Paediatric Patients Dose Optimisation and Risk Assessment in Computed Tomography Examination

Theophilus A. Sackey[1], Issahaku Shirazu[1*], Raymond Edziah[2], Y. B Mensah[3], Elvis K. Tiburu[4], and C. Schandorf[5]

[1]Medical Sciences Research Institute, Ghana Atomic Energy Commission, Accra-Ghana.
[2]Department of Physics, University of Cape Coast, Cape Coast
[3]Department of Radiology, Korle-Bu Teaching Hospital, Accra Ghana
[4]Department of Biomedical Engineering, University of Ghana, Legon, Accra Ghana
[5]School of Nuclear and Allied Sciences, University of Ghana, Legon, Accra Ghana

***Corresponding Author:** sissahaku@ug.edu.gh

ABSTRACT

Children are a distinct group of patients and should not be consider as small adults in terms of medical imaging procedures. Their size, physiology and the location of their organs change as they grow. Additionally, children have a longer life expectancy than adults hence consideration must be taken into account when the appropriate radiation dose is delivered. Therefore, the study was to estimate paediatric patients' lifetime attributable radiation risk during computed tomography examination. The materials used include five different multi-detector computed tomography (MDCT) Machines, Head and Body phantom and MeVisLab (MVL) workstation. The weighted CTDI (CTDIw) and DLP values obtained were used estimate effective and organ doses to estimate the cancer incidence and mortality. In all 300 images of paediatric patients undergoing CT scans of head, chest, and abdomen-Pelvis from six CT centres were randomly selected. 200 images that met the selection criterion were analysed. The average values for organ dose and effective dose for Brain CT exam for age 0-5, 6-10 and 11-16 years were10.3 mGy, 1.3965 mSv; 11.18 mGy, 2.2785 mSv; and 19.82 mGy, 4.5102 mSv respectively for male patients. These values indicated increased values for Chest and abdominal pelvis examinations, with the dose increasing depending on the paediatric protocols that were used which depended on patient age band. The average cancer risk for incidence and mortality for head, chest and abdomen-pelvis examinations were in the range 1 in 10,000 to in 1,000 of the study population.

1.0 INTRODUCTION

Diagnostic radiological examinations in infants and children carry a higher risk, on average, for the development of cancer per unit of radiation dose compared with adults (Brady et al., 2011; Brenner et al., 2001). The higher risk in children is explained by their longer life expectancy, which allows more time for any harmful effects of radiation to manifest; and the fact that developing organs and tissues are more sensitive to the effects of radiation (ICRP, 2007). Moreover, the average risk is higher in infants and young children compared with other children. The increasing use of X-ray technology has resulted in a

compared with older children. The increasing use of X-ray technology has resulted in a situation where the annual collective and per-capita doses of ionizing radiation due to diagnostic radiology have exceeded those from the former largest source (natural background radiation) in several developed countries. Hence, it is imperative that all radiological examinations must be justified and optimized with regard to radiological protection for every patient, and this is especially important in paediatric patients. Computed tomography (CT) examinations may involve relatively high doses of radiation, and an estimated 7–10% of CT examinations are performed on children (Charles, 2010; ICRP, 2007; Wiest et al., 2002) . The absorbed doses to organs and tissues from paediatric CT are relatively high, and typically range from approximately 2 to 30 mGy to exposed organs (Charles, 2010).

Therefore, risk assessment is essential for justification of examinations and consideration of alternative examinations if available which does not involve ionising radiation exposure (Moss & McLean, 2006; Shrimpton et al., 2006; Smith-Bindman et al., 2009; Wiest et al., 2002). This study aimed at estimating risk associated with paediatric patients undergoing CT scans of head, chest, and abdomen-Pelvis at the selected CT facilities.

2.0 OBJECTIVES OF THE STUDY

The objectives of this study are to use retrospect method to obtain reliable and validated information on paediatric imaging practices, equipment performance, and to estimate effective doses incurred by paediatric patients during CT imaging leading to radiation risk assessment. In addition to develop and implement optimization strategies in paediatric imaging so as to enhance patients' protection and safety.

3.0 METHODOLOGY

The equipment used include; two Philips Brilliance 64 Multislice, 1 Toshiba Aquilion One Multislice, 1 General Electric, 1 Lightspeed VCT 64 Multislice and 1 Siemens Emotions 16 Multislice CT scanners which were installed between 2012 and 2016.Three Hundred (300) patients were randomly selected for this study. The Parameters of interest were $\mathrm{kVp, mA, DLP, CTDI_{Vol}}$, Pitch and scan length were collected from the image data on the PAC system. Data analysis was done using MeVisLab for viewing and extraction of dose parameters and Minitab for statistical analysis.

The study measured patients dose parameters that are associated with paediatric patients' risk Assessment in CT Examination in relation to the use of contiguous multidetector paediatric CT imaging in Ghana. This was done by using retrospective data from the PAC system to obtain $\mathrm{CTDI_{VOL}}$ to estimate $\mathrm{CTDI_W}$ in addition to DLP from the dose report. All the measured primary data were based on the body region, the age and gender variation of the patient. The selection criteria of the facilities were based on the availability of paediatric images and the willingness to be part of the study by the facility.

While the selection of the body region was based on the common clinical examination of paediatric imaging in the selected facilities. The study analyzed 200 CT images from a sample size of 300 CT images for five different CT units in Ghana using MeVisLab DICOM application software, which is a standard software for viewing any kind of medical image. Details of the equipment used are indicated in Table 1 and Figure 1 shows the experimental setup for the measurements.

Table 1: Specifications of CT Scanners

Manufacturers	Scanner Model/Scan Mode
Philips	Brilliance 64, Multislice, Axial and Helical Modes
Siemens	Emotions 16, Multislice, Axial and Helical Modes
General Electric	Lightspeed VCT 64, Multislice, Axial and Helical Modes
Toshiba	Toshiba-Aquilion ONE, Multislice, Axial and Helical Modes

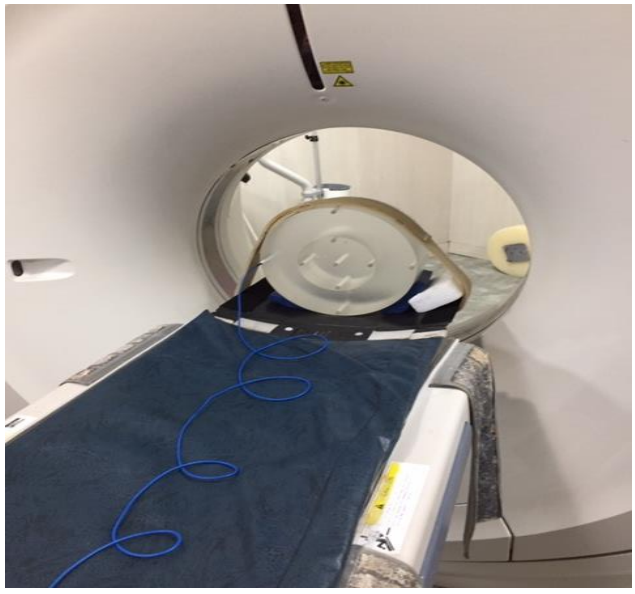

Figure 1: Phantom setup for CTDI measurements

3.1 Quality Control Measurement

The ACR designed phantom for CT image quality evaluation (CATPhan 600) was used to provide a comprehensive set of measurements to measure the maximum performance of all the CT scanners used in terms of image noise, uniformity, geometric and low-contrast sensitivity measurement. The scanner readings were calibrated and validated to standard measurement. The daily necessary scanning procedure and protocol of the various manufacturers were used to complete the calibration check. The measured parameters were compared with the parameters in the dose report and the necessary corrections done before the required data was collected for analysis.

3.2 Measurement of Effective Dose

The weighted CTDI ($CTDI_W$) was estimated by multiplying the volume weighted CTDI ($CTDI_{vol}$) by the pitch factor expressed mathematically as:

$$CTDI_W = \rho CTDI_{vol} \quad (1)$$

Where p is the pitch factor and varies from 0.813-1.0 for the scanning protocol that were used.

It has been shown by (Chung T et. al, 1998) that DLP is approximately proportional to Effective Dose (E). Hence, to estimate the various effective dose values, DLP and region- specific normalizing constant or DLP conversion factor (E_{DLP}) as developed by ICRP Publication 103 (ICRP, 2007) were used and define as: $E = \mu DLP$ (2)

where μ is the region-specific normalizing constant and the slope of E versus the DLP relationship.

3.3 Measurement of Organ Dose

Recommendation by ICRP103 provide appropriate dosimetric indicator for the probability of stochastic radiation effects by using the average absorbed dose in a tissue or organ. Absorbed dose is defined as the mean of the stochastic distribution of energy deposited in specific tissue or organ. The mean absorbed dose in a specified organ or tissue is simply referred to as organ dose.

In this study the organ dose was estimated using ICRP publication 103 recommendation, defined as:

$$P = \frac{organ\ dose\ (D_T)}{measured\ or\ calculated\ quantity} \quad (3)$$

For CT, when stochastic effects are of interest, the specified dosimetric quantity is the organ dose estimate, D_T, and the CT Dose Index.

Thus

$$C_{T\ CTDI}(P) = \frac{(D_T)}{CTDI} \quad (4)$$

Implied

$$Organ\ dose\ (D_T) = P\ CTDI\ (measured\ or\ calculated\ quantity)$$

$$D_T = P \times CTDI_W \quad (5)$$

Where in the case of the Brain, Chest and Abdomen –Pelvis regions represented by grey matter, lungs and kidney respectively.

The P values for grey matter, lungs and kidney *are* ***0.009, 0008, 0.006*** respectively.

Furthermore, as indicated by ICRP publication 103, the conversion factor for organs/tissues is determined using the $CTDI_W$, the weighted Computed Tomography dose Index, and exposure. The effective mAs, which were obtained by dividing the exposure (mAs) by the pitch factor. That is

$$\text{eff}(mAs) = \frac{\overline{mAs}}{0.813} \quad (6)$$

Experimentally, the real practical estimated average exposure (mAs) for this study was 48.19mAs. Hence the eff(mAs) is 56.27mAs. The weighted CTDI ($CTDI_W$) was estimated by multiplying the volume CTDI ($CTDI_{vol}$) by the pitch factor (Equation 3) expressed mathematically as:

$$CTDI_W = 0.813 \times CTDI_{vol} \quad (7)$$

where 0.813 is the average pitch factor of the scanning protocol used.

3.4 Cancer Risk Assessments

Cancer risk was assessed using the Lifetime Attribute Risk (LAR) principle. The LAR is defined as additional cancer risk above and beyond baseline cancer risk and can be calculated for specific cancers as well as for all cancers combined ((ICRP, 1991; ICRP, 2007).

Table 12D–1 and Table 12D–2 of the BEIR VII report was used in the calculations of LAR (Appendix 1) When data was not available for specific age then linear interpolation to the nearest integer is made from the above information.

The LAR was calculated using the following equation.

$$\text{BEIR VII LAR at an age} = \left(\frac{\text{E(mSv)}}{\text{D}} \times \frac{\text{LAR(cancer incidence)}}{100{,}000}\right) \times 100\% \quad (8)$$

Equation 22 was used for calculating cancer incidence

$$\text{BEIR VII LAR at an age} = \left(\frac{\text{E(mSv)}}{\text{D}} \times \frac{\text{LAR(cancer mortality)}}{100{,}000}\right) \times 100\%. \quad (9)$$

Equation 23 was used for calculating cancer mortality.

D = 100 mGy, the reference dose to the population considered in the BEIR VII report.

ICRP publication 103, provide details data on organ dose for accurate estimate of risk factors (cancer incidence and mortality) by using organ dose rather than effective dose.

3.5 ICRP Modelling of Risk

ICRP methodology for risk estimation prescribed in Publication 103 of 2007 is as follows:

For medical exposure, the risk of cancer incidence (R_i) and cancer mortality (R_m) in a particular organ for a imaging procedures (e.g CT) can be estimated from equation 5

$$R_{i,m} = \sum_T r_T \times H_T \quad (10)$$

Where r_T is the risk coefficient taking from ICRP Publication 103 which provides a listing of the nominal risk factor values. Extracted examples are given in the Table 2

4.0 RESULTS AND DISCUSSION

Table 2 shows Age-specific μ-factors (mSv mGy^{-1} cm^{-1}) for < 1 y old; 1-4y old 5-9 y old;10-14 y old and 15-16 y old for reference phantoms for different scan types based on ICRP 103 head and body CTDI phantoms (ICRP, 2007). Table 4a provides the effective and organ doses and cancer risk assessment for incidence and mortality by BEIR VII method (BEIR, 2009).

Table 2: Age-specific μ-factors (ICRP reference phantoms, Publication 103)

Scan region	**<1 y-old**		**1-4 y-old**		**5-9 y-old**		**10-14 y-old**		**15-16 y-old**	
	Head	**Body**	**Head**	**Body**	**Head**	**Body**	**Head**	**Body**	**Head**	**Body**
Head	0.009		0.006		0.004		0.003		0.002	
Chest	0.051	0.099	0.033	0.064	0.024	0.047	0.017	0.033	0.012	0.024
Abdomen	0.045	0.088	0.032	0.063	0.022	0.043	0.017	0.032	0.014	0.027
Pelvis	0.028	0.054	0.021	0.041	0.015	0.028	0.009	0.017	0.008	0.015

Table 3: Extracted values of nominal risk factors for some organs at risk (ICRP reference phantoms, Publication 103)

Organ/ Risk ($10^{-4}Sv^{1}$)	Organs at risk (r_T)							
	Thyroid	Oesophagus	Lungs	Liver	Stomach	Colon	Gonads	Bladder
Incidence Risk	32.5	15.1	114.2	30.3	79.1	65.4	20.0	43.4
Mortality Risk	23.3	29.1	110.8	67.5	71.8	71.8	226.3	71.7

Table 4a: Effective dose and Risk assessment for male by BEIR VII method

Examination	Age Years	*Organ Dose*	*Effective dose*	*Risk Incidence*	*Risk Mortality*
		mGy	mSv	%	%
Brain	0-5	10.83	1.3965	0.031620	0.01396
	6–10	11.18	2.2785	0.039687	0.01877
	11-16	19.82	4.5102	0.062799	0.03113
Chest	0-5	70.14	5.8213	0.140503	0.06110
	6–10	72.85	15.889	0.276770	0.13093
	11-16	96.14	24.059	0.335029	0.16606
Abdomen/pelvis	0-5	0.06153	4.6980	0.113391	0.07918
	6–10	0.06319	12.334	0.214825	0.16014
	11-16	0.00783	13.965	0.187106	0.14356

Table 4b: organ dose and Risk assessment for male by ICRP method

Examination	Age Years	*Organ Dose*	*Effective dose*	*Risk Incidence*	*Risk Mortality*
		mGy	mSv	%	%
Brain	0-5	10.83	1.3965	0.15573	0.24501
	6–10	11.18	2.2785	0.16076	0.25300
	11-16	19.82	4.5102	0.28501	0.44853
Chest	0-5	70.14	5.8213	1.13450	1.14469
	5–10	72.85	15.889	1.17871	1.18711
	11-16	96.14	24.059	1.55541	1.56901
Abdomen/pelvis	0-5	0.06153	4.6980	0.000163	0.000173
	6–10	0.06319	12.334	0.000137	0.000137
	11-16	0.00783	13.965	0.000171	0.00071

For Head CT scan the tissue at risk is the brain and the lens of the eye. For chest CT scan the tissues at risk are esophagus, thyroid and lung. For the abdomen/pelvis CT scan the following organs; kidney, colon, liver, stomach and bladder at risk were considered. The average values for organ dose and effective dose for Brain CT exam for age 0-5, 6-10 and 11-16 years were 10.3 mGy, 1.3965 mSv; 11.18 mGy, 2.2785 mSv; and 19.82 mGy, 4.5102 mSv respectively for male patients. The average values for organ dose and effective dose for Chest CT exam for age 0-5, 6-10 and 11-16 years 70.1 mGy,5.813 mSv; 72.85 mGy, 15.889 mSv; 96.14 mGy, 24.059 mSv respectively for male patients. The average values for organ dose and effective dose for Abdomen /Pelvis CT exam for age 0-5, 6-10 and 11-16 years were 61.5 µGy, 4.698 mS; 63.19 µGy, 13.33 mSv; 7.83 µGy, 13.965 mSv respectively for male patients.

Table 5a: Effective dose and risk assessment for female by BEIR VII method

Examination	Age Years	*Organ Dose*	*Effective dose*	*Risk Incidence*	*Risk Mortality*
		mGy	mSv	%	%
Brain	0-5	10.98	1.374	0.057941	0.02199
	6–10	15.65	3.190	0.102831	0.04142
	11-16	15.65	3.846	0.096211	0.04100
Chest	0-5	64.96	3.985	0.179196	0.06714
	5–10	68.41	14.97	0.482555	0.19435
	11-16	92.60	21.16	0.529230	0.22552
Abdomen/pelvis	0-5	57.32	3.516	0.158115	0.03690
	6–10	59.76	11.36	0.366159	0.09359
	11-16	7.52	13.74	0.328688	0.09184

Table 5b: Organ dose and risk assessment for female by ICRP method

Examination	Age Years	*Organ Dose*	*Effective dose*	*Risk Incidence*	*Risk Mortality*
		mGy	mSv	%	%
Brain	0-5	10.98	1.374	0.15789	0.24848
	6–10	15.65	3.190	0.22974	0.36516
	11-16	15.65	3.846	0.22974	0.36516
Chest	0-5	64.96	3.985	1.04877	1.05955
	6–10	68.41	14.97	1.10083	1.11571
	11-16	92.60	21.16	1.49822	1.51038
Abdomen/pelvis	0-5	57.32	3.516	1.25072	1.62159
	6–10	59.76	11.36	1.3039	2.11970
	11-16	7.52	13.74	0.16373	0.21273

Table 6: Risk of fatal Cancer from CT Examination (ICRP reference phantoms, Publication 103)

Risk Level	Approximate additional Risk of fatal Cancer from CT Examination
Negligible	Less than 1 in 1,000,000
Minimal	1 in 1,000,000 to 1 in 100,000
Very Low	1 in 100,000 to 1 in 10,000
Low	1 in 10,000 to 1 in 1,000
Moderate	1 in 1,000 to 1 in 500

The details of the dose and estimated risk are captured in Tables 3a and Table 4a for male and female patients respectively. The risk values were within the low range of 1 in 10,000 to 1 in 1,000 range as indicated in Table 6. Tables 4b and 5b capture the cancer risks for incidence and mortality estimated by the ICRP 103 method for male and female patients respectively. ICRP estimates were in the moderate range 1in 1,000 to 1in 500 (BEIR, 2009).

The application of the optimization principle to CT imaging procedures requires a special approach, since too low a radiation dose could be as bad as a too high radiation dose which in both case the images obtained could be of unsuitable diagnostic quality. To achieve this a comprehensive Clinical Decision Support Application Software was designed to provide a user-friendly platform to aid in the optimisation process. This is to allow the radiographers to predict the possible dose to the patients and when the approved imaging protocol are known for the examinations of the head, chest and abdomen /pelvis regions of the body. Figure 5 shows the user interface for the estimation of cancer risk incidence and mortality. It serves as a predictive model in paediatric diagnostic radiology. Input data required for regression models calculations for head, Chest examination and abdomen/pelvis examinations are: Examination protocol parameters: kVp; mAs; gender. Figure 2 shows the user interface for the estimate of incidence and mortality risks. It serves as a predictive model for the paediatric imaging at the CT facilities considered for this study. Twelve incidence and mortality risk modeled equations used are shown in Table 5.

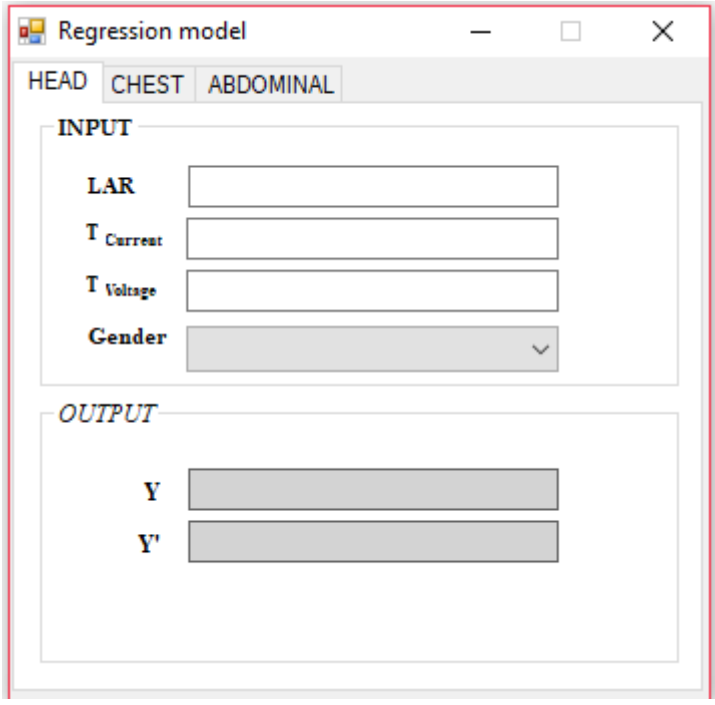

Figure 2: Graphic User Interface for the regression model

Table 7: Head model equations

Head Model	Model Equation
Male Incidence	$Y = 0.0501 - 0.000030\ LAR + 0.000131X_1 + 0.000268X_2$
Female Incidence	$Y = 0.1098 - 0.000033\ LAR + 0.000004\ X_1 + 0.000517\ X_2$
Male Mortality	$Y' = 0.0548 - 0.000062\ LAR - 0.000000\ X'_1 + 0.000108\ X'_2$
Female Mortality	$Y' = 0.0718 - 0.000052\ LAR + 0.000001\ X'_1 + 0.000184\ X'_2$

Table 8: Chest model equations

Chest Model	Model Equation
Male Incidence	$Y = 0.228 - 0.000079\ LAR - 0.00056\ X_1 + 0.00137\ X_2$
Female Incidence	$Y = 1.379 - 0.000203\ LAR - 0.00276\ X_1 - 0.00209\ X_2$
Male Mortality	$Y' = 0.488 - 0.000344\ LAR - 0.000730\ X'_1 - 0.000679\ X'_2$
Female Mortality	$Y' = 0.689 - 0.000295\ LAR - 0.00113\ X'_1 - 0.00095\ X'_2$

Table 9: Abdomen/Pelvis model equations

Abdominal-Pelvis Model	Model Equation
Male Incidence	$Y = -0.239 + 0.000083\ LAR - 0.00013\ X_1 + 0.00183\ X_2$
Female Incidence	$Y = -0.438 + 0.000082\ LAR - 0.00018\ X_1 + 0.00337\ X_2$
Male Mortality	$Y' = -0.1203 + 0.000094\ LAR + 0.000668\ X'_1 + 0.000595\ X'_1$
Female Mortality	$Y' = -0.246 + 0.000110\ LAR + 0.000719\ X'_1 + 0.001358\ X'_1$

Where,

Y is cancer risk incidence

Y' is cancer risk mortality

X_1 is the mAs

X_2 is the kVp

LAR is the life time attributable risk

5.0 CONCLUSION

The study established range of organ doses and effective doses received by paediatric patients undergoing CT examinations for the head, chest and abdomen /pelvis regions. Radiation risks were estimated using BEIR VII and ICRP models ((ICRP, 1996, ICRP, 2001)). The organ doses and effective doses were comparable to those quoted in the literature. BEIR VII model risk estimates were within the low range of 1 in 10,000 to 1 in 1,000 range. The ICRP model risks estimates were within the moderate range of 1 in 1,000 to 1 in 500. A regression model with a Graphic User interface was produced to aid in patient dose monitoring and optimisation of patient protection prior to executing the imaging protocols.

ACKNOWLEDGEMENT

I would like to acknowledge Ghana Atomic Energy Commission and the ICTP through the Associate program (2020–2025) for the support I received from the two institutions. Additionally, I acknowledge the participating facilities for allowing me to carry out the research in their facilities.

REFERENCE

Brady, Z., Cain, T. M., & Johnston, P. N. (2011). Differences in using the international commission on radiological protection's publications 60 and 103 for determining effective dose in paediatric CT examinations. Radiation Measurements, 46(12). https://doi.org/10.1016/j.radmeas.2011.08.005

Brenner, D. J., Elliston, C. D., Hall, E. J., & Berdon, W. E. (2001). Estimated risks of radiation-induced fatal cancer from pediatric CT. American Journal of Roentgenology, 176(2). https://doi.org/10.2214/ajr.176.2.1760289

Charles, M. (2010). Effects of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation: UNSCEAR 2006 Report, Volume 1—Report to the General Assembly, with Scientific Annexes A and B. Oxford University Press.

Moss, M., & McLean, D. (2006). Paediatric and adult computed tomography practice and patient dose in Australia. Australasian Radiology, 50(1). https://doi.org/10.1111/j.1440-1673.2005.01544.x

International Commission on Radiological Protection (ICRP). (1991). 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Annals of the ICRP, 21(1-3).

International Commission on Radiological Protection (ICRP). (1996). Radiological protection and safety in medicine. ICRP Publication 73. Annals of the ICRP, 26(2), 1-47.

International Commission on Radiological Protection (ICRP). (2001). Diagnostic reference levels in medical imaging: Review and additional advice. Annals of the ICRP, 31(4), 33–52.

International Commission on Radiological Protection (ICRP). (2007). ICRP Publication 105. Radiation protection in medicine. Ann ICRP, 37(6), 1–63.

Shrimpton, P. C., Hillier, M. C., Lewis, M. A., & Dunn, M. (2006). National survey of doses from CT in the UK: 2003. In British Journal of Radiology (Vol. 79, Issue 948). https://doi.org/10.1259/bjr/93277434

Smith-Bindman, R., Lipson, J., Marcus, R., Kim, K. P., Mahesh, M., Gould, R., Berrington De González, A., & Miglioretti, D. L. (2009). Radiation dose associated with common computed tomography examinations and the associated lifetime attributable risk of cancer. Archives of Internal Medicine, 169(22). https://doi.org/10.1001/archinternmed.2009.427

Wiest, P. W., Locken, J. A., Heintz, P. H., & Mettler, F. A. (2002). Ct scanning: A major source of radiation exposure. Seminars in Ultrasound CT and MRI, 23(5). https://doi.org/10.1016/S0887-2171(02)90011-9