

Full title

Evaluation of moyamoya disease in CT angiography using ultra-high-resolution
computed tomography: application of deep learning reconstruction

Article type

Original Research

Abstract

Purpose: The aim of this study was to examine the evaluation of ultra-high-resolution computed tomography angiography (UHR CTA) images in moyamoya disease (MMD) reconstructed with hybrid iterative reconstruction (Hybrid-IR), model-based iterative reconstruction (MBIR), and deep learning reconstruction (DLR).

Methods: This retrospective study with institutional review board approval included patients with clinically suspected MMD who underwent UHR CTA between January 2018 and July 2020. CTA images were reconstructed with three reconstruction methods. Qualitative visualization was evaluated in comparison with digital subtraction angiography. Quantitative evaluation included assessment of edge sharpness, full width at half maximum (FWHM), vessel contrast, and tissue signal-to-noise ratio ($\text{SNR}_{\text{tissue}}$). One-way analysis of variance was used to analyze differences. In addition, reconstruction time were assessed.

Results: Qualitative evaluation of CTA for 33 sides did not differ significantly between reconstruction methods. In quantitative evaluation for 54 patients, edge sharpness for right and left cortical segments of the middle cerebral artery was significantly higher for Hybrid-IR than for other reconstructions. No significant difference was seen between MBIR and DLR. Edge sharpness for STA-MCA bypass was significantly higher for

Hybrid-IR than for MBIR, but no significant difference was seen between Hybrid-IR and DLR. FWHM for STA-MCA showed no significant difference between the three reconstruction methods. DLR displayed the highest $\text{SNR}_{\text{tissue}}$. The time required for reconstruction was 40 s for Hybrid-IR, 2580 s for MBIR, and 180 s for DLR.

Conclusion: UHR CTA with DLR adequately visualized vessels in patients with MMD within a clinically feasible reconstruction time.

Keywords: Deep learning; Image Reconstruction; Digital subtraction angiography; X-ray computed tomography

Abbreviations

MMD, moyamoya disease; UHR CTA, ultra-high-resolution computed tomography angiography; DLR, deep learning reconstruction; Hybrid-IR, hybrid iterative reconstruction; MBIR, model-based iterative reconstruction; DSA, digital subtraction angiography; SNR, signal-to-noise ratio.

Introduction

Moyamoya disease (MMD) is defined as progressive steno-occlusion of the cerebral vasculature seen at angiography, with particular involvement of the terminal internal carotid artery (ICA) and circle of Willis [1,2]. Cerebral angiography or digital subtraction angiography (DSA) are now regarded as essential diagnostic tools for MMD, but DSA is expensive, time-consuming, and invasive, with a small but non-negligible risk of complications [3]. Although MR angiography (MRA) can be substituted in the definitive diagnosis of MMD if steno-occlusion and an abnormal vascular network are visualized on MRA [1,4–7], DSA is still necessary for preoperative evaluation [3,8,9].

Recent technical advances in computed tomography angiography (CTA) can provide detailed vascular information within a short scan time [10,11], which will be significantly beneficial for patients with MMD, particularly in pediatric and emergency cases [12]. Ultra-high-resolution (UHR) CT offers superior resolution to conventional CT because of technological improvements such as the reduced detector size (0.25 mm, 1792 channels in 160 rows) and focal spot size (minimum, 0.4×0.5 mm), which can visualize small vessels. Image reconstruction with a matrix size of 1024×1024 pixels or more becomes possible, while image noise becomes more pronounced compared to conventional CT images due to the relative shortage of incident photons in small detectors.

To reduce image noise, hybrid iterative reconstruction (Hybrid-IR) and model-based iterative reconstruction (MBIR) are widely used [13]. MBIR is more effective than Hybrid-IR for improving image quality in the delineation of small vessels [14], but the long image reconstruction time of a few hours in UHR CT represents a bottleneck in routine clinical practice for emergent cases. A new image reconstruction method based on deep learning reconstruction (DLR) has become available very recently, and a deep convolutional neural network kernel trained with ideal MBIR offers markedly reduced reconstruction time [15]. The image quality of abdominal UHR CT has been reported to be better using DLR than using Hybrid-IR or MBIR [16,17]. To the best of our knowledge, no studies have evaluated the performance of UHR CT with DLR in the evaluation of MMD in clinical practice [18,19].

We hypothesized that the very high spatial resolution of UHR CT using DLR would improve the evaluation of MMD. The primary purpose of this study was to compare CTA reconstructed with Hybrid-IR, MBIR and DLR with the reference standard DSA. And the secondary purpose was to perform a quantitative analysis of visualization of vessels and signal-to-noise (SNR) between the three image reconstruction methods.

Materials and methods

Patients

This retrospective study was approved by the local institutional review board, and the requirement to obtain written informed consent was waived. From 100 consecutive patients with clinically suspected MMD who underwent CTA between January 2018 and July 2020, 46 patients were excluded due to unavailable datasets or different scanning parameters ([Fig. 1](#)).

CT angiography

CT examination was performed using a UHR CT (Aquilion Precision; Canon Medical Systems) [20]. Our CTA protocols consisted of pre-contrast and contrast-enhanced scan, using helical scan mode with orbital synchronization. The following scanning parameters for pediatric patients (< 15 years old) were used: tube voltage, 100 kV; automatic exposure control tube current; pitch factor, 0.569; rotation speed, 0.75 s; focus size, 0.6×0.6 mm (second smallest of the six focal sizes); super-high-resolution mode (matrix size, 1024×1024 pixels or more and slice thickness, 0.25 mm are available); detector configuration, $0.25 \text{ mm} \times 160$ slices. A 24-gauge catheter was positioned in an antecubital vein and 25 ml of iopromide at 370 mg I/ml (Iopromide; FUJIFILM Toyama Chemical) was injected at 1 ml/s, using the bolus tracking method.

In adult patients, tube voltage was set at 120 kV, tube current was fixed at 260 mA or 310 mA, and 50 ml of iopromide was injected at 4 ml/s using a 20-gauge catheter.

CT images were reconstructed from the stored rawdata with the following parameters: slice thickness, 0.25 mm; slice interval, 0.25 mm; matrix size, 1024×1024 ; and display field-of-view, 210 mm. Reconstruction kernels were FC44 with Hybrid-IR (Adaptive Iterative Dose Reduction 3D, enhanced standard setting; Canon Medical Systems), MBIR (forward-projected model-based iterative reconstruction solution [FIRST, BRAIN CTA standard setting]; Canon Medical Systems), and DLR (Advanced Intelligent Clear-IQ Engine, BODY standard setting; Canon Medical Systems). When this study was conducted, only BODY setting was commercially available for DLR. CTA images were reformatted as maximum intensity projection (MIP) with 10-mm slab thickness in the coronal plane. Pre- and post-contrast images were transferred to a workstation (Ziostation2; Ziosoft) to create whole brain subtracted MIP images.

DSA

DSA was performed by a board-certified neurosurgeon (T.F.) using a biplane DSA system (Artis zee biplane; Siemens Healthineers). Frontal and side views were obtained by hand injection of half-diluted iohexol 300 mg I/ml (Iopaque; FujiPharma, Tokyo,

Japan) using a 4-Fr catheter. A power injector was not used in angiography for MMD in our institute since the mechanical pressure may become harmful for the vulnerable collateral vessels. The injection rate was carefully determined according to the disease severity and the diameter of the vessels to avoid the hemorrhagic complications. In most cases, injection rate for adult patients was 1 ml/s for ICA and external carotid artery (ECA), and 2 ml/s for vertebral artery (VA). In pediatric patients, injection rate was 0.5–1 ml/s for ICA and ECA and 2 ml/s for VA.

Qualitative analysis

Among the enrolled patients, those who underwent both CTA and DSA within 3 months were analyzed. Non-MMD cases and non-affected sides were excluded. Considering that the vascular condition of the left and right sides of the same patient is different in MMD, each hemisphere was treated and evaluated independently. The degree to which the CTA of each reconstruction was visualized compared to the DSA was assessed on a 4-point Likert scale (1, Poor; $\leq 25\%$: 2, Moderate; 26–50%: 3, Good; 51–75%: 4, Excellent; 76–100%) by two board-certified radiologists (A.S. and T.H., 12 and 11 years of neuroradiology experience, respectively) in a blinded manner [6]. CTA slab MIP images were displayed on two 21.3-inch liquid-crystal display monitors (RadiForce

GS521; EIZO) along with DSA. Visualization of terminal ICA occlusion, distal middle cerebral artery (MCA), superficial temporal artery (STA), STA-MCA bypass, and moyamoya vessels were assessed using DSA findings as the reference standard. Hybrid-IR, MBIR, and DLR were evaluated in this order.

We also treated the left and right sides of each patient as the clustered data, then performed the Wilcoxon signed-rank test for clustered data.

Quantitative analysis

STA, which runs within the temporalis muscle fascia, is used for the anastomosis to the cortical segment of MCA during STA-MCA bypass surgery in MMD. Visualization of these arteries and the adjacent muscle is important for operation. To elucidate the effect of the three reconstruction methods for UHR CTA transverse images, edge sharpness of the right and/or left STA-MCA bypass, right and left cortical segment (M4 segment) of the MCA, full width at half maximum (FWHM) of vessel and contrast between vascular and brain tissue as vessel contrast were calculated in 54 patients with suspected MMD ([Fig. 1](#)). This quantitative analysis was performed by one board-certified radiologist (Y.F., with 22 years of neuroradiology experience), who was blinded from the qualitative analysis. Edge sharpness, FWHM, and vessel contrast were obtained from the vessel

profile using the definitions shown in [Fig. 2](#) by setting a linear region of interest (ROI) using ImageJ version 1.53g (National Institutes of Health, Bethesda, MD) on the vessel in the transverse image.

Tissue signal-to-noise ratio ($\text{SNR}_{\text{tissue}}$) for each reconstruction method was calculated by CT number divided by standard deviation by setting ROIs in the right and left temporalis muscle which exist along STA. ROIs were also placed in the pons rather than the basal ganglia, which is often affected by collateral moyamoya vessels.

Radiation dose

The volume CT dose index (CTDI_{vol}) and dose-length product (DLP) for CTA displayed on the CT scanner console was recorded for each patient.

Reconstruction time

The time to reconstruct 621 slices of brain CTA images (scan range, 155.3 mm) of one patient was measured for each of the three reconstruction methods by measuring the time from the start of the reconstruction until 621 images were displayed on the CT console. Because almost no difference in the number of slices for brain CTA images was seen between patients, measurements were performed on a single patient.

Statistical analysis

All analyses were performed using R version 4.0.3 (The R Foundation for Statistical Computing, <https://www.R-project.org>). The Wilcoxon signed-rank test with Bonferroni correction was used to compare the reconstruction methods for each vessel visualization score. The Wilcoxon signed-rank test with Bonferroni correction for data clustered by patient was used to compare the reconstruction methods by using the package “clusrank” (version 1.0-2) [21]. Interobserver agreement for visualization scores was evaluated with the Gwet’s AC1 using the package “rel” (version 1.4.2) with a confidence level of 0.95 [22,23]. One-way analysis of variance with Bonferroni correction was used to test for differences in edge sharpness, FWHM, vessel contrast, and $\text{SNR}_{\text{tissue}}$. $P < 0.05$ was considered indicative of a significant difference.

Results

Patients

Among 100 patients, 46 patients were excluded for the following reasons: (a) different contrast media ($n = 6$), (b) different contrast injection volume or injection rate ($n = 30$), (c) different radiation dose ($n = 8$), and (d) unavailable datasets ($n = 2$). A total

of 54 patients (33 women and 21 men; age range, 3–68 years; mean age, 33.4 ± 19.6 years; 16 pediatric [< 15 years] and 38 adult patients) were enrolled in this study. Of the enrolled patients, 18 patients underwent both CT angiography and digital subtraction angiography (DSA) examinations within a 3-month interval. Of the 36 left and right sides of the 18 patients included in the qualitative assessment, 15 sides on which STA-MCA bypass surgery was performed and 18 affected sides without operation were analyzed visually. The demographic characteristics of patients are shown in [Table 1](#).

Qualitative analysis

Images of 33 sides for which CTA and DSA images were included in the qualitative evaluation ([Fig. 1](#)). Vessel visualization scores are summarized in [Table A.1 in the Supplementary material](#) (vessel visualization score range, 3.5–4.0). Vessel visualization scores did not differ significantly between reconstructions with Hybrid-IR, MBIR and DLR ([Fig 3, 4](#)). Interobserver agreements for both observers were excellent for all vessels and reconstruction methods (AC1 range, 0.9–1.0). Statistical analysis clustered by the patient also showed no significant differences in vessel visualization scores between reconstruction methods. Whole-brain subtracted MIP images of the patients are shown in the [Fig. A.1 and A.2. in the Supplementary material](#).

Quantitative analysis

The edge sharpness of each vessel across all patients are shown in [Fig. 5](#). Edge sharpness for the right and left M4 was significantly higher for Hybrid-IR than for the other reconstructions ($P < 0.05$), with no significant difference between MBIR and DLR. Edge sharpness for STA-MCA bypass was significantly higher for Hybrid-IR than for MBIR ($P = 0.007$), but no significant difference was evident between Hybrid-IR and DLR and between MBIR and DLR.

The FWHM of each vessel across all patients is shown in [Fig. 6](#). FWHM for right and left M4 was significantly lower for Hybrid-IR than for the other reconstructions by 0.1 mm ($P < 0.05$), and no significant difference was seen between MBIR and DLR. FWHM for STA-MCA bypass did not differ significantly between the three reconstruction methods.

The vessel contrasts of each reconstruction method are shown in [Fig. 7](#). Hybrid-IR tended to show higher contrast among the three methods, but no significant difference in vessel contrast was seen, except between Hybrid-IR and DLR at right M4.

The $\text{SNR}_{\text{tissue}}$ in Hybrid-IR, MBIR and DLR were 1.7 ± 0.2 , 2.8 ± 0.4 and 2.7 ± 0.3 for the pons, 2.3 ± 0.8 , 4.1 ± 1.2 and 4.2 ± 1.3 for the right temporalis muscle, and $2.3 \pm$

0.8, 4.0 ± 1.3 and 4.2 ± 1.3 for the left temporalis muscle. Hybrid-IR showed significantly lower $\text{SNR}_{\text{tissue}}$ compared with MBIR or DLR ($P < 0.001$). No significant difference was seen between MBIR and DLR at any tissue noise ratios, but DLR displayed the highest $\text{SNR}_{\text{tissue}}$ in the right and left temporalis muscles.

Radiation dose

Median CTDI_{vol} and DLP values for CTA scans in pediatric patients were 33.5 mGy (range, 25.6–34.5 mGy), 706.5 mGy×cm (range, 553.8–778.6 mGy×cm), respectively. Median CTDI_{vol} and DLP values for CTA scans in adult patients were 53.8 mGy (range, 45.1–53.8 mGy) and 706.5 mGy×cm (range, 952.7–1270.5 mGy×cm), respectively. These values were comparable to those from brain CT images reported as the Japanese diagnostic reference levels [24].

Reconstruction time

The time required to reconstruct 621 head CTAs was 40 s for Hybrid-IR, 2580 s (43 min) for MBIR, and 180 s for DLR. Creating a subtraction MIP requires plain CT volume data and CTA volume data, which doubled the reconstruction time.

Discussion

The current results suggest that DLR is a clinically favorable and feasible reconstruction method to assess MMD, given the high $\text{SNR}_{\text{tissue}}$ of temporalis muscles and feasible reconstruction time in clinical practice with similar vessel visualization score. Hybrid-IR was slightly superior to MBIR and DLR in some quantitative assessments, but its $\text{SNR}_{\text{tissue}}$ was significantly lower among the three methods ($P < 0.001$).

Qualitative evaluation revealed that DLR did not impair vessel visualization. The high visual assessment scores for all reconstructions in this study were partly because both source image and MIP image were created with a matrix size of 1024×1024 pixels, and the smaller pixel size prevents small vessels from becoming blurred.

Quantitative evaluation showed no significant differences in edge sharpness or FWHM between DLR and MBIR in any of the vessels, but Hybrid-IR was superior to DLR in M4. A previous phantom study using conventional-detector CT revealed that MBIR showed the higher spatial resolution at 100 HU and a higher CT number than DLR, and Hybrid-IR showed the worst spatial resolution [25,26]. Meanwhile, mean vessel contrasts in any vessel and reconstruction method were over 100 HU in the present clinical study, but MBIR did not show the highest edge sharpness or lowest FWHM. This

was because images in this study were reconstructed with 1024×1024 pixels using UHR CT and vessel diameter may affect the results of quantitative assessment.

The major differences between DLR and Hybrid-IR reconstructed images were in vessel contrast and $\text{SNR}_{\text{tissue}}$. The vessel contrast of DLR may be lowered by beam hardening correction, which is necessary for DLR to avoid unfavorable artifacts. The FC44 used for Hybrid-IR does not have a beam hardening correction function. The $\text{SNR}_{\text{tissue}}$ of DLR is about twice as high as that of Hybrid-IR, which suggest that DLR may be more suitable for creating 3-dimensional (3D) volume-rendered images and viewing source images of 0.25 mm with 1024×1024 pixels.

CTA radiation doses were less than half of Japanese diagnostic reference levels in adults and about the same in children, depending on age [24], and were comparable to those in previous reports [11]. Current UHR CT has limitations on the tube currents that can be set at each focus size [11]. In the present study, the tube voltage of 100 kV was used to increase the CT values of vessels in pediatric CTA, but the upper limit of the tube current was smaller than 120 kV. The strong noise reduction with DLR is thus useful to reconstruct high-quality images from UHR CT with a limited dose, and the possibility of dose reduction should be considered in the future.

Although the reconstruction time for DLR was slightly longer than that of Hybrid-

IR in this study, the waiting time was still acceptable even in emergency situations to obtain source images and high-quality 3D MIP images on UHR CT. The reconstruction time of MBIR in this study was markedly longer than that of cervical spine CT in a previous study (360 s) [27], probably due to the increase in matrix size from 512 to 1024 pixels and software tuning in development.

In the present study, the rate of contrast injection was limited to 1 ml/s for pediatric MMD patients, who may have brain dysfunction to prevent heat sensations that may cause arousal during sedation or body movements. Heat sensation occurs during contrast injection [28], especially when using higher contrast concentrations [29]. The slow injection rate leads to a lower volume of contrast injection and resultant lower CT values. Nevertheless, moyamoya vessels can be visualized because the UHR CT images offer high spatial resolution, which may improve the CT values of vessels including small collateral vessels.

Several limitations to this study should be kept in mind when interpreting the results. First, the DLR used in this study was optimized for abdominal CT, whereas MBIR was in brain CTA mode. DLR for coronary CTA has been developed and evaluated [30], but DLR for brain CTA was not commercially available at the time of the study. Even though we used DLR optimized for abdominal CT, the results were comparable to those of the brain CTA

mode of MBIR. Second, CT images evaluated in this study were based on 0.25-mm slices with 1024×1024 pixels only. Therefore, whether the same results would be obtained from the three reconstruction methods using conventional-detector CT is unclear. Third, iodine delivery rates differ between children and adults. Iodine delivery rate represents the rate at which iodine delivered into the arterial system and is the main determinant of arterial enhancement in CTA [31]. Contrast enhancement should be evaluated at the same iodine delivery rates, but in this study, the contrast media injection conditions for children were set at 1 ml/s to avoid re-examination due to motion caused by arousal. Peripheral venous access at high injection rate is usually difficult in children, and the venous access at 1ml/s will be beneficial for pediatric MMD patients. Moreover, considering that the visual evaluation was high in all cases, the effect of differences in image acquisition would be limited. Fourth, in the visual assessment, images of different sides of the same patient were treated as independent data, and there is a concern that this may result in overestimation.

Conclusions

UHR CT with three reconstruction methods adequately visualized vessels in

patients with MMD. DLR achieves the same improvement in SNR as a MBIR within a clinically feasible reconstruction time.

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Table 1. The demographics of patients.

	Interval between CTA and DSA < 3 months			
	All patients (N=54)		with MMD (N=18)	
	Child	Adult	Child	Adult
N	16	38	3	15
Sex				
Male	9	12	1	7
Female	7	26	2	8
Patient age (years)	7.0 ± 2.1 (3–11)	44.5 ± 11 (18–68)	5.3 ± 1.2 (4–6)	49.3 ± 10.8 (31–68)
Height (cm)	122.2 ± 12.3	162.7 ± 8.5	111.4 ± 6.1	165 ± 8.7
Weight (kg)	24.6 ± 5.6	57.4 ± 10.2	20.0 ± 1.5	57.4 ± 13.2
Iodine delivery rate (mg I/s)	370	1480	370	1480
Weight-dependent iodine delivery rate (mg I/kg/s)	15.8 ± 3.4	26.5 ± 4.6	18.6 ± 1.4	27.0 ± 6.0

Average values and standard deviations are given for continuous variables. Numbers in parentheses are ranges.

MMD, moyamoya disease; CTA, computed tomography angiography; DSA, digital subtraction angiography.

Figure captions

Fig. 1

Flowchart of inclusion and exclusion criteria in this study. MMD, moyamoya disease; CTA, computed tomography angiography; DSA, digital subtraction angiography. Note that non-affected side (3 sides) represents the normal ICA of unilateral MMD.

Fig. 2

Edge sharpness and FWHM were calculated for the right and/or left STA-MCA bypass, right and left M4. Edge sharpness of the vessel is defined as the slope of a line passing through 20% and 80% of maximum CT value for the Gaussian-fitted line profile. FWHM of the CT value is measured from the fitted profiles. Vessel contrast is calculated as the difference between peak (100%) and baseline (0%) CT value of the fitted profile. M4, cortical segment of middle cerebral artery; FWHM, full width at half maximum.

Fig. 3

A 47-year-old woman with moyamoya disease (post left STA-MCA bypass

surgery). CT angiography with ultra-high-resolution CT. Source image **(a-c)** and 10-mm slab thickness maximum intensity projection **(d-f)** are reconstructed with hybrid-IR, DLR and MBIR. STA, superficial temporal artery; MCA, middle cerebral artery; Hybrid-IR, hybrid iterative reconstruction; DLR, deep learning reconstruction; MBIR, model-based iterative reconstruction.

Fig. 4

A 4-year-old boy with moyamoya disease (post-bilateral STA-MCA bypass surgery). CT angiography with ultra-high-resolution CT. Source image **(a-c)** and whole-brain subtraction maximum intensity projection **(d-f)** are reconstructed with hybrid-IR, MBIR, and DLR. STA, superficial temporal artery; MCA, middle cerebral artery; Hybrid-IR, hybrid iterative reconstruction; MBIR, model-based iterative reconstruction; DLR, deep learning reconstruction.

Fig. 5

Edge sharpness for each reconstruction method for **(a)** right M4 (hybrid-IR, 310.2 ± 120.8 ; MBIR, 228.5 ± 96.2 ; DLR, 229.8 ± 113.6), **(b)** left M4 (hybrid-IR, 324.7 ± 117.8 ; MBIR, 245.5 ± 103.0 ; DLR, 248.2 ± 120.7), and **(c)** STA-MCA bypass (hybrid-

IR, 298.2 ± 127.6 ; MBIR, 219.6 ± 97.5 ; DLR, 248.9 ± 138.3). M4, cortical segment of middle cerebral artery; Hybrid-IR, hybrid iterative reconstruction; MBIR, model-based iterative reconstruction; DLR, deep learning reconstruction; STA, superficial temporal artery; MCA, middle cerebral artery.

Fig. 6

Full width half maximum of vessels for each reconstruction method for **(a)** right M4 (hybrid-IR, $0.859 \text{ mm} \pm 0.174 \text{ mm}$; MBIR, $0.986 \text{ mm} \pm 0.146 \text{ mm}$; DLR, $0.945 \text{ mm} \pm 0.155 \text{ mm}$), **(b)** left M4 (hybrid-IR, $0.851 \text{ mm} \pm 0.144 \text{ mm}$; MBIR, $0.990 \text{ mm} \pm 0.172 \text{ mm}$; DLR, $0.950 \text{ mm} \pm 0.215 \text{ mm}$), and **(c)** STA-MCA bypass (hybrid-IR, $1.440 \text{ mm} \pm 0.491 \text{ mm}$; MBIR, $1.500 \text{ mm} \pm 0.457 \text{ mm}$; DLR, $1.453 \text{ mm} \pm 0.461 \text{ mm}$). Hybrid-IR, hybrid iterative reconstruction; MBIR, model-based iterative reconstruction; DLR, deep learning reconstruction; STA, superficial temporal artery; MCA, middle cerebral artery.

Fig. 7

Vessel contrast for each reconstruction method for **(a)** right M4 (hybrid-IR, 204.9 ± 79.0 ; MBIR, 188.4 ± 75.4 ; DLR, 166.8 ± 75.8), **(b)** left M4 (hybrid-IR, 216.5 ± 78.2 ; MBIR, 204.9 ± 79.0 ; DLR, 179.9 ± 79.7), and **(c)** STA-MCA bypass (hybrid-IR,

323.5 $\pm$ 140.9; MBIR, 255.6 $\pm$ 124.2; DLR, 275.0 $\pm$ 150.0). MCA, middle cerebral artery; STA, superficial temporal artery; Hybrid-IR, hybrid iterative reconstruction; MBIR, model-based iterative reconstruction; DLR, deep learning reconstruction.

Fig A.1.

Whole-brain subtracted MIP images in a 47-year-old woman with moyamoya disease (post-STA-MCA bypass surgery) for the same patient shown in Figure 3. Window width and window level are adjusted manually. CT angiography with ultra-high-resolution CT. Zoomed in images of source image (**a-c**) and whole-brain subtraction MIP (**d-f**) are reconstructed with hybrid-IR, DLR and MBIR. MIP, maximum intensity projection; STA, superficial temporal artery; MCA, middle cerebral artery; Hybrid-IR, hybrid iterative reconstruction; DLR, deep learning reconstruction; MBIR, model-based iterative reconstruction.

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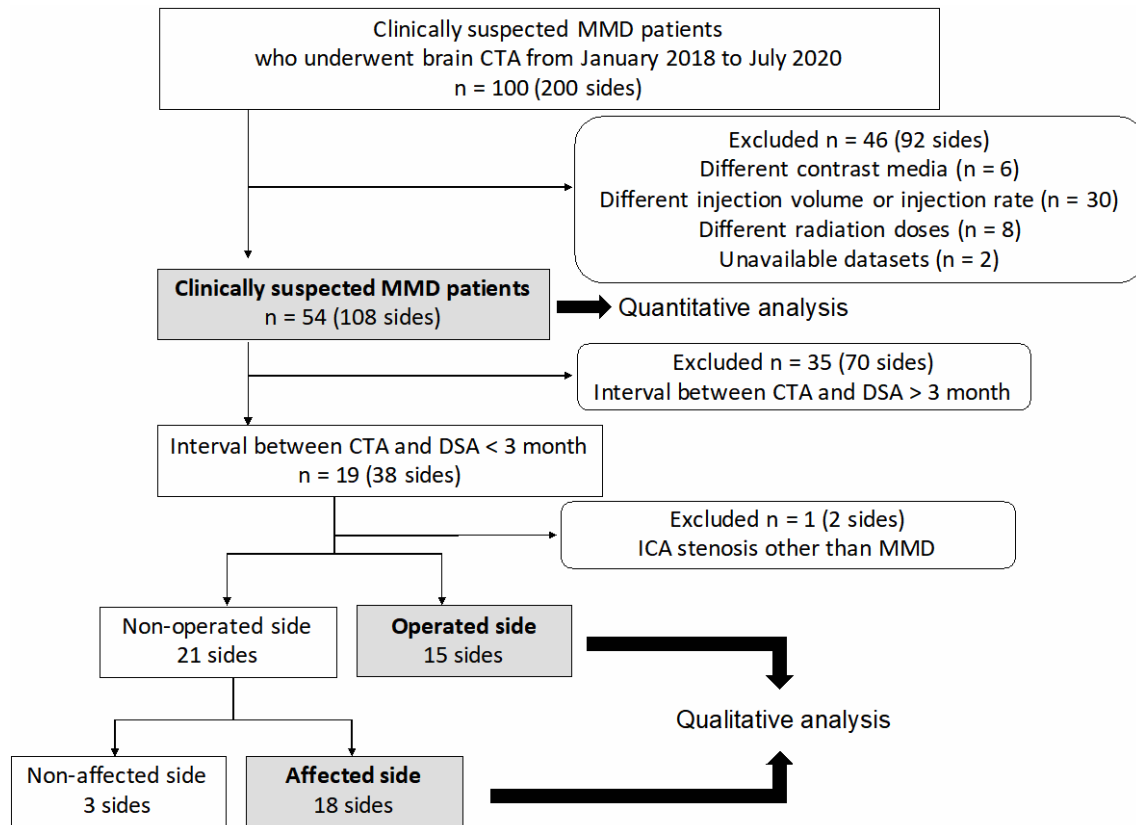


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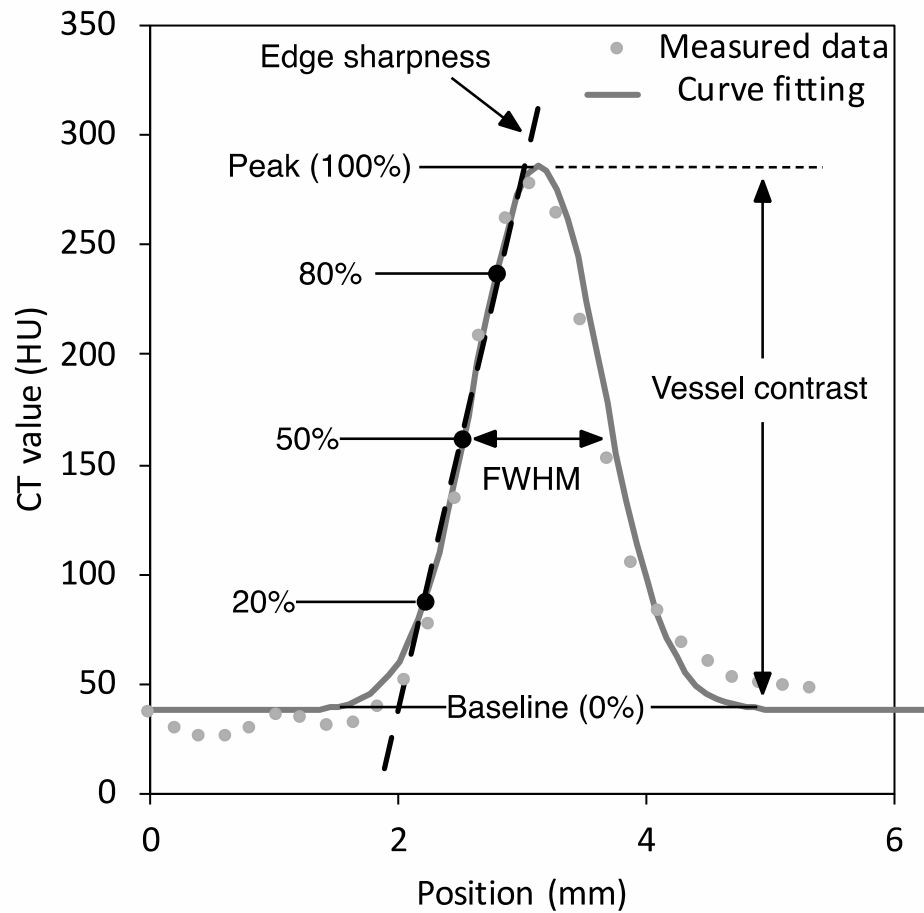


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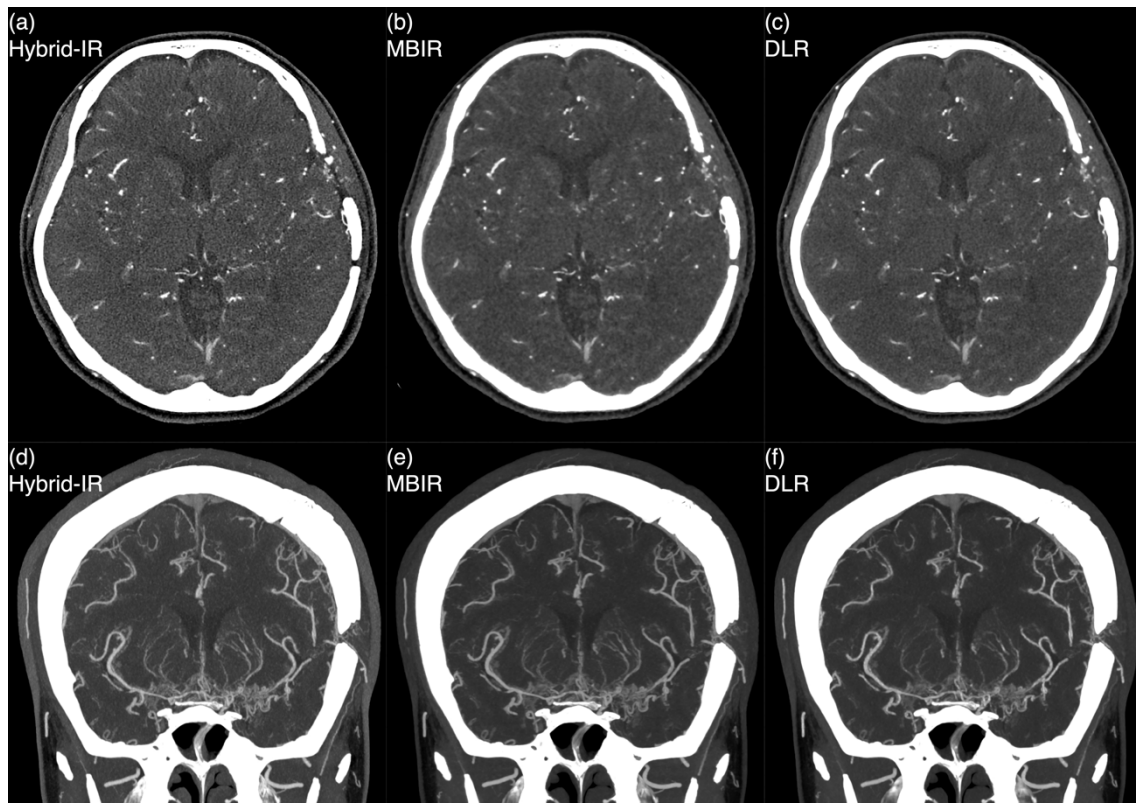


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Images in a 47-year-old woman with moyamoya disease (post STA-MCA bypass surgery). CT angiography with ultra-high-resolution CT. Source image **(a-c)** and 10-mm slab thickness maximum intensity projection **(d-f)** were reconstructed with hybrid-IR, DLR and MBIR. Hybrid-IR, hybrid iterative reconstruction; DLR, deep learning reconstruction; MBIR, model-based iterative reconstruction.

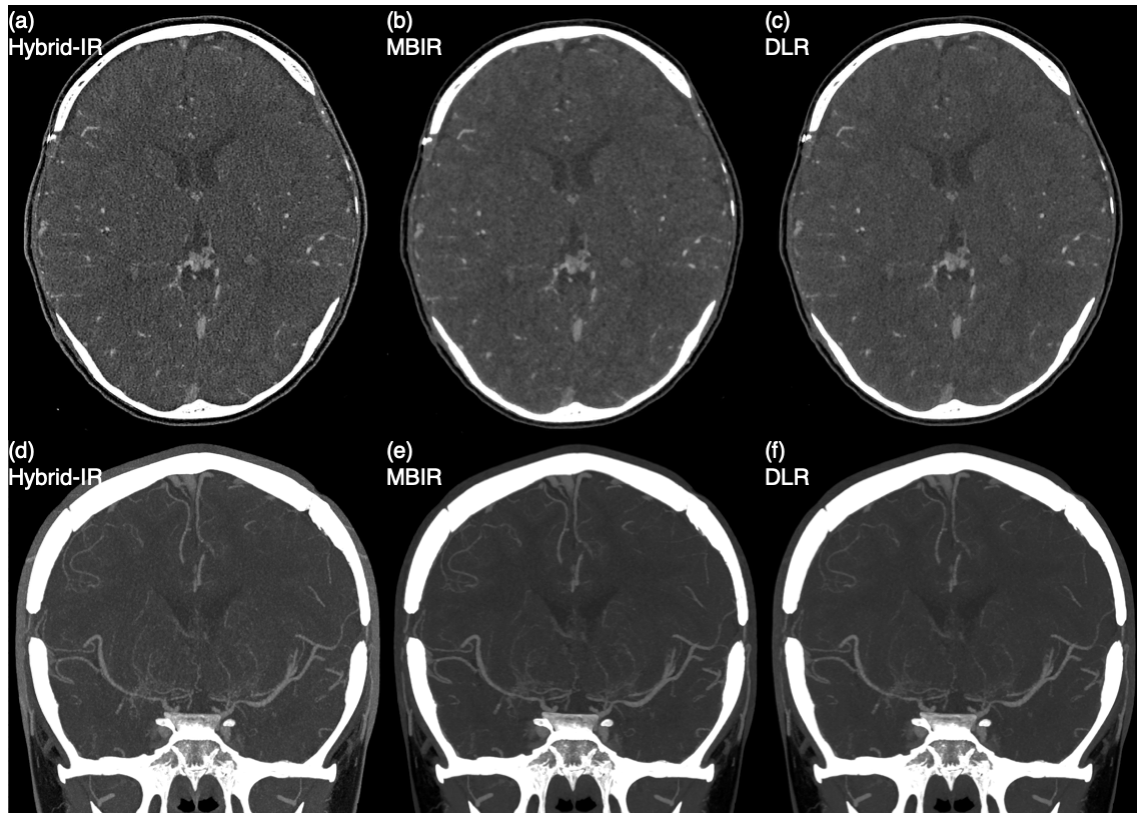


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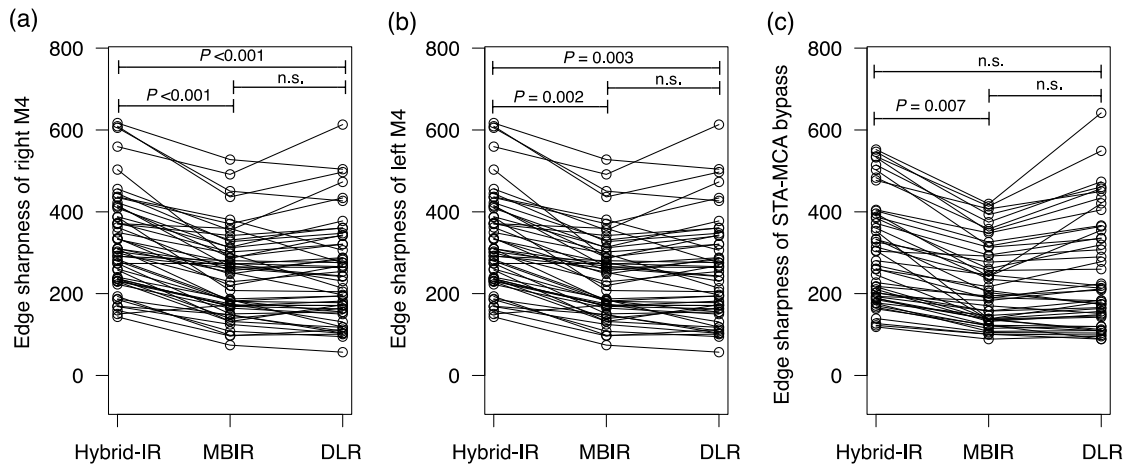


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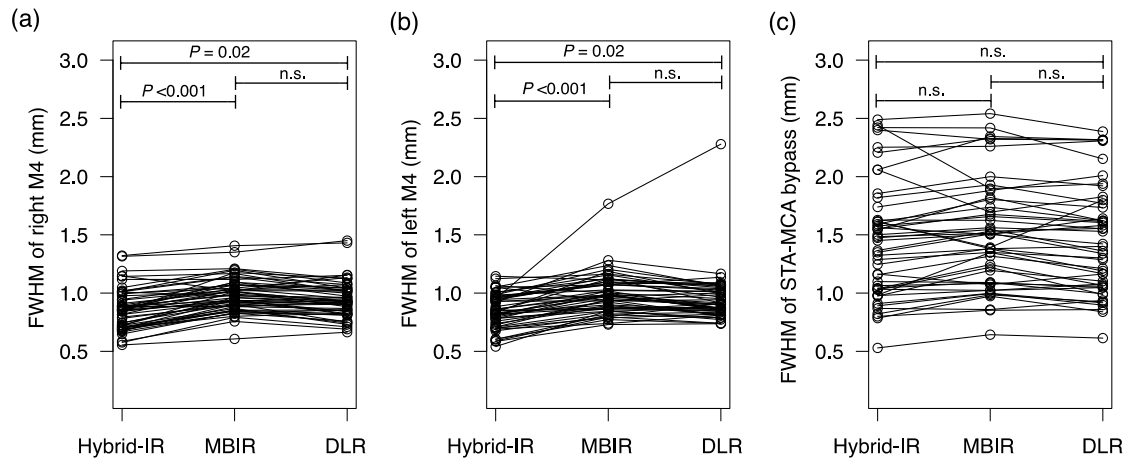


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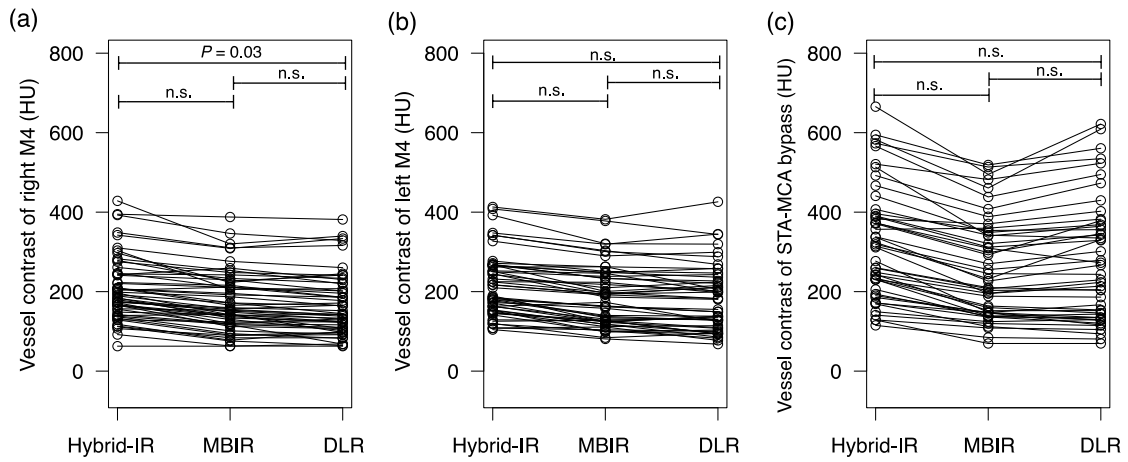


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Supplementary materials

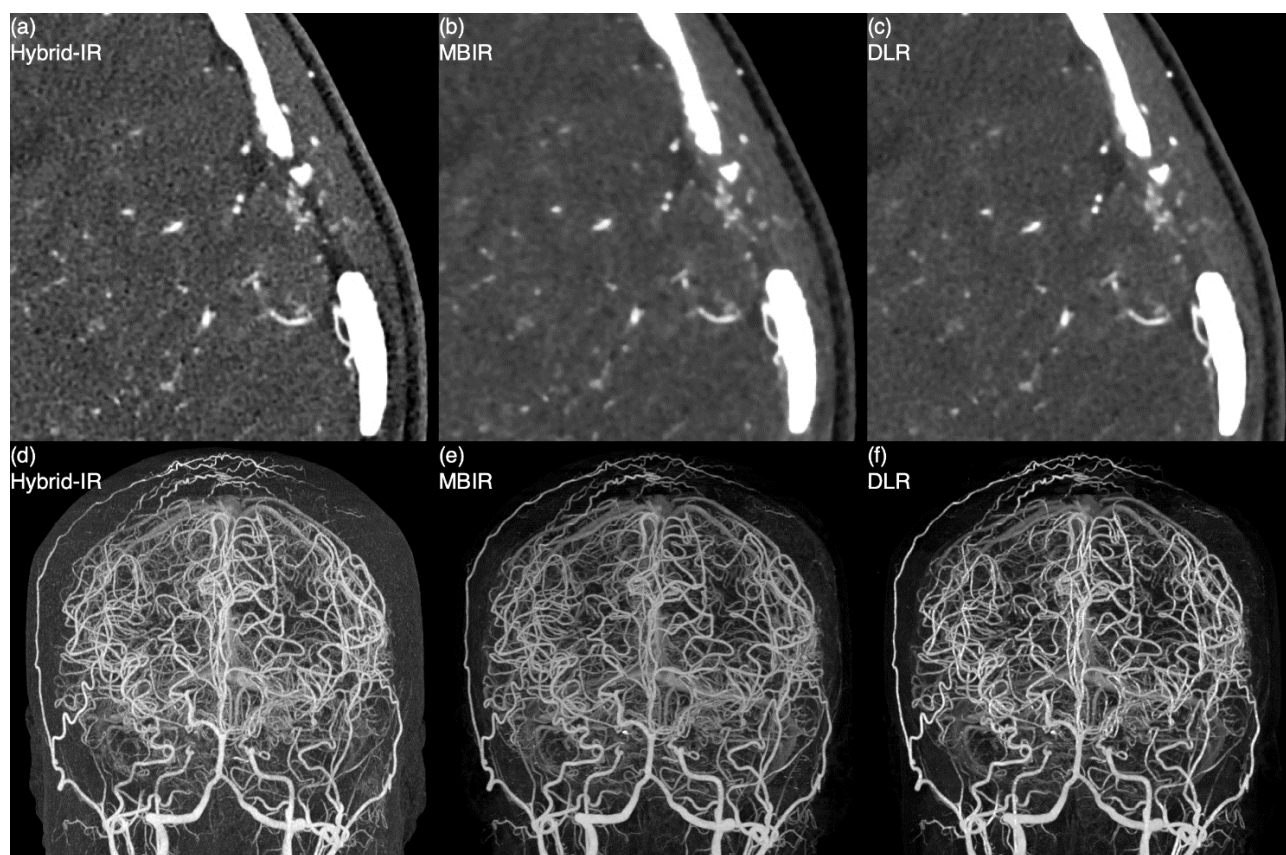


Fig. A.1.

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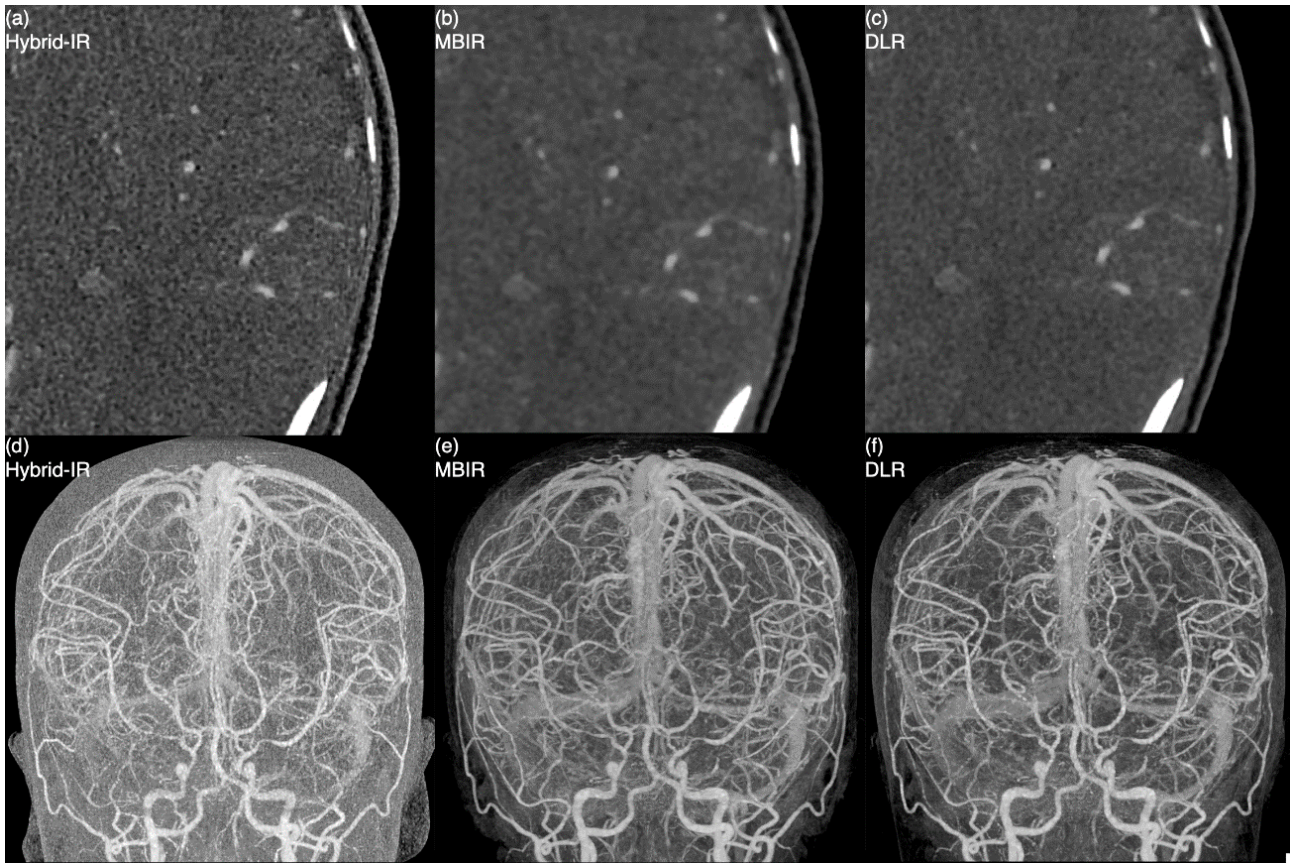


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Whole brain subtracted MIP images in a 4-year-old boy with moyamoya disease (post bilateral STA-MCA bypass surgery) for the same patient shown in Figure 4. Window width and window level were adjusted manually. CT angiography with ultra-high-resolution CT. Zoomed in images of source image **(a-c)** and whole brain subtraction MIP **(d-f)** were reconstructed with hybrid-IR, DLR and MBIR. MIP, maximum intensity projection; STA, superficial temporal artery; MCA, middle cerebral artery; Hybrid-IR, hybrid iterative reconstruction; DLR, deep learning reconstruction; MBIR, model-based iterative reconstruction.

Table A.1.

Scores for qualitative evaluation of vessel visualization.

Left IC top					Left MCA distal				Left STA				Left STA-MCA bypass				Left moyamoya vessel			
Observer	Hybird-IR	MBIR	DLR	<i>p</i> -value	Hybird-IR	MBIR	DLR	<i>p</i> -value	Hybird-IR	MBIR	DLR	<i>p</i> -value	Hybird-IR	MBIR	DLR	<i>p</i> -value	Hybird-IR	MBIR	DLR	<i>p</i> -value
1	3.9 ± 0.2	4.0 ± 0.0	4.0 ± 0.0	0.37	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	NaN	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	NaN	3.8 ± 0.6	3.8 ± 0.6	3.8 ± 0.6	NaN	3.8 ± 0.4	4.0 ± 0.0	3.9 ± 0.3	0.26
2	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	NaN	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	NaN	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	NaN	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	NaN	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	NaN

Right IC top					Right MCA distal				Right STA				Right STA-MCA bypass				Right moyamoya vessel			
Observer	Hybird-IR	MBIR	DLR	<i>p</i> -value	Hybird-IR	MBIR	DLR	<i>p</i> -value	Hybird-IR	MBIR	DLR	<i>p</i> -value	Hybird-IR	MBIR	DLR	<i>p</i> -value	Hybird-IR	MBIR	DLR	<i>p</i> -value
1	3.9 ± 0.3	4.0 ± 0.0	4.0 ± 0.0	0.37	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	NaN	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	NaN	3.7 ± 0.5	3.7 ± 0.5	3.5 ± 0.5	0.37	3.9 ± 0.3	4.0 ± 0.0	3.9 ± 0.3	0.61
2	3.9 ± 0.3	3.9 ± 0.3	3.9 ± 0.3	NaN	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	NaN	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	NaN	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	NaN	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	NaN

Data are expressed as the mean ± standard deviation. A *P*-value of NaN indicates that the scores were the same and therefore not computable. ICA, internal carotid artery; MCA, middle cerebral artery; STA, superficial temporal artery; Hybrid-IR, hybrid iterative reconstruction, MBIR; model-based iterative reconstruction; DLR, deep learning reconstruction; NaN, not a number.