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Radiation exposure during computerized tomography-based neuroimaging for acute ischemic stroke: a case-control study

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Patients and clinicians often raise concerns about radiation exposure to various organs during computerized tomography-based imaging. We evaluated radiation exposure during standard and low-dose imaging protocols for non-contrast computerized tomography, computerized tomography angiography and computerized tomography perfusion of the head. Whether reducing the radiation dose affected the image quality was also evaluated. Radiation data were retrieved for computerized tomography-based imaging studies performed for acute ischemic stroke patients during 2015. The volume-weighted computerized tomography dose index, dose-length product, scan length, effective dose and whole-body integral dose for brain, skin, eye, thyroid and red bone marrow were extracted from dose-tracking software. Dose metrics for low-dose protocols data were compared with standard protocols. The calculated effective doses for non-contrast computerized tomography, computerized tomography angiography and computerized tomography perfusion were 2.56 $\pm$ 0.67 mSv, 4.45 $\pm$ 2.5 mSv, and 4.47 $\pm$ 0.85 mSv, respectively for 391 acute ischemic stroke patients. Corresponding radiation exposures for low-dose protocol (n = 31) were non-contrast computerized tomography (2.36 $\pm$ 0.65 mSv), computerized tomography angiography (1.57 $\pm$ 0.74 mSv) and computerized tomography perfusion (2.20 $\pm$ 0.55 mSv). Overall, the effective dose for one complete stroke imaging protocol (non-contrast computerized tomography + computerized tomography angiography + computerized tomography perfusion) for the standard-dose protocol was 11.48 mSv, which was reduced to 6.13 mSv (46.6% reduction) using a low-dose protocol ($p < 0.001$). Reduced radiation exposure was noted for other radiosensitive organs. Radiation exposures of sensitive organs are within acceptable limits with standard neuroimaging protocols for acute ischemic stroke. Lower-dose computerized tomography imaging protocols reduced the radiation doses without appreciable deterioration in image quality.

Keywords

Neuroimaging; Acute ischemic stroke; Radiation; Radiation dose; Computerized tomography

1. Introduction

Acute ischemic stroke (AIS) is a leading cause of mortality and permanent disability [1]. Computerized tomography (CT) based neuroimaging techniques continue to be the mainstay for selecting patients eligible for thrombolytic therapy. Non-contrast CT (NCCT) and CT angiography (CTA) of cervico-cerebral vessels are routinely performed for AIS, while CT perfusion (CTP) of the brain is performed in selected patients. One important reason for selecting CT-based imaging is the fast data acquisition in multi-detector row CT systems [2]. Recent clinical trials have demonstrated that CTP imaging of the brain using an increased detector width can detect additional potentially salvageable ischemic lesions even in the extended therapeutic time window [2, 3].

American Heart Association recommends NCCT to evaluate patients presenting with stroke-like symptoms to exclude various mimicking conditions [2]. An NCCT of the head excludes intracranial hemorrhage with high reliability. However, multimodal imaging with NCCT, CTA and CTP significantly increase diagnostic accuracy compared to NCCT alone. CTA depicts the presence and site of arterial occlusion as well as various collateral flow patterns. CTP further helps in cases with an uncertain time of symptom-onset, especially to evaluate the amount of salvageable penumbra and eligibility for various endovascular procedures in AIS [2, 3]. Importantly, whole-brain perfusion measurement can be achieved very fast and avoid any significant delays in the initiation of definitive therapy [2, 3].

CT scanners are the significant contributors to the radiation exposure received by patients in radiology departments, predisposing them to an increased risk of somatic and genetic effects of ionizing radiation [4–7]. In addition to the brain, red bone marrow, thyroid, and the eyes' lens are the most radiosensitive tissues for these CT procedures. Patients and clinicians often raise concerns about radiation exposure to various organs during computerized tomography (CT) based imaging. Therefore, various strategies are employed to minimize the radiation exposure associated with CT protocols

Table 1. Stroke protocol scanning parameters.

Variable	NCCT		CTA		CTP	
	Standard dose	Low dose	Standard dose	Low dose	Standard dose	Low dose
Scan type	Helical	Helical	Helical	Helical	Axial	Axial
Detector Configuration	64 × 0.625	64 × 0.625	128 × 0.625	128 × 0.625	64 × 0.625	64 × 0.625
Pitch	0.4	0.4	0.4	0.4	-	-
FOV (mm)	250	250	260	250	250	250
kVp	120	120	120	100	80	80
mAs/SLICE	330	280	300	200	150	100
Rotation Time (sec)	0.5	0.5	0.5	0.5	0.5	0.5
Section thickness (mm)	3	3	1	1	5	5
CTDI vol (mGy)	54.4	44.4	38.3	15.6	120	72

CTA, computerized tomographic angiography; CTDI vol, computerized tomographic dose index volume; CTP, computerized tomographic perfusion; FOV, field of view; NCCT, non-contrast computerized tomography.

for brain imaging. Some of these strategies involve changes in the acquisition parameters (kVp, mill-ampere, pitch, etc.) [5, 6]. Although described scarcely, the risks due to the radiation exposure are believed to be related to the dose received by various radiosensitive organs. Hence, evaluating patient doses during various imaging procedures is essential to justify repeated exposure and optimize them to balance the benefit against radiation risk [7–9]. We evaluated the amount of radiation exposure to the brain and various organs in our stroke patients during various CT-based imaging studies. We created a low-dose protocol to hypothesize that a low-dose protocol would be associated with less radiation exposure, specifically to individual organs, without reducing diagnostic accuracy. We compared radiation exposure between the low-dose protocol and the standard protocol used at our institution using the low-dose protocol. Additionally, we compared to control the image quality between low-dose and standard protocol.

2. Material and methods

2.1 Patients and scanning parameters

This retrospective study included 391 consecutive AIS patients admitted to our tertiary center between January and December 2015. The institutional review board approved it. An additional prospective study was performed on the low-dose protocol in 32 consecutive patients. We used Brilliance iCT 256-slice CT scanner (Philips Medical Systems, Eindhoven, Netherlands) that made it possible to shorten the acquisition time, improve image quality with iDose4 algorithms technology and scan a larger anatomical volume during NCCT, CTA, and CTP. The radiometric software was used for tracking the individual as well as a cumulative dose for patients. The dose records were used to audit radiation dose awareness and patient safety at our radiology department. Radimetrics Enterprise (Bayer Healthcare LLC, Whippany, NJ, USA), a web-based dose monitoring solution, allowed the institution to monitor patients' radiation doses and ensure they were kept as low as reasonably achievable (ALARA). This software integrated with our CT units provided several dose matrices from CT procedures such as organ doses, effective dose and whole body integral dose, calculated from Monte Carlo simulations using a library of Cristy phantoms. It is based on scanner-specific values. It uses mathematical descriptions or voxels from scan images. It calculates organ dose and effective dose estimates from the volume-weighted CT dose index CTDI vol (as mGy) and dose length product DLP (as mGy.cm) provided in the DICOM data. The effective dose (E) represents the sum of equivalent doses from all organs, weighted by tissue factors [9, 10]. Effective doses, whole body integral dose and radiation dose to brain, skin, eye, thyroid and red bone marrow doses were extracted for analyses. For the head scan, DLP was measured on the head phantom of 16cm made up of polymethyl-methacrylate (PMMA). This software estimated a size-specific dose estimate (SSDE) based on the water equivalent diameter (WED) according to AAPM calculations [11]. Phillips iDose4 iterative reconstruction technique was employed to maintain image quality after applying dose reduction parameters in NCCT, CTA, and CTP protocols.

The CTDI vol (mGy) and the DLP (mGy.cm) were recorded from the console and tested for their reliability within the 10% range. Under our institution's quality assurance and control program, we developed a low-dose radiation stroke protocol for NCCT and CTP optimized by reducing tube current (mAs) only. In contrast, in CTA, both mAs and kVp were reduced, keeping other exposure factors unchanged (Table 1). We optimized exposure factors for head CT imaging protocols on two Philips CT units, Brilliance 64 slice and i256 slice CT, with iDOSE4 and IMR techniques. We used an anthropomorphic complete angiographic head phantom for making CT images, as it was moulded in tissue-equivalent material. CT image quality could be evaluated quantitatively and qualitatively with actual measurements of details and contrast under the same exposure conditions, repeated many times. For each examination, the weighted CTDI vol and DLP were recorded, and the noise was measured by placing an ROI on two areas in the image on the selected slice for measurements of Hounsefield

Table 2. Patient metrics.

Variable	NCCT			CTA			CTP		
	Standard dose (n = 391)	Low dose (n = 32)	*p* value	Standard dose (n = 149)	Low dose (n = 32)	*p* value	Standard dose (n = 61)	Low dose (n = 32)	*p* value
Mean Age in years (± SD)	62 (17)	63 (17)	0.098	59 (14)	63 (17)	0.087	60 (17)	63 (17)	0.082
Mean Skull Diameter in mm (± SD)	171.4 (6.9)	171.3 (7.3)	0.092	186.8 (17.6)	186.3 (24.3)	0.074	172.7 (23.1)	172.6 (30.1)	0.95
Water Equivalent Diameter in mm	164.9 (7.9)	164.3 (7.9)	0.022	186.8 (17.6)	192.5 (38.5)	0.067	172.4	176.2	0.068
Scan length in mm	202.8 (52.1)	204.5 (54.8)	0.091	558.1 (364.9)	395.1 (320.8)	<0.001	2114.4 (278.1)	1912.4 (418.9)	<0.001

CTA, computerized tomographic angiography; CTP, computerized tomographic perfusion; NCCT, non-contrast computerized tomography.

units. Each study was also reviewed for image quality by two technologists, a medical physicist and two radiologists. Continuous variables (CTDI vol, DLP, noise) were compared. Finally, the optimized data for low-dose scanning regimens were compared with the standard protocols. All scans were reviewed by experienced neuroradiologists and stroke neurologists for image quality. The NCCT and the CTA protocol were performed in spiral mode, while CTP was done on axial mode without gantry angulation. For CTA, scanning was performed from the arch of the aorta to the vertex. Scan lengths in both sets of protocols of NCCT, CTA, and CTP were kept similar. We calculated patients' skull diameter and water equivalent diameter to avoid the possible confounding effect of anthropometric variables. Although the effective skull diameter can be calculated automatically, the calculations only in the lateral or anterior-posterior direction may result in a high variability. In addition, such calculations from scout images may vary according to patient centering. We measured the diameter only for axial images to avoid over-estimation, which is not affected by patient centering and produces high accuracy. In addition, we measured water equivalent diameter as this value reflects the x-ray attenuation of the patient and is a good descriptor of patient size.

2.2 Radiation dose calculations

Radimetrics software platform (Radimetrics, Bayer Healthcare, Germany), a web-based dose monitoring solution, was used to estimate the organ-specific radiation dose. Monte-Carlo-Simulation was employed for individual organs such as the brain, eyes, skin, red bone marrow and thyroid, ICRP 103 dose equivalent and whole body integral dose [10].

The interrater and interrater reliability for NCCT, CTA and CTP was assessed using intraclass correlation coefficients. The scan quality was graded as 'reasonable' and 'poor'. All measurements performed by 2 blinded investigators (JK and VKS) showed an inter- and intra-observer agreement for NCCT, CTA, and CTP were 0.87/0.90, 0.90/0.93, and 0.86/0.89, respectively (n = 10 samples for each from standard and low dose scanning protocols).

2.3 Statistical analysis

All statistical tests were performed with Statistical Package for the Social Sciences (Version 12.0; SPSS, Chicago, Ill, USA). Mann-Whitney U test was used for statistical analysis to compare the means for various quantitative parameters. Customarily distributed quantitative indices were compared using unpaired *t*-test, and means of various radiation exposure values for standard and low-dose radiation protocols were compared. All tests were two-tailed, and a *p*-value of <0.05 was considered statistically significant. All data are presented as the mean ± standard deviation (SD) unless stated otherwise.

3. Results

The radiation data for standard-dose protocol for brain imaging for NCCT (n = 391), CTA (n = 149) and CTP (n = 61) were retrieved from the institutional dose tracking system attached to a dedicated CT scanner (Phillips iCT256 with iDose4). Data for the optimized low-dose protocol for NCCT, CTA, and CTP were obtained prospectively for 32 adult AIS patients (mean age 63 ± 17 years vs. 62 ± 17 years for standard-dose patients; $p = 0.098$). Details of various scan parameters such as kVp, mAs, collimation, scan length, rotation time and pitch for standard dose scanning of the head (AAPM) [11] and low-dose optimized stroke protocols for NCCT, CTA and CTP procedures are summarized in Table 1.

3.1 NCCT

The patient dose metrics age (years), skull diameter (mm), water equivalent diameter (mm) and scan-length (mm) for NCCT in the standard protocol and low dose protocol are shown in Table 2. Briefly, there were no significant differences in patient metrics in both groups.

The radiation dose parameters such as CTDI vol, DLP, effective dose and whole-body integral dose of the two groups are shown in Table 3. Briefly, the low-dose protocol showed a 10% decrease in dose metrics than the standard protocol, mainly due to the 12.5% decrease in tube current. Similarly, the low-dose protocol showed reduced radiation dose to various radiosensitive organs ($p < 0.001$), as shown in Table 4. There were no significant differences in patient metrics such as skull diameter, water equivalent diameter and scan length between the two radiation dose protocols of NCCT but significant reduction ($p < 0.001$) in dose exposure to all radiosensitive organs except thyroid ($p < 0.58$) in the low-dose protocol.

Table 3. Radiation dose metrics.

Variable	NCCT		CTA		CTP	
	Standard dose	Low dose	Standard dose	Low dose	Standard dose	Low dose
	(n = 391)	(n = 32)	(n = 149)	(n = 32)	(n = 61)	(n = 32)
Mean CTDI vol in mGy (SD)	52.4 (0.3)	47.4 (0.05)	28.7 (8.1)	14.7 (2.4)	93.0 (0.9)	72.0 (1.4)
Mean DLP in mGy.cm (SD)	1061.9 (272.8)	972.9 (260.2)	1415.5 (471.1)	584.6 (281.6)	1916.2 (339.7)	995.1 (233.2)
Mean ED ICRP 103 in mGy (SD)	2.6 (0.7)	2.4 (0.6)	4.5 (2.5)	1.6 (0.7)	4.5 (0.9)	2.2 (0.5)
Whole Body integral in mGy (SD)	0.4 (0.1)	0.39 (0.1)	0.6 (0.2)	0.2 (0.02)	0.8 (0.14)	0.4 (0.09)

CTA, computerized tomographic angiography; CTDI vol, computerized tomographic dose index; CTP, computerized tomographic perfusion; DLP, dose length product; ED ICRP, Effective dose International commission of radiation protection; NCCT, non-contrast computerized tomography.

Table 4. Radiation dose to various sensitive organs.

Variable	NCCT		CTA		CTP	
	Standard dose	Low dose	Standard dose	Low dose	Standard dose	Low dose
	(n = 391)	(n = 32)	(n = 149)	(n = 32)	(n = 61)	(n = 32)
Mean Brain dose in mGy (SD)	57.7 (12.1)	43.1 (9.1)	101.8 (17.8)	20.7 (5.7)	82.1 (3.2)	55.7 (4.5)
Mean Skin dose in mGy (SD)	8.5 (3.1)	5.8 (1.6)	11.6 (2.2)	2.6 (1.8)	11.2 (1.7)	6.1 (1.5)
Mean Red Bone Marrow dose in mGy (SD)	7.4 (2.9)	5.2 (1.5)	9.7 (2.9)	2.6 (1.5)	8.7 (0.9)	4.7 (1.3)
Mean Eye dose in mGy (SD)	83.4 (17.4)	63.6 (17.8)	159.1 (26.7)	33.6 (11.7)	152 (3.2)	100.3 (24.6)
Mean Thyroid dose in mGy (SD)	26.6 (9.4)	8.7 (3.8)	13.4 (5.8)	11.9 (3.9)	5.1 (0.9)	3.3 (0.8)

CTA, computerized tomographic angiography; CTP, computerized tomographic perfusion; NCCT, non-contrast computerized tomography.

3.2 CTA

Patient dose metrics with standard and low-dose CTA protocol are presented in Table 2, while the organ-specific radiation doses for both groups are shown in Table 3. The low-dose protocol was optimized for lower kVp (120 kVp to 100 kVp) and mAs (300 mAs to 200 mAs), maintaining an optimum image quality using the iterative reconstruction of iDose4 similar to the standard protocol. CTDI vol (14.71 $\pm$ 2.39 mGy vs. 28.72 $\pm$ 8.02 mGy) and DLP (584.61 $\pm$ 281.63 mGy.cm vs. 1415.45 $\pm$ 471.01 mGy.cm) were lower in the low-dose imaging protocol ($p < 0.001$).

The brain, skin, red bone marrow, eyes and thyroid received relatively higher radiation doses during CTA than NCCT. However, the effective doses ICRP (103) evaluated in CTA with standard and low-dose protocols were 4.45 $\pm$ 2.5 mSv and 1.57 $\pm$ 0.74 mSv, respectively, showing a reduction of approximately 64% ($p < 0.001$) as well as the advantage of reducing kVp and mAs with low-dose protocols (Table 3). Similarly, dose metrics parameters and organ doses were also reduced (48–50%) considerably ($p < 0.001$) in the low-dose protocol.

3.3 CTP

CTP was performed on the same CT machine using the iDose4 iterative reconstruction imaging technique. As suggested by AAPM [11], modified CTP protocol was used, where tube current was reduced to 100 mAs at 80 kVp compared to standard protocol using tube current of 150 mAS at 80 kVp. The patient metrics and dose metrics of both groups are shown in Table 2 and Table 3. In both groups, the scan lengths used in CTP (2114.35 $\pm$ 278.01 mm and 1912.39 $\pm$ 418.99 mm, respectively) are 4–5 times higher than NCCT and CTA protocols. Comparing to the standard protocol of CTP, the optimized low-dose protocol reduced the dose metrics parameters by 45–47% ($p < 0.001$) with a similar reduction of 36–72% in specific organ doses.

3.4 The radiation dose for overall stroke protocol in standard and optimized exposure settings

In addition to improving the diagnostic capability of NCCT, CTP and CTA provide important information about cerebral hemodynamics. While CTA demonstrates the patency of the cervico-cranial arterial tree and various intracranial collaterals, CTP estimates the ischemic core and salvageable penumbra in AIS. Most comprehensive acute stroke centers perform one emergent NCCT and CTA at presentation and one NCCT on day 2 (especially in thrombolysis patients). CTP is often performed in patients with the undetermined time of stroke onset, for example, wake-up stroke. CTP is a functional study that utilizes continuous CT acquisition over the same slab of tissue during the dynamic administration of a small contrast bolus. It certainly exposes patients' radiosensitive organs with a higher than usual radiation dose. We employed a low-dose protocol for CTP and could reduce the total effective dose and whole-body equivalent dose by approximately 43% and 46%, respectively, compared to the standard stroke imaging protocol ($p < 0.001$). The corresponding decrease in CTDI vol (134.07 $\pm$ 1.23 mGy vs. 174.08 $\pm$ 3.05 mGy) and DLP (2552.65 $\pm$ 258.33 mGy.cm vs. 4393.56 $\pm$ 361.18 mGy.cm) showed 22.9% and 41.9% reduction in radiation exposure, respectively. Importantly, the image quality of NCCT, CTA, and CTP did not show any appreciable de-

terioration, confirmed by independent neuroradiologists and stroke neurologists blinded to the clinical and radiation data. All evaluations performed by the two blinded investigators showed inter-and intra-observer agreement for NCCT, CTA and CTP of 0.88/0.92, 0.92/0.94 and 0.89/0.91, respectively (n = 32 samples for each).

The total effective dose for comprehensive stroke imaging (NCCT + CTA + CTP) by standard protocol was 11.48 mSv, while the low-dose protocol delivered a radiation dose of 6.13 mSv, a reduction of 46.6% (Table 3). Patients' age, length of scan coverage, maximum transverse skull diameters, and water equivalent diameter did not differ between the standard dose and low-dose imaging protocols (Table 2).

3.5 Organ dose

The software calculated the organ-specific dose for the brain, eye lens, thyroid, red bone marrow and skin for standard and low-dose protocols. All radiosensitive organs showed lower radiation exposure with the low-dose scanning protocol ($p < 0.001$). Table 4 summarizes the organ-specific radiation dose results.

4. Discussion

Our findings demonstrate that radiation exposure to the sensitive organs during standard dose neuroimaging protocols employed in AIS patients is within acceptable limits. However, the radiation doses to these organs may be reduced further by using low-dose CT imaging protocols and dose tracking software, without any significant deterioration in the image quality.

The preferred neuroimaging in AIS remains CT-based, mainly due to the widespread availability, rapid acquisition, and acceptable image quality [2, 3]. An NCCT is the first diagnostic test for rapid exclusion of a hemorrhagic stroke, identifying early ischemic signs as well as a quick estimation of tissue damage. Intravenous thrombolysis is often initiated in eligible patients immediately after the completion of NCCT. In patients without any contraindications to radiocontrast, CTA is performed according to the 'bolus tracking' technique and shows the arterial tree from the aortic arch to the circle of Willis. Identification of thrombotic occlusion of a relevant artery helps in early prognostication, prediction of response to intravenous thrombolysis, and early planning for endovascular treatment. Most comprehensive stroke centers employ additional parenchymal imaging to estimate the amount of salvageable penumbra, especially in patients presenting beyond the thrombolysis window. The preferred imaging in this subset of AIS patients is CTP [2]. Furthermore, additional CT scans may be needed in patients with clinical fluctuations, elevating the cumulative radiation dose exposure. Therefore, various radiation dose reduction strategies are often explored, such as modifying exposure factors like tube voltage, lowering tube current, and applying iterative reconstruction of CT images [12–15]. Such strategies may carry a risk of degrading the image quality. This work estimated the radiation dose delivered to various radiosensitive organs in the head and neck region. Furthermore, we demonstrated that employing low-dose imaging protocols for NCCT, CTA, and CTP can reduce the radiation dose delivered to sensitive organs without compromising the image quality. An example of the image quality with standard radiation dose protocol and the low dose protocol for plain CT, CTA and CTP is shown in Fig. 1.

Decreasing the peak voltage (kV) results in a lower dose exposure to the imaged tissues proportional to the square of the change in tube voltage. Furthermore, CT manufacturers have also introduced new techniques of dose reduction, such as dose modulation and iterative reconstruction (iDose4, ADMIRE, and ASIR) to achieve these aims [15–17]. While evaluating the feasibility of low-dose imaging protocol by reducing tube current or current and tube voltage together. We ensured that the level of image quality remained acceptable for diagnostic purposes. We decreased the tube current during stroke imaging protocols for NCCT, CTA as well as CTP. Additionally, we decreased kVp with lower mAs for CTA only to increase the effectiveness of contrast enhancement [15–17].

CTDI vol and DLP are routinely reported on scanner consoles in clinical practice. They do not quantify the patients' dose metrics and provide only the output radiation of the CT scanners determined by many factors, including kVp, mAs, collimation, pitch, slice thicknesses and reconstruction techniques, etc. CTDI vol is a good index when comparing protocols and technical parameter settings. However, it overestimates skin dose if the scan is performed without table movement. We estimated that the CTDI vol value was less than the reference value of 60 mGy for NCCT brain set by ACR guidelines based on AAPM and ICRP recommendations [10, 11, 18]. We used lower mAs in the low-dose protocols (decrease tube current from 330 to 280 mAs) that resulted in a 15% reduction (2.36 mSv) of the radiation dose during NCCT. While trying the low-dose scanning protocols, we found acceptable image quality for CTP at 80 kV and 100 mAs, whereas CTA required100 kV and 200 mAs for similar results. All CT protocols at our center used the iDose4 iterative reconstruction algorithm as a standard scanning procedure, which has been described[1] to ensure the better image quality of CTA and CTP in dynamic enhancing imaging within a reduced radiation dose [16].

Our work provides detailed organ-specific radiation dose values associated with the standard and low-dose scanning protocol for CT-based studies in AIS. Doses to individual organs may be more appropriate in estimating cancer risk from CT exposure [17–19]. Eye lenses are susceptible to radiation as they are directly in the radiation beam and exposed to higher radiation doses. ICRP (2012) has recently set the thresholds in absorbed dose to 500 mGy for the eye lens [19].

[1] ACR Practice Guideline for the Performance of Computed Tomography (CT) Perfusion in Neuroradiologic Imaging 2017 (https://www.acr.org/-/media/ACR/Files/Practice-Parameters/ct-perfusion.pdf); accessed on 16 May 2020.

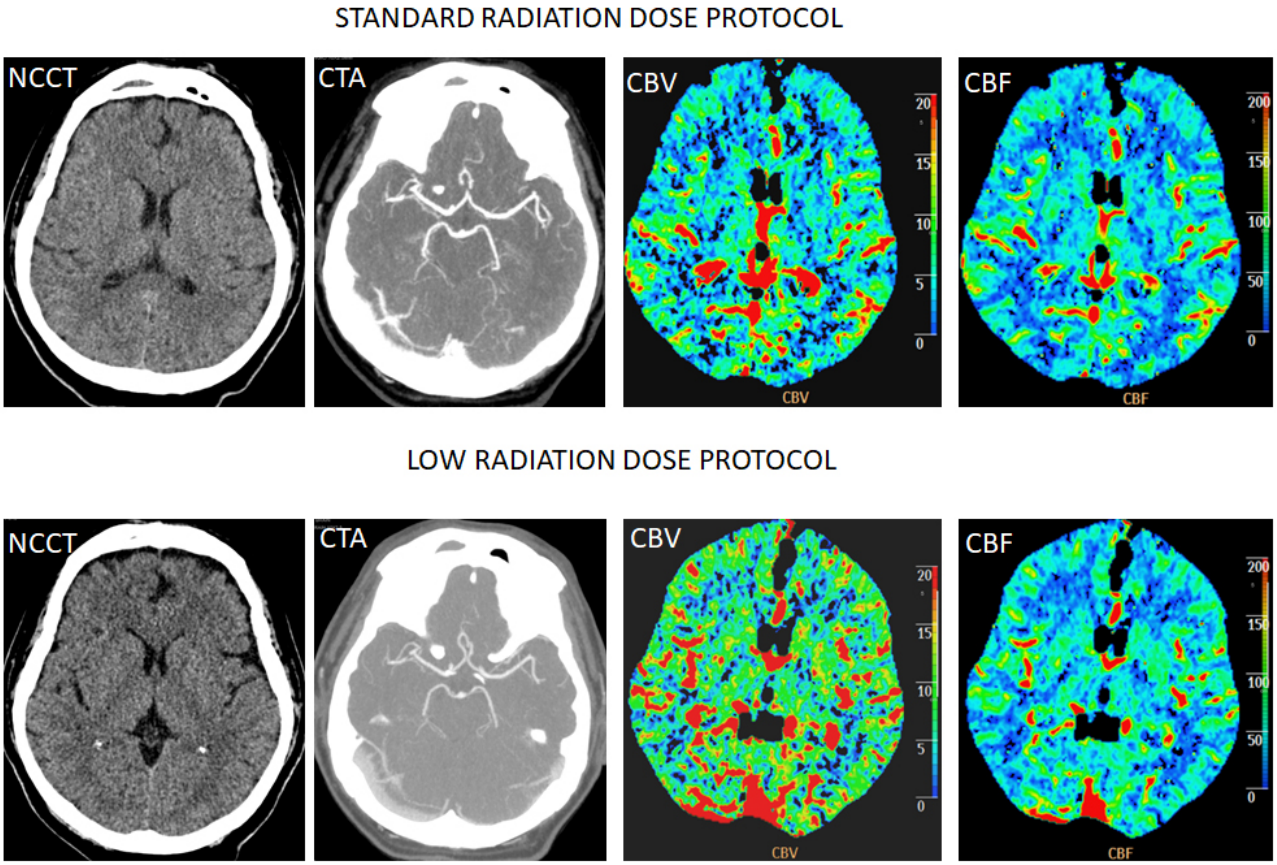

Fig. 1. Comparative Image quality with standard radiation dose protocol and the low dose protocol for non-contrast-enhanced computed tomography (NCCT), CT angiography (CTA) and CT perfusion (CTP) in a 62 years old patient who presented with acute ischemic stroke. The top panel shows NCCT, CTA and CTP images performed using the standard radiation dose protocol. As a part of a research project, this patient underwent repeat imaging studies using the low radiation dose protocol. The resultant representative images are shown in the lower panel.

The radiation exposure to eye lens was only 197.58 mGy in the low-dose group when NCCT, CTA, and CTP were performed in a patient. Other sensitive organs such as skin and red bone marrow showed significantly reduced exposure in the low-dose protocol. For example, the estimated dose exposure to the thyroid gland was 25.35 mGy, which is similar to the reported literature [19, 20]. Importantly, the total effective dose during comprehensive scanning (NCCT + CTA + CTP) was 6.128 mSv in the low-dose protocol as compared 11.48 mSv in the standard scanning, a reduction of 46.6%. Furthermore, we used the statistical Iterative Reconstruction IDose4 algorithm for CT reconstruction, which ramps the image clarity and reduces noise compared to the standard filtered back projection (FBP) technique. This enabled comparable image quality even with significantly reduced radiation dose in all CT-based imaging protocols.

Some limitations need to be acknowledged. First, the standard dose and low-dose CT scans were not acquired in the same patient. Standard dose CT studies would have served as a reference against which the diagnostic quality and imaging findings of low-dose scans could have been assessed. However, it would have been unethical to expose the human subjects to additional radiation exposure. Second, the blinded neuroradiologists and stroke neurologists had a good agreement in reading various imaging studies. The low-dose CT studies might have failed to detect tiny parenchymal lesions in some patients. Last, there was no reference standard for CTP studies. We strongly feel that faster MRI brain perfusion studies (with no ionizing radiation) in a smaller subset of the study population could have served as the standard control to evaluate the scan quality for CTP. However, this approach would have exposed our patients to an additional dose of a nephrotoxic contrast agent. Acute stroke care had changed considerably since this research work was performed. An increasing number of endovascular interventions are being performed, especially among patients with large vessel occlusions. This certainly increases the amount of radiation exposure. However, we cannot comment on this aspect since no acute stroke interventions were performed.

Furthermore, reduction of radiation exposure in CTP did not degrade the quality of images. However, one should be careful in optimizing the post-processing of the source images since the reduced dose might lead to clinically relevant infarct core overestimation in individual cases [21]. Lastly,

Dose Area Product (DAP) size or Kerma Area Product (KAP) size are currently used to represent patient exposure during diagnostic X-ray examinations and interventional procedures. DAP is greatly affected due to scattered radiation being the primary source of exposure (mostly during interventional procedures). However, this information was not collected.

5. Conclusions

Radiation dose is a significant concern for clinicians and patients with the increased use of CT-based examination. Our data show that although the standard dose techniques deliver an acceptable radiation dose, a low-dose scanning protocol may be adopted while maintaining acceptable image quality. Continuous radiation monitoring, controlling and optimizing stroke CT protocols with dose tracking software will help implement best practices for the safe use of ionizing radiation in medical imaging.

Abbreviations

AIS, acute ischemic stroke; ALARA, as low as reasonably achievable; CT, computerized tomography; CTA, computerized tomographic angiography; CTP, computerized tomographic perfusion; DLP, dose length product.

Author contributions

SCK and VKS conceived and designed the study; SCK and JK performed the radiation dose measurements; SCK wrote the initial draft of the paper; JK and VKS provided critical revision and final approval.

Ethics approval and consent to participate

The study was approved by institutional ethics committee (NHG DSRB 2012/00517).

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Conflict of interest

The authors declare no conflict of interest.

References

[1] Go AS, Mozaffarian D, Roger VL, Benjamin EJ, Berry JD, Borden WB, *et al.* Heart disease and stroke statistics–2013 update: a report from the American Heart Association. Circulation. 2013; 127: e6–e245.

[2] Powers WJ, Rabinstein AA, Ackerson T, Adeoye OM, Bambakidis NC, Becker K, *et al.* 2018 Guidelines for the early management of patients with acute ischemic stroke: A guideline for healthcare professionals from the American Heart Association/American Stroke Association. Stroke. 2018; 49: e46–e110.

[3] Powers WJ, Derdeyn CP, Biller J, Coffey CS, Hoh BL, Jauch EC, *et al.* Focused Update of the 2013 Guidelines for the Early Management of Patients With Acute Ischemic Stroke Regarding Endovascular Treatment: A Guideline for Healthcare Professionals From the American Heart Association/American Stroke Association. Stroke. 2015; 46: 3020–3035.

[4] Smith AB, Dillon WP, Gould R, Wintermark M. Radiation dose-reduction strategies for neuroradiology CT protocols. American Journal of Neuroradiology. 2007; 28: 1628–1332.

[5] Kalra MK, Maher MM, Toth TL, Hamberg LM, Blake MA, Shepard JA, *et al.* Strategies for CT radiation dose optimization. Radiology. 2004; 230: 619–628.

[6] Faulkner K, Moores BM. Radiation dose and sometic risk from computed radiography. Acta Radiologica. 1987; 28: 483–438.

[7] McCollough CH, Primak AN, Braun N, Kofler J, Yu L, Christner J. Strategies for reducing radiation dose in CT. Radiologic Clinics of North America. 2009; 47: 27–40.

[8] The 2007 Recommendations of the International Commission on Radiological Protection. ICRP publication 103. Annals of the ICRP. 2007; 37: 1–332.

[9] Valentin J. International Commission on Radiation Protection. Managing patient dose in multi-detector computed tomography (MDCT). ICRP Publication 102. Annals of the ICRP. 2007; 37: 1–79.

[10] Huda W, Magill D, He W. CT effective dose per dose length product using ICRP 103 weighting factors. Medical Physics. 2011; 38: 1261–1265.

[11] McCollough C, Bakalyar DM, Bostani M, Brady S, Boedeker K, Boone JM, *et al.* Use of Water Equivalent Diameter for Calculating Patient Size and Size-Specific Dose Estimates (SSDE) in CT: The Report of AAPM Task Group 220. AAPM Report. 2014; 2014: 6–23.

[12] Wintermark M, Maeder P, Verdun FR, Thiran JP, Valley JF, Schnyder P, Meuli R. Using 80 kVp vs. 120 kVp in perfusion CT measurement of regional cerebral blood flow. American Journal of Neuroradiology. 2000; 21: 1881–1884.

[13] Hirata M, Sugawara Y, Fukutomi Y, Oomoto K, Murase K, Miki H, *et al.* Measurement of radiation dose in cerebral CT perfusion study. Radiation Medicine. 2005; 23: 97–103.

[14] Lin CJ, Wu TH, Lin CH, Hung SC, Chiu CF, Liu MJ, *et al.* Can iterative reconstruction improve imaging quality for lower radiation CT perfusion? Initial experience. American Journal of Neuroradiology. 2013; 34: 1516–1521.

[15] Huda W, Lieberman KA, Chang J, Roskopf ML. Patient size and x-ray technique factors in head computed tomography examinations. II. Image quality. Medical Physics. 2004; 31: 595–601.

[16] Padole A, Ali Khawaja RD, Kalra MK, Singh S. CT radiation dose and iterative reconstruction techniques. American Journal of Roentgenology. 2015; 204: W384–W392.

[17] Cohnen M, Wittsack HJ, Assadi S, Muskalla K, Ringelstein A, Poll LW, *et al.* Radiation exposure of patients in comprehensive computed tomography of the head in acute stroke. American Journal of Neuroradiology. 2006; 27: 1741–1745.

[18] Rehani MM. ICRP and IAEA actions on radiation protection in computed tomography. Annals of the ICRP. 2012; 41: 154–160.

[19] Stewart FA, Akleyev AV, Hauer-Jensen M, Hendry JH, Kleiman NJ, Macvittie TJ, *et al.* ICRP publication 118: ICRP statement on tissue reactions and early and late effects of radiation in normal tissues and organs–threshold doses for tissue reactions in a radiation protection context. Annals of the ICRP. 2012; 41: 1–322.

[20] Omer H, Alameen S, Mahmoud WE, Sulieman A, Nasir O, Abolaban F. Eye lens and thyroid gland radiation exposure for patients undergoing brain computed tomography examination. Saudi Journal of Biological Sciences. 2021; 28: 342–346.

[21] Karwacki GM, Vögele S, Blackham KA. Dose reduction in perfusion CT in stroke patients by lowering scan frequency does not affect automatically calculated infarct core volumes. Journal of Neuroradiology. 2019; 46: 351–358.