Received:
24 July 2016

Revised:
17 November 2016

Accepted:
13 December 2016

<https://doi.org/10.1259/bjr.20160634>

Cite this article as:

Shirasaka T, Hiwatashi A, Yamashita K, Kondo M, Hamasaki H, Shimomiya Y, et al. Optimal scan timing for artery–vein separation at whole-brain CT angiography using a 320-row MDCT volume scanner. *Br J Radiol* 2017; **90**: 20160634.

FULL PAPER

Optimal scan timing for artery–vein separation at whole-brain CT angiography using a 320-row MDCT volume scanner

¹TAKASHI SHIRASAKA, BS, ²AKIO HIWATASHI, MD, ²KOJI YAMASHITA, MD, ¹MASATOSHI KONDO, MS, ¹HIROSHI HAMASAKI, BS, ¹YAMATO SHIMOMIYA, MS, ¹YASUHIKO NAKAMURA, RT, ³YOSHINORI FUNAMA, PhD and ²HIROSHI HONDA, MD

¹Department of Medical Technology, Division of Radiology, Kyushu University Hospital, Fukuoka, Japan

²Department of Clinical Radiology, Graduate School of Medical Sciences, Kyushu University, Fukuoka, Japan

³Department of Medical Physics, Faculty of Life Sciences, Kumamoto University, Kumamoto, Japan

Address correspondence to: Mr Takashi Shirasaka

E-mail: shirasa@med.kyushu-u.ac.jp

Objective: A 320-row multidetector CT (MDCT) is expected for a good artery–vein separation in terms of temporal resolution. However, a shortened scan duration may lead to insufficient vascular enhancement. We assessed the optimal scan timing for the artery–vein separation at whole-brain CT angiography (CTA) when bolus tracking was used at 320-row MDCT.

Methods: We analyzed 60 patients, who underwent whole-brain four-dimensional CTA. Difference in CT attenuation between the internal carotid artery (ICA) and the superior sagittal sinus (D_{att}) was calculated in each phase. Using a visual evaluation score for the depiction of arteries and veins, we calculated the difference between the mean score for the intracranial arteries and the mean score for the veins (D_{score}). We

assessed the time at which the maximum D_{att} and D_{score} were simultaneously observed.

Results: The maximum D_{att} was observed at 6.0 s and 8.0 s in the arterial-dominant phase and at 16.0 s and 18.0 s in the venous-dominant phase after the contrast media arrival time at the ICA (T_{aa}). The maximum D_{score} was observed at 6.0 s and 8.0 s in the arterial-dominant phase and at 16.0 s in the venous-dominant phase after the T_{aa} . There were no statistically significant differences in D_{att} ($p = 0.375$) or D_{score} ($p = 0.139$) between these scan timings.

Conclusion: The optimal scan timing for artery–vein separation at whole-brain CTA was 6.0 s or 8.0 s for the arteries and 16.0 s for the veins after the T_{aa} .

Advances in knowledge: Optimal scan timing allowed us to visualize intracranial arteries or veins with minimal superimposition.

INTRODUCTION

CT angiography (CTA) is widely used to evaluate the intracranial arteries and veins.^{1–7} Simultaneous enhancement of the arteries and veins on brain CTA allows us to evaluate these structures precisely. However, enhancing the venous structures may interfere with detailed evaluation of the arterial structures and *vice versa*.^{1,2,8,9} Therefore, a demonstration of artery–vein separation at brain CTA¹⁰ is desirable for increasing diagnostic accuracy and improving surgical planning.

The scan timing after the arrival of contrast media (CM) is one factor that affects the separation of intracranial arteries and veins. Matsumoto et al¹⁰ reported a technique for obtaining a separate demonstration of the arterial and venous phases on brain three-dimensional (3D)-CTA at 16-row multidetector CT (MDCT). However, 16-row MDCT is inferior to the novel wide coverage detector CT

in terms of temporal resolution. A 320-row MDCT is thus expected for the artery–vein separation on brain 3D-CTA. This is because the scanner equipped with a detector coverage of 160 mm per rotation leads to a scan of <1.0 s for the whole brain.¹¹ As the degree of cardiac output or the presence of vascular obstruction could affect differences in contrast media arrival in various areas of the cerebral vasculature, we could miss the optimal scan timing with sufficient enhancement for entire intracranial arteries or veins, given such a short scan duration. Therefore, it is important to optimize the scan delay¹² to achieve acceptable CTA using bolus tracking.^{6,13} However, to the best of our knowledge, the optimal scan timing for artery–vein separation at whole-brain CTA using 320-row MDCT has not yet been established. The artery–vein separation is available to analyze temporally repeated whole-brain images like four-dimensional (4D)-CTA. Therefore, the

purpose of this study was to determine the optimal scan timing for artery–vein separation at whole-brain CTA based on whole-brain 4D-CTA images.

METHODS AND MATERIALS

Patients

This prospective study was approved by our institutional review board, and written informed consent was obtained from each patient. The initial candidates for the study were 111 consecutive patients who underwent whole-brain 4D-CTA between April 2012 and March 2013. The inclusion criterion was as follows: patients who underwent whole-brain 4D-CTA for the pre-operative evaluation of intracranial masses. In our clinical practice, we obtained 4D-CTA routinely for the pre-operative evaluation of intracranial masses.¹⁴ The exclusion criteria were as follows: patients with tumours and cerebrovascular disease (occlusion, stenosis, aneurysm, venous sinus thrombosis, moyamoya disease or arteriovenous malformation), multiple metastatic tumours, post-operative status and severe motion artefacts during scanning. In a total of 51 subjects, 27 patients with cerebrovascular disease, 8 patients with multiple metastatic tumours, 10 patients with post-operative status and 6 patients with severe motion artefacts during scanning were excluded owing to the exclusion criteria. Finally, 60 subjects (32 females and 28 males; age range, 17–86 years; median age, 56 years) were enrolled in this study. There were 20 meningiomas, 11 gliomas, 9 schwannomas, 7 lymphomas, 5 pituitary adenomas, 4 metastatic tumours, 1 haemangioblastoma, 1 epidermoid tumour, 1 cavernous malformation and 1 demyelinating disease.

Data acquisition

Whole-brain 4D-CTA examinations were performed using a 320-row MDCT volume scanner (Aquilion™ ONE Vision Edition; Toshiba Medical Systems Corporation, Otawara, Japan). A total of 20 acquisitions were obtained during a total examination time of 60.0 s. Acquisition was started at 5.0 s after the start of CM injection. The first 16 acquisitions were obtained every 2.0 s, and the next 4 acquisitions were obtained every 5.0 s (Figure 1). Wintermark *et al.*¹⁵ studied the optimal temporal sampling interval and CM volume without altering the quantitative accuracy of brain perfusion CT. They reported that with an injection rate of 4 ml s^{-1} and 40 ml of the CM volume, a 3.0-s interval was the maximal allowable temporal sampling, and the time to entrance of the CM into the artery and time to exit of the CM in the vein was about 5 s and 27 s, respectively. On the basis of their results and a prior experimental study,¹⁶ scan start time and duration were determined so as not to miss the attenuation upslope of arteries and downslope of the veins. Images were acquired in volume scan mode with $320 \times 0.5\text{-mm}$ collimation. The first 16 acquisitions were obtained at 80 kVp, 100 mA and a rotation time of 1.0 s. The next four acquisitions were obtained at 80 kVp, 50 mA and a rotation time of 1.0 s. For whole-brain 4D-CTA, the volume of the CM was adjusted according to the patient body weight; all patients received 245 mg kg^{-1} of non-ionic CM (iopamidol) (Iopamiron 370; Bayer HealthCare, Osaka, Japan) injected over a fixed duration of 10.0 s, followed by a 40-ml saline flush injected at the same rate as the CM.^{13,17,18} A dual-shot injector (Nemoto Kyorindo, Tokyo, Japan) was used to inject both the

CM and saline flush *via* a 20-gauge i.v. injection catheter placed in an antecubital vein.

Measurement of CT attenuation

We considered the optimal scan timing for artery–vein separation as the time when the maximum attenuation difference between the intracranial artery and vein was observed. For monitoring the CM arrival at the circle of Willis for 3D-CTA using bolus tracking, we investigated the time from CM arrival at the internal carotid artery (ICA). For quantitative analyses, we investigated the time when the maximum difference in CT attenuation between the intracranial arteries and veins was observed. CT attenuation in the supraclinoid segment of the ICA, and in the superior sagittal sinus (SSS) at the level of the obelion, was considered representative of the vessels and was measured in each acquisition for all patients. Measurement was performed in the contralateral side without a mass lesion. Regions of interest with a diameter of 0.5 mm in the ICA and 2.8 mm in the SSS were placed at the centres of the target vessels by one of the authors (TS) with 13 years' experience as a radiological technologist at the CT console. Time–density curves (TDCs) for the ICA and for the SSS were obtained for each patient (Figure 1). In the TDCs, we basically estimated the contrast media arrival time as the observed time ascent of the ICA attenuation from the baseline.¹⁹ The contrast media arrival time at the ICA (T_{aa}) and contrast media arrival time at the SSS (T_{av}), peak enhancement time at the ICA (T_{pa}) and peak enhancement time at the SSS (T_{pv}) and interval time at the ICA (T_{ia}) and interval time at the SSS (T_{iv}) were defined as follows:

$T_a = 2.0 \text{ s}$ earlier than the acquisition time when CT attenuation exceeded 150 HU and $T_i =$ time difference between T_a and T_p ($T_p - T_a$) (Figure 1). In addition, the transit time (T_{tra}) from the ICA to the SSS was calculated as the difference between T_{pa} and T_{pv} .

The difference in CT attenuation between the ICA and the SSS (D_{att}) was calculated for each acquisition: $D_{att} =$ CT attenuation at the ICA – CT attenuation at the SSS. The arterial-dominant phase was defined as $D_{att} > 0$ and the venous-dominant phase was defined as $D_{att} < 0$ (Figure 1). In the arterial- and venous-dominant phases, the time after T_{aa} was measured when the maximum D_{att} was observed.

Visual evaluation

The degree of simultaneous description of the intracranial arteries or veins in the craniocaudal direction was evaluated at each dominant phase. For qualitative analyses, two board-certified neuroradiologists (AH and KY with 17 and 13 years' experience) independently evaluated the depiction of the major intracranial arteries and veins on the contralateral side without a mass lesion. We extensively selected the vessels in the craniocaudal direction for the evaluation of simultaneous depiction of the vessels. The vessels evaluated were as follows: the intracranial arteries (ICA, M1–M2 segments in the middle cerebral artery, anterior communicating artery, pericallosal artery, vertebral artery and basilar artery tip) and veins (SSS, sphenoparietal sinus and jugular bulb). Maximum intensity projection

Figure 1. A graph showing the scanning protocol for whole-brain four-dimensional CT angiography: the scanning speed was 1.0 s per rotation. First, 16 acquisitions were obtained every 2.0 s. Next, four acquisitions were obtained every 5.0 s. Solid lines are indicating the time-density curve (TDC) for the internal carotid artery (ICA) and dashed lines are indicating the TDC for the superior sagittal sinus (SSS). D_{att} , difference in CT attenuation between ICA and SSS; HU, Hounsfield unit; T_{aa} , contrast media arrival time at the ICA; T_{av} , contrast media arrival time at the SSS; T_{ia} , interval time between T_{aa} and T_{pa} ; T_{iv} , time interval time between T_{av} and T_{pv} ; T_{pa} , peak enhancement time at the ICA; T_{pv} , peak enhancement time at the SSS; T_{tra} , transit time of contrast media from ICA to SSS.

images were reconstructed from the 4D-CTA data for each patient. Of the 20 acquired data sets, the first 2 data sets were used as the mask images for bone subtraction. As a result, the observers reviewed 18 maximum intensity projection images for each patient (Figure 1). The observers were allowed to adjust the window level and window width on the monitor—preset settings of the window level and window width were 400 HU and 800 HU—and no limit was placed on the reading time. For each image, the observers judged the presence or absence of vessels using stereoscopic anteroposterior and lateral views and rated their confidence level using a 4-grade scale where 0 = definitely absent or uncertain (non-diagnostic), 1 = probably present but discontinuous (non-diagnostic), 2 = definitely present and continuous (diagnostic) and 3 = definitely present and continuous with sufficient enhancement (diagnostic). In each phase, the mean scores were calculated for the intracranial arteries and veins, and the mean score of the two readers was also calculated for a comprehensive evaluation. The number of patients with mean scores of >2 for the arteries and veins was also evaluated. The difference between the mean score for the intracranial arteries and the mean score for the veins (D_{score}) was calculated for each phase: $D_{score} = \text{mean score for the intracranial arteries} - \text{mean score for the intracranial veins}$.

Statistical analyses

Statistical analyses were conducted using commercially available software (SPSS® v. 11.0.1; IBM Corp., New York, NY; formerly SPSS Inc., Chicago, IL). Dunnett's test was used to evaluate the D_{att} in each arterial- and venous-dominant phase. We defined the time when the maximum attenuation difference between the ICA and the SSS was observed as the control. The Kruskal–

Wallis test was used for comparison of the D_{score} in each arterial- and venous-dominant phase. When the overall differences were statistically significant, *post hoc* analyses were performed using the Steel test. Differences of $p < 0.05$ were considered statistically significant. The Cohen's kappa test was used to assess the degree of agreement between the observers, with a kappa value of 0.01–0.20 for slight agreement, 0.21–0.40 for fair, 0.41–0.60 for moderate, 0.61–0.80 for substantial and 0.81–1.00 for almost perfect agreement.

RESULTS

Measurement of CT attenuation

Figure 2 shows the mean TDCs of the ICA and SSS after T_{aa} . The ICA and SSS were visualized for 20.0 s after T_{aa} in all patients. Therefore, evaluation was performed within 20.0 s after T_{aa} . T_{ia} was 9.2 ± 1.1 s (mean $\pm$ standard deviation) (range: 6.0–12.0 s). T_{iv} was 9.9 ± 1.2 s (range: 8.0–12.0 s). T_{tra} was 5.7 ± 1.4 s. The arterial-dominant phase continued until 12.0 s, and the venous-dominant phase extended from 12.0 to 20.0 s after T_{aa} . The maximum D_{att} in the arterial-dominant phase was observed at 6.0 s ($D_{att} = 387.1$ HU) followed by the value at 8.0 s ($D_{att} = 364.7$ HU) after T_{aa} . These values were significantly higher than those in the other arterial-dominant phases ($p < 0.001$). However, there was no statistically significant difference in D_{att} between 6.0 s and 8.0 s ($p = 0.38$). The maximum D_{att} in the venous-dominant phase was observed at 16.0 s ($D_{att} = -334.9$ HU) followed by the value at 18.0 s ($D_{att} = -305.8$ HU) after T_{aa} . These values were significantly higher than those in other venous-dominant phases ($p < 0.001$). However, there was no statistically significant difference in D_{att} between 16.0 s and 18.0 s ($p = 0.15$) (Table 1).

Figure 2. Coronal maximum intensity projection images reconstructed from four-dimensional CT angiography data in 78-year-old female: each figure is showing the image at (a) 0 s, (b) 4.0 s, (c) 6.0 s and (d) 10.0 s after contrast media arrival time at the internal carotid artery.

Visual evaluation

With regard to the arteries, 60 (100%) of the 60 patients had a mean score of ≥ 2 at 8.0 s and 10.0 s after T_{aa} . The percentage was 98% at 6 s after T_{aa} . With regard to the veins, 58 (97%) of the 60 patients had a mean score of ≥ 2 at 14.0 s and 16.0 s after T_{aa} (Table 1). Figure 3 shows the images at the time after T_{aa} in the

arterial-dominant phase. The maximum D_{score} in the arterial-dominant phase was observed at 6.0 s ($D_{score} = 1.97$) followed by the value at 8.0 s ($D_{score} = 1.88$) after T_{aa} . These values were significantly higher than those in other arterial-dominant phases ($p < 0.001$). However, there was no statistically significant difference in D_{score} between 6.0 s and 8.0 s ($p = 0.14$). The maximum D_{score} in the venous-dominant phase was observed at 16.0 s ($D_{score} = -1.92$) after T_{aa} . This value was significantly higher than those in other venous-dominant phases ($p < 0.05$) (Table 1). A substantial interrater agreement was observed ($\kappa = 0.613$).

DISCUSSION

The present study was conducted to determine the optimal scan timing for artery-vein separation at whole-brain CTA. For our injection protocol, we recommend a scan timing of 6.0 s or 8.0 s for the arterial phase and 16.0 s for the venous phase after T_{aa} . These scan timings allow the intracranial arteries or veins to be demonstrated in their entirety with minimal superimposition in each phase. This makes it easy to reconstruct 3D volume-rendered images with fusion of the arteries and veins.

In the present study, T_{tra} was 5.7 s, which is in accordance with the findings of a previous study regarding the cerebral circulation time calculated from patients without any vascular pathology.²⁰ Therefore, we considered that our results obtained on the contralateral side without a mass lesion could be adapted to other patients requiring 3D-CTA. For artery-vein separation, a period of at least T_{tra} , the cerebral circulation time, is required between the arterial phase and the venous phase. One could argue that scanning at peak enhancement of the ICA and SSS

Table 1. Difference in CT attenuation between the internal carotid artery and the superior sagittal sinus (D_{att}), number of patients with mean score ≥ 2 and difference between the mean score for the intracranial arteries and the mean score for the veins (D_{score}) in arterial- and venous-dominant phases. Dunnett's test was used to evaluate the D_{att} and the Kruskal-Wallis test followed by Steel test was used to evaluate the D_{score} in each arterial- and venous-dominant phase

Dominant phase	Time after T_{aa} (s)	D_{att} (HU) (mean $\pm$ SD)	p -value	Number of patients with mean score ≥ 2 (%)		D_{score} (mean $\pm$ SD)	p -value
				Intracranial arteries	Veins		
Arterial-dominant phase	0.0	19.0 $\pm$ 37.4	^a	0/60 (0)	0/60 (0)	0.15 $\pm$ 0.27	^a
	2.0	154.8 $\pm$ 71.7	^a	0/60 (0)	0/60 (0)	1.03 $\pm$ 0.42	^a
	4.0	312.1 $\pm$ 87.8	^a	33/60 (55)	0/60 (0)	1.80 $\pm$ 0.39	^a
	6.0	387.1 $\pm$ 85.4	^b	59/60 (98)	0/60 (0)	1.97 $\pm$ 0.51	^b
	8.0	364.7 $\pm$ 114.2	0.375	60/60 (100)	2/60 (3)	1.88 $\pm$ 0.47	0.139
	10.0	245.2 $\pm$ 144.5	^a	60/60 (100)	25/60 (42)	0.97 $\pm$ 0.80	^a
	12.0	9.3 $\pm$ 150.3	^a	40/60 (67)	47/60 (78)	-0.32 $\pm$ 0.81	^a
Venous-dominant phase	14.0	-233.2 $\pm$ 134.7	^a	7/60 (12)	58/60 (97)	-1.50 $\pm$ 0.76	^a
	16.0	-334.9 $\pm$ 96.2	^b	0/60 (0)	58/60 (97)	-1.92 $\pm$ 0.58	^b
	18.0	-305.8 $\pm$ 87.6	0.15	0/60 (0)	38/60 (63)	-1.72 $\pm$ 0.58	^c
	20.0	-223.7 $\pm$ 96.5	^a	0/60 (0)	15/60 (25)	-1.35 $\pm$ 0.59	^a

SD, standard deviation; T_{aa} , contrast media arrival time at the internal carotid artery.

^aIndicates $p < 0.001$.

^bIndicates control.

^cIndicates $p < 0.05$.

Figure 3. A graph showing mean time-density curves (TDCs) up to 20.0 s from contrast media arrival time at the internal carotid artery (ICA): the solid line is the TDC for the ICA and dashed line is the TDC for the superior sagittal sinus (SSS). HU, Hounsfield unit.

can achieve stronger enhancement; however, D_{att} is reduced (Figure 2 and Table 1). As a result, simultaneous opacification of the arteries and veins occurs, making it difficult to separate these vessels on brain CTA. In addition, it is difficult to visualize small vessels with 3D volume rendering using the threshold technique if D_{att} is small. On the other hand, the arterial phase can be obtained before CM arrival in the veins and the venous phase can be obtained after the first pass through the arteries; however, the optimal timing for enhancing the arteries and veins is lost (Figure 2 and Table 1). Smit et al²¹ reported the usefulness of a simultaneous evaluation technique for the arteries and veins with their CT perfusion data. However, their technique is associated with modest venous superimposition in the evaluation of the circle of Willis. We therefore conducted the present study to determine the optimal timing for the arterial and venous phases at whole-brain CTA.

In our quantitative and qualitative assessment, the optimal arterial scan timing should be present between 6.0 s and 8.0 s after T_{aa} . However, owing to the limited temporal resolution of 4D-CTA as performed in this study (1.0-s acquisition, 1.0-s gap), a more precise value could not be determined. Further studies with higher temporal resolutions are recommended, although this may be difficult owing to concerns regarding radiation exposure. In the arterial-dominant phase, attenuation of the vein begins to rise after around 6.0 s from T_{aa} . The D_{att} continues in equilibrium until after 8.0 s, a period of 2.0 s, from T_{aa}

(Figure 2). Therefore, we could scan the arterial phase in the time period between 6.0 s and 8.0 s from T_{aa} . If the artery-vein separation was performed for the whole-brain CTA using bolus tracking at different scanners with a narrow detector (e.g. 64-row MDCT), we could adapt the scan timing in consideration of a period of 2.0 s. Das et al²² reported that cerebral CTA images with significant reduction of venous contamination could be achieved with a low CM dose using a 320-detector CT. In their study, they determined the peak time of the CTA scan using the test bolus technique. However, there was no quantitative evaluation of the degree of venous contamination relating to the D_{att} . We evaluated the difference in attenuation between the intracranial arteries and veins. If our results were adapted to the test bolus technique, whole-brain CTA could achieve an additional reduction of venous contamination.

In this study, we investigated the optimal scan timing for the case of bolus tracking. A previous study preferred a fixed delay time for bolus tracking owing to the lack of consistency in optimal triggering.²³ In another study of brain CTA at 320-row MDCT, a test bolus was also used for a similar reason.²² However, the combination of our proposed scan timing and detection of the CM arrival at the ICA, confirming the ascent of the ICA attenuation from the baseline, could resolve this defect in 3D-CTA with bolus tracking. We injected the CM for over 10.0 s, which is in line with the T_{ia} and T_{iv} . Awai et al¹⁷ reported that the time from CM arrival to peak enhancement at the aorta

depends on the injection duration. In the brain, inflow to the venous system is simply due to outflow from the arteries. Therefore, our results showing that the TDC of the SSS corresponded to that of the ICA with T_{tra} are in agreement with the findings of a previous study. Based on our results, we believe that we can achieve optimal CTA with good artery–vein separation, if we can accurately detect CM arrival at the ICA using bolus tracking.

The present study suffers from a number of limitations. First, we analyzed 4D-CTA data scanned with a tube voltage of 80 kVp. Our results were analyzed under sufficient vascular attenuation, because CT attenuation can be influenced by tube voltage.^{24,25} If these results were adapted to the 3D-CTA commonly employed for higher tube voltage in clinical cases, we would need to perform additional studies of the CM dose to maintain sufficient enhancement. Second, we assessed the scan timing for artery–vein separation using a fixed CM injection duration of 10.0 s. Our results showed that appropriate setting of the scan timing allowed observation of the intracranial arteries or veins in their entirety, with minimal superimposition in each phase, when this

short CM injection duration was adapted. If different injection durations were employed, we would need to perform additional studies. Third, we did not directly assess the differentiation between the artery and vein. However, we considered this acceptable evaluation because our assessment was performed on the basis of each sufficient depiction of the major intracranial arteries and veins. Additional studies are needed to evaluate more distal arteries limited by the opacification of veins. Fourth, we tried to separate intracranial arteries and veins for patients without vascular lesions. We will try to investigate the optimal timing for patients with arteriovenous malformations, aneurysms or stenoses.

CONCLUSION

The optimal scan timing to achieve good artery–vein separation at whole-brain CTA using 320-row MDCT with a CM injection duration of 10.0 s was found to be 6.0 s or 8.0 s for the arteries and 16.0 s for the veins after CM arrival at the ICA. These recommended scan timings allow the intracranial arteries or veins to be demonstrated in their entirety with minimal superimposition in each phase.

REFERENCES

- Alberico RA, Patel M, Casey S, Jacobs B, Maguire W, Decker R. Evaluation of the circle of Willis with three-dimensional CT angiography in patients with suspected intracranial aneurysms. *AJNR Am J Neuroradiol* 1995; **16**: 1571–8; discussion 1579–80.
- Jayaraman MV, Mayo-Smith WW, Tung GA, Haas RA, Rogg JM, Mehta NR, et al. Detection of intracranial aneurysms: multi-detector row CT angiography compared with DSA. *Radiology* 2004; **230**: 510–18. doi: <https://doi.org/10.1148/radiol.2302021465>
- Pozzi-Mucelli F, Bruni S, Doddi M, Calgaro A, Braini M, Cova M. Detection of intracranial aneurysms with 64 channel multi-detector row computed tomography: comparison with digital subtraction angiography. *Eur J Radiol* 2007; **64**: 15–26. doi: <https://doi.org/10.1016/j.ejrad.2007.02.018>
- Lubicz B, Levivier M, Francois O, Thoma P, Sadeghi N, Collignon L, et al. Sixty-four-row multisection CT angiography for detection and evaluation of ruptured intracranial aneurysms: interobserver and intertechnique reproducibility. *AJNR Am J Neuroradiol* 2007; **28**: 1949–55. doi: <https://doi.org/10.3174/ajnr.A0699>
- McKinney AM, Palmer CS, Truwit CL, Karagulle A, Teksam M. Detection of aneurysms by 64-section multidetector CT angiography in patients acutely suspected of having an intracranial aneurysm and comparison with digital subtraction and 3D rotational angiography. *AJNR Am J Neuroradiol* 2008; **29**: 594–602. doi: <https://doi.org/10.3174/ajnr.A0848>
- Lell MM, Anders K, Uder M, Klotz E, Ditt H, Vega-Higuera F, et al. New techniques in CT angiography. *Radiographics* 2006; **26**(Suppl. 1): S45–62. doi: <https://doi.org/10.1148/rg.26si065508>
- Enterline DS, Kapoor G. A practical approach to CT angiography of the neck and brain. *Tech Vasc Interv Radiol* 2006; **9**: 192–204. doi: <https://doi.org/10.1053/j.tvir.2007.03.003>
- Takeyama N, Ohgiya Y, Hayashi T, Takahashi T, Takasu D, Nakashima J, et al. Comparison of different volumes of saline flush in the assessment of perivenous artefacts in the subclavian vein during cervical CT angiography. *Br J Radiol* 2011; **84**: 427–34. doi: <https://doi.org/10.1259/bjr/86966343>
- Takeyama N, Ohgiya Y, Itokawa H, Takahashi Y, Obuchi M, Shinjyo H, et al. Comparison of 40 and 60 milliliters of contrast in assessment of the carotid artery by computed tomography angiography. *Acta Radiol* 2008; **49**: 1068–78. doi: <https://doi.org/10.1080/02841850802403748>
- Matsumoto M, Kodama N, Sakuma J, Sato S, Oinuma M, Konno Y, et al. 3D-CT arteriography and 3D-CT venography: the separate demonstration of arterial-phase and venous-phase on 3D-CT angiography in a single procedure. *AJNR Am J Neuroradiol* 2005; **26**: 635–41.
- Orrison WW Jr, Snyder KV, Hopkins LN, Roach CJ, Ringdahl EN, Nazir R, et al. Whole-brain dynamic CT angiography and perfusion imaging. *Clin Radiol* 2011; **66**: 566–74. doi: <https://doi.org/10.1016/j.crad.2010.12.014>
- Takeyama N, Kuroki K, Hayashi T, Sai S, Okabe N, Kinebuchi Y, et al. Cerebral CT angiography using a small volume of concentrated contrast material with a test injection method: optimal scan delay for quantitative and qualitative performance. *Br J Radiol* 2012; **85**: e748–55. doi: <https://doi.org/10.1259/bjr/31882420>
- Tamura Y, Utsunomiya D, Sakamoto T, Hirai T, Nishiharu T, Urata J, et al. Reduction of contrast material volume in 3D angiography of the brain using MDCT. *AJR Am J Roentgenol* 2010; **195**: 455–8. doi: <https://doi.org/10.2214/AJR.07.2969>
- Hiwatashi A, Togao O, Yamashita K, Kikuchi K, Yoshimoto K, Mizoguchi M, et al. Evaluation of glioblastomas and lymphomas with whole-brain CT perfusion: comparison between a delay-invariant singular-value decomposition algorithm and a Patlak plot. *J Neuroradiol* 2016; **43**: 266–72. doi: <https://doi.org/10.1016/j.neurad.2016.01.147>
- Wintermark M, Smith WS, Ko NU, Quist M, Schnyder P, Dillon WP. Dynamic perfusion CT: optimizing the temporal resolution and contrast volume for calculation of perfusion CT parameters in stroke patients. *AJNR Am J Neuroradiol* 2004; **25**: 720–9.
- Murayama K, Katada K, Nakane M, Toyama H, Anno H, Hayakawa M, et al. Whole-brain

- perfusion CT performed with a prototype 256-detector row CT system: initial experience. *Radiology* 2009; **250**: 202–11. doi: <https://doi.org/10.1148/radiol.2501071809>
17. Awai K, Hiraishi K, Hori S. Effect of contrast material injection duration and rate on aortic peak time and peak enhancement at dynamic CT involving injection protocol with dose tailored to patient weight. *Radiology* 2004; **230**: 142–50. doi: <https://doi.org/10.1148/radiol.2301021008>
 18. Tatsugami F, Awai K, Takada H, Yoshikawa S, Takeda Y, Morita H, et al. Reduction of interpatient variability of arterial enhancement using a new bolus tracking system in 320-detector computed tomographic coronary angiography. *J Comput Assist Tomogr* 2013; **37**: 79–83. doi: <https://doi.org/10.1097/rct.0b013e318278e996>
 19. Awai K, Hachio A, Nakayama Y, Kusunoki S, Liu D, Hatemura M, et al. Simulation of aortic peak enhancement on MDCT using a contrast material flow phantom: feasibility study. *AJR Am J Roentgenol* 2006; **186**: 379–85. doi: <https://doi.org/10.2214/AJR.04.1591>
 20. Siebert E, Diekmann S, Masuhr F, Bauknecht HC, Schreiber S, Klingebiel R, et al. Measurement of cerebral circulation times using dynamic whole-brain CT-angiography: feasibility and initial experience. *Neurol Sci* 2012; **33**: 741–7. doi: <https://doi.org/10.1007/s10072-011-0785-z>
 21. Smit EJ, Vonken EJ, van der Schaaf IC, Mendrik AM, Dankbaar JW, Horsch AD, et al. Timing-invariant reconstruction for deriving high-quality CT angiographic data from cerebral CT perfusion data. *Radiology* 2012; **263**: 216–25. doi: <https://doi.org/10.1148/radiol.11111068>
 22. Das K, Biswas S, Roughley S, Bhojak M, Niven S. 3D CT cerebral angiography technique using a 320-detector machine with a time-density curve and low contrast medium volume: comparison with fixed time delay technique. *Clin Radiol* 2014; **69**: e129–35. doi: <https://doi.org/10.1016/j.crad.2013.10.021>
 23. Pekkola J, Kangasniemi M. Imaging of blood flow in cerebral arteries with dynamic helical computed tomography angiography (DHCTA) using a 64-row CT scanner. *Acta Radiol* 2009; **50**: 798–805. doi: <https://doi.org/10.1080/02841850903055629>
 24. Ertl-Wagner BB, Hoffmann RT, Bruning R, Herrmann K, Snyder B, Blume JD, et al. Multi-detector row CT angiography of the brain at various kilovoltage settings. *Radiology* 2004; **231**: 528–35. doi: <https://doi.org/10.1148/radiol.2312030543>
 25. Luo S, Zhang LJ, Meinel FG, Zhou CS, Qi L, McQuiston AD, et al. Low tube voltage and low contrast material volume cerebral CT angiography. *Eur Radiol* 2014; **24**: 1677–85. doi: <https://doi.org/10.1007/s00330-014-3184-z>