Yang *et al. BMC Medical Imaging* (2024) 24:193
https://doi.org/10.1186/s12880-024-01373-7

BMC Medical Imaging

RESEARCH **Open Access**

Contrast enhancement boost improves the image quality of CT angiography derived from 80-kVp cerebral CT perfusion data

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Abstract

Rationale and objective To investigate the impact of the contrast enhancement boost (CE-boost) technique on the image quality of CT angiography (CTA) derived from 80-kVp cerebral CT perfusion (CTP) data, and to compare it with conventional $\mathrm{CTA}_{\mathrm{peak}}$ as well as other currently employed methods for enhancing CTA images, such as $\mathrm{CTA}_{\mathrm{tMIP}}$ and $\mathrm{CTA}_{\mathrm{tAve}}$ extracted from CTP.

Materials and methods The data of forty-seven patients who underwent CTP at 80 kVp were retrospectively collected. Four sets of images: $\mathrm{CTA}_{\mathrm{peak}}$, $\mathrm{CTA}_{\mathrm{tMIP}}$, $\mathrm{CTA}_{\mathrm{tAve}}$, and CE-boost images. The $\mathrm{CTA}_{\mathrm{peak}}$ image represents the arterial phase at its peak value, captured as a single time point. $\mathrm{CTA}_{\mathrm{tMIP}}$ and $\mathrm{CTA}_{\mathrm{tAve}}$ are 4D CTA images that provide maximum density projection and average images from the three most prominent time points. CE-boost is a postprocessing technique used to enhance contrast in the arterial phase at its peak value. We compared the average CT value, standard deviation (SD), signal-to-noise ratio (SNR), and contrast-to-noise ratio (CNR) of the internal carotid artery (ICA) and basilar artery (BA) among the four groups. Image quality was evaluated using a 5-point scale.

Results The CE-boost demonstrated and CNR in the ICA and BA (all $p < 0.001$). Compared with the other three CTA reconstructed images, the CE-boost images had the best subjective image quality, with the highest scores of 4.77 ± 0.43 and 4.87 ± 0.34 for each reader (all $p < 0.001$).

Conclusion Compared with other currently used techniques,CE-boost enhances the image quality of CTA derived from 80-kVp CTP data, leading to improved visualization of intracranial arteries.

Keywords Computed tomography angiography, Contrast enhancement boost, Cerebral arteries

Introduction

Stroke is a major cause of death and disability globally and is usually quantitatively assessed by cerebral computed tomography perfusion (CTP) [1, 2]. In addition to conventional whole-brain perfusion maps, 4D CTA obtained through CTP can provide the collateral circulation and dynamic angiographic information of intracranial vessels that comprehensively evaluates vascular status and cerebral hemodynamics, where adequate or high-quality images from each individual phase of CTP are necessary [3]. Nevertheless, due to the need for

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repeated examinations for CTP, drawbacks associated with radiation exposure are inevitable. The use of 80-kVp CTP scanning is common in clinical practice for its low-dose capabilities, and other significant efforts have also been dedicated to minimizing radiation doses. Maintaining adequate image quality for subsequent dynamic CTA analysis presents a challenge in the context of this low-dose scenario [4].

Nowadays, various post-processing techniques are applied in medical image analysis, including deep learning-based image recognition, segmentation, classification, and some traditional methods [5–7]. For the CTA image quality enhancement, the commonly proposed approaches [8, 9] involved integrating multiple image datasets from various time points into a final image stack, and time-resolved maximum intensity projection (CTA_{tMIP}) or time-resolved mean (CTA_{tAve}) calculations are then performed. The processed image incorporates data from multiple images with consistently employed integrated noise reduction algorithms to enhance CTA image quality.

Contrast enhancement boost (CE-boost) is a post-processing technique used to increase the degree of contrast enhancement on contrast-enhanced CT [10]. Previous studies have indicated that the CE-boost technique facilitates clear visualization of type II endoleak cavities [10] and can also improve the image quality of cranio-cervical CTA [11], pulmonary vasculature [12], abdominal CTA [13], and the portal vein [14]. However, the clinical utility of CE-boost images derived from 80-kVp CTP data for enhancing the image quality of brain CTAs remains unexplored. Therefore, the objective of this study was to investigate the impact of the CE-boost technique on the image quality of CTA images obtained from 80-kVp brain CTP data, and to compare its effectiveness with other existing methods for enhancing CTA.

Methods and materials

Patient population

This retrospective study was approved by the Institutional Review Board, and all patient requirements for informed consent were waived. From June to July 2023, 47 patients who underwent CTP at our institution for various reasons, including follow-ups for suspected stroke and/or intravascular diseases, were reviewed. The exclusion criteria were as follows: (1) had a history of iodine allergy; (2) pregnancy(3) had severe cardiac, hepatic, pulmonary, or renal dysfunction or hematological disorders; and (4) had significant imaging artifacts. Patient sex, age, body weight, and height were assessed and documented.

Scan protocols and reconstruction methods

The acquisitions were performed using a 320-row detector CT scanner (Aquilion ONE Genesis Edition, Canon Medical Systems, Japan). The patient was placed in a supine position with their hands resting on both sides of the body and head in an advanced position and was instructed to remain still throughout the examination. The CTP scanning parameters and the contrast agent administration protocol are summarized in Table 1. In accordance with our standard CTP protocol, all patients received a fixed 40-mL intravenous bolus of Iomeron, 370 mg iodine per mL, followed by a 30-mL bolus of saline at an injection rate of 5 mL/s [15]. The CTP acquisition comprised 19 phases, including one noncontrast scan (430 mA), three scans during the early arterial phase (300 mA, every 2 s), six scans during the arterial phase (420 mA, every 2 s), four scans during the late arterial phase (300 mA, every 2 s), and five scans during the venous phase (300 mA, every 5 s). CTP images from each phase were reconstructed using adaptive iterative dose reduction via three-dimensional processing [AIDR 3D, kernel FC41].

Data processing

The CTP data were transferred to a dedicated workstation (Canon console, Canon Medical Systems, Japan), where a radiologist with 4 years of experience in head and neck CTA imaging conducted the image processing. Following motion correction, the time decay curves of the middle cerebral artery were generated from the CTP data, resulting in three distinct images: a single-phase

Table 1 CT parameters and contrast material protocols

Parameter	4D CTA-CTP
Scanning parameter	
z-axis coverage (cm)	16
Tube voltage (kV)	80
Tube current (mA)	300–430
Collimator (mm)	320 × 0.5
No. of scans	19
Pitch	/
Rotating speed (s/r)	0.75
Contrast material injection protocol	
Iodine concentration (mg/mL)	370
Contrast volume (mL)	40
Contrast injection rate (mL/s)	5
Saline volume (mL)	30
Saline injection rate (mL/s)	5
Reconstruction parameter	
Slice thickness (mm)	0.5
Slice interval (mm)	0.5

image representing the peak time point (CTA_{peak}) and a time-resolved maximum intensity projection image (CTA_{tMIP}), which displayed the three phases with the greatest intensification, and a time-resolved average image (CTA_{tAve}). Subsequently, the enhanced images obtained at the time points of single-phase peak enhancement were imported into dedicated software (CE-boost, SURESubtraction Iodine map, Canon Medical Systems, Japan) to generate CE-boost images.

Image analysis

Quantitative image analysis

The quantitative image analysis was performed by a radiologist with 4 years of experience in interpreting head and neck CTA images. In each reconstruction sequence, four regions of interest (ROI) were consistently placed at the same anatomical location by copying and pasting, including the basilar artery (BA), right and left internal carotid artery (ICAs), and brain stem (BS). The size of the ROIs was optimized to minimize the effect of artifacts and arterial calcification while maximizing their coverage area. Vessel noise and brainstem noise were defined as the standard deviations (SDs) of these measurements and were recorded as the SD_{vessel} and $SD_{brainstem}$, respectively. The signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) were calculated using the following formulas:

$$\mathrm{SNR} = \mathrm{CT}_{\mathrm{vessel}}/\mathrm{SD}_{\mathrm{vessel}}$$

$$\mathrm{CNR} = (\mathrm{CT}_{\mathrm{vessel}} - \mathrm{CT}_{\mathrm{brainstem}})/\mathrm{SD}_{\mathrm{brainstem}}$$

Qualitative image analysis

The images were independently evaluated by two radiologists specializing in head and neck CTA imaging, with 4 and 12 years of experience respectively. The five-point Likert scale criteria (Table 2) [16] were used to assess image quality. The radiologists were blinded to the reconstruction approaches during image evaluation. Images from the four CT image sets were randomly arranged and reviewed after blinding patient information. Standardized window width and level settings were applied across all reconstruction sequences for each patient. In cases where a discrepancy occurred in the assessment of image quality scores between the two readers during the collaborative reading process, they engaged in deliberations to reach a final consensus.

Radiation dose

The CT dose index (CTDIvol) and the dose length product (DLP) were recorded for each patient, while the effective dose (ED) was calculated by multiplying the DLP with a conversion coefficient k factor of 0.0021 ($\mathrm{mSv}\bullet\mathrm{mGy}^{-1}\bullet\mathrm{cm}^{-1}$) specifically designed for head examinations [17].

Statistical analysis

Statistical analyses were performed using R software (version 3.6.1). The normality of the data distribution was assessed using the Shapiro–Wilk test. For nonnormally distributed data, the Friedman test was employed, followed by multiple comparisons using the Wilcoxon signed rank test. One-way repeated analysis of variance (ANOVA) was utilized to compare continuous variables with a normal distribution, and paired-samples t tests were used for the subsequent multiple comparisons. Bonferroni correction was applied for these multiple comparisons. Statistical significance was considered as a p value <0.05. The interobserver agreement of subjective image analysis was evaluated using kappa statistics, with the following criteria: 0–0.20, poor; 0.21–0.40, fair; 0.41–0.60, moderate; 0.61–0.80, good; and 0.81–1.00, excellent.

Results

Patient sample and radiation dose

Fifty-three patients met the inclusion criteria, six of whom were excluded due to bleeding on noncontrast CT ($n=3$) or motion artefacts ($n=3$). Ultimately, 47 patients (mean age: 61.8 ± 12.9 years; range: 19–81 years; 17 women) were included in this study. The CTDIvol,

Table 2 Description of the categories of image quality characteristics

Score	Image quality	Motion artifacts	Vessel contours	Vessel definition
1	Poor	Severe	Poor vessel definition and not sufficient for the diagnosis	Poor and not acceptable
2	Weak	Obvious	Poor vessel definition but sufficient for the diagnosis	Poor but acceptable
3	Satisfactory	Some artifacts	Moderate vessel definition	Moderate
4	Good	Few artifacts	Good vessel definition	Good
5	Excellent	No artifact	Excellent vessel definition	Excellent

DLP and ED were 173.87 mGy, 1876.96 mGy•cm, and 3.94 mSv, respectively.

Quantative evaluation

Quantitative results are presented in Table 3, indicated that in the ICA and BA regions,the CT value of the CE-boost group was significantly greater than that of the CTA_{peak}, CTA_{tAve}, and CTA_{tMIP} groups (all $p < 0.001$). The CE-boost images exhibited the highest noise levels in the ICA, BA and BS regions among the four datasets (all $p < 0.001$). In terms of SNR in both ICA and BA regions, CE-boost showed a significant improvement over $CTA_{peak,}$ CTA_{tAve} and CTA_{tMIP}. The CNRs of the ICA and BA of the CE-boost algorithm were significantly greater than those of the other three algorithms mentioned above (all $p < 0.001$). The image quality produced by the four datasets is shown in Fig. 1, while an illustration of right posterior cerebral artery stenosis is shown in Fig. 2.

Qualitative evaluation

The results demonstrated an agreement of 0.721 between the two readers, indicating a substantial level of agreement. The subjective image quality scores of CE-boost (Reader 1: 4.77 ± 0.43 and Reader 2: 4.87 ± 0.34) were higher than those of CTA_{tMIP} (Reader 1: 4.26 ± 0.53 and Reader 2: 4.26 ± 0.49) and CTA_{tAve} (Reader 1: 3.66 ± 0.60 and Reader 2: 3.77 ± 0.56) (all $p < 0.001$). According to the score criteria, the results indicated that CE-boost improved the visualization of intracranial arteries from moderate to good, or good to excellent. Qualitative results are presented in Table 4.

Discussion

This study aimed to explore whether CE-boost enhances the image quality of CTA derived from 80 kVp CTP data compared to other existing methods like tMIP and tAve. The results showed that the image quality of CE-boost postprocessing is superior to that of other imaging techniques in both subjective and objective assessments.

CE-boost images are produced using a subtraction CT technique that employs reliable registration algorithms. The process involves subtracting noncontrast images from arterial-phase images to create subtraction images. This subtraction images are then added back to the original arterial-phase images with an automatic denoising procedure, resulting in the final contrast-enhanced CT images. Several recent studies [10, 12, 14] have shown that a CE-boost can improve the visualization of pulmonary vasculature, type II endoleak after endovascular aortic aneurysm repair, and portal vein imaging. The application of a CE-boost in head and neck CT angiography was initially investigated by Otgonbaatar C et al. [11]. They found that the CE-boost technique improved image quality in both objective and subjective analyses without requiring an increase in contrast media flow rate or concentration. Additionally, vessel completeness and delineation were superior between CE-boost images and conventional images. Our findings aligned with the study by Otgonbaatar C et al., who emphasized the benefits of using CE-boost to enhance image quality. Moreover, our results indicated that in this ultralow-dose head CTA scenario, there was an approximately 20–30% increase in the SNR and a 30–40% increase in the CNR with the CE-boost. These values are lower than those reported by Otgonbaatar C et al., where the percentage increase was almost double. This difference could be attributed to a relatively greater increase in vascular and brainstem noise after the application of the CE-boost under low-dose 80 kV scanning conditions. The operations of image subtraction and addition in the CE-boost technique will lead to an increase in image noise even with the denoising filter. In particular, the magnitude of vascular noise increase (ICA: 26%, BA: 28%) was higher than the magnitude of background noise increase (BS: 5%). Since the SNR is inversely proportional to vascular noise and the CNR is inversely proportional to brainstem noise amplitude, our study showed that the increase in the SNR following the CE-boost was relatively modest, while the increase in the CNR was comparatively substantial.

Horinouchi et al. [18] demonstrated the utility of time-resolved imaging in maintaining optimal contrast enhancement and image quality for endovascular abdominal aortic repair planning while significantly reducing the amount of contrast material needed. Li et al. [19] reported that the image quality from tAve reconstructions of pancreatic CTP data provides image quality comparable to or even surpassing that of native biphasic CT, thereby enabling the use of pancreatic perfusion CT alone for insulinoma detection without the need for an additional biphasic CT. These findings were consistent with our studies, where CTA_{tAve} and CTA_{tMIP} maintained or improved both objective and subjective image quality compared to traditional CTA_{peak} images, leading to improved visualization of vascular branches and collateral circulation.

Moreover, in this study, we observed that compared with CTA_{tMIP} and CTA_{tAve}, CE-boost technology not only improved the SNR and CNR but also enhanced the subjective image quality of intracranial arteries visualization, suggesting that CE-boost technology is a more effective approach for enhancing intracranial vascular visualization. The CE-boost technique differs from tMIP and tAve in two key aspects. Firstly, regarding data utilization, CE-boost employs noncontrast and arterial phase images, whereas tMIP and tAve use adjacent image datasets from different time points. Secondly, in terms of

Table 3 Quantitative image quality parameter comparison

Parameters	CTA_{peak} (group 1)	CTA_{tAve} (group 2)	CTA_{tMIP} (group 3)	CE-boost (group 4)	*P* values						
					All	1 vs. 2	1 vs. 3	1 vs. 4	2 vs. 3	2 vs. 4	3 vs. 4
CT value											
ICA(*n* = 94)	648.62 (143.09)	595.71 (130.50)	655.76 (146.56)	916.60 (225.14)	< 0.001	< 0.001	0.002	< 0.001	< 0.001	< 0.001	< 0.001
BA(*n* = 47)	581.35 (145.32)	536.80 (131.69)	595.22 (141.55)	841.18 (218.20)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
BS(*n* = 47)	46.10 (5.30)	45.65 (5.15)	52.98 (5.33)	51.20 (6.58)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Noise											
ICA(*n* = 94)	14.82 (8.14)	12.47 (8.21)	15.10 (9.67)	18.67 (10.08)	< 0.001	< 0.001	1.00	< 0.001	< 0.001	< 0.001	< 0.001
BA(*n* = 47)	23.57 (8.27)	21.31 (7.59)	23.74 (8.76)	30.28 (12.60)	< 0.001	< 0.001	1.00	< 0.001	< 0.001	< 0.001	< 0.001
BS(*n* = 47)	9.15 (1.83)	6.49 (1.74)	7.81 (1.90)	9.56 (2.15)	< 0.001	< 0.001	< 0.001	0.007	< 0.001	< 0.001	< 0.001
SNR											
ICA(*n* = 94)	55.84 (29.77)	62.94 (31.39)	57.29 (30.50)	66.03 (41.65)	< 0.001	< 0.001	1.00	< 0.001	0.03	1.00	< 0.001
BA(*n* = 47)	28.87 (14.83)	30.30 (17.46)	31.17 (23.34)	37.16 (27.82)	< 0.001	1.00	1.00	< 0.001	1.00	< 0.001	0.002
CNR											
ICA(*n* = 94)	67.48 (18.24)	88.63 (26.67)	79.64 (21.50)	92.90 (26.52)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.005	< 0.001
BA(*n* = 47)	60.01 (18.75)	79.17 (26.85)	71.72 (21.27)	85.12 (26.51)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.03	< 0.001

CE-Boost Contrast enhancement boost, CTA_{peak} a single-phase image representing the peak time point, CTA_{tMIP} a time-resolved maximum intensity projection image, CTA_{tAve} a time-resolved average image, *BA* basilar artery, *BS* brainstem, *SNR* signal-to-noise ratio, *CNR* contrast-to-noise ratio

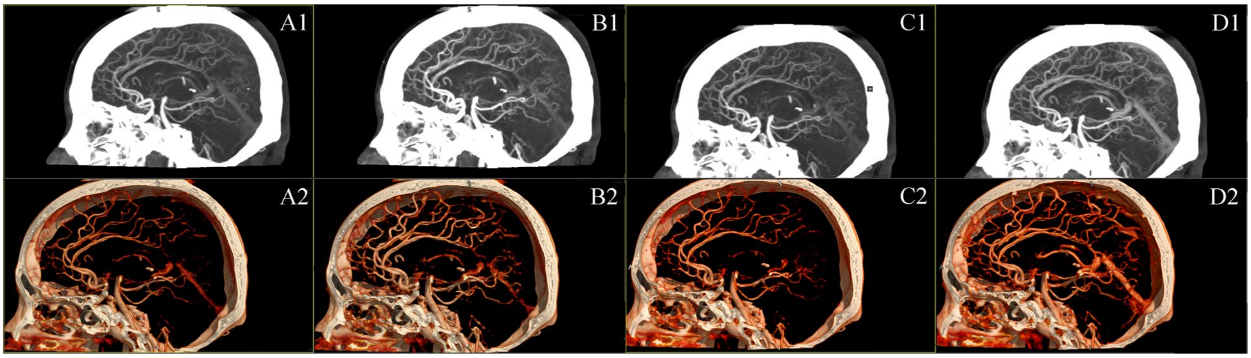

Fig. 1 Example of qualitative assessment for image quality: A patient underwent a CTP scan, and the cerebral arteries were reconstructed from 4D CTA images to generate MIP and VR images. The MIP and VR images of CTA obtained from $\mathrm{CTA_{peak}}$ (A1, A2), $\mathrm{CTA_{tMIP}}$ (B1, B2), and $\mathrm{CTA_{tAve}}$ (C1, C3) were assigned a score of 4. Additionally, the MIP image of the CTA image derived from the CE-boost (D1, D2) received a score of 5 due to enhanced visualization of the distal second-order branches

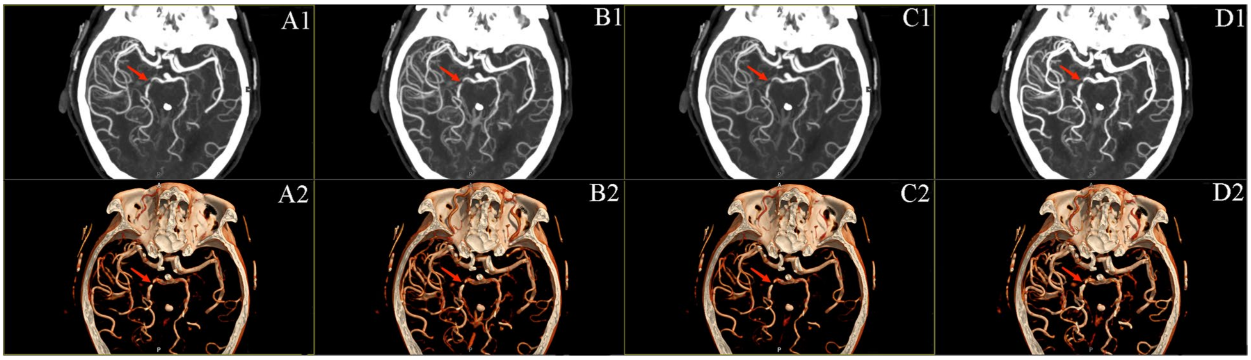

Fig. 2 The right posterior cerebral artery exhibited severe stenosis in all images (indicated by arrows). However, compared with $\mathrm{CTA_{peak}}$ (A1, A2), $\mathrm{CTA_{tMIP}}$ (B1, B2), and $\mathrm{CTA_{tAve}}$ (C1, C3) images, CE-boost (D1, D2) images demonstrated enhanced visualization of the distal vessels of the right posterior cerebral artery

technical principles, CE-boost maximizes the utilization of iodine map information in contrast-enhanced images and enhances it. On the other hand, tAve enhances image quality primarily through noise reduction by averaging multiple images, and tMIP enhances vascular visualization by selecting the maximum value from multiple images without exceeding the actual value.

A high risk of kidney damage is associated with high concentrations of contrast agents [20, 21]. To mitigate the risk of contrast-induced nephropathy, there is a growing research focus on minimizing the total concentration of contrast agent while ensuring the optimal quality of CTA images. Our study showed that compared with conventional CT, the CE-boost could augment CT attenuation. This ability implies the potential of reducing the flow rate or concentration of contrast agent while preserving image quality in clinical use. Theoretically, a stronger contrast enhancement capability could be obtained by iteratively using the CE-boost technique multiple times. On the other hand, repeatedly adding the iodine image to the original image will further increase motion-related artifacts. It might be challenging to accurately generate subtraction images via registration in patients with autonomous or involuntary motion, which can cause image blurring [13]. In patients with severe movement, blurred images might appear even with nonrigid registration integrated in the CE-boost algorithm. Further investigations are warranted to determine optimal imaging protocols involving multiple iterations.

This study has several limitations. Firstly, we performed a single-center study with a relatively small sample size. Secondly, we compared $\mathrm{CTA_{tAve}}$ and $\mathrm{CTA_{tMIP}}$ based solely on the three time points exhibiting maximum CTP enhancement, and future investigations will be conducted to determine the optimal post-processing strategy for averaging. Additionally, since CE-boost could significantly improve the enhancement of vascular, it could be employed to optimize the design of CT imaging protocols by reducing radiation dose. Therefore, it is imperative to compare CE-boost

Table 4 Qualitative image quality parameter comparison

	CTA$_{\text{peak}}$ (group 1)	**CTA$_{\text{tAve}}$ (group 2)**	**CTA$_{\text{tMIP}}$ (group 3)**	**CE-boost (group 4)**	***P* values**						
					All	**1 vs. 2**	**1 vs. 3**	**1 vs. 4**	**2 vs. 3**	**2 vs. 4**	**3 vs. 4**
Reader 1	3.53 (0.58)	3.66 (0.60)	4.26 (0.53)	4.77 (0.43)	< 0.001	1.00	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Reader 2	3.43 (0.50)	3.77 (0.56)	4.26 (0.49)	4.87 (0.34)	< 0.001	0.007	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

CE-Boost Contrast enhancement boost, *CTA$_{peak}$* a single-phase image representing the peak time point, *CTA$_{tMIP}$* a time-resolved maximum intensity projection image, *CTA$_{tAve}$* a time-resolved average image under reduced radiation dose conditions by employing a lower tube current than that utilized in the present study.

In conclusion, our study results indicate that compared with other currently used techniques, CE-boost delivers better qualitative and quantitative image quality of CTA derived from 80-kVp CTP data and improves visualization of intracranial arteries. Furthermore, it offers insights into optimizing CTA imaging protocols at reduced radiation doses.

Abbreviations

CTA	Computed tomography angiography
CTP	Cerebral CT perfusion
CE-boost	Contrast enhancement boost
tMIP	Time-resolved maximum intensity projection
tAve	Time-resolved average
AIDR	Adaptive Iterative Dose Reduction
CTDIvol	CT dose index volume
ED	Effective dose
BA	Basilar artery
VA	Vertebral artery
ICA	Internal carotid artery
BS	Brainstem
ROI	Region of interest
SD	Standard deviation
CNR	Contrast-to-noise ratio
SNR	Signal-to-noise ratio

Acknowledgements

Not applicable.

Authors' contributions

Y.L.: Term, Conceptualization, Writing—Original Draft. H.Z.: Software, Writing—Review & Editing. J.S.: Methodology. M.W.: Formal analysis, Investigation. Y.L.: Resources. M.X.: Data Curation, Supervision. X.Y.: Image Postprocessing. B.W.: Validation. X.H.: Visualization. L.G.: Collection of cases. C.Z.: Project administration, Funding acquisition.

Funding

This work was supported by the Key Science and Technology Program of Shaanxi Province (2022SF-556) as well as the Shaanxi Provincial Health Commission (2022B011).The article has obtained consent for publication and funding.

Availability of data and materials

The data used for the analysis are available from the corresponding authors upon request.

Declarations

Ethics approval and consent to participate

This retrospective study was approved by the Institutional Review Board of Hanzhong Central Hospital, and all patient requirements for informed consent were waived.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 21 May 2024 Accepted: 19 July 2024

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