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Research article

Radiation Dose Reduction in Whole Brain Perfusion Computed Tomography Using 320-detector Computed Tomography

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Abstract

Background: Radiation dose reduction in whole-brain perfusion computed tomography (CT) can be performed using various methods. We used a protocol with approximately 30% tube current of the original control protocol (Protocol 1) and a reduced total scan volume protocol (Protocol 2).

Methods: We conducted a retrospective consecutively analysis of whole-brain perfusion CT in 15 adult patients using the control protocol. A further 10 patients underwent protocol 1, and another 10 patients underwent protocol 2. We performed quantitative analyses and assessed the diagnostic image quality of the parametric map images. The percentage of radiation dose reductions was calculated.

Results: The gray and white matter signal intensities were higher in the cerebral blood volume and flow maps of protocol 1 than protocol 2, whereas this opposite results pattern was reversed for the time to peak and mean transit time maps. The signal-to-noise ratios of the gray and white matter for protocol 1 was inferior to that of protocol 2 for all perfusion parameters. No significant quantitative differences in parametric maps were found between the control protocol and protocol 1 or 2. The differences in the radiation dose reduction between protocols 1 and 2 and the control protocol were 33.23% and 19.95%, respectively. The effective dose of protocol 1 was reduced to approximately half that of the control protocol.

Conclusions: Radiation dose was significantly lower in protocol 1 than in the control protocol while providing comparable parametric image quality in regard to both the gray and white matter signal and signal-to-noise ratios of the parametric maps.

Keywords: 320-detector CT, radiation dose, whole- brain perfusion CT.

Introduction

The basic principle of perfusion computed tomography (CT) is based on temporal changes in tissue density following intravenous administration of iodinated contrast media. Chronological changes in tissue density are dependent on iodine concentration (the contrast is distributed within the tissue, resulting in increased tissue density on CT) and are a reflection of tissue vascularity[1]. The most significant contribution of perfusion CT has been in the assessment of stroke patients, where its rapid scanning and post-processing have made it the modality of choice for evaluating the structural and functional status of the cerebral vasculature. Perfusion CT studies involve repeated dynamic scanning of the passage of contrast into and out of the brain. The derived parametric maps of cerebral blood flow (CBF), cerebral blood volume (CBV), and transit times are integral to the evaluation and management of acute stroke and chronic neurovascular steno-occlusive diseases[2].

The 320-detector CT scanner allows whole-brain imaging owing to its large z-coverage of 160 mm, which minimizes the chances of misregistration of lesions regardless of location and allows easy selection of arterial input function[3]. A dynamic CT protocol, which involves a single intravenous contrast medium injection, facilitates the management of stroke patients and comprises CT angiography, CT venography, and CT perfusion (CTP).

The major limitation of whole-brain perfusion CT is the high radiation dose and the associated risks. The Food and Drug Administration has raised concerns regarding the high radiation dose associated with brain perfusion CT in routine neuroradiological evaluations[4], This has led to the development of various approaches to reduce the radiation dose, such as reduced sampling frequency[5, 6], reduced tube voltage[7, 8] and the use of iterative reconstruction[9].

Othman et al[10] demonstrated that qualitative perfusion maps from simulated data at 144 and 108 mAs (i.e., 20% and 40% of tube current reduction) are not significantly different from perfusion maps from original data (180 mAs) or ischemic lesions. Moreover, they found that the modified Alberta Stroke Program Early CT Score (ASPECTS) scores of CBV and CBF maps of the simulated data perfectly matched those of the original datasets.

The aim of this study was to develop a whole-brain perfusion CT protocol with a reduced radiation dose, which comprised 30% of the tube current of the original protocol and a lower number of scan volumes than the control protocol.

Methods

We used the Toshiba Aquilion One 320-detector row CT scanner (Aquilion ONE, Toshiba Medical Systems Corporation, Nasu, Japan) and Vitrea Fx Workstation version 3.0.3 (Vital Images, Minnetonka, MN, USA). Statistical analyses were performed using the SPSS software version 18.0 (Statistical Package for the Social Sciences, IBM, Chicago, Illinois, United States).

Study participants

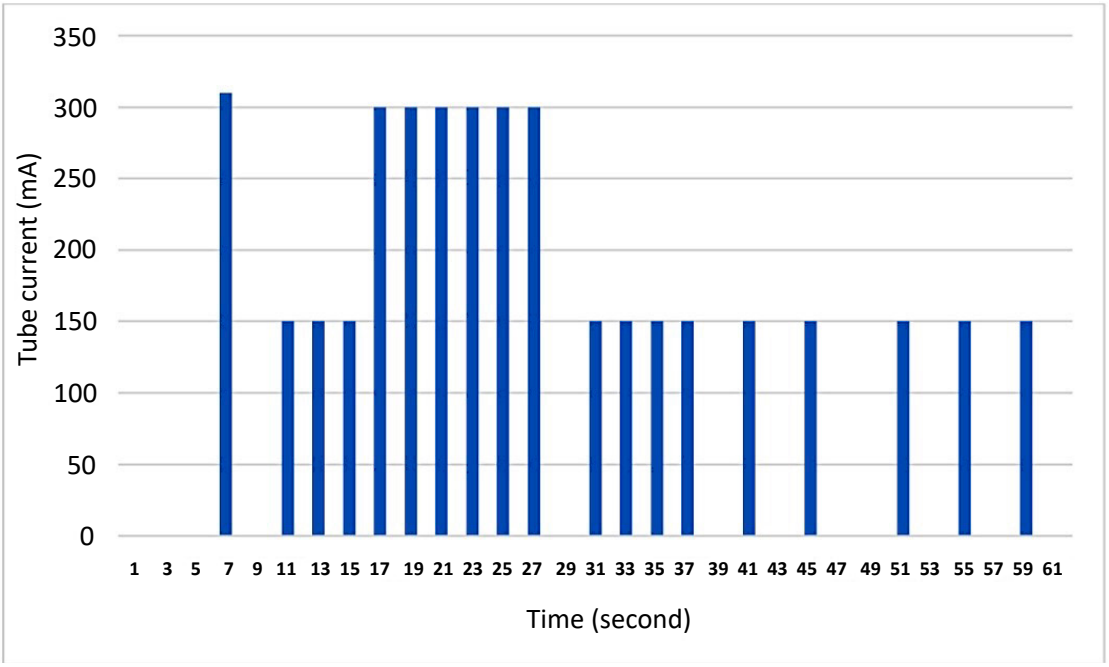
We conducted retrospective data analysis of 15 randomly selected adult patients who underwent control protocol CTP and prospective data analysis of 20 patients who underwent different optimized protocols. Most patients had ischemic stroke and moyamoya disease. Patients provided written informed consent before the examination. The study was approved by the Institutional Review Board of Ramathibodi Hospital, Mahidol University (ID 08-58-27).

Scanning Techniques

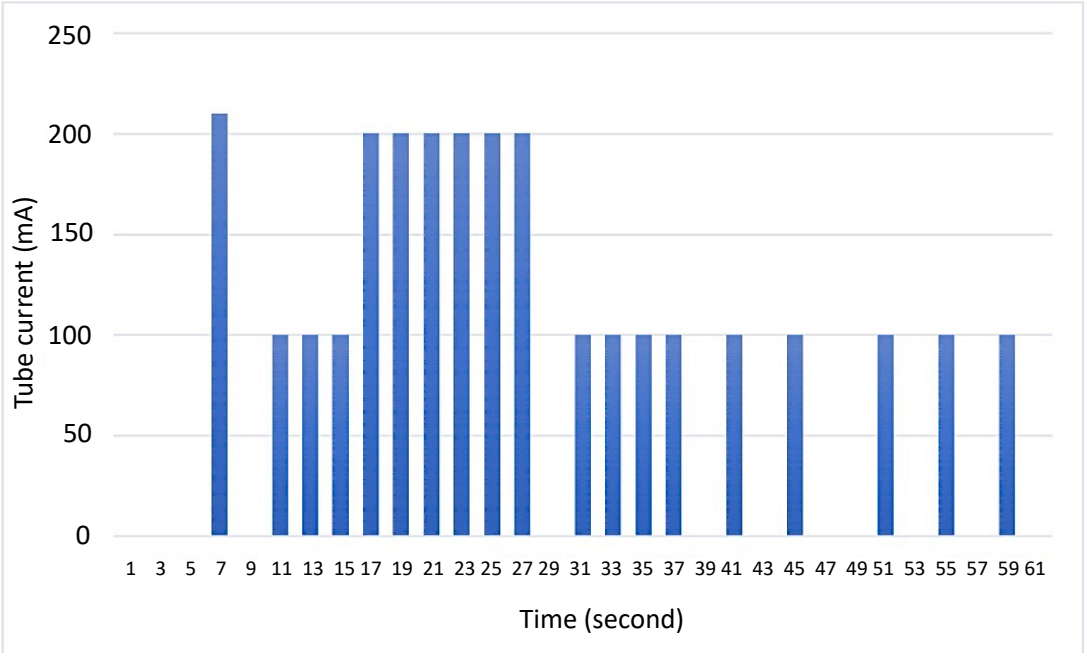
Whole-brain perfusion CT was performed using a 50 mL bolus of non-ionic contrast media and iopromide with an iodine concentration of 370 mg/mL iodine (Ultravist 370, Bayer Schering Pharma AG, Berlin). The contrast media was administered via the antecubital vein, with an injection flow rate of 5 mL/s, followed immediately by 40 mL of normal saline solution to increase peak arterial enhancement by forcing the whole injected contrast material volume into the cardiovascular system and improving bolus geometry by limiting contrast medium dispersion[7]. The contrast media were administered at the same injection rate using

a dual-head power injector. Schematic diagrams representing the methods used to acquire the control protocol, the approximately 30% tube current of the original tube current protocol, and the reduced scan volume protocol datasets are shown in Figure 1A–C.

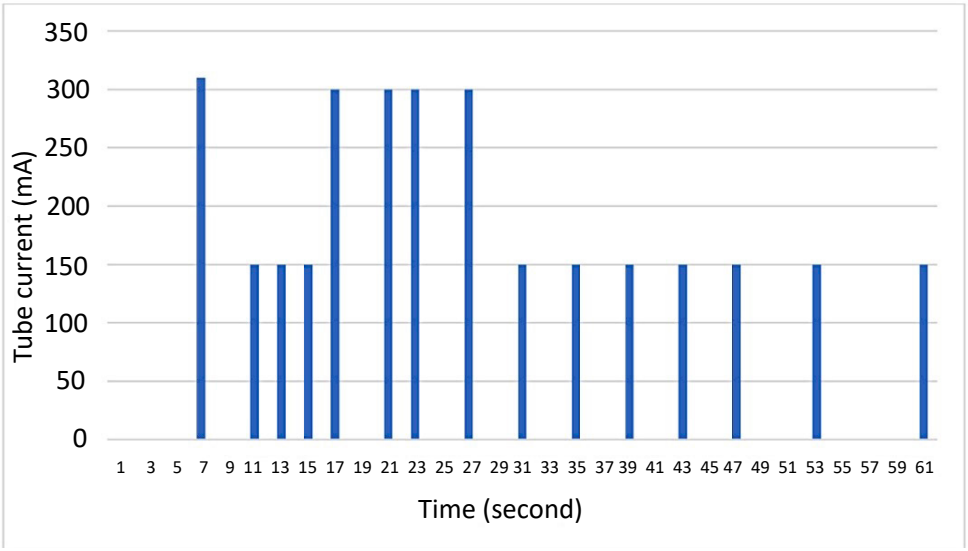
All whole-brain perfusion CT examinations were performed using a continuous acquisition (cine) or dynamic axial volume scan mode without the gantry angle tilted, which allowed a 160-mm whole-brain coverage in the z-axis per volume. The whole-brain perfusion CT protocols were the control protocol; protocol 1, which used approximately 30% of the original tube current values; and protocol 2, which had a lower number of total scan volumes. All other parameters were fixed. The scanning parameters of each protocol are shown in Table 1.



(A)



(B)



(C)

Figure 1. Time sequence schematic diagrams of the methods used to acquire whole-brain perfusion computed tomography datasets for the control protocol (A); protocol 1, which used approximately 30% of the tube current of the original protocol (B); and protocol 2, which was a reduced scan volume protocol (C).

Table 1. The scanning parameters of the control protocol, protocol 1, and protocol 2 for whole-brain perfusion computed tomography

Scanning parameters	**Control Protocol**	**Protocol 1**	**Protocol 2**
Scan mode type	**Dynamic axial volume**	**Dynamic axial volume**	**Dynamic axial volume**
Slice collimation (mm)	0.5	0.5	0.5
Slice thickness (mm)	0.5	0.5	0.5
Z-axis coverage (mm)	160	160	160
Rotation time (seconds)	0.75	0.75	0.75
Tube potential (kV_p)	80	80	80
Scan window (seconds)	60	60	55
Time per pass (seconds)	0.75/6.75/8.75/ 6.75/20.75	0.75/6.75/8.75/ 6.75/ 20.75	0.75/6.75/6.75/ 5.75/18.75
Total volume (passes)	19	19	15
Number of volumes per pass	1/3/6/4/5	1/3/6/4/5	1/3/4/3/4
Tube current (mA) per pass	310/150/300/ 150/150	210/100/200/ 100/100	310/150/300/ 150/150

Data analysis

All perfusion CT data had a thickness of 1 mm, and commercial CT Perfusion 4D software (SVD plus Dynamic Volume CT: Delay Insensitive Brain Perfusion Analysis)[11] was used for analysis, which is based on the deconvolution method embedded into the Vitrea Fx Workstation version 3.0.3 (Vital Images, Minnetonka, MN, USA) using the delay-insensitive singular-value decomposition plus perfusion algorithm. Arterial and venous input functions were automatically selected by the CT perfusion 4D software; typically, the algorithm defaults to the proximal internal carotid or basilar artery and the sigmoid or superior sagittal sinus, respectively.

For the quantitative analysis of the parametric images, identical single regions of interest (ROIs) measuring 5 mm^2 were placed in the white matter (WM) and gray matter (GM) of the medial left occipital lobe on the CBF, CBV, mean transit time (MTT), and time to peak (TTP) maps of the three perfusion CT protocols. The medial occipital lobe was selected because it is less likely than the larger middle cerebral artery (MCA) territory to be involved in ischemia. If the left posterior cerebral area was involved, the ROI was placed on the healthy contralateral side[2].

The quantitative parameters were signal (S), image noise (IN), and signal-to-noise ratio (SNR), which were represented as the mean CT attenuation values in Hounsfield units (HU), the standard deviation (SD) of CT attenuation values, and the ratio of signal and image noise, respectively.

The diagnostic image quality of the four perfusion parameters (CBF, CBV, MTT, and TTP) based on the ASPECTS levels (at the level of basal ganglia and corona radiata) was assessed by two neuroradiologists with 8 and 5 years of experience, who were blinded to the type of perfusion CT protocol. The diagnostic image quality was assessed on a four-point Likert scale: 0, non-diagnostic; 1, moderate; 2, good; 3, excellent[12].

Overall image quality was scored according to an adapted version of the scoring system developed by Abels et al. The observers determined which of the three perfusion CT protocols was superior (or equal if no differences were observed) based on each of the following three points: (a) GM-WM differentiation of CBF and CBV maps and grading of the MTT and TTP maps, (b) homogeneity (contrast, contours, and coherency/dissemination), and (c) compensation for artifacts[2].

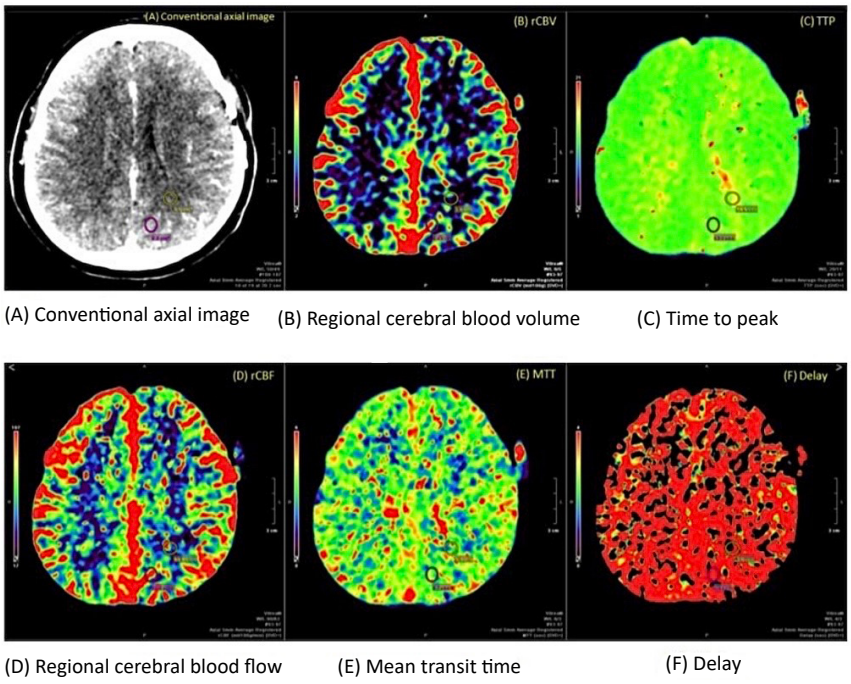


Figure 2. Identical regions of interest, measuring 5 mm^2, were placed in the white matter and gray matter of the medial left occipital lobe on the (A) conventional axial image (B) regional cerebral blood volume (rCBV), (C) TTP, (D) regional cerebral blood flow (rCBF), (E) MTT, and (F) delay of tissue response curve (Delay) parameter maps for all CTP protocols.

Radiation dose assessment

The patient data and scanning parameters were extracted from the scan dose page on the Digital Imaging and Communications in Medicine info available on Picture Archiving and Communication System. The mean radiation doses in terms of CT dose index volume ($CTDI_{vol}$; in mGy) and dose-length product (DLP; mGy*cm) for both protocols were recorded and compared. The percentages of $CTDI_{vol}$ and DLP reductions of protocols 1 and 2 were compared with those of the control protocol using the following two formulas, respectively.

$$\%\ \text{of}\ CTDI_{vol} = \frac{(CTDI_{vol}\ \text{of protocol 1 or 2-}CTDI_{vol}\ \text{of control protocol})}{CTDI_{vol}\ \text{of control protocol}} \times 100 \quad (1),$$

$$\%\ \text{of DLP} = \frac{(\text{DLP of protocol 1 or 2-DLP of control protocol})}{\text{DLP of control protocol}} \times 100 \quad (2),$$

The effective dose in millisieverts (mSv) was estimated by multiplying the DLP with a constant region-specific conversion coefficient of the brain (0.0023 mSv/mGy*cm)[13].

Statistical Analysis

The radiation dose was compared between the control protocol and protocols 1 and 2 using Student's independent t-tests in the SPSS software. Numerical data are expressed as means ± SDs. A 95% confidence level with a $p < 0.05$ was considered significant.

Results

Patients

Of the 15 control cases, eight were male and seven were female, with a median age of 47.8 ± 18.0 years (range 16–73 years). Twenty patients, comprising nine males and 11 females, with a mean age of 44.65 years (range 25–81 years), underwent whole-brain perfusion CT. Of these, 10 cases (four men and six women; mean age 44.6 ± 15.74 years) underwent protocol 1 (i.e., 30% of the tube current of the control protocol), and the remaining cases (five men and five women; mean age 44.7 ± 15.95 years) underwent protocol 2 (i.e., lower total scan volume).

Image quality

The S and SNR were obtained by placing ROIs in the WM and GM of the medial left occipital lobe in the CBF, CBV, and time-to-maximum maps of the three protocols. The mean signal intensities (in Hus) for the GM and WM CBV, CBF, MTT, and TTP in the medial left occipital lobe image quality data are shown in Table 2.

The mean signal intensities of the GM and WM for the CBV and CBF parameters were higher for protocol 1 than protocol 2. This pattern was reversed for the TTP and MTT parameters. As shown in Table 2, there was no significant difference in the signal intensity between the control protocol and protocols 1 or 2 ($p < 0.05$).

The SNR of CBV, CBF, MTT, and TTP in the GM and WM in the medial left occipital lobe image quality data are shown in Table 3.

Table 2. Mean signal intensities (in Hounsfield units) for gray and white matter cerebral blood volume (CBV), cerebral blood flow (CBF), time to peak (TTP) and mean transit time (MTT) in the medial left occipital lobe

Parametric map images		Signal intensity (HU)				
		Control protocol	Protocol 1	P-value [a]	Protocol 2	P-value [b]
CBV	Gray matter	3.15 ± 2.84	2.84 ± 1.00	0.35	2.76 ± 0.36	0.50
	White matter	1.69 ± 0.63	1.10 ± 0.34	0.51	0.94 ± 0.26	0.32
CBF	Gray matter	47.51 ± 19.57	54.62 ± 17.65	0.82	46.48 ± 9.80	0.22
	White matter	24.09 ± 10.73	24.02 ± 6.86	0.24	15.98 ± 4.5	0.13
TTP	Gray matter	13.15 ± 3.51	11.54 ± 2.06	0.46	14.00 ± 4.69	0.68
	White matter	15.11 ± 3.68	13.06 ± 2.52	0.54	15.62 ± 4.23	0.87
MTT	Gray matter	4.15 ± 1.06	3.30 ± 0.92	0.95	3.70 ± 0.74	0.57
	White matter	4.67 ± 1.31	2.96 ± 1.05	0.92	3.70 ± 0.54	0.36

Note: [a]P-value for protocol 1 vs control protocol

[b]P-value for protocol 2 vs control protocol

$P < 0.05$ was considered significant

Table 3. The mean signal-to-noise ratio (SNR) of CBV, CBF, TTP, and MTT in the gray and white matter in the medial left occipital lobe

Parametric map images		Signal-to-noise ratio (SNR)				
		Control protocol	Protocol 1	P-value [a]	Protocol 2	P-value [b]
CBV	Gray matter	4.85 ± 1.76	4.54 ± 2.25	0.65	6.50 ± 0.94	0.10
	White matter	4.59 ± 1.61	3.36 ± 0.68	0.10	4.66 ± 1.61	0.87
CBF	Gray matter	5.12 ± 2.12	5.80 ± 3.68	0.61	6.68 ± 2.95	0.39
	White matter	4.18 ± 1.02	4.32 ± 1.55	0.45	5.10 ± 1.40	0.43
TTP	Gray matter	43.00 ± 24.06	44.72 ± 20.39	0.65	78.56 ± 45.97	0.04
	White matter	21.66 ± 7.62	19.08 ± 12.03	0.40	41.26 ± 40.66	0.08
MTT	Gray matter	6.97 ± 2.45	5.46 ± 1.76	0.34	9.60 ± 5.11	0.09
	White matter	4.30 ± 1.01	4.20 ± 1.31	0.97	4.30 ± 0.78	0.37

Note: [a]P-value for protocol 1 vs control protocol

[b]P-value for protocol 2 vs control protocol

$P < 0.05$ was considered significant

The SNR of the GM and WM for protocol 1 was inferior to that of protocol 2 for all perfusion parameters (i.e., CBV, CBF, TTP, and MTT), due to the quantum mottle noise in image is proportional to $1/mAs^{0.5}$ [14] when the tube current decreased for a fixed tube voltage. However, no significant quantitative differences in the parametric maps were found between protocol 1 and the control protocol or between protocol 2 and the control protocol ($p > 0.05$), except the TTP in the GM of protocol 2 (p-value =0.04).

For overall image quality, as measured by GM-WM differentiation and homogeneity, the average score of protocol 2 was slightly superior to that of protocol 1 (81% and 98% versus 74% and 75%, respectively). Both protocols had an average score of 100% for compensation for artifacts, as shown in Figure 3.

The diagnostic image quality of the four perfusion parameters at the level of the basal ganglia and corona radiata, was assessed by two neuroradiologists who were blinded to the type of CTP protocol. The comparison between protocols 1 and 2 showed a significant difference ($p > 0.05$) for all levels of the basal ganglia and corona radiata in CBF, CBV, MTT, and TTP images. However, there was a significant Pearson correlation between the two observers at the 0.01 level ($p < 0.01$).

Radiation dose assessment

Radiation doses in terms of $CTDI_{vol}$, DLP, and effective dose for the control protocol and protocols 1 and 2 whole-brain perfusion CT are shown in Figures 4–6.

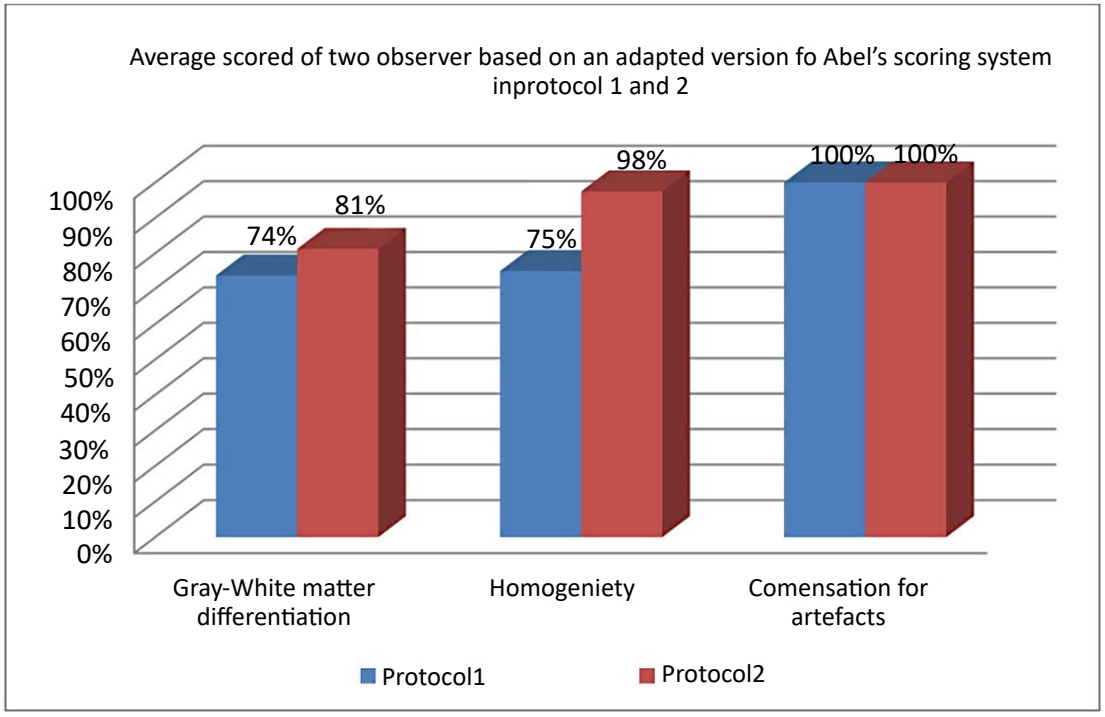


Figure 3. Overall image quality, as measured by gray matter-white matter differentiation, homogeneity, and compensation for artifacts.

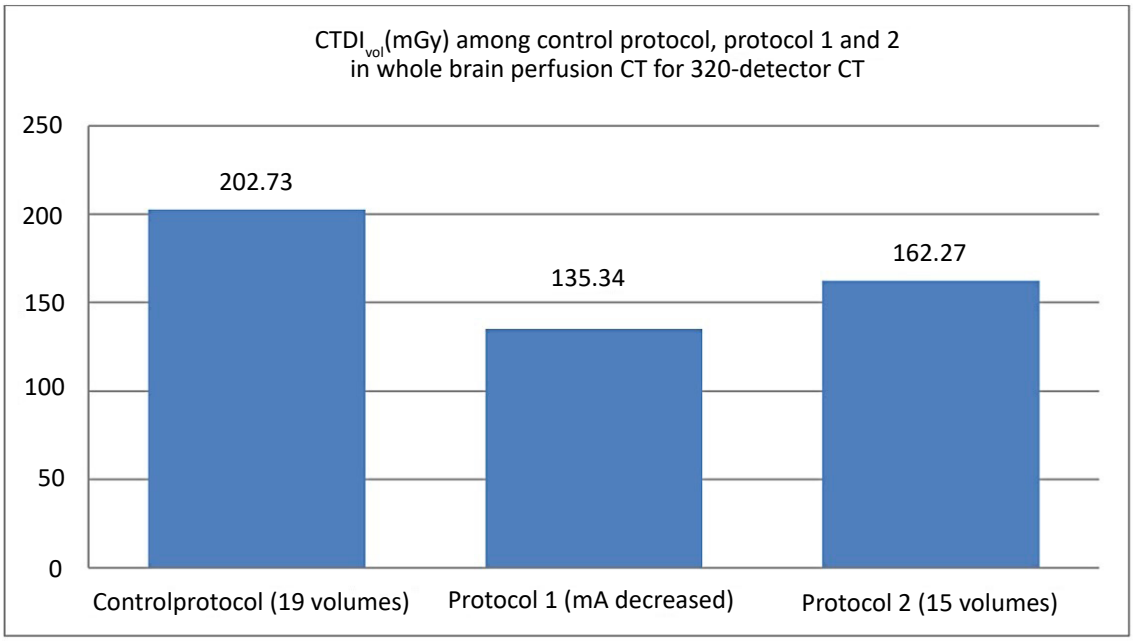


Figure 4. Radiation doses in terms of computed tomography (CT) dose index volume ($CTDI_{vol}$; mGy) for the control protocol and protocols 1 and 2 whole-brain perfusion CT.

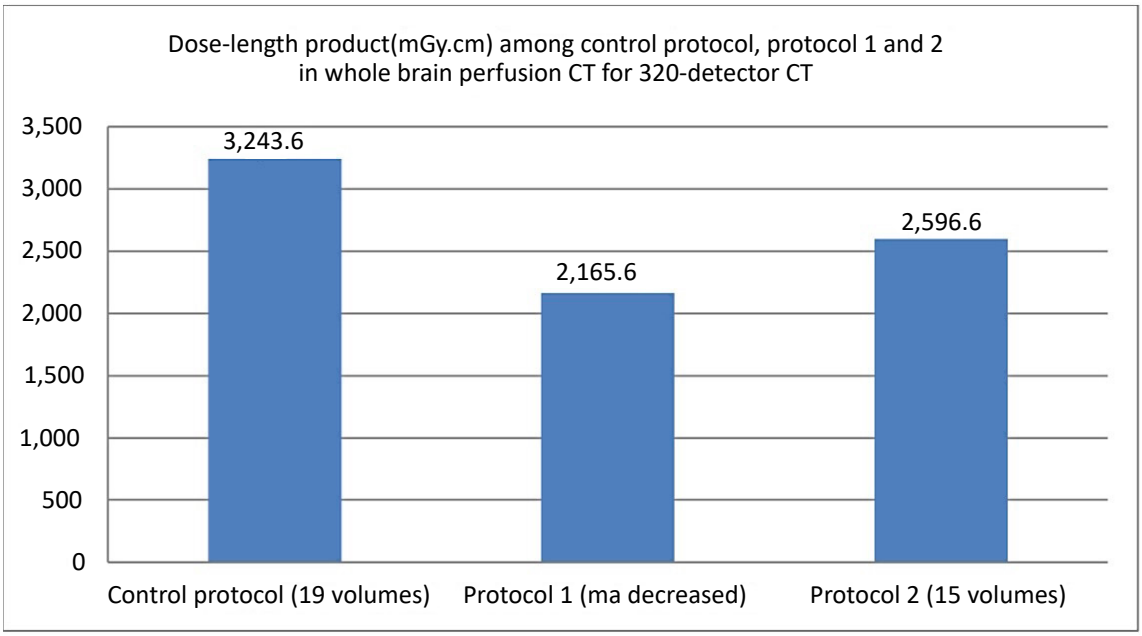


Figure 5. Radiation doses in terms of dose-length products (mGy*cm) for the control protocol and protocols 1 and 2 whole-brain perfusion CT.

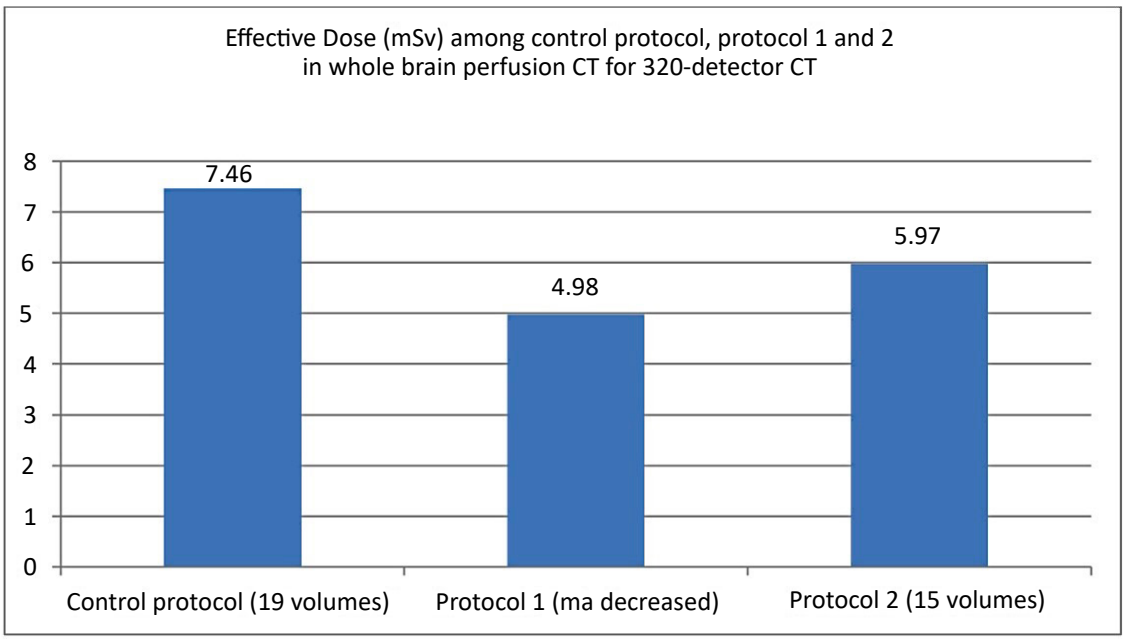


Figure 6. Radiation doses in terms of effective dose (mSv) for the control protocol and protocols 1 and 2 whole-brain perfusion CT.

The percentages of radiation dose reductions in terms of CT dose metrics ($CTDI_{vol}$, DLP and effective dose) for protocols 1 and 2 compared with the control protocol were 33.2% and 19.9%, respectively. The effective dose of protocol 1 (4.98 mSv), which used 30% of the tube current of the control method, was approximately half that of the control protocol (7.46 mSv) as shown in Table 4.

Discussion

Several methods have been proposed to limit the radiation dose in CTP, which include a reduction in tube voltage[8, 9, 15], tube current[9], temporal resolution[7, 16, 17], and scan duration. The reduction in the number of scan volumes (protocol 2), which decreases the scan window, can also lower the radiation dose (the dose is directly proportional to the scan duration). A shorter scan duration increases the risk of insufficient time to capture the whole passes of iodinated contrast media bolus through the brain from the venous input vessel return to baseline due to the variability in cardiac output of patient. This can impact the calculation of parametric maps based on deconvolution principles[5, 6].

Table 4. The percentage of radiation dose reduction for protocols 1 and 2 compared with that of the control protocol in terms of computed tomography (CT) dose index volume ($CTDI_{vol}$), dose-length product (DLP), and effective dose for whole-brain perfusion CT

Radiation dose metrics	Control protocol	Protocol 1	Control protocol	Protocol 2
$CTDI_{vol}$ (mGy)	202.73	135.34	202.73	162.27
DLP (mGy*cm)	3,243.60	2,165.60	3,243.60	2,596.60
Effective dose (mSv)	7.46	4.98	7.46	5.97
Percentage reduction	33.23		19.95	

Traditional fixed-sampling approaches use a uniform scanning rate during the entire CTP data acquisition. Because certain portions of the contrast passage are less sensitive to sampling frequency, such as the pre-enhancement baseline and the downward slope toward and beyond the baseline, reducing sampling rates during these segments is appealing. The omitted samples can be traded for a dose reduction or higher temporal resolution during key segments of arterial tissue passage. Variable sampling for CTP has been used with wide 320-channel detector systems with favorable results[2].

Previous studies using whole-brain CTP imaging with 160-mm coverage of 320 MDCT have reported the effective doses of 6.7 mSv[18], 5.4 mSv[19], and 3.6 mSv[20]. Our protocol 1 achieved an effective dose of 4.98 mSv, which was similar to that of the studies of Diekmann et al[20] and Siebert et al[19] but was lower than that of the study by Saifhon et al[18]. The limitation in small sample size of our study may have introduced sampling errors or other dataset biases. However, this was a pilot study. Despite of the limitation, our proposed two acquisition protocols for whole-brain perfusion CT result in a radiation dose reduced by dose- length product of 2165.6 and 2596.6 mGy*cm for protocol 1 and 2, respectively.

Conclusions

We aimed to reduce the radiation dose of whole-brain perfusion CT by using 320-detector CT, and we showed that protocol 1 (which used 30% of tube current of the control protocol) resulted in a greater radiation dose reduction than protocol 2 (reduction in total scan volume method). The radiation dose could be reduced by 33.24% while providing parametric image quality comparable to that of the control protocol, as measured by the S and SNR of the GM and WM parametric maps. For overall image quality, as assessed by GM-WM differentiation and homogeneity, the average score of protocol 2 was slightly superior to that of protocol 1. However, none of the parametric maps differed significantly between protocols 1 and 2. Moreover, the correlation between the two observed was significant. In conclusion, the image quality required for diagnostic accuracy should be considered when selecting the whole-brain perfusion CT protocol in routine practice.

Conflict of interest

The authors declare no conflicts of interest.

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