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Dose optimization of adult head computed tomography examination in an academic hospital in Ghana

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ABSTRACT

The study investigated radiation doses and image quality of adult head CT and optimization options using an anthropomorphic RANDO phantom on the only available AquilionONE CT scanner in Ghana. Dose length product (DLP) and volume-weighted CT dose index ($CTDI_{vol}$) dose descriptors were retrospectively obtained from 402 adult head CT examinations performed (from 2020 to 2021) at a Ghanaian hospital, while the effective dose (D_{eff}) was estimated from the product of the DLP and a convention coefficient ($k = 0.0023$). Using the same routine head CT protocol, the anthropomorphic RANDO phantom was scanned with the hospital's 640-slice Toshiba AquilionONE CT scanner. Subsequently, exposure factors were varied to study their effects on the dose and image quality. The adult head and phantom images were obtained in Digital Imaging and Communications in Medicine (DICOM) format, and their signal-to-noise (SNR) ratios were analyzed with ImageJ software. The facility's mean $CTDI_{vol}$, DLP, and effective dose (D_{eff}) were 86.00 ± 0.00 mGy, 1559.68 ± 197.18 mGy cm, and 3.57 ± 0.46 mSv respectively (SNR = 7.04). For a fixed tube potential, $CTDI_{vol}$, DLP, and D_{eff} of 51.30 mGy, 1013.80 mGy cm, and 2.33 mSv were respectively achieved (SNR = 5.49) after optimization. Using automatic exposure control (AEC) in the optimization process, the respective $CTDI_{vol}$, DLP and D_{eff} values were 59.50 mGy, 1176.00 mGy cm and 2.70 mSv (SNR = 5.62). We conclude that substantial D_{eff} reductions of 40.4% and 31.0% using a fixed tube potential, and AEC while maintaining diagnostic image quality were respectively achieved. The protocols associated with these dose-reductions are, therefore, recommended as optimization measures for head CT on the AquilionONE scanner in Ghana.

1. Introduction

Computed tomography (CT) is a non-invasive medical imaging modality that utilizes ionizing radiation to produce cross-sectional and detailed images of parts of the body, as defined by the World Health Organization (2021). Advances in CT imaging technology and its extensive use in clinical practice have resulted in increased CT examinations and reduced the need for emergency surgery from 13% to 5%, eliminating many exploratory surgical procedures (Power et al., 2016). In Ghana, Botwe et al. (2020) estimated that 204,760 patients undergo CT examinations yearly. High radiation doses delivered to patients undergoing CT examinations are a major global concern due to the associated biological effects and inherent risks compared to other radiological examinations (Anim-Sampong et al., 2016; Sackey, 2015). Although CT procedures deliver organ doses in the range of 10 mGy–100 mGy which are generally below levels required to induce deterministic effects, according to the linear non-threshold theory, patient risk of stochastic effects is correlated with radiation dose at any level (Alm-Carlsson et al., 2007; Shrimpton et al., 2016). It is thus, essential to reduce patient dose while maintaining diagnostic image quality, and consequently minimize the associated health effects.

Several CT dose-reduction approaches including the alteration of exposure factors (lowering tube current and peak tube voltage), use of automated exposure control (AEC), monitoring, and integration of different iterative reconstruction software have been provided by various manufacturers. These approaches, however, have different effects on the image quality needed for a specific diagnosis or task (Demb et al., 2017). Hence, appropriate dose optimization measures are

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required to ensure that patients presenting for a particular CT imaging including head scans receive optimized radiation doses to reduce the inherent risk but maintain diagnostic image quality (Smith-Bindman et al., 2019).

According to Bauhs et al. (2008), the CT dose index (CTDI) is the integral of the single scan radiation dose profile along the *z*-axis, normalized to the thickness of the imaged section and expressed differently for single-slice computed tomography (SSCT) and multi-slice computed tomography (MSCT) as:

$$CTDI_{SSCT} = \frac{1}{T}\int_{-\infty}^{+\infty} D(z)dz \quad (1)$$

$$CTDI_{MSCT} = \frac{1}{NT}\int_{-L/2}^{+L/2} D(z)dz \quad (2)$$

where T is the detector width or minimal beam collimation thickness, D is the dose profile, and N is the number of detectors. The volume-weighted CTDI ($CTDI_{vol}$) is the pitch-corrected weighted CTDI ($CTDI_w$) and is expressed as

$$CTDI_{vol} = \frac{CTDI_w}{p} = \frac{1}{p}\left[\frac{1}{3}CTDI_{100,centre} + \frac{2}{3}CTDI_{100,periphery}\right] \quad (3)$$

where p is the scan pitch. According to Smith-Bindman et al. (2011), the $CTDI_{vol}$ and dose length product (DLP) are important CT dose descriptors for estimating the average absorbed dose for a series of irradiated tissue sections. The DLP reflects the potential biologic effect as it represents the total energy produced by a given protocol in a complete scan acquisition and varies directly with the total scanned radiation dose (Kisembo et al., 2015; Strauss, 2014). It is calculated as the product of the intensity ($CTDI_{vol}$) and the length of the scanned tissue (Nagel, 2007) via Eqn (4) as

$$DLP = CTDI_{vol} x L = \frac{L}{p} CTDI_w \quad (4)$$

where L is the scan length for the examinations determined via

$$L = \frac{DLP}{CTDI_{vol}} \quad (5)$$

The effective dose (D_{eff}) is an inference of an individual's whole-body dose resulting from radiation exposures and relates to the risk resulting from the exposure to the individual organ and tissue contributions of the absorbed doses. It is determined to assess incidence rates for biological responses such as the stochastic effects. According to Semelka et al. (2007), D_{eff} is the product of an organ's equivalent dose (H_T) and radiosensitivity which offers a whole-body dose with the same risk as a partial dose provided by a localized radiologic procedure. It is dependent on patient size, imaging parameters and scanner technology, and is often clinically estimated from measured DLPs, as reported in the literature (Sodickson et al., 2009).

Quantitatively, D_{eff} for a patient can be calculated from the product of DLP and a conversion factor coefficient (k) for the specific body region (Brady et al., 2015; Postorino et al., 2021) as

$$D_{eff} = \sum W_t H_t \quad (6)$$

and

$$D_{eff} = kDLP = k[CTDI_{vol}] = \frac{kL}{p} CTDI_w \quad (7)$$

where W_t is the tissue-specified weighting factor for tissue or organ (t) under examination, and $k = 0.0023$ for head CT scan according to the European guidelines on quality criteria for CT (Bongartz et al., 2000). The signal-to-noise ratio (SNR) is a measure of image quality and is defined as the ratio of the mean to the standard deviations of the pixel value of regions of interest (ROIs) (Chang et al., 2017).

One of the central goals of medical radiation protection is to minimize the risks of stochastic effects of radiation to levels considered as low as reasonably achievable (ALARA), while dose optimization ensures that minimum patient doses are administered to achieve the desired purpose and image quality. This study, therefore, investigated a method of optimizing the dose received by adult patients undergoing CT head examinations while maintaining the quality of the diagnostic image. This is important to minimize head CT doses and biological effects associated with high radiation exposures, provide new protocols for adult head CT examinations, create awareness and education of radiographers in optimizing head CT doses, and thereby enhance patient radiation protection per the ALARA principle.

2. Materials and methods

A retrospective and quasi-experimental design which allowed for alteration of the scan parameters for head CT examinations and non-probability purposive sampling were used in this study which was conducted at the CT unit of the radiology department of a hospital in Ghana. According to Anim-Sampong et al. (2016), adult patients are more commonly referred for CT examinations of the head and other parts of the body than pediatric patients. Therefore, this study consisted of 402 adult patients who presented for head CT examinations at the hospital from January 2020–January 2021.

Constant values of tube voltage, tube current, rotation time, and pitch were used for routine head CT examinations, while scan lengths depending on the coverage area planned on the scanogram and limited to head CT examination with a major focus on the brain varied. These and other head CT scan parametric (slice number, slice thickness, $CTDI_{vol,}$ and DLP) data, as well as patient demographics, were retrospectively retrieved from the Picture Archiving and Communication System (PACS) workstation of the hospital's 640 multi-slice Toshiba Aquilon ONE TSX-301A CT scanner (Table 1) and recorded on the self-designed data collection sheet. The technical specifications of the Toshiba Aquilon ONE TSX-301A CT scanner are presented in Table 2. Quality control (QC) tests to validate the efficiency of the CT scanner have been reported in the literature (Botwe et al., 2021).

The D_{eff} for each patient was subsequently calculated from the product of DLP and a conversion coefficient for the specific body region

Table 1
Patient characteristics, exposure factors, and scanning parameters.

Age (yrs)	Male		Female		Total	
	Number	Percent, %	Number	Percent, %	Number	Percent, %
18–27	27	6.5	21	5.2	48	11.7
28–27	16	4.0	33	8.2	49	12.2
38–47	37	9.2	26	6.5	63	15.7
48–57	32	8.0	43	10.7	75	18.7
58–67	44	11.0	41	10.2	85	21.1
68–77	28	7.0	31	7.7	59	14.7
78–87	7	1.7	12	3.0	19	4.7
88–97	1	0.2	3	0.7	4	0.9
Total	192	47.8	210	52.2	402	100.0
Mean	51.83 ± 17.54					

Exposure factors and scanning parameters	Value
Tube voltage (kV_p)	120.00
Tube current (mA)	300.00
Rotation time (sec)	0.75
Pitch	0.66
Scan length (cm)	18.14 ± 2.29
Slice thickness (mm)	5.00
Sequence(s)	1.00

Table 2
Technical specifications of Toshiba Aquilon CT scanner.

Design parameter	Value (quantity, volume, etc)
CT scanner mode: Multislice	Multislice
Slices per rotation	16-cm volume (320 × 0.5 mm)
Other rotation speed options (sec)	0.35, 0.375, 0.4, 0.45, 0.5, 0.6, 0.75, 1, 1.5
Minimum rotation speed	350msec
Gantry diameter	72 cm
Minimum temporal resolution (msec)	16 cm full volume 350 msec
Maximum beam width	16 cm
Minimum room size (length x width x height)	Site dependent
Table weight limit	660 lb
Table movement range	33–98.8 vertical/20–195 cm longitudinal
X-ray generator kV range	80-135 kV_p
Maximum scan range	200 cm
X-ray tube heat capacity	7.5 MHU
Power requirement	480 VAC, 135 kVA

(0.0023) proposed by the European Commission (Brady et al., 2015). Subsequently, the mean D_{eff} was calculated for all 402 patients.

With knowledge of the average dose output ($CTDI_{vol}$ and DLP) used for performing routine diagnostic head CT examinations at the study site, an optimization study was then conducted. The RANDO anthropomorphic phantom was used for the optimization study by scanning it with the routine head scan protocols used at the facility and subsequently varying the exposure factors to study their effects on the dose and image quality.

Image quality analyses were performed on the phantom images obtained in DICOM format to identify the best modified protocol(s) that resulted in radiation dose-reduction while maintaining acceptable image quality for the intended purpose. Both objective and subjective image quality analyses were conducted. Objectively, four square ROIs of the same dimensions (10 mm × 10mm) were drawn on the homogeneous 5 mm cut brain tissue at the same slice number for each image, located about midway between the total number of slices for each image. The signal-to-noise ratio (SNR) values were estimated using ImageJ software version 1.53 (Wayne Rasband and Contributors, National Institutes of Health, USA) to assess the objective image quality. Fig. 1 shows how the signal and the noise information were obtained quantitatively using ImageJ software version 1.53. Subjectively, image quality can be assessed via radiologists' reviews of images. In this regard, radiologists at the hospital reviewed and approved the images as fit for diagnostic purposes for routine head CT examinations. The subjective assessment provided information on whether the images were diagnostically acceptable (good) or not (bad) for the intended clinical task.

The ethical clearance for this study was reviewed and approved by the Ethics and Protocol Review Committee of the School of Biomedical and Allied Health Sciences of the University of Ghana (Reference: SBAHS/AA/RAD/10680009/2020–2021).

3. Results

The highest and least number of referrals for head CT procedures were recorded among patients aged 58–67 years (21.1%), and 88–97 years (0.9%). More females (52.2%) presented for head CT scans than males (47.8%).

3.1. Dosimetry

The mean $CTDI_{vol}$ and DLP values were 86.00 mGy and 1559.70 mGy cm respectively, with associated 75th percentiles of 86.00 mGy and 1613.60 mGy cm. The measured values at the CT unit exceeded values recommended by the ICRP 73, American College of Radiology (ACR) and other literature reports (ACR, 2008; Shrimpton et al., 2016). The mean D_{eff} (of all 402 patients) obtained for the images of the adult head CT patients was 3.57 ± 0.46 mSv.

3.2. Dose optimization of routine protocol for head scans

Eight phantom head CT images were assessed to determine the image quality and mean dose descriptor values were obtained for different exposure parameters (Table 4). Image A was obtained using the mean routine adult CT head parameters with a DLP of 1699.60 mGy cm. A DLP of 1037.30 mGy cm was obtained from scanning Image B with the same tube potential (120.00 kV) and pitch (0.66) but with a reduced tube current of 200.00 mA. Images C and D were acquired with the same tube current and pitch as Image A, but with reduced tube potentials of 100.00 kV and 80.00 kV respectively, resulting in DPL of 1013.80 mGy cm (Image C) and 553.80 mGy cm (Image D). Image E was acquired with the same scan parameters utilized in the study except that a higher pitch of 0.84 was used, yielding a DLP of 792.90 mGy cm. Other phantom Images F, G and H were obtained using different tube potentials of

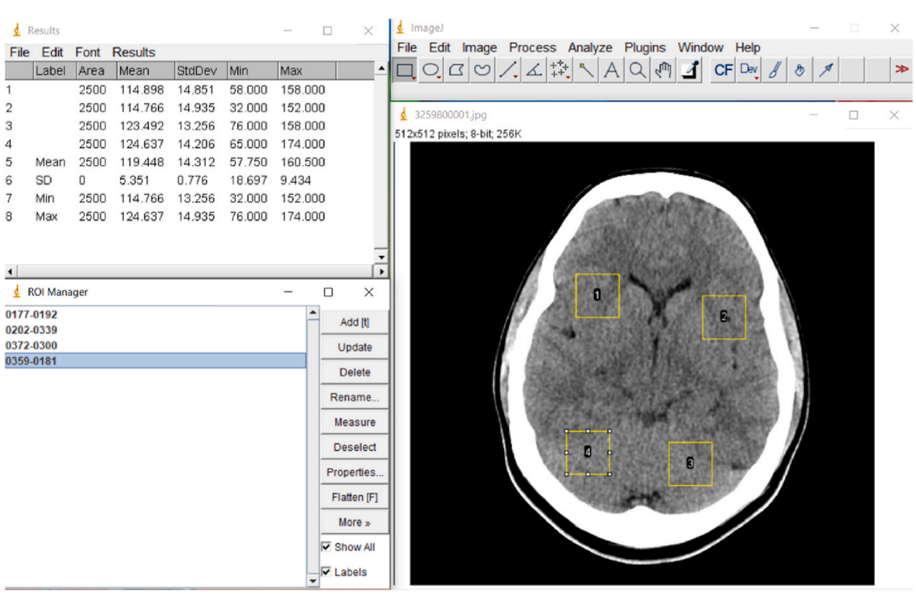

Fig. 1. Analysis of image quality using ImageJ software.

120.00 kV, 100.00 kV and 80.00 kV respectively with the AEC standard (Sure Exp. 3D) switched on. The resulting DLP values were 1227.70 mGy cm, 1176.00 mGy cm and 778.80 mGy cm, respectively.

In accordance with the Rose model criteria (Burgess, 1999; Hsieh et al., 2022), a signal must be five standard deviations from the above background to be detectable. This means that diagnostic images with SNR >5 are adjudged as having acceptable image quality. In this study, the calculated SNRs for all the phantom images at the different parameters exceeded 5 except for Images D, E and H. The highest SNR of 6.88 was found for Image A, which was acquired with the routine scan protocol for adult head CT. A reduced tube current of 200.00 mA for Image B resulted in reduced SNR of 5.25. Also, using reduced tube potentials of 100.00 kV and 80.00 kV for Images C and D resulted in reduced SNR values of 5.49 and 3.50 respectively. Accordingly, Image D was declared unfit for diagnostic purposes. An increased pitch factor of 0.84 for image E resulted in an SNR of 4.9 and hence was also regarded as unfit for diagnostic purposes. Images F, G, and H were obtained with the AEC switched on which yielded SNRs of 6.11, 5.62, and 4.63 respectively.

A comparison of DLP and SNR as well as the D_{eff} and SNR of the various studied protocols for head CT imaging are presented in Figs. 2 and 3 and showed that 5 out of 8 phantom images (Images A, B, C, F, and H) satisfied the Rose model's acceptance criteria for good image quality.

The lowest DLP (1013.80 mGy cm) and D_{eff} (2.33 mSv) were estimated for Image C which was subsequently, selected as the best option among the optimized images. This was achieved by reducing the tube potential from 120.00 kV to 100.00 kV while keeping other parameters unchanged. This resulted in a 40.4% reduction in D_{eff} through the optimization process without deteriorating image quality.

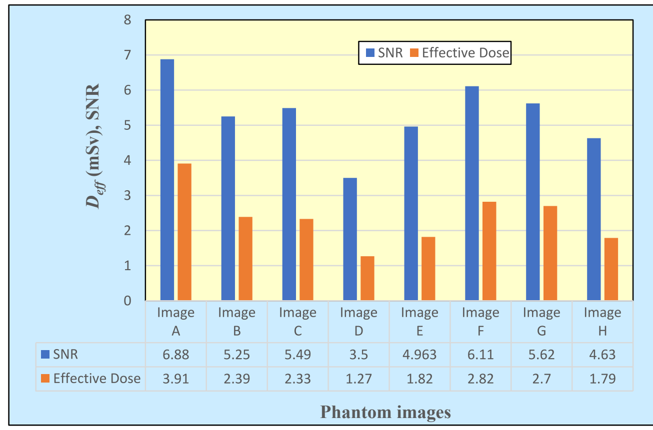

Fig. 3. Comparison of D_{eff} and SNR values associated with the studied protocols.

4. Discussions

4.1. Patient characteristics

According to the age distribution (age range: 18–94 years; mean age: 51.83 ± 17.54 years), the majority of patients were younger and middle-aged (58.2%) compared to older adults (41.8%). However, the largest referrals for head CT examinations were recorded among patients aged 58–67 years (21.2%), of whom the majority were males (11.0%). This finding may be associated with a higher incidence of dementia as well as Parkinson's disease with old age as suggested by Orozco-Arroyave et al. (2014) for which head CT examination may be the first line for diagnosis. Hernández et al. (2015) observed that the proportion of individuals that undergo medical imaging procedures increased with age.

More female patients (52.2%) presented for head CT examinations. Consistent with the literature, Akyea-Larbi (2015) reported that more females (67.6%) than males (32.4%) presented for CT procedures in a Ghanaian health facility, while Shrimpton et al. (2016) indicated that more females (60.0%) presented for head CT examinations than males (40.0%). In the context of cumulative radiation exposures, the findings of this study suggest that females are more liable to medical radiation exposures and associated risks from CT examinations, and are thus, more likely to develop radiation-induced stochastic and non-stochastic damages as well as diseases such as cancer (Smith-Bindman et al., 2011).

4.2. Dosimetry

Constant values of $CTDI_{vol}$ for adult head CT were recorded at the CT unit irrespective of patient age or gender. This may be attributed to the use of fixed exposure factors and pitch. The mean value of the $CTDI_{vol}$ was 86.00 ± 0.00 mGy. The DLP values however varied depending on the area of coverage selected by the radiographer, with corresponding recorded mean and 75th percentile values of 1559.68 ± 197.18 mGy cm and 1613.60 mGy cm respectively. This yielded a substantially high mean D_{eff} of 3.57 ± 0.46 mSv compared with the ICRP international standards.

The measured $CTDI_{vol}$ and DLP values obtained in this study were comparatively higher than reported elsewhere in the literature (Table 3), necessitating actions to reduce the radiation doses. In a Kenyan study conducted on 50% of CT facilities in that setting, Korir

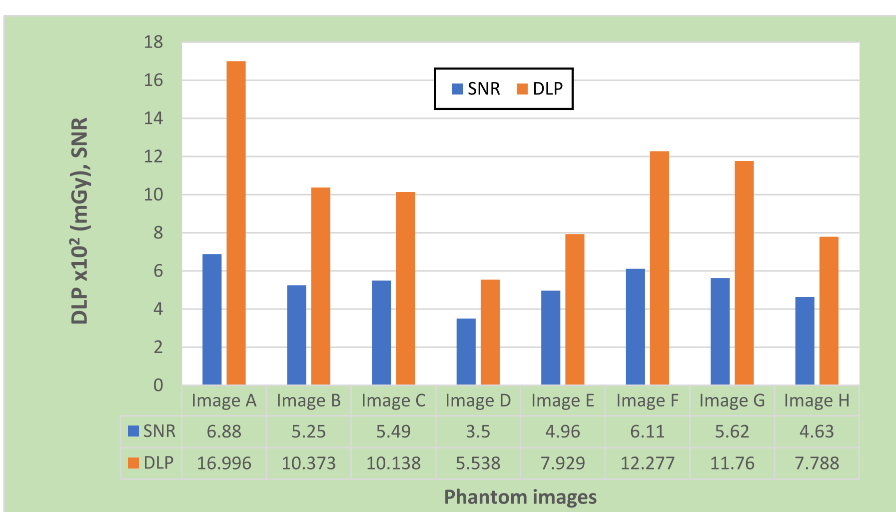

Fig. 2. Comparison of DLP and SNR values associated with the studied protocols.

Table 3
Exposure parameters and dosimetry.

Reported studies	Mean values		75th percentile
	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	DLP (mGy.cm)
This study	**86.00**	**1559.68**	**1613.60**
Shrimpton et al [7]	–	–	787.00
Bongartz et al [22]	–	–	1050.00
ACR [24]	–	–	–
Korir et al [29]	55.00	1274.00	1612.00
Salama et al [30]	28.80	1000.50	1358.60
Tsapaki et al [31]	39.00	527.00	544.00
Sakhnini [32]	43.80	760.00	–
Gharbi et al [33]	46.79	837.25	–
Toori et al [34]	–	–	750.00
Moifo et al [35]	–	–	1151.00
Najafi et al [36]	–	–	700.00
Brix et al [42]	60.60	1016.00	–
ICRP 73 [43]	–	–	1050.00

- = No available data given in the publication.

et al. (2016) reported optimized mean $CTDI_{vol}$ and DLP doses of 55.00 mGy and 1274.00 mGy cm respectively. Although a lower average $CTDI_{vol}$ value of 28.80 mGy was reported in an Egyptian study conducted on a cohort of 900 patients undergoing head CT examination, Salama et al. (2017) concluded that further actions were needed to reduce the DLP of 1000.50 mGy cm. Tsapaki et al. (2006) also reported mean $CTDI_{vol}$ and DLP values of 39 mGy and 527 mGy cm in a dose-reduction head CT scans study. Substantial dose-reductions in CT examinations are achievable through dose optimization strategies. In particular, Sakhnini (2017) recorded a 44.3% reduction in $CTDI_{vol}$ and a 37.6% reduction in DLP after optimization. In a dose optimization study employing the use of tube current modulation (AEC), Gharbi and Labidi (2017) also stated a 20.1% reduction in average D_{eff} without loss of image quality.

From Table 3, the 75th percentile values for the CT dose descriptors were also higher than the ICRP 73 recommendations of 60.0 mGy for $CTDI_{vol}$ and 1050.00 mGy cm for the DLP. Toori et al. (2015) reported large scales of CT dose for the same examination among 7 different Iranian hospitals and, therefore, established optimized $CTDI_{vol}$ and DLP doses of 59.5 mGy and 750 mGy cm respectively, which were relatively lower compared to the ICRP 73 reference doses. Other studies (Bongartz et al., 2000; Shrimpton et al., 2016) have demonstrated similar and lower findings concerning dose-reductions. The difference between reported values in this study and the literature is explained by the use of higher exposure parameters at the study site, which required dose-reduction strategies to keep the patient dose ALARA.

4.3. Dose optimization for adult head CT examination

According to Power et al. (2016), several dose optimization strategies are available. Optimization methods for Images C and G were considered suitable and acceptable for this study site, subsequent to a 16.7% reduction in tube potential (Image C) with a slight increase in noise (20.20%) as shown in the SNR value. However, this increase did not sufficiently degrade the image quality for the intended clinical purpose since the subjective assessment or radiologists reported the images as good for the task (as shown in Table 4). Therefore, the associated exposure parameters (Table 4) are recommended for head CT examinations using the only AquilionOne 640-slice scanner currently in use in Ghana. Meanwhile, it was also found that AEC may be used in circumstances where image quality may have considerably deteriorated while employing fixed tube potential. This will also result in a significant dose-reduction, as predicted by Zarb et al. (2011) and confirmed with a 31.0% D_{eff} reduction (Image G) with a good radiologist comment. The results of this study are further supported by Khan et al. (2013) who indicated that a reduction in tube voltage from 120.0 kVp to 100.0 kVp reduces radiation dose by 33.0%. Smith-Bindman et al. (2019) also suggested that a 50.0% dose-reduction is achievable without reducing its diagnostic purpose.

Vetter (2008) reported that dose-reduction strategies using AEC systems significantly reduced radiation dose in CT imaging. However, Greess et al. (2000) emphasized that the use of AEC as a dose-reduction approach was dependent on the scanned body region and certain circumstances. According to Singh et al. (2011), the use of AEC may not be recommended in CT head scans due to the fact that the variations of patients' brain sizes and shapes are expected to be small. Also, relatively different lesser attenuations in the head compared to other regions may attribute to the poor recommendation of AEC in head CT scans. Generally, AEC systems reduce patient dose; therefore in cases where image quality may be significantly deteriorated using fixed tube current and tube potential, AEC may be incorporated (Greess et al., 2000). If the use of AEC is prevalent, then the optimization method adopted for image G in this study will be deemed suitable for diagnostic purposes, even though it is expected that the dose-reductions by using AEC would be small for these patients.

5. Conclusion

The measured $CTDI_{vol}$ and DLP values were higher than the ICRP 73 recommended values and other published studies. The consideration of tube potential alteration and utilization of AEC as dose optimization protocols for adult head CT examinations resulted in reductions in the DLP and D_{eff} without affecting image quality sustancially for diagnostic purposes. Therefore the study recommends optimization methods C and the associated exposure parameters (Table 4) for scanning CT head when using the only AquilionOne-640 slice scanner currently in Ghana. However, due to the small variations in patients' head sizes and shapes, the AEC approach is not strongly recommended and may be utilized when fixed tube potential significantly deteriorates image quality.

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Table 4
Mean phantom dose descriptor values, SNR and subjective assessment of images obtained with different exposure parameters.

Image ID	SL (cm)	Tube voltage (kV)	Tube current mA	Pitch	$CTDI_{vol}$ (mGy)	DLP (mGy. cm)	D_{eff} (mSv)	AEC	SNR	Radiologist quality assessment comment
A	18.00	120.00	300.00	0.66	86.00	1699.60	3.91	No	6.88	Good
B	18.00	120.00	200.00	0.66	52.50	1037.30	2.39	No	5.25	Good
C	18.00	100.00	300.00	0.66	51.30	1013.80	2.33	No	5.49	Good
D	18.00	80.00	300.00	0.66	28.00	553.80	1.27	No	3.50	Bad
E	18.00	100.00	300.00	0.84	39.90	792.90	1.82	No	4.96	Bad
F	18.00	120.00	124.00	0.66	62.10	1227.70	2.82	Yes	6.11	Good
G	18.00	100.00	191.00	0.66	59.50	1176.00	2.70	Yes	5.62	Good
H	18.00	80.00	315.00	0.66	39.40	778.80	1.79	Yes	4.63	Bad

Author statement

All authors disclose that there have no financial or personal relationships that may be perceived as influencing their work. The corresponding author of this manuscript certifies that the contributors' and conflicts of interest statements included in this paper are correct and have been approved by all co-authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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