

# Health effects on humans: lessons for the ICRP system of radiological protection from the Chornobyl and Fukushima nuclear power plant accidents

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# Introduction: Chornobyl vs Fukushima (1)

- Chornobyl and Fukushima reactor accidents are two most serious nuclear accidents to have occurred
- On 26<sup>th</sup> April 1986 steam/hydrogen explosion occurred in reactor 4 at Chornobyl nuclear power plant in Ukraine. Reactor largely destroyed and there being no secondary containment, meltdown and fire that released radioactivity, most over next 10 days
- On 11<sup>th</sup> March 2011 magnitude 9.1 Mw earthquake + tsunami resulted in cooling loss to shut-down reactors 1-3 at Fukushima, which suffered meltdowns+hydrogen explosions, breaching containment, releasing radioactivity, most over next 20 days
- Chornobyl releases much more serious than Fukushima – see Table 1

Table 1 Releases from Chornobyl and Fukushima (from UNSCEAR 2008, 2021)

Radionuclide	Half life	Activity releases (PBq) to atmosphere	
		Chornobyl	Fukushima
<b>Inert gases</b>			
<sup>85</sup> Kr	10.72 y	33	
<sup>133</sup> Xe	5.25 d	6500	7300
<b>Volatile elements</b>			
<sup>129</sup> Te	33.6 d	240	
<sup>132</sup> Te	3.26 d	~1150	
<sup>131</sup> I	8.04 d	~1760	120
<sup>133</sup> I	20.8 h	910	
<sup>134</sup> Cs	2.06 y	~47	10
<sup>136</sup> Cs	13.1 d	36	
<sup>137</sup> Cs	30.17 y	~85	10
<b>Elements with intermediate volatility</b>			
<sup>89</sup> Sr	50.5 d	~115	
<sup>90</sup> Sr	29.12 y	~10	<0.01

Most significant radionuclides for human health

<sup>131</sup>I, <sup>137</sup>Cs and <sup>90</sup>Sr

# Introduction: Chornobyl vs Fukushima (2)

	Chornobyl	Fukushima
Number of persons developing acute radiation syndrome (ARS)	134	0
Deaths from ARS	28	0
Number of people evacuated	116,000 in 1986	78,000 (precautionary, 20 km zone) 30,000 (voluntary, 20-30 km zone) 10,000 (based on measurements)
Number of people relocated	~340,000 (116,000+220,000 (1989-92))	118,000 (78,000+30,000+10,000)
Collective effective dose to cleanup workers	61,000 man Sv	860 man Sv
Effective dose to population	445,000 man Sv to Europe (1986-2005)	32,000 man Sv to Japan 2011-2021

❑ **Chornobyl was much more significant than Fukushima in impact on humans and environment**

❑ workers with acute radiation syndrome (ARS), relocations, collective dose

❑ **Measures taken by Japanese government meant that population exposure (apart from to workers at Fukushima plant) was minimal**

(UNSCEAR 2013)

❑ 174 (out of ~20,000) workers with effective doses > 100 mSv

# Fukushima health consequences

- ❑ **However, non-radiological impact of Great East Japan earthquake and tsunami, and associated evacuation has been considerable**
  - ❑ Tsunami and earthquake directly caused ~18,500 deaths, some of these missing
  - ❑ 50-200% increased deaths in evacuated elderly in nursing care, likely due to disrupted care arrangements (Hasegawa *et al Lancet* 2015 386 479-88, Hasegawa *et al Clin Oncol* 2016 28 237-44)
  - ❑ Increases in mental health problems, elevated blood glucose, hyperlipidemia in Fukushima prefecture, likely due to psychosocial consequences of tsunami and nuclear accident (Hasegawa *et al Lancet* 2015 386 479-88, Hasegawa *et al Clin Oncol* 2016 28 237-44, Leppold *et al Bull WHO* 2016 94 859-60)
- ❑ **Few studies of what may be radiation-related human health effects**
  - ❑ Tsuda *et al* (*Epidemiology* 2016 27 316-22) assessed thyroid cancer prevalence of <18 y olds via ultrasound scan in 9 areas of Fukushima prefecture up to 31/12/2014
  - ❑ Tsuda *et al* concluded “An excess of thyroid cancer has been detected ... in Fukushima Prefecture and is unlikely to be explained by a screening surge”
  - ❑ However, this study, and its conclusion, has been much criticised (Wakeford *et al Epidemiology* 2016 27 e20-e21)
- ❑ **Other studies to date of radiation-related human health uninformative**
  - ❑ From this point forward concentrate on what may be learned from Chornobyl

# Chornobyl cancer studies

# Childhood thyroid screening studies

	Country	Endpoint	ERR/Gy (95% CI)	Thyroid cancers
<b>Brenner et al (2011)</b>	Ukraine	Thyroid cancer incidence	1.91 (0.43, 6.34)	65
<b>Little et al (2014)</b>	Ukraine	Thyroid cancer prevalence unadjusted for dose error	5.38 (1.86, 21.01)	45
		Thyroid cancer prevalence adjusted for dose error	4.78 (1.64, 19.69)	
<b>Tronko et al (2017)</b>	Ukraine	Thyroid cancer	1.36 (0.39, 4.15)	47
		Follicular adenoma	2.03 (0.55, 6.69)	33
<b>Little et al (2015)</b>	Belarus	Thyroid cancer prevalence unadjusted for dose error	1.51 (0.53, 3.86)	87
		Thyroid cancer prevalence adjusted for dose error	1.48 (0.53, 3.87)	
<b>Low dose childhood exposed pooling study</b> (Lubin et al <i>J Clin Endocrinol Metab</i> 2017 102 2575-83)				
<b>Lubin et al (2017)</b>			8.5 (5.5, 12.0)	252

- ❑ **Thyroid doses are substantial, exceeding 30 Gy for some in all studies**
- ❑ **Risks (ERR/Gy) are somewhat less than those in pooling study of childhood exposed groups exposed < 200 mGy** (Lubin et al *J Clin Endocrinol Metab* 2017 102 2575-83)

# Screening study of thyroid cancer and nodules after exposure *in utero* (Hatch et al J Clin Endocrinol Metab 2019 104 41-48)

Reference	Country	Endpoint	ERR/Gy (+95% CI)	Cases
Hatch et al (2019)	Ukraine	Thyroid cancer	3.91 (-1.49, 65.66)	8
		Large (>10 mm) benign thyroid nodule	4.19 (0.68, 11.62)	43
		Small (<10 mm) benign thyroid nodule	0.34 (-0.67, 2.24)	178
<b>Cancer risk following X-ray <i>in utero</i> (Bithell &amp; Stiller Stat Med 1988 7 857-64)</b>				
Bithell & Stiller (1988)	UK	Trimester 1	284.2 (75.3, 1141.6)	
		Trimester 2	20.8 (0.27, 61.8)	
		Trimester 3	28.8 (17.1, 43.6)	

- ❑ Dose mainly internal via ingestion of <sup>131</sup>I
- ❑ Some postnatal dose
- ❑ Doses are moderate/high over range <20 - 2268 mGy, so mostly high dose rate (at least for higher dose exposed)
- ❑ Thyroid cancer risks (ERR/Gy) are generally lower than, but statistically compatible with, those medically exposed *in utero* (Bithell & Stiller Stat Med 1988 7 857-64)

# Case-control studies of thyroid cancer in cleanup workers

Study	Country	Endpoint	EOR/Gy (95% CI)	Cases
Kesminiene <i>et al</i> (2012)	Belarus, Russia, Baltic states	Thyroid cancer	3.8 (1.0, 10.9)	127
Little <i>et al</i> (2022)	Ukraine	Thyroid cancer	0.437 (-0.042, 1.577)	149
			0.517 (-0.039, 2.035)	
		Follicular morphology tumors	3.224 (-0.082, 30.615)	24
			4.708 (-0.075, 85.143)	24
<b>Japanese atomic bomb survivors age at exposure &gt; 20</b>				
Furukawa <i>et al</i> (2013)	Japan	Thyroid cancer	0.27 (<0, 1.07)	180

- ❑ Thyroid doses (external, <sup>131</sup>I and other radionuclides), spanning range 0 - > 600 mGy, mostly low dose rate, were obtained via RADRUE/Rockville, based on interviews in 2010-2016 (25 - 30 years after accident)
- ❑ Risks (ERR/Gy) are somewhat more than those in adulthood exposed group in atomic bomb survivors (Furukawa *et al Int J Cancer* 2013 132 1222-6) although statistically compatible at least with findings in Ukraine
- ❑ Doses in all studies adjusted for dose error

# Leukaemia after exposure *in utero* or age < 6 – case-control study (Davis et al Int J Epidemiol 2006 35 386-96)

Country	Endpoint	EOR /Gy (95% CI)	Cases
Belarus	All leukaemia	4.09 (NA, 37.7)	114
Russia		-4.94 (NA)	39
Ukraine		78.8 (22.1, 213)	268
All countries		32.4 (8.78, 84.0)	421
<b>9-cohort childhood exposure leukaemia low dose pooling <small>(Little et al Lancet Haematol 2018 5 e346-e358)</small></b>			
	All leukaemia excluding CLL	8.4 (-0.3, 20.8)	221
	Acute leukaemia	17.0 (4.0, 37.1)	139

- ❑ Dose mainly external  $\gamma$  and via ingestion, from  $^{137}\text{Cs}$ , and  $^{134}\text{Cs}$  adjusted for dose error
- ❑ Doses are moderate – maximum for cases 391 mGy, for controls 265 mGy, so low dose rate
- ❑ There may be an issue with control selection in this study
- ❑ Risks (ERR/Gy) are slightly higher than but statistically compatible with those in pooling study of childhood exposed groups < 100 mGy (Little et al Lancet Haematol 2018 5 e346-e358)

# Haematological malignancies in cleanup workers

Reference	Country	Endpoint	ERR/Gy (95% CI)	Cases
Kesminiene <i>et al</i> (2008)	Belarus, Russia, Baltic states	All haematological malignancies	6.0 (-0.2, 23.5)	70
		All haematological malignancies excluding multiple myeloma	6.9 (0.0, 27.1)	65
		Leukaemia excluding CLL	5.0 (-3.8, 57)	19
		Chronic lymphocytic leukaemia (CLL)	4.7 (NA, 76.1)	21
		Non-Hodgkin lymphoma (NHL)	28.1 (0.9, 243)	20
Zablotska <i>et al</i> (2013)	Ukraine	CLL	2.58 (0.02, 8.43)	65
		Leukaemia excluding CLL	2.21 (0.05, 7.61)	52
		All leukaemia	2.38 (0.49, 5.87)	117
<b>All age Japanese atomic bomb survivors (Hsu <i>et al Radiat Res</i> 2013 179 361-82)</b>				
Hsu <i>et al</i> (2013)	Japan	Leukaemia other than CLL or ATL	4.75 (3.36, 6.60)	259
		NHL male	0.46 (-0.08, 1.29)	501
		NHL female	0.02 (<-0.44, 0.64)	

- ❑ Dose mainly via external  $\gamma$
- ❑ Doses spanning range 0 - > 500 mGy, mostly at low dose rate
- ❑ Notable increase in risk of CLL – also seen in Japanese atomic bomb survivors (but not many other groups)
- ❑ Risks (ERR/Gy) are slightly higher than but statistically compatible with those in atomic bomb survivors (Hsu *et al Radiat Res* 2013 179 361-82)

# Breast cancer in environmentally exposed – Bryansk case-control study (Rivkind et al Int J Epidemiol 2020 49 448-56)

Reference	Country	Endpoint	EOR/Gy (+95% CI)	Cases	Notes
Rivkind et al (2020)	Russia	All breast cancers among women age <55	57 (-0.1, 1550)	468	Adjusted for menopausal status, breast cancer in 1 <sup>st</sup> degree relatives, nulliparity, age at 1 <sup>st</sup> live birth, education, employment in metallurgy or mining
<b>Japanese atomic bomb survivors (Brenner et al Radiat Res 2018 190 433-44)</b>					
Brenner et al 2018	Japan		1.12 (0.73, 1.59)	1470	

- ❑ Dose mainly via external  $\gamma$  and ingested  $^{137}\text{Cs}$ , generally moderate (maximum dose to cases 410 mGy, to controls 210 mGy) – so low dose rate
- ❑ Risk (ERR/Gy) very much higher than but statistically compatible with Japanese atomic bomb survivors (Brenner et al Radiat Res 2018 190 433-44)

# Summary of Chernobyl cancer studies

- ❑ **Apart from thyroid screening studies, most Chernobyl studies are at low dose rate (<5 mGy/h), although in some cases for moderate/high total dose (>100 mGy)**
  - ❑ There are 345 cleanup workers in Ukrainian-American cohorts who received dose rates > 25 mGy / day for certain periods, generally in 1986 – so some likely getting > 5 mGy / h
- ❑ **These show elevated risks comparable with those from high dose rate studies**
- ❑ **Little evidence of ameliorating effect of low dose rate exposure**

# Chornobyl non-cancer studies

# Cataract in cleanup workers (Worgul et al Radiat Res 2007 167 233-43)

Reference	Country	Type of cataract	EOR/Gy (95% CI)	Prevalent cases	Ascertainment method
<b>Worgul et al (2007)</b>	Ukraine	Stage 1 cataract	0.49 (0.08, 1.06)	1870	Slit-lamp biomicroscopy using Merriam-Focht scoring
		Stage 1-5 cataract	0.70 (0.22, 1.38)	1944	
		Stage 1 non-nuclear cataract	0.52 (0.10, 1.12)	1693	
		Stage 1-5 non-nuclear cataract	0.65 (0.18, 1.30)	1757	
		Stage 1 posterior subcapsular cataract	0.42 (0.01, 1.00)	1464	
<b>Japanese atomic bomb survivor cataracts</b> <small>(Hida et al Radiat Res 2026 205 284-94)</small>					
<b>Hida et al (2026)</b>	Japan	Posterior subcapsular cataract	0.68 (0.13, 2.50)	154	Slit lamp / Scheimpflug / retroillumination
		Nuclear cataract	0.29 (-0.07, 0.79)	722	
		Cortical cataract	-0.13 (-0.33, 0.13)	97	

- ❑ Eye lens  $\beta + \gamma$  doses derived via combination of questionnaire derived, badge doses and tooth enamel electron paramagnetic resonance (EPR)
- ❑ Doses low/moderate – 98% < 700 mGy, low dose rate
- ❑ EOR/Gy are comparable with those in atomic bomb survivors (Hida et al Radiat Res 2026 205 284-94)

# Cardiovascular disease (CVD) in cleanup workers

Reference	Country	Endpoint	ERR / Gy (+95% CI)	Cases/deaths	Mortality/incidence + adjustments
Kashcheev <i>et al</i> (2016)	Russia	Cerebrovascular disease (CeVD) (ICD10 I60-I69)	0.45 (0.28, 0.62)	23,264	Incidence
Kashcheev <i>et al</i> (2017)	Russia	Ischaemic heart disease (IHD) (ICD10 I20-I25)	0.42 (0.25, 0.60)	22,220	Incidence
		CVD (ICD10 I00-I99)	0.47 (0.31, 0.63)	27,456	
Chekin <i>et al</i> (2022)	Russia	CVD (ICD10 I00-I99)	0.35 (0.15, 0.56)	15,025	Mortality
Tatarenko (2018)	Ukraine	Myocardial infarction	1.45 (-4.31, 7.70)	251	Prevalence, adjusted for diabetes, hypercholesterolemia, serum creatinine
Krasnikova <i>et al</i> (2013)	Ukraine	Chronic CeVD (ICD10 I67, I69)	0.52 (0.35, 0.77)	NA	Incidence, adjusted for smoking, diabetes, hypertension, hypercholesterolemia, alcohol abuse, salt intake, thyroid disease, physical and emotional strain
		Cerebral atherosclerosis (ICD10 I67.2)	1.13 (1.06, 1.20)	NA	
<b>Low dose rate meta analysis (Little <i>et al</i> BMJ 2023 380 e072924 rev 2025)</b>					
Little <i>et al</i> (2023)	Various	IHD	0.22 (0.10, 0.34)		
		CeVD	0.30 (0.10, 0.50)		
		CVD	0.23 (0.14, 0.32)		

- ❑ Doses generally moderate – most < 300 mGy, low dose rate
- ❑ Significant issues with dosimetry (using all Ministry of Defence registry) and methods of follow-up (via NRER registry) in Russian studies, which also lack lifestyle information
- ❑ Ukraine studies small – may also be problematic
- ❑ ERR/Gy somewhat higher than those in recent meta-analysis (Little *et al* BMJ 2023 380 e072924 rev 2025) (which include Russian incidence studies)

# Transgenerational effects in cleanup workers and evacuees from 30 km exclusion zone (Yeager et al Science 2021 372 725-9)

Reference	Country	Endpoint	ERR/ Gy (95% CI)
Yeager et al (2021)	Ukraine	Paternal <i>de novo</i> mutations	-0.00594 (-0.0340, 0.0221)
		Maternal <i>de novo</i> mutations	-0.176 (-0.443, 0.0910)

- ❑ Parent/offspring trio study assessing *de novo* mutations in offspring
- ❑ Preconceptional doses (low dose rate) – 0 - 4080 mGy for fathers  
0.13 - 550 mGy for mothers
- ❑ Consequently study has statistical power > 99.9% to detect doubling dose of 1 Gy (1-sided test  $\alpha=0.05$ )
- ❑ Implied lower 95% CI of gonadal doubling doses  
paternal =  $1 / 0.0221/\text{Gy} \sim 45.2 \text{ Gy}$   
maternal =  $1 / 0.0910/\text{Gy} \sim 11.0 \text{ Gy}$
- ❑ These vastly exceed ICRP assumed doubling dose (largely based on 7-locus mouse data) of 1 Gy

# Overall conclusions

- ❑ **As yet little to be learned from Fukushima accident, where population exposures are much lower than for Chernobyl accident, limited follow-up**
  - ❑ However, this may soon change
- ❑ **Chernobyl cancer studies**
  - ❑ For all apart from thyroid screening studies radiation is at low dose rate
  - ❑ Little evidence of ameliorating effects of low dose rate exposure
  - ❑ Weak evidence of thyroid cancer risk following *in utero* exposure to <sup>131</sup>I
- ❑ **Chernobyl non cancer studies**
  - ❑ Mostly moderate dose and low dose rate studies
  - ❑ Excess risk of cataract, cardiovascular disease (CVD) – but CVD studies may be of low quality
    - ❑ Suggests ICRP assumed threshold of 0.5 Gy for tissue reaction effects may not be low enough
  - ❑ No evidence of transgenerational effect
    - ❑ Implied doubling dose >10 Gy

# Links to ongoing work of ICRP

- ❑ Chernobyl studies provide unique contribution to available knowledge on radiation-related health effects, particularly valuable because dose rates are mostly low
- ❑ **ICRP Task Group TG118**
  - ❑ The findings for those studies where dose is largely from  $^{131}\text{I}$  has obvious application to estimation of relative biological effectiveness (RBE) for beta emitters
- ❑ **ICRP Task Group TG121**
  - ❑ The largely negative findings for the study of transgenerational effects and thyroid cancer *in utero* require assessment
- ❑ **ICRP Task Group TG123**
  - ❑ The findings of excess risk of cataract and cardiovascular disease have obvious implications for assessments of tissue reactions

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