# Understanding the harm of low-dose computed tomography radiation to the body (Review)

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**Abstract.** Computed tomography (CT) is a modern examination method whose radiation characteristics vary depending on the population groups, the part of the body being examined, and other implementation conditions. The use of CT has become increasingly widespread. However, there is a growing concern regarding the harm caused by CT radiation. The opinions regarding whether low-dose CT can induce cancer differ. It is necessary to consider the research population, radiation characteristics, and different parts of the body being exposed to radiation before the application of radiation to ensure the knowledge used is scientifically sound and reasonable. Therefore, different studies have different opinions on whether low-dose CT induces cancer, and not all physicians are aware of this. The present review article aimed to impart relevant insights and a correct understanding of the hazardous effects of low-dose CT radiation on the human body and help physicians reduce unnecessary CT radiation exposure.

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## 1. Introduction

Humans are exposed to natural sources of radiation every day (1-9). Computed tomography (CT) has received increasing attention in previous years. The risk of CT radiation-induced cancer has been reported in several epidemiological studies (10-13). Studies have shown that even low doses of diagnostic CT radiation can induce cancer development (10,14). In contrast, some authors have reported no association between repeated CT scans and an increased risk of cancer (15,16). Notably, an increasing number of studies have indicated that radiation below certain doses may benefit the body by stimulating the repair mechanisms to reverse existing damage, which can protect organisms from subsequent radiation exposure or other risk exposures that may induce cancer (1,17,18).

The academic viewpoints related to the characteristics of CT radiation and research design characteristics vary. Careful consideration of the research population, radiation characteristics, and other implementation conditions is necessary prior to the application of research conclusions about low-dose CT scans or other relevant radiation research to ensure that the treatment is scientifically sound and reasonable.

Considering the different academic viewpoints and characteristics of CT radiation, it is necessary to comprehensively and correctly understand the hazards associated with low-dose CT radiation. However, not all physicians are aware of the nature and complexity of low-dose CT radiation hazards or prescribe a comprehensive and rational low-dose CT examination in line with the low-dose CT radiation research conclusions. Unfortunately, there is no specialized or concise literature pertaining to this topic. Thus, the present study mainly reviews low-dose CT radiation characteristics and discusses how to interpret low-dose CT-related research conclusions and the hazards of low-dose CT to help reduce unnecessary CT radiation.

## 2. Object and search criteria

The present study reviewed how to correctly understand the harm caused by low-dose CT radiation to the body. As far as low-dose CT radiation is concerned, it is necessary to reduce unnecessary CT examinations or low-dose radiation to reduce the hazardous effects associated with it. However, there are different academic viewpoints regarding whether low-dose CT radiation is harmful to the body, and some physicians do not accurately understand the hazards associated with low-dose CT. In addition, an outline of CT radiation characteristics that are not easy to interpret is also provided in the present study. A literature search was performed to review how to correctly understand low-dose CT radiation. Databases such as PubMed, Wangfang, Chinese National Knowledge Infrastructure, and Web of Science were searched. The present review did not require informed patient consent or approval by an ethics committee.

## 3. Inclusion and exclusion criteria

The inclusion criteria were literature published in peer-reviewed medical academic journals, medical reports, or books with content on CT radiation in English, Chinese, or translated into English. Non-medical peer-reviewed studies were excluded.

## 4. Literature selection and data extraction

Each author selected relevant articles and reviewed the title and abstract initially. The entire body of the selected articles was reviewed subsequently. Authors HS and FJ jointly decided on the choice of literature. The selected articles included clinical and experimental studies as well as review articles, medical reports and books. In the case of disagreement between the two authors regarding an article, the article was excluded from the study.

## 5. CT use and low-dose radiation

CT is widely used worldwide (19-28). In 2017, over 84 million CT scans, after accounting for multiple scans, were performed in the United States (29). There are no accurate data on the number of individuals who undergo CT examinations in China in one year. Nevertheless, one study reported that the frequency of CT scans in the Jiangsu province in China was 223 per 1,000 individuals; according to estimations, 17, 897, 994 CT scans were performed in the Jiangsu province in 2016 (19). Therefore, it is evident that the use of CT is important. Moreover, the use of CT is expected to increase rapidly with the development of medical and economic CT.

CT screening can detect early tumors, reducing the mortality associated with tumors; for example, screening for early lung cancer can reduce the mortality associated with lung cancer (30-33). However, the importance of strict screening targets, appropriate screening intervals (34), and good radiation protection (35-43) in minimizing unnecessary CT scans and CT radiation dose must be emphasized (44).

The extensive use of CT scans, which has increased over time, is a medical concern. Thus, clinicians should carefully consider whether the use of CT is justified or whether other types of scans would suffice. Low-dose CT scanning reduces the radiation dose compared with conventional CT scans. The US National Academy of Sciences defined low doses of radiation as those up to ~100 mSv (45). At present, low-dose CT imaging methods can be mainly divided into three categories: image postprocessing methods, iterative reconstruction methods, or projection domain filtering methods (46).

*Measurement of CT radiation*. The differences between the absorbed, equivalent, and effective doses must be identified while calculating the radiation exposure dose. The equivalent and effective doses are measured in sieverts (Sv) and are used to calculate the doses from external sources and different radionuclides for a comparison with the dose levels related to whole-body radiation exposure risks. The absorbed dose is the energy absorbed per unit mass of tissue and is measured in gray (Gy) (35). A single conventional CT scan ranges from 2 millisieverts (mSv) to 20 mSv, with an average dose of 10 mSv for each CT scan of the pelvis and abdomen and 2 mSv for each CT scan of the head (20). Moreover, it should be noted that most individuals worldwide receive approximately 2-3 mSv of radiation per year from natural background radiation (47).

*Evidence of cancer induction by CT hazards*. An excess relative carcinogenic risk was observed in association with acute doses of radiation of 10-50 and 50-100 mSv for protracted exposures. Exposure to a dose of ~10 mSv of radiation *in utero* increases the risk of childhood cancer (48). Researchers found that when the mean follow-up duration was 9.5 years for the exposed group and 17.3 years for the unexposed group, the incidence rate ratio (IRR) for all cancers was 1.14 (95% CI, 1.01-1.28) for children exposed to facial CT. The IRR for all cancers was 1.13 (95% CI, 1.00-1.28) for children exposed to neck/spine CT. The IRR of thyroid malignancy was 1.78 (95% CI, 1.24-2.58) after exposure to neck/spine CT (49). It was also reported that the excess relative risk ranged from 0.01-0.05 for solid cancers due to acute exposure to 100 mGy of radiation between the age of 30-70 years; however, the excess relative risk following childhood exposure was 2.2 for brain tumors and 4.5 for leukemia according to a life-span study (50).

*Conclusions of CT radiation studies should be extrapolated correctly*. A study using high-quality case-control and cohort methodology supports the finding that the risk of cancer was induced by exposure to radiation at a dose of ~100 mSv as a threshold and possibly ~200 mSv. According to that study, the risk of cancer induced by radiation dose was minimal and exposure to 10 CT scans, and possibly 20 CT scans, is unlikely to cause cancer (20). However, it should be noted that the study included different types of radiation (X-ray and $\gamma$-ray), diagnosis, environment (including atomic bomb survivors), occupational exposure, and included both adults and children (20). In addition, the type of rays, specific population, or exposure methods were not specifically considered; therefore, a more systematic, cautious, and comprehensive view of the research results is necessary, especially when extrapolating the results to clinical applications.

*Preventive methods to reduce the harms of CT radiation*. Due to the danger associated with CT radiation, the 'as low as reasonably achievable principle', a radiation safety guiding principle that states that even a small dose of radiation must be avoided if there is no direct benefit, must be followed (51).

The risk of CT radiation can be reduced using several methods such as the use of bismuth breast shielding during chest CT of young women, the use of automated tube current modulation technique to optimize tube current on body scan protocols (52), and the use of iterative reconstruction (used when CT was introduced as a computationally complex method of CT postprocessing). The overall effective radiation dose can be reduced by >30% (52).

*How to correctly understand the harm of low-dose CT radiation.* Various factors, including the age of the study population (adult or child), type of rays (X-ray, γ-ray), exposure characteristics, and body parts exposed to radiation, should be considered during radiation analysis. The harm may differ depending on these parameters. The following factors should be considered when analyzing the conclusions of clinical studies involving low-dose CT radiation or designing clinical studies associated with the harm of low-dose CT radiation to the human body.

*CT rays must be distinguished from other types of rays.* CT rays must be distinguished from other types of rays. Different types of rays exhibit different modes of action and characteristics. CT rays are X-rays and are unlike the radiation from atomic explosions, which is a mixture of neutrons and γ-rays. Furthermore, the rays in a CT scan act instantly on the exposed organs. The radiation produced by an atomic bomb lasts for several years, and individuals in the surrounding areas are subject to long-term radiation exposure; the radiation from an atomic bomb irradiates the entire body. Individuals closer to the center of the blast receive a larger dose of radiation, whereas those farther away from the center of the blast receive a smaller dose of radiation. Therefore, when applying research knowledge to understand the dangers of radiation from atomic bomb explosions or nuclear power plant explosions, it should be noted that the research results cannot be directly extrapolated to the effects of CT scan (including low-dose CT scan) exposure (35). In addition, when comparing the hazards associated with different rays, the relative biological effectiveness of an ionizing particle, which is defined as the ratio of the absorbed dose of a usually low linear energy transfer reference radiation ray to the absorbed dose of another radiation ray that produces the same biological effect (53), should be considered.

*Different populations have different sensitivities to CT radiation hazards.* The differences in the sensitivity to radiation damage among different populations should be considered. Children are susceptible to CT radiation (35) and are up to 10 times more sensitive than adults; girls may possibly be more radiosensitive (54). In addition, since children have a longer expected life after undergoing CT scans than adults, they have more time and are at a higher risk of radiation-induced cancer from CT scans (54). Individuals with previous malignant tumors are also at a higher risk of radiation-induced malignant tumors than the general population (35). Therefore, since children and populations with a history of cancer are more sensitive to radiation hazards, the results of studies on adults or populations with malignant tumors cannot be generalized to children.

*Awareness of the differences between the different body parts exposed to radiation during examination.* The influence of radiation examination on specific body parts should be considered because different body parts require different doses of radiation in CT scans (20) as different tissues and organs have different structures and different absorption coefficients for ray radiation (35). The weighting factor refers to the inherent cell differences, which lead to radiation-induced cancer. For example, the bone marrow is more prone to cancer development than the skin after exposure to the same radiation dose (35). Therefore, even with the same dose of CT radiation, the harm caused by scanning different parts of the body is not the same. In addition, some scans were performed near the glands that are particularly sensitive to radiation damage (35). Chest CT scans often pose a higher risk of thyroid cancer than that associated with head or paranasal sinus CT scans (55).

*Distinction between diagnostic CT scan radiation and therapeutic radiation.* There is a need to distinguish between diagnostic CT and medical radiation therapy for cancer. They have different characteristics for the radiation on the human body. The dose of the diagnostic CT scan radiation is usually much lower than that of tumor radiation therapy. CT scan examination is usually completed in one session, whereas radiotherapy requires multiple sessions. The scope of CT scan examination is usually larger than that of radiotherapy, and tumor radiotherapy usually affects local control of the tumor. In addition, patients with cancer are more likely to develop tumors than those without a history of cancer (35). Therefore, the risk of secondary tumors induced by radiotherapy cannot be equated with the risk of CT radiography. The conclusion regarding the radiation hazard of tumor radiotherapy cannot be regarded the same as the harm caused by CT scan radiation, at least not without criticism.

*Distinction between the general population's CT scan radiation exposure and occupational radiation exposure.* There is a need to distinguish between radiation risks associated with CT scans and occupational exposure. As mentioned above, CT scan examinations are mainly performed on a specific part of the body in a single session. However, occupational radiation exposure occurs over long periods. Owing to these protective measures, the daily occupational exposure dose is often much lower than the radiation dose of a single CT scan. However, long-term occupational exposure leads to a high cumulative radiation dose. Therefore, because of the differences in the mode of action and dose of radiation between the two, the risk of occupational exposure cannot be equated to the induced cancer risk from CT scans.

*Consideration of sufficient follow-up duration in radiation hazard study.* When assessing the CT scan examination-induced radiation exposure risk, the adequacy of follow-up after CT scan examination needs to be considered as 30% of the cases of radiation-induced leukemia may occur 10 years after radiation exposure, while the proportion of radiation-induced brain tumors occurring 10 years after radiation exposure may be as high as 90% (56). Therefore, it is necessary to consider whether the follow-up time is sufficiently long and whether lifelong follow-up results are more accurate.

*Consideration of intrauterine implications of radiation*. It must be noted that radiation exposure due to CT scan examination of the population prior to pregnancy impacts their descendants (35) and increases the risk for the offspring (57). This finding needs to be confirmed using large-scale epidemiological data.

*The cumulative effects of repeated radiation tests*. It is important to consider that with economic and medical development, the number of CT scans received may increase throughout life. One study showed that the cumulative effective radiation dose from CT exposure increases the baseline risk of cancer (58). Therefore, even in the case of low-dose CT scans, it is important to minimize unnecessary scans as the possible need for CT scans or X-ray radiation and cumulative radiation dose in the future should be considered since the cumulative effects dose from radiation may also add to the baseline cancer risk.

*Differences between animals and humans, and between basic research and clinical practice*. It must be acknowledged that the results observed in animal studies are not necessarily applicable to humans because of different weight characteristics and species and that *in vitro* results are not applicable to *in vivo* monitoring (35). It is also unlikely to have the same quality of epidemiological data for animal experiments as humans. Moreover, basic research results should not be directly equated with clinical results. The relevant literature can be reviewed once the above characteristics are understood with respect to CT scan radiation. For example, studies have suggested a difference between low- and high-dose radiation, as the former has an anti-cancer treatment effect and may even be used as an important means to prevent tumors (1,17,18). However, it should be emphasized that this low-dose radiation does not necessarily equal the radiation generated by low-dose CT scanning. Furthermore, the scope of the application related to low-dose radiation, as shown in the above study, needs to be carefully considered.

As emphasized above, there is a need to correctly understand the relevant conclusions of radiation research and clarify the conditions under which these conclusions were generated. The complexity of CT radiation-induced tumor risks and the use of a scientific approach in its evaluation must be understood. The rational use of CT, the reduction of unnecessary CT, and an adequate process for reducing unnecessary CT scans and radiation doses are protective measures in this regard. When a CT scan must be used, optimizing the CT scan dose to minimize the radiation risk is detrimental (59).

To the best of the authors' knowledge, this is the first specialized and concise review devoted to a comprehensive and scientific understanding of low-dose CT scan radiation research conclusions. The present study had some limitations. The discussion and exposition given in the article are not comprehensive or sufficiently in-depth, and the authors hope to publish more in-depth and closely-related literature in the future. However, low-dose CT scans are widely used, and it is necessary to promote awareness regarding the hazards of low-dose CT at present.

## 6. Conclusions

Although CT scans emit low-dose radiation, the potential radiation risk should still be considered. When drawing conclusions from low-dose radiation research, it is necessary to consider the suitability of the patient to undergo a CT scan. Even in the investigation of the risk of CT scan, it is necessary to assess the conditions of the study, the suitability to extrapolate the research conclusions, the differences in the study populations, the body part examined, follow-up time, and other factors. The insights gained from this study will help reduce the risks posed by CT scan radiation to the patients. Therefore, low-dose CT should be systematically investigated.

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## Availability of data and materials

Data sharing is not applicable to this article, as no data sets were generated or analyzed during the current study.

## Authors' contributions

HMS and FHJ performed the analysis. HMS and ZCS wrote the original draft. FHJ contributed to writing, reviewing and editing the manuscript. Data authentication is not applicable. All authors read and approved the final manuscript.

## Ethics approval and consent to participate

Not applicable.

## Patient consent for publication

Not applicable.

## Competing interests

The authors declare that they have no competing interests.

## References

1. Yang G, Li W, Jiang H, Liang X, Zhao Y, Yu D, Zhou L, Wang G, Tian H, Han F, *et al*: Low-dose radiation may be a novel approach to enhance the effectiveness of cancer therapeutics. Int J Cancer 139: 2157-2168, 2016.
2. López R, García-Talavera M, Pardo R, Deban L and Nalda JC: Natural radiation doses to the population in a granitic region in Spain. Radiat Prot Dosimetry 111: 83-88, 2004.
3. Psichoudaki M and Papaefthymiou H: Natural radioactivity measurements in the city of Ptolemais (Northern Greece). J Environ Radioact 99: 1011-1017, 2008.
4. Mc Laughlin JP: Some characteristics and effects of natural radiation. Radiat Prot Dosimetry 167: 2-7, 2015.

5. Sankaran Pillai G, Chandrasekaran S, Sivasubramanian K, Baskaran R and Venkatraman B: A review on variation of natural radioactivity along the southeast coast of Tamil Nadu for the past 4 decades (1974-2016). Radiat Prot Dosimetry 179: 125-135, 2018.
6. Hosoda M, Nugraha ED, Akata N, Yamada R, Tamakuma Y, Sasaki M, Kelleher K, Yoshinaga S, Suzuki T, Rattanapongs CP, *et al*: A unique high natural background radiation area-Dose assessment and perspectives. Sci Total Environ 750: 142346, 2021.
7. Sreekumar A, Jayalekshmi PA, Nandakumar A, Nair RRK, Ahammed R, Sebastian P, Koriyama C, Akiba S, Nakamura S and Konishi J: Thyroid nodule prevalence among women in areas of high natural background radiation, Karunagappally, Kerala, India. Endocrine 67: 124-130, 2020.
8. Omori Y, Hosoda M, Takahashi F, Sanada T, Hirao S, Ono K and Furukawa M: Japanese population dose from natural radiation. J Radiol Prot 40: R99-R140, 2020.
9. Kendall GM, Little MP and Wakeford R: A review of studies of childhood cancer and natural background radiation. Int J Radiat Biol 97: 769-781, 2021.
10. Meulepas JM, Ronckers CM, Smets AMJB, Nievelstein RAJ, Gradowska P, Lee C, Jahnen A, van Straten M, de Wit MY, Zonnenberg B, *et al*: Radiation exposure from pediatric CT scans and subsequent cancer risk in the Netherlands. J Natl Cancer Inst 111: 256-263, 2019.
11. Lee KH, Lee S, Park JH, Lee SS, Kim HY, Lee WJ, Cha ES, Kim KP, Lee W, Lee JY and Lee KH: Risk of hematologic malignant neoplasms from abdominopelvic computed tomographic radiation in patients who underwent appendectomy. JAMA Surg 156: 343-351, 2021.
12. Feng ST, Law MW, Huang B, Ng S, Li ZP, Meng QF and Khong PL: Radiation dose and cancer risk from pediatric CT examinations on 64-slice CT: A phantom study. Eur J Radiol 76: e19-e23, 2010.
13. Griffey RT and Sodickson A: Cumulative radiation exposure and cancer risk estimates in emergency department patients undergoing repeat or multiple CT. AJR Am J Roentgenol 192: 887-892, 2009.
14. Journy NM, Lee C, Harbron RW, McHugh K, Pearce MS and Berrington de González A: Projected cancer risks potentially related to past, current, and future practices in paediatric CT in the United Kingdom, 1990-2020. Br J Cancer 116: 109-116, 2017.
15. Kuo W, Ciet P, Tiddens HA, Zhang W, Guillerman RP and van Straten M: Monitoring cystic fibrosis lung disease by computed tomography. Radiation risk in perspective. Am J Respir Crit Care Med 189: 1328-1336, 2014.
16. Journy N, Rehel JL, Ducou Le Pointe H, Lee C, Brisse H, Chateil JF, Caer-Lorho S, Laurier D and Bernier MO: Are the studies on cancer risk from CT scans biased by indication? Elements of answer from a large-scale cohort study in France. Br J Cancer 112: 185-193, 2015.
17. Lehrer S and Rosenzweig KE: Lung cancer hormesis in high impact states where nuclear testing occurred. Clin Lung Cancer 16: 152-155, 2015.
18. Dobrzyński L, Fornalski KW and Feinendegen LE: Cancer mortality among people living in areas with various levels of natural background radiation. Dose Response 13: 1559325815592391, 2015.
19. Du X, Wang J and Zhu B: The frequencies of x-ray examinations and CT scans: Findings from a sample investigation in Jiangsu, China. Radiat Prot Dosimetry 190: 38-44, 2020.
20. Schultz CH, Fairley R, Murphy LS and Doss M: The risk of cancer from CT scans and other sources of low-dose radiation: A critical appraisal of methodologic quality. Prehosp Disaster Med 35: 3-16, 2020.
21. Viry A, Bize J, Trueb PR, Viry A, Bize J, Trueb PR, Ott B, Racine D, Verdun FR and LeCoultre R: Annual exposure of the Swiss population from medical imaging in 2018. Radiat Prot Dosimetry 195: 289-295, 2021.
22. Masjedi H, Zare MH, Keshavarz Siahpoush N, Razavi-Ratki SK, Alavi F and Shabani M: European trends in radiology: Investigating factors affecting the number of examinations and the effective dose. Radiol Med 125: 296-305, 2020.
23. Nekolla EA, Schegerer AA, Griebel J and Brix G: Frequency and doses of diagnostic and interventional X-ray applications: Trends between 2007 and 2014. Radiologe 57: 555-562, 2017 (In German).
24. Wachabauer D, Mathis-Edenhofer S and Moshammer H: Medical radiation exposure from radiological and interventional procedures in Austria. Wien Klin Wochenschr 132: 563-571, 2020.
25. Bosch de Basea M, Espinosa A, Gil M, Figuerola J, Pardina M, Vilar J and Cardis E: CT scan exposure in Spanish children and young adults by socioeconomic status: Cross-sectional analysis of cohort data. PLoS One 13: e0196449, 2018.
26. Bosch de Basea M, Salotti JA, Pearce MS, Muchart J, Riera L, Barber I, Pedraza S, Pardina M, Capdevila A, Espinosa A and Cardis E: Trends and patterns in the use of computed tomography in children and young adults in Catalonia-results from the EPI-CT study. Pediatr Radiol 46: 119-129, 2016.
27. Dreger S, Krille L, Maier W, Pokora R, Blettner M and Zeeb H: Regional deprivation and non-cancer related computed tomography use in pediatric patients in Germany: Cross-sectional analysis of cohort data. PLoS One 11: e0153644, 2016.
28. Pearce MS, Salotti JA, McHugh K, Kim KP, Craft AW, Lubin J, Ron E and Parker L: Socio-economic variation in CT scanning in Northern England, 1990-002. BMC Health Serv Res 12: 24, 2012.
29. Mettler FA Jr, Mahesh M, Bhargavan-Chatfield M, Chambers CE, Elee JG, Frush DP, Miller DL, Royal HD, Milano MT, Spelic DC, *et al*: Patient exposure from radiologic and nuclear medicine procedures in the United States: Procedure volume and effective dose for the period 2006-2016. Radiology 295: 418-427, 2020.
30. Rampinelli C, De Marco P, Origgi D, Maisonneuve P, Casiraghi M, Veronesi G, Spaggiari L and Bellomi M: Exposure to low dose computed tomography for lung cancer screening and risk of cancer: Secondary analysis of trial data and risk-benefit analysis. BMJ 356: j347, 2017.
31. Hoffman RM, Atallah RP, Struble RD and Badgett RG: Lung cancer screening with low-dose CT: A meta-analysis. J Gen Intern Med 35: 3015-3025, 2020.
32. de Koning HJ, van der Aalst CM, de Jong PA, Scholten ET, Nackaerts K, Heuvelmans MA, Lammers JJ, Weenink C, Yousaf-Khan U, Horeweg N, *et al*: Reduced lung-cancer mortality with volume CT screening in a Randomized trial. N Engl J Med 382: 503-513, 2020.
33. Hunger T, Wanka-Pail E, Brix G and Griebel J: Lung cancer screening with low-dose CT in smokers: A systematic review and meta-analysis. Diagnostics (Basel) 11: 1040, 2021.
34. Heuvelmans MA and Oudkerk M: Appropriate screening intervals in low-dose CT lung cancer screening. Transl Lung Cancer Res 7: 281-287, 2018.
35. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP publication 103. Ann ICRP 37: 1-332, 2007.
36. Lakhwani OP, Dalal V, Jindal M and Nagala A: Radiation protection and standardization. J Clin Orthop Trauma 10: 738-743, 2019.
37. Miller DL: Make radiation protection a habit. Tech Vasc Interv Radiol 21: 37-42, 2018.
38. Boice J Jr, Dauer LT, Kase KR, Mettler FA Jr and Vetter RJ: Evolution of radiation protection for medical workers. Br J Radiol 93: 20200282, 2020.
39. Biso SMR and Vidovich MI: Radiation protection in the cardiac catheterization laboratory. J Thorac Dis 12: 1648-1655, 2020.
40. Wagner JB: Radiation protection and safety in interventional radiology. Radiol Technol 91: 431-442, 2020.
41. Seki Y, Fukushima Y, Ando M, Yarita K, Suto T and Tsushima Y: Exposure dose reduction for radiologists with combination of angular beam modulation and radiation protection drape in CT fluoroscopy: A phantom study. Nihon Hoshasen Gijutsu Gakkai Zasshi 74: 667-674, 2018 (In Japanese).
42. Dankerl P, May MS, Canstein C, Uder M and Saake M: Cutting staff radiation exposure and improving freedom of motion during CT interventions: Comparison of a novel workflow utilizing a radiation protection cabin versus two conventional workflows. Diagnostics (Basel) 11: 1099, 2021.
43. Lawson M, Kuganesan A, Parry G and Badawy MK: The efficacy of Radpad as a radiation protection tool in CT fluoroscopy guided lung biopsies. Radiat Prot Dosimetry 191: 328-334, 2020.
44. Al Naemi H, Aly A, Kharita MH, Hilli SA, Al Obadli A, Singh R, Rehani MM and Kalra MK: Multiphase abdomen-pelvis CT in women of childbearing potential (WOCBP): Justification and radiation dose. Medicine (Baltimore) 99: e18485, 2020.
45. 1990 Recommendations of the International Commission on Radiological Protection. Ann ICRP 21: 1-201, 1991.
46. Li M, Du Q, Duan L, Yang X, Zheng J, Jiang H and Li M: Incorporation of residual attention modules into two neural networks for low-dose CT denoising. Med Phys 48: 2973-2990, 2021.

47. Epstein L, Koch J, Riemer T, Haquin G and Orion I: An estimation of the exposure of the population of Israel to natural sources of ionizing radiation. Radiat Prot Dosimetry 176: 264-268, 2017.
48. Wall BF, Kendall GM, Edwards AA, Bouffler S, Muirhead CR and Meara JR: What are the risks from medical X-rays and other low dose radiation? Br J Radiol 79: 285-294, 2006.
49. Chen JX, Kachniarz B, Gilani S and Shin JJ: Risk of malignancy associated with head and neck CT in children: A systematic review. Otolaryngol Head Neck Surg 151: 554-566, 2014.
50. Berrington de Gonzalez A, Daniels RD, Cardis E, Cullings HM, Gilbert E, Hauptmann M, Kendall G, Laurier D, Linet MS, Little MP, *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: 97-113, 2020.
51. Prasad KN, Cole WC and Haase GM: Radiation protection in humans: Extending the concept of as low as reasonably achievable (ALARA) from dose to biological damage. Br J Radiol 77: 97-99, 2004.
52. Costello JE, Cecava ND, Tucker JE and Bau JL: CT radiation dose: Current controversies and dose reduction strategies. Am J Roentgenol 201: 1283-1290, 2013.
53. Stewart RD, Carlson DJ, Butkus MP, Hawkins R, Friedrich T and Scholz M: A comparison of mechanism-inspired models for particle relative biological effectiveness (RBE). Med Phys 45: e925-e952, 2018.
54. Ogbole GI: Radiation dose in paediatric computed tomography: Risks and benefits. Ann Ib Postgrad Med 8: 118-126, 2010.
55. Su YP, Niu HW, Chen JB, Fu YH, Xiao GB and Sun QF: Radiation dose in the thyroid and the thyroid cancer risk attributable to CT scans for pediatric patients in one general hospital of China. Int J Environ Res Public Health 11: 2793-2803, 2014.
56. Brenner DJ and Hall EJ: Cancer risks from CT scans: Now we have data, what next. Radiology 265: 330-331, 2012.
57. Shakeel O, Pace N, Chambers TM, Scheurer ME, Ganguly AA, Lupo PJ and Bunin GR: Medical radiation exposure and risk of sporadic retinoblastoma. Pediatr Blood Cancer 67: e28633, 2020.
58. Frija G, Damilakis J, Paulo G, Loose R and Vano E; European Society of Radiology (ESR): Cumulative effective dose from recurrent CT examinations in Europe: Proposal for clinical guidance based on an ESR EuroSafe Imaging survey. Eur Radiol 31: 5514-5523, 2021.
59. Siegel JA, Sacks B, Pennington CW and Welsh JS: Dose optimization to minimize radiation risk for children undergoing CT and nuclear medicine imaging is misguided and detrimental. J Nucl Med 58: 865-868, 2017.