 2016). However, the need for a small slice thickness should be balanced with the accuracy requirement for delineation and radiation exposure to patients. The choice of slice thickness is therefore recommended to be based on treatment intent and technique. For example, 2 to 4 mm is often appropriate for many radical 3D conformal radiotherapy treatments, whilst thicker slices may be acceptable for equivalent palliative treatments. Conversely, advanced radiotherapy techniques such as IMRT, VMAT and SBRT/SRS require high-quality and high-resolution images for structure delineation and treatment planning, due to the high-dose gradient region(s); hence, thin slices of less than 2 mm may be appropriate. It should also be noted that where thinner slices are used, increased tube currents may be necessary to ensure acceptable noise levels in the final images.
11. ***Pitch***: The pitch is the ratio of the patient table increment to the total nominal beam collimation. A high-pitch protocol is associated with reduced scanning times, but with potential deterioration of image resolution in the z-axis due to interpolation artefacts. A low-pitch technique in general produces images of relatively higher image quality. However, with all other parameters held constant (such as tube current and rotation time), a low-pitch technique will result in higher radiation dose. It should be noted, however, that most CT scanners use the concept of ‘effective mAs’ or ‘mAs per slice’, whereby the impact of pitch on radiation dose is regulated by automatic adjustment of the tube current to maintain similar image noise levels.
12. ***Dual-Energy CT***: (DECT) or ‘spectral’ CT provides more accurate material decomposition information and stopping power ratios for dose calculation, which is particularly relevant to particle therapies. DECT may also be used for reducing metal artefacts, though many vendors implement reconstruction based corrections to overcome this. It is also possible to generate ‘virtual non-contrast’ images from DECT scans, which effectively remove contrast enhancement from the CT image set; this mitigates for a potential source of error in dose calculations when contrast agents are used to enhance delineation in planning, as these contrast agents will not be used during treatment delivery. This is relevant for gastric and/or vascular regions. This may enable some dose optimisation as an additional ‘true non contrast’ scan may not be required for the TPS. The dose implications of DECT are complex and depend on the method of acquisition implemented on the specific CT scanner; some may use similar doses to conventional single energy acquisitions, but other techniques may result in greater exposure due to the acquisition of two separate data sets. It is therefore critical to understand the implemented technology and how it impacts both dose and image quality. For this reason, radiotherapy staff may require the support of colleagues trained in diagnostic radiology to optimise the relevant imaging protocols (ICRP, 2024b).

#### CT image reconstruction algorithms

1. Filtered back projection has been the method of reconstruction used for the majority of the first 50 years of CT imaging but is now being replaced by other techniques. Iterative reconstruction algorithms enable the generation of higher quality images with reduced noise and artefacts, without the need for increased radiation doses to patients (Desai et al., 2012; Korn et al., 2012; Mitsumori et al., 2012; Andrabi et al., 2015); it is therefore recommended that iterative reconstruction algorithms are applied for simulation where possible. However, a UK survey of doses from CT simulation revealed no difference in the dose levels between scanners using filtered back projection and iterative reconstruction (Wood et al., 2018). Therefore, if iterative reconstruction is to achieve any reduction in dose from imaging, adjustments to exposure factors are required that lower patient exposure but maintain appropriate image quality. It should also be noted that simple measures of image quality such as signal-to-noise ratio and contrast-to-noise ratio may not be appropriate for iterative reconstruction or other advanced algorithms, with methods involving signal detection-based metrics similar to clinical tasks being required (AAPM, 2019a; ICRP, 2023).
2. There are numerous variants of iterative reconstruction algorithms from different vendors, and even multiple selections within one model of CT scanner (but descriptions are beyond the scope of this report). The impact of reconstruction algorithms on CT number is complicated and depends on which algorithm is selected (Kirwin et al., 2004; Zurl et al., 2014; Davis et al., 2018). Users should be familiar with and understand the impact of the iterative reconstruction algorithms offered on their CT scanner and select the appropriate one to give the required level of image quality. Exposure factors may require adjustment following any changes, and the impact on CT number calibration understood. Iterative reconstruction can also allow the reduction of metal artefact reduction and this is used increasingly in radiotherapy planning. The suitability of these images for dose calculation needs to be carefully investigated.

### Magnetic Resonance Imaging (MRI)

1. MRI provides additional anatomical information and has better soft tissue contrast than CT, which may enhance precision and efficiency in treatment planning. While MRI is widely used for diagnostic imaging, it is generally a secondary imaging modality in radiotherapy due to the absence of electron density information for dose calculation with the TPS, potential image artefacts and a smaller field of view. In many clinical applications, the MRI image set is registered with CT imaging to overcome the limitations in both techniques. These issues are recognised within MRI protocols generated for radiotherapy planning which usually require high spatial resolution, a larger field of view with 3D volumetric acquisitions and the application of distortion corrections to retain the geometric fidelity required for accurate structure segmentation. MRI is established as the standard technique for contouring of targets in SRS (Stross et al., 2019) and many brachytherapy applications (Pötter et al., 2018). MRI plays a crucial role in modern treatment planning as it enables superior delineation of anatomical structures, particularly in areas such as the brain where it can provide detailed insights into intricate brain anatomy and allow precise targeting of millimetre-sized tumours.
2. To address the limitations of MRI imaging, one solution involves creating a virtual CT image, also known as a pseudo-CT, from the MR dataset (Persson et al., 2107). Synthetic CT images have the potential to revolutionise the radiotherapy workflow, allowing treatment planning directly on MR datasets (Johnstone et al., 2018), and possibly enable MR-only treatments including online MR-based localisation and adaptation. Studies have demonstrated the feasibility of an MRI-only approach, achieving an acceptable level of quality using various techniques (Edmund and Nyholm, 2017). Such integration of MRI into the radiotherapy treatment planning process underscores its potential role in optimising standard and adaptive treatment strategies and reducing patient exposure to ionising radiation by eliminating the need for additional CT scans.

### Positron emission tomography/CT (PET/CT)

1. PET/CT is an important modality in oncology for diagnosis and staging, as well as providing crucial prognostic and predictive information. During radiotherapy treatment planning, PET images are commonly co-registered with planning CT to aid in defining the target volume as well as nodal disease in many sites including head and neck, mediastinum and pelvis, and to locate bone metastases (see section 1.3 and Annex A.1). [18F] FDG is currently the most widely used tracer for oncology practice. A PET/CT study specifically for radiotherapy treatment planning must be appropriately justified in order to avoid unnecessary radiation exposure to the patient.
2. It has been reported that FDG-PET/CT improves the accuracy of radiotherapy treatment planning in terms of target definition (MacManus et al., 2009) and reduced inter-observer variability (Tejwani et al., 2012) compared with CT alone. PET/CT has been reported to be beneficial for radiotherapy treatment planning in non-small cell lung cancer, small cell lung cancer, head and neck tumours, lymphoma and oesophageal cancer (IAEA, 2008b) with indications increasing.
3. If the patient is set up in the treatment position (with the correct immobilisation devices) the CT scan from the PET/CT can be used for treatment planning provided appropriate commissioning of the imaging protocol has been done. If the CT component is used for treatment planning dose calculations, the CT number-electron density map should be calibrated specifically for the PET/CT tube and the potential to be used for radiotherapy imaging. Processes must be in place to ensure the correct calibration curve is selected in the TPS. The benefits of this, if done correctly, are the possible reduction in the number of CT scans performed on the patient, and hence reduced radiation exposure, which also has the potential for reducing the time between PET/CT scans and the start of treatment (as there does not need to be another planning CT scan appointment to proceed).
4. When a ‘diagnostic’ CT is performed as part of the PET/CT examination, the CT component typically contributes a higher proportion of the radiation exposure to the patient compared with the PET component (Huang et al., 2009; Li et al., 2019). However, a full diagnostic scan should only be performed if required, as a low dose CT scan will be sufficient for the purpose of attenuation correction and localisation of the uptake. Compliance with DRLs for both the PET and CT components should be evaluated, with the latter reflecting the clinical intent of the CT scan (see section 10.3.2); for example, the UK have established national diagnostic reference levels for CT scans in PET/CT that are specifically for the purposes of ‘attenuation correction and localisation’ (UKHSA, 2022). Techniques for optimising the CT dose component are described in section 6.2.2.
5. It is also important to remember that the PET component of a PET/CT examination involves many tasks that contribute to occupational radiation exposure due to handling of the radiopharmaceuticals and patient contact. These issues may be less familiar to radiotherapy staff who perform standard CT planning scans who may require further education and training if they are to be involved in radiotherapy planning PET/CT scans. These matters are considered in other ICRP Publications (Alenezi and Soliman, 2015; ICRP, 2024c).

### Image handling, registration and combined images

1. All modern imaging or radiation treatment planning software has the ability to provide rigid and/or deformable image registration and fusion capabilities in order to supply accurate information for the delineation from multi-modality images. With rigid registration, a moving image data set is translated and rotated to be aligned with respect to a reference image set. Deformable registrations apply complex geometric or physical transformations to the moving data set. They may be helpful when patient images, which are to be fused, are acquired in different positions, or to correct image distortion characteristics of MRI scans. However, limitations in the models used for the deformable transformations can lead to inaccuracies and create artefacts resulting in errors for the segmentation of tumours or normal tissues (Brock et al., 2017) (see section 11.2.5). As a deformed image has no easily documentable link to the original image, labelling and documentation can also be challenging. Methods for the validation and QA of image registration are extensively described in Brock et al. (2017).
2. In brachytherapy, specifically, image registration must account for significant anatomical changes introduced by the applicator. Therefore, the applicator itself should be used as a landmark for registering images throughout the treatment course, rather than relying on bony structures or other typical landmarks used in EBRT.

## The impact of AI on image analysis

1. The use of artificial intelligence (AI) in imaging and radiotherapy planning is developing rapidly. AI can potentially play a significant role in image acquisition, reconstruction, registration, segmentation, as well as error detection, QA procedures and many other processes.
2. Artificial intelligence (AI) in the form of deep learning-based image reconstruction (DLIR) is the latest tool for image reconstruction and forms an active area of research. The current generation of commercial DLIR algorithms is designed to effectively mitigate imaging noise and can be used successfully to reconstruct high quality images from low dose CT acquisitions (Wang et al., 2019; Brady et al., 2020; Zhang and Seeram, 2020; Nagayama et al., 2021; Immonen et al., 2022; ICRP, 2024b). DLIR also holds the promise of rapid image reconstruction, significantly reducing processing time.
3. In this approach, the network is trained with a set of paired low-dose and high-dose images and can subsequently be used to predict a virtual high-dose image with only low-dose image data (or a pre-reconstruction sinogram) as input. A number of different methods have been explored for this purpose in various clinical sites and using various network architectures. An example is that of low dose reconstruction for high quality CT images in paediatric patients (Brady et al., 2020; Nagayama et al., 2021). An example of low-dose CT reconstruction for brain radiosurgery is given in Fig. 6.1 (Wang et al., 2019).

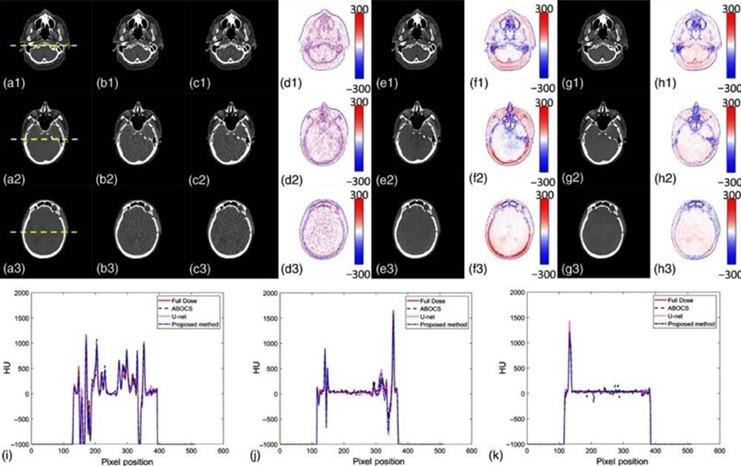


Fig. 6.1. Full dose CT scans (a) are compared with simulated low-dose CT scans generated using filtered back-projection of raw projection data with imposed noise contamination corresponding to 0.5 % mAs (b), and with predicted denoised images using respectively an iterative reconstruction algorithm ABOCS (c), a standard unit based DL network (e), and a cycleGAN based DL network (g). Difference maps between the full dose image (a) and the predicted images (c), (e) and (g) respectively, are shown in (d), (f) and (h). In the bottom row of the figure, line profiles are shown at three different positions as indicated by yellow dashed lines in (a). (Wang et al., 2019) (Permission for reproduction is being sought from the publisher).

1. In direct comparison to filtered back projection or iterative reconstruction methods, DLIR demonstrates improvements in image quality, especially when operating at lower doses (Greffier et al., 2022) with enhanced high and low contrast resolution, preserved CT number accuracy, and superior spatial resolution (Szczykutowicz et al., 2022). One of the distinctive advantages of DLIR is its ability to suppress the undesirable 'plastic' or 'blotchy' noise that is often introduced by conventional IR methods. However, similarly to advanced IR methods, the suitability of images generated by DLIR algorithms for dose calculation needs to be carefully investigated.
2. As with iterative reconstruction, vendor implementations may vary and the consequences of this must be understand, specifically with respect to the impact on patient dose, image quality (including changes in image noise texture that can impact threshold contrast detectability) and CT number accuracy (Greffier et al., 2022; Szczykutowicz et al., 2022). It should also be noted that aggressive reduction in patient doses with such algorithms may lead to the generation of clinically significant artefacts, so care must be taken when optimising DLIR based protocols.
3. Another use of DL in image reconstruction is for the removal of artefacts caused for instance by dental fillings or metal implants. Such artefacts may potentially have detrimental effects on the calculated dose distribution in the treatment plan, and it will be an advantage to employ methods for their removal if possible. Several studies have shown the potential of using DL networks to achieve artefact reduction in CT images, both for instance for metal implants (Gjesteby et al., 2017), as well as for artefacts caused by other issues, such as motion in 4D imaging (Mori et al., 2019).
4. Cone beam CT imaging is even more prone to artefacts than CT, and removal of artefacts in these images by use of DL has been given particular attention, for improving image quality in both patient localisation and setup, and daily dose recalculation/optimisation for adaptive radiotherapy therapy planning (Griner et al., 2020; Dong et al., 2021).
5. DLIR may also play an important role in the generation of synthetic-CT from MR images giving the potential to avoid exposure from imaging (section 6.2.3). A number of studies have been published using the methods specific to generalised adversarial networks (GANs), which can generate accurate synthetic-CT images with electron density reproduction for radiotherapy planning purposes (Peng et al., 2020; Lerner et al., 2021). In Fig. 6.2, an example is shown with comparison of two GAN methods to generate pseudo-CT images, both showing good results in terms of predicting reliable CT number values, resulting in promising dose calculation possibilities.
6. The most mature use of AI in image analysis for radiotherapy is that of image segmentation. Manual segmentation of organs at risk and target volumes is a challenging, high-cost, and time-consuming task prone to large inter-observer variations, and image segmentation is a task well suited for deep neural networks. Automated segmentation of organs at risk in CT images using deep learning is integrated in many commercial systems and is becoming widely used as a routine practice (Isaksson et al., 2023). Dose prediction using AI is less mature, and is not yet standard practice, although it is becoming available in some applications (Jiang et al., 2024).

A collage of images of a brain

Description automatically generated

Fig. 6.2. Synthetic CT (SCT) images generated from MRI images using two DL models (cGAN = conditional generative adversarial network; cycleGAN = cycle-consistent generative adversarial network) trained with 135 patient image samples and showing (a) the average performance in terms of HU (cGAN mean absolute error (MAE) = 68.44 HU; cycleGAN MAE = 94.01 HU) and (b) the worst performance (cGAN MAE = 89.41 HU; cycleGAN MAE = 108.95 HU) (Peng et al., 2020). (Permission for reproduction is being sought from the publisher).

# IMAGING DURING THE TREATMENT CYCLE

1. **Key points in this section:**

The majority of imaging techniques used during radiotherapy delivery rely on x-rays and deliver additional dose to the patient. The magnitude of the dose depends on field size, required image quality and imaging frequency (e.g. daily or weekly) as part of a radiotherapy course that typically consists of 20 or more fractions.

Imaging during the treatment cycle allows actions such as modifications to patient position and adapting the plan to account for changes in anatomy. These actions need to be based on clear images and protocols that are easy to understand with staff trained to correctly interpret and act as appropriate.

Margins around the target and critical structures are used to account for uncertainty in target delineation, anatomical changes, patient set-up and delivery. Image guidance may enable smaller margins to be used and the protocol for imaging should take account of the margins to be achieved.

Motion is a significant problem in radiotherapy as it interferes with the accuracy and precision of treatment delivery. Imaging can help to ensure that motion during delivery is similar to that for which the treatment plan was created but requires the acquisition of multiple images which can increase the imaging dose to the patient.

Adaptive radiotherapy takes account of changes in patient anatomy from day to day by modifying the treatment plan to suit the ‘patient anatomy of the day’. Daily volumetric imaging is essential for this and while MRI linacs are showing promise for some treatment scenarios, most adaptation is based on x-ray CBCT.

Online adaptive radiotherapy is possible with improved image quality and faster treatment planning computers. This requires higher levels of image quality than conventional CBCT and specialised techniques are required for better visualisation with more computer assistance and automation.

Imaging options using non-ionising radiation techniques for localisation and verification may provide viable alternatives in some situations.

## Objectives of imaging during therapy delivery

1. Imaging at time of treatment delivery is an integral part of modern radiotherapy and it is rare that treatment units are purchased and installed without some type of image guidance capability. Objectives for the image acquisition may vary and optimisation of imaging based on the task are important. Typical tasks are:

* Verification of the treatment field outline in relation to anatomy using the treatment beam. In many photon beams this can be done using the treatment beam itself and an EPID. In some circumstances a larger field is also delivered to provide anatomical context (double exposure), but if this is not required a fraction of the treatment beam can be used without delivering additional dose to the patient. In the context of IMRT or arc deliveries this is more complicated as many field segments must be added.
* Verification of patient, target or organ position in relation to the isocentre (see Annex A.1.). This can be done using a variety of imaging modalities including kV CBCT and MRI. The frequency of imaging depends on the anatomical site and the required precision.
* Assessment of organ shape or size prior to treatment. Achieved with volumetric imaging such as CBCT or MRI (see sections 7.1.1 and 7.1.3).
* Monitoring motion of the target or critical structures during delivery. This is done to allow for breathing motion. It requires an imaging frequency commensurate with the speed of motion and favours in many circumstances planar imaging but options are available that avoid the use of ionising radiation (see section 7.1.2).

### Anatomical changes to patient and structure positioning

1. Ideally imaging will depict directly the organ of interest and put it into a spatial relation with the radiation delivery apparatus. This requires at present mostly x-ray imaging or increasingly MRI. Ultrasound may also be an option in some scenarios such as trans-perineal ultrasound for prostate localisation. However, regardless of imaging modality, for some treatment sites the target or organ of interest may not be easily visible on imaging, in which case surrogates are used for localisation. For x-ray imaging these are typically bones and at times air cavities such as the trachea. Alternatively fiducial markers, often gold seeds, can be implanted into relevant organs such as liver, prostate or lung. This does not necessarily require conventional imaging and radio-beacons have been successfully used in many centres (Langen et al., 2008).
2. While skin marks (such as tattoos) are often considered to be less reliable than imaging the internal anatomy, the introduction of optical surface guidance that uses three stereoscopic cameras to monitor multiple positions across the patient’s skin has become more widely accepted (Naumann et al., 2020). Optical surface imaging systems (Freislederer et al., 2020) offer non-ionising radiation solutions for performing patient set-up and monitoring intra fraction motion of the patient’s skin. Surface Guided Radiation Therapy (SGRT) is currently used for frameless intracranial stereotactic radiation therapy, alignment and deep inspiration breath hold (DIBH) gating for breast and chest wall treatments, and a variety of other applications. The clinical use for respiratory motion monitoring is being investigated.
3. Optical surface guidance can be correlated initially with a single x-ray image and then used continuously without the need for further imaging dose. Optical surface guidance can only observe the displacement of the patient's surface during the treatment process, it cannot reflect changes in the relative positions of the patient's tumour and surrounding organs. However, a deep-learning based method associating the body surface with internal structure deformation, which predicted dynamic internal anatomies from quasi-real-time optical surface images for IGRT navigation has been proposed by Huang et al. (2022).

### Imaging for motion management during treatment delivery

1. Motion is a significant problem in radiotherapy as it interferes with accurate treatment delivery. Imaging during treatment planning and delivery can identify motion and ensure that motion during delivery is similar to that observed when the treatment plan was created. Imaging to identify motion typically requires the acquisition of multiple images which can lead to an increase in imaging dose to the patient.
2. Imaging for management of internal organ motion must be fast enough to depict motion in quasi-real time. In its most simple form, it verifies whether or not motion just prior to treatment is identical to the motion encountered during planning exposures and accounted for at treatment planning. Information on quantification of motion prior to treatment can either be used to adjust the treatment to be performed (online) or be considered in offline review.
3. Motion management can be used to reduce the impact of regular and irregular motion on the margins required for treatment. Irregular motion may be swallowing or peristaltic motion of the intestines. In this case the main objective is to detect any significant motion and interrupt the treatment if needed. Regular motion such as cardiac and breathing motion can be assessed and accounted for in different ways:

* Immobilisation devices such as a compression belt can be used to reduce motion in the patient.
* The amplitude of the motion can be measured, and the target volume extended to encompass it by creating an Internal Target Volume (ITV). While the ITV is created during treatment planning, the consistency of motion during treatment must be verified using image guidance, for example with 4D CBCT or optical surface imaging. Any hysteresis must be included.
* The beam can be turned on only when the target volume is in a specified location, a process called gating.
* The radiation beam can ‘follow’ the target as it moves. This motion adaptive therapy relies on software to track the tumour and predict its position taking any latency into consideration.

1. Surrogate markers that move with the patient’s chest or abdomen are often used to indicate motion in particular if the motion is internal and cannot be easily visualised because of their simplicity (Keall et al., 2006; Korreman, 2015; Brandner et al., 2017). While it is possible to see high contrast objects move it is more difficult to quantify motion of low contrast objects, so fiducial markers may be implanted into the tissue of interest to make the organ more easily visible. Surrogate markers can be used to assess both treatment delivery and guide the acquisition of time resolved images such as 4D CBCT. Typical markers are:

* External physical markers such as blocks with infra-red visible markers
* A belt that monitors expansion of the abdomen during breathing
* Implanted fiducials
* Radio beacons
* Existing structures such as lipiodol from ablative procedures in liver cancer, surgical clips or small calcifications

1. Other tools are available most of which are add-ons from different manufacturers. Optical surface guidance has become widely adopted (see section 7.1.1) and spirometry with or without arresting breathing in a particular phase of the breathing cycle is also used. These techniques require special QA attention, as interfaces between manufacturers create vulnerabilities.
2. In all these cases, motion management requires frequent imaging to assess and follow motion. While MRI has made its way into some clinics, x-ray imaging is the most common method ranging from fluoroscopy to 4D CBCT. In 4D or gated CBCT an external or internal marker is used to identify a specific phase of a patient's breathing cycle and oversampling allows enough projections to be collected to reconstruct images for several phases of the breathing cycle. 4D CBCT acquisition typically takes several minutes and consequently radiation dose may be of concern (Thengumpallil et al., 2016). However, it provides the advantage to directly compare the tumour movement during treatment with that observed during planning using 4D CT. Fluoroscopy and 4D CBCT are typically used to verify that amplitude, frequency and pattern of motion match the ones on which treatment planning is based prior to delivery of the treatment.
3. Real time motion management requires continuous monitoring. While this can be done with on-board imaging during arc therapy (Keall et al., 2018), a more common scenario consists of two orthogonal x-ray imaging systems that are independent of the linac and usually floor mounted under an angle to avoid being blocked by many gantry positions. Fig. 7.1 shows such an installation and several other image guidance tools included in a modern linac. To avoid radiation dose, the system is often coupled with optical imaging that monitors the patient’s surface continuously or ultrasound, while the x-ray imaging is used to update the position every few seconds.

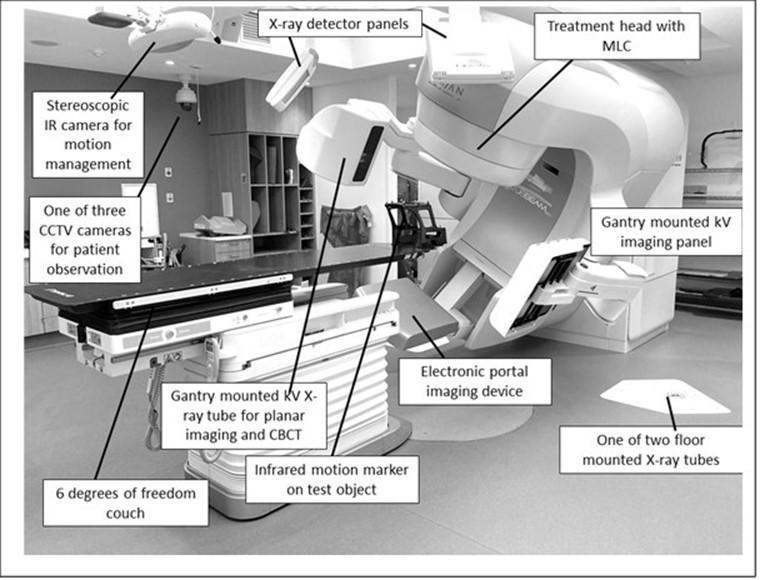


Fig. 7.1. A modern linear accelerator with several image guidance tools (T Kron, Peter MacCallum Cancer Centre, Melbourne, Australia)

## Imaging for adaptive radiotherapy

1. In addition to ensuring correct position of the patient and accounting for organ motion in the patient. For abdominal and pelvic lesions stomach, intestinal or bladder filling can change from day to day thereby modifying the anatomy. Another example is neck cancers where primary tumour and nodal volumes can shrink or grow, patient weight loss during radiotherapy may impact the location of targets and OARs in relation to the treatment dose distribution, and there mya be significant change in oedema during post-surgical head and neck radiotherapy.
2. It is important to account for any changes that occur between the time of treatment planning and treatment delivery. This is broadly termed ‘adaptive radiotherapy’ and allows for the correction of target shape and size as well as the relation of the target to surrounding OARs, taking possible change in the size and shape into account by modifying the treatment plan to suit the ‘patient of the day’. It uses image guidance as a basis to assess and correct for that and several different adaptation approaches can be taken ranging from offline (Figen et al., 2020) to online (Kron et al., 2012) and real time (Keall et al., 2018) applications. Daily volumetric imaging is essential and, while MRI linacs are showing great promise for several treatment scenarios, most adaptation is based on kV CBCT.
3. Imaging for adaptive radiotherapy generally needs to be 3-D and the most common modality is kV CBCT, though CT on rails (Owen et al., 2009), MV CBCT (Kupelian and Langen, 2011) and more recently MRI (Lagendijk et al., 2008) are also useful tools. Ultrasound can also be used to assess bladder filling and adjust treatment geometry accordingly (Haworth et al., 2014). Adaptive radiotherapy is challenging and by its nature is both patient- and institution-specific and a risk management approach would be well suited as the dose/benefit relation is complex and QA is highly specific to the process.
4. Adaptation was originally mostly used as an offline procedure with imaging during treatment used to trigger a more thorough evaluation and a re-planning process for future fractions. This has been successfully implemented by many groups for head and neck cancer for example when target volumes shrink during treatment. This approach is not suitable for situations where the treatment scenario changes for each fraction such as in the case of bladder cancer where the bladder filling determines the location and shape of the target volume. An elegant approach in this scenario is to develop more than one treatment plan (a “plan library”) and choose the one most suitable for the patient on the day based on volumetric imaging.
5. With improving image quality and faster treatment planning computers, online re-planning is also possible. This has become a driver for several recent developments in radiotherapy delivery technology with MRI linacs and CBCT based online adaptive RT platforms being specifically aimed at adaptive RT treatments.
6. There are several challenges for online adaptive radiotherapy:

* maintaining image quality suitable for re-planning
* re-contouring of structures for planning, a process that requires at least some degree of automation
* fast dose optimisation which may require the need to perform dose calculations based on accurate representation of radiological properties of structures
* a governance structure that ensures that the treatment is approved by a registered medical practitioner (justification)
* independent quality assurance (QA).

1. Online adaptive radiotherapy requires higher daily image quality than the conventional CBCT that is mainly used for positioning purposes. Therefore, iterative reconstruction and low dose dual-energy CBCT have been proposed for better visualisation and more accurate acquisition of electron density distribution (Li et al., 2023). Integrated diagnostic CT has also been used with a linac for online adaptive radiotherapy (Yu et al., 2023; Li et al., 2023).
2. The faster adaptation is required, the more computer assistance and automation is necessary. Motion adaptation, where the treatment beam is adjusted in real time to cover a changing target takes this to the logical conclusion. Table 7.1 summarises the adaptation approaches possible.
3. The requirement for speed during adaptive radiotherapy, in particular for online adaptive radiotherapy, makes automation of manual tasks a practical necessity. Recent advances in Artificial Intelligence therefore play an increasingly large role in facilitating adaptive radiotherapy (Landry et al., 2023).
4. Artificial Intelligence may be used to predict likely anatomical changes over the treatment course as demonstrated in Smolders et al. (2024). This information may be used to decide on adaptation strategy up front, as well as to guide decision making during each treatment fraction.

Table 7.1. Imaging requirements and adaptative radiotherapy

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Adaptation | Techniques | Typical imaging | Time scale | Comment |
| Real time | Gating, Motion adaptation | Optical, planar x-ray, Ultrasound | Seconds | Fully automated – requires computer control |
| Online | Plan of the day, replan | CBCT, MRI | Minutes | Skilled operator required |
| Offline (next fraction) | New plan based on imaging at treatment | CBCT, MRI | Next day | Allows for more complex decision making |
| Future fractions | Re-imaging for planning | Planning CT | Several days | New plan with all options |
| Future treatments | Different modality | Functional imaging | Months | Response assessment, retreatment |

1. In order to perform daily online adaptation, fast structure segmentation and dose optimisation must be available, to be performed while the patient is on the treatment table. For CBCT guided adaptation, both of these processes suffer from the CBCT images typically being of a lower quality, which may pose a particular problem for reliable dose calculation. Deep learning based image segmentation is well developed in CT scans and is being developed and evaluated for CBCT as well, see for instance (Liang et al., 2023; Radici et al., 2024). Likewise, dose prediction based on CT scans is well advanced, and methods for dose prediction for CBCTs is being explored using various methods including generation of synthetic CTs or direct use of CBCTs (Chan et al., 2023; Dong et al., 2023; Bogowicz et al., 2024).
2. For MR-guided online adaptive radiotherapy, similar procedures are needed, and although the specific methods will be slightly different, the principles of using AI for instance for synthetic CT generation are similar to those used for CBCT. For a recent review of methods and state of the art, see for instance (Landry et al., 2023).

## Imaging technologies and frequencies used during therapy delivery

1. Treatment scenario and scope largely determines the choice of imaging technique, the required image quality and imaging frequency. Table 7.2 provides a summary of techniques available. Image guidance can only be as good as the reference information, in providing a perfect match between treatment and planning. Therefore, reference images are of considerable importance and can include other information that can help the treatment staff to reach a decision as quickly as possible. For example, an isodose contour from planning, which is relevant for toxicity, e.g. for spinal cord tolerance, will allow the operator to quickly assess not only if the dose delivery to the target is as planned, but also that the normal tissue tolerance is not exceeded if the target has moved in relation to the critical structure.
2. For imaging performed in relation to radiotherapy, the goal is to balance the ALARA principle with an AAARA principle (As Accurate As Reasonably Achievable) (IAEA, 2016), taking into consideration the therapeutic dose and volume, potential reductions in dose and volume achievable through image guidance, and the imaging dose delivered.

### Imaging technologies

1. Whatever the treatment objective and fractionation, imaging prior to or during treatment delivery provides important information on target location, shape and motion in order to optimise the treatment delivery. A variety of imaging options are available to verify patient and target position, and information on the techniques, their use and the dose levels involved is given in Table 7.2. The majority of the techniques, in particular the commonly used volumetric CBCT imaging, rely on x-rays and deliver additional dose to the patient. The magnitude of the dose for the x-ray techniques depends on the field size, required image quality and the imaging frequency as part of a radiotherapy course that typically consists of 20 or more fractions.

### Imaging frequency

1. Imaging frequencies are adopted depending on the treatment site and delivery technique in addition to the requirements in terms of accuracy (see sections 1.6 and 3.3). Common frequency protocols are:

* Once at commencement of the treatment course to ensure treatment set-up of the patient matches the treatment plan
* Once per week to check treatment delivery remains consistent throughout the treatment
* Several times in the first week of treatment and then weekly for action level protocols and to check that the treatment delivery on the first day is followed consistently throughout the course of treatment
* Every day to make sure every treatment fraction is accurately delivered
* More than once during a fraction to assess any significant changes in the internal anatomy occurring during treatment
* Continuously to assess regular motion (breathing, cardiac) or irregular movement (peristaltic motion, swallowing)

1. For the first two frequencies, actions are often not taken ‘offline’ unless a gross mistake is found, after which any findings based on imaging are applied on the next treatment day. The advantage of offline is that actions can be thoroughly discussed and carefully implemented. The use of image guidance assumes that treatment staff act on the imaging findings immediately before delivering the therapeutic radiation.
2. It is important to note that all imaging and the decisions based on it have the potential to improve future radiotherapy practice through evaluation of past image guidance results. This requires the set-up of a data base and recording of actions based on imaging and the subsequent clinical outcomes.

Table 7.2 Image guidance approaches – the list does not imply endorsement and the dose levels simply provide an order of magnitude

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Imaging technology | Details | Dimensions | Typical absorbed dose (mGy) | Motion management | Common clinical scenario | Comment |
| Marker beacons | Radiofrequency | n/a | NIL | yes | Prostate | Position of markers only – no ‘image’ |
| MV planar imaging |  | 2D | 20 | Limited, CINE EPI | Breast Mid Lung Distance | Often done as orthogonal or tangential image pair |
| MV CT imaging | Fan beam geometry | 3D | 10-40 | no | Various –suitable for metallic implants | Dose can be included in treatment plan |
| MV CT imaging | Cone Beam geometry | 3D | 50 | no | Lung | Dose can be included in treatment plan |
| kV planar imaging | Independent of linac | 2D x 2 | 2 | yes | Brain, spine | Usually installed as image pair |
|  | Linac mounted | 2D | 1 | Limited: Fluoroscopy, KIM | Head and neck, prostate, lung | Often done as orthogonal image pair |
| kV CT imaging | Fan beam geometry, ‘CT on rails’ | 3D | 5 CTDI | Possible as 4D CT | Various | Patient/couch must be moved from treatment to imaging location |
|  | Cone Beam geometry | 3D | 10 CTDI | Limited | Various | Most common approach |
| Optical imaging |  | n/a | NIL | yes | Breast | Limited to surface |
| Ultrasound |  | 2D or 3D | NIL | limited | Prostate | Common tool for brachytherapy |
| MRI |  | 3D | NIL | yes | Various | Used also in brachytherapy |
| PET |  | 3D | 10 |  | Multiple metastases | Biology guided radiotherapy (Oderinde et al., 2021) |

### Alternatives to imaging with ionising radiation

1. Imaging for localisation and verification, which is the most common application for IGRT, is, as a rule, performed on a daily basis although action level protocols that check positioning only in the first few fractions and then weekly may be used for reduced imaging burden. As can be seen in Table 7.2 many different options exist and at least four methods do not require the use of ionising radiation:

* ***Radio beacons*** can be used as fiducial markers and implanted into tissues of interest. The markers are relatively large and have been successfully used for prostate and lung cancers.
* ***Ultrasound*** has been available for many years and is commonly used in brachytherapy. It has reasonable soft tissue contrast which makes it useful for pelvic and abdominal imaging. However, ultrasound image quality is often operator dependent, and it has been noted that the pressure required to establish good imaging contact may deform the anatomy of interest.
* ***Optical surface guidance*** has demonstrated potential for set-up verification for breast cancer patients and has been used for stereotactic procedures intra- and extra-cranially (see section 7.1.1). More recently software has also been adapted to allow for motion management.
* ***MRI:*** One of the most interesting recent introductions has been the combination of MRI scanners with linacs. Initially combined with cobalt-60 sources to overcome some of the tremendous technological challenges to combine two systems that rely on highly accurate electromagnetic fields, there are now several commercial systems available and it is expected that the number of MRI linacs will continue to increase. This setup provides volumetric imaging on the treatment couch without ionising radiation, a significant advantage in terms of imaging dose. However, a drawback is the absence of electron density information for dose calculation (see section 6.2.3). Although in-room MR images offer excellent soft tissue contrast, they cannot be used alone for plan adaptation based on dose recalculation. Matching a CT planning image with the in-room MR image for localisation may also pose challenges.

### Image quality requirements for therapy delivery

1. Radiotherapy involves target localisation in three dimensions, which requires a suitable image review environment that allows the operator to review and compare two volumetric image sets in an efficient manner. CBCT is the technology used most widely for image guidance as it provides images in a similar form to the CT scans used for planning the treatment. It allows modifications to patient position to be made on the day of treatment and assessments of changes in patient anatomy, e.g., bladder filling, both of which may need adaptation of the plan and so require clear images and protocols that are easy to interpret.
2. For online image guidance, decisions need to be made in a fast and efficient way while the patient is on the treatment couch. Automatic image matching procedures have become common in image guidance (Choi et al., 2019). While in most circumstances a human operator needs to verify the match, there are already situations where this is not practical, e.g., real-time image guidance and gating. Therefore, the image quality should be fit for purpose without significant post processing. Clear images and protocols that are easy to interpret are needed, so the level of image quality must be sufficient to accurately assess and compare target sizes and make judgement on margins left around the target and critical structures (see section 2.3.2.). The selection of CBCT exposure factors, which is similar to CT, is discussed in section 6.2.2.1.
3. Another important part is the ongoing review of practice, which can be done offline even if decisions need to be made online. Offline decision making after imaging aims to introduce changes for the next treatment fraction. This typically allows for thorough review by all professionals that may be required to reach a decision. Complex decisions such as re-planning are also possible even if they may take a few extra days to enact. While online adaptive radiotherapy is cost prohibitive for many radiotherapy treatment centres, offline adaptive radiotherapy can easily be implemented especially in low to mid income countries, provided that robust decision-making procedures or support systems are available (Gros et al, 2022). Decision making based on Artificial Intelligence has the potential to become an important tool to support this.
4. Fig. 7.2 shows various image guidance strategies as a function of the decision-making time and image quality requirements. It is important to note that all imaging and the decisions based on it have the potential to improve future radiotherapy practice by evaluating past image guidance results. This requires the set-up of a data base and recording of actions based on imaging and the subsequent clinical outcomes.

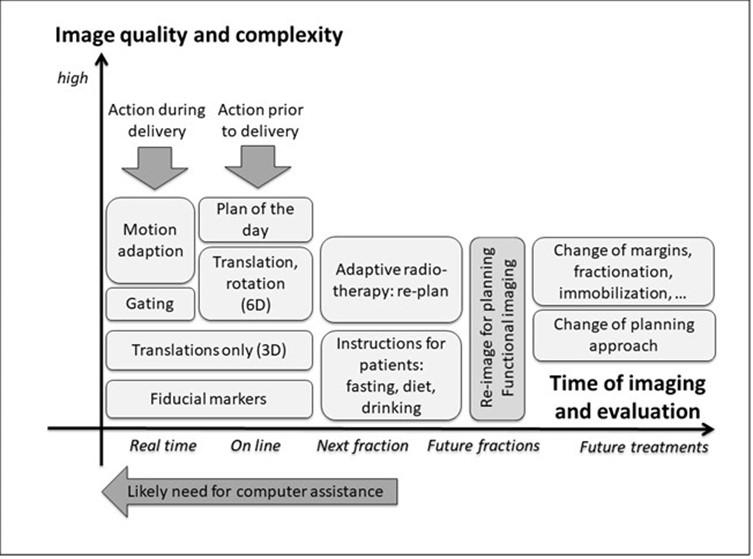


Fig. 7.2. Image guidance options as a function of time available for imaging and decision making (T Kron, Peter MacCallum Cancer Centre, Melbourne, Australia).

1. With improving image quality and faster treatment planning computers, online re-planning is also possible. This has become a driver for several recent developments in radiotherapy delivery technology with MRI linacs and CBCT based online adaptive RT platforms being specifically aimed at adaptive RT treatments. There are several challenges in this context from maintaining image quality suitable for re-planning to re-contouring of structures for planning, fast dose optimisation and some degree of independent QA.

# IMAGING FOR BRACHYTHERAPY

1. **Key points in this section:**

Medical imaging is essential in brachytherapy to enable a localised high dose to be delivered accurately. Selection of the most appropriate imaging modality depends on many factors including tumour site, duration of the implant, complexity of the technique, type of applicator, available resources and clinical practice.

Imaging for brachytherapy is integrated into the workflow to support clinical decision-making, to facilitate and verify the implant, and to improve clinical outcomes.

Resources, feasibility, operationality and risks should be considered when establishing the imaging modalities and protocols in the institutional standardised guideline for brachytherapy.

Non-ionising imaging modalities (MRI, ultrasound) should be identified as an option to replace ionising imaging modalities (CT, x-rays) where clinically equivalent and relevant in the institutional setting. Use of these modalities will give optimal reduction of radiation dose from imaging and is likely to provide better soft tissue contrast which is important for brachytherapy.

The brachytherapy workflow should be analysed carefully to identify aspects where there is a potential for reducing dose and avoiding unnecessary radiation exposure from imaging.

## Use of ionising and non-ionising imaging modalities in brachytherapy

1. Brachytherapy delivers localised high radiation doses for patient treatment. Medical imaging plays a pivotal role in assuring accurate delivery of highly localised and precise brachytherapy treatments. The choice of imaging modality is influenced by the tumour site, the duration of the implant treatment and the complexity of the procedure (IAEA, 2015a, 2015b; Hellebust, 2018; Tharmalingam et al., 2018; Chargari et al., 2019), alongside considerations such as the available resources and institutional practices. Imaging aids clinical decision-making and supports implant placement verification and the enhancement of treatment outcomes. The brachytherapy workflow should be analysed carefully to identify optimal imaging procedures and evaluate how they can best be integrated into the workflow, as well as considering the potential for reducing the dose from imaging.
2. Use of non-ionising imaging techniques, such as MRI and ultrasound reduces radiation exposure and can enhance soft tissue contrast, which is crucial for the efficacy of brachytherapy. The ultimate reduction of dose would be exclusive use of non-ionising imaging modalities where this was possible. However, in limited resource settings, full replacement of radiography, fluoroscopy and CT by MRI scans is often not reasonably achievable while use of ultrasound can require special training and may be operator dependent. Radiological imaging in brachytherapy is justifiable, where it results in a clinical gain or increased dosimetric accuracy, but unnecessary radiation exposure from additional radiological imaging should be avoided at all times.

## The purpose of imaging in brachytherapy (justification)

1. The purpose of imaging in brachytherapy differs slightly from external beam radiotherapy (EBRT), as in addition to clinical localisation of the target and OARs, exact visualisation of the applicators (implant) or other sources is required in order to deliver a localised high dose accurately. Imaging is involved from the start in positioning the applicator and performed with the applicator (implant) in situ. While the use of images for clinical assessment of the tumour, staging, and treatment decision making is similar to that for external beam radiotherapy, the entire workflow in brachytherapy can change with the introduction of image guided brachytherapy (IAEA, 2015b; Michaud et al., 2016; Kim et al., 2021).
2. Cervical Cancer High Dose Rate Brachytherapy is an example where prescribing, recording, and reporting (ICRU, 2013) are directly linked to the underlying medical image modality. Levels of complexity in brachytherapy (IAEA, 2015b) include the methodology of imaging and tools that are associated with each step of the procedure (brachytherapy workflow). These levels can be categorised as follows:

* Level 1: No radiological images or planar images (radiographs or fluoroscopy images) and library-based treatment planning (standard plan).
* Level 2: Planar images with or without contrast agents and ‘2-D’ treatment planning based on anatomical landmarks such as reference points for target and OARs.
* Level 3: Cross-sectional imaging, namely CT, MRI and ultrasound with or without contrast agents and ‘3-D’ treatment planning based on the target and dose constraints for the organ at risk volumes.
* Level 4: Image guided adaptive brachytherapy (Potter et al., 2008). This approach often requires an increased number of medical images possibly including functional images and complex applications (using interstitial implants and advanced hybrid brachytherapy applicators combining intracavitary and interstitial (Mahantshetty et al., 2019) to improve the clinical outcome.

1. When optimising and tailoring the dose distribution with the aim of increasing the dose to the target and decreasing dose to adjacent normal tissue / OARs, inter-fraction, intra-fraction, and inter-application effects, as well as uncertainties, risks, and benefits for the treatment outcome, must be considered.

### Brachytherapy workflow

1. Imaging for brachytherapy is integrated into the workflow to support clinical decision-making, to facilitate the implant and with the aim of improving clinical outcomes (Fig. 8.1). The complexity and timing of brachytherapy workflow (IAEA, 2015b) needs to be analysed step by step to identify any potential for dose reduction (e.g., decreased frequency of imaging and optimised protocols) or replacement of ionising imaging (CT, radiographs, and fluoroscopy) by non-ionising imaging modalities (ultrasound and MRI).
2. For each step in Fig. 8.1, the underlying imaging modality varies by tumour site and clinical practice. Although the brachytherapy workflow is primarily sequential, image acquisition is usually used in various steps, so the whole process of image guided adaptive brachytherapy (IGABT) can be represented as a sequence that may be repeated as an iterative process with imaging playing a central role (Fig. 8.2). Medical images are increasingly used to support the clinical decision to deliver, abandon, or repeat and modify the treatment. Modification of the brachytherapy implant (applicator placement) itself often results in the adaptive approach to further optimise the treatment plan with the aim to improve the clinical outcome.

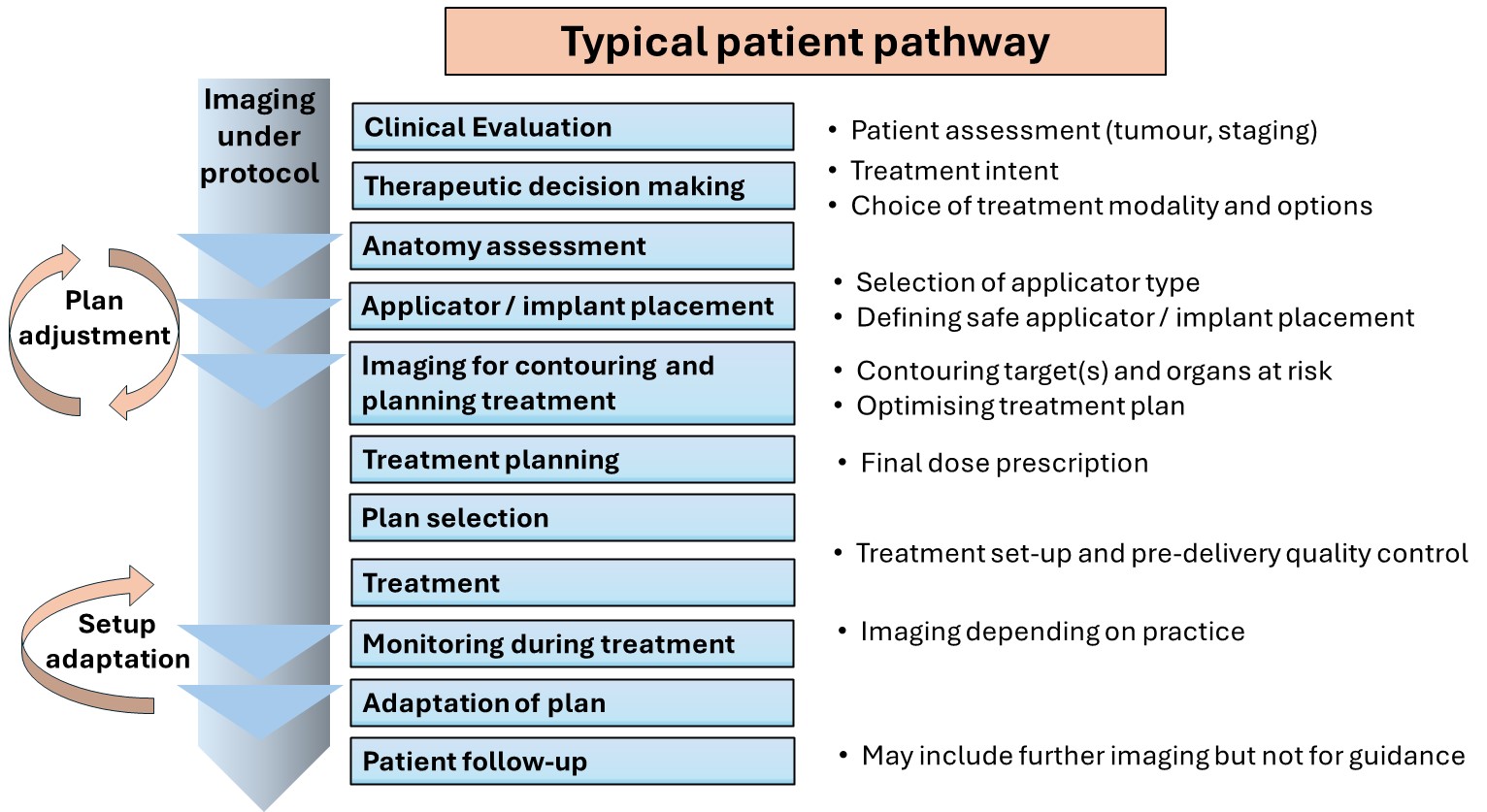


Fig. 8.1. Brachytherapy workflow: The clinical brachytherapy steps indicating the procedures and tasks involved.

### Key factors and parameters to consider when selecting (justifying) an imaging method

1. To consider the place of modern or alternate imaging in brachytherapy (Dimopoulos et al., 2012; Grover et al., 2016; Hellebust, 2018), four key factors should be analysed, answering relevant questions to establish an institutional standardised guideline. Deviation from the predefined imaging protocol for an individual patient should necessitate a clinical justification. The decision to use any added radiological imaging, which will result in additional radiation exposure to the patient, must be balanced by the clinical benefit foreseen (IAEA, 2018). The key factors that should be incorporated into good clinical practice, based on clinical guidelines and reflecting evidence are:

* ***Resources*** - Which image modality is available / accessible for the brachytherapy patient with the time and staff available?
* ***Feasibility 1*** – How well will the key anatomical structures, such as target and OARs, be visualised and defined by the additional imaging?
* ***Feasibility 2*** - Is the imaging modality compatible with the applicators in use (e.g. MR compatibility)?
* ***Operationality*** - Can applicator reconstruction and treatment planning (including logistics of patient transportation) be performed if indicated by the imaging?
* ***Benefits and risks*** – What are the potential benefits to the patient in relation to potential risks when selecting a specific imaging modality and frequency? Have the uncertainties and limitations been identified and evaluated?

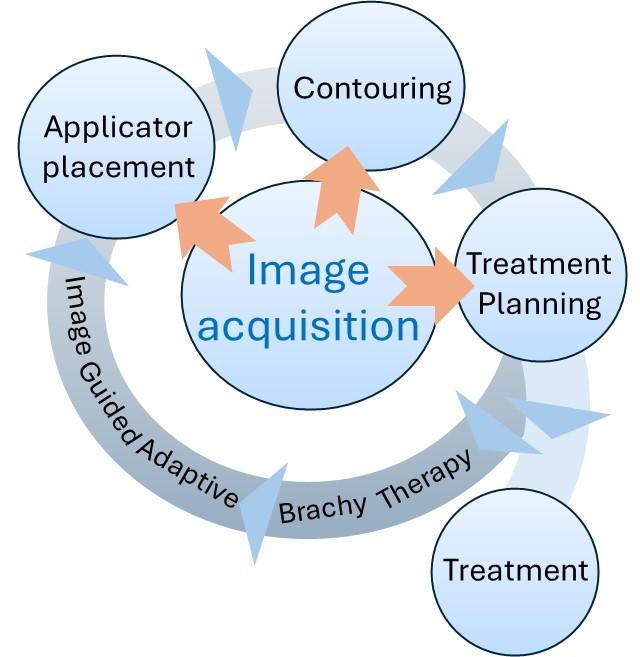


Fig. 8.2. ‘Dynamic’ brachytherapy workflow, illustrating a scenario with intensive use of medical imaging linked into several steps of the process. (\*Medical imaging is a trigger point for treatment optimisation of each individual step or iteration in the workflow of image guided adaptive brachytherapy). Modified from a figure in The Transition from 2-D Brachytherapy to 3-D High Dose Rate Brachytherapy, Human Health Reports No. 12, IAEA, Vienna (2015) (IAEA, 2015b)) with permission from the IAEA.

1. One resource that affects the patient workflow and transportation logistics and the specific imaging modality utilised in brachytherapy is the room design itself. Brachytherapy procedures (applicator insertion), imaging (radiographs, C-arm, ultrasound, CT/MRI scanner) and treatment delivery may be undertaken in dedicated separate rooms, in a combination of rooms or in an ‘integrated brachytherapy suite’ (IAEA, 2015a). In some cases, additional image acquisition for treatment planning purposes and pre-treatment verification is required to ensure treatment accuracy. This may require that the patient is transported to an imaging facility with an MRI or CT scanner either within the department or at an external site, introducing complex logistics in the clinical workflow and the possibility of applicator dislocation itself.

### Imaging options

1. The imaging modalities recommended, which may include combinations of ionising (CT, fluoroscopy, radiographs, PET-CT, DECT) and non-ionising modalities (MRI, ultrasound, visual, endoscopy), should be predefined in the institutional standardised guideline. Imaging recommendations, and a list of available alternatives, should be identified and summarised for each tumour site and for each step of the brachytherapy workflow. Non-ionising imaging modalities (MRI, ultrasound) should be identified as an option to replace ionising imaging modalities (CT, x-rays) where clinically equivalent and relevant in the institutional setting.
2. Table 8.1 gives an example of the potential space for alternative, non-ionising imaging modalities to reduce or avoid radiation dose from medical imaging. The aim of the table is to provide a guide and it will require adaptation for each institutional setting. It assures, that the key factors (1- Resources, 2- Feasibility, 3- Operationality, and 4- Risks) and clinical practice are assessed.

Table 8.1. Alternate imaging options in brachytherapy used for typical tumour sites based on evidence-based medicine and clinical experience.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Treatment site** | **Applicator insertion /guidance** | | | | | | **Implant/Image verification** | | | | | | **Treatment Planning** | | | | | |
|  | CT | Fluoroscopy / radiographs | MRI | Ultrasound | Visual | Endoscopy | CT | Fluoroscopy / radiographs | MRI | Ultrasound | Visual | Endoscopy | CT | Fluoroscopy / radiographs | MRI | Ultrasound | Visual | Endoscopy |
| Cervix (limited stage) | o | **×** | o | o | - | - | **×** | **×** | o | o | - | - | **×** | **×** | o | e | - | - |
| Cervix (advanced stages) | o | **×** | o | **×** | - | e | **×** | **×** | o | **×** | - | e | **×** | **×** | o | e | - | - |
| Endometrium (post op.) | - | **×** | - | - | **×** | - | o | **×** | o | - | - | - | **×** | **×** | o | - | **×** | - |
| Endometrium (definitive) | - | **×** | - | o | - | - | **×** | **×** | o | - | - | - | **×** | **×** | o | - | - | - |
| Vagina | o | **×** | o | **×** | o | - | **×** | **×** | o | **×** | o | - | **×** | **×** | o | e | - | - |
| Vulva | - | **×** | - | - | **×** | - | - | **×** | - | - | **×** | - | o | **×** | - | - | **×** | - |
| Breast (Partial Breast) | - | **×** | - | o | **×** | - | **×** | **×** | - | o | - | - | **×** | **×** | - | - | o | - |
| Prostate LDR | - | **×** | - | **×** | - | - | **×** | **×** | o | **×** | - | - | **×** | - | o | **×** | - | - |
| Prostate HDR | - | o | e | **×** | - | - | - | **×** | e | **×** | - | - | **×** | - | o | **×** | - | - |

(**×** - standard or in widespread clinical use, o - optional available modality, e - experimental or research-oriented modality, - - not applicable)

## Techniques of dose reduction and optimisation

1. When imaging with ionising radiation in brachytherapy, the same techniques of optimisation of radiological protection to achieve dose reduction as in EBRT are applicable. While CT is the main pillar for dose calculation (estimating radiation attenuation based on electron-density) in EBRT, dose calculation in high dose rate brachytherapy is currently independent of the underlying imaging modality (Rivard et al., 2004). In theory, brachytherapy has the potential to incorporate a wider range of imaging modalities for treatment planning offering greater opportunity for reducing radiation doses.
2. However, logistical access to non-ionising imaging modalities like MRI and ultrasound may be limited and may not therefore be practicable. As more complex dose calculation algorithms become available that take tissue type and inhomogeneity into account more reliance on quantitative imaging is likely to emerge (Beaulieu et al., 2012). Care must be taken to identify tissues and their radiological properties for dose calculation if algorithms compliant with the report of AAPM task group 186 are used (Beaulieu et al., 2012).
3. For example, addressing the factors in sub-section 8.2.2 with regard to brachytherapy treatment for patients with cervical cancer, where MRI, if available, is the gold standard (Haie-Meder et al., 2005; Grover et al. 2016; Tharmalingam, et al., 2018; Mahantshetty et al., 2021). treatment may be performed entirely using non-ionising imaging modalities such as MRI and ultrasound (Pinkavova et al., 2013; van Dyk et al., 2016). Nevertheless, not all patients are clinically suitable, additional training may be required and it may not be desirable logistically for all patients to undergo image guided therapy due to a high patient workload.

### Duration, timing of brachytherapy procedures and efficiency of the workflow

1. The duration of the brachytherapy procedure and variability in the timing of individual steps in the workflow is often underestimated. Applicator insertion (step 1) can be performed and verified with image guidance (ultrasound substituting for fluoroscopy/radiographs). In step 2, level 3 ‘3D’ imaging (MRI replacing CT) may be used for treatment planning by contouring all essential anatomical structures, defining the applicator (applicator reconstruction) and optimising the treatment plan to evaluate the dose-distribution. Finally, a decision is made to treat based on a risk benefit assessment by the health professional team and a plan made (step 3).
2. For a straightforward cervical cancer treatment, the entire brachytherapy workflow will take at least 2 hours: 30 min for applicator insertion, 30 min for imaging, 40 min treatment planning and decision making and 20 min treatment (step 4) on the unit. This is without considering complications during applicator insertion and adjustments that might need to be made for shifts or displacements.
3. The imaging time for a scenario with MRI will be in the range of 30 to 60 min depending on the scanner and protocols and not including the logistics of patient scheduling. Time on the CT scanner will be much shorter than with MRI and could reduce the scan time by a factor of two. If radiography/fluoroscopy-based level 2 (“2D”) brachytherapy is performed, the imaging time could be further reduced to 5-10 min. The actual time for each step and resulting efficiency of the workflow depends on the patient load, logistics, equipment available (including software and networking) and clinical experience. The time estimates given here are based on expert consensus and reports (Mayadev et al., 2014; Michaud et al., 2016; Kim et al., 2018). Overall, workflow duration and the timing of processes can influence patient treatment efficiency and limit imaging dose reduction strategies. A potential imaging substitution with a non-ionising imaging modality necessitates an allocation of resources for the increased workload.
4. Steps should be taken to minimise the possibility of applicator shifts throughout the entire brachytherapy workflow using immobilisation techniques such as packing with sufficient gauze during applicator placement for cervical brachytherapy. Real-time imaging with ultrasound, can be used to monitor applicator position and then adjustments can be made for any displacements without increasing radiation dose to the patient to maintaining accurate dose delivery. Any shift will impact the dosimetry and may result in a need for additional imaging.

### Clinical examples and practical applications

#### Cervical cancer

1. In brachytherapy for cervical cancer, reduction of dose from imaging is not the primary reason for selecting MRI over CT, it is to improve soft tissue contrast. The feasibility and operationality of using MRI-guided adaptive brachytherapy for patients with cervical cancer has been demonstrated clearly in a multicentre prospective study (Pötter et al., 2021). But additional radiographic exposures may be necessary to clarify the needle-channel assignment for applicator reconstruction in a complex interstitial implant.
2. Nevertheless, the risk needs to be assessed in a high workload brachytherapy environment to ensure effective and efficient treatment to all patients. Determining who will benefit most and hence prioritising for planning with MRI, which can facilitate better target definition and individualised dose prescription (higher dose to the target and lower dose to OARs), becomes a clinical, ethical and logistical decision.

#### Prostate cancer permanent implant

1. The prostate is another typical site where brachytherapy is widely used (Zaorsky et al., 2017). Implanted Low-Dose-Rate (LDR) brachytherapy is prescribed for patients with favourable intermediate-risk disease and here identifying the implanted radioactive seeds may become a safety issue. Verification of the exact number of implanted radioactive seeds often requires the use of radiological imaging (CT, fluoroscopy, radiographs) (Ash et al., 2000; ICRP, 2005b). A CT scan is usually performed four to six weeks after implantation for post implant dosimetry (when swelling of the gland has subsided and no further seed migration can be expected). Radiological imaging should not be discarded for the sake of dose reduction, but this should be a consideration in the overall assessment of treatment effectiveness and radiation protection.

#### Prostate cancer HDR implant

1. High-Dose-Rate (HDR) brachytherapy is mainly used as a boost to EBRT. Replacement of ionising radiation imaging (CT, radiographs or fluoroscopy) by ultrasound and MRI is feasible. In the case of HDR brachytherapy, the plastic or metallic needles which are implanted temporarily are identified using imaging for applicator guidance during insertion (step 1) under fluoroscopy and/or ultrasound imaging. For planning (step 3) several options are available to reconstruct the implant (application) and perform all the necessary delineations to carry out the treatment planning. For imaging (step 2), the full range of options - CT, MRI and ultrasound - are feasible and can – at least to some degree - substitute for each other. The clinical decision about the extent to which dose reduction from imaging is applicable in prostate brachytherapy can be expanded to other brachytherapy tumour sites with a comparable strategy.

#### Other interstitial implants

1. Other interstitial implants such as breast, sarcomas and some head and neck treatments typically follow the same imaging work as described for prostate cancer (Shah et al., 2020; Strnad et al., 2015). However, brachytherapy is also used for lesions where limited imaging is required such as skin lesions when ultrasound may be used to assess their depth (Likhacheva et al., 2017). Another technique where non-ionising imaging can be used is for radioactive plaques for uveal melanomas that can rely on fundus photography (Binder et al., 2020).
2. Based on the key factors and scenarios described above, the entire brachytherapy workflow should be analysed carefully to identify optimal imaging procedures. The potential for reducing the dose from imaging using non-ionising radiation techniques should be assessed, considering resources, feasibility, operationality and risks.

# PAEDIATRIC IMAGING IN RADIOTHERAPY

1. **Key points from this section:**

The risks of second radiation induced primary cancers must be given special attention for paediatric patients, as children have a longer remaining life span during which they could develop cancer and have a higher radiosensitivity for certain cancers, such as brain, skin, thyroid cancer and leukaemia.

Radiation oncologists working with paediatric patients, have an obligation to estimate the long-term consequences of radiation therapy in survivors. This requires balancing target volume coverage with the avoidance of long term complications, and imaging plays a crucial role in these evaluations.

Children have higher radiosensitivity in certain organs and tissues, such as bone marrow and will receive higher doses than adults if kV CBCT imaging exposures are not adjusted for patient size. The dose to bone can be two to four times greater than to soft tissue for kV x-rays and needs special consideration.

There may be a lack of awareness among some radiation oncologists and other groups involved in the treatment of paediatric patients that imaging exposes non-target, healthy tissues to repeated diagnostic quality x-rays.

There is little consensus on best practices in paediatric radiotherapy and concerns about exposure of larger tissue volumes to lower radiation doses have led some centres to continue use of established techniques. More studies are needed to evaluate doses outside the PTV and improve guidelines on the use of imaging to reduce tissue volumes treated.

The number of paediatric patients treated with radiotherapy is relatively small, so technical developments emerge more slowly. Opportunities to optimise radiological imaging parameters, such as reducing field of view, employing new reconstruction techniques with lower exposures for CT, and use of non-ionising imaging tools such as MRI and optical surface guidance should be promoted for children.

Special training should be given to radiotherapy staff in paediatric imaging and liaison with a diagnostic radiology department can be of significant benefit.

## Factors affecting choices in paediatric oncology

1. Radiation therapy plays a continuous and critical role in the frontline management of paediatric cancer. Cancer is the leading cause of death in children who survive infancy. Worldwide, the incidence of cancer in children is increasing and is anticipated to be diagnosed in more than 400,000 children each year between 2020 and 2050 (Atun et al., 2020).
2. The indications for radiation therapy are frequently modified as novel therapies and alternative treatment regimens are developed to replace both traditional radiation therapy techniques and alternative methods of treatment. Examples of alternative therapies include using intensified systemic and intrathecal therapy to eliminate cranial radiation therapy for acute lymphoblastic leukaemia (Pui et al., 2009), response-adaptive therapy and monoclonal antibodies for Hodgkin lymphoma (Bristol-Myers Squibb, 2020) and aggressive local and regional therapy for retinoblastoma (Brennan, 2013). New methods and technological advancements, including x-ray–based image guidance, have made radiation therapy safer, especially for the youngest patients. Through well-designed clinical trials, the use of radiation therapy in children with cancer has been refined, leading to reduced treatment-related complications, increased tumour control, and new indications.
3. However, children are more susceptible to second radiation induced cancers than adults due to their longer life span and higher frequency of cell division in the growing organism. UNSCEAR notes that evidence is available for brain, skin, thyroid cancer and leukaemia (UNSCEAR 2013). In female patients, breast and uterine cancer peaks at puberty. As such, consideration must be given to the risk benefit analysis of all additional x-ray imaging.
4. In high-income countries, nearly one-half of children with cancer will receive radiation therapy during their treatment course. However, there are exceptions. Concerns about radiation-related complications sometimes lead paediatric oncologists to recommend alternatives and accept the increased risk of disease progression and uncertainty of salvage treatment.
5. As new technologies and techniques are introduced, the risk of structural and functional deficits, second primary tumours, and other complications requires ongoing reappraisal. Using x-ray–based imaging for treatment planning, localisation and verification, and adaptive replanning is part of the standard workflow at specialised centres that provide paediatric radiation oncology services. Understanding the role of x-ray–based imaging and the scope of its use in paediatric radiation oncology will identify areas for consideration, improvement, and study.
6. Investigators for both the Children’s Oncology Group (Hua et al., 2020) and International Society for Paediatric Oncology surveyed their members to learn more about x-ray–based imaging and other imaging modalities used in treatment planning and delivery for paediatric oncology patients. The availability of volumetric imaging, practice and frequency of verification imaging, and protocols used when planning and delivering treatment were remarkably variable.
7. Despite recent advances, at least 25 % of paediatric patients treated by radiation oncology teams with curative intent will experience disease progression within 3 years of completing radiation therapy (Lucas et al., 2020). This statistic highlights the intermediate to high-risk disease-specific classification assigned to those who are referred for radiation therapy. Over longer follow-up periods, fewer additional failures will occur. For patients followed for many years, the risk of life-threatening conditions associated with prior therapies can become a leading cause of death, reducing the number of patients who ultimately benefit from therapeutic radiation (Armstrong et al., 2009). However, this should not reduce or put into question the role of radiation therapy for paediatric cancer because long-term survivors would not be alive without the therapeutic benefits of radiation therapy. Considering the negative health consequences of both radiation therapy and other treatments is important because some of these complications may be attributed to past practices and methods. Finally, the long-lasting consequences of any treatment are influenced by hereditable, lifestyle, and environmental factors. Indeed, the high prevalence of smoking (Huang et al., 2018), obesity (Zhang and Parsons, 2015), and other contributors to poor health, including lack of access to health care, can certainly play a role.

## Imaging in paediatric radiation oncology

### Imaging in preparation for radiotherapy

1. Patients undergoing radiotherapy typically have had a number of other imaging procedures in the past and involvement of radiologists and the whole multidisciplinary team is important. While radiation oncologists have limited control over x-ray–based imaging modalities for patient evaluations leading up to diagnoses, they can be involved early in the process of clinical staging for patients with known or suspected malignant neoplasms that may require radiation therapy. Most cooperative clinical trials group protocols with radiation therapy guidelines suggest the same. Radiation oncologists may promote methods or modalities for completing workups, thereby obviating the need for supplemental or additional studies for planning. Imaging patients in a neutral position or acquiring data that will contribute to the planning process are excellent examples of this. Regardless, radiation oncologists can be mindful of patients who have had considerable diagnostic x-ray exposure and tailor subsequent imaging for planning or delivering treatment.
2. Radiation oncologists working with paediatric patients, have an obligation to carefully estimate the consequences of radiation therapy in long-term survivors. This requires consideration of the balance between limiting disease progression and avoiding long term complications, including consideration of out-of-field doses from treatment as well as the dose from imaging as parameters in these evaluations.
3. Computed tomography (CT) continues to be the most frequent imaging modality used for paediatric patients with solid and musculoskeletal tumours. Access, expense, sedation and anaesthesia considerations, and experience have facilitated the continued use of CT for diagnosis, staging, response evaluations, and follow-up evaluations. Nevertheless, the use of MRI examinations, particularly whole-body scans, could simply resolve these issues of additional ionising radiation exposure and needs to be investigated more extensively and potentially promoted.

### Imaging in the treatment room

1. As for adults, the primary objective when using x-ray–based imaging in the treatment room is to verify positioning. The secondary objective is to evaluate the external contour of the patient and changes in dimensions that may affect treatment dosimetry. The tertiary objective is to evaluate tumours, tumour beds, or internal healthy tissue deformities that may affect dosimetry at the primary site.
2. Given that typically many fractions of treatment are delivered, both imaging frequency and image acquisition parameters need to be considered. Optimising imaging for paediatric patients instead of using the imaging protocols for adults that are often the only ones provided by the manufacture offers tremendous opportunities to minimise radiation doses in healthy tissues.
3. Paediatric Radiation Oncology Society investigators presented and discussed the results of a survey of European radiation therapy centres that treat children with cancer (Windmeijer et al., 2020). The survey measured patient volumes, treatment preparations, planning and delivery, and image guidance practices. The assembled information provided a detailed and descriptive overview of a range of practices at 33 paediatric-capable centres in 2018. Image guided radiation therapy (IGRT), as defined by the investigators, was an important component of high-precision radiation therapy for children, but a consensus of best practices did not exist. Image guidance has many benefits and some potential risks. The survey results provided an honest assessment of the wide-ranging capabilities of European centres and revealed room for improvement.
4. The information gleaned from the survey benefits entire teams, including RTTs, medical physicists, and radiation/clinical oncologists. It also creates awareness and facilitates important dialogue for establishing best practices. The study highlighted the benefit of IGRT and linked it, along with surgery and chemotherapy, to improved survival. Nevertheless, some institutions continued to use 3D-conformal radiation therapy when intensity-modulated and volumetric-modulated radiation therapy methods were available. This was due to the potential concern for increasing the volumes that receive the lowest radiation doses. Expanding the discussion about low-dose volumes should be considered in future surveys and development of guidelines. To enable this, solutions are necessary to assess and record low doses associated with treatments and imaging. Understanding the association between in-room imaging and delivery methods by treatment site would also be helpful. The survey did not disclose anaesthesia practices or statistics, compare IGRT practices for paediatric or adult patients at each treatment centre, or define how long each centre practiced their reported image guidance methods.

## Medical considerations for imaging during paediatric radiation therapy

1. There are many different types of paediatric tumour, but there would not be sufficient space to deal with imaging for every individual type, so a selection of the more common ones that are representative of other tumour types are included.

### Paediatric solid and musculoskeletal tumours

#### Neuroblastoma

1. Neuroblastoma is the most common paediatric solid tumour. Most neuroblastoma diagnoses in children are classified as high risk. This is based on dissemination beyond the primary site—retroperitoneal primary tumours are most common—to bone, bone marrow, or lymph nodes. Radiation therapy is usually indicated for treatment of the primary site, adjacent involved nodal regions, and nonresponding metastatic sites. The recent frontline protocols for neuroblastoma are ANBL1531 (DuBois, 2017) for the Children’s Oncology Group (COG) and HR-NBL2/SIOPEN for the International Society of Paediatric Oncology (SIOP) (National Library of Medicine, 2020). Both protocols include induction chemotherapy and surgery, followed by consolidation with high-dose chemotherapy with stem cell support. Radiation therapy to the primary, with or without treatment to nonresponding metastatic sites depending on COG or SIOP trials, is delivered during consolidation and after high-dose chemotherapy. Post consolidation therapy follows and depends on the response to the treatment regimen and clinicopathologic molecular features. During the treatment regimen that includes the induction and consolidation phases (Smith and Foster, 2018), patients with neuroblastoma according to the SIOPE or COG trials are expected to receive MRI or CT imaging before treatment, after four cycles of induction chemotherapy for the COG trial, at the end of induction chemotherapy, at the end of High Dose Chemotherapy for the SIOPE trial and at the end of consolidation. Imaging with 131I-metaiodobenzylguanidine or fluorodeoxyglucose-based positron emission tomography is performed at the same time and at multiple additional time points. During the first 3 years after therapy, x-ray–based imaging requirements are relatively simple, with only five planned CT (or MRI) or ultrasound evaluations of the primary site.
2. In the context of radiation therapy, once postoperative targets are outlined with intraoperative and surgical pathology findings incorporated, the treatment of neuroblastoma is straightforward. Most patients have abdominal (retroperitoneal) paraspinal primary tumour sites, and the prescribed dose is 21.6-23.4 Gy or 36 Gy administered in 12-13 fractions or 20 fractions of 1.8 Gy. Metastatic sites, when irradiated, receive 21.6-23.4 Gy. The proximity of these radiosensitive tumours to the kidneys and vertebral bodies invites the use of conformal treatment methods and occasionally 4DCT for treatment planning (Beltran et al., 2010).
3. Treatment planning CT can be limited to the primary and metastatic sites. The late timing of radiation therapy (i.e., after high-dose chemotherapy consolidation) reduces the likelihood of shifting of healthy tissues after surgery and the responding tumours that would necessitate replanning.
4. No guidelines for using x-ray–based imaging for treatment planning or x-ray parameters for daily imaging during treatment exist. In the ANBL0531 protocol, x-ray–based localisation imaging is recommended before each treatment when the planning target volume margins should be reduced from 0.5–0.8 cm to 0.3–0.5 cm. No recommendation is available in the SIOP European trial. Neuroblastoma may be amendable to use of non-ionising imaging methods of localisation for radiation therapy (Sueyoshi et al., 2019). Although using proton therapy for treating paediatric patients with neuroblastoma is limited, it is promising for further reducing radiation doses in healthy tissues (Bagley et al., 2019). The focal nature of proton therapy and the evolution to smaller clinical target volume margins necessitates highly advanced verification imaging.
5. Nephroblastoma is not included explicitly here as many aspects of the approach for treatment imaging are similar to those for neuroblastomas which occurs in a similar region of the anatomy and for which the doses are higher.

#### Rhabdomyosarcoma

1. Rhabdomyosarcoma is the most common paediatric musculoskeletal tumour. Rhabdomyosarcoma treatment is complicated by its diversity of primary tumour sites, marked responses during radiation therapy, potential need for irradiating metastatic sites (including large volumes such as the lungs), current interest in dose escalation to increase control rates for large tumours, and potential for adverse effects in long-term survivors.
2. Most paediatric rhabdomyosarcoma tumours are classified as intermediate or high risk at the time of diagnosis. This classification is based on unresectable or partially resected primary tumours or dissemination beyond the primary site to the lymph nodes, bone, bone marrow, lung, or soft tissues. Radiation therapy is indicated for treating primary and metastatic sites. Primary site irradiation occurs relatively early in the treatment process, and metastatic site irradiation generally occurs later unless it is easily encompassed at the time of primary site irradiation. The recent frontline protocol for intermediate-risk rhabdomyosarcoma in the Children’s Oncology Group is ARST1431 (Gupta, 2015).
3. The required imaging time points for paediatric rhabdomyosarcoma include a single evaluation before treatment and 5 to 6 time points during protocol therapy, which is planned over 66 weeks and includes radiation therapy. After therapy, imaging is performed every 3 months during the first year, every 4 months during the second and third years, and every 6 months until year five. Imaging of the primary site (CT or MRI) and chest x-ray or CT is performed at each time point.
4. Most patients receive a single treatment planning CT and daily localisation imaging when treated with contemporary methods. Changes in patient anatomy, especially weight loss, or in the size and shape of the tumour or tumour bed can be problematic. When small clinical target volume margins are used along with highly focused methods of radiation therapy, replanning, and additional treatment planning CTs may be required. Deferring radiation therapy to limit the need for replanning treatment is not an option. Indeed, a protocol that attempted to defer radiation therapy was amended to move radiation therapy earlier in the treatment regimen because of a high rate of local failure (Lucas et al., 2018).
5. Proton therapy is highlighted for its ability to further reduce radiation doses in healthy tissues (Leiser et al., 2016). Localisation imaging is especially important for proton therapy as it also reduces range uncertainty (Knopf and Lomax, 2013). Although CT is primarily used for planning and replanning, interest in MRI as a primary treatment planning modality has increased. The key aspect for using MRI for treatment planning is demonstrating equivalence to that of CT (see section 6.3).

### Paediatric brain tumours

#### Ependymoma

1. Except for craniopharyngioma and selected central nervous system (CNS) germ cell tumours, some paediatric brain tumours can avoid x-ray–based imaging from the time of diagnosis through follow-up, although this does not include therapeutic radiation. Increasingly, children with symptoms suggestive of brain tumours should first be evaluated with MRI if possible and not CT. The factors driving the selection of imaging modalities include acute symptoms, health care settings, access, patient age, sedation or anaesthesia requirements.
2. Two different tumours provide divergent examples of the burden of x-ray–based imaging for radiation therapy planning and delivery. Ependymoma is the third most common brain tumour in children and the most prevalent in very young children. It commonly arises in the infratentorial compartment, where it is intimately associated with neurovascular structures and cerebrospinal fluid (CSF) pathways. Ependymoma tumours arising in the supratentorial compartment equally involve critical healthy tissues and disrupt CSF flow. Paediatric ependymoma is usually treated with immediate postoperative radiation therapy in children as young as 12 months of age. Changes in the tumour bed and healthy tissues are common, which may lead to imaging during treatment (usually MRI) and replanning with CT.
3. Target volume margins are systematically reduced in these patients to reduce the risk of adverse effects. The use of smaller margins necessitates daily verification imaging during treatment. Ependymoma is a leading indication for proton therapy, which is helpful for reducing the irradiation of healthy tissues. Image-guidance at many of the earliest proton therapy centres largely comprised orthogonal x-ray imaging (Kim and Kim, 2011), exposing patients and healthy tissues in a manner that has not been studied. Most facilities have chosen CBCT for localisation imaging with the goal to optimise protocols to achieve the lowest possible exposure (Dzierma et al., 2018) understanding that for most treatment sites exposures to children exceed those for adults (Son et al., 2017).
4. Second primary malignant neoplasms are rare yet always a concern when treating these patients. Second cancers most often arise in high-dose volumes.

#### Medulloblastoma

1. The treatment of medulloblastoma—the most common malignant brain tumour in children—is markedly different from that of ependymoma. Medulloblastoma also arises in the infratentorial compartment and has the propensity to seed CSF pathways and the subarachnoid space. Therefore, craniospinal radiation therapy is a necessity. The adverse effects associated with craniospinal radiation therapy are well known in paediatric oncology and serve as the benchmark for severe acute and long-term radiation-related complications.
2. Treatment of medulloblastoma is administered in two phases: the craniospinal phase and the boost phase. The craniospinal phase consists of treatment of the subarachnoid spaces of the brain and spine. The craniospinal radiation doses administered in current protocols for children older than 3 years range from 15 to 36 Gy. The boost phase comprises treatment of the primary site. The cumulative dose administered to the primary site in current protocols ranges from 51 to 54 Gy. Twenty years ago, boost treatment of the primary site included the entire posterior fossa. Contemporary protocols specify irradiation of the postoperative tumour bed with a clinical target volume margin ranging from 0.5 to 1.0 cm, not including the 0.3–0.5 cm planning target volume margin used in photon therapy or the positional uncertainty of 0.3 cm and range uncertainty of 3 % used in scenario-based planning for proton therapy. Some centres use the same CT for both phases, but other centres plan each phase separately. The risks associated with the second CT may be offset by the gain in targeting precision for the boost phase. The boost phase may begin 4 to 6 weeks after the initial CT for craniospinal radiation treatment planning.
3. The volume of healthy tissues irradiated during craniospinal radiation therapy is substantial, with variations associated with the planning and delivery methods. This includes conventional beam’s eye view for photon planning with limited-intensity modulation, formal intensity-modulated radiation therapy, and passively scattered and now pencil-beam scanning proton therapy. Imaging during treatment may be performed daily for more advanced treatment methods or weekly for less advanced methods. Imaging may include all or part of the targeted volumes. Imaging frequency may be reduced when larger target volume margins are used. These patients may be eligible for optical surface imaging. Second primary cancers most often arise in high-dose volumes like those for paediatric patients with ependymoma. This often constitutes a barrier for considering additional doses associated with imaging for patients with medulloblastoma.

### Discussion about the use of image guidance

1. In the mid-1990s, children with ependymoma had poor prognoses after receiving the tri-modality therapy of surgery, craniospinal radiation, and chemotherapy. Radiation therapy was withheld for young children who represented the greatest patient population with this tumour. The fear of radiation-related complications was linked to *primum non nocere* (first do no harm). Limiting the use of radiation therapy for these patients led to the poor outcomes documented over many decades. With the advent of conformal radiation therapy and a framework for targeting guidelines, clinicians who cared for these patients accepted the challenge to implement first-generation conformal radiation therapy and evaluate its risks and benefits in this vulnerable group of patients. The result of this major change was a notable increase in tumour control and patient survival. This success was then repeated and documented for a variety of brain tumours, including CNS embryonal tumours in children younger than 3 years. When combined with clinical, pathologic, and molecular factors, the primary objectives of clinical trials are to improve outcomes, incorporate radiation therapy, and document its safety and ability to reduce radiation doses in healthy tissues. As new methods are developed with an overarching goal to reduce target volumes, patient positions must be verified, and treatments must be adapted to accommodate changes in patient body habitus, tumour size and shape, or postoperative anatomy.
2. As described above, the indications for radiation therapy are modified as new therapies and methods are developed. Some aspects of the environment of cancer care are unknown outside of defined specialties. Awareness that modern image-guided radiation therapy (IGRT) exposes nontarget, healthy tissues to repeated diagnostic quality x-rays may be lacking among many radiation oncologists and others who treat paediatric patients, patients themselves, parents, and those who care for long-term survivors. Verification imaging is often not included in clinical protocols. In order to better assess the effects of these exposures and associated risks, it is necessary to improve dose estimation and include these in treatment documents. Further work is needed to define the measures required to monitor adverse effects and long-term complications associated with collateral radiation exposure.

## Technical considerations for paediatric radiation oncology imaging

1. Paediatric radiation oncology has different technological challenges and opportunities from the treatment of adults. These range from imaging prior to treatment to imaging during treatment and treatment monitoring. In general, practitioners are more concerned about non-target radiation dose in paediatric radiotherapy. This affects treatment choices. Intensity modulated photon treatments (IMRT and VMAT) feature generally more out of field dose (Hall and Wuu, 2003) and longer beam on times resulting in more leakage (Hall, 2006; Klein et al., 2006). Unsurprisingly it took longer for IMRT to be generally accepted in paediatrics than in adult radiotherapy. More recently, the reduction of out-of-field dose in flattening filter free (FFF) beams and collimator angle choice to utilise additional shielding by the MLC have been identified to effectively reduce integral dose (Covington et al., 2016; Wijesooriya, 2019; Garrett et al., 2021). In parallel there is a strong push to use protons for radiotherapy of children as they result in lower out of field doses (Lautenschlaeger et al., 2019; Kahalley et al., 2020).
2. It is important to note that the improved dose distributions are typically achieved using more conformal treatment techniques with smaller margins for error. This goes hand in hand with more imaging. However, the considerations also affect the choice of imaging for treatment planning and imaging technologies not relying on ionising radiation such as MRI, ultrasound, and increasingly optical surface guidance play an important role in both (Rwigema et al., 2017).
3. Given the relatively small number of paediatric patients in radiotherapy technical solutions specifically aimed at the treatment and imaging are only slowly emerging. However, many options such as optimising imaging parameters, reducing field of view, iterative reconstruction, and non-ionising imaging tools such as MRI and optical surface guidance show significant promise.

### Imaging for treatment planning

1. All advanced radiotherapy requires 3D or 4D image sets for target and normal tissue contouring with x-ray CT being the most important imaging modality due to its lack of spatial distortion and its link to electron densities which allow dose calculations. Radiotherapy planning CTs are typically acquired by radiotherapy staff in the radiotherapy department and staff training is focused on patient set-up. While awareness of imaging dose is common, amongst radiation oncologists, RTTs and radiotherapy medical physicists, the expertise in optimisation techniques is less so. This becomes even more problematic for children as the number of paediatric patients seen in most departments – even if specialised – is small and body habitus varied.
2. Equipment is typically set-up and selected for radiotherapy of adults and wide bore scanners with their larger focus to detector distance are common (Wu et al., 2011). Special training for radiotherapy staff in paediatric imaging is important and liaison with a diagnostic radiology department can be of significant benefit. The effect and dose benefit of using iterative reconstruction with modified exposure factors and the appropriate choice of automatic adjustment of kV and mA need to be considered for all aspects of imaging, including CT number (HU) accuracy and settings must be documented. For children the need for repeat imaging must be taken into consideration when choosing imaging parameters. The principles of ‘image gently’ (Bulas et al., 2009; Strauss et al., 2009; Applegate and Frush 2017). Namely to improve safe and effective imaging care of children through advocacy, should also be applied to imaging in treatment planning.
3. Two trends make dose considerations more urgent:

* Motion management which requires respiratory gated CT is now increasingly considered in the radiotherapy of children (Kalapurakal et al., 2013; Huijskens et al., 2019). Given the need to reconstruct around ten image sets at different phases of the breathing cycle longer scan times and therefore higher dose may be required. Setting up these protocols for children does require expert staff to optimise the dose without affecting image quality. For children requiring anaesthetics breathing is typically very regular which allows optimisation of pitch and imaging time.
* Proton radiotherapy and particularly proton dose calculation can benefit from dual energy or spectral CT (Bar et al., 2017; Wohlfahrt and Richter, 2020), which – at least in principle – may increase the dose in planning. Li et al. proposed size-dependent protocol optimisation for dual energy imaging, balancing the radiation dose against the accuracy of electron density and stopping power ratio (Li et al., 2023). It is also important to realise the large variety of methods that can be employed to realise dual energy or spectral CT. In practice, medical physicists with expert imaging knowledge are required to set-up the protocols and advise on the best imaging parameters for children of different age.

1. As in all of radiotherapy planning repeat images need to be avoided – if a suitable MRI in treatment position is available the possibility exists to use it for treatment planning provided image distortion can be managed (Hsu et al., 2018). Similarly, there may be no need for a second CT scan if patients have already had a scan as part of their nuclear medicine investigation. Good planning and communication are essential and in general, consideration should be given to staff specialising in paediatric radiotherapy planning.

### Imaging for treatment verification

1. Frequent volumetric image guidance has become standard practice when using highly conformal radiation therapies and CBCT has become the method of choice (Martin et al., 2021). kV-CBCT doses are higher for smaller sized patients (Zhang et al, 2012), so children receive higher doses than adults when kV-CBCT imaging exposures are not adapted for patient size (Deng et al., 2012). It has been reported in the literature that doses measured in the critical organs are multiplied by a factor up to 2 (Ding et al., 2010; Deng et al., 2012).
2. Ding and Coffey (2009) also drew attention to the fact that the dose to bone is two to four times greater than the dose to soft tissue for kV x-rays, which should be considered, especially for paediatric patients, where growth deformation can be a concern. As an indication, in the study conducted by Ding and Coffey (2009), for a paediatric patient (2.6 years old) and for a single kV-CBCT acquisition, the mean doses calculated in the abdominal region are 170 mGy to the femoral heads (compared to 70 mGy for a large adult patient) and 60 to 80 mGy to soft tissues (compared to 20-30 mGy for a large adult patient).
3. A problem is that most commercial CBCT systems do not have automatic dose modulation tools and the poor scatter to primary ratio requires a relatively high mAs despite modest image quality requirements. Improvements in dose displays, coupled with dose monitoring and setting of DRLRTs is needed to improve knowledge and awareness of dose levels. The fact that the imaging must be done quickly to minimise the time the patient is on the treatment couch makes extensive manual dose optimisation impractical and most of the image and dose optimisation work occurs at the time of setting up the protocols.
4. Fortunately, manufacturers have become aware of the need to at least consider low dose imaging for paediatric patients and staff need to be trained to decide on patient selection for a particular protocol as age may not be the best indicator. Patient weight and body circumference are better indicators of imaging dose and protocol optimisation (Zhang, 2012; Zhang, 2015b). Any reduction in dose is helpful as the imaging frequency is determined by the number of fractions which frequently exceeds 20 in curative radiotherapy. Repeat imaging after shifts in patient position are also sometimes required and consideration of alternative methods for verifying a change in patient position should be considered
5. In addition, as described above, solutions are necessary to assess and record the relatively low doses associated with treatments and imaging. These data are needed to assess the risks associated with low doses and to take optimisation further. Manufacturers and users need to work together to achieve this goal.
6. Surface guidance, an optical method to monitor the patient surface, has become an interesting option as it allows not only for position verification during patient set-up but also continuous monitoring of the patient (Freislederer et al., 2020). This is an attractive option as paediatric treatments can take longer to deliver than adult radiotherapy (Rwigema et al., 2018). Patient co-operation and anxiety on one hand and anaesthetics on the other will prolong the time the patient is on the couch and as such the need to monitor her/his movement.
7. The introduction of MRI linac combinations also offers patient set-up verification and monitoring during treatment using imaging based on non-ionising radiation (Lagendijk et al, 2008; Mutic and Dempsey, 2014; Liney et al., 2019). While applications in the paediatric setting are to date rare (Henke et al., 2019), there is the potential for MR linacs to play an important role in future paediatric radiotherapy.

### 9.4.3 The application of artificial intelligence in paediatric imaging

1. The application of AI to paediatric imaging is less advanced compared to other areas, due in part to the relatively smaller paediatric workload resulting in smaller training datasets (Davendralingam et al., 2020; Sammer et al., 2023). Nearly all image data sets that are available publicly do not include paediatric patients. Paediatric images acquired with the reduced CT radiation doses recommended (Image Gently, 2024; ICRP, 2024b) are likely to have higher image noise levels and may not be processed correctly by AI algorithms trained on higher dose adult images. Moreover, the changes in size, shape, and appearance of organs with patient age cannot be addressed through training based on adult images (Sammer et al., 2023). However, DLIR is applied in reduction of noise with neural networks trained on paediatric image data sets, which should enable reductions in dose (MacDougall et al., 2019) and reduction of artefacts (Xie et al., 2018) and AI has facilitated reductions in imaging acquisition times improving image quality through reduction in motion artefacts (Chea and Mandell, 2020).
2. More attention is needed to progress the safe application of AI tools in radiological imaging of children (Sammer et al., 2023). This requires inclusion of paediatric patients when AI models, which are potentially applicable to children, are being developed and in the design of effective and efficient methods for developing, testing, and deployment of AI tools. In addition, suitable regulatory frameworks should be established to control the implementation of AI tools.

# THE IMAGING EQUIPMENT LIFE CYCLE, QUALITY ASSURANCE AND AUDITS

1. **Key points in this section are:**

Professional skills, methodology and process all play a vital role in management of the equipment life cycle. An optimisation team comprising radiation oncologist, RTT and medical physicist experienced in diagnostic imaging is required to ensure all aspects are covered during commissioning and review of imaging protocols.

Commissioning tests on imaging equipment will determine settings used in clinical protocols for acquiring images and have a direct influence on optimisation of radiological protection, so it is essential that sufficient time is allocated to enable this to be achieved.

The involvement of a medical physicist with experience in diagnostic imaging in commissioning, design of routine testing programmes and optimisation of imaging protocols is strongly recommended for imaging in both planning and verification.

Quality Assurance (QA) is part of a quality management system to provide the confidence that quality requirements are being achieved. QA helps to focus attention on the different aspects of performance that need to be maintained including the dose delivered to the patient during imaging.

Patient dose audits are recommended for planning and verification imaging based on surveys of measurable quantities linked to patient dose with median values being compared against dose reference levels (DRLRTs). The DRLRT concept is designed to identify procedures or centres where doses are unnecessarily high, requiring investigation to identify the cause so that remedial action can be taken.

A cone beam dose index (CBDI) is proposed to allow initial practical dosimetry measurements to be made for cone beam CT (CBCT) equipment, so that patient dose surveys can be carried out for imaging during treatment delivery.

Vendors should include accurate displays of the wide beam CTDI on imaging equipment, which is adjusted according to the exposure factors used, as proposed by the IEC/IAEA. This will allow dosimetric performance to be confirmed and can be used for patient dose surveys in the future.

## The imaging equipment life cycle

1. Fig. 10.1 shows the life cycle of imaging equipment, from the acquisition, acceptance and commissioning, deployment, through the use in clinical practice with maintenance, quality control (QC), and repair, to eventual disposal. Within this main cycle there is a sub-cycle that is needed to maintain performance and improve optimisation once the equipment has been put into clinical use. The steps involved are described in detail in *Publication 154* that deals with optimisation of digital radiology equipment (ICRP, 2023) but has many similarities to imaging equipment for radiotherapy (IPEM/SoR/CoR/RCR, 2021; IAEA, 2019). For radiotherapy additional consideration will be required on inclusion of non-ionising imaging equipment, such as MRI and optical surface guidance, especially for paediatric facilities. Following the proper procedures ensures that equipment is used in an effective and sustainable manner, continues to perform to its specification throughout its scheduled lifespan and is eventually disposed of in a way that minimises any adverse health related effects on the environment, if it cannot be repurposed for another use (Rühm et al., 2023).

### Specification, acquisition and installation

1. The appropriate imaging modalities required for a radiotherapy treatment unit need careful consideration at an early stage in setting up. A technical specification should be prepared with input from radiation oncologists, RTTs, medical physicists and other members of the treatment team based on the clinical requirements. The specifications should include technical performance requirements relating to image quality and patient dose, enabling and infrastructure work with the level of connectivity to other equipment, and maintenance requirements. It should also include the provision of initial optimised clinical imaging protocols and the type and amount of training for staff in operation of the equipment. In radiotherapy the choice of image guidance equipment may be more limited that in diagnostic imaging as the primary purchase is therapy equipment and compatibility with the preferred unit will restrict choices of associated imaging tools. Once a contract has been agreed, the equipment will be installed according to agreed standards, followed by acceptance and commissioning, personnel trained in its use, and a QA programme put in place to ensure that standards are maintained (ICRP, 2023). The expertise and professional skills of all members of the clinical team, including radiation oncologists, RTTs and medical physicists all play a vital role in the management of the equipment life cycle; understanding and managing it appropriately is essential if imaging for planning and treatment is to be optimal.

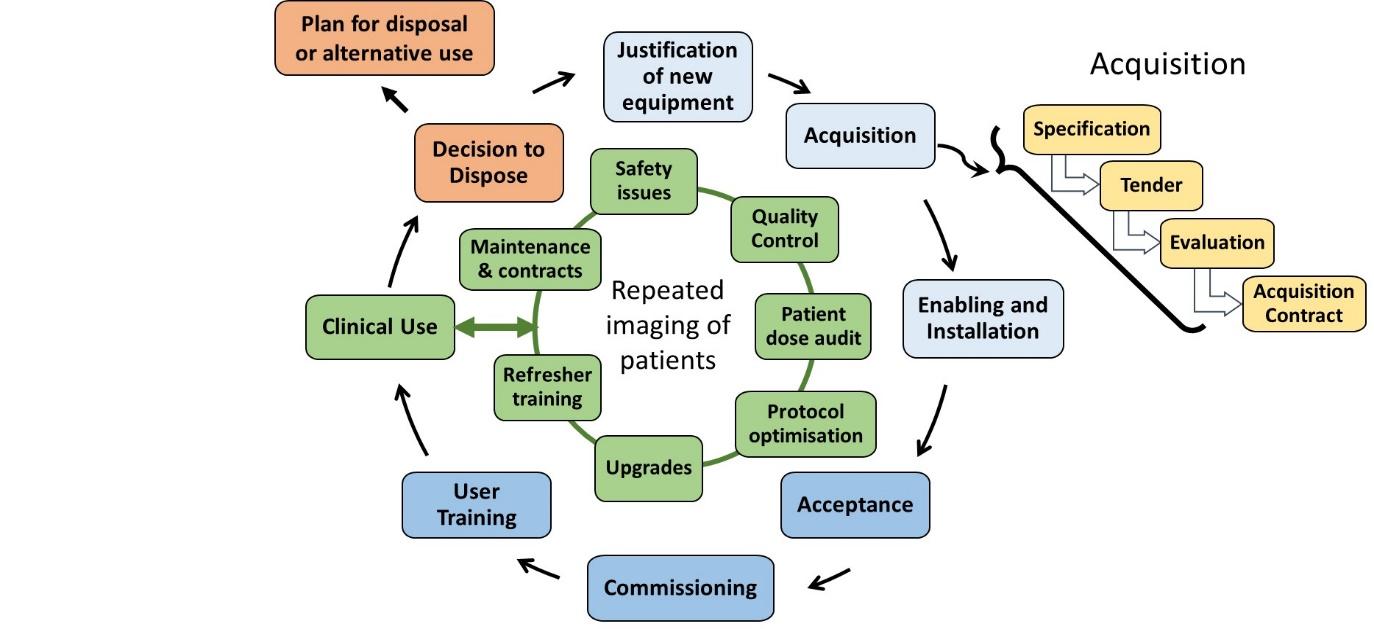


Fig. 10.1. The imaging equipment life cycle. Adapted from ICRP (2023).

### Acceptance testing and commissioning of x-ray imaging equipment

1. The acceptance testing procedures are performed to ensure that the procured system meets the specifications and requirements as stated in the specification and purchase agreement, and to demonstrate that the equipment complies with the relevant standards and regulations. Acceptance testing of imaging equipment will be carried out during the period of formal testing of the therapy equipment. It is likely to involve quantitative measurements, which may be vendor-specific and follow the vendor’s methodology. The procedures should be carried out by a qualified medical physicist and can be assisted by a service engineer or a representative from the vendor. Acceptance testing often uses test equipment and tools provided by the vendor and may also include reference images. If the imaging performance criteria are not part of the specification, the acceptance test will be performed according to the vendor’s documentation; however, consideration should be given to adding relevant specifications at the time of purchase, if needed. The presence of operator and service manuals should be verified as part of the acceptance.
2. The purchaser should ensure that the equipment is ready for clinical use during the commissioning phase. The information acquired during commissioning is usually also required for licensing of the equipment for clinical use by the regulatory authority. The commissioning tests depend on the imaging equipment used, the intended use and other equipment (hardware and software) with which the imaging equipment is interfaced. A programme for commissioning should be developed and agreed before the equipment is installed and should involve all members of the imaging team, medical physicists, RTTs and radiation oncologists to a greater or lesser extent. An important aspect of the commissioning is to establish baseline values of performance against which results of subsequent routine performance tests (constancy or QC) tests can be compared.
3. The commissioning of imaging equipment should include the protocols used for treatment planning, the in-room laser indicating the treatment coordinate system for alignment, the patient immobilisation and set-up, contouring of structures, transfer of images from the TPS to the treatment unit and confirmation of a consistent coordinate system from imaging, treatment planning and treatment delivery. Other aspects that need to be considered are internal motion and deformation over the time of delivery, the action levels for differences between reference and verification images, adjustment of patient or isocentre position during imaging, and recording of data and storage of images (IAEA, 2019; IPEM/SoR/CoR/RCR, 2021; McCullough et al., 2021). Guidelines for acceptance and commissioning of x-ray-based imaging systems for radiotherapy have been published by AAPM (Bissonnette et al., 2012; Fontenot et al., 2014; McCullough et al., 2021) and IAEA (IAEA, 2019). An end-to-end test should be performed as part of the commissioning (or routine QC) that allows independent verification of the entire chain of processes that underpin the use of image guidance, from CT simulation to treatment setup and delivery (IAEA, 2019).
4. The imaging parameters relating to optimisation of radiological protection for clinical use will be determined during commissioning. It is important to emphasise the need to involve a medical physicist familiar with diagnostic imaging techniques. If the expertise is not available within the radiotherapy department, then a diagnostic medical physicist from another department, centre, or private consulting group should be called upon to advise. Specific commissioning tests will determine the imaging settings to be used in clinical practice. They should assess whether vendor protocols for acquiring images are appropriate and whether further optimisation of radiological protection is required, and the settings decided upon should be evaluated thoroughly before being put into clinical use. A diagnostic physicist can also advise on what equipment is required for QA of imaging equipment. This is important as imaging QA tools such as a 10 cm long CTDI ionisation chamber and associated PMMA phantoms or an automatic half value layer measurement tool are not readily available in most radiotherapy departments.
5. Evaluating the safety aspects of the imaging system for positioning should also be performed during commissioning. The components listed above offer a non-exhaustive overview of the items requiring confirmation during commissioning. They serve to illustrate the range of performance aspects that need attention during commissioning. It also emphasises the importance of allowing sufficient time for the commissioning process, which will have a fundamental influence on the subsequent performance of the system and the level of optimisation of radiological protection. It is important to note that safety tests also need to include any interlocks (i.e. door) and warning signs as well as emergency off buttons.

### Training in use of imaging equipment

1. User training is essential for safe, optimised use of any imaging facilities with radiotherapy equipment. User training in operation of imaging equipment should be part of the Quality Management Programme. Vendors have responsibility for providing users with training that includes a full understanding of imaging options available. Training should be delivered by an agreed cascade process to account for those unable to attend initial sessions with vendor representatives. Educated “superusers” can be identified for dissemination of the user knowledge and provide practical guidance for subsequent refinement of protocol optimisation. Employers have a responsibility to provide the time necessary for future users to undergo proper and full training. The training undertaken should be documented for quality, continuing professional development (CPD), safety and regulatory purposes.
2. Medical physicists specialising in radiotherapy are often only trained in the aspects of diagnostic imaging relating to the radiotherapy process. This does not necessarily include image quality optimisation, the determination of imaging dose and its interpretation. Hence, in order to understand implications of various settings on imaging equipment a medical physicist with specialist knowledge and training in diagnostic radiology should both be included in the training in imaging equipment provided by the vendor and contribute to the training of other staff (see section 12).

## Quality assurance programme of imaging equipment

1. Quality Assurance (QA) is part of a quality management system that focuses on providing the confidence that quality requirements are being achieved. It is the first level on the scale of clinical efficacy in ensuring that the imaging equipment performs to the necessary standard (ICRP, 2024a) The primary aim of a QA programme for imaging in radiotherapy is to ensure that the simulation and treatment images used are of appropriate quality for accurate treatment planning and verification. This ensures that patients are treated correctly and safely and means that lessons are learned when the required standards are not being met. As part of the overall QA process, a wide range of processes, procedures and policies must be implemented to ensure the intended outcomes and standards (which must be clearly defined) are being achieved. In addition, a good QA programme defines procedures to acquire images with optimised radiation exposure to patients. QA in radiotherapy should also include audits to provide an overview of the system performance against the defined standards. A QA programme should encompass the following aspects:

* Acceptance testing and commissioning (section 10.1.2)
* Clinical imaging and correction protocols
* QC of imaging systems
* Review and audit

1. An important component in the QA programme for imaging in radiotherapy involves the setup and utilisation of clinical imaging and correction protocols for various treatment sites. Specifically, appropriate machine parameters and settings should be used when imaging for treatment simulation and delivery. Unlike in diagnostic procedures the accurate relationship between imaging and treatment co-ordinate systems is essential, as is the need to test for spatial accuracy.
2. Most centres adopt vendor’s default imaging protocols although the use of institutional machine parameters is also common particularly for special cases (e.g. paediatric and obese patients). Vendor protocols may not be optimised in terms of radiological protection, and a detailed evaluation of radiation dose performance is recommended at this stage to determine whether additional optimisation would be appropriate to fine tune the performance to the patient cohort being treated. The protocols should be re-evaluated periodically for image quality and radiation exposure through routine QC checks for the planning CT system (section 10.2.2) and treatment verification system (section 10.2.3).
3. External review and audit of procedures and processes are crucial components of quality management. Inclusion of procedures to encompass more aspects relating to image quality and imaging dose represents the next stage in development of the QA process. The procedures performed in the future may include, but are not limited to:

* Audits of whether QC tests are performed to ensure standards are being met, including calibration of dose indicators and image quality assessments.
* Confirmation of servicing and maintenance contracts.
* Audits to determine whether imaging and image guidance correction protocols that are in place are being followed, applied to the correct patient and executed correctly.
* Audits of set-up procedures can feed into changes in practice (either imaging or treatment or both) and might include revision of treatment margins, etc.
* Image reject analysis should identify reasons for retakes, e.g. inappropriate patient preparations or equipment issues.
* Patient dose audits to be reviewed and benchmarking of values for DRLRTs or typical doses against international guidance.

### Clinical imaging and correction protocols

1. Written imaging protocols should be available for the various treatment sites and radiotherapy techniques performed in the institution, setting out the accuracy requirements, recommended settings, need for contrast, and frequencies of imaging during treatment. These will depend on the application. While daily 3D x-ray imaging for verification may be justified for dose-escalated treatment performed with SRS or SBRT but will not be required for some other treatments. In addition, there should be evidence based protocols for setup based on the type of imaging system used, which should include patient setup information and action levels for correction.
2. Generally, image guidance correction protocols can be broadly divided into the categories of offline and online, and the choice of which to use depends on the site being treated, training of staff, imaging modality and departmental resources, including the need to balance treatment accuracy with workload and expertise (IAEA, 2019). The UK Royal College of Radiologists, Society and College of Radiographers and Institute of Physics and Engineering in Medicine had jointly published guidelines on positional correction or verification protocols for treating institutions to refer and adapt appropriately (IPEM/SoR/CoR/RCR, 2021; McNair et al., 2022).

### Quality control

1. Quality control (QC) is the part of the QA programme whereby appropriate tests and checks are performed to ensure that there are no failures in the safe and accurate delivery of the treatment. QC in radiotherapy should include a wide range of testing on the imaging equipment given the importance of accurate image information in modern IGRT treatments. Whilst the QC procedures for ensuring safe planning and execution of treatment plans are long established and integrated into radiotherapy centres (IPEM, 2018), the inclusion of imaging in this QA programme has been shown to be variable across the world (Martin et al., 2021). Appropriate dosimetry measurements will show whether the radiological protection of imaging is adequate. It is essential given the potential for repeated exposures on the same patient. Additionally, rigorous image quality assessments are crucial to guarantee the extraction of necessary clinical information from the data.
2. Baseline performance levels against which comparisons can be made should be established, linked to values for measurable quantities recorded during commissioning. Tolerances that would require action, if they were exceeded, should be agreed at the start of the QC programme. It is beneficial to define two action levels, based on tolerances, one to act as an investigation level where equipment can remain in clinical use, but for which additional measurements, review and remedial action is required, and a second that, if exceeded, should trigger action in terms of taking the equipment out of clinical use until the problem has been addressed (IPEM, 2010). Results of all tests together with any actions taken should be documented. Treatment verification systems using non-ionising radiation such as MRI, surface-guidance and ultrasound also require routine QC checks but are beyond the scope of this report.
3. A risk-based approach can be taken to determine the frequencies and types of check to be performed, considering the likelihood a test parameter goes wrong and the potential clinical consequences. Appropriate tools and equipment for QC such as image quality phantoms and dosimeters should be available to perform these checks.

#### Quality control of planning CT systems

1. In modern radiotherapy, the planning CT system is fundamental to most treatment regimes, since it provides the data on which the treatment plan is formulated. For this reason, it is essential to ensure that the data collected from the planning CT system is robust with a high level of geometric accuracy, whilst also providing images with reproducible CT numbers that allows a robust conversion between CT number (Hounsfield Units) and electron density for dose calculation in the planning system. However, beyond this, the fundamental requirement for optimisation must not be forgotten – hence, it is essential to ensure that both radiation dose and image quality form part of the planning CT QC programme.
2. The purpose of imaging for radiotherapy planning is not the same as that in radiology where diagnosis is the primary aim (Hubbard et al., 2015). The differences set out below should be borne in mind:

* Patients are set-up for therapeutic beam placement rather than diagnostic efficacy.
* Set-up may take longer, making the patient more vulnerable to discomfort and motion.
* The couch must be accurately aligned with minimal sag.
* Therapy imaging may use a large bore scanner to accommodate patient positioning which results in larger source to detector distances that increase the dose required.
* Motion management (in particular of breathing) is required for a large number of patients resulting in the requirement for 4DCT and higher associated doses.
* The axial field of view may be larger in therapy as all external contours (such as shoulders) need to be included.
* Craniocaudal scan length may be longer in therapy as extra information is required for dose calculation (5 cm beyond high dose region) and non-coplanar beam directions.
* The kV may be purposely higher to make conversion of CT number to electron density more robust.

1. QC testing will demonstrate that systems are performing as would be expected against what can be quite broad national/international guidance. This does not mean clinical image quality is at the appropriate level, nor that the doses are as low as reasonably practicable (ALARP) i.e. basic equipment QC does not mean the system and imaging protocols are optimised. A number of publications on general QC testing for CT scanners are available (e.g. Samei et al., 2019). In addition, there are several guidelines that are radiotherapy specific which include aspects such as geometric accuracy and CT number (Mayles et al., 1999; Mutic et al., 2003; IPEM, 2018; Hanley et al., 2021). IAEA published a report harmonising the CT QA and QC checks applied to both diagnostics and therapy (IAEA, 2012).
2. For dosimetry QC of a planning CT system, it is generally recommended to perform CT Dose Index (CTDI) measurements. These are carried out with two sets of transparent acrylic cylinder phantoms, i.e., the body phantom (32 cm diameter, 15 cm long) and the head phantom (16 cm diameter, 15 cm long). A calibrated 100 mm ionisation chamber is used as the detector, and the CTDI measurement using this chamber is known as CTDI100 which is subsequently used to derive the weighted CTDI (CTDIw) representing an average CTDI across different measurement points in the field-of-view (Samei et al., 2019) (see Annex B). The CTDI values change as a function of scan parameters, and measurements can be performed for a subset of standard combinations of scan parameters. This check should be performed at least annually and after any major service/repair to each imaging modality, along with other parameters such as the geometric accuracy and CT-number calibration, all of which should be compared against the baseline values obtained during commissioning.
3. It is important to ensure all aspects of the QA programme are implemented. Often the dosimetry side, leading into optimisation alongside image quality evaluation, can wrongly be neglected as the expertise and/or equipment may not be available in the department (Martin et al., 2021).

#### Quality control of treatment verification systems

1. Advanced radiotherapy systems allow assessment and correction of patient positioning as well as organ motion management through verification before or during treatment administration. Therefore, a robust QC programme for treatment verification systems must be in place, including aspects such as the linearity of CT numbers, the uniformity of axial reconstructions, high contrast spatial resolution and the long-term stability of flat-panel detector to ensure that systems continue to perform to specification.
2. There are numerous QC guidelines available for treatment verification systems (Klein et al., 2009; Fontenot et al., 2014; IAEA, 2019; Hanley et al., 2021; McCullough et al., 2021). CT-based technologies (CBCT in particular) are the most widely used treatment verification systems and there are several QC guidelines published for these modalities (Bissonnette et al., 2008, 2012; de Las Heras Gala et al., 2017; Taneja et al., 2020).
3. It should be noted that the dosimetry (for imaging systems utilising x-rays), image quality and geometric aspects of the treatment verification systems are of equal importance to ensure the required clinical information can be obtained with the optimised amount of radiation exposure to patients. The methods and requirements of QC dosimetry checks for imaging systems depend on the type of imaging modality used and their dosimetric quantities. Table 10.1 presents a summary of the recommended QC dosimetry tests for the main imaging modalities used in radiotherapy. It should be noted that methodologies for CBCT dosimetry are still in the development stage and although techniques are available for measuring either a CTDI or the cumulative dose at the centre of a CT phantom, techniques have yet to be standardised (ICRP, 2015). It is recommended that all radiotherapy departments acquire CTDI instruments and phantoms for measurement of the wide beam CTDI supported by the IEC/IAEA (Annex B.2) and that vendors include calibrated CTDI displays that are adjusted according to exposure factors. A temporary alternative for patient dose surveys using equipment available in most radiotherapy departments is described in Annex B.3. Other QC activities in particular pertaining to geometric accuracy and coincidence of imaging and therapy co-ordinate systems are required, typically with higher frequencies.

Table 10.1. Recommended QC checks for dosimetry of main imaging systems used for radiotherapy verification against baseline values.

|  |  |  |  |
| --- | --- | --- | --- |
| Imaging modality | Dosimetric test | Minimum test frequency | Reference |
| EPID | Imaging (effective) dose | Annually | (Klein et al., 2009; Murphy et al., 2007) |
| MV-CBCT | Axial and skin dose | Annually | (Bissonnette, 2018; Yin et al., 2009) |
| CTDI | Annually | (Bissonnette et al., 2012) |
| Imaging (effective) dose | When required | (Klein et al., 2009; Murphy et al., 2007) |
| kV-planar | Entrance surface air-kerma | Annually | (Fontenot et al., 2014) |
| Imaging (effective) dose | When required | (Klein et al., 2009; Murphy et al., 2007) |
| kV-CBCT | Axial and skin dose | Annually | (Bissonnette et al., 2018; Yin et al., 2009) |
| Cumulative dose or CTDI | Annually | (Dixon and Boone, 2010; Bissonnette et al., 2012; ICRP, 2015) |
| Imaging (effective) dose | When required | (Klein et al., 2009; Murphy et al., 2007) |
| Tomotherapy (MVCT) | Multiple slice average dose (MSAD) | Annually (More frequent recommended) | (Langen et al., 2010) |

## Reviews and audits

### Audits of doses from imaging exposures

#### The process of audit against dose reference levels (DRLRTs)

1. If radiation protection for medical imaging used in radiotherapy planning and treatment is to be optimised, operators need to be aware of dose levels. These are not immediately apparent from the clinical images, and the information can only be gained from surveys of imaging doses to patients. Knowledge of doses delivered to patients is the first step in the optimisation process, but currently the number of RT centres that make any record of imaging doses is limited (IRSN, 2020; Martin et al., 2021). Dose surveys should provide information about the range of doses patients receive from both planning and treatment imaging exposures at a facility, which can then enable the comparison of doses between different centres.
2. Patient dose audit is the process, widely used in diagnostic radiology, whereby the results of a patient dose survey are compared against relevant standards (ICRP, 2023). Prior to surveys being initiated, the standard against which the results are to be compared should be determined, but such surveys in radiotherapy are still at a preliminary stage. The standards used for diagnostic medical exposures are diagnostic reference levels (DRLs) (ICRP, 2017). These can provide a benchmark against which facilities can make comparisons to assess their practices in terms of dose and identify whether further optimisation of imaging protocols is required.
3. DRLs are established at national or regional level by collecting median doses from many centres and selecting the third quartile or 75th percentile values of the resulting distribution (ICRP, 2017). This means that three quarters of centres consider that acceptable images can be obtained at this dose level or lower. A similar approach has been used to develop (DRLRTs) for imaging used in treatment planning (Wood et al., 2018) and imaging during treatment (Wood et al., 2024). Such national surveys across multiple countries might provide useful reference data in the early stages of developing a dose audit programme.
4. The purpose of setting and applying DRLRTs is to identify procedures for which doses are higher than national or regional values. The facility can then take measures to optimise and reduce doses as needed. However, DRLRTs must not be considered as dose limits; they are just the first step in the optimisation process and doses below a DRLRT do not indicate that there is no further room for optimisation. It is important to remember that DRLRTs do not apply to individual patients, as dose indices may vary with the size and attenuation properties of the patient. They are solely a means of comparing samples of patient data through summary statistics. They have the limitation that compliance with national or local DRLRT values does not replace the evaluation of image quality; the patient dose audit alone does not indicate whether images are adequate or inadequate for a particular clinical purpose.
5. An essential component of dose audit is that actions are assigned where appropriate, following the comparison with a DRLRT. When doses exceed the DRLRT, an investigation should be undertaken to identify the cause and remedial action taken if required. This must involve relevant members of the multi-disciplinary team (e.g. Physicists with appropriate training in imaging, RTTs and Radiation Oncologists), and should encompass an evaluation of equipment performance and image quality, settings used, imaging examination protocols and the patient cohort. For example, whilst a medical physicist may be able to comment on the performance of the measuring equipment used (and relate them to the results of QC performance tests), the imaging requirements and operator training issues are the remit of the clinical staff involved. The establishment of multi-disciplinary optimisation teams is of great value and recommended for optimisation of protocols in radiology (ICRP, 2023) and IGRT (Jaffray et al, 2013; IAEA, 2019)
6. The dose metrics used in patient dose surveys should be representative and readily available to users of the equipment, so practical quantities such as DLP and CTDIvol for CT, which are displayed on CT scanners or KAP for radiography and fluoroscopy are preferable (Annex B.1). The calibration of the displayed dose metrics used in patient dose surveys should be verified, preferably at intervals of no more than 1–2 years and should be traceable to national standards and this should form part of the routine QA programme. These measurable dose quantities are not linked directly to doses to patients’ organs but are useful for dose surveys as they are more relevant to the operator of the equipment. However, they can often be linked via calculations to organ and effective doses in the optimisation programme.
7. The CTDIvol represents a measurement of dose within a polymethyl methacrylate (PMMA) phantom of standard size (16 or 32 cm diameter) and is suitable for dose surveys and optimisation of practices, but it is known to be a poor indication of doses to individual patients with varying sizes. The doses to tissues within lighter patients will be greater than the CTDIvol, while those for overweight patients will be smaller, because the x-ray beams are more attenuated in tissues overlying the sensitive organs. A size specific dose estimate (SSDE) has been developed, based on the CTDIvol, to provide doses adjusted for patient size (AAPM 2011, 2014). This can in principle be calculated using a measure of patient body dimension taken from CT images and is often available on modern CT scanners. This may provide more accurate dosimetric information on individual patients with various sizes. Since the DLP is derived from the CTDIvol, it is subject to the same limitations of CTDIvol in terms of accounting for various patient’s body sizes.
8. The Digital Imaging and Communications in Medicine (DICOM) committee developed the Radiation Dose Structured Report (RDSR) (IEC, 2014; Sechopoulos et al., 2015; DICOM, 2017; NEMA, 2020) to handle the recording and storage of radiation dose information from imaging modalities. Patient dose monitoring is facilitated by transferring this information to Picture Archiving and Communication System (PACS), Radiology Information System (RIS), Oncology Information System (OIS), and vendor neutral electronic dose management systems (AAPM, 2019b). However, manual recording on paper may be the only practical method available in the early stages of establishing a patient dose survey programme. Ideally in the longer term the dose metrics recorded should be transferred automatically to and retrieved from a patient dose information system.

#### Audit of patient doses from imaging for radiotherapy planning

1. CT is the most common imaging modality used for radiotherapy planning. Hence, patient doses from CT scans involved in radiotherapy should be assessed using similar dose quantities and methods to those used for diagnostic CT (ICRP, 2024b). Patient imaging dose surveys in a radiotherapy centre should ideally cover imaging linked to the predominant treatments performed and the associated requirements.
2. ICRP recommend that a survey of a particular type of examination should involve the collection of data from at least 20 patients for each procedure for every CT scanner (ICRP, 2017). However, inclusion of more data using automated systems would enable more representative doses to be derived. Typically, the results from a survey carried out within a single facility may show large dose variations depending on patient size. If only small numbers of patients are available, constraints should be placed on patient weight, ideally those associated with the standard being used as a comparator.
3. The median value from the dose distributions for each examination on each CT scanner should be calculated and then compared with the DRLRT (ICRP, 2017). If the median dose exceeds the DRLRT, action should be taken to optimise the imaging procedure. Where multiple scanners perform the same examination in a centre, multiple comparisons should be made and if doses differ for the same clinical procedures, the reason must be investigated and remedial action taken if appropriate. Note, in some cases where the scanners are not matched, technological factors may explain discrepancies between different systems (e.g. an older generation scanner compared with a brand new system with additional dose and image quality optimisation options) – however, where scanners are matched in performance, and the patient demographics are closely aligned, dose levels should be similar on two systems in the same centre. Any comparison should take into account the uncertainty budget associated with the dose quantity recorded during the dose survey.

#### Audit of doses from imaging during treatment

1. Dose recording for imaging in radiotherapy is not widely undertaken at present. Moreover, a variety of techniques are used for imaging during treatment. The most widely used technique at the present time is kV CBCT (ICRP, 2015; Martin et al 2021), which results in higher patient doses compared with planar 2D kV radiography. Consequently, this report focuses primarily on CBCT. The standard dosimetry quantity displayed on radiotherapy CBCT equipment equates to the wide beam CTDI (IEC, 2016). This is a development of the CTDI defined originally for a narrow beam. This is not displayed on all equipment at the present time, but it is recommended that this should be implemented by all vendors and that displayed values should be adjusted automatically with exposure factors. Calibration of the displayed quantity should be verified before performance is compared against national or international reference data. Once calibrated displays of the wide beam CTDIs are available on most CBCT systems, values for complete scans can be used for patient dose surveys
2. In the meantime, an alternative approach is required, as most equipment does not display the wide beam CTDI and patient dose surveys are not currently standard practice for radiotherapy-related imaging. The initiation of CBCT patient dose surveys will require a straightforward approach so that centres can readily contribute dose measurements, as comparison of performance for multiple systems is required. The Cone Beam Dose Index (CBDI) was introduced by Amer et al. (2007) to resolve this limitation. Similar to CTDI, the CBDI represents the dose measured over the length of a CTDI chamber in a standard CTDI phantom. The current publication proposes measurements based on the CBDI, which will give values suitable for benchmarking and comparing the performance of equivalent CBCT protocols for the same clinical indication. This is a simple measure related to the level of dose to the patient that captures the effect of kV and filtration. A detailed description of the measurements is provided in Annex B.3.
3. In the long term it is hoped that CBCT vendors will provide a wide beam CTDI display with defined methods for measurement, which will facilitate comparisons between centres and with DRLRTs (IEC, 2009; IAEA, 2011; Platten et al., 2013; Abuhaimed et al., 2014; ICRP, 2015). If every linac CBCT system had a properly calibrated wide beam CTDI display using the same IEC standard, the normal conventional methods used for CT dose audit could be applied, but there is much that needs to be changed before this can be accomplished.
4. An attempt has been made to audit CBCT doses across the UK, whilst working within these limitations. Simple dose metrics based around a weighted CBDI, as are described here, have been measured for a large number of systems. This has established DRLRTs in terms of the CBDI with median doses from future surveys expected to be below these values. This has allowed a simple comparison of ‘typical values’ of dose for Elekta and Varian linac imaging systems, and those centres using multiple size-based protocols against those who use the single default protocol provided by the vendor (Wood et al., 2024). It is hoped the publication of this data will allow centres to compare their own performance against the national picture.

#### Regular audit of imaging doses

1. Surveys of patient dose quantities should be added to the programme of other audits carried out in radiotherapy departments. Intervals of about 3 years may be appropriate in the initial stages of setting up a programme, but as automated systems for patient data collection and management become more widely available, the dose audit process may take the form of a more regular review (ICRP, 2023). When a survey reveals that a DRLRT value has been exceeded, an investigation should be conducted, and, if appropriate, corrective actions taken to optimise patient protection. The investigation should include a review of equipment performance, the settings used, the examination protocols, and related procedural factors. Where intervention is required, it should be undertaken as soon as practicable and in any event prior to the next audit being initiated. Reauditing of doses is recommended after changes have been made to protocols.
2. It is important that the personnel involved in the delivery of patient doses are involved in the process of dose audit and have a feeling of ownership. All individuals who have a role in subjecting a patient to a medical exposure should be familiar with the DRLRT concept and its use for optimisation. Patient dose surveys and subsequent analysis should be performed with their collaboration and input. Aids that are readily understood, such as box and whisker plots, bar charts, and tables should be used for dissemination of results. The results from dose audits should feed into regular reviews of imaging protocols carried out by optimisation teams comprising radiation oncologists, RTTs and medical physicists. Image quality must be evaluated alongside the dose to determine what if any action is to be taken. The process then becomes a natural part of clinical audit. Professional organisations are encouraged to promote the process of dose audit and collaborate in the establishment of national or regional DRLRTs.

### Repeat imaging analysis

1. Routine QC testing and appropriate maintenance should help to reduce the number of repeat imaging episodes due to technical reasons such as equipment faults. However, repeat imaging may occur due to a wide range of other reasons. The repetition of imaging procedures will give unnecessary doses to patients. A process of reject analysis can track episodes of repeat imaging to monitor for any long term trends that may indicate faults, long term deterioration of the equipment, or other process issues within the patient pathway and thereby promote optimal practice.
2. Reject analyses of this type are well established for diagnostic imaging in some countries (RCR, 2024). Regular audits of the reason for image rejection and repeat exposures can help to drive quality improvement in terms of image acquisition, but also within the procedures that lead up to that exposure. For this to be effective, it is vital to capture the reason for repeat imaging at the time the decision is made, which might be done using the Oncology Information System (with automated reports generated to summarise the data on a regular basis). Reasons for repeat imaging may include unacceptable image quality, image artefacts, equipment fault/breakdown, inadequate patient preparation (for example bowel or bladder status) or patient setup errors (patient not positioned correctly at the start of treatment). The treatment site/intent may also need to be considered in the analysis of reject data as a higher level of patient related repeat imaging may inherently be expected with some types of treatment e.g. prostate patients where bowel and bladder status are important and harder to control.
3. The reject analysis process should be overseen by the multi-disciplinary image optimisation team. An appropriate baseline of performance can be established, as it will not be possible to eliminate all repeat imaging episodes. Repeat imaging due to setup issues may prevent potentially much more serious incidents that could result in the high dose treatment being delivered incorrectly. Following the identification of any deficiencies, remedial actions with follow-up audits should be performed to evaluate the effectiveness of the intervention. Ultimately, through appropriate actions, the number of repeat imaging episodes may be reduced, and hence patient doses further optimised.

# AVOIDANCE OF ERRORS ORIGINATING FROM IMAGING IN RADIOTHERAPY

1. **Key points in this section:**

Incidents and errors are an important opportunity to learn and improve processes. This also applies to imaging in radiotherapy.

All necessary measures should be taken so that a treatment cannot proceed until the patient’s complete medical file is available to confirm the consistency of information from different documents. This is particularly important for bilateral organs and when several lesions are visible on images.

The patient should be positioned in a similar orientation (prone/supine or feet first/head first) for the preparatory scans, the planning and the treatment, whenever possible in order to reduce the risk of tumour localisation errors.

Procedures should be developed for importing images into the TPS to lower the risk of using the wrong set of CT images. These may include setting up planning systems to recognise CT image information relating to patient IDs and use of names for planning scans that include the date and site to be treated.

The same unique identifying fields (e.g. name, age, unique ID) should be used across all systems that acquire, store and handle patient image information, if at all possible.

A systematic approach should be adopted to reduce the risk of incorrect vertebral body localisation by matching at multiple anatomic points. This can be facilitated by increasing the length of the FOV. Maximum tolerances should be set on the shifts allowed between set-up and treatment.

A complete reliance on automatic contouring and identification of fiducials should be avoided at present by including human confirmation checks to reduce the risk of incorrect target identification. This is particularly important in the context of re-treatment.

Multi-disciplinary team meetings and peer review of procedures and check lists are effective measures for reducing errors.

## Terminology used for unintended and accidental medical exposures

1. *Publication 86* (ICRP, 2000c) develops the criteria for accidental exposures with radiotherapy patients. This publication considers that a ‘normal’ radiation exposure is a treatment that closely follows the plan specified in the treatment prescription including all imaging required to achieve this goal. An accidental medical exposure can therefore be considered to have occurred if there is a substantial deviation from the prescription. Additionally, an error in the prescription can also result in a substantial deviation from the intended radiation exposure and lead to an accidental exposure.
2. In response, the International Basic Safety Standards (IAEA, 2014), through requirement 41 related to ‘unintended and accidental medical exposures’, requires that Registrants and licensees shall ensure that all practicable measures are taken to minimise the likelihood of unintended or accidental medical exposures. Registrants and licensees shall promptly investigate unintended or accidental medical exposures and, if appropriate, shall implement corrective actions. In connection with *Publication 86* (ICRP, 2000c), IAEA (2014) also states that investigations must be conducted when doses or dose fractionations differ substantially from (over or under) the values prescribed by the radiological medical practitioner. This approach should also be applied to imaging in radiotherapy.
3. Among the various recommendations for risk management and reporting systems, there is little uniformity in the terminology used (EC, 2015). In this chapter, the term ‘errors’ covers different types of events that can lead to unintended and accidental medical exposures as defined by the IAEA (IAEA, 2014) and Euratom (EC, 2013), and also near misses (incidents which did not reach the patient) as defined by the WHO (WHO, 2009). The study of near misses is powerful in identifying work process problems that can lead to an incident (ASTRO, 2019). Focusing on major events with catastrophic consequences and very low probability of occurrence may result in overlooking other types of error that can occur with a higher probability and have lower, but still significant, consequences (ICRP, 2009b; SAFRON, 2016; IAEA, 2018 [Section 5 and Appendix 1]). While doses from imaging are smaller than the therapeutic dose, imaging can be frequent and is likely to fall into the latter category.
4. One of the more effective ways of identifying things that may go wrong is learning from the mistakes of others. National and regional organisations in many countries, to which radiotherapy centres report incidents that occur, share information through the issue of newsletters and reports (e.g. RO-ILS, 2016; ASN, 2018; AFCN, 2019; IRSN, 2020). In addition, the IAEA has set up an integrated voluntary reporting and learning system for incidents and near misses called SAFRON (Safety in Radiation Oncology). The goal of SAFRON is to improve the safe planning and delivery of radiotherapy and radionuclide therapy by sharing safety-related events and safety analysis around the world (SAFRON, 2016, 2024). Radiotherapy centres are encouraged to report incidents to SAFRON and similar systems at a national or regional level to allow others to learn from their experiences.
5. Since the 1990s, the significant technological developments in the preparation and the delivery of the treatment have resulted in the use of more advanced imaging in radiotherapy. Errors can result from misinterpretation of images or use of incorrect images and the additional complexity and computerisation may lead to types of incidents that are different from those occurring in the past (Fraass, 2012). An Australian study (Crouch et al., 2024) identified ‘verification imaging’ as the 2nd source (about 20%) of incident reports in their ILS (Learning In Radiation ONcology (LIRON)).
6. The following sections give brief descriptions of the types of error that can occur and measures that should be put in place to prevent them. Short descriptions of some events reported in the literature resulting from imaging at the treatment preparation stage and during the treatment are included in Annex C.

## Errors resulting from imaging during plan preparation

### Incorrect target volume delineation

1. Modern radiotherapy treatment planning and reporting depends on contouring of targets and critical structures. Incorrect delineation of the target can result when there is doubt about the location of a lesion to be treated. This might occur when there is uncertainty about the side of the body (laterality) or when multiple lesions are present, such as an additional benign target or a target that has been treated previously. These types of situations can be exacerbated if the quality of the images being used is poor or multiple image sets are incorrectly registered with respect to each other.
2. There are many failure modes related to interpretation of the data ranging from incorrect windowing/levelling during contouring (e.g. in lung) to the use of incorrect Boolean operations and expansions and contractions of structures. Of particular importance is the increasing utilisation of auto-contouring which relies on atlases or artificial intelligence (AI).
3. **Preventative measures** to avoid delineation errors:

* Take all necessary measures to ensure that the treatment cannot proceed until the patient’s complete medical file including the surgical report, the pathology report and the imaging files (CT, MRI, PET as applicable) are available to confirm the consistency of information from different documents.
* For bilateral organs, ensure that information from different documents is consistent with that supplied by the patient or their family and the multidisciplinary team meeting report.
* Additional attention should be paid to unusual imaging situations, such as the presence of prostheses or implanted devices, which may be a source of image artefacts.
* For more complex treatments such as SRT consider the appropriate spatial resolution and applying enhanced safety checks such as explicit review of diagnostic images by the attending physician (with an accompanying checklist that is reviewed by others in the workflow).
* Image registration or fusion between different modalities is often essential to facilitate target contouring. Multidisciplinary input can be important to ensure this is done accurately
* Avoid simply placing blind trust in auto-contouring tools and include independent review of contours, e.g. in chart rounds as part of QA procedures.
* Consider scripting and/or automation of processes in plan preparation to reduce the risks of factors being overlooked.

### Differences in patient positioning between imaging and treatment

1. Errors can result from differences in patient orientation for imaging with different modalities and at different stages of preparation and treatment, as outlined in *Publication 112* (ICRP, 2009b).
2. **Preventative measures** to take account of differences in orientations used for imaging:

* Position the patient in a similar orientation (prone/supine or feet first/head first) for the preparatory scans, the planning and the treatment, whenever possible.
* Ideally, use an identical couch type (flat or curved) and the same immobilisation during imaging and treatment delivery.
* Make a clear distinction between the orientations used for CT, MRI, PET or other imaging modality data acquisition for treatment planning and for treatment delivery.
* Familiarise radiotherapy staff with imaging conventions in nuclear medicine and other imaging departments.
* Make sure RTTs are aware of the importance of verification of concordance between the “patient scanning position” and the “patient treatment position” in the treatment plan.
* Ensure that procedures, protocols and documentation are clear and that the treatment prescription indicates the precise locations of lesions to be treated.
* Use regular case discussions or chart rounds between the physicians involved and the radiotherapy team to confirm image correspondence.
* Where available, optical surface guidance can offer an independent check on patient positioning.

### Differences in motion management techniques

1. Possible errors can occur due to differences in patient breath management techniques and related images between planning and treatment.
2. **Preventative measures:**

* Both images taken for treatment planning and verification images can be affected by motion artefacts. Careful consideration of these artefacts is required, a task that most commonly would be performed by the medical physicist in the team (Antony et al., 2020).
* Take all measures to account for motion during treatment into consideration during imaging for treatment planning.
* For planning lung or liver gated treatment, evaluate the extent of tumour motion. Slow contrast infusion can be helpful in the case of liver tumours. Make ITV delineation in accordance with the appropriate phases selected for the gated treatment delivery (ICRU, 1999).
* If the dose calculation is performed on a non-gated planning CT, evaluate the density of the ITV on such a CT and possibly adjust (via density override) to reflect the density of the ITV contoured on the maximum intensity projection or average intensity projection. This is especially relevant for lung treatment, where not handling tissue heterogeneity appropriately could result in significant dose calculation errors.
* For treatments in breath hold mode, undertake imaging with breath hold and make checks to ensure that relevant parameters such as the depth of breath are consistent.

### Wrong set of images

1. Using the wrong set of images for treatment planning will inevitably lead to errors. This can occur due to incorrect transfer of images, either by associating them with the wrong patient or using image data sets from prior treatments. In the context of this publication, “wrong images” also includes secondary images such as MRI or PET scans that are registered to the primary planning CT.
2. **Preventative measures** to reduce the risk of using the wrong set of images:

* Develop methodologies for importing images into the TPS that include recognition of patient IDs.
* Use nomenclature for planning scans that includes the date and site to be treated.
* Use the same unique identifying fields (e.g. name, age, unique ID) across all systems that acquire, store and handle patient image information.
* Reinforce the traceability of the preceding treatment history of a patient as soon as a planned new treatment is prescribed.
* Ask the manufacturer to provide a methodology for importing images (CT scans, MRI, PET, structures, etc.) into the TPS to guarantee that files for new treatments will be used for the planning, e.g. by providing a warning when a new plan is being created on an old scan and asking for confirmation
* Verification of secondary image dets, such as PET and MRI, should include confirming the acquisition date to ensure that the most recent and clinically relevant data sets (e.g. for tumour delineation in SRS) are used to for treatment planning.

### Errors from processing of image data

1. **Digitally reconstructed radiographs (DRR):** A variety of different errors can occur with DRRs. Examples have been reported with distortion of a DRR resulting from an error in loading information and creation of DRRs with the wrong reference point.
2. **Preventative measures:**

* Carry out annual consistency checks on DRR generation using a suitable phantom.
* Check DRR generation after any upgrade.

1. **Image registration:** With the increasing availability of deformable image registration algorithms for dose accumulation and retreatment errors in image registration can have a significant effect on treatment quality. However, this is an extensive topic and proper coverage is beyond the scope of this publication (Rong et al., 2021).
2. **Preventative measures:**

* Include image registration checks in the QA process.
* Verify the validity of rigid or deformable registration before contouring the target and OARs. This is especially important for SRT when checking MRI to CT registrations, as MRI distortions could result in target localisation errors. Multiple registrations (e.g. up to one per target) are often appropriate.
* Evaluate deformable image registrations qualitatively and quantitatively with built in QA tools (AAPM, 2017).
* Ensure that the consistency of image registrations is carefully reviewed after any upgrade with digital phantoms or with previously registered patients.
* Automatic registration is increasingly becoming available and is an essential tool for adaptive radiotherapy. It is recommended to have all such registration results reviewed by a human operator (Teuwen et al., 2022).

1. **CT number calibration:** Errors may arise if an incorrect calibration curve is used to establish the relationship between CT numbers (Hounsfield units) and tissue density used for dose calculation, such as when employing different CT protocols with different tube voltages or applying contrast agents.
2. Preventative measures:

* Create a list of names for relevant CT to electron density curves that is easily understood by the operator so the correct file can be chosen.
* Lock acquisition protocols when a new radiotherapy CT scanner is commissioned.
* Have a requirement for modifications only to be allowed after strong validation, requiring a request for a password and specific administration rights.
* Pay attention to the tube voltage used in CT scanners with automatic tube voltage selection function. The automated adjustment of kV in the AEC tool should be disabled and locked.
* When multiple images are acquired on the same scanner, or images are transferred between different CT or PET-CT scanners, ensure that the acquisition protocol with the same tube voltage is used consistently.
* Use non-contrast CT for dose calculation, to avoid misinterpretation of CT numbers and inconsistency between planning and treatment phases.
* Check the CT number calibration carefully after any system upgrade or change. After major maintenance or upgrade involving the x-ray tube, the CT-number-electron density curve should be recalibrated and the consistency with the TPS confirmed. The energy spectrum may vary between x-ray tubes, even using the same tube potential setting.

## Errors resulting from imaging during the treatment

### Incorrect vertebral body localisation

1. Errors due to the wrong identification of vertebrae have been identified as one of the main causes of significant events in radiotherapy in France (ASN, 2018) and elsewhere. These result from poor matching of vertebral bodies and generally result in shifts of several cm in the position of treatment delivery.
2. **Preventative measures** to minimise the risk of incorrect vertebral body localisation. These are also applicable to circumstances where there is a deviation from the standard procedure to minimise patient discomfort.

* Adopt a systematic approach to reduce the risk of incorrect vertebral body localisation.
* Indicate clearly in the prescription/written directive the desired matching process (i.e. align to bony anatomy or ITV)
* Consider relevant training in anatomy for operators where needed.
* In cases where identification of the correct vertebra could be an issue, increase the length of the FOV to include either the superior or inferior portion of the section of spine being treated.
* Ensure that the visual identification of vertebral bodies is not based solely upon bony anatomy and follow a consistent pattern of matching multiple anatomic points.
* Include dose contours overlying adjacent structures.
* Set maximum tolerances on the shifts allowed between set-up and treatment.
* Where available, optical surface guidance can offer an independent check on patient positioning.

### Other errors in matching protocols

1. A variety of factors can contribute to the occurrence of errors in matching images from CBCT at the time of treatment to the original planning CT. These include confusion between use of soft tissue or bony matching, unfamiliarity of staff with techniques when new equipment or imaging systems are introduced, confusion with a previous target volume nearby combined with poor image quality, and overreliance on automatic identification of markers (see Annex C.3.2).
2. **Preventative measures** that may avoid some of these are:

* Image using agreed protocols with standard matching techniques whenever practicable.
* Ensure matching of coordinate systems between all imaging systems used for planning and during treatment delivery.
* Include additional systems to verify alignments when there is any deviation from normal protocols.
* Include additional checks for situations where different target matching strategies are in use.
* Include additional checks during the early stages after introduction of new systems or new equipment.
* Avoid reliance solely on automatic identification of markers, clips or surrogates by including human confirmation checks to reduce the risk of confusion between old and new targets.
* Carry out additional checks if staff observe potential issues such as the image not including the entire treatment volume due to placement of the image receptor.

1. An emerging method of imaging matching relies on the generation of synthetic CTs from other imaging modalities, most notably MRI. In this practice an additional step is required in the generation of reference images for treatment verification which involves a computer generated image. Careful checks of the workflows as well as review of reference images for individual patients is important (Emin et al., 2024).

## Promotion of good practice in imaging in radiotherapy

1. Images play an important role in the safety and precision of treatment delivery. However, as pointed out in *Publication 112* (ICRP, 2009b), errors in imaging can have significant consequences for treatment outcome. Greater attention is needed to imaging-related issues and such concerns have been raised in a RO-ILS focus on Image-Guided Radiation Therapy (IGRT)/Setup-Related Events (RO-ILS, 2016). A retrospective analysis performed on 17610 registrations between planning scans and pretreatment CBCT scans (2414 patients) through an AI based image review algorithm highlighted the reliability and safety of IGRT, with an absolute gross patient misalignment error rate of 0.04% per delivered fraction (Luximon et al., 2024). However, the authors stressed that the incidents that occurred expose safety gaps still present within the patient alignment process. The powerful advance that the use of imaging in radiotherapy brought to the quality of the treatment is undeniable, particularly during therapy delivery. However, if it is not used with sufficient care and vigilance, it can result in a very complex treatment being ‘precisely wrong’ (Jaffray et al., 2013).
2. Given the large number of emerging image guidance tools discussed earlier in this publication, a wide range of failure modes must be considered. A Failure Mode and Effects Analysis (FMEA) as recommended by AAPM Task Group 100 (Huq et al., 2016) offers a structured approach to identify these risks. By employing FMEA and other prospective risk management tools, practitioners can proactively identify vulnerable aspects of their imaging procedures. A detailed discussion of these methodologies is beyond the scope of this report.
3. Jaffray et al. (2013) propose ten foundational elements for good practice to establish a foundation for safe and effective use of image guidance (see Table 11.1). Establishing a multi-professional team responsible for IGRT activities is key to achieving optimisation of imaging practice in general (see section 4), as is the provision of device- and process-specific training for all staff operating imaging systems or responsible for treatment delivery (section 12). These recommendations should be considered when implementing IGRT in a radiotherapy department and components should be considered in building patient-specific checklists. Further information on improving practices can be found in ASN (https://www.french-nuclear-safety.fr/) and AFCN newsletters and RO-ILS aggregate reports (https://www.astro.org/), and references for some examples are included in Annex C to this report.

Table 11.1. Recommendations to establish a foundation for safe and effective IGRT practices

| Recommendations (adapted and extended from Jaffray et al. (2013)). |
| --- |
| 1. Establish a multi-professional team responsible for IGRT activities. |
| 2. Establish and monitor a program of daily, monthly, and annual QA for all new or existing IGRT sub-systems. |
| 3. Provide device- and process-specific training for all staff operating IGRT systems or responsible for IGRT delivery. |
| 4. Perform ‘end-to-end’ testing for all new IGRT procedures (from simulation to dose delivery) and document performance prior to clinical release. |
| 5. Establish process-specific documentation and procedures for IGRT. |
| 6. Clearly identify who is responsible for approval of any IGRT correction decision and the process whereby this decision is made and documented. |
| 7. Establish and document site-specific planning procedures; specifically, the procedure for defining PTV margins. Link these planning procedures to IGRT procedures. |
| 8. Multi-professional peer-review of PTV volumes. Peer-review of GTV/CTV volumes by radiation oncologists. |
| 9. Verify proper creation and transfer of IGRT reference data (PTV, OARs, DRRs, etc) to IGRT system. |
| 10. Establish a reporting mechanism for IGRT-related variances in the radiation treatment process. |
| 11. Review computer generated image fusion, target and OAR volumes as well as automatic matching for individual patients. |

1. As pointed out in previous sections of this report, many imaging modalities beyond CT for planning and CBCT for treatment verification are making their way into radiotherapy clinics. The rapid advances of automation and the use of AI add to the complexity of the task (Boldrini, 2024). For many of these applications it is too early to perform a retrospective risk analysis based on past incidents and near misses, however, an additional point was added to Table 11.1 to acknowledge this development. Ensuring adequate training and education for staff utilising these new technologies is imperative to mitigate errors and near misses. A prime example lies in the incorporation of AI-based auto-contouring tools into commercial planning software, which presents a significant advancement for time and resource management within treatment planning workflows. Nonetheless, these tools are not infallible and may yield inaccurate segmentations, particularly in regions of low contrast. Therefore, a meticulous review of auto-segmentation results should be deemed an essential step prior to initiating the treatment planning process.

# EDUCATION AND ONGOING TRAINING OF RADIOTHERAPY STAFF

1. **Key points in this section:**

Specific training for medical physicists and RTTs in appropriate use of imaging and techniques for optimisation of imaging including dose audits is essential. The awareness of radiation oncologists about imaging dose should also be raised.

Knowledge about imaging technology and techniques as well as the dose delivered in these procedures should be included in the syllabus for teaching for all radiation oncology professionals. An expansion of relevant curricula and practices is likely to be required.

Given the rapid development, inclusion of imaging topics into continuing professional development (CPD) is essential.

Equipment vendors should provide proper training before a new imaging system is put into clinical use, to ensure staff fully understand the appropriate use and operation of the equipment, and the implications for dose and image quality of the setting used.

Employers have responsibility to provide sufficient time for future users of imaging equipment to be trained in appropriate use and techniques for optimisation of radiological protection relating to imaging.

Training of radiotherapy staff should include techniques for optimisation of radiological protection for paediatric and pregnant patients.

A medical physicist with training in diagnostic radiology dosimetry and optimisation techniques, should be available in every facility to perform imaging dosimetry measurements, assist in patient dose audits and advise on optimisation.

## Importance of education and training in radiotherapy

1. Radiotherapy process involves various groups of professionals: physicians of different specialities referring patient for radiotherapy, radiation oncologists, therapy radiographers / radiation technologists (RTTs), medical physicists, dosimetrists, radiation oncology nurses, biomedical engineers, IT specialists, hospital management, administrative and other support staff. Qualification and professional competence of these professionals, commensurate with their roles and responsibilities, underpin quality and safety of patient care (ICRP, 1996, 2000c, 2007c, 2009b).
2. The core radiotherapy team, whose competence, behaviour, and inter-professional relationships have a strong impact on the radiation exposure of patients, include radiation oncologists, RTTs and medical physicists. Other professionals with an important role are maintenance engineers, as well as dosimetrists and oncology nurses. The required competences in radiological protection, especially related to the use of imaging devices, will depend on the level of involvement of professionals with radiation.
3. Education and training for the core radiotherapy team members to acquire competence in radiation protection is normally complemented by formal examination systems to test competency before the person is awarded certification. Records should be kept of training provided. The certificate is obtained before a professional is involved in practising the specialty at a specific centre. Certification in radiological protection would be limited in time, and renewal require staff to participate in periodic refresher activities and continuing professional development programmes. Accreditation of organisations that provide formal courses is a prerequisite for ensuring quality of training.
4. Deficiencies in staff training and expertise, along with poor infrastructure, insufficient QA, and absence of overall supervision, have been recognised to be the major factors contributing to accidental exposures in radiotherapy (ICRP, 2000c, 2009b; Weintraub, 2021). Errors due to lack of training can happen at any stage of the radiotherapy process, including use of imaging devices (ICRP, 2000c):

* Insufficient knowledge on the part of the maintenance engineer and deficiencies in training and expertise in diagnosing the cause of equipment faults.
* Erroneous calibration of radiotherapy beams and brachytherapy sources caused by inadequate education and training of medical physicists.
* Insufficient training or inadequate understanding of some aspects of the computerised treatment planning system.
* Lack of proper training of personnel handling sources and applicators.
* Insufficient training of RTTs in patient positioning, simulation and treatment delivery.
* Untrained staff working without supervision and proper procedures.
* Lack of training on identification and response to an abnormal situation or an incident.
* Ignorance by management of the need to reassess staff, resources and training when a new technology is introduced.
* Poor communication between staff members, often linked to the lack of training on communication skills.
* Lack of culture of reporting and learning from errors.

1. There is a generally lack of training for radiotherapy physicists and RTTs in techniques for optimisation of imaging and more particularly methods of dose audit and application of DRLRTs. As a result, staff do not have the same level of awareness of when patient doses from imaging might be high, and so the level of optimisation, particularly for imaging during treatment may be far below that in diagnostic radiology departments. Training of staff in appropriate use of imaging and techniques for optimisation of imaging including imaging dose audit need to be expanded.
2. *Publication 112* recommends that when embarking on or operating a radiation therapy programme, governments should make provisions for a system of education and training of staff (ICRP, 2009b). Hospital managers are responsible for putting in place a quality management system that addresses education, training, continuous professional development, assessment of the required number and qualification of staff, appropriate assignment of duties and responsibilities of qualified staff, a clear organisational structure, written procedures, and supervision of compliance.
3. Equipment vendors have responsibility for providing appropriate training before a new system is being introduced into clinical use. Major safety issues in the introduction of new technologies include the danger of underestimating the staff resources required, and replacing proper training with a short briefing or demonstration from which important safety implications of new techniques cannot be fully appreciated. (ICRP, 2009b). This replacement of proper training applies especially to imaging components of the equipment for which the risks are perceived as being far lower and so of less importance than the therapeutic radiation delivery. This omission has led to failure in many centres to address issues relating to optimisation of imaging.
4. The statement for conventional radiation therapy from *Publication 86* (ICRP, 2000c), reinforced in the *Publication 112* (ICRP, 2009b) for introducing new radiotherapy technologies and techniques, is still highly applicable for technologies using imaging in radiotherapy: ‘purchasing new equipment without a concomitant effort in education and training and on a programme of QA is dangerous’.

## Competence-based training

1. Radiation oncology has for many years relied on proper imaging used for diagnostic, planning, verification, monitoring treatment results, and patient follow-up, which defines the need for inclusion of imaging topics in the curricula for education and training of radiotherapy professionals. However, the “classic” radiotherapy in the past used images for planning purposes acquired by dedicated imaging technologists, and simple portal imaging used occasionally for verification of positioning. Hence, the knowledge related to imaging of radiotherapy technologists and radiation oncologists was limited to modalities used for these purposes.
2. The rapid introduction of real time imaging for improving accuracy and precision of radiation delivery, raises new challenges to education and training of the radiation oncology team and their inter-professional dependencies (Jaffray et al., 2013; ESTRO, 2019; ACR-ASTRO, 2019). *Publication 112* recognises training as a key safety strategy when introducing complex new technologies, and recommends revisiting training at three levels: ‘(1) generic training on the in-depth understanding of the science involved in the new technology at both clinical and physical levels, (2) specific training in the equipment and techniques to be used, and (3) ‘hands-on’ training to obtain the necessary competence before being allowed to use the new techniques in the clinical environment.’ (ICRP, 2009b)
3. Education and training should be consistent with the roles and responsibilities assigned to each group of professionals, and the competence of the radiotherapy team sufficient for practicing justified and optimised use of the imaging techniques. This is guaranteed by including in curricula of academic education and clinical training programmes sufficient knowledge, skills and competences related to image formation, image interpretation, patient doses and their assessment, associated risks, and QC procedures.
4. Radiation oncologists, RTTs, and medical physicists who have not received sufficient training with respect to pre-planning imaging systems, such as CT, PET/CT, MRI, or for the imaging modalities used during therapy delivery, need to obtain such training prior to performing any new procedures involving these modalities (IAEA, 2018; ACR-ASTRO, 2019). This training would include theory of imaging operation, the application interface, the concepts of image guidance, the decision-making process, and the clinical process of the use of imaging in radiotherapy (Jaffray et al., 2013). In addition, it should include methods of dose assessment, patient dose audit, and optimisation of radiological protection for imaging.
5. Modern radiation therapy education comprises the classic didactive instructions, coupled with training in the clinical environment to acquire practical skills and patient communication skills. In recent years, there has been growing interest in the application of virtual environments and simulation techniques for teaching on imaging use in radiotherapy, especially during therapy delivery. The integration of imaging theory with hands-on practice training using simulation improve analytical skills and confident practice so trainees are better prepared for clinical environments. (Chamunyonga et al., 2018, 2021; Wijeysingha et al., 2021).
6. It is important that the education and training programmes for health professionals at all levels integrate approaches for developing knowledge, skills and competences in applying ethical values in the radiotherapy practice and communication with patients (ICRP, 2023). Team teaching or interprofessional learning approaches should be considered (Ball et al 2021).
7. The following section describes the competencies that need to be acquired by the core radiotherapy professional groups prior to clinical initiation of IGRT, in terms of learning outcomes from the theoretical education and practical training. Hospital management should understand the need of education investment in the multi-professional team responsible for IGRT activities, including development of inter-disciplinary communication skills, a culture of teamwork and ethics.

### Radiation oncologists

Table 12.1. Minimum knowledge and practical training on IGRT for radiation oncologists

|  |  |
| --- | --- |
| Knowledge | Practical training |
| * X ray and other imaging modalities and procedures. * Image quality parameters (e.g. signal to noise and spatial resolution). * Image handling, including contrast enhancement and image matching. * Common artefacts in CT and CBCT (e.g. motion, metal artefacts and ring artefacts). * Radiation dose delivered in diagnostic procedures, quantities, spatial distribution of the dose in the patient. * Clinical relevance of the dose from imaging. * Methods of dose evaluation in imaging. * Risk of second primary cancer induction from the dose associated with the use of imaging. * General cross-sectional CT anatomy. * Organ motion as relevant to radiotherapy treatment. * Prescribing, recording, and reporting photon beam therapy, including the ITV concept. * Concept of justification when prescribing the frequency and type of imaging during treatment delivery. * Random and systematic geometric variations in radiotherapy treatment and their impact on CTV to PTV margins. * Uncertainties and limitations of IGRT. * Impact of changes in patient anatomy on the dose delivered to targets and OARs. * Clinical impact of random or systematic target/organ at risk misalignment. * Dose–volume effects on OARs. * Techniques for optimisation of radiological protection for paediatric imaging * Automatic contouring and segmentation including methods based on artificial intelligence (AI) | * Image registration and review. * Fiducial marker placement. * Motion management * Automatic segmentation (where available) * Participate in adaptive radiotherapy workflow (where available) |

1. The radiation oncologist is responsible for overall management of disease-specific treatment regimen, including assessing, recording and evaluating patient outcomes following the implementation of imaging during treatment delivery. They are responsible for justification and appropriate use of imaging and participate in optimisation of imaging techniques. Table 12.1 describes the minimum necessary knowledge and practical training of radiation oncologists to meet these objectives (IAEA, 2019; ACR-ASTRO, 2019; ESTRO, 2019).

### Therapy radiographers / radiation technologists (RTTs)

1. RTTs are professionals who are responsible for the implementation of the treatment plan and the treatment delivery. Table 12.2 describes the minimum necessary knowledge and practical training of RTTs related to the use of imaging in radiotherapy (IAEA, 2019; ACR-ASTRO, 2019, Coffey et al, 2018).
2. Despite their central role in the radiotherapy process, education and training of RTTs varies considerably in terms of their level, duration, programme type, pre-clinical and clinical training, with a serious impact on the ability of graduates to work independently (McNulty et al., 2021; Foley et al., 2021).

### Medical physicists

1. Radiotherapy medical physicists play a key role in equipment specification, commissioning, calibration, and in defining QC programme of all modalities used in radiotherapy, including imaging devices (IAEA, 2014, 2018). Table 12.3 lists the knowledge and practical skills required for imaging prior to and during therapy and includes skills relating to the practical assessment and evaluation of CBCT and other imaging devices on Linacs (Eriksen et al., 2011; ACR-AAPM, 2019; IAEA, 2019).

Table 12.2. Minimum knowledge and practical training on imaging in radiotherapy for RTTs

|  |  |
| --- | --- |
| Knowledge | Practical training |
| * X ray and other imaging modalities and procedures. * Parameters affecting image quality for different imaging modalities. * QC of image quality, including geometric accuracy and imaging dose. * Image registration methods, including registration algorithm functionality. * Image processing tools and their impact on image appearance * Image handling, including contrast enhancement and image matching. * Common artefacts in CT and CBCT (e.g. motion, metal artefacts and ring artefacts). * Radiation doses delivered in diagnostic procedures and dose quantities used. * Parameters affecting dose quantities. * General awareness of relationships between dose quantities and organ and tissue doses * Optimisation strategies for different imaging modalities * Relevant anatomy in relation to the treatment sites covered. * Motion management strategies. * Techniques for optimisation of radiological protection for paediatric imaging * Changes in IGRT in response to abnormal conditions or events * Basics of automatic registration and its advantages and limitations * Basics of adaptive radiotherapy and associated workflows | * Compare the different imaging modalities and the rationale for their selection. * Implement the IGRT treatment plan under the supervision of the radiation oncologist and the qualified medical physicist. * Assess the most appropriate image format and implement this in the context of virtual simulation. * Select and implement the optimal imaging protocol and perform optimal in-room image acquisition. * Perform optimal image registration. * Compare and contrast bony anatomy and soft tissue matching. * Evaluate the images, make corrections in accordance with protocol, record any corrections. * Perform daily QC procedures. * Understanding dose displays of imaging modalities * Participate in surveys of patient doses * Participate in adaptive radiotherapy workflow (where available) |

Table 12.3. Knowledge and practical training on image guidance for radiation oncology medical physicists

|  |  |
| --- | --- |
| Knowledge | Practical training |
| * Image formation in different modalities (CT, MRI, PET, US) * Image quality parameters (e.g. modulation transfer function, signal to noise and spatial resolution) and the tools to assess them. * Image registration methods, including registration algorithm functionality. * Image processing tools and their impact on image appearance * Image handling, including image registration, contrast enhancement and image fusion. * Common artefacts in CT and CBCT (e.g. motion, metal artefacts and ring artefacts). * Radiation dose delivered in diagnostic procedures, dose metrics (e.g. CTDI, DLP) and the tools required to assess the dose. * Parameters affecting dose quantities. * Application of the concept of DRLRTs * Optimisation strategies for different imaging modalities * Cross-sectional anatomy of common radiotherapy treatment sites. * Organ motion as relevant to radiotherapy treatment. * Methods for motion management * Random and systematic geometric variations in radiotherapy treatment and their impact on CTV to PTV margins. * QC of image quality, including geometric accuracy and imaging dose. * Commissioning and acceptance of diagnostic imaging equipment, including CT and CBCT. * Image formats, including DICOM. * Automatic contouring / segmentation including AI based methods. * Adaptive radiotherapy and associated workflows. * Data handling. | * Operation of the imaging equipment planned for IGRT. * Handling images, including annotation, transfer and archiving. * Performance testing of imaging equipment. * Design of programmes for QC on imaging equipment * Methods for measuring dose quantities for CT and how these can be adapted for measurements on CBCT systems. * Assessing and interpreting the radiation dose from imaging modalities * Methods for motion management * Methodologies for accessing imaging dose information from DICOM, PACS, and other information systems. * Methods for organising surveys of DRLRT quantities and carrying out patient dose audits. * Methods for analysing results from patient dose surveys and interpreting requirements for optimisation using results from performance tests. * Optimisation of image acquisition protocols. * Automatic segmentation (where available). * Participate in adaptive radiotherapy workflow (where available). |

* 1. **Knowledge, skills and competences**

1. As outlined in section 12.2, each of professional group needs a specific set of knowledge, with the practical skills and competencies (KSCs) to ensure participation in the optimisation process. Competencies define the application of the knowledge, skills, and behaviours in the setting of daily practice.
2. The education and training in optimisation for imaging in radiotherapy should be based on Bloom’s taxonomy of learning. Learning takes place at an increasing level of complexity from the simple recall of facts to the process of analysis and evaluation (Fig. 12.1). This was first described by Benjamin Bloom, an American educationalist (Bloom and Krathwohl, 1956) and has since been revised to reflect more recent approaches to teaching, learning, and evaluation (Anderson and Krathwohl, 2001). The taxonomy classifies levels of learning based on the premise that an individual cannot apply or evaluate something until they understand it. Therefore, learning at the higher level is dependent on the individual having acquired the prerequisite knowledge and skills at lower levels. This is the basis for qualifications frameworks for lifelong learning worldwide (EPC, 2008; UNESCO, 2018).

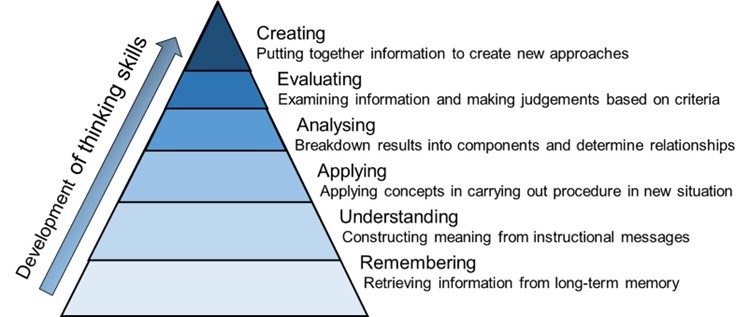


Fig. 12.1. The forms and levels of learning identified in Bloom’s Taxonomy, with brief description of the processes to which they might apply in the context of optimisation. Reproduced from *Publication 154* (ICRP, 2023).

1. This format should enable the educator to define student learning outcomes based on the knowledge, skills and competences that are necessary for radiotherapy professionals to apply to optimisation at various levels in the clinical setting. The key knowledge and the skills and competencies for which practical training is required are set out in tables 12.1, 12.2 and 12.3 for the different professional groups, many of which overlap. These should be considered in the development of training modules on optimisation of radiological protection for imaging.

## Development of inter-professional communication and team culture

1. Within the multi-disciplinary team, it is the role of the medical physicist to ensure that imaging equipment in the radiotherapy process is used appropriately, effectively and safely (Eriksen et al., 2011). Medical physicists qualified in radiotherapy are often not trained in imaging modalities, image quality, dose quantities and optimisation approaches. Hence, either access to a medical physicist specialising in diagnostic radiology is required (e.g. from a radiology department) or the medical physicist specialising in radiotherapy needs to receive adequate education and training in medical imaging physics (IAEA, 2019). Since the optimisation of imaging protocols requires knowledge of both image quality and dose performance, the experience to be able to organise and undertake surveys of patient doses is an important component. A medical physicist with appropriate training in diagnostic radiology should be available in every facility to perform dose measurements, assist in patient dose audit, and advise on optimisation of techniques.
2. It is increasingly important to have a computer literate member of the radiotherapy team who is able to understand networks and has basic scripting skills. In most departments medical physicists play this role and appropriate training opportunities must be provided.
3. The implementation of the imaging technology affects the entire radiotherapy process, and because of its nature, use of imaging prior and during therapy delivery involves every member of the multi-professional radiotherapy team. The safe and effective application of imaging technologies requires a high level of inter-professional communication and coordinated effort by many individuals with varied responsibilities (White and Kane, 2007; Gillan et al., 2010).
4. In the education context, integration of imaging technologies is facilitated through multi-professional learning, especially important for the continuing medical education (CME). (Jaffray et al., 2013). Formation of an imaging team comprising a radiation oncologist, radiation technologist and a medical physicist, similar to the approach in diagnostic radiology (ICRP, 2023), has advantages in identifying individuals with responsibility to ensure that all aspects of imaging are optimised, with imaging protocols that are reviewed and updated continually based on experience gained and results from dose audits. Simultaneous training of radiation oncologists, medical physicists and RTTs on imaging integration and practical implementation enable the team members to understand each other's roles within the process, build trust and respect, and improve communication skills, in addition to professional competencies.
5. Investment made by hospital management in continuous education and training of radiotherapy staff would greatly support the optimal and safe use of imaging technology. Attendance of radiotherapy teams in scientific forums such as congresses and workshops help maintain and upgrade competence by learning from the international peers and equipment vendors about new developments and clinical applications. Multi-disciplinary sessions and discussion forums are central to strengthening inter-professional communication.
6. The hospital leadership has a key role in creating a culture of safety and empowering all staff to actively participate in improving clinical processes through free reporting of errors and learning initiatives (ASTRO, 2019). In the radiotherapy team, the radiation oncologist is the team leader for patient safety, who coordinates with the team and the hospital management. Voluntary incident reporting systems, either local, or international, such as SAFRON of the IAEA, ROSEIS of ESTRO, RO-ILS of ASTRO and other similar, facilitate sharing learning and contributing safety and quality. Good practice is to organise multidisciplinary sessions in every radiotherapy department, with a focus on analyses of errors, near misses and incidents (see section 11).
7. Safety culture can be improved through learning to recognise and strengthen important traits that contribute to a strong safety culture, such as individual responsibility, questioning attitude, effective safety communication, clearly identified leadership responsibility, effective decision-making, respectful work environment, continuous learning, problem identification and resolution, environment for raising concerns, and work processes. The IAEA handbook on Radiation Safety: Trait Talks, provides scenarios for practical training on safety culture traits (IAEA, 2021a).
8. Modern radiotherapy heavily depends on the technology, and hence, the collaboration between hospital users and equipment vendors underpins safety and optimal use of technologies. Vendors need to provide comprehensive training on the capabilities and limitation of their products and provide an application training at the introduction of new technology. On the other hand, feedback from users on equipment faults and application problems, help vendors make assessment and improve technology.

# RECOMMENDATIONS TO IMPROVE RADIOLOGICAL PROTECTION FOR IMAGING IN RADIOTHERAPY

1. Actions are required by radiotherapy department staff and managers to optimise radiological protection of patients for imaging procedures in radiotherapy. However, there are a number of recommendations discussed in this report that are difficult if not impossible unless there are developments in imaging equipment, particularly in respect to the documentation of imaging doses. Therefore, equipment vendors will perform essential roles in any improvements and regulators will perform a key role in promoting radiological protection. In this final section recommendations are set out relating to the different groups involved.

## Health professionals involved in radiotherapy processes

1. Justification and optimisation of imaging should be a recognised part of radiotherapy processes considering the treatment objective and written explicitly into practices (including the choice of the imaging modality, and definition of the imaging frequency and quality).
2. Optimisation of image quality and dose should be a part of the purchasing, acceptance, commissioning and quality assurance process for all imaging equipment that uses ionising radiation in radiotherapy.
3. Imaging optimisation teams comprising radiation oncologists, RTTs, and medical physicists should be established in each radiotherapy facility to review imaging protocols at regular intervals.
4. Resources should be allocated in a radiotherapy department for image dose assessment and optimisation of radiological protection for imaging.
5. Radiotherapy centres should employ or have access to a suitably qualified medical physicist with diagnostic imaging specialisation who should assist in review of imaging protocols and optimisation of radiological protection aspects and be involved in patient dose audit and QA activities.
6. Wherever possible dose records should be included in the DICOM information of medical images, in particular all CT data sets.
7. Imaging dose, volume and frequency for image guidance should be reviewed and documented for all radiotherapy protocols.
8. The justification of imaging dose, volume and frequency should be documented for each individual patient by the radiological medical practitioner involved in the patient’s care.
9. Radiotherapy centres involved in radiotherapy of children should develop specific protocols for paediatric imaging.
10. Guidelines should be developed for the use of repeat imaging for example after patients have been moved.
11. There should be a move towards the inclusion of doses from MV imaging explicitly into treatment plans. Doses from kV imaging used as part of the radiotherapy treatment process should be considered in protocols and reported.
12. Consideration should be given to the development of guidance about when the dose from imaging procedures should be included in treatment plans.
13. A QA program should be in place for all imaging equipment used in radiotherapy. If the imaging involves ionising radiation the QA activities should include a dose measurement confirming the accuracy of displayed values and a quality check after any relevant technology change and at least on an annual basis.
14. Systems for periodic audit of patient imaging doses should be established under the guidance of qualified medical physicists. In the short to medium term this may be accomplished through measurement of the CBDI described in this publication.
15. Results from dose surveys should be taken into consideration, when optimising imaging protocols and lead to the establishment of dose reference levels (DRLRTs).
16. The image optimisation team should develop a system for capture of the reasons for repeat imaging so that reject analysis audits can be performed. Corrective actions identified in these audits and follow-up audits should be implemented to reduce the number of repeat images, and hence optimise patient doses.
17. Curricula and syllabi for training and education of radiotherapy professionals should include knowledge and skills in diagnostic imaging, including techniques for optimisation of radiological protection. Special training of staff should be provided in respect of paediatric imaging where applicable.

## Equipment vendors and software developers

1. Vendors should include displays of measurable dose quantities (e.g. CTDIw,IEC) linked to the exposure factors used for all imaging systems. These should be in terms of quantities that can be linked to dose measurements, the accuracy of which can be confirmed through verification. Records of dose quantities should be included in the DICOM information of medical images. In the longer term, consideration should be given to display of a dose quantity, such as the CBDI described in this publication for use in patient dose surveys.
2. Specifications for equipment provided for tender and purchasing considerations should include information about doses delivered in imaging procedures and possibilities for optimisation of radiological protection.
3. Factory settings and imaging protocols supplied by vendors should include consideration of optimisation of radiological protection. Vendors should provide users with imaging protocols optimised for paediatric radiotherapy.
4. Features to facilitate optimisation of radiological protection for imaging procedures performed on individual patients through adjustment of parameters such as exposure factors, and field sizes should be included in all therapy imaging equipment, together with the ability for radiotherapy centres to create local protocols to meet their clinical needs.
5. There should be facilities to enable the exposure arcs in CBCT to be limited to protect radiosensitive organs.
6. Vendors should provide treatment planning systems with the possibility of calculating dose distributions from kV imaging.
7. Vendors should include automatic tools to optimise radiation dose to patients being imaged on CBCT devices. Such a tool might take the form of an automatic exposure control.
8. Vendors should provide training for staff in use of imaging equipment that includes methods and techniques for optimisation of radiological protection.

## Regulators and professional bodies

1. Regulators should link authorisation of imaging equipment in radiotherapy to requirements modelled on diagnostic imaging.
2. Regulatory agencies and/or professional organisations should consider developing national DRLRTs for imaging in radiotherapy to promote optimisation of radiological protection. The uptake of DRLRTs in radiotherapy should be encouraged at a minimum for imaging used for treatment planning purposes but would also have benefits for treatment imaging in particular if CBCT is used.
3. Regulators should provide requirements on education, training and competences in imaging for professionals involved in radiotherapy.
4. Professional bodies should provide certification and accreditation in imaging for professionals involved in radiotherapy and encourage a strong safety culture.

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1. IMAGING TECHNIQUES USED IN RADIATION THERAPY
   * + 1. This Annex includes pictorial examples of the uses of imaging in radiation therapy. This includes the identification of target tissues for planning treatments, matching digitally reconstructed radiographs derived from planning CT images with images recorded during treatment and fusion between planning CT and verification images.
   1. Treatment planning
      * 1. Imaging modalities such as MRI and PET provide information on different tissue characteristics from CT. MRI provides better soft tissue contrast than CT (Fig. A.1), but while MRI is widely used for diagnostic imaging, it is a secondary imaging modality in RT due to potential image artefacts, the lack of tissue density information, and a smaller field of view. These issues are recognised within MRI protocols generated for RT planning which usually require high spatial resolution, a larger field of view with 3D volumetric acquisitions and the application of distortion corrections to retain the geometric fidelity required for accurate structure segmentation. MRI is established as the standard technique for contouring of targets in SRS (Stross et al., 2019) and many brachytherapy applications (Pötter et al., 2018). It does not have the risk of inducing second primary cancers associated with ionising radiations.

A close-up of a brain scan

Description automatically generated

Fig. A.1 Example intracranial SRS case. Left: treatment planning CT. Right: stereotactic post contrast T1 MRI. The locations of two metastases are highlighted by the yellow arrows. While both metastases are clearly visible on the stereotactic MRI scan, they are barely visible on the treatment planning CT scan. (Images used with permission from Loyola University Medical Center, Maywood, U.S.A).

* + - 1. Functional imaging can map tumour characteristics such as hypoxia, vascularity, and cellular proliferation, which are known to impact on the outcome of radiation therapy. PET scanners show the distribution of a radiolabelled compound based on its biochemical behaviour (Croteau et al., 2016), in contrast to CT and MR which display morphologic information (ICRP, 2024). The most common radionuclide is [18F] FDG which shows metabolically active tissue. PET and PET-CT modalities are able to identify areas of metabolic activity and are used routinely for the localisation of nodal targets in many sites including head and neck, mediastinum, and pelvis and to locate bone metastases. Fig. A.2 illustrates the use of a 18F FDG PET-CT scan to locate metabolically active targets in a left lung lobe case. Besides its use for locating targets, PET imaging combined with CT helps refine target volumes by highlighting the most metabolic active tumours or areas within a tumour. PET can also be used to monitor tumour response, since metabolic changes precede changes in tumour shape and size (Grégoire et al., 2007).
      2. Research and development on the concept of emission guided radiation therapy (EGRT) has led to the recent design of the first treatment unit that combines PET, CBCT and linac, which will have the capability to guide radiation treatment delivery with radiotracer uptake as a biologic fiducial marker (Fan et al., 2012; Hrinivich et al., 2020).

A close-up of a chest x-ray

Description automatically generated

Fig. A.2 Example of a lung case. Left: treatment planning CT highlighting two RT treatment targets, including ITVs (blue and red contours) and PTVs (light and dark green contours) located in the left lung. Right: image fusion between diagnostic FDG-PET uptake and planning CT. The ITVs are indicated by the red and blue contours, PTV margins highlighted in green. The areas of high metabolic activities in the lung correlate with the delineated ITVs. (Images used with permission from Loyola University Medical Center, Maywood, U.S.A).

* 1. Patient positioning, verification and replanning
     + 1. External beam radiation therapy treatment units are equipped with in-room imaging facilities for guidance of treatments. Digitally reconstructed radiographs (DRRs) generated from the treatment planning CT scan are compared with orthogonal 2D kV radiographic images (Fig. A.3) or with MV portal images (Fig. A.4) acquired prior to treatment delivery to accurately position the patient, and to verify the correct alignment of the treatment fields with respect to the patient anatomy.A close-up of a x-ray

          Description automatically generated

Fig. A.3 Example of 2D alignment for a breast treatment, between digitally reconstructed radiographs (DRRs) generated from the treatment planning CT (top) and orthogonal kV projections acquired with the gantry mounted kV imaging system prior to treatment fraction delivery (bottom). 2D translations are performed by the RTTs at the treatment console sometimes assisted by automated matching software. The corresponding 2D shifts are then automatically applied by the treatment couch for patient set-up correction (Images used with permission from Loyola University Medical Center, Maywood, U.S.A).

A collage of images of a person's body

Description automatically generated

Fig. A.4. Example of MV portal verification with EPID for a breast treatment field. The DRR (left) is compared to the MV portal image (right) acquired with the treatment field to verify the field alignment with the patient anatomy. The yellow contour indicates the projected field boundaries matched by the MLCs on the portal image. (Images used with permission from Loyola University Medical Center, Maywood, U.S.A).

* + - 1. More precise patient alignment can be achieved with the direct 3D comparison of the planning CT with kV or MV CBCT acquired immediately before treatment (Fig. A.5).
      2. Devices that combine MR scanners with 60Co sources or linacs allow online tracking of tumours directly with MRI during delivery of radiation treatments (Corradini et al., 2019). These are particularly useful for gated treatment of abdominal tumours subject to respiratory motion that is invisible to radiological imaging (van Sörnsen de Koste et al., 2018), such as liver metastases and pancreatic tumours. These MR images can be used for replanning in the context of adaptive radiation therapy (MRgART) (Pathmanathan et al., 2018; Christiansen et al., 2022; Romano et al., 2024).

A close-up of a brain scan

Description automatically generated

Fig. A.5. Example of fusion between planning CT and CBCT from 3D alignment performed prior to the delivery of a head and neck radiation treatment. Selected targets treated to different overall doses (GTV, PTV70, PTV63, PTV56) and landmark structures (external body, parotids, mandible and spinal canal) from the original CT image are displayed over the CBCT acquired on the day of treatment for verification of proper patient set-up. (Images used with permission from Loyola University Medical Center, Maywood, U.S.A).

* + - 1. In the case of brachytherapy, the position of applicators and interstitial needles can be verified prior to the initiation of the radiation treatment with a CT scan, or with 2D radiographic images (Fig. A.6).

A close-up of a x-ray of a person's body

Description automatically generated

Fig. A.6. Example of post operative cervical cancer brachytherapy implant verification with 2D radiographic imaging (left) and CT (right). The titanium needles and Syed obturator location are clearly visible on both imaging modalities. The green contour represents the treatment volume. (Images used with permission from Loyola University Medical Center, Maywood, U.S.A).

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1. KV CONE BEAM CT DOSIMETRY
   1. Computed tomography dosimetry
      * 1. The dose descriptor employed for dosimetry on standard CT scanners is the CT dose index (CTDI), which is based on integrating the axial (z-axis) dose profile from a single axial rotation. The accepted tool for measurement is a 100 mm long pencil ionisation chamber (CTDI100). The chamber measures air kerma and the result has to be normalised by the nominal width of the CT beam relative to the 100 mm length. The pencil chamber may be used free in air to assess the output of a CT scanner or within standard cylindrical phantoms made of polymethyl methacrylate (PMMA), 320 mm and 160 mm in diameter, representing the body and head, respectively, and 150 mm in length. The pencil chamber is placed in holes in the phantoms centre and at four positions at 90º intervals around the periphery of each phantom 10 mm below the surface. A weighted value for the CTDI100 measurements made in a phantom (CTDIw) is derived to give an indication of the dose to tissue and takes the form:

(B.1)

* + - 1. where CTDIc is the CTDI100 measurement at the centre of the phantom and CTDIp is the average of the four CTDI100 measurements made at the peripheral positions. A volume averaged value of the CTDIw, referred to as CTDIvol, which is the dose quantity displayed on CT scanners, together with a dose length product (DLP), which is the CTDIw multiplied by the scan length, are used for surveys of patient doses from CT scans. The CTDIvol is equal to CTDIw divided by the pitch of the CT scan, which is determined by the movement of the scanner couch during one rotation of the x-ray tube.
      2. The cone beams used in radiotherapy are wider than both the 100 mm ionisation chamber and the standard 150 mm long phantoms, so the CTDI concept does not provide a realistic reflection of the dose for wider beams (Mori et al 2005; Kyriakou et al 2008; Abuhaimed et al 2014). The CTDI concept to capture all the radiation within a narrow fan beam is only applicable to beam widths of 40 mm (IEC, 2016).
      3. Several different approaches have been proposed to adapt the method (ICRP, 2015). The International Electrotechnical Commission and the International Atomic Agency have developed a method to derive a quantity that equates to the standard CTDI (IEC, 2016; IAEA, 2011) while the American Association of physicists in medicine (AAPM, 2010, 2020) have proposed a method for assessing the cumulative dose from a scan in the centre of a larger phantom. These approaches allow reasonably representative measures of dose that can be related to doses to the tissues of the patient being scanned. However, the methodologies are complex, take significant lengths of time to carry out and require specialist equipment that will not be available in the majority of radiotherapy centres. They will be described briefly here, but the focus of this Annex is to purpose a simpler method that can be performed more readily in radiotherapy centres.
      4. Specific dose quantities and units used to describe radiation exposure in different x-ray imaging applications are set out in Table B.1 for reference. These are indicators in terms of air kerma characterising radiation exposure for the purposes of QC, comparison of practice, and setting DRLRTs as a tool for optimising CBCT protocols. Abbreviations in common use and other terms sometimes used for the same quantities are also included.

Table B.1. Dose quantities and units currently used in imaging for radiotherapy, their recommended notation and other commonly used symbols are included

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Dose quantity | Equation notation (ICRU) | Unit used in practice | Abbreviation and other symbols used | Similar quantities | Field of application |
| Incident air kerma at patient entrance surface | Ka,i | mGy | Ki; IAK | Entrance surface air kerma (+ backscatter) | Radiography, fluoroscopy |
| Air kerma-area product | PKA | mGy·cm2 | KAP | Dose-area product (DAP) | Radiography, fluoroscopy, |
| Computed tomography air kerma index (free in air measurement) | CK | mGy | CTDI, CK | CT dose index (CTDI)\* | CT, CBCT (IAEA, 2007, 2011) |
| Weighted CT air kerma index | Cw | mGy | CTDIw | Weighted CT dose index (CTDIw) | CT |
| Volume CT air kerma index | Cvol | mGy | CTDIvol, Cvol | Volume CT dose index (CTDIvol) | Multi-detector CT |
| Weighted CTDI for wide beams (nT>40 mm) | C | mGy | Cw,nT, CTDIw,nT | CTDIw,IEC | Wide CT beams (>40 mm); CBCT (IEC 2016; IAEA 2011) |
| Air kerma-length product† | PKL | mGy.cm | DLP, PKL | Dose-length product† | CT |
| Weighted CBDI with 100 mm cha., 150 mm pha. (kV) | - | mGy | CBDI100,w D(100,150)w | Cone beam dose index | CBCT (Amer et al., 2007; this publication) |
| Weighted CBDI with 20 mm cha., 150 mm pha. (kV) | - | mGy | CBDI20,w |  | CBCT (This publication) |
| Cumulative dose at midpoint of scan length L. | - | mGy | DL(0) |  | CT, CBCT (AAPM, 2010) |
| Equilibrium air kerma in infinite phantom | - | mGy | Deq | Equilibrium dose | CT, CBCT (AAPM, 2010) |

\* Air kerma and dose in air are equal for practical purpose in diagnostic radiology energy range.

† This quantity is a cumulative dose for a procedure. It is not directly measured, but due to the standardised approach for its calculation, it is commonly displayed on x-ray equipment.

cha. – chamber length, pha. - phantom length, Deq - The equilibrium, or limiting dose at a point in an infinite phantom for an infinite scan.

* 1. Standard dosimetry methods applied to Cone Beam CT
     + 1. The International Electrotechnical Commission (IEC) approach aims to provide a standard wide beam CTDI measurement (CTDIw,IEC), which closely relates to the CTDIvol for narrow beam CT scanners for display on cone beam CT systems. However, display of the wide beam CTDI on clinical linacs has so far been variable, so its use as a dose audit quantity in a similar manner to the use of the CTDIvol and DLP in surveys of patient doses from standard CT scanners, is impractical at the present time. Looking towards the future, all CBCT systems should aim to display the CTDIw,IEC value with automatic adjustment for the exposure factors used.
       2. The recommended practical method for measurement of the CTDIw,IEC for wide beams utilises CTDI100 dosimetry equipment that is available in diagnostic radiology departments and is based on the acquisition of CTDI100 measurements for a reference beam of width ≤40 mm within the standard PMMA CT phantoms. A correction factor equal to the ratio of CTDI100 measurements free in air for the wide beam of interest and the reference beam is applied (IEC, 2016; IAEA, 2011; Platten et al., 2013). The measurements for wider beams are made either with a longer chamber (e.g. 300 mm) or by moving a 100 mm ionisation chamber across the entire beam width in 100 mm steps to cover the required length using the couch movement control and to provide chamber integration lengths that are multiples of 100 mm (i.e. 200 mm, 300 mm, etc). The sum of the dose resulting from these steps is then multiplied by the ionisation chamber length 100 mm and divided by the width of the beam of interest to calculate the CTDI free in air. Measurements at the centre and periphery of the phantom can be combined using equation B.1 to give a weighted value CTDIw,IEC. The efficiency of this approach in accounting for all the scattered radiation occurring during CBCT scans has been shown through Monte Carlo (MC) simulations to be independent of beam width (Fig. B.1) (Abuhaimed et al 2014).

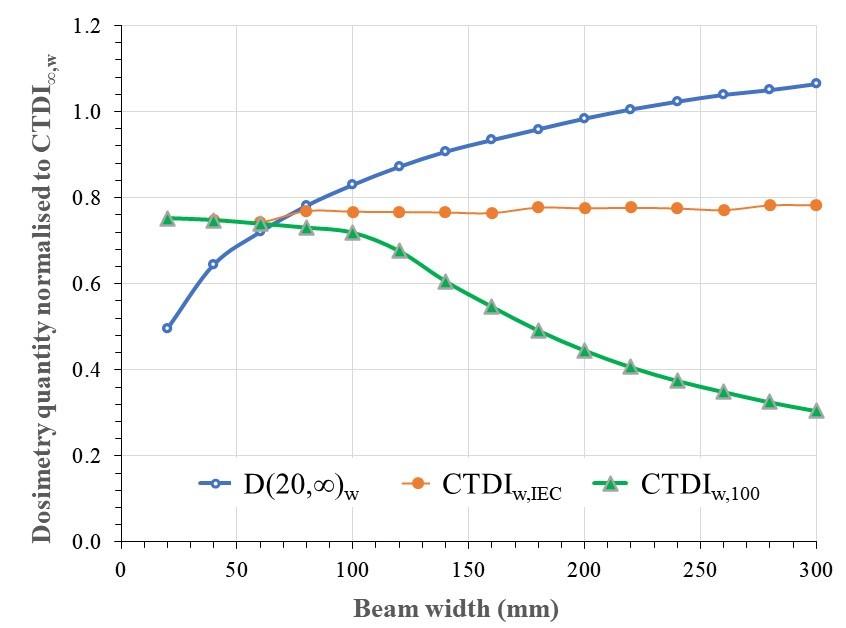


Fig. B.1. A comparison between dose ratios for different laboratory methods proposed for CBCT dosimetry in a 32 mm diameter PMMA body phantom. D(20,∞)w is the weighted dose in the middle of a long (>600 mm) phantom measured with a 20 mm long ionisation chamber. CTDIw-IEC and CTDIw,100 are measurements of the weighted CTDI with a 100 mm chamber in a 150 mm phantom using the IEC method described and the standard measurement method. The dose values are normalised to CTDI∞,w values measured in an infinitely long phantom. Plots by courtesy of Abdullah Abuhaimed, KACST, Riyadh, Saudi Arabia).

* + - 1. Since the wide beam CTDI is independent of beam width, incorporation of displays of the wide beam CTDI into CBCT systems should enable the calibration of CBCT dose levels (IEC, 2016). Methods for calibration are described in IAEA (2011).
      2. The American Association of Physicists in Medicine (AAPM) approach (Dixon, 2003) uses a measurement of the dose with a small chamber at the centre of a large phantom to assess the magnitudes of doses to tissues. The CTDI method underestimates the dose to tissues in the centre of a scan, as scattered radiation is lost from the ends of the short phantom. To address this deficiency, the phantom should be long enough to provide a ‘full scatter’ equilibrium condition, i.e. further extension of the length of the phantom will have a negligible effect on the measurement. The “equilibrium dose” [Deq], representing the upper limit to the scatter contribution is measured with a small ionisation chamber within a long phantom (e.g. 600 mm) made of PMMA, water, or polyethylene (AAPM 2010; ICRU, 2012; AAPM, 2020). Measurements at the centre and periphery of the phantom can again be combined to provide a weighted value (Deq,w). This dose measurement is represented by D(20,∞)w measured with a 20 mm chamber in the middle of the phantom in Fig. B.1. Even with a 300 mm wide beam further incremental increases in beam width will contribute to Deq,w and for wider beams D(20,∞)w exceeds CTDI∞,w measured over a 100 mm length so the ratio exceeds 1.0.
      3. The two methodologies described here provide methods that can be used as laboratory standards to provide different measurements relating to dose performance. Fig. B.1 shows how they vary with the width of the cone beam. However, although they can be performed in principle in radiotherapy centres, many radiotherapy centres do not have the equipment or the staff time available to undertake them. Therefore, a simpler approach is described here to provide a dose quantity for use in surveys of patient doses until all CBCT equipment displays the wide beam CTDI value. Any survey aiming to obtain results from a large number of centres will require a method that is easy to follow, as a dose survey needs comparisons of performance across as many systems as possible in order to be successful. Simplicity is important as imaging patient dose surveys are new to radiotherapy treatment.
  1. Practical methods for measurement of CBCT patient doses for surveys
     1. Cone beam dose index with cylindrical phantom and 100 mm chamber
        1. The purpose of the approach that is described here is to enable surveys of patient doses to be conducted at the present time. In the future, all CBCT systems should aim to display CTDIw,IEC values adjusted for exposure factors that can be used directly for such surveys. Amer et al (2007) suggested replacing the CTDI100 concept for CBCT scans with an approach called a cone beam dose index (CBDI), in which the cone beam covers the whole CT phantom. This involves measurement of the cumulative dose for a CBCT scan with a 100 mm pencil ionisation chamber within the standard PMMA CT phantoms (section B.1). However, unlike measurements for the CTDI on standard CT scanners, where the x-ray beam only irradiates a narrow section, the CBDI measurement requires the 150 mm long phantom to lie entirely within the cone beam (Fig. B.2). Dose measurements are made at the centre and periphery of the phantom and combined to give a weighted value using equation (A1), as for the standard CTDIw. This approach has since been applied in clinical practice (Sykes et al., 2013; Abuhaimed et al., 2015; Buckley et al., 2018) and since it utilises equipment that is more readily available, it has been adopted here as a measurement that can be used in the radiotherapy centres.

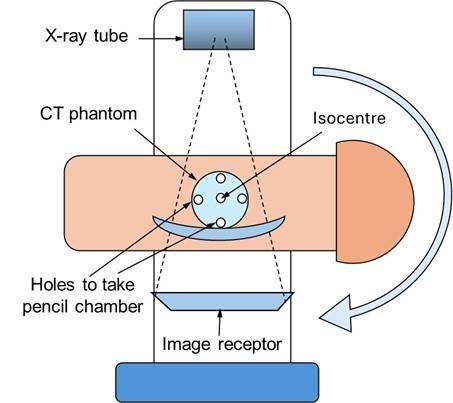


Fig. B.2. Arrangement for measurements of cone beam doses with a 100 mm pencil chamber at central and peripheral positions within a cylindrical CT phantom.

* + - 1. The aim is to obtain measurements of doses for single rotations of the x-ray source with chambers at the centre and periphery of standard CT phantoms, 160 and 320 mm in diameter, and 150 mm in length representing the head and body, respectively. This approach resembles the standard method for dose measurement in CT, but with the wide beam from CBCT covering the whole phantom. The measurement would represent a cumulative dose with the same exposure parameters used for patient imaging and the widest beam used in clinical practice, and long enough to cover the full 150 mm longitudinal dimension of the phantom.
      2. The preferred method would be to use a 100 mm pencil chamber and to perform measurements at the centre and four peripheral positions around the phantom circumference, combined to give a weighted CBDI (CBDI100,w) or with the alternative symbolformat [D(100,150)w] (Fig. B.3a and 3b). However, if a 100 mm chamber was not available, a smaller 0.6 cc Farmer chamber, as suggested in AAPM (2010) or similar could be used to give a dose essentially in the middle section of the phantom (CBDI20,w) and a correction factor applied for making comparisons (Fig. B.3c). The reason for using different chambers at this stage is that access to 100 mm chambers is limited in the majority of radiotherapy centres. However, the use of a 0.6 cc chamber would be a viable alternative as these are reference ionisation chambers for absolute dosimetry of megavoltage therapy beams (IAEA, 2000; Almond et al., 1999) and should be available in all radiotherapy centres. It should be noted that a calibration adjustment factor will need to be applied if an appropriate calibration factor for x-ray imaging beam qualities is not available.

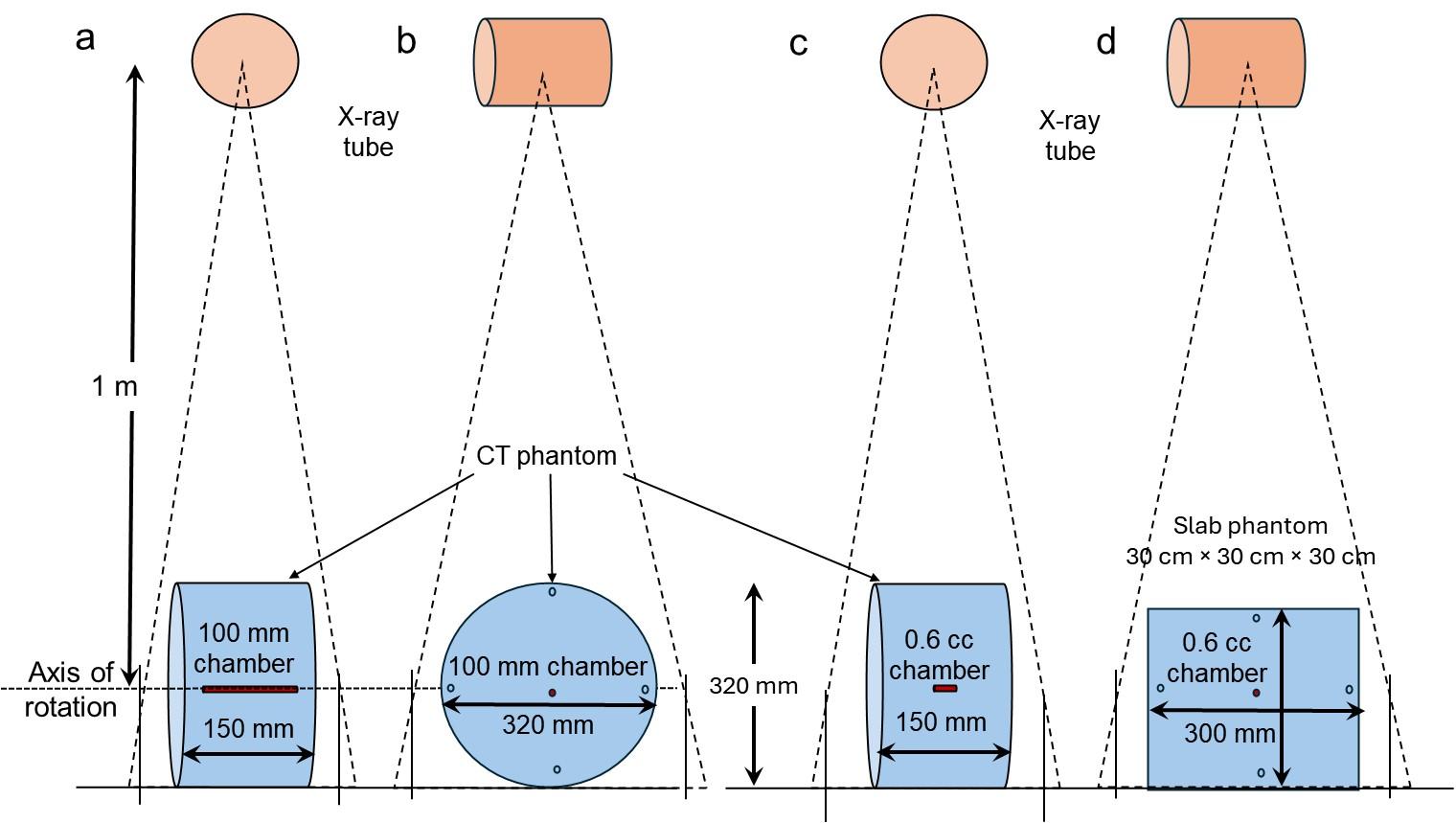


Fig. B.3. Arrangements for measurement of cone beam CT dose: in a cylindrical CT phantom with a 100 mm chamber a) viewed perpendicular and b) parallel to the scan axis, c) with a 0.6 cc chamber in a cylindrical phantom viewed perpendicular to the scan axis, and d) with a 0.6 cc chamber in a slab phantom viewed parallel to the scan axis.

* + - 1. The dose measured at the centre of the phantom and the average of the four doses at the periphery would be combined into a weighted value using equation B1 with the accepted 2:1 weighting. The variation in these measurements with the width of the cone beam derived from Monte Carlo simulation are shown in Fig. B.4. The dose measurement would be normalised by dividing by the exposure (mAs) to provide a mGy mAs-1 coefficient. Measurements of this type would be required for each kV/filter combination used for clinical scans. The normalised values could then be used to derive values for the cone beam dose index (CBDI) for all scans using the same kV and filter combination simply by multiplying by the mAs. This enables a measurement relating to the patient dose to be obtained that can be used to compare doses from different protocols and dose levels used for CBCT imaging in different radiotherapy centres for similar procedures. It is through recording of such values in surveys of different radiotherapy centres that Dose reference Levels (DRLRTs) can be established to commence the process of continual review and optimisation of imaging.
      2. Because the x-ray beam will be larger than the phantom, the efficiency of the technique in terms of making a measure of dose to tissues in the body will only be 40 %-50 % (Abuhaimed et al, 2015). But the fact that this is not an absolute measure of dose to a patient does not matter at this stage, as the measurements are design primarily for comparing the performance of CBCT protocols. They capture a simple measure related to the level of dose to the patient, and the effect of kV and filtration. Placing more constraints on measurement of the dose quantity to make a measure more meaningful in terms of dose to the patient would increase the difficulty of the measurement and inevitably reduce the number of centres able to take part. Factors linking the measured dose quantity to doses that are more meaningful in terms of doses to tissues will be developed subsequently.

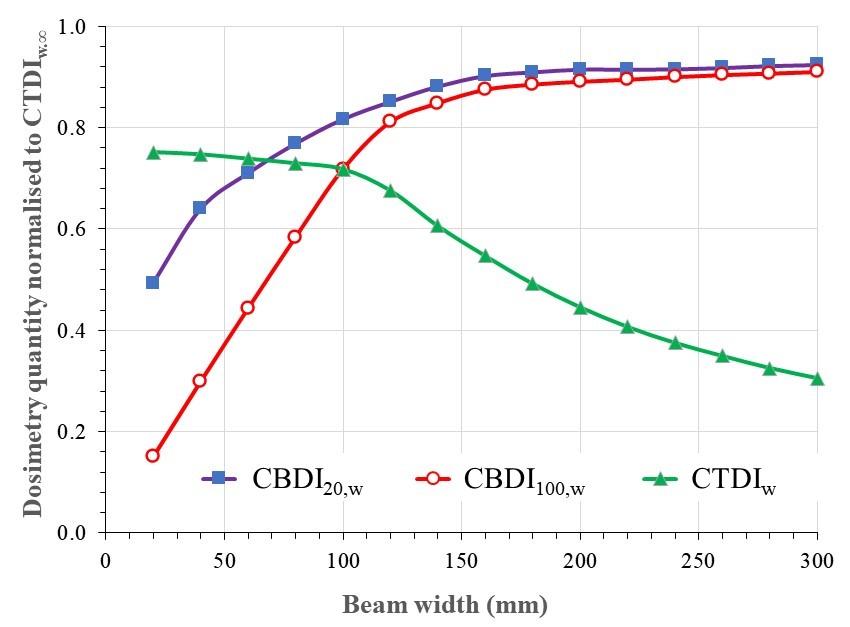


Fig. B.4. A comparison between dose ratios for different practical methods proposed for CBCT dosimetry in a 32 mm diameter body phantom. CBDI20,w and CBDI100,w are the weighted doses in the middle of a standard 150 mm long phantom from measurements with a small (e.g. 0.6 cc, 20 mm) chamber and a 100 mm chamber. CBDI100,w being the quantity that is proposed as a cone beam CT index (CBDI). CTDIw is a measurement using CTDI methodology in a 150 mm phantom that is divided by the beam width and so declines beyond 100 mm. The dose values are normalised to CTDIw values measured in an infinitely long phantom (CTDI∞,w). (Plots by courtesy of Abdullah Abuhaimed, KACST, Riyadh, Saudi Arabia).

* + 1. Approach where CT dosimetry equipment is not available
       1. Radiotherapy centres in many parts of the world do not at the present time have access to100 mm pencil chambers or standard PMMA CT phantoms (Djukelic et al., 2025, 2026), so an alternative arrangement to replicate these measurements approximately with equipment available in radiotherapy departments is also described below. It is hoped that this arrangement will enable a more equitable and inclusive approach to the task of evaluating doses to patient from imaging. The alternative setup uses a 0.6 cc Farmer type ionisation chamber and a 30 × 30 × 30 cm cube phantom comprised of slabs of solid water or similar material taped together to enable measurements to be made in different orientations (Figs. B.3d and B.5). The equivalent cylindrical diameter is approximately 33.7 cm, and so is similar in attenuating properties to the 32 cm CT body phantom.

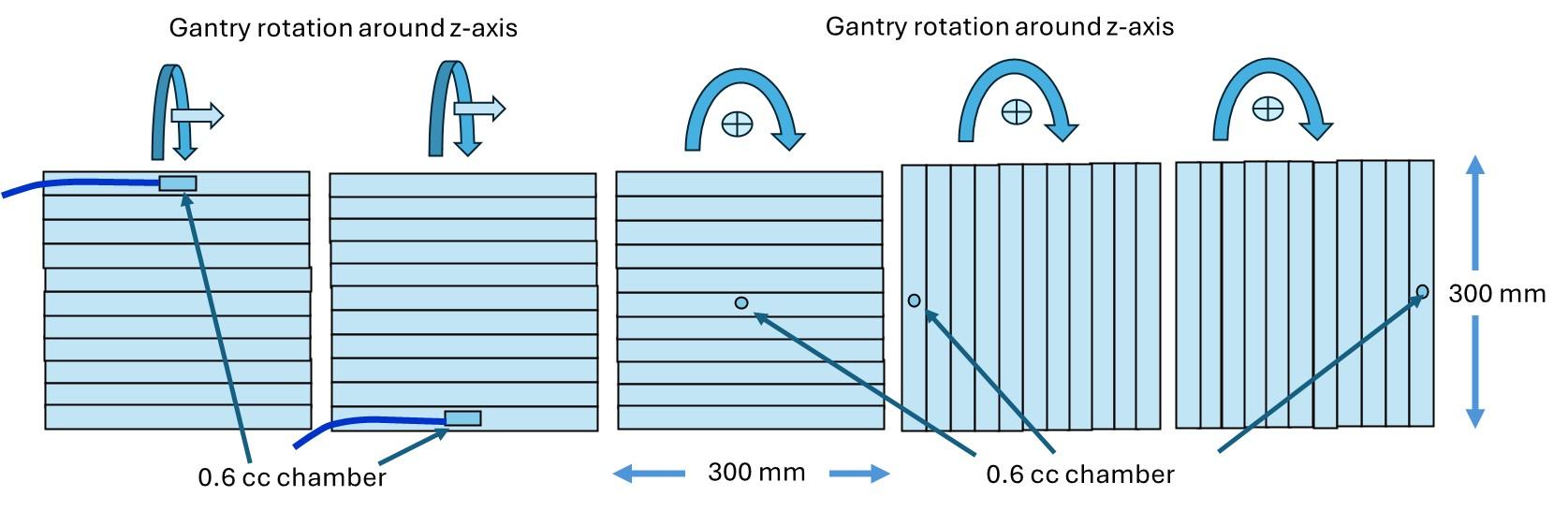


Fig. B.5 Arrangement for assembling a 300 mm cube from solid water slabs for use in making CBDI measurements. The cube can be oriented in different ways to allow the chamber axis to remain parallel to the z-axis of x-ray tube rotation. The photographs show measurement of peripheral doses at the top (left) and side (right) of the phantom, or the central dose (centre). (Photographs courtesy of Sebastien Gros, Loyola University Medical Center, Maywood, U.S.A).

* + - 1. Since the materials used and the shape of the phantom are different, a set of adjustment factors have been derived through experiment and Monte Carlo simulation to enable the values of measurements made with the slab phantom to be adjusted to give similar results to the cylindrical phantom and 100 mm chamber (Table B.2).

*Table B.2– Values being derived as part of Mentee Project*

* + - 1. While the radiation oncology medical physicists can be trained to perform the CTDI-style measurement, it can be a challenge for these institutions to justify the procurement of the CTDI cylindrical phantom required for such measurements. Inclusion of the equipment in the procurement budgets of new therapy machines may help to improve availability.
      2. Development of expertise within large teaching hospitals, resource sharing between institutions, and roll out of techniques through training to other radiotherapy centres may be ways in which imaging dose measurement can be promoted in low- and middle-income countries and underserved communities.
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1. Errors in treatment involving the application of imaging
   1. Examples of treatment errors linked to imaging
      * 1. Some errors occurring in radiotherapy treatments result from the use of imaging. Short descriptions of examples of some events reported in the literature are given here. Most are extracted from the Radiation Oncology Incident Learning System® (RO-ILS) quarterly reports, reports from the French and Belgian periodic newsletters for experience feedback issued by the two nuclear safety authorities (ASN and AFCN) and from the SAFRON database of the IAEA (SAFRON, 2016, 2024). Descriptions of events specific to the use of imaging are given in the form of case reports. Some initiatives and precautions that have arisen from particular events are given here, but more complete lists of preventative measures are included in section 11 of this document.
   2. Errors from imaging during plan preparation
      1. Errors in target delineation
         1. **Wrong side of the body and images with poor quality:** 13 events related to treatments delivered on the wrong side of the body were reported to the French nuclear safety authority between 2010 and 2013 (ASN, 2014). The errors in nine of these events occurred during the delineation stage and the causes were linked with the use of images. In the majority of cases, the target volume on the images for treatment preparation was of poor quality (e.g. after a surgical procedure or for prophylactic treatment) and this resulted in an incorrect target volume being delineated. This kind of event has also been reported by the Belgian nuclear safety authority in 2023 (AFCN, 2023c).
         2. Preventative measures: Analysis of the cases identified the following preventative measures:

* to take all necessary measures so that a radiotherapy treatment cannot begin without first having the patient’s complete medical file, including the surgical report, the pathological report and the imaging file,
* to ensure, for bilateral organs, that information from different documents is consistent with that supplied by the patient or their family and the multidisciplinary team meeting report.
  + - 1. **Delineation of wrong target from multiple lesions**: Errors of this type have been described in a RO-ILS report from 2016 and 2024 (RO-ILS, 2016a, 2024). In one example, a stereotactic body radiation therapy (SBRT) treatment (50 Gy in 5 fractions) was delivered to a benign liver haemangioma instead of the intended metastatic liver target. The patient had previously been treated with SBRT for two liver metastases and returned with a new lesion. A simulation directive was performed by the resident complete with axial image snapshots from an MRI scan as well as a contrast-enhanced CT scan illustrating the lesion to be treated. After simulation, the resident contoured a gross tumour volume (GTV) based on the wrong liver lesion, and treatment planning and QA were completed based on the incorrect target. The error was not detected at the time of attendance nor in peer-review rounds. The complete treatment was delivered to the benign liver haemangioma.
      2. Preventative measures: Following analysis of the case, the clinic instituted a new policy and procedure which included the explicit review of diagnostic images by the attending physician (with an accompanying checklist that was reviewed by others in the workflow). Analysis of the case underscores the need for peer-review and suggests that for SBRT treatments it may take a special form with enhanced safety checks.
      3. **Misjudgement due to artefacts**: An error in delineation of the target volume was reported in SAFRON from 2022. The automatic outlining of the body contour produced a small indentation close to a prothesis artefact with linear dimension of about 0.8 cm. This had been overlooked during treatment planning and several plan checks; and was found only during planning of the second treatment phase. It resulted in 30 fractions being delivered incorrectly.
      4. Preventative measures: Additional attention paid to unusual imaging situations with which there may be a potential for image artefacts.
    1. Wrong set of CT images
       1. **Images for the wrong patient:** In one case reported through SAFRON, a set of CT images had been transferred from the CT unit and introduced into the records of a different patient, but the next dosimetrist detected the error in this case and so avoided the treatment error that might have resulted. This type of error has also been reported in the Radiation Oncology Safety Information System (ROSIS) platform and presented in the *Publication 112* (ICRP, 2009). In one case, an additional contributing factor was the similarity between two patients’ names.
       2. Preventative measures: Having facilities in planning systems able to recognise CT image information such as patient ID.
       3. **Images from previous treatments:** For patients receiving successive treatments, several cases have been reported of patient plans being developed on old CT simulation data sets (for the same patients) (RO-ILS, 2015; ASN, 2016, 2020; AFCN, 2023b).
       4. Preventative measures: For cases of patients receiving successive treatments, it is recommended to:
* reinforce the traceability of the preceding treatment history of a patient as soon as the planned new treatment is prescribed
* define a methodology for importing images (CT scans, MRI, structures, etc.) into the TPS to guarantee that the files for the new treatment that is envisaged are used for the planning and not those of a preceding treatment.
* reduce the likelihood of such errors, the RO-ILS case review proposed that planning scans could be given names that clearly identified the date of the scan and the site being treated. This emphasises the need for planning systems to provide a warning when a new plan is being created on an old scan and ask for confirmation.
  + 1. Erroneous digitally reconstructed radiographs (DRR)
       1. **Wrong set of DRRs:** In one case reported in SAFRON, the planning department transferred incorrect DRRs to the patient database. When the first day’s images were displayed, the RTTs noticed large discrepancies between these and the DRRs from the Planning department. Further investigation revealed that images from a different plan (same patient) had been sent.
       2. **Geometrical distortion of DRR:** Incorrect formation and display of the DRR in a TPS has been reported in *Publication 112* (ICRP, 2009). In one case, the TPS used several methods in parallel for the creation of DRRs. For one method introduced with an updated version of the treatment planning software, an error resulted in incorrect formation and display of the DRR when certain conditions were fulfilled. The problem originated from an error in how the information from the CT slices was loaded into the graphics memory of the TPS computer. This error caused the volume to be stretched out in the z-axis in relation to the scale of the actual CT series.
       3. Preventative measure: Annual consistency checks together with checks after any upgrade can assist in avoiding this type of error.
       4. **Creation of the DRR based on the wrong reference:** Two cases, reported from ROSIS and included in SAFRON, related to the creation of DRRs based on an incorrect reference. In one case, the incorrect scan slice had been selected as the zero slice (nasogastric tube mistaken for ball bearing marker), while in a second case, the DRR was created with the origin – not the isocentre – as the positioning point.
    2. Incorrect CT calibration curve
       1. Errors can occur due to the use of an incorrect calibration curve to establish the relationship between CT numbers and tissue density used for dose calculation (ICRP, 2009). A 4D stereotactic radiotherapy treatment technique was set up for which CT images were acquired with a voltage of 100 kV, whereas a value of 120 kV had been used to establish the calibration curve recorded in the TPS (ASN, 2019).
       2. Preventative measures: Following analysis of this case, both organisational and technical solutions were proposed. The technical one being that the acquisition protocols should be locked when a new radiotherapy CT scanner is commissioned, and any modifications only allowed after strong validation, and requiring a request for a password and specific administration rights.
  1. Errors in matching to the plan during treatment
     1. Incorrect vertebral body localisation
        1. During the years 2015 to 2017, 40 events relating to vertebra identification errors have been reported to the French nuclear safety authority (ASN, 2018). 25 of these errors were linked with the use of 2D kV on-board imaging, 7 with 2D MV imaging (portal imaging). The majority of the events concerned treatments targeting vertebral (17), pulmonary or thoracic (10), and oesophageal (5) locations. All these events led to the delivery of at least one treatment session with a head-foot offset of several centimetres. The main cause identified by the centres lay in the difficulty in differentiating the vertebrae (lumbar and thoracic) from one another. This kind of errors has also been described by the Federal Agency for Nuclear Control (Belgium) in several reports during the years 2017 to 2023 (AFCN, 2020, 2022b, 2023a, 2024) and in a RO-ILS report from 2018 and 2024 (RO-ILS, 2018, 2024) and in SAFRON.
        2. **Case report 1:** A CBCT scan had been carried out by fast acquisition in order to minimise the processing time, but the CBCT images generated were of lower quality. Following acquisition of the images an automatic matching had been carried out that produced a co-registration on the wrong vertebra and resulted in a RTT positioning error with a 2.7 cm shift. Several treatment fractions were delivered at the wrong position and the error was detected a few days later when another RTT reviewed the registrations from the previous days.
        3. **Case report 2:** Another case involved the incorrect alignment of a patient’s vertebral body and rib for three of their initial 18 fractions of palliative treatment. This incorrect alignment occurred on separate non-consecutive treatment days and was made by three different RTTs. The patient’s carina was contoured but was poorly visible on the kV images. Medical physics reviewed the incorrectly aligned images and estimated the offset to be approximately 2 cm. A plan sum was generated in the TPS to demonstrate the dose difference due to the incorrect alignment. This was discussed with the physician who decided to add two additional fractions to account for the lower PTV coverage due to the offset. Critical structure doses were still within acceptable limits. In the RO-ILS 2018 report, the authors acknowledge that it can be challenging to identify the correct vertebral body on imaging and this probably happens more often than is reported or identified.
        4. Preventative measures: Several elements were proposed for inclusion in the standard procedure to minimise the risk of incorrect vertebral body localisation. These are also applicable to circumstances where there is a deviation from the standard procedure, such as steps to minimise patient discomfort. The RO-ILS report proposed that a systematic approach should be implemented, designed so that visual identification of vertebral bodies is not solely based upon bony anatomy, and the team should follow a consistent pattern of matching multiple anatomic points in order to prevent errors of this type from occurring.
        5. Other proposals were to:
* include dose contours overlying adjacent structures.
* increase the FOV length to include either the superior or inferior portion of the section of spine being treated.
* institute maximum tolerances on the allowed shift between set-up and treatment, and not to use only CBCT for alignment of vertebral bodies etc.
  + 1. Other examples of errors in matching protocols
       1. **Wrong matching protocol:** Several cases have been reported in SAFRON in which there has been confusion about the type of target matching required.
       2. **Case report 1:** A patient was to be soft tissue matched as per imaging note. The staff performed a bony match in error for one treatment, resulting in a 0.9 cm variation in the superior/inferior dimension. The error was picked up in offline image review (image-based position verification). A contributory factor identified was that the patient was not being imaged as per protocol, i.e. bony matching, however the RTT should have been checking the imaging note prior to matching.
       3. **Case report 2:** A patient was receiving radiation treatment for a small laryngeal cancer and daily IGRT was correctly documented as a soft tissue match on the correct CTV-structure. However, the RTTs discovered at fraction number four that they have made a bone match instead of the intended soft tissue match for the first three fractions, and the match type was corrected for fraction four and onwards. The type of treatment was rare in the department, which is why the RTTs were not aware that the small laryngeal cancer was soft tissue- matched rather than bone-matched, which was standard in other head and neck treatments.
       4. Contributory factors were:
* The patient had several sites for radiation therapy with different match strategies.
* The department was undergoing a transition process to a paperless system, where treatment documentation was only available in electronic form.
  + - 1. **Incorrect alignment of the CBCT:** Several cases were reported in SAFRON regarding incorrect alignment of the CBCT to the original planning CT of which two are described here.
      2. **Case report 1:** A patient was given an abdominal palliative treatment in 25 fractions of 2 Gy. VMAT and daily kV-CBCT were used, because one of the kidneys was close to a high dose area. At the 5th fraction, the patient had less pain than before and seemed to have been rotated compared to the planning CT image. Since the kidney was not sufficiently visible in the images, it was decided to increase the CBCT from arc (0-180°) to full arc (0-360°) from the next fraction onwards. At the next fraction, there was still a rotation, and when all the former CBCT images were reviewed, it was discovered that there was an incorrect bone match in the longitudinal direction for four of the fractions.
      3. **Case report 2:** A patient was undergoing radiation therapy to the left breast. An error was identified in the alignment of images acquired with a newly installed CBCT with respect to the original planning CT images. This caused incorrect couch parameters to be applied for the treatment. The patient received an unintended dose of approximately 0.22 Gy to an area 7.5 cm inferior to the intended treatment site. The novelty of the equipment and the unfamiliarity of staff contributed to the incident.
      4. **Case report 3:** A patient was treated for breast cancer with integrated boost. At the first treatment the staff noticed that the boost-volume was not in the setup image due to placement of the image detector. Physicist#1 performing the image check did not react to this and treatment continued for four fractions with daily imaging where the boost area was outside the image field. At the fifth fraction physicist#2 corrected the placement of the imaging detector, so that the boost volume was imaged correctly. As a result, there was no image verification of the boost volume for the first four fractions.
      5. **Confusion between old and new targets in the lung:** During a hypofractionated stereotactic treatment of a second target volume with a linac attached to a robotic arm, the first fraction of the new treatment was delivered to a target volume treated one year earlier. The two sites, the one treated by mistake and the other to be treated, were situated 10 cm from each other in the same pulmonary lobe and projected close to each other. The position of the clips on the image varied depending on the respiratory phase. Furthermore, the images displayed on the treatment console were small in size (ASN, 2016). Two main contributing factors were identified: firstly, the treatment machine was prepositioned on the wrong clip, and secondly excessive confidence was placed in the system for automatically identifying the pulmonary clip on the images. Clip identification was displayed as having a confidence level of 100 %, but this was for the wrong clip. A recommendation to reduce the risk of confusion between old and new targets was to avoid reliance solely on automatic identification of clips or surrogates.
      6. **Error in automatic gold marker detection:** Another case reported through SAFRON in 2022 involved CBCT monitoring of the gold marker during prostate treatment. An error occurred in the automatic gold marker detection, probably due to the patient’s hip implant, which the RTT on the linac did not notice. Insufficient attention, with the lack of a standard procedure, were identified as contributing factors.
      7. **Use of incorrect imaging protocol:** Several cases involving the use of incorrect imaging protocols have been reported.
      8. **Case report 1:** A case reported in SAFRON involved the use of the wrong CBCT protocol for stereotactic radiosurgery. During patient positioning, the stabilisation film was found to be torn and a new one was used. For imaging, the treatment team chose the wrong CBCT protocol: 4D instead of 3D. A different team noticed that the wrong protocol was being used during the 2nd fraction, as it was running more slowly. The 4D CBCT was stopped and the 3D CBCT was then started.
      9. **Case report 2**: A case reported by the AFCN was related to the change of imaging protocol during development of the treatment procedure (AFCN, 2022a). It was decided to move away from kV/kV imaging and to opt for CBCT imaging which allows better localisation and matching of the glandular regions. kV/kV imaging is done with the table already in the prescribed treatment position. With CBCT, this is often not possible because it’s not always possible to rotate around the patient when the table is in the treatment position, due to the lateral location of the lesions. The change in imaging protocol had as consequence the delivery of the treatment in the incorrect positioning of the patient for some fractions.
  1. Errors due to differences in patient positioning
     + 1. **Prone / supine positioning:** IAEA Safety Reports Series No. 17 (IAEA, 2000) reported the case (event No. 45) of a patient with metastatic lung disease who received a nuclear medicine bone scan in the prone position (face down). A metastatic lesion was found in the left hip, for which the patient was to receive 27 Gy. For radiation therapy, the patient was positioned in the supine position (face up). The orientation of the bone scan was misinterpreted and the patient was treated on the right hip rather than the left hip. The treatment continued for two weeks, until a resident radiation oncologist discovered the error while reviewing the patient’s chart.
       2. **Preventative measures:** Ineffective procedures, protocols and documentation were identified as contributory factors: together with different imaging conventions (for x-ray and nuclear medicine images). The radiotherapy staff was not familiar with imaging conventions in the nuclear medicine department and did not review the report of the bone scan and the prescription for radiotherapy did not indicate clearly which hip was to be treated. A case discussion between case physicians could have aided in avoiding this type of error and procedures were revised and staff trained in their use.
       3. **Head first/ feet first positioning 1:** Several cases have been reported in SAFRON regarding differences in the positioning of patients (head first/feet first) on CT scanners between preparation and treatment stages. For example, in one case, a patient undergoing a radiosurgery procedure was positioned in a CT scanner feet-first rather than the usual head-first position, and the CT images were reversed, and as a result the patient was treated on the opposite side of the brain from that prescribed.
       4. **Head first/ feet first positioning 2:** In another case a patient was referred for radiotherapy in order to benefit from analgesic treatment (a fraction of 8 Gy) to the left femur. The patient had a CT scan in the “head first” position. When planning the treatment, the decision was made to reverse the images so that the patient was positioned “feet first” to ensure that the treatment on the linac was possible without collision. For one fraction, the patient was positioned in the treatment room according to the photographs taken at the CT scanner (patient in “head first”).
       5. **Preventative measures:** Following analysis of this case, the centre decided on several corrective actions, among them: treatment planning on a treatment position other than the simulated one is no longer allowed; long bone/ long volume treatments are planned on Tomotherapy ® or other helicoidal treatment machines rather than conventional linacs in order to allow a simplified imaging and treatment process; the RTTs have been made aware of the need for verification of concordance between the “patient scanning position” and the “patient treatment position” in the treatment plan.
       6. **Motion management:** The Federal Agency for Nuclear Control (Belgium) (AFCN, 2022c) described a case in which a patient was treated with external radiotherapy for gastric lymphoma. Given the significant mobility of the stomach due to respiratory movement, it was decided to simulate and treat the patient using the Breath Hold (BH) inspiration technique. A CBCT was carried out with the patient holding their breath (BH) at one fraction, but the remainder of the patient treatment was performed while the patient was able to breathe freely.
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ABBREVIATIONS

AAARA As accurate as reasonably achievable

AAPM American Association of Physicists in Medicine

ABC Automatic brightness control

ACR American College of Radiology

AEC Automatic exposure control

AERC Automatic exposure rate control

AFCN Agence fédérale de Contrôle nucléaire (Belgium)

AI Artificial intelligence

ALARA As low as reasonably achievable

APBI Accelerated partial breast irradiation

ART Adaptive radiation therapy

ASN Autorité de Sûreté Nucléaire

ASTRO American Society for Radiation Oncology

AV Audio visual

BH Breath hold

BNCT Boron neutron capture therapy

CINE Cinématographe: Acquisition of multiple images of the same anatomy over time

CNR Contrast-to-noise ratio

CBCT Cone beam computed tomography

CNS Central nervous system

COG Children’s Oncology Group

CPD Continuing professional development

CSF Cerebrospinal fluid

CT Computed tomography

CTDI Computed tomography dose index

CTDIvol Volume averaged CTDI

CTV Clinical target volume

DICOM Digital Imaging and Communications in Medicine

DL Deep learning

DLIR Deep learning-based image reconstruction

DLP Dose length Product

DRR Digitally reconstructed radiograph

DRL Diagnostic reference level (diagnostic imaging)

DRLRT Dose reference level (therapy imaging)

DVH Dose volume histogram

D50 Dose received by 50 % of a given organ

EBRT External Beam Radiation Therapy

EC European Commission

EGRT Emission guided radiation therapy

EPI Electronic portal imaging

EPID Electronic portal imaging device

ESAK Entrance surface air kerma. (also Ka,e) (ICRP Glossary - Air-kerma, entrance surface)

ESTRO European Society for Radiation Oncology

FBP Filtered back projection

FDG Fluorodeoxyglucose

FGI Fluoroscopically guided intervention

FMEA Failure mode and effects analysis

FOV Field of view

GAN Generalised adversarial network

GTV Gross tumour volume

HDR High dose rate

HERCA Heads of European Radiation Protection Authorities

HU Hounsfield Unit

IAEA International Atomic Energy Agency

ICRP International Commission on Radiological Protection

ICRU International Commission on Radiation Units and Measurement

IEC International Electrotechnical Commission

IGABT Image guided adaptive brachytherapy

IGRT Image guided radiation therapy

IMRT Intensity modulated radiation therapy

IPEM Institute of Physics and Engineering in Medicine (UK)

IR Iterative reconstruction

IRSN Institut de Radioprotection et de Sûreté Nucléaire

ISO International Standards Organisation

ITV Internal target volume

IV Intravenous

KAP Kerma-area product (also PKA) (ICRP Glossary - Air-kerma, product)

kV Kilovoltage

KSC Knowledge, skills and competences

LDR Low dose rate

LD50 Lethal dose (that kills 50 % of population)

Linac Linear accelerator

LIRON Learning In Radiation ONcology

LMICs low to middle income countries

LNT Linear non threshold

ML Machine learning

MLC Multi-leaf collimator

MR Magnetic resonance

MRI Magnetic resonance imaging

MU Monitor unit (≈1 cGy, 10 mGy)

MV Megavoltage

NCRP National Council on Radiation Protection and Measurement (US)

NEMA National Electrical Manufacturers Association (US)

NRG eNeRGy (‘NGR Oncology’ is a platform for finding better treatments for cancer)

NTCP Normal tissue complication probability

OARs Organs at risk

OIS Oncology information system

PA Postero-anterior (projection)

PACS Picture archiving and communication system

PDR Pulsed dose rate

PET Positron emission tomography

PSMA prostate specific membrane antigen

PMMA Polymethyl methacrylate

PTV Planning Target Volume

QA Quality Assurance

QC Quality Control

QMS Quality Management System

RBE Radio-biological effectiveness

RDSR Radiation dose structured report

RIS Radiology information system

RO-ILS Radiation oncology incident learning system

ROSIS Radiation oncology safety information system

RT Radiotherapy

RTT Radiation technologist / therapy radiographer

SAFRON Safety in radiation oncology

SBRT Stereotactic body radiotherapy

SIOP International Society of Paediatric Oncology

SNR Signal to noise ratio

SPECT Single photon emission tomography

SRS Stereotactic radiosurgery

SRT Stereotactic radiotherapy

TG Task Group

TOF Time-of-flight

TPS Treatment planning software

UKHSA UK Health Security Agency

UNSCEAR United Nations Scientific Committee on the Effects of Atomic Radiation

US Ultrasound

VMAT Volumetric modulated arc therapy

WHO World Health Organisation

2-, 3-D & 4-D 2-, 3-and 4-dimensional

3DCRT Three-dimensional conformal radiation therapy

3DCT 3-dimensional computed tomography

4DCT 4-dimensional computed tomography

GLOSSARY

Only terms not yet included in the ICRP Glossary are included here. The ICRP Glossary can be viewed at: http://icrpaedia.org/ICRP\_Glossary.

Accidental medical exposure

An accidental medical exposure in radiotherapy treatment is one in which there is a substantial deviation from the radiation treatment prescription due to flaws in design and operational failures of medical radiological equipment, from failures of and errors in software, or because of human error or an error in the prescription leading to a substantial deviation from the intended radiation treatment exposure.

Action level protocol

Protocol for checking patient positioning set-up for treatment through imaging including giving criteria for adjustments to ensure radiation is delivered consistently throughout the course of treatment.

Artificial intelligence (AI)

Artificial intelligence (AI) can be characterised as a collection of algorithms performing tasks that give a machine the capability to imitate human intelligence. AI is becoming important in medical imaging, as lesions and organs appearing in medical images are too complex to be described by a simple equation or a hand-crafted model as used in conventional computer aided diagnostics. AI methodology has sub-domains: machine learning (ML) and deep learning (DL) that are used to create decisions based on analysis of large-scale training data sets.

Automatic dose rate control (ADRC)

Device that automatically determines the exposure rate needed to provide an image of selected image quality during fluoroscopy by sampling the x-ray intensity transmitted through the patient at the image receptor. The changes in exposure are achieved through adjustment of the tube potential (kV) and tube current (mA) according to predetermined relationships.

Automatic tube current modulation (ATCM)

ATCM or automatic exposure control (AEC) determines the tube current level in CT required to maintain the level of image quality or image noise selected by the operator throughout a scan. The adjustments are based on the scan projection radiograph recorded before the main scan.

Clinical Target Volume (CTV)

A term coined by the ICRU to describe the volume that should receive a certain dose in order to achieve the desired treatment outcome according to the prescription.

Cone Beam Dose Index (CBDI)

A dose quantity derived from measurements using a 100 mm ionisation chamber and standard CT cylindrical phantoms made from PMMA, or equivalent, for use in patient dose surveys for CBCT imaging used in IGRT. The CBDI values represent weighted measurements from the centre and periphery of the phantoms, equating to the method used for derivation of CT dose indices.

Deep learning (DL)

Deep learning is a subset of machine learning developed to learn from data without being explicitly programmed. In DL the data are fed through several data processing layers in a neural network architecture, providing higher abstraction level features from the original input data. As with machine learning, DL methods require to be trained using datasets containing large numbers of appropriate images and has become feasible due to the enormous number of medical images now being produced. DL methods are yielding promising results in medical imaging related to diagnostic tasks, such as lesion or tissue localisation, segmentation, classification and prediction of clinical outcomes. DL image reconstruction (DLIR) is being used for CT.

DICOM-Digital Imaging and Communications in Medicine

Digital imaging standard describing a set of protocols describing how radiology images are identified in a structured way, formatted and communicated. DICOM is manufacturer-independent and was developed by the American College of Radiology and the National Electronic Manufacturers Association. Provision of an agreed structured format facilitates the exchange of files between devices that have the capability of accepting image and patient data in DICOM format. DICOM 3.0 is the current version. http://medical.nema.org/

Dose Reference Level for therapy imaging (DRLRT)

A reference level established for imaging processes used in radiotherapy, analogous to the diagnostic reference level (ICRP, 2017) applied in diagnostic imaging. A DRLRT would be set at the 75th percentile of median doses collected from surveys of imaging doses carried out in a group of radiotherapy centres and used as a dose reference for triggering action to optimise radiological protection.

Electronic portal imaging (EPI)

Use of a flat panel device to obtain an image using the MV treatment beam.

Filtered back projection

Analytic image reconstruction method used to reconstruct section images in CT and MRI. It uses back projection of image data with application of an algorithm in which a convolution filter is applied to remove blurring. It has long been the standard method for reconstruction of CT images but is being replaced by iterative reconstruction.

Image guided radiation therapy (IGRT)

The process of using images during the period of radiation therapy delivery, after the initial plan has been prepared, to ensure that the treatment is delivered as intended. Imaging is applied predominantly within the treatment room during the course of treatment for verification purposes and for making decisions with respect to the remainder of the treatment process.

Isocentre

In external beam radiotherapy the point around which all components of a linear accelerator rotate: namely the gantry, collimator and couch.

Iterative reconstruction

CT image reconstruction technique which typically applies repeated iterative loops of forward projection (producing simulated projection raw data) and back-projection (creating image from projections). Thus, the image reconstruction happens by several iteration cycles where the iterated image gradually approaches the final image result converging either by CT image pixel values or by the difference between the simulated and true (measured) raw data projections. Iterative methods enable higher image quality to be achieved but require more computing power. The technique can be used with to achieve similar image quality to filtered back projection with lower dose levels.

Machine learning (ML)

Machine learning involves the development of computer programmes that can find complex patterns, which might represent lesions or other features, within complex data sets. ML has been developed to learn from data without being explicitly programmed. In medical imaging, a model or mathematical algorithm is trained on image data sets to enable it to predict an outcome for new patient data similar to that given by a human expert. ML predicts outcomes from new data based on earlier training on large scale. See also deep learning.

Multi-leaf Collimator

Collimators made from thick high density tungsten alloy leaves that are motorised to enable movement in order to conform the irradiation field delivered by high energy therapy equipment to the shape of the tumour target.

Oncology Information System (OIS) and Radiology information system (RIS)

A system that supports the information processing and business requirements of oncology (OIS) or radiology (RIS) departments and freestanding image centres.

Planning Images

Images taken prior to radiotherapy for the purpose of planning treatment delivery.

Planning Target Volume

The volume that is planned to be treated with radiation in order to achieve the treatment goal. The PTV typically includes the CTV which is expanded by margins to take into consideration the uncertainty of locating the target within the patient and the variations in patient set-up from day to day

Radiation Dose Structured Report

Part of the DICOM standard defining the set of DICOM objects providing the radiation dose related parameters by hierarchical description of the irradiation event (e.g., within entire CT examination or pulsed fluoroscopy image series).

Radiological medical practitioner

A health professional with specialist education and training in the medical uses of radiation, who is competent to perform independently or to oversee radiological procedures in a given specialty. This includes radiation oncologists for therapeutic procedures, and radiologists, cardiologists, orthopaedic surgeons and other clinicians for diagnostic and interventional procedures, who have undertaken appropriate training for this role. Competence of the person is normally assessed by the State through a formal mechanism for registration, accreditation or certification of radiological medical practitioners in the given specialty.

Radiation oncologist

A radiation oncologist is a specialist physician who uses ionising radiation in the treatment of cancer or benign disease. Radiation oncologists undergo specialist education and training in the medical uses of radiation after completion of a medical degree. Their competence to prescribe and oversee radiation therapy treatments and related imaging procedures will normally have been assessed by the State through a formal mechanism for registration, accreditation or certification of medical practitioners.

Second primary cancer

A new primary cancer that occurs in a person who has had cancer in the past. The risk of developing a second primary cancer may be increased by radiotherapy.

Stereotactic Body Radiotherapy (SBRT) or Stereotactic Ablative Body Radiotherapy (SABR)

A highly focused radiation treatment that gives an intense dose of radiation to a tumour in one to five fractions, while limiting the dose to the surrounding organs.

Stereotactic Radiosurgery (SRS)

Delivery of a large single fraction of precisely targeted radiation to sterilise a small well localised area, typically in the brain, while preserving healthy tissue.

Therapy radiographer / Radiation technologist (RTT)

A therapy radiographer is a health professional, with specialist education and training in medical radiation technology, competent to perform therapeutic radiological procedures and related imaging for guidance on delegation from the radiation oncologist (Radiological medical practitioner). Competence of persons is normally assessed by the State by having a formal mechanism for registration, accreditation and/or certification of medical radiation technologists.

Tomotherapy

Delivering intensity modulated radiotherapy (IMRT) using a small linear accelerator mounted onto a CT type ring gantry. The technique inherently combines diagnostic and therapeutic radiology.

Typical value (for dose relating to DRLRT)

See Glossary in ICRPeadia

Unintended medical exposure

Any medical exposure of a patient unintended by the operator, including due to operating error, equipment failure or other mishap that is significantly different from the medical exposure intended for a given purpose.

Volumetric Modulated Arc Therapy (VMAT)

An intensity modulated treatment delivery based on a continuously rotating gantry while the MLC is moving.

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ICRP has produced a number of publications on radiation therapy and separate ones on medical imaging, however, these have not dealt explicitly with the use of imaging in radiation therapy. Advancements in treatment techniques have in recent decades made the use of imaging a crucial component of achieving the potential of new radiotherapy techniques. The additional exposure to radiation from imaging presents risks to organs and tissues surrounding the target to be treated. This publication sets out guidance on the appropriate use of imaging and considers radiation dosimetry and techniques that need to be implemented to optimise the related radiological protection. ICRP thanks all those involved in the development of this publication for their hard work and dedication over many years, and members of Committee 3 for helpful review and discussion about the content of the publication. ICRP also thanks colleagues of Task Group members, namely Magali Edouard, Laetitia Padovani and Jennifer Chard for detailed review of parts of the document relating to their areas of expertise.

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