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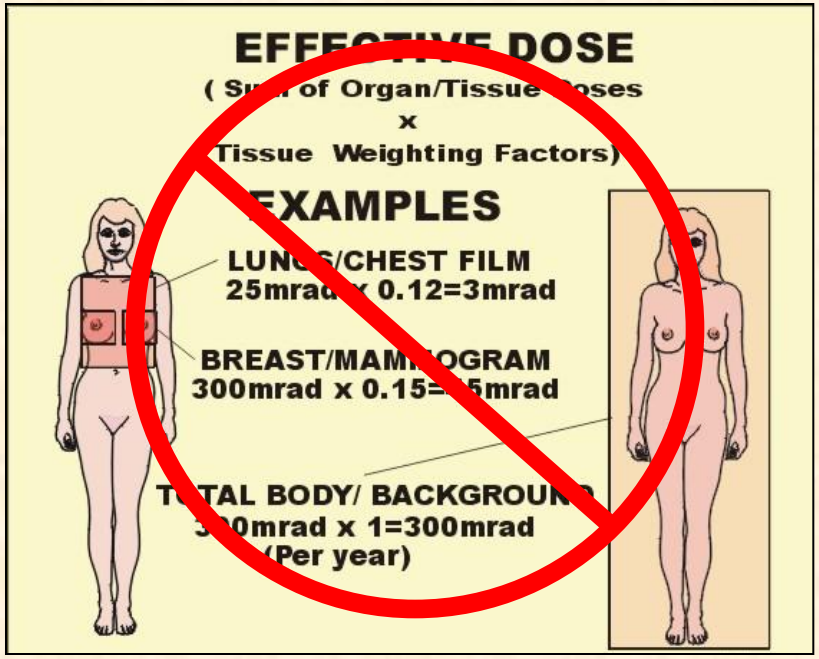
Effective Dose – A Flawed Concept that Could and Should be Replaced



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The British Journal of Radiology, 81 (2008), 521–523

COMMENTARY

Effective dose: a flawed concept that could and should be replaced

D J BRENNER, PhD, DSc

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ABSTRACT. The effective dose is designed to provide a single number proportional to the radiobiological "detriment" from a particular, often inhomogeneous, radiation exposure, with detriment representing a balance between carcinogenesis, life shortening and hereditary effects. It is commonly used to allow a comparison of the risks associated with different spatial dose distributions produced by different imaging techniques. The effective dose represents questionable science: two of the most important reasons for this are that the tissue-specific weighting factors used to calculate effective dose are a subjective mix of different endpoints, and that the marked and differing age dependencies for different endpoints are not taken into account. Importantly, the effective dose is prone to misuse, with widespread confusion between effective dose, equivalent dose and absorbed dose. It is suggested here that effective dose could and should be replaced by a new quantity that does not have these problems. An appropriate new quantity could be "effective risk", which, like effective dose, is a weighted sum of equivalent doses to different tissues; unlike effective dose, where the tissue-dependent weighting factors are a set of subjective committee-defined numbers, the weighting factors for effective risk would simply be evaluated tissue-specific lifetime cancer risks per unit equivalent dose. The resulting quantity would perform the same comparative role as effective dose; it would have the potential to be age- and, if desired, gender-specific, just as easy to estimate, less prone to misuse, more directly interpretable, and based on more defensible science.

Correspondence

(The Editors do not hold themselves responsible for opi

Effective dose: a flawed concept that could and should be replaced. Comments on a paper by D J Brenner (Br J Radiol 2008;81:521–3)

The Editor — Sir,

The author is uncompromising in his criticisms of the quantity "effective dose" and proposes its replacement with a quantity termed "effective risk". The uninformed use and misapplication of effective dose is a recognised problem [
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ments of an exposure received by an individual worker, as might be required if dose limits are exceeded, will always need to take account of all available information to provide best estimates of risk. Similarly, estimates of risk to population groups should properly be based on the best available data. The new ICRP recommendations [1] provide an explanation of the intended application of effective dose. Further guidance will be provided in a forthcoming ICRP report that will also discuss approaches to assessments in situations, including medical applications, for which effective dose was not intended.

Yours etc.,

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(Chairman[1] and members of Committee 2 of the International Commission on Radiological Protection)

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What is effective dose for?

- Effective dose aims to provide a single number that is proportional to the radiobiological "detriment" from a particular, often inhomogeneous, type of radiation exposure
- "Detriment" represents a balance between cancer incidence, cancer mortality, life shortening, and hereditary effects
- It was designed to allow comparisons of the risks associated with different spatially-inhomogeneous exposures, now most frequently from different imaging techniques / scenarios

What is effective dose for?

In fact, effective dose is always used as a measure of risk

Effective dose is always used as a measure of risk

'Effective dose' has been defined and introduced by ICRP for risk management purposes

ICRP 2009

A quite typical use of effective dose in radiology

Pediatr Radiol (2009) 39:1059–1065
DOI 10.1007/s00247-009-1327-1

ORIGINAL ARTICLE

Radiation exposure from pediatric head CT: a bi-institutional study

Mary A. King · Kalpana M. Kanal · Annemarie Relyea-Chew · Mark Bittles · Monica S. Vavilala · William Hollingworth

Received: 24 February 2009 / Revised: 6 May 2009 / Accepted: 1 June 2009 / Published online: 25 June 2009

Abstract
Background Medical radiation from CT should be kept as low as reasonably achievable (ALARA), particularly in young patients.
Objective To examine radiation dose from head CT in children in a trauma center (TC) and a regional children's hospital (RCH).
Materials and methods A random sample of 240 children (0–3, 4–9, 10–14 years of age) from the TC were compared with a similar cohort from the RCH. All children had undergone at least one head CT scan without contrast enhancement; data from PACS and Department of Radiology Information System were used to estimate normalized effective dose (ED). Lifetime attributable risk of cancer incidence was estimated using the Biologic Effects of Ionizing Radiation (BEIR) VII report.
Results The mean normalized ED was significantly higher in the youngest children at the TC (2.74 mSv in those aged 0–3 years vs. 2.23 mSv in those aged 10–14 years; $P<0.001$) and at the RCH (2.44 mSv in those aged 0–3 years vs. 1.71 mSv in those aged 10–14 years; $P<0.001$). Each decreasing year of age was independently associated with a 0.06 mSv higher mean normalized ED ($P<0.001$). After adjusting for the age difference between the institutions, the

A quite typical use of effective dose in radiology

Table 3 Comparison of mean normalized ED within each age cohort between institutions.

Age cohort	Mean normalized ED (mSv)		95% CI	*P* value
	TC (*n*=80)	RCH (*n*=80)		
1 (0–3 years)	2.74	2.44	0.04–0.55	0.026
2 (4–9 years)	2.52	2.13	0.12–0.65	0.005
3 (10–14 years)	2.23	1.71	0.37–0.66	<0.001

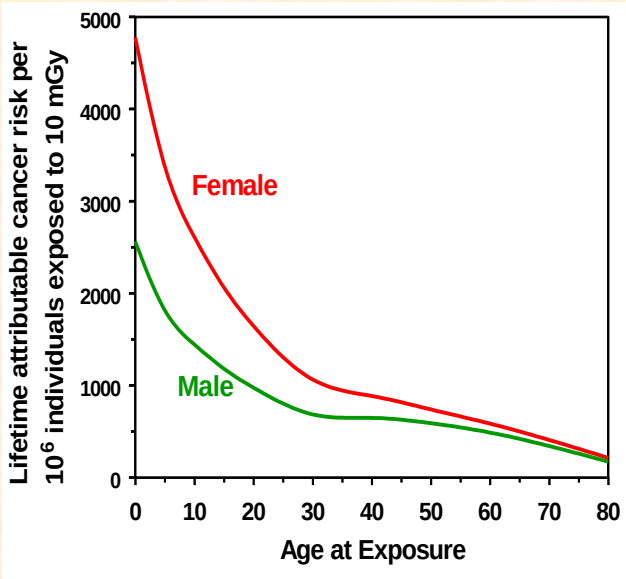
A quite typical use of effective dose in radiology

Table 5 Lifetime attributable risk estimates: cancer incidence and mortality per 1000,000 persons attributable to radiation exposure from one head CT scan (mean ED), presented by age, cohort and by institution (based on the BEIR VII report)

Cohort		TC				RCH			
		All solid cancer		Leukemia		All solid cancer		Leukemia	
		Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys
1 (0–3 years)	Cases in absence of exposure	36,900	45,500	590	830	36,900	45,500	590	830
	All excess cases (fatal and nonfatal)	35.6	21.9	1.9	2.7	31.7	19.5	1.7	2.4
	Deaths in absence of exposure	17,500	22,100	530	710	17,500	22,100	530	710
	Excess deaths from exposure	16.7	11.2	1.4	1.9	14.9	10.0	1.2	1.7
2 (4–9 years)	Cases in absence of exposure	36,900	45,500	590	830	36,900	45,500	590	830
	All excess cases (fatal and nonfatal)	32.8	20.2	1.8	2.5	27.7	17.0	1.5	2.1
	Deaths in absence of exposure	17,500	22,100	530	710	17,500	22,100	530	710
	Excess deaths from exposure	15.4	10.3	1.3	1.8	13.0	8.7	1.1	1.5
3 (10–14 years)	Cases in absence of exposure	36,900	45,500	590	830	36,900	45,500	590	830
	All excess cases (fatal and nonfatal)	29.0	17.8	1.6	2.2	22.2	13.7	1.2	1.7
	Deaths in absence of exposure	17,500	22,100	530	710	17,500	22,100	530	710
	Excess deaths from exposure	13.6	9.1	1.1	1.6	10.4	7.0	0.9	1.2

A quite typical use of effective dose in radiology

1. **Estimate effective dose….**
2. **Based on effective dose, either**
   - A. **Draw inferences about individual cancer risk, or**
   - B. **Explicitly estimate individual cancer risk from age- and gender- dependent BEIR data**



There is even convenient software to do this….

G Model
EURR-5649; No. of Pages 5

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A novel tool for user-friendly estimation of natural, diagnostic and professional radiation risk: Radio-Risk software

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functional strategy based on the personal collection of each radiological exposure derived from diagnostic, natural, and professional sources. The program uses templates to collect and archive data, and provides reference values for radiology and nuclear medicine procedures, since the real effective dose delivered is usually not available in the medical records. We estimated reference doses from four main sources: American Heart Association 2009 imaging guidelines for cardiology examinations [10]; UK Royal College of Radiology 2007 [11] and European Union Commission 2008 imaging guidelines (for non-cardiological examinations) [11]; President's Cancer Panel 2010 for other examinations not listed in previous guidelines [9], and peer-reviewed literature for most recent examinations [12]. For each reference effective dose, cancer age- and gender-weighted risks were derived from the BEIR VII Committee 2006 report [13].

Natural background sources were also included, both terrestrial radiation (which varies in different regions) and cosmic radiation (increasing for instance with airplane flights) [14]. The dose is expressed as multiples of chest X-rays (postero-anterior, single projection – 0.02 mSv), or days/years of natural background radiation (worldwide average, 2.4 mSv), or as a distance (in km) from Hiroshima ground zero. Average background dose is available for the major Italian and selected US cities, and as the average exposure in European countries.

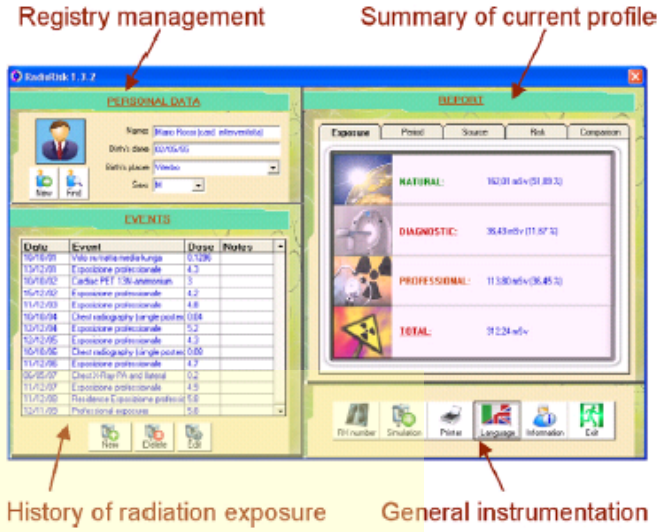


Fig. 1. The entry interface of RadioRisiko with simple demographics and geographic mapping of natural background exposure in a 55-year old interventional cardiologist.

Issues with effective dose?

- It is only useful when it is used to provide a measure of risk to individuals
- When it is useful to provide a measure of risk to individuals, it represents bad science
  - It is based on highly subjective judgments
  - It does not reflect the major age / gender dependencies in radiation sensitivity
  - It is confusing to most users
  - It is unnecessarily hard to interpret

The Definition of Effective Dose

$$\textit{Effective Dose} = E = \sum_{T} w_T \, H_T$$

- H_T are the tissue-specific equivalent doses in tissues T
- w_T are committee-defined dimensionless tissue-specific weighting factors

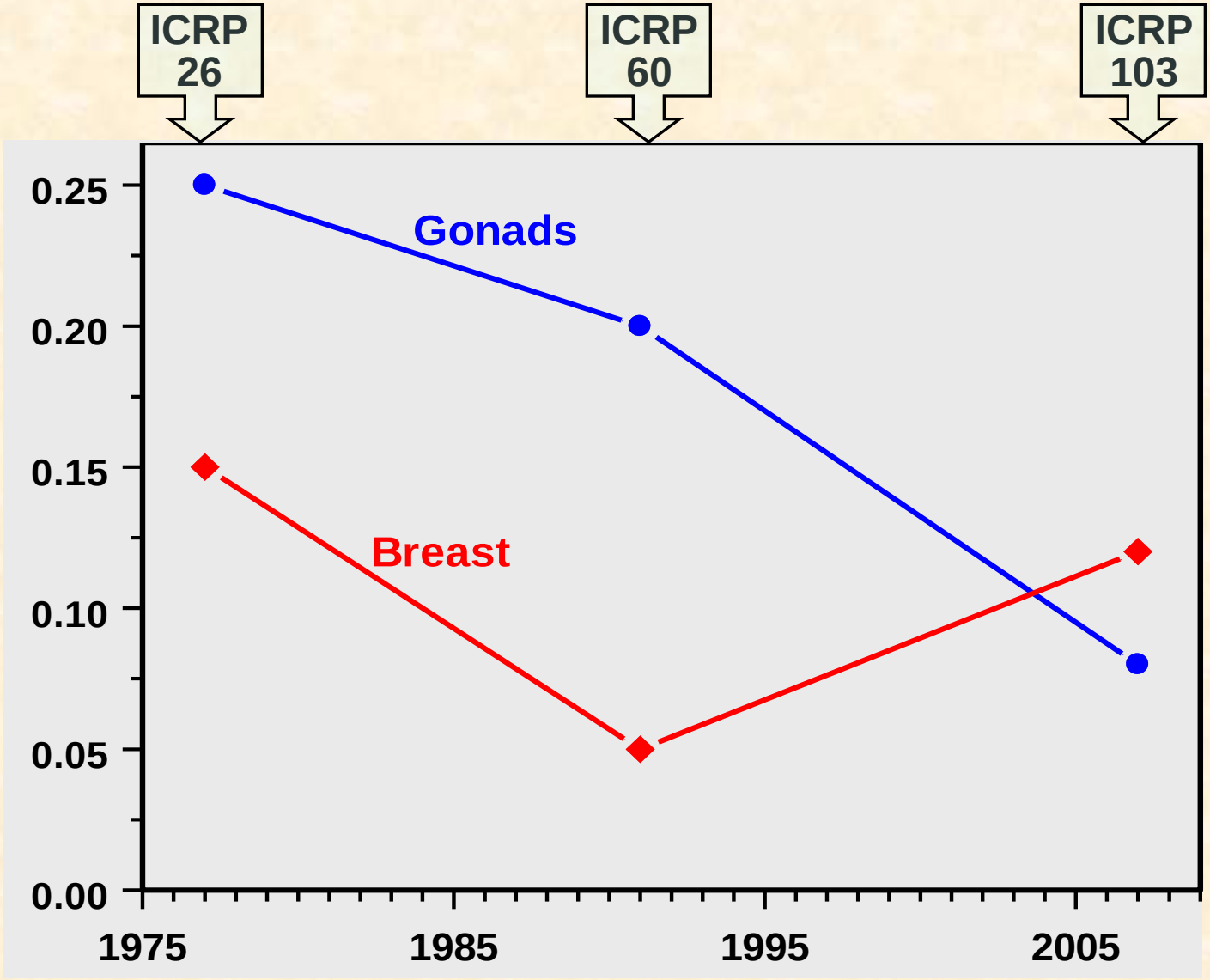
Organ/tissue	w_T ICRP (2007)	ICRP (1991)
Breast	0.12	0.05
Bone marrow	0.12	0.12
Colon[a]	0.12	0.12
Lung	0.12	0.12
Remainder	0.12[b]	0.05[c]
Stomach	0.12	0.12
Gonads[d]	0.08	0.20
Bladder	0.04	0.05
Liver	0.04	0.05
Oesophagus	0.04	0.05
Thyroid	0.04	0.05
Bone surfaces	0.01	0.01
Brain	0.01	—
Salivary glands	0.01	—
Skin	0.01	0.01

Objectivity

- **Effective dose is designed as a measure of "radiation detriment", which is a subjective mix of cancer incidence, cancer mortality, life shortening and hereditary effects.**
  - **The nature of this mix is a committee-determined decision, and changes as ICRP committees change**

2007 Committee 1, from left to right:
Front row: Bob Ullrich, Julian Preston, Jolyon Hendry, Bill Morgan.
Middle row: Margot Tirmarche, Elaine Ron, Fiona Stewart, Ranajit Chakraborty, Ohtsura Niwa.
Back row: Werner Rühm, Pingkun Zhou, Alex Akleyev, Colin Muirhead, Dale Preston, Maria Blettner, Roy Shore.

Evolution of some organ / tissue weighting factors



The tissue weighting factor for the breast increased dramatically

In our opinion, it is not a valid criticism that weighting factors change every decade or so; on the contrary the ICRP would be open to criticism if relevant scientific advances were not taken into account

Dietze, Harrison and Menzel, 2009

- 1991: 0.05, 2007: 0.12
  - Arguably the most important change in the entire 2007 ICRP report
- This change in w_T was NOT because we learned more about radiation-induced breast cancer between 1991 and 2007
- Rather it was because the 2007 ICRP committee chose to put more emphasis on cancer incidence, as opposed to cancer mortality

Age de[illegible]

- The tis[illegible] per orga[illegible],

Reminder!

Effective dose is always used to provide a measure of risk…

Estimated cancer incidence estimates, derived from BEIR-VII

	Children (per 0.1 Sv/10^5)	Adults (per 0.1 Sv/10^5)
Lung	373	166
Breast	865	160

- So for example, two different dose distributions which result in the same radiation risk for adults, would not result in equal risks for children

Effective Dose is Confusing

- **The confusion between organ dose and effective dose is widespread in the field of radiology.**
  - **in a significant proportion of relevant papers, they are interchangeably referred to as "the dose"**
- **This confusion is probably inevitable for a quantity which…**
  a) **has dose in its name,**
  b) **has units of dose,**
  c) **but is actually a measure of radiological detriment**

A proposal to replace effective dose

Brenner, BJR 2008

- **replace effective dose (i.e. summed organ doses, each weighted with committee-generated numbers) ….**
- **with "effective risk" (i.e. summed organ doses, each weighted with *actual epidemiologically-based cancer risks*)**

Effective risk would perform all the comparative functions that we agree are needed, but

1) **would eliminate the subjectivity associated with committee-generated weighting factors,**
2) **would provide a more intuitively interpretable quantity relating to risk, leading in turn to**
3) **less potential for misuse.**

Effective Dose vs. Effective Risk

$$\textit{Effective Dose} = E = \sum_{T} w_T \; H_T$$

H_T are the tissue-specific equivalent doses in tissues T

w_T are committee-defined dimensionless tissue-specific weighting factors

$$\textit{Effective Risk} = R = \sum_{T} r_T \; H_T$$

r_T are lifetime radiation-attributable organ-specific cancer risk estimates (per unit equivalent dose to tissue T)

The effective risk is thus a generic lifetime radiation-attributable cancer risk

Effective Dose vs. Effective Risk

$$\textit{Effective Dose} = E = \sum_{T} w_T \, H_T$$

$$\textit{Effective Risk} = R = \sum_{T} r_T \, H_T$$

- **The two equations have exactly the same structure, so calculations will be no harder / easier**
- **And any inherent assumptions (e.g. LNT) will be the same for both**

Features of Effective Risk

"We see no reason to discount hereditary disease in the protection system… we believe that this would be a backward step that the public and radiation professionals would not understand"

Dietze, Harrison, Menzel 2009

- It can still change with time, but now based on the science, not the personalities
- It refers only to cancer
  - cancer risk data now represent the scientific basis for all contemporary dose limits
  - the use of a subjectively-defined genetic component is a hangover from the 1950s

Features of Effective Risk

2. Less potential for confusion

- **Currently, there is widespread confusion in the radiological literature between organ dose and effective dose**
- **The confusion would be entirely avoided if measures of radiobiological detriment were in units of (for example) "per 10,000 individuals" (as in effective risk), rather than in Sieverts (as in effective dose).**

Features of Effective Risk

3. Potential to include age effects

- It is true that for occupational radiation protection (ages 18 to 70), it may be OK to ignore age dependencies
- But more than 2/3 of the usage of the effective dose concept is for radiology, where we cannot ignore age dependencies

	r_T		
	Children	Adults	All Ages
Stomach	66	30	37
Lung	373	166	208
Colon	203	96	118
Liver	32	14	18
Bladder	153	75	91
Uterus	37	14	19
Ovary	76	28	37
Prostate	67	34	41
Breast	865	160	299
Thyroid	200	18	54
Leukemia	133	68	82

Features of Effective Risk

4. Interpretability

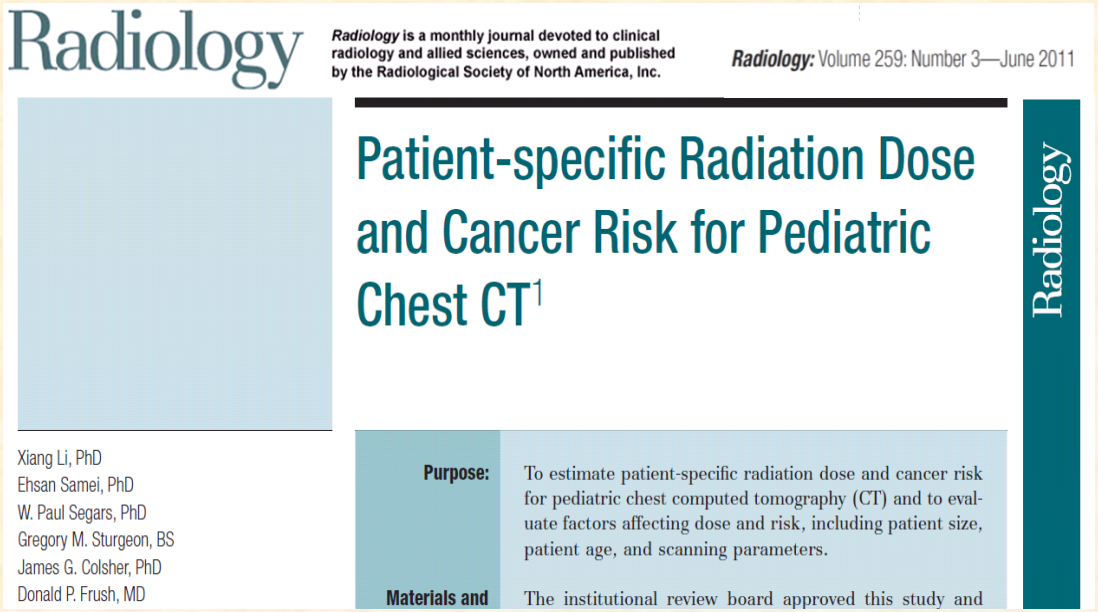
- The goal is to have a generic quantity reflecting radiobiological detriment or risk, so the ICRP adoption of a quantity (effective dose) that has units of Sieverts, is puzzling
- A major advantage of "effective risk" is that it is directly interpretable as a risk
- As we struggle with the rapidly increasing radiology contribution to the population exposure, it is surely advantageous to have a measure of the radiological detriment which actually means something to most users

- Which is more intuitively interpretable?
  1. An effective dose of (say) 1 mSv
  2. An effective risk of (say) 4 per 100,000

Summary
The case for replacing effective dose

- **For radiation protection one could perhaps make an argument for the continued use of effective dose, flawed and confusing as it is**
  - **In practice, however, effective dose is now largely used for patient risk comparison and characterization, and there its use cannot be justified**
- **Effective risk, where organ doses are weighted with cancer risks estimates, would perform the same comparative role as effective dose, and would**
  - **be just as easy to estimate**
  - **be age-dependent, if required**
  - **be less prone to misuse**
  - **be more directly understandable,**
  - **and would be based on objective science**

The radiology community are starting to use more scientific approaches



Radiology

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Radiology: Volume 259: Number 3—June 2011

Patient-specific Radiation Dose and Cancer Risk for Pediatric Chest CT[1]

Xiang Li, PhD
Ehsan Samei, PhD
W. Paul Segars, PhD
Gregory M. Sturgeon, BS
James G. Colsher, PhD
Donald P. Frush, MD

Purpose: To estimate patient-specific radiation dose and cancer risk for pediatric chest computed tomography (CT) and to evaluate factors affecting dose and risk, including patient size, patient age, and scanning parameters.

Materials and The institutional review board approved this study and

Radiology

While widely used as a surrogate for population radiation risk, effective dose does not reflect individual patient risk; the tissue-weighting factors are mean values representing averages across both sex and age (20). Therefore, to more accurately estimate individual patient risks, we further implemented a metric of risk, termed *risk index*, defined as

$$\text{Risk index} = \sum_T r_T(\text{sex},\text{age})H_T, \quad (2)$$

where H_T is the equivalent dose for organ or tissue T and r_T is the sex-, age-, and tissue-specific risk coefficient (cases per 100000 exposed to 0.1 Gy) for lifetime attributable risk of cancer incidence. The metric of risk index presented here was adopted from the recently proposed concept of effective risk (24).