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Research Article

Estimation of organ-specific cancer and mortality risks associated with common indication-specific CT examinations of the abdominopelvic region

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ABSTRACT

Introduction: There is a paucity of large-scale studies reporting organ doses and cancer risks in patients who undergo indication-specific CT examinations. This study estimated organ-specific lifetime attributable risk (LAR) of cancer incidence and mortality among patients who underwent indication-based computed tomography (CT) examinations [(involving abdominopelvic lesion, kidney stones and computed tomography-intravenous urography (CT-IVU)] in about 70% of the functioning CT facilities in Ghana.

Methods: With a total of 1,100 data sets, organ doses were first determined using the National Cancer Institute Dosimetry System for CT (NCICTX) software version 2.1, and LAR values were predicted using the BEIR VII model.

Results: The estimated radiation-induced colon cancer risks were likely in 39.4-59.8 out of 100,000 patients who underwent CT because of abdominopelvic lesion. The risk was even higher in CT-IVU examinations (53.3-66.4 patients in 100,000 procedures) but was relatively less (16.8-26.3 patients) in kidney stone procedures. Accordingly, the risk of radiation-induced colon mortality was more common in CT-IVU than in kidney stone procedures (22.7-28.2 versus 7.2-12.5 patients in 100,000 procedures).

Conclusion: These results call for further optimisation actions for indication-specific CT examinations to appropriately reduce the potential risk levels for patients' protection and safety.

RéSUMé

Introduction: Il y a peu d'études à grande échelle rapportant les doses aux organes et les risques de cancer chez les patients qui subissent des examens de tomodensitométrie en fonction de leur indication. Cette étude a estimé le risque attribuable à vie (RAV) spécifique à un organe pour l'incidence du cancer et la mortalité chez les patients qui ont subi des examens de tomodensitométrie (TDM) basés sur l'indication [(impliquant une lésion abdominopelvienne, des calculs rénaux et une urographie intraveineuse par tomodensitométrie (TDM-UIV)] dans environ 70 % des installations de TDM en service au Ghana.

Méthodologie: Avec un total de 1 100 ensembles de données, les doses aux organes ont d'abord été déterminées à l'aide du logiciel NCI-

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CTX (National Cancer Institute Dosimetry System for CT), version 2.1, et les valeurs RAV ont été prédites à l'aide du modèle BEIR VII.

Résultats: Les risques estimés de cancer du côlon radio-induit étaient probables chez 39,4-59,8 patients sur 100 000 procédures de lésions abdominopelviennes. Le risque était encore plus élevé dans les examens TDM-UIV (53,3-66,4 patients sur 100 000 procédures) mais était relativement moindre (16,8-26,3 patients) dans les procédures de calculs rénaux. En conséquence, le risque de mortalité radio-induite dans le côlon était plus fréquent dans les examens TDM-UIV que dans les procédures de calculs rénaux (22,7-28,2 contre 7,2-12,5 patients pour 100 000 procédures).

Conclusion: Ces résultats appellent à de nouvelles actions d'optimisation pour les examens TDM spécifiques à une indication afin de réduire de manière appropriée les niveaux de risque potentiels pour la protection et la sécurité des patients.

Keywords: Organ-specific lifetime attributable risk; Indication-based cancer risks; computed tomography; Ghana; common indication dose

Introduction

There is no doubt that computed tomography (CT) imaging is a very reliable tool in medical imaging, and it continues to be used to improve patients' health outcomes globally. The extensive use of CT in clinical practice has been shown to decrease the proportion of patients needing inpatient admission [1,2]. Due to its usefulness, the demand has increased drastically in recent years not only in general applications, but also in newer areas such as dual energy CT [3].

However, these examinations are not radiation-risk free. There have been regular reports of potential radiation risks for the past two decades, to the extent that CT utilisation in radiation medicine has generated a lot of interest all these years[4–8]. The available measures recommended to reduce the potential risk of radiation include dose optimization. However, as part of the optimization process, there is the need to first appreciate the dose levels emanating from any given radiological examination and their impact on human organs in order to proffer appropriate optimization measures.

In Ghana, a number of studies have been conducted on CT dose levels. However, there is a paucity of large-scale studies reporting organ doses and cancer risks in patients who undergo indication-specific CT examinations. This study, therefore, estimated organ-specific lifetime attributable risk (LAR) of cancer incidence and mortality among patients who underwent CT examinations for various indications of the abdominopelvic region of the body in Ghana.

Methods and materials

The study was approved by the Ethics Committee for Basic and Applied Sciences of University of Ghana (REF. No: ECBAS 041/17-18), the Ghana Health Service Ethics Review Committee (REF NO: GHS-ERC002/04/18), Korle Bu Teaching Hospital's Scientific and Technical Committee (KBTH-STC) and the Institutional Review Board (KBTHIRB) (REF NO: KBTH-IRB/00092/2017). Using a cross-sectional study design, demographic, CT dose descriptors/quantities, exposure factors and image quality data were collected from 24 CT facilities in Ghana. These facilities (Table 1) constituted about 70% of CT scanners in Ghana at the time of the study [9] and were those which were functioning, dedicated for diagnostic purposes and available for the study. Before the data collection process, quality control (QC) tests on all the equipment were undertaken. Upon observing satisfactory QC results (published elsewhere [10]) across the facilities, image folders of CT scans performed on the account of an abdominopelvic lesion, kidney stones and urothelial malignancy (CT-IVU) were collected across the participating facilities. The folders contained the scan images as well as the CT dose descriptors/quantities and exposure factors.

To estimate the effective dose associated with each of the considered indications, equation 1.0 was used:

$$E_D = \mathrm{DLP} \times \mathrm{k} \tag{1.0}$$

where:

E_D is the effective dose, DLP is the dose length product and k is the region-specific DLP to E_D conversion factor (where k for abdominopelvic region is 0.0150 $\mathrm{mSv \cdot mGy^{-1} cm^{-1}}$) [11].

In evaluating the magnitude of the effective doses, the average effective doses for the indications were compared to the global average natural background radiation of approximately 2.4 mSv [12,13].

Organ dose estimation

Organ doses, which are important for the estimation of cancer risks [8,14], were first determined using the National Cancer Institute Dosimetry System for CT (NCICTX) (software version 2.1, Bethesda, USA) [14,15]. The software is based on a comprehensive library of computational human phantoms (surrogate anatomy for patients) combined with Monte Carlo radiation simulation of reference CT scanners and is a known reliable tool for estimating organ doses [15]. Through the graphical user interface (GUI), the relevant parameters were entered into the NCICT software and organ doses for individual patients were normalized and derived from the output interface as required by the system. Variables that were plugged in included age, gender, scan manufacturer, model, body part, filter type, tube potential, current-time product, pitch, total collimation, $\mathrm{CTDI_{vol}}$ and scan length. Fig. 1 shows the NCICTX software GUI which allowed organ doses to be obtained based on the entered $\mathrm{CTDI_{vol}}$ and patient- and scan-specific parameters.

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Table 1
CT equipment in facilities

CT ID	Ownership	Manufacturer	Model	MY	IY	Detector row/slice
I	G	Toshiba	Aquilion One TSX-301A	2012	2012	320/640
II	P	Siemens	Somatom Emotion 6	2006	2011	6
III	P	GE	Brightspeed Elite	2011	2011	16
IV	PPP	Philips	Brilliance ICT	2015	2016	128
V	P	GE	VCT Lightspeed	2008	2009	64
VI	P	Siemens	Somatom Perspective	2016	2017	64
VII	G	GE	Lightspeed Pro 16	2011	2011	16
VIII	P	GE	Brivo CT 385 series	2015	2016	16
IX	G	Siemens	Somatom Emotion	2007	2008	6
X	G	Toshiba	Aquilion TSX-101A	2016	2016	16
XI	G	Toshiba	Aquilion TSX-101A	2013	2013	16
XII	G	Toshiba	Aquilion CXL TSX-101A	2015	2015	32
XIII	G	Toshiba	Aquilion CXL TSX101A	2012	2015	32
XIV	P	GE	Revolution Evo	2017	2017	64
XV	P	Philips	Brilliance	2009	2010	4
XVI	P	Hitachi	Supria	2015	2015	16
XVII	PPP	Philips	Brilliance extended	2007	2010	64
XVIII	P	Siemens	Somatom Emotion	2009	2010	16
XIX	PPP	GE	GE Revolution 5492001	2018	2018	64
XX	P	Siemens	Somatom Definition AS	2015	2016	64
XXI	P	Toshiba	Asteion	2009	2016	4
XXII	G	Toshiba	Aquilion TSX-101A	2015	2015	16
XXIII	G	Toshiba	Aquilion TSX-101A	2012	2013	16
XXIV	G	GE	Optima 660	2016	2016	64

Key: P: private, G: government/public, PPP: public–private partnership, MY: manufactured year, IY: installation year. CT: computed tomography. ID: Identity number.

Estimation of cancer risk

After deriving the organ doses, the BEIR VII model was applied to predict the Lifetime Attributable Risk (LAR) of cancer based on the magnitude of a single radiation exposure, patient's age and gender [16]. The LAR is defined as an additional cancer risk above and beyond baseline cancer risk [16]. The model was developed based on the extensive studies on the survivors of the Hiroshima and Nagasaki atomic bombs, and medical, occupational and environmental radiation studies [16]. Theoretically, the model is grounded on the linear no-threshold model (LNT) which is centred on the assumption that the smallest dose has the potential to cause a small increase in radiation risk to humans for doses below 100 mSv [16]. LAR of cancer and mortality coefficients data as presented in Tables 12D-1 and 12D-2 of the BEIR VII report [16] were utilised to estimate the cancer risks. Using the age of exposure and gender parameters, the *LAR* of cancer incidence (*LARi)* and cancer mortality (*LARm)* from organ doses were subsequently extrapolated for patients (at age 20, 40 and 60 years) by the BEIR VII model as presented in proportions via Equations (2) and (3) below.

$$\mathrm{LAR}i = \left[\left(\frac{\mathrm{D_{org}}}{0.1}\mathrm{Gy}\right)\mathrm{LAR}if\right]\text{in 100, 000 patients} \quad (2)$$

$$\mathrm{LAR}m = \left[\left(\frac{\mathrm{D_{org}}}{0.1}\mathrm{Gy}\right)\mathrm{LAR}mf\right]\text{ in 100, 000 patients} \quad (3)$$

where LAR_i and LAR_m represent the lifetime attributable risk of cancer incidence and mortality, respectively whereas the *LARif* and *LARmf* represent the BEIR VII organ-specific cancer incidence and mortality coefficients/indices, normalised to age and gender as given in Table 12D-2 in the BEIR VII report [16], and D_{org} is the organ dose in gray (Gy). The 0.1 Gy in the equa-

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Table 2
Descriptive statistics of exposures used in acquiring the images of the various indications considered in this study.

CT ID	Abdominopelvic lesion					Kidney stones					Urothelial malignancy (CT-IVU)				
	Tube voltage (kVp	Tube load (mAs)	Pitch	Trot (s)	SL (mm)	Tube voltage (kVp)	Tube load (mAs)	Pitch	Trot (s)	SL (mm)	Tube voltage (kVp)	Tube load (mAs)	Pitch	Trot (S)	SL (mm)
I	120*	46.5[a]±15[b] (41[c]) [40-104][d]	0.81*	0.5*	5*	120*	65.4[a]± 33[b] (55[c]) [33-156][d]	1.12[a]±0.3[b] (1.38[c]) [0.81-1.39][d]	0.5*	5*	120*	60.7[a]±34[b] (52[c]) [30-190][d]	1.2[a]±0.3[c] (1.4[c]) [0.8-1.39][d]	0.5*	5*
II	122[a]±10[b] (130[c]) [110-130][d]	83.2[a]±20[b] (83[c]) [38-113][d]	1.2[a]1±0.4[b] (1.2[c]) [0.8-1.8][d]	2*	5*	130*	76[a]±21[b] (72[c]) [34-113][d]	1.4[a]±0.3[b] (1.5[c]) [0.8-1.8][d]	2*	5*	122$_a$±10[b] (130[c]) [110-130][d]	63.4[a]±16.7[b] (65[c]) [34-88][d]	1.22[a]±0.4[b] (1.25[c]) [0.8-1.8][d]	2*	5*
III	120*	125.7[a]±69[b] (91[c]) [61-303][d]	1.38*	0.8*	5*	120*	128.5[a]± 80[b] (88[c]) [60-281][d]	1.38*	0.8*	5*	120*	147.8[a]± 87[b] (103[c]) [80-349][d]	1.38*	0.8*	5*
IV	120*	151[a]±40[b] (155.5[c]) [88-221][d]	1.3[a]±0.1[b] (1.4[c]) [1.1-1.5][d]	0.5[a]±0.02[b] (0.5[c]) [0.4-1][d]	5*	120*	159.5[a]±46[b] (150[c]) [83-265][d]	1.3[a]±0.1[b] (1.3[c]) [1.1-1.5][d]	0.5[a]±0.1[b] (0.5[c]) [0.4-1][d]	5*	120*	22.9[a]±93.6[b] (193[c]) [127-418][d]	1.22[a]±0.14[b] (1.24[c]) [0.93-1.38][d]	0.59[a]±0.2[b] (0.5[c]) [0.4-1][d]	5*
V	120*	160[a]±91[b] (163[c]) [32-298][d]	1.375*	0.5*	5*	120*	131$_a$±77[b] (95[c]) [35-250][d]	1.375*	0.5*	5*	120*	170.4[a]±33[b] (180[c]) [101-199][d]	1.38*	0.5*	5*
VI	117[a]±8[b] (110[c]) [110-130][d]	104.1[a]± 42[b] (91[c]) [59-244][d]	0.78[a]± 0.2[b] (0.6[c]) [0.6-1.2][d]	0.65*	5*	115[a]±9[b] (110[c]) [110-130][d]	100.3[a]± 41[b] (83[c]) [54-224][d]	0.7[a]±0.01[b] (0.6[c]) [0.6-1.2][d]	0.62[a]± 0.02[b] (0.6[c]) [0.6-0.65][d]	5*	120[a]±10.3[b] (120[c]) [110-130][d]	95.5[a]±27[b] (86[c]) [58-169][d]	0.6	0.6	5*
VII	120*	250[a]± 73[b] (200[c]) [220-400][d]	1.38*	0.8*	3.9[a]±1.8[b] (5[c]) [1.25-5][d]	120*	256[a]±74[b] (220[c]) [220-400][d]	1.36*	0.8*	4.3[a]±1.5[b] (5[c]) [1.25-5][d]	-	-	-	-	-
VIII	120*	91.4[a]± 41[b] (80[c]) [60-190][d]	1.6[a]±0.1[b] (1.75[c]) [1.38-1.75-1][d]	1*	5*	120*	84.6[a]±42[b] (64[c]) [60-109][d]	1.6[a]±0.2[b] (1.75[c]) [1.38-1.75][d]	1*	5*	120*	113.2[a]±43[b] (122.5[c]) [56-161][d]	1.3**	0.18*	5*

(*continued on next page*)

Table 2 (*continued*)

CT ID	Abdominopelvic lesion					Kidney stones					Urothelial malignancy (CT-IVU)				
	Tube voltage (kVp	Tube load (mAs)	Pitch	Trot (s)	SL (mm)	Tube voltage (kVp)	Tube load (mAs)	Pitch	Trot (s)	SL (mm)	Tube voltage (kVp)	Tube load (mAs)	Pitch	Trot (S)	SL (mm)
IX	127.5[a]±6[b] (130[c]) [110-130][d]	75.4[a]±29[b] (56[c]) [33-432][d]	1.3[a]±0.3[b] (1.13[c]) [0.8-1.8][d]	1.0[a]±.05[b] (1.2[c])0.5-2][d]	4.4[a]±1.4[b] (5[c]) [3-6][d]	130*	54.6[a]±29[b] (54[c]) [30-90][d]	1.1[a]±0.3[b] (1.13[c]) [0.8-1.65][d]	0.92[a]±0.04[b] (1[c]) [0.8-2][d]	3.9[a]±1.3[b] (3[c]) [3-6][d]	130*	53[a]±16.7[b] (53.5[c])]33-90][d]	1.18[a]±0.3[b] (1.2[c]) [0.8-1.65][d]	0.8*	3*
X	120*	54.5[a]±15[b] (50[c]) [46-116][d]	0.9[a] ±0.2[b] (0.9[c]) [0.9-0.5][d]	0.5*	10*	120*	51.2[a]±4[b] (52[c]) [48-65][d]	1[a]±0.2[b] (0.9[c]) [0.9-1.5][d]	0.5*	10*	120*	79.31[a]±38[b] (91[c]) [56-153][d]	0.98*	0.5*	10*
XI	120*	187*	0.94*	0.8*	7*	120*	187*	0.94*	0.8*	7*	-	-	-	-	-
XII	120*	56.7[a]±27[b] (42[c]) [40-120][d]	0.8*	0.5*	6.8[a]± 3.1[b] (5[c]) [3-10][d]	120*	51.4[a]±23[b] (42.5[c]) [40-120][d]	0.83*	0.5*	6.6[a]±2.9[b] (5[c]) [3-10][d]	120*	46.5[a]±9.8[b] (42[c]) [40-68][d]	0.82*	0.5*	6.8[a]±2.7[b] (5[c]) [3-10][d]
XIII	120*	52±4.6[a] (51[c]) [50-65][d]	0.94*	0.5*	10*	120*	51[a]±2.7[b] (50[c]) [50-60][d]	0.94*	0.5*	10*	120*	60.35[a]±33.7[b] (61[c]) [54-198][d]	0.98*	0.5*	8.7[a]±2.7[b] (10[c]) [1.25-10][d]
XIV	117[a]±7[b] (120[c]) [100-120][d]	285.2[a]± 131[b] (270.5[c]) [100-471][d]	1.38*	0.9[a]± 0.1[b] (0.8[c]) [0.8-1][d]	1.25*	100*	415.2[a]± 70[b] (431[c]) [196-477][d]	1.38*	1*	1.25*	120*	235[a]±63[b] (198[c]) [185-406][d]	1.1[a]±0.16[b] (0.98[c]) [0.98-1.38][d]	1*	1.25
XV	120*	222.5[a]±30[b] (200[c]) [200-300][d]	0.96[a]±0.01[b] (0.9[c]) [0.7-1.2][d]	0.8*	3.2[a]±0.7[b] (3[c]) [2-5][d]	120*	205[a]±15[b] (200[c]) [200-250][d]	0.92[a]±0.06[b] (0.9[c]) [0.9-1.1][d]	0.8*	3*	-	-	-	-	-
XVI	120*	243.8*	1.06*	0.75*	2.5*	120*	243.8*	1.06*	0.8*	2.5*					
XVII	120*	279[a]±96[b] (267[c]) [168-431][d]	1.1[a]±0.09[b] (1.1[c]) [0.89-1.17][d]	0.91[a]±0.16[b] (1[c]) [0.5-1][d]	1*	120*	269.7[a]±76[c] (256[c]) [182-445][d]	1.45[a]±0.04[b] (1.17[c]) [1.02-1.17][d]	0.95[a]±0.15[b] (1[c]) [0.5-1][d]	1*	120*	287.8[a]± 69.7[b] (268[c]) [194-392][d]	0.89*	0.75*	1*

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Table 2 (*continued*)

CT ID	Abdominopelvic lesion					Kidney stones					Urothelial malignancy (CT-IVU)				
	Tube voltage (kVp	Tube load (mAs)	Pitch	Trot (s)	SL (mm)	Tube voltage (kVp)	Tube load (mAs)	Pitch	Trot (s)	SL (mm)	Tube voltage (kVp)	Tube load (mAs)	Pitch	Trot (S)	SL (mm)
XIII	130*	81.2[a]±28[b] (76[c]) [45-141][d]	0.8*	0.6*	5*	130*	74.7[a]±26[b] (70[c]) [30-141][d]	0.8*	0.6*	5*	130*	60.2[a]±23[b] (53[c]) [34-117][d]	0.8*	0.6*	5*
XIX	120*	122.9[a]±45[b] (127.5[c]) [53-176][d]	1.72[a]±0.03[b] (1.75[c]) [1.68-1.75][d]	0.98[a]±0.008[b] (0.98[c]) [0.98-1][d]	5*	120*	115.3[a]±57[b] (132.5[c]) [40-180][d]	1.73[a]±0.03[b] (1.75[c]) [1.67-1.75][d]	1*	5*	110[a]±10.3[b] (110[c]) [110-120][d]	137.[7a]±50.4[b] (174.5[c]) [53-176][d]	1.7[a]±0.03[b] (1.68[c]) [1.67-1.75][d]	0.98*	5*
XX	100*	139.5[a]±39[b] (130[c]) [80-254][d]	0.6*	0.5*	3*	100*	142.1[a]±40[b] (141[c]) [80-254][d]	0.60*	0.5*	3.8[a]±0.4[b] (4[c]) [3-4][d]	100*	128.9[a]±41.0[b] (109[c]) [79-215][d]	0.6*	0.5*	1.2[a]±0.2[b] (1[c]) [1-1.5][d]
XXI	100*	79.7[a]±42.1[b] (60[c]) [60-187][d]	0.6*	0.5*	5*	100*	83.9[a]± 41[b] (60[c]) [60-187][d]	0.88*	0.8*	5*	100*	79.1[a]±35.6[b] (60[c]) [60-165][d]	0.88*	0.75*	5*
XXII	120*	199.6[a]±25.8[b] (187[c]) [187-250][d]	0.94*	0.75*	10*	120*	190.3[a]± 14[b] (187[c]) [18-250][d]	0.94*	0.8*	10*	-	-	-	-	-
XXIII	120*	62.8[a]±22.2[b] (56[c]) [50-125][d]	0.94*	0.5*	10*	120*	60.7[a]± 16[b] (60[c]) [50-125][d]	0.94*	0.5*	8.3[a]±0.7[b] (8[c]) [8-10][d]	120*	54[a]±7.8[b] (52[c]) [54-78][d]	0.98*	0.5*	8*
XXIV	120*	128.7[a]±59[b] (110[c]) [70-230][d]	1.38*	0.7*	5*	120*	115[a]±40[b] (110[c]) [70-202][d]	1.38*	0.7*	5*	120*	65.9[a]±16.6[b] (69[c]) [49-100][d]	1.38*	0.7*	5*

Key: ID= identify, kVp=peak kilovoltage, mAs=milliampere-second, trot=rotation time, std = standard deviation. CT-IVU = computed tomography Intravenous urogram.

[a] = mean

[b] =standard deviation

[c] = median

[d] = range (minimum to maximum), * = same values were used for same indication examinations, - facility was not performing such procedure, SL =Scan length, mm =millimeters, s = second.

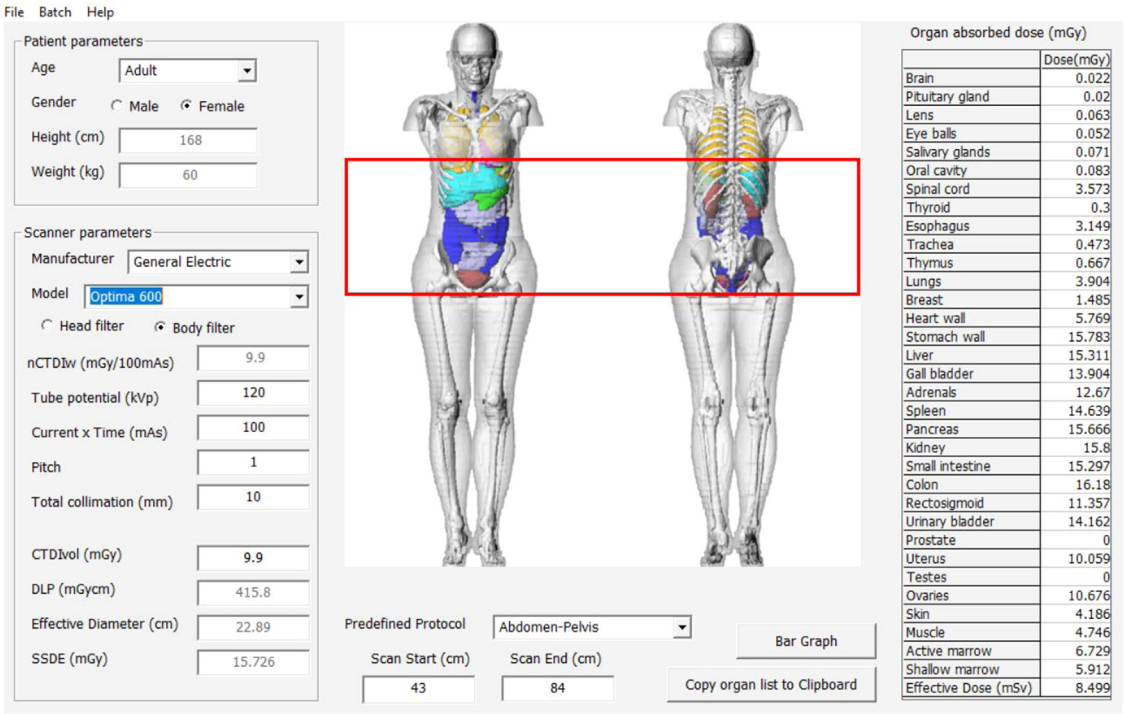

Fig. 1. Graphical user interface (GUI) of the NCICT program [14,15] showing an example of entered patient- and scan-specific parameters (on the right and middle) and generated estimated organ doses in milligray (mGy) (on the left)

tion was used to account for the standardized 100 mGy used in Table 12D-2 in the BEIR VII report.

Results and discussion

The radiation dose levels and their impact on the body in relation to effective doses, LAR of cancer and mortality were estimated for common indication-specific CT procedures of the abdominopelvic region, using data from about 70% of the CT scanners in the country. The equipment coverage, to the best of our knowledge, is the largest that has been used in evaluating organ-specific cancer risks in CT in Ghana. In all, a total of 1,100 CT dose data sets were utilised in this study. These comprised data from the abdominopelvic lesion (n=400), kidney stones (n=400) and urothelial malignancy/CT-IVU (n=300), respectively. The descriptive statistics of the scan parameters used in each facility have been presented in Table 2. Moreover, the summarized demographic characteristics and average exposure parameters of all the facilities that were utilized for the various indications are presented in Table 3.

The estimated mean effective doses (Table 4) for single-phase (non-contrast) procedures were generally lower than multiple-phase (both contrast and non-contrast) procedures, due to the number of examination series. The result was consistent with data previously reported by Smith-Bindman et al [17]. The highest (20.09 ± 12.19 mSv) and least (8.51 ± 3.0 mSv) mean effective doses were reported for the CT-IVU and kidney stone examinations, respectively. The doses associated with these two examinations differed by a factor of 2.4, suggesting that the high-dose examinations could subject a patient to radiation levels equivalent to 8.4 years of natural background radiation. This necessitates radiation dose optimisation in CT imaging at the facilities, especially for CT-IVU procedures.

Despite the fact that there are considerable uncertainties associated with cancer statistics and risk estimation, there has been steady recognition that organ doses are the best to estimate radiation risks [4,5]. The organ doses derived in this study included the colon, uterus, testes, ovary, active marrow and shallow marrow among others (Table 5). Among these organs, the colon received the highest dose during imaging for CT-IVU (41.1 - 56.7 mGy), abdominopelvic lesion (41.7-41.9 mGy) and kidney stones (17.9 - 18.5 mGy) across all ages (20, 40 and 60 years old). Even though the ranges of organ doses are generally below the level required to yield deterministic effects, stochastic effects of radiation dose on the other hand could not be ruled out [18].

Due to the relatively high colon dose observed in the study, it was not surprising that radiation-induced colon cancer risks were very high in the region of about 39.4 - 59.8 patients in 100,000 abdominopelvic lesion procedures. The risk was even higher in CT-IVU examinations, in a range of 53.3 - 66.4 patients in 100,000 procedures, but was relatively less (16.8-26.3 patients) in kidney stone procedures. Accordingly, the risk of radiation-induced colon mortality was more common in CT-IVU than in abdominopelvic lesion and kidney stone procedures as indicated in Table 6.

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Table 3
Average scan parameters across all the facilities utilized to acquire the various images.

Indication	Mean Age (years)	Gender Male: Female	Scan parameters (mean ± std)					
			Tube voltage (kVp)	Tube load (mAs)	Pitch	*Trot* (s)	Mean slice thickness (mm)	Scan length (cm)
Abdominopelvic lesion	49.3±14.2	188:212	117.5 ± 6.5	136.0 ± 81.4	1.11 ± 0.2	0.75 ± 0.2	5.20 ± 2.6	46.84 ± 4.3
Kidney stones	40.1±5.1	191:209	119.0 ± 5.1	127.7 ± 70.3	1.12 ± 0.2	0.75 ± 0.3	5.30 ± 2.5	44.31 ± 3.2
Urothelial malignancy (CT-IVU)	48.7±13.2	186:114	117.0 ± 9.5	115.0 ± 73.0	1.08 ±0.2	0.74 ± 0.3	5.10 ± 2.4	45.13 ± 4.3

kVp=peak kilovoltage, mAs=milliampere-second, trot=rotation time, std = standard deviation, CT-IVU = computed tomography Intravenous urogram.

Table 4
Indication-specific effective doses and their equivalent background radiation levels

Indications	Effective dose, $E_{D,}$ (mSv)			
	Non-contrast phase Mean± SD	Contrast phase Mean± SD	Overall for examination Mean± SD	Background radiation equivalent*
Abdominopelvic lesion	8.30 ± 5.24	8.87 ± 5.18	17.17 ±10.00	7.2 years
Kidney stones	8.51 ± 5.01	-	8.51 ± 3.01	3.5 years
Urothelial malignancy (CT-IVU)	6.71± 3.78	14.26 ± 8.74	20.09 ± 12.19	8.4 years

*Average yearly natural background radiation used ≈ 2.4 mSv (Canadian Nuclear Safety Commission, 2019). CVA: cerebrovascular accident, CKD: chronic kidney disease, SD: standard deviation, E_D: effective dose.

Table 5
Various organ doses associated with CT imaging for AP lesion, kidney stones and urothelial malignancy indications

Organ	Organ doses (mGy)								
	AP lesion			Kidney stones			Urothelial malignancy		
	20 yrs Mean ± SD	40 yrs Mean ± SD	60 yrs Mean ± SD	20 yrs Mean ± SD	40 yrs Mean ± SD	60 yrs Mean ± SD	20 yrs Mean ± SD	40 yrs Mean ± SD	60 yrs Mean ± SD
Stomach wall	39.3 ± 25.8	39.0 ± 22.8	38.3 ± 22.8	17.2 ±11.1	17.2 ± 10.4	16.3 ± 9.9	38.0 ± 24.1	49.5 ± 30.2	51.7 ± 30.2
Liver	37.9 ± 25.1	37.7 ± 22.2	37.2 ± 22.2	16.7 ±10.8	16.7 ± 10.2	15.6 ± 9.5	36.6 ± 23.3	49.1 ± 29.5	49.6 ± 28.9
Gall bladder	35.6 ± 22.8	35.5 ± 20.2	35.5 ± 21.1	15.6 ± 9.9	15.7 ± 9.0	15.1 ± 9.4	34.9 ± 21.9	46.4 ± 27.6	47.7 ± 28.3
Adrenals	32.7 ± 20.9	32.7 ± 18.5	32.7 ± 19.4	14.3 ± 9.0	14.4 ± 8.2	13.9 ± 8.7	32.1 ± 20.1	42.8 ± 25.6	44.0 ± 26.1
Spleen	36.6 ± 24.0	36.4 ± 21.3	36.1 ± 21.5	16.1 ±10.4	16.1 ± 9.7	15.2 ± 9.3	35.5 ± 22.5	47.3 ± 28.3	48.2 ± 28.2
Pancreas	38.0 ± 25.4	37.8 ±22.5	37.2 ± 22.3	16.7±10.9	16.7 ± 10.3	15.6 ± 9.5	36.7 ± 23.4	49.0 ± 29.4	49.5 ± 28.8
Kidney	39.9 ± 25.7	39.8 ±22.8	39.7 ± 23.6	17.5±11.1	17.6 ± 10.2	16.8 ± 10.4	39.0 ± 24.5	51.7 ± 30.7	53.3 ± 31.5
Small intestine	39.9 ± 25.1	40.2 ±22.3	40.4 ± 24.1	17.6±11.0	17.8 ± 9.9	17.3 ± 10.9	39.7 ± 24.8	52.0 ± 30.4	54.9 ± 33.0
Colon	41.7 ± 26.4	41.8 ±23.4	41.9 ± 24.9	18.3±11.5	18.5 ± 10.4	17.9 ± 11.2	41.1 ± 25.7	54.4 ± 32.1	56.7 ± 33.8
Rectosigmoid	29.8 ± 19.0	32.5 ±17.7	32.3 ± 20.0	13.9 ± 9.1	14.3 ± 7.8	13.6 ± 8.7	32.2 ± 20.2	39.7 ± 24.7	45.5 ± 28.4
U. Bladder	34.0 ± 21.9	37.4 ±21.2	36.2 ± 22.1	16.2±10.6	16.3 ± 9.5	15.0 ± 9.2	36.2 ± 23.0	43.4 ± 26.3	50.9 ± 30.9
Prostate	8.1 ± 10.9	11.0 ±14.2	12.1 ± 16.2	4.2 ± 6.1	4.6 ± 5.6	5.5 ± 7.0	11.3 ± 15.8	14.1 ± 21.3	22.6 ± 27.6
Uterus	13.9 ± 19.2	15.3 ±19.4	12.0 ± 17.1	7.0 ± 9.1	6.6 ± 9.2	3.8 ± 5.7	12.7 ± 18.6	16.2 ± 18.7	13.5 ± 19.4
Testes	1.6 ± 3.1	2.1 ± 3.8	3.8 ± 8.0	0.6 ± 0.9	1.0 ± 2.3	2.0 ± 5.7	1.6 ± 2.4	1.9 ± 3.4	5.0 ± 7.0
Ovary	14.9 ± 20.5	16.3 ±20.6	12.8 ± 18.2	7.5 ± 9.6	7.0 ± 9.8	4.1 ± 6.1	13.5 ± 19.8	16.1 ± 19.6	14.4 ± 20.7
Skin	11.2 ± 7.2	11.8 ± 6.5	12.0 ± 7.2	5.1 ± 3.4	5.3 ± 3.0	5.0 ± 3.0	11.6 ± 7.1	14.1 ± 8.5	16.5 ± 9.7
Muscle	12.7 ± 8.3	13.6 ± 7.5	13.8 ± 8.5	5.9 ± 4.0	6.1 ± 3.5	5.6 ± 3.5	13.4 ± 8.2	16.6 ± 9.3	19.1 ± 11.3
*Act. marrow	16.9 ± 11.0	17.5 ±10.1	17.2 ± 10.3	7.5 ± 5.0	7.6 ± 4.6	7.1 ± 4.4	17.0 ± 10.8	21.6 ± 12.5	23.4 ± 13.9
+S. marrow	14.5 ± 9.6	13.8 ± 8.1	14.2 ± 8.6	5.9 ± 3.1	6.4 ± 4.1	5.8 ± 3.5	14.1 ± 9.2	18.3 ± 10.7	19.3 ±11.3

*Act. = Active marrow
+ S = Shallow; AP= abdominopelvic, SD = standard deviation, Yrs = years.

Although the organ dose likely to cause radiation-induced leukaemia was lower than that received by the urinary bladder across all indications, the LAR of leukaemia mortality was higher than those observed in the urinary bladder (Table 6). This suggests a high likelihood of leukaemia mortality across all the examinations and hence optimization of radiation exposure is highly recommended. The ovaries were also likely to develop abdominopelvic lesion CT examination-induced cancer in 7.5/100,000 (1 in 13,000), 5.1/100000 (1 in 19,608), and 2.3/100,000 (1 in 43,478) people at age 20, 40 and 60 years, re-

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Table 6
Cancer and mortality risks associated with CT doses for AP lesion, kidney stones and urothelial malignancy/CT-IVU

Cancer site	AP lesion				Kidney stone			Urothelial malignancy/CT-IVU		
	Age (yrs)	Organ dose (mGy)	LARi/ 100,000	LARm /100,000	Organ dose (mGy)	LARi/ 100,000	LARm /100,000	Organ dose (mGy)	LARi/ 100,000	LARm /100,000
Stomach	20	39.3 ± 25.8	18.1	9.8	17.2 ± 11.1	7.9	4.3	38.0 ±24.1	17.5	9.5
	40	39.0 ± 22.8	10.5	6.6	17.2 ± 10.4	4.6	3.0	49.5 ±30.2	13.4	8.7
	60	38.3 ± 22.8	7.7	3.0	16.3 ± 9.9	3.3	2.2	51.7 ±30.2	10.3	7.0
Liver	20	37.9 ± 25.1	8.3	6.6	16.7 ±10.8	3.7	2.9	36.6 ±23.3	8.1	6.4
	40	37.7 ± 22.2	7.9	4.5	16.7 ± 10.2	3.5	2.0	49.1 ±29.5	10.3	5.9
	60	37.2 ± 22.2	5.2	3.5	15.6 ± 9.5	2.2	1.5	49.6 ±28.9	6.9	4.7
Colon	20	41.7 ± 26.4	59.8	28.6	18.3 ±11.5	26.3	12.5	41.1 ±25.7	59.0	28.2
	40	41.8 ± 23.4	51.0	20.3	18.5 ± 10.4	22.6	9.0	54.4 ±32.1	66.4	26.4
	60	41.9 ± 24.9	39.4	16.8	17.9 ± 11.2	16.8	7.2	56.7 ±33.8	53.3	22.7
Prostate	20	8.1 ± 10.9	3.8	0.7	4.2 ± 6.1	2.0	0.4	11.3 ±15.8	5.4	1.0
	40	11.0 ± 14.2	3.9	0.7	4.6 ± 5.6	1.6	0.3	14.1 ±21.3	5.0	0.8
	60	12.1 ± 16.2	3.2	0.9	5.5 ± 7.0	1.4	0.4	22.6 ±27.6	6.0	1.6
Leukaemia	20	16.9 ± 11.0	14.1	10.0	7.5 ± 5.0	14.6	10.3	17.0 ±10.8	14.4	10.1
	40	17.5 ± 10.1	12.8	10.4	7.6 ± 4.6	12.8	10.5	21.6 ±12.5	12.5	10.2
	60	17.2 ± 10.3	12.0	11.0	7.1 ± 4.4	15.0	13.8	23.4 ±13.9	16.3	15.0
Urinary	20	34.0 ± 21.9	37.1	18.4	16.2 ± 10.6	17.7	4.4	36.2 ± 23.0	39.5	9.8
Bladder	40	37.4 ± 21.2	29.5	7.5	16.3 ± 9.5	12.9	3.3	43.4 ± 26.3	34.3	8.7
	60	36.2 ± 22.1	23.5	7.1	15.0 ± 9.2	9.8	2.9	50.9 ± 30.9	33.1	9.9
Uterus	20	13.9 ± 19.2	3.6	0.8	7.0 ± 9.1	1.8	0.42	12.7 ± 18.6	3.3	0.76
	40	15.3 ± 19.4	2.4	0.6	6.6 ± 9.2	1.1	0.31	16.2 ± 18.7	2.6	0.65
	60	12.0 ± 17.1	1.9	0.4	3.8 ± 5.7	0.3	0.11	13.5 ± 19.4	1.2	0.41
Ovary	20	14.9 ± 20.5	7.5	4.2	7.5 ± 9.6	3.8	2.1	13.5 ± 19.8	6.8	3.8
	40	16.3 ± 20.6	5.1	3.3	7.0 ± 9.8	2.2	1.4	16.1 ± 19.6	5.0	3.2
	60	12.8 ± 18.2	2.3	1.9	4.1 ± 6.1	0.7	0.6	14.4 ± 20.7	2.6	2.2

LARi: lifetime attributable risk of cancer incidence, LARm: Lifetime attributable risk of cancer mortality, AP: abdomino-pelvic, CT-IVU: computed tomography intravenous urography, Yrs: year.

spectively. Kidney stone examinations were also likely to induce ovarian cancer in 3.8, 2.2 and 0.7 patients in a pool of 100,000 procedures at the ages of 20, 40 and 60 years, respectively. More so, about 1 in 38, 462 to 1 in 14,706 patients were also likely to develop ovarian cancer due to CT-IVU examinations in Ghana. Since the ovaries contain reproductive information, it is indicative that hereditary effects were also possible in patients who received high ovarian doses. Although all the upper LAR values for the indications were within 1 in 10,000 to 1 in 1,000 of the population and suggested a low radiation risk, there was a need for further optimisation to reduce the dose levels and risks, as noted by Varghese et al [19] and other international bodies and studies [12,13,16,20]. This may include the optimization of exposure factors/parameters and scan coverages, use of iterative reconstruction and automatic exposure control systems, effective use of the equipment and its accessories, and implementation of diagnostic references levels (DRLs), as suggested in recent studies conducted in Ghana [20–22], among many other measures in literature [3,6,11,16]. This is important because small individual risks applied to a large population could lead to a public health issue some years in the future [16,20].

Conclusion

Although there are some considerable uncertainties about cancer risk estimations, this study has attempted to provide reasonable estimates of radiation-induced cancer risks associated with CT dose levels utilized in Ghana based on the BEIR VII model. Among the organs subjected to CT exposures during abdominal pelvic examinations, radiation-induced colon cancer risks were observed to be the highest, and most likely among 39.4 -59.8 peopleout of 100,000 patients who underwent CT becuase of abdominopelvic lesions. The estimated risk was even higher in CT-IVU examinations, in a range of 53.3 - 66.4 patients in 100,000 procedures but was relatively less (16.8-26.3 patients) in kidney stone procedures. Accordingly, the risk of radiation-induced colon mortality was more common in CT-IVU in than abdominopelvic lesion and kidney stone procedures. Although all the upper LAR values for all the indications were within 1 in 10,000 to 1 in 1,000 of the population and suggested a low radiation risk, there was a need for further optimisation to reduce the dose levels and risks for patients' protection and safety. This is because small individual risks applied to a large population could lead to a public health issue some years in the future.

References

[1] Power SP, Moloney F, Twomey M, James K, O'Connor OJ, Maher MM. Computed tomography and patient risk: facts, perceptions and uncertainties. *World J Radiol.* 2016;8(12):902–915. doi:10.4329/wjr.v8.i12.902.

[2] Bellolio MF, Heien HC, Sangaralingham LR, Jeffery MM, Campbell RL, Cabrera D, Shah ND, Hess EP. Increased computed tomography utilization in the emergency department and its association with hospital admission. *West J Emerg Med.* 2017 Aug;18(5):835–845 Epub 2017 Jul 19. doi:10.5811/westjem.2017.5.34152.

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[3] Ebdon-Jackson S, Frija G. & European Society of Radiology. Improving justification of medical exposures using ionising radiation: considerations and approaches from the European Society of Radiology. *Insight Imag*. 2021;12:2. doi:10.1186/s13244-020-00940-0.

[4] Brower C, Rehani MM. Radiation risk issues in recurrent imaging. *Br J Radiol*. 2021;94. doi:10.1259/bjr.20210389.

[5] Rehani MM. Old enemy, new threat: You can't solve today's problems with yesterday's solution. *J Radiol Prot*. 2021;41(2):452–458. doi:10.1088/1361-6498/abe2ba.

[6] Rehani MM. What makes and keeps radiation risks associated with CT a hot topic? *Am J Roentgenol*. 2015;204(3):W234–W235. doi:10.2214/AJR.14.12860.

[7] Meulepas JM, Ronckers CM, Smets AMJB, Nievelstein RAJ, Gradowska P, Lee C, Jahnen A, van Straten M, de Wit MY, Zonnenberg B, Klein WM, Merks JH, Visser O, van Leeuwen FE, Hauptmann M. Radiation exposure from pediatric CT scans and subsequent cancer risk in the Netherlands. *J Natl Cancer Inst*. 2019 Mar 1;111(3):256–263. doi:10.1093/jnci/djy104.

[8] Zewde N, Ria F, Rehani MM. Organ doses and cancer risk assessment in patients exposed to high doses from recurrent CT exams. *Eur J Radiol*. 2022;149(2022):110224 April. doi:10.1016/j.ejrad.2022.110224.

[9] Botwe BO, Schandorf C, Inkoom S, Faanu A, Rolstadaas L, Goa PE. National indication-based diagnostic reference level values in computed tomography: preliminary results from Ghana. *Phys Med*. 2021;84:274–284. doi:10.1016/j.ejmp.2021.03.012.

[10] Botwe B, Schandorf C, Inkoom S, Faanu A. Status of quality management systems in computed tomography facilities in Ghana. *Radiol Technol*. 2020;91(4):324–332.

[11] AAPM Report 96. *The measurement, reporting and management of radiation dose in CT*. American Association of Physicists in Medicine; 2007.

[12] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Sources and effects of ionizing radiation. UNCEAR 2008 Report to the General Assembly with Scientific. Annexes https://www.unscear.org/docs/reports/2008/09-86753_Report_2008_Annex_B.pdf

[13] Canadian Nuclear Safety Commission. *Radiation doses*; 2019 Retrieved from Accessed on: 30/10/19. http://nuclearsafety.gc.ca/eng/resources/radiation/introduction-to-radiation/radiation-doses.cfm#targetText=A%20typical%20annual%20dose%20received.energy%20workers%20is%2050%20mSv

[14] Lee C, Kim KP, Long D, Fisher R, Tien C, Simon SL, Bolch WE. Organ doses for reference adult male and female undergoing computed tomography estimated by Monte Carlo simulations. *Med Phys*. 2011;38(1):1196–1206.

[15] Lee C, Kim PK, Bolch EW, Moroz1 BE, Folio L. NCICT: a computational solution to estimate organ doses for pediatric and adult patients undergoing CT scans. *J Radiol Prot*. 2015;35:891–909 2015.

[16] . *Health risks from exposure to low levels of Ionising radiation: BEIR VII Phase 2*. Washington, DC: The National Academies Press; 2006:259–267.

[17] Smith-Bindman R, Lipson J, Marcus R, Kim KP, Mahesh M, Gould R, Miglioretti DL. Radiation dose associated with common computed tomography examinations and the associated lifetime attributable risk of Cancer. *Arch Internal Med*. 2009;169(22):2078–2086.

[18] Shrimpton PC, Jansen JT, Harrison JD. Updated estimates of typical effective doses for common CT examinations in the UK following the 2011 national review. *Br J Radiol*. 2016;89(1057):20150346. doi:10.1259/bjr.20150346.

[19] Varghese A, Keshava SN, Moses V, Koshy G, Mammen S, Ahmed M, Livingstone RS. Radiation dose reference card for interventional radiology procedures: Experience in a tertiary referral centre. *Indian J Radiol Imag*. 2019;29(3):247–252. doi:10.4103/ijri.IJRI_35_19.

[20] IAEA. *IAEA safety standards for protecting people and the environment: Radiation protection and safety in medical uses of Ionising radiation*. Vienna: International Atomic Energy Agency; 2018 IAEA Safety standards Series No. SSG-46.

[21] Botwe BO, Schandorf C, Inkoom S, Faanu A. Variability of redundant scan coverages along the Z-axis and dose implications for common computed tomography examinations. *J Med Imaging Radiat Sci*. 2022;53(1):113–122. doi:10.1016/j.jmir.2021.10.007.

[22] Botwe B.O, Schandorf C, Inkoom S. et al., Towards the establishment of national imaging practice guidelines: a preliminary study of the basic computed tomography imaging protocols in Ghana, J Med Imag Radiat Sci, https://doi.org/10.1016/j.jmir.2022.03.004.

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