HHS Public Access

Author manuscript

Radiat Res. Author manuscript; available in PMC 2023 December 01.

Published in final edited form as:

Radiat Res. 2022 December 01; 198(6): 615–624. doi:10.1667/RADE-22-00132.1.

The Evidence for Excess Risk of Cancer and Non-Cancer Disease at Low Doses and Dose Rates

S.L. Simon[a], **G.M. Kendall**[b], **S.D. Bouffler**[c], **M.P. Little**[d,1]

[a]Division of Cancer Epidemiology and Genetics, National Cancer Institute (retired)

[b]Cancer Epidemiology Unit, Oxford Population Health, University of Oxford, Richard Doll Building, Old Road Campus, Headington, Oxford, OX3 7LF, United Kingdom

[c]Radiation Effects Department, UK Health Security Agency (UKHSA), Chilton, Didcot OX11 0RQ, United Kingdom

[d]Radiation Epidemiology Branch, Division of Cancer Epidemiology and Genetics, National Cancer Institute, Bethesda, Maryland 20892-9778

Abstract

The question of whether there are excess radiation-associated health risks at low dose is controversial. We present evidence of excess cancer risks in a number of (largely pediatrically or in utero exposed) groups exposed to low doses of radiation (<0.1 Gy). Moreover, the available data on biological mechanisms do not provide support for the idea of a low-dose threshold or hormesis for any of these endpoints. There are emerging data suggesting risks of cardiovascular disease and cataract at low doses, but this is less well established. This large body of evidence does not suggest and, indeed, is not statistically compatible with any very large threshold in dose (>10 mGy), or with possible beneficial effects from exposures. The presented data suggest that exposure to low-dose radiation causes excess cancer risks and quite possibly also excess risks of various non-cancer endpoints.

INTRODUCTION

The detrimental tissue-reaction (deterministic) and stochastic effects associated with moderate- and high-dose ionizing low-linear energy transfer (LET) radiation (e.g., X rays, γ rays) exposure are well known (1). Much more controversial are the health effects at low doses (<0.1 Gy) or low dose rates (<5 mGy/h) (2, 3). In contrast to tissue-reaction effects, for stochastic effects scientific committees generally *assume* that at low doses there is a positive linear component to the dose response and that there is no threshold, or beneficial effect (1). However, as we review below there is also accumulating *direct* evidence of excess risk[2] of cancer and various other health endpoints in a number of populations exposed at moderate and low doses.

[1]Address for correspondence: Radiation Epidemiology Branch, National Cancer Institute, 9609 Medical Center Drive, Bethesda, MD 20892-9778; mark.little@nih.gov.

[2]For clarity, here we define excess risk. *Risk* is an individual attribute that is most often measured at the level of a population. It can be determined as the fraction of a population developing a well-defined medical condition (e.g., cancer, cardiovascular disease)

The health risks of low-level exposure to ionizing radiation have been assumed to be associated primarily with cancer (1). However, evidence has recently emerged of an association between lower doses (<0.5 Gy) and late-presenting cardiovascular disease (CVD) (all circulatory disease) (4-6). There is also accumulating evidence from various occupational groups exposed at low dose rate of excess risks of cataract (7, 8). The possible associated mechanisms are necessarily somewhat uncertain for both endpoints, although some plausible hypotheses have been advanced (9-11).

Nevertheless, the issue of low-dose radiation risk is controversial, and there have been claims that low dose risks are markedly overestimated by the use of linear extrapolation from moderate dose exposed groups (12) and there are also those claiming that linear extrapolation substantially underestimates low dose risk (13-16).

A related question to that of the existence or non-existence of low-dose risk is whether the risk at low doses is approximately linear with dose, an assumption which underlies the linear-no-threshold (LNT) model commonly assumed by expert advisory bodies (2). LNT is recognized to be an approximation, made for practicality in the context of radiological protection, although one for which there is some radiobiological basis, based on DNA damage considerations, as we demonstrate below; as we argue there is also a considerable body of evidence that it is not excessively conservative, indeed that there is considerable evidence of cancer risk at low dose (<0.1 Gy), and emerging evidence of certain types of non-cancer risk at somewhat higher levels of dose (<0.5 Gy). The present paper briefly summarizes a large number of comprehensive reviews of the low-dose epidemiologic literature (17, 18) as well as more specialist and mostly systematic reviews (5, 19-23); there have been similar reviews of radiobiologic data (24), albeit not so narrowly focused on low doses. This commentary does not address the question of possible genetic risks.

Radio-Epidemiological Findings

Detrimental tissue-reaction effects (deterministic effects) and cancer initiation and development (which, along with assumed hereditary effects constitute stochastic radiation effects) associated with moderate- and high-dose low-LET ionizing radiation (e.g., X ray) exposure are well known (1). There is abundant evidence that moderate doses (0.1–1 Gy) and high doses (>1 Gy) (19) of sparsely ionizing low-LET radiation (e.g., X rays, γ rays), particularly when received at a high dose-rate, are associated with elevated cancer risks (1, 2, 25, 26). Reduced statistical power means that less is known about the risks arising from exposures at low doses (<0.1 Gy) and low dose rates (<5 mGy/h). Many regulatory bodies assume that at sufficiently low doses there is an increasing linear component to the dose response for stochastic effects, i.e., that there is a positive correlation of risk with dose, with no threshold, or beneficial effect of radiation exposure (2). However, there is accumulating direct evidence of excess risk of cancer in a number of populations exposed to low doses. Some of these data are summarized in Table 1. We review some of this evidence below. A more comprehensive review of the findings from various radio-epidemiological studies of cancer is provided by Rühm *et al* (27).

over a given interval of time. *Excess risk* refers to that proportion of the *risk* which is greater in magnitude than the usual baseline (background rate) which can sometimes be attributed to a particular causal factor, e.g., radiation exposure.

One of the most important sources of information on radiation risks is a study of the survivors of the atomic bombings of Hiroshima and Nagasaki, a cohort of about 120,000 persons identified via information collected from the 1950 Japanese national census and assembled in the early- to mid-1950s, i.e., 5–10 years after the bombings. Despite what is often thought, the mean dose in the Japanese atomic bomb survivor Life Span Study (LSS) cohort is quite low, about 0.1 Gy, with many analyses restricted to 4 Gy or less (28, 29). The most recent analyses of the Japanese atomic bomb survivor LSS incidence data suggest that there is significant excess risk of all solid cancers for assessed doses of less than 0.1 Gy (29). A combined analysis of data for leukemia and myeloid neoplasms among groups exposed in childhood in the LSS and elsewhere found evidence of significant excess risk of all myeloid malignant neoplasms under 100 mSv,[3] and for acute lymphoblastic leukemia under 20 mSv (30) (see also Table 1).

Another important source of information on radiation risks is studies of radiation workers, i.e., of those exposed to radiation in the course of their work in the nuclear industry or elsewhere. One of the most important such studies is the International Nuclear Workers Study (INWORKS), which included over 300,000 workers with a mean cumulative exposure of 20.9 mGy (31). Although not a low-dose study (the maximum cumulative dose is about 1.3 Gy), the exposures are all at low dose rate and yield significant excess risks of solid cancer and leukemia (31, 32).

Many of the low-dose studies cited in Table 1 yield significant excess risk for various cancer endpoints, strongly suggesting that risk at low doses is not zero. It is also clear from comparison of the excess relative risks per Gy (ERR/Gy) given in Table 1 that they are consistent with each other and with ERR/Gy that can be derived from the LSS. They would not be consistent with risks several orders of magnitude higher than those derived from the LSS, as has been suggested by various researchers (13-16).

In particular, there is evidence of excess risk of most types of childhood cancer associated with radiation exposures of the order of 10–20 mGy from diagnostic X-ray exposure in the Oxford Survey of Childhood Cancers and in various other groups exposed in utero (20, 33, 34) (see Table 1). While these data are not yet universally accepted, Wakeford and Little note “the consistency of the childhood cancer risk coefficients derived from the Oxford Survey and from the Japanese cohort irradiated in utero supports a causal explanation of the association between childhood cancer and an antenatal X-ray examination found in case-control studies. This implies that doses to the foetus in utero of the order of 10 mSv discernibly increase the risk of childhood cancer” (33). There are also a number of studies of childhood cancer and natural background radiation exposure, at doses of the order of 10–20 mGy, suggesting excess risk for leukemia and brain cancer (35, 36). At slightly higher doses, increased risks of leukemia and brain cancer have been observed in pediatrically-exposed groups given multiple computed tomography (CT) examinations, at doses of about 60 mGy to the respective tissues (active bone marrow, brain) (37-40). Again, the excess risks in all these studies are consistent with each other and with those observed among the Japanese atomic bomb survivors (33, 35-39).

[3]In many studies where most dose deposition originates with photon absorption, mSv and mGy may be taken as equivalent.

The health risks of low-level exposure to ionizing radiation are most commonly assumed to be associated primarily with cancer (1). However, there is evidence of excess CVD risk in a number of moderate dose (<5 Gy) exposed groups, including the Japanese atomic bomb survivors (41, 42). Evidence has recently emerged of an association between lower doses (<0.5 Gy) and CVD, in particular in a number of groups of nuclear workers (43, 44). This has been reinforced by conclusions of a number of recent (systematic and non-systematic) reviews, all suggesting an excess radiation-associated CVD risk at occupational and environmental dose levels (<0.5 Gy) (4, 5, 45) (see also Table 2). However, the presence and magnitude of the excess CVD risk at low doses is still relatively controversial, largely due to the difficulties in accurately assessing the role of confounding exposures and other contributory risk factors for CVD. Interstudy heterogeneity complicates a causal interpretation of the observed risks, so that much remains unknown as to the shape of the dose response (4, 5, 46), if indeed the observed trends represent causal relationships.

Although there are long-established risks of cataract at high doses (47), there is now a considerable body of evidence of excess risk of cataract at moderate levels of dose (<5 Gy) (7, 48), and some large and well powered occupational studies suggesting excess risk at <0.1 Gy (8) (see also Table 3). The cataract risks derived from various studies are reasonably consistent with each other (Table 3). However, most of the studies [all except Little et al. (8)] are not at exposure levels that can truly be defined as low dose (<0.1 Gy), although many are at low dose rate (7, 8, 49-51).

Radiobiological Considerations

There are data, reviewed elsewhere (52), suggesting an increase in stable chromosome aberrations and other markers of biological damage in the peripheral blood lymphocytes of nuclear workers and other groups with protracted radiation exposures. Chromosome changes play a major role in carcinogenesis (the process by which normal cells are transformed into cancer cells) and there is mounting evidence that the presence of increased frequencies of chromosome aberrations in peripheral blood lymphocytes in healthy individuals could be a surrogate for the specific changes associated with carcinogenesis and, therefore, indicative of cancer risk (53-57).

Cancer is thought to result from mutagenic damage to a single cell, specifically to its nuclear DNA, which in principle could be caused by clustered single-strand breaks (SSB) which result in a double-strand break (DSB) of the DNA, as well as DNA-replication processing of SSBs that lead to DNA DSB (58); this argues against the existence of a threshold of dose below which cancer risk is not elevated, as discussed elsewhere (52). A more recent evaluation of the biological mechanisms relevant for low dose radiation cancer risk inference concluded that “There remains good justification for the use of a non-threshold model for risk inference for radiation protection purposes, given the present robust knowledge on the role of mutation and chromosomal aberrations in carcinogenesis” and, in relation to the potential targets in addition to nuclear DNA, “The potential contributions of phenomena such as transmissible genomic instability, bystander phenomena, induction of abscopal effects and adaptive response remain unclear.” (24). As shown in Table 4, for orthovoltage (250 kV) X rays with various degrees of standard filtration irradiating cells having a mean

4–10 μm diameter nucleus (a reasonable range), a radiation dose of 1 mGy (0.001 Gy) corresponds to between 0.051 to 0.53 electron tracks traversing the cell nucleus (59). Table 4 also demonstrates that the number of electron tracks per cell nucleus are slightly lower, with a range of 0.046 to 0.39, for the lower radiation energy (65 kV) X rays that were likely used obstetrically in the 1950s (59). This suggests that at low doses (0.01 Gy or less spread over a year), it is unlikely that temporally and spatially separate electron tracks could cooperatively produce DNA damage (60), so that in this very low-dose region, DNA damage at a cellular level would be proportional to dose.

Cells have substantial repair mechanisms. It is known that the efficiency of cellular repair processes varies with dose and dose rate (61, 62), and this may be the reason for the curvature that is observed in the cancer dose response at higher levels of dose [e.g., for leukemia (63) and some solid cancers (28)] and dose rate effects observed in epidemiological (1) and animal (61, 64, 65) data. However, none of these repair processes are 100% efficient, so after mutagenic damage there is a non-zero probability of a damaged cell surviving with unrepaired damage, that may manifest later as cancer. Here, we point out that not all radiation protection theory is based on a simple linear relationship, indeed the idea of non-linearity in biological response is clearly implied by use of concepts such as the dose and dose rate effectiveness factor (DDREF) (2) and, thus, is actually more complex than implied by some (12).

Some Considerations on Interpretation of Epidemiologic Studies

Not all epidemiological studies have equal degrees of validity or generalizability and, for that very reason, academic, research, and other expert institutions like the National Academy of Sciences (NAS), the International Agency for Research on Cancer (IARC/WHO), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) routinely examine the evidence on radiation-associated health risk and produce a group consensus opinion that weighs the strengths and limitations of the many published studies that contribute to the total knowledge base on radiation health risks. Conclusions about the nature of radiation-associated health risk should not be drawn from single studies, but by the overall weight of evidence. In this kind of evaluation, study findings are weighted by specific criteria including type of study (cohort, case-control, randomized trial, correlational), population (sample) size, degree of control of bias and confounding, statistical methods used for analysis, use of pooled- or meta-analyses, uncertainties in diagnoses and estimated exposures, and the degree to which specific and well-known criteria for causality have been satisfied. Readers are referred to, for example, discussions on these issues by NAS (25), IARC (26) and UNSCEAR (1). Focusing on just a few studies can easily lead to unreliable conclusions, whether in the direction of underestimating risk (12) or substantially overestimating risk (13-16); that neither extreme position is tenable is strongly suggested by review of the totality of epidemiological data, as for example shown in part in Table 1. The requirement to understand the theoretical bases as well as the limitations of epidemiology cannot be over-emphasized for those attempting to derive conclusions about the existence as well as the magnitude of radiation health risks.

CONCLUSIONS

Based on the data and explanations we have provided, we believe that the arguments proposed by some that LNT overestimates low-dose cancer risk (12, 66) are likely to be grossly invalid. Likewise, the overall body of epidemiologic data are clearly inconsistent with cancer risks substantially higher than those implied by LNT, as has been suggested by others (13-16).

We have presented evidence that excess cancer risks have been noted in a number of (largely pediatrically or in utero exposed) groups exposed to low radiation doses (<0.1 Gy) (19, 20). The available data on biological mechanisms do not provide general support for the idea of a low-dose threshold or hormesis for any of these endpoints (24, 61, 62). This large body of evidence does not suggest and, indeed, is not statistically compatible with any very large threshold in dose (>10 mGy), or with possible beneficial effects from exposures.

ACKNOWLEDGMENTS

The work of SLS and MPL was funded by the Intramural Research Program of the National Institutes of Health, National Cancer Institute. The authors are grateful for the detailed and helpful comments of the Associate Editor and of the three referees, also to Professor Dudley Goodhead for provision of extra data.

REFERENCES

1. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UNSCEAR 2006 Report. Annex A. Epidemiological Studies of Radiation and Cancer. New York: United Nations; 2008; E.08.IX.6, 13–322.
2. International Commission on Radiological Protection (ICRP), The 2007 Recommendations of the International Commission on Radiological Protection. ICRP publication 103. Ann ICRP 2007; 37(2-4), 1–332.
3. Wakeford R, Tawn EJ, The meaning of low dose and low dose-rate. J Radiol Prot 2010; 30, 1–3. [PubMed: 20234068]
4. Little MP, Azizova TV, Bazyka D, Bouffler SD, Cardis E, Chekin S, et al. Systematic review and meta-analysis of circulatory disease from exposure to low-level ionizing radiation and estimates of potential population mortality risks. Environ Health Perspect 2012; 120, 1503–11. [PubMed: 22728254]
5. Little MP, Azizova TV, Hamada N, Low- and moderate-dose non-cancer effects of ionizing radiation in directly exposed individuals, especially circulatory and ocular diseases: a review of the epidemiology. Int J Radiat Biol 2021; 97, 782–803. [PubMed: 33471563]
6. Azizova TV, Moseeva MB, Grigoryeva ES, Hamada N, Incidence risks for cerebrovascular diseases and types of stroke in a cohort of Mayak PA workers. Radiat Environ Biophys 2022; 61, 5–16. [PubMed: 35182179]
7. Azizova TV, Hamada N, Grigoryeva ES, Bragin EV, Risk of various types of cataracts in a cohort of Mayak workers following chronic occupational exposure to ionizing radiation. Eur J Epidemiol 2018; 33, 1193–204. [PubMed: 30306422]
8. Little MP, Kitahara CM, Cahoon EK, Bernier M-O, Velazquez-Kronen R, Doody MM, et al. Occupational radiation exposure and risk of cataract incidence in a cohort of US radiologic technologists. Eur J Epidemiology 2018; 33, 1179–91.
9. Little MP, Gola A, Tzoulaki I, A model of cardiovascular disease giving a plausible mechanism for the effect of fractionated low-dose ionizing radiation exposure. PLoS Comput Biol 2009; 5, e1000539. [PubMed: 19851450]
10. Ainsbury EA, Dalke C, Mancuso M, Kadhim M, Quinlan RA, Azizova T, et al. Introduction to the Special LDLensRad Focus Issue. Radiat Res 2022; 197, 1–6. [PubMed: 34788470]

11. Lowe D, Raj K, Premature aging induced by radiation exhibits pro-atherosclerotic effects mediated by epigenetic activation of CD44 expression. Aging Cell 2014; 13, 900–10. [PubMed: 25059316]
12. Cuttler J, Can we abolish the 60-year-old international consensus that connects nuclear radiation to cancer? Nuclear News 2022; 5, 46–49.
13. Mancuso TF, Stewart A, Kneale G, Radiation exposures of Hanford workers dying from cancer and other causes. Health Phys 1977; 33, 369–85. [PubMed: 591314]
14. Schmitz-Feuerhake I, Pflugbeil S, 'Lifestyle' and cancer rates in former East and West Germany: the possible contribution of diagnostic radiation exposures. Radiat Prot Dosimetry 2011; 147, 310–3. [PubMed: 21835840]
15. Gofman JW, X-rays and breast cancer. JAMA 1995; 274, 1762. [PubMed: 7500504]
16. Gofman JW, Preventing Breast Cancer: The Story of a Major, Proven, Preventable Cause of This Disease. San Francisco, CA: Committee for Nuclear Responsibility, Inc.; 1995,1–423.
17. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UNSCEAR 2019 Report. Annex A. Evaluation of selected health effects and inference of risk due to radiation exposure. New York: United Nations; 2020; E.20.IX.5, 21–192.
18. National Council on Radiation Protection and Measurements (NCRP), Implications of recent epidemiologic studies for the linear-nonthreshold model and radiation protection. NCRP Commentary no 27. Bethesda, MD, USA: National Council on Radiation Protection and Measurements (NCRP); 2018, i-ix+1–199.
19. Little MP, Wakeford R, Bouffler SD, Abalo K, Hauptmann M, Hamada N, et al. Review of the risk of cancer following low and moderate doses of sparsely ionising radiation received in early life in groups with individually estimated doses. Environ Int 2022; 159, 106983. [PubMed: 34959181]
20. Little MP, Wakeford R, Bouffler SD, Abalo K, Hauptmann M, Hamada N, et al. Cancer risks among studies of medical diagnostic radiation exposure in early life without quantitative estimates of dose. Sci Total Environ 2022; 832, 154723. [PubMed: 35351505]
21. Kendall GM, Little MP, Wakeford R, A review of studies of childhood cancer and natural background radiation. Int J Radiat Biol 2021; 97, 769–81. [PubMed: 33395329]
22. Hauptmann M, Daniels RD, Cardis E, Cullings HM, Kendall G, Laurier D, et al. Epidemiological Studies of Low-Dose Ionizing Radiation and Cancer: Summary Bias Assessment and Meta-Analysis. J Natl Cancer Inst Monogr 2020; 2020, 188–200. [PubMed: 32657347]
23. Berrington de Gonzalez A, Daniels RD, Cardis E, Cullings HM, Gilbert E, Hauptmann M, et al. Epidemiological Studies of Low-Dose Ionizing Radiation and Cancer: Rationale and Framework for the Monograph and Overview of Eligible Studies. J Natl Cancer Inst Monogr 2020; 2020, 97–113. [PubMed: 32657348]
24. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UNSCEAR 2020/2021 Report. Volume III. Annex C. Biological mechanisms relevant for the inference of cancer risks from low-dose and low-dose-rate radiation. New York: United Nations; 2021; E.22.IX.3, 1–238.
25. Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation, National Research Council (NRC), Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII - Phase 2. Washington, DC, USA: National Academy Press; 2006, 1–406.
26. Armstrong B, Brenner DJ, Baverstock K, Cardis E, Green A, Guilmette RA, et al. Radiation. Volume 100D. A review of human carcinogens. Lyon, France: International Agency for Research on Cancer; 2012, 1–341.
27. Rühm W, Laurier D, Wakeford R, Cancer risk following low doses of ionising radiation – Current epidemiological evidence and implications for radiological protection. Mutat Res/Genet Toxicol Environ Mutagen 2022; 873, 503436. [PubMed: 35094811]
28. Little MP, Pawel D, Misumi M, Hamada N, Cullings HM, Wakeford R, et al. Lifetime mortality risk from cancer and circulatory disease predicted from the Japanese atomic bomb survivor Life Span Study data taking account of dose measurement error. Radiat Res 2020; 194, 259–76. [PubMed: 32942303]
29. Grant EJ, Brenner A, Sugiyama H, Sakata R, Sadakane A, Utada M, et al. Solid cancer incidence among the Life Span Study of Atomic bomb survivors: 1958–2009. Radiat Res 2017; 187, 513–37. [PubMed: 28319463]

30. Little MP, Wakeford R, Borrego D, French B, Zablotska LB, Adams MJ, et al. Leukaemia and myeloid malignancy among people exposed to low doses (<100 mSv) of ionising radiation during childhood: a pooled analysis of nine historical cohort studies. Lancet Haematol 2018; 5, e346–e58. [PubMed: 30026010]
31. Richardson DB, Cardis E, Daniels RD, Gillies M, O'Hagan JA, Hamra GB, et al. Risk of cancer from occupational exposure to ionising radiation: retrospective cohort study of workers in France, the United Kingdom, and the United States (INWORKS). BMJ 2015; 351, h5359. [PubMed: 26487649]
32. Leuraud K, Richardson DB, Cardis E, Daniels RD, Gillies M, O'Hagan JA, et al. Ionising radiation and risk of death from leukaemia and lymphoma in radiation-monitored workers (IN-WORKS): an international cohort study. Lancet Haematol 2015; 2, e276–e81. [PubMed: 26436129]
33. Wakeford R, Little MP, Risk coefficients for childhood cancer after intrauterine irradiation: a review. Int J Radiat Biol 2003; 79, 293–309. [PubMed: 12943238]
34. Wakeford R, Bithell JF, A review of the types of childhood cancer associated with a medical X-ray examination of the pregnant mother. Int J Radiat Biol 2021; 97, 571–92. [PubMed: 33787450]
35. Kendall GM, Little MP, Wakeford R, Bunch KJ, Miles JCH, Vincent TJ, et al. A record-based case-control study of natural background radiation and the incidence of childhood leukaemia and other cancers in Great Britain during 1980-2006. Leukemia 2013; 27, 3–9. [PubMed: 22766784]
36. Spycher BD, Lupatsch JE, Zwahlen M, Rösli M, Niggli F, Grotzer MA, et al. Background ionizing radiation and the risk of childhood cancer: a census-based nationwide cohort study. Environ Health Perspect 2015; 123, 622–8. [PubMed: 25707026]
37. Pearce MS, Salotti JA, Little MP, McHugh K, Lee C, Kim KP, et al. Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study. Lancet 2012; 380, 499–505. [PubMed: 22681860]
38. Meulepas JM, Ronckers CM, Smets A, Nievelstein RAJ, Gradowska P, Lee C, et al. Radiation Exposure From Pediatric CT Scans and Subsequent Cancer Risk in the Netherlands. J Natl Cancer Inst 2019; 111, 256–63. [PubMed: 30020493]
39. Nikkilä A, Raitanen J, Lohi O, Auvinen A, Radiation exposure from computerized tomography and risk of childhood leukemia: Finnish register-based case-control study of childhood leukemia (FRECCLE). Haematologica 2018; 103, 1873–80. [PubMed: 29976736]
40. Foucault A, Ancelet S, Dreuil S, Caër-Lorho S, Ducou Le Pointe H, Brisse H, et al. Childhood cancer risks estimates following CT scans: an update of the French CT cohort study. Eur Radiol 2022; 32, 5491–98. [PubMed: 35230516]
41. Shimizu Y, Kodama K, Nishi N, Kasagi F, Suyama A, Soda M, et al. Radiation exposure and circulatory disease risk: Hiroshima and Nagasaki atomic bomb survivor data, 1950-2003. BMJ 2010; 340, b5349. [PubMed: 20075151]
42. Takahashi I, Shimizu Y, Grant EJ, Cologne J, Ozasa K, Kodama K, Heart disease mortality in the Life Span Study, 1950-2008. Radiat Res 2017; 187, 319–32. [PubMed: 28170314]
43. Gillies M, Richardson DB, Cardis E, Daniels RD, O'Hagan JA, Haylock R, et al. Mortality from circulatory diseases and other non-cancer outcomes among nuclear workers in France, the United Kingdom and the United States (INWORKS). Radiat Res 2017; 188, 276–90. [PubMed: 28692406]
44. Hinksman CA, Haylock RGE, Gillies M, Cerebrovascular disease mortality after occupational radiation exposure among the UK National Registry for Radiation Workers cohort. Radiat Res 2022; 197, 459–70. [PubMed: 35139226]
45. Little MP, Radiation and circulatory disease. Mutat Res 2016; 770, 299–318.
46. Wakeford R, Risk of diseases of the circulatory system after low-level radiation exposure-an assessment of evidence from occupational exposures. J Radiol Prot 2022; 42, 020201.
47. International Commission on Radiological Protection (ICRP), Recommendations of the ICRP. ICRP Publication 26. Annals ICRP 1977; 1(3), i-vi+1–80.
48. Neriishi K, Nakashima E, Akahoshi M, Hida A, Grant EJ, Masunari N, et al. Radiation dose and cataract surgery incidence in atomic bomb survivors, 1986-2005. Radiology 2012; 265, 167–74. [PubMed: 22875798]

49. Worgul BV, Kundiyev YI, Sergiyenko NM, Chumak VV, Vitte PM, Medvedovsky C, et al. Cataracts among Chernobyl clean-up workers: implications regarding permissible eye exposures. Radiat Res 2007; 167, 233–43. [PubMed: 17390731]
50. Azizova TV, Hamada N, Bragin EV, Bannikova MV, Grigoryeva ES, Risk of cataract removal surgery in Mayak PA workers occupationally exposed to ionizing radiation over prolonged periods. Radiat Environ Biophys 2019; 58, 139–49. [PubMed: 30879144]
51. Su Y, Wang Y, Yoshinaga S, Zhu W, Tokonami S, Zou J, et al. Lens opacity prevalence among the residents in high natural background radiation area in Yangjiang, China. J Radiat Res 2021; 62, 67–72. [PubMed: 33006372]
52. Little MP, Wakeford R, Tawn EJ, Bouffler SD, Berrington de Gonzalez A, Risks associated with low doses and low dose rates of ionizing radiation: why linearity may be (almost) the best we can do. Radiology 2009; 251, 6–12. [PubMed: 19332841]
53. Bonassi S, Ugolini D, Kirsch-Volders M, Strömberg U, Vermeulen R, Tucker JD, Human population studies with cytogenetic biomarkers: review of the literature and future prospectives. Environ Mol Mutagen 2005; 45, 258–70. [PubMed: 15688363]
54. Norppa H, Bonassi S, Hansteen I-L, Hagmar L, Strömberg U, Rössner P, et al. Chromosomal aberrations and SCEs as biomarkers of cancer risk. Mutat Res 2006; 600, 37–45. [PubMed: 16814813]
55. Boffetta P, van der Hel O, Norppa H, Fabianova E, Fucic A, Gundy S, et al. Chromosomal aberrations and cancer risk: results of a cohort study from Central Europe. Am J Epidemiol 2007; 165, 36–43. [PubMed: 17071846]
56. Farkas G, Kocsis ZS, Székely G, Dobozi M, Kenessey I, Polgár C, et al. Smoking, chromosomal aberrations, and cancer incidence in healthy subjects. Mutat Res/Genet Toxicol Environ Mutagen 2021; 867, 503373. [PubMed: 34266629]
57. Peters S, Portengen L, Bonassi S, Sram R, Vermeulen R, Intra- and interindividual variability in lymphocyte chromosomal aberrations: implications for cancer risk assessment. Am J Epidemiol 2011; 174, 490–93. [PubMed: 21652601]
58. Cannan WJ, Pederson DS, Mechanisms and consequences of double-strand DNA break formation in chromatin. J Cell Physiol 2016; 231, 3–14. [PubMed: 26040249]
59. Goodhead DT, Communication to Dr MP Little re electron tracks per cell nucleus, 8/2022. 2022.
60. Brenner DJ, Doll R, Goodhead DT, Hall EJ, Land CE, Little JB, et al. Cancer risks attributable to low doses of ionizing radiation: assessing what we really know. Proc Natl Acad Sci USA 2003; 100, 13761–66. [PubMed: 14610281]
61. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), Sources and effects of ionizing radiation. UNSCEAR 1993 report to the General Assembly, with scientific annexes. United Nations: New York; 1993; E.94.IX.2, 1–922.
62. National Council on Radiation Protection and Measurements (NCRP), Report No. 136. Evaluation of the linear-nonthreshold dose-response model for ionizing radiation. Bethesda, MD: National Council on Radiation Protection and Measurements (NCRP); 2001, 1–287.
63. Hsu W-L, Preston DL, Soda M, Sugiyama H, Funamoto S, Kodama K, et al. The incidence of leukemia, lymphoma and multiple myeloma among atomic bomb survivors: 1950-2001. Radiat Res 2013; 179, 361–82. [PubMed: 23398354]
64. Tran V, Little MP, Dose and dose rate extrapolation factors for malignant and non-malignant health endpoints after exposure to gamma and neutron radiation. Radiat Environ Biophys 2017; 56, 299–328. [PubMed: 28939964]
65. Haley BM, Paunesku T, Grdina DJ, Woloschak GE, The increase in animal mortality risk following exposure to sparsely ionizing radiation is not linear quadratic with dose. PloS One 2015; 10, e0140989. [PubMed: 26649569]
66. Cuttler JM, Calabrese EJ, What would become of nuclear risk if governments changed their regulations to recognize the evidence of radiation's beneficial health effects for exposures that are below the thresholds for detrimental effects? Dose Response 2021; 19, 15593258211059317, 1–6.
67. Lubin JH, Adams MJ, Shore R, Holmberg E, Schneider AB, Hawkins MM, et al. Thyroid cancer following childhood low-dose radiation exposure: a pooled analysis of nine cohorts. J Clin Endocrinol Metab 2017; 102, 2575–83. [PubMed: 28323979]

68. Berrington de Gonzalez A, Pasqual E, Veiga L, Epidemiological studies of CT scans and cancer risk: the state of the science. Br J Radiol 2021; 94, 20210471. [PubMed: 34545766]

69. Bithell JF, Statistical issues in assessing the evidence associating obstetric irradiation and childhood malignancy. In: Lengfelder E, Wendhausen H editors. Neue Bewertung des Strahlenrisikos: Niedrigdosis-Strahlung und Gesundheit. MMV Medizin Verlag; 1993, 53–60.

70. Gilman EA, Kneale GW, Knox EG, Stewart AM, Pregnancy x-rays and childhood cancers: effects of exposure age and radiation dose. J Radiol Prot 1988; 8, 3–8.

71. Mole RH, Childhood cancer after prenatal exposure to diagnostic X-ray examinations in Britain. Br J Cancer 1990; 62, 152–68. [PubMed: 2202420]

72. Tran V, Zablotska LB, Brenner AV, Little MP, Radiation-associated circulatory disease mortality in a pooled analysis of 77,275 patients from the Massachusetts and Canadian tuberculosis fluoroscopy cohorts. Sci Rep 2017; 7, 44147. [PubMed: 28287147]

73. Moseeva MB, Azizova TV, Grigoryeva ES, Haylock R, Risks of circulatory diseases among Mayak PA workers with radiation doses estimated using the improved Mayak Worker Dosimetry System 2008. Radiat Environ Biophys 2014; 53, 469–77. [PubMed: 24482017]

74. Azizova TV, Grigoryeva ES, Haylock RGE, Pikulina MV, Moseeva MB, Ischaemic heart disease incidence and mortality in an extended cohort of Mayak workers first employed in 1948-1982. Br J Radiol 2015; 88, 20150169. [PubMed: 26224431]

75. Zhang W, Haylock RGE, Gillies M, Hunter N, Mortality from heart diseases following occupational radiation exposure: analysis of the National Registry for Radiation Workers (NRRW) in the United Kingdom. J Radiol Prot 2019; 39, 327–53. [PubMed: 30860078]

76. Krestinina LY, Epifanova S, Silkin S, Mikryukova L, Degteva M, Shagina N, et al. Chronic low-dose exposure in the Techa River Cohort: risk of mortality from circulatory diseases. Radiat Environ Biophys 2013; 52, 47–57. [PubMed: 23124827]

77. Nakashima E, Neriishi K, Minamoto A, A reanalysis of atomic-bomb cataract data, 2000-2002: a threshold analysis. Health Phys 2006; 90, 154–60. [PubMed: 16404173]

78. Booz J, Microdosimetric spectra and parameters of low LET-radiations. In: Booz J, Ebert HG, Smith BGR editors. Fifth Symposium on Microdosimetry, Verbania Pallanza (Italy), 22-26 September 1975. Commission of the European Communities: Luxembourg; 1976; EUR 5452 d-e-f, 311–344.

TABLE 1

Cancer Risks of Childhood or In Utero Exposure in Selected Higher Quality Studies of Medical Diagnostic Radiation Exposure [taken in part from Little et al. (19)]

Description of study data	Ref.	Mean dose (range) (Gy)	Persons (person years of follow-up)	Notes	Endpoint [incidence unless otherwise stated]	Number of cases/deaths	ERR/Gy (95% CI)
Exposure in childhood							
Pooled analysis of 9 datasets	Lubin et al. (67)	0.02991 (0−<0.2)	107,594 (4,454,516)	Dose < 0.2 Gy	Thyroid cancer	252	11.1 (6.6,19.7)
		0.01730 (0−<0.1)	96,318 (3,980,642)	Dose < 0.1 Gy	Thyroid cancer	184	9.6 (3.7,17.0)
Nine cohort pooled moderate dose medical+LSS analysis - dose < 0.1 Gy	Little et al. (30)	0.0196 (0−<0.1)	262,573 (5,154,464)		Acute myeloid leukemia + MDS	87	20.9 (4.1,49.2)
					Acute lymphoblastic leukemia	40	46.6 (3.5,187.1)
					Chronic myeloid leukemia	36	−6.4 (<−10,13.6)
					Leukemia excluding CLL	221	8.4 (−0.3,20.8)
Finnish Cancer Registry based case-control study of computed tomography (CT) 1990–2011	Nikkilä et al. (39)	0.00629 (0−<0.0332)	1093 cases, 3279 controls	Median dose for controls, using NCICT software	Leukemia	1093	130 (20,260)
Dutch CT study of children (age <18 years) at first CT, 1979–2012	Meulepas et al. (38)	0.0385 (0−>0.22)	168,394 (1,201,357)	Exclusion and lag 5 years, brain dose	Brain/CNS	84	8.6 (2.0,22.2)
		0.0095 (0−>0.017)		Exclusion and lag 2 years, ABM dose	Leukemia	44	2.1 (−1.2,24.0)
		0.0095 (0−>0.017)		Exclusion and lag 2 years, ABM dose	Leukemia + MDS	63	0.4 (−1.2,16.1)
French CT study of children (age <10) at first CT in years 2000–2011, followed up 2012–2016	Foucault et al. (40)	0.0103 (SD 0.0128)	100,560 (NA)	Lag and exclusion 2 years, ABM dose	Leukemia	39	16 (7, 26)
		0.0277 (SD 0.0392)		Lag 5 y, exclusion 2 years, brain dose	Brain/CNS	75	6 (2, 9)
		0.0103 (SD 0.0128)		Lag and exclusion 2 years, ABM dose	Lymphoma	41	−11 (−39, 30)
Meta-analysis of childhood CT studies	Berrington de Gonzalez et al. (68)	0.006–0.012 (0−>0.1)	NA	5 studies in relation to ABM dose	Leukemia	1259	10.5 (−5.8, 26.9)
		0.018–0.043 (0−>0.1)	NA	5 studies in relation to brain dose	Brain/CNS (including meningioma)	344	7.9 (4.7, 11.1)

Description of study data	Ref.	Mean dose (range) (Gy)	Persons (person years of follow-up)	Notes	Endpoint [incidence unless otherwise stated]	Number of cases/deaths	ERR/Gy (95% CI)
Exposure in utero							
Oxford Survey of Childhood Cancers, case-control pairs born 1953–1979	Bithell (69)	NA (0−<0.03)	14,759 cases and matched controls[a]	Estimated via log linear-quadratic model of OR fitted to data of Gilman *et al* (70) by year for 1959, using dose estimate of 6.1 mGy per obstetric radiograph of Mole (71) for that year	All cancer mortality	14,759	51 (28, 76)

Abbreviations: CI, confidence interval; MDS, myelodysplastic syndrome; CLL, chronic lymphocytic leukemia; NCICT, National Cancer Institute Dosimetry System for Computed Tomography; CNS, central nervous system; ABM, active bone marrow; OR, odds ratio.

[a]Numbers taken from Gilman et al. (70).

TABLE 2

Cardiovascular Disease Risks in Selected Higher Quality Diagnostically Exposed Groups, in the Japanese Atomic Bomb Survivors and in Certain Higher Quality Occupationally and Environmentally Exposed Groups, taken from Little *et al* (5). All Data are In Relation to Underlying Cause of Death, Unless Otherwise Indicated

Description of study data	Ref.	Mean (range) heart/brain dose (Gy)	Persons (person years of follow-up)	Endpoint (mortality unless otherwise indicated)	Cases/ deaths	Excess relative risk Gy^{-1} (95% CI)
Diagnostically exposed groups						
Canadian and Massachusetts TB fluoroscopy cohorts	Tran et al. (72)	0.18 (0–0.50) [<0.5 Gy]/1.16 (0–27.77) [total]	77,275 (1,945,041)	All cardiovascular disease ICD9 390–459: <0.5 Gy	10,209	0.246 (0.036, 0.469)[a]
				Ischemic heart disease ICD9 410–414: < 0.5 Gy	6410	0.268 (0.003, 0.552)
				Cerebrovascular disease ICD9 430–438: < 0.5 Gy	1561	0.441 (−0.119, 1.090)[a]
Japanese atomic bomb survivors						
Japanese atomic bomb survivors 1950–2003	Shimizu et al. (41)	0.1 (0–4)[b]	86,611 (NA)	Cerebrovascular disease total (ICD9 430–438)	12,139	0.12 (0.05, 0.19)[c]
				Heart disease total (ICD9 393-429 excluding 401, 403, 405)	14,018	0.18 (0.11, 0.25)[c]
				Circulatory disease apart from heart disease and stroke (ICD9 390-392, 401, 403, 405, 439–459)	5846	0.58 (0.45, 0.72)[c]
				All cardiovascular disease (ICD9 390–459)	25,113	0.15 (0.10, 0.20)[c]
Japanese atomic bomb survivors 1950–2008	Takahashi et al. (42)	0.1 (0–4)[b]	86,600 (3,462,847)	Heart disease (ICD10 I05–I08, I09.1, I11, I13, I20–25, I34–I39, I50) overall	9303	0.140 (0.060, 0.220)
				Ischemic heart disease (ICD10 I20–I25)	3556	0.030 (−0.080, 0.150)
				Myocardial infarction (ICD10 I21–I23)	1883	0.020 (−0.130, 0.200)
				Other ischemic heart disease (ICD10 I20, I24–I25)	1673	0.040 (−0.120, 0.220)
				Valvular heart disease (ICD10 I05–I08, I09.1, I34–I39)	744	0.450 (0.130, 0.850)
				Rheumatic valvular heart disease (ICD10 I05–I08, I09.1)	223	0.960 (0.280, 1.920)
				Non-rheumatic valvular heart disease (I34–I39)	521	0.240 (−0.080, 0.680)
				Hypertensive organ damage (ICD10 I11–I13)	1122	0.360 (0.100, 0.680)
				Heart failure (ICD10 I50)	3334	0.210 (0.070, 0.370)
Occupational studies						

Description of study data	Ref.	Mean (range) heart/brain dose (Gy)	Persons (person years of follow-up)	Endpoint (mortality unless otherwise indicated)	Cases/ deaths	Excess relative risk Gy^{-1} (95% CI)
International Nuclear Workers Study (INWORKS)	Gillies et al. (43)	0.0252 (0–1.932)	308,297 (8.2×10^6)	Cardiovascular disease (ICD10 I00–I99)	27,848	0.22 (0.08, 0.37)[d]
				Ischemic heart disease (I20–I25)	17,463	0.18 (0.004, 0.36)[d]
				Acute myocardial infarction (I21)	11,076	0.26 (0.03, 0.51)[d]
				Chronic ischemic heart disease (I25)	6238	0.07 (−0.19, 0.36)[d]
				Cerebrovascular disease (I60–I69)	4444	0.50 (0.12, 0.94)[d]
Mayak workers	Moseeva et al. (73); Azizova et al. (74)	0.62 ± 0.80 (males)[e]	22,377 (447,281)	Ischemic heart disease morbidity (ICD9 410–414)	7225	0.14 (0.08, 0.21)[a]
		0.51 ± 0.68 (females)[e]	22,377 (836,048)	Ischemic heart disease mortality (ICD9 410–414)	2848	0.05 (−0.01, 0.13)[a]
			18,856 (341,663)	Cerebrovascular disease morbidity (ICD9 430–438)	7440	0.497 (0.393, 0.601)[a]
			18,856 (272,525)	Cerebrovascular disease mortality (ICD9 430–438)	1382	0.057 (−0.046, 0.161)[a]
Mayak workers stroke subtypes	Azizova et al. (6)	NA	22,377 (459,520)	Cerebrovascular disease morbidity (ICD10 I60–I69)	9469	0.39 (0.31, 0.48)[f]
			22,377 (573,781)	Stroke morbidity (ICD10 I60–I64)	2078	0.00 (−0.08, 0.10)[f]
			22,377 (593,051)	Hemorrhagic stroke morbidity (ICD10 I61)	262	0.10 (−0.16, 0.58)[f]
			22,377 (585,806)	Ischemic stroke morbidity (ICD10 I63)	1611	0.06 (−0.04, 0.20)[f]
UK NRRW heart disease	Zhang et al. (75)	0.0232 (0−>0.4)	174,541 (NA)	All heart disease (ICD9 393–398, 402, 404, 410–429)	11,014	0.37 (0.11, 0.65)
UK NRRW stroke	Hinksman et al. (44)	0.0031[g] (0–1.9)	166,812 (3,665,413)	Cerebrovascular disease mortality (ICD9 430–438)	3219	0.57 (0.00, 1.31)
				Ischemic stroke mortality (ICD9 433-435)	422	1.03 (−0.28, 3.48)
				Hemorrhagic stroke mortality (ICD9 430–432)	666	1.06 (−0.52, 2.01)
				Ill-defined and other cerebrovascular disease mortality (ICD9 436–438)	2131	0.54 (−0.10, 1.42)
Environmental studies						
Techa River study	Krestinina et al. (76)	0.035 (0–0.51)[h]	29,735 (901,563)	All cardiovascular disease mortality (ICD9 390–459)	7595	0.18 (−0.13, 0.52)[a, h]
				Ischemic heart disease mortality (ICD9 410–414)	3194	0.26 (−0.22, 0.81)[a, h]

Abbreviations: CI, Confidence Interval; ICD, International Classification of Diseases; NRRW, National Registry for Radiation Workers; TB, tuberculosis.

[a] Assuming a lag period of 5 years.

[b] Analysis based on colon dose.

[c] Analysis using underlying or contributing cause of death.

[d] 90% CI.

[e] Risk estimates in relation to cumulative whole body external gamma dose; doses given here are from Moseeva et al. (73).

[f] Assuming a lag period of 10 years.

[g] Median dose.

[h] Analysis based on dose to muscle.

TABLE 3

Risks for Cataract in Selected Higher Quality Radiation-Exposed Cohorts, Taken from Little et al. (5)

Description of study data	Ref.	Dose (Gy), mean (range)	Persons (person years of follow-up)	Notes (method of ascertainment)	Endpoint	Cases	Excess hazard ratio Gy^{-1} or excess odds ratio Gy^{-1} (95% CI)
Japanese atomic bomb survivor AHS	Nakashima et al. (77)	0.522 (0–4.94)	730 (NA)	LOCS II	Cortical	618[a]	0.30 (0.10, 0.53)
					Posterior subcapsular	214[a]	0.44 (0.19, 0.73)
					Nuclear opacity	415[a]	0.07 (−0.11, 0.30)
					Nuclear colour	358[a]	0.01 (−0.17, 0.24)
Chernobyl recovery worker	Worgul et al. (49)	NA (0−>1.095)	8607 (NA)	Merriam-Focht	Non-nuclear stage 1–5	3369[b,c]/274[d]	0.65 (0.18, 1.30)
					Posterior subcapsular stage 1	2781[b,c]/252[d]	0.42 (0.01, 1.00)
					Nuclear	382[b,c]/113[d]	0.07 (−0.44, 1.04)
					All cataract stage 1–5	3751[b,c]/384[d]	0.70 (0.22, 1.38)
Japanese atomic bomb survivor AHS cataract surgery	Neriishi et al. (48)	0.500 (0–5.14)	6066 (84,209)	Surgical removal	All cataract removal	1028	0.32 (0.17, 0.52)[d, e]
US Radiologic Technologists	Little et al. (8)	0.056 (0–1.514)	67,246 (832,479)	Questionnaire	Cataract history	12,366	0.69 (0.27, 1.16)
			67,709 (888,420)		Cataract surgery	5509	0.34 (−0.19, 0.97)
Mayak nuclear workers	Azizova et al. (7)	0.526 (0−>2.0)	22,377 (486,245)	Slit lamp exam	Cortical	3132	0.62 (0.50, 0.75)[f]
			22,377 (489,162)		Posterior subcapsular	1239	0.90 (0.67, 1.19)[f]
			22,377 (492,004)		Nuclear	2033	0.47 (0.35, 0.60)[f]
Mayak nuclear workers	Azizova et al. (50)	0.515 (0 - >2.0)	22,377 (495,868)	Slit lamp exam	Cataract surgery	701	0.09 (−0.02, 0.22)[f]
Chinese high natural background area	Su et al. (51)	NA (0.0221 - 0.3104)	941 (NA)	LOCS III	Cortical	101	2.6 (0.0, 6.0)
					Posterior subcapsular	23	7.3 (0.5, 18.5)
					Nuclear	245	−1.9 (−3.6, 0.1)

Abbreviations: CI, confidence interval; AHS, Adult Health Study; LOCS, Lens Opacities Classification System

[a] All cases with LOCS II grade I and above.

[b] Summed over cataracts in left and right eyes.

[c] Prevalent cataract.

[d] Incident cataract.

[e] Adjusted to persons in Hiroshima, aged 70, exposed at age 20 years.

[f] Lag period of 5 years.

TABLE 4

Mean Number of Electron Tracks Traversing a Cell Nucleus for Given Mean Dose, as Function of X-Ray Energy/Filtration and Nuclear Diameter, as Evaluated by Goodhead (59) from Measurements of Frequency Mean Lineal Energy of Braby and Ellett as Summarized by Booz (78)

Cell nuclear diameter (μm)	Radiation energy, filtration	Mean nuclear electron tracks per 1 mGy	Mean nuclear electron tracks per 10 mGy
4	65 kV 1.9 mm Al HVL	0.046	0.46
4.5	65 kV 1.9 mm Al HVL	0.061	0.61
5	65 kV 1.9 mm Al HVL	0.078	0.78
6	65 kV 1.9 mm Al HVL	0.12	1.2
8	65 kV 1.9 mm Al HVL	0.23	2.3
10	65 kV 1.9 mm Al HVL	0.39	3.9
4	250 kV 0.44 mm Cu HVL	0.051	0.51
4.5	250 kV 0.44 mm Cu HVL	0.067	0.67
5	250 kV 0.44 mm Cu HVL	0.086	0.86
6	250 kV 0.44 mm Cu HVL	0.13	1.3
8	250 kV 0.44 mm Cu HVL	0.26	2.6
10	250 kV 0.44 mm Cu HVL	0.43	4.3
4	250 kV 1.77 mm Cu HVL	0.073	0.73
4.5	250 kV 1.77 mm Cu HVL	0.095	0.95
5	250 kV 1.77 mm Cu HVL	0.12	1.2
6	250 kV 1.77 mm Cu HVL	0.17	1.7
8	250 kV 1.77 mm Cu HVL	0.33	3.3
10	250 kV 1.77 mm Cu HVL	0.53	5.3

Abbreviations: HVL, half value layer; Al, aluminum; Cu, copper.