Radiology

# Timing-Invariant Reconstruction for Deriving High-Quality CT Angiographic Data from Cerebral CT Perfusion Data[1]

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**Purpose:** To suggest a simple and robust technique used to reconstruct high-quality computed tomographic (CT) angiographic images from CT perfusion data and to compare it with currently used CT angiography techniques.

**Materials and Methods:** Institutional review board approval was waived for this retrospective study, which included 25 consecutive patients who had had a stroke. Temporal maximum intensity projection (tMIP) CT angiographic images were created by using prior temporal filtering as a timing-insensitive technique to produce CT angiographic images from CT perfusion data. The temporal filter strength was optimized to gain maximal contrast-to-noise ratios (CNRs) in the circle of Willis. The resulting timing-invariant (TI) CT angiography was compared with standard helical CT angiography, the arterial phase of dynamic CT angiography, and nonfiltered tMIP CT angiography. Vascular contrast, image noise, and CNR were measured. Four experienced observers scored all images for vascular noise, vascular contour, detail of small and medium arteries, venous superimposition, and overall image quality in a blinded side-by-side comparison. Measurements were compared with a paired *t* test; $P \leq .05$ indicated a significant difference.

**Results:** On average, optimized temporal filtering in TI CT angiography increased CNR by 18% and decreased image noise by 18% at the expense of a decrease in vascular contrast of 3% when compared with nonfiltered tMIP CT angiography. CNR, image noise, vascular noise, vascular contour, detail visibility of small and medium arteries, and overall image quality of TI CT angiograms were superior to those of standard CT angiography, tMIP CT angiography, and the arterial phase of dynamic CT angiography at a vascular contrast that was similar to that of standard CT angiography. Venous superimposition was similar for all techniques. Image quality of the arterial phase of dynamic CT angiography was rated inferior to that of standard CT angiography.

**Conclusion:** TI CT angiographic images constructed by using temporally filtered tMIP CT angiographic data have excellent image quality that is superior to that achieved with currently used techniques, but they suffer from modest venous superimposition.



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Computed tomographic (CT) perfusion imaging is increasingly used in the quantitative assessment of tissue perfusion (1). Currently, its main application is evaluation of brain ischemia, usually in the setting of acute stroke (1,2). Such brain ischemia protocols typically combine three separate examinations. First, nonenhanced CT is performed to exclude hemorrhage, to evaluate early signs of manifest ischemia, and to detect old lesions. Second, perfusion CT is performed to localize acute ischemia and define at-risk tissue. Third, CT angiography is performed to evaluate vascular disease.

If CT angiographic findings could be derived from perfusion CT data, a separate CT angiographic acquisition could be omitted or limited to the extracranial portions of the carotid artery. Advantages of this approach include reduction of both the total radiation dose and the amount of contrast material needed. In addition, the quality of standard CT angiography is strongly affected by the timing of imaging. Variations in cardiac output or vascular obstructions that lead to differences in contrast material arrival in various areas of the cerebral vasculature may result in suboptimal CT angiography. Data acquired during perfusion CT have the potential to overcome the problems with contrast material arrival because multiple images are acquired over time and cover the whole period of contrast material inflow into the brain. Previously, only limited portions of the brain could be covered by perfusion CT. With the newest generation of scanners, however, whole-brain coverage is feasible.

With the increase of spatial coverage in modern CT scanners, dynamic evaluation of vascular contrast material in- and outflow on perfusion CT source images has become feasible. Evaluation of the perfusion CT source images over time is referred to as *dynamic* (3), *four-dimensional* (4), or *multiphase* (5) CT angiography. This dynamic evaluation tool is currently available in several commercial workstations and offers promising applications for functional vascular imaging (3,4,6,7). However, dynamic CT angiography was found to be inferior to standard CT angiography with respect to detail visibility and image noise (5,8), making dynamic CT angiography less suited for use in the evaluation of vascular morphology. In addition, routine evaluation of dynamic CT angiography data sets is cumbersome in clinical practice.

In this study, we suggest a simple and robust technique with which to reconstruct high-quality CT angiographic data from CT perfusion data and compare it with currently used approaches.

## Materials and Methods

In CT perfusion imaging, a series of low-dose scans are performed over time after intravenous injection of contrast material. Usually, 5–10-mm-thick sections are reconstructed, from which perfusion parameters are calculated by using local time-attenuation curves. The perfusion parameters, such as cerebral blood volume, mean transit time, and cerebral blood flow, are used to determine information about regional tissue perfusion. However, the data also contain information about the vasculature. To extract this information, the data have to be reconstructed as a sequence of thin-section data sets. The simplest way to provide this four-dimensional data is to present it as a dynamic angiography sequence (dynamic CT angiography or four-dimensional CT angiography). Although it allows for functional vascular imaging, dynamic CT angiography is less suited for use in the evaluation of vascular morphology: since individual CT perfusion scans are performed at a low dose level, image noise of the thin-section data is substantial, and image quality of dynamic CT angiography is limited. Furthermore, in case of vascular obstruction, contrast material may not arrive simultaneously in the various areas of the cerebral vasculature. For this reason, scrolling over time is required to evaluate vascular morphology.

Rather than simply displaying the four-dimensional data, we suggest a technique to reconstruct a three-dimensional CT angiography data set from this four-dimensional data to yield a high-quality overview of the full cerebral vasculature. A possible CT angiographic reconstruction technique would be temporal maximum intensity projection (tMIP), which displays maximal enhancement over time (9). This tMIP operation results in a three-dimensional

### Advance in Knowledge

- Timing-invariant (TI) CT angiography of the brain is insensitive to contrast material arrival time and yields image quality that is superior to that achieved with conventional or dynamic CT angiography in the evaluation of vascular morphology.

### Implications for Patient Care

- TI CT angiography makes additional standard CT angiography of the brain superfluous; thus, it may help reduce the total radiation dose and the amount of contrast material needed.
- Standard CT angiography can be omitted for indications in which only the cerebral vasculature has to be evaluated.

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**Abbreviations:**
CNR = contrast-to-noise ratio
ROI = region of interest
TI = timing invariant
tMIP = temporal maximum intensity projection

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Potential conflicts of interest are listed at the end of this article.

CT angiography volume that is referred to as *tMIP CT angiography*. Its advantages include high vascular enhancement (temporal maximum) and insensitivity to delayed contrast material arrival (collateral arteries, vascular obstruction), as shown in Figure 1. A feature of tMIP CT angiography is the enhancement of both the arteries and the veins: On one hand, this allows simultaneous evaluation of arterial and venous disease. On the other hand, venous structures might obscure arterial disease or vice versa. A limitation of tMIP CT angiography is its high susceptibility to noise because the maximum intensity projection preferentially displays positive outliers because of noise and the maxima because of contrast enhancement.

We propose to reduce noise by using a temporal filter before the creation of tMIP CT angiographic data. It is important to note that this filter operates in the temporal direction only and that no spatial filtering is applied. We refer to temporal-filtered tMIP CT angiography as timing-invariant (TI) CT angiography because it combines the good noise properties of standard CT angiography with the timing invariance of tMIP CT angiography.

### Patient Group

Approval for this retrospective study was waived by the ethics committee of the University Medical Center Utrecht. We selected the records of 25 consecutive patients from the clinical database; these patients underwent scanning at our center for the indication of stroke between December 2009 and March 2010. Inclusion criteria were as follows: Both CT angiographic data and CT perfusion data from the same study were available, and the volume of CT perfusion included the circle of Willis. Exclusion criteria were as follows: Patients had metal artifacts, severe motion artifacts resulting from motion during scanning, and severe interscan motion during CT perfusion that resulted in nonoverlapping volumes. All scans were performed with a 128–detector row scanner (iCT; Philips, Cleveland, Ohio).

### CT Perfusion Data Acquisition

For CT perfusion, 40 mL of nonionic contrast material (Ultravist 300; Bayer Schering Pharma, Berlin, Germany) was injected into the antecubital vein at a rate of 6 mL/sec and was followed by a 40-mL saline flush. Images were acquired in the axial mode by using 128 × 0.625-mm collimation and a z-flying focal spot. A total of 25 acquisitions were obtained by using 80 kVp, 150 mAs, and a rotation time of 0.33 second (volume CT dose index, 5.8 mGy per acquisition) every 2 seconds during a total of 48 seconds. Acquisitions started together with contrast material injection.

To reconstruct the vasculature, cone-beam reconstructions of slightly overlapping data were performed at 1.0-mm section thickness and 0.8-mm reconstruction increment with a 512 × 512 matrix and the brain standard reconstruction kernel. This typically resulted in a volume of 512 × 512 × 80 × 25 voxels. The scans over time were registered to the first scan on a subpixel level by using rigid registration based on a skull mask (Elastix; Image Sciences Institute, Utrecht, the Netherlands) (10).

### Standard CT Angiography

For CT angiography, 50 mL of nonionic contrast material was injected into the antecubital vein at a rate of 6 mL/sec and followed by a 40-mL saline flush. Scans were performed in the helical mode by using 128 × 0.625-mm collimation and a pitch of 0.3. Images were obtained by using 120 kVp, 150 mAs, and a 0.4-second rotation time (volume CT dose index, 19.5 mGy). Reconstruction of overlapping data was performed with a 0.9-mm section thickness and a 0.45-mm reconstruction increment with a 512 × 512 matrix and the standard reconstruction kernel. Timing of the CT angiographic acquisition to the arterial phase was based on the peak contrast enhancement in the CT perfusion data. For the purpose of this study, the volume of CT angiography was manually clipped to the volume of CT perfusion.

### Dynamic CT Angiography

Dynamic CT angiography primarily consisted of the 25 thin-section scans performed during CT perfusion. Because dynamic CT angiography could not be blinded to the other techniques (four-dimensional data vs three-dimensional data), the arterial phase of dynamic CT angiography was evaluated. This arterial phase was defined as the data set in which the largest portion of the circle of Willis was maximally enhanced. An experienced observer (E.J.S.) selected this phase. Data evaluation was performed at a four-dimensional research workstation (iX Viewer; Image Sciences Institute) that enabled us to scroll through the data sets with interactive multiplanar reformation and maximum intensity projection settings (arbitrary planes and slab thicknesses) and switch between phases to identify the one with optimum arterial contrast enhancement.

### tMIP CT Angiography

The tMIP CT angiographic images were reconstructed from CT perfusion data at the four-dimensional research workstation. The tMIP operation is used to evaluate enhancement over time for each voxel in the resulting three-dimensional data volume and to select the time point with maximum enhancement. The result is a three-dimensional data set, referred to as tMIP CT angiography, in which enhancing structures, such as vessels, are preferentially displayed. However, the temporal maximum is also displayed in the background (brain tissue) and leads to increased CT numbers in these regions because of the effect that the voxel with the highest CT number over time is always displayed. This is similar to the effect described for standard maximum intensity projections of noisy data sets (11).

### TI CT Angiography

The TI CT angiographic images were reconstructed from CT perfusion data at the four-dimensional research workstation by using a temporal filter prior to the creation of tMIP CT angiographic images. This filter has the task of reducing image noise by using a Gaussian filter along the time axis. This smoothing filter operates in only the temporal direction; therefore, it tends to reduce maximum contrast enhancement if the filter is too strong.

**Figure 1**

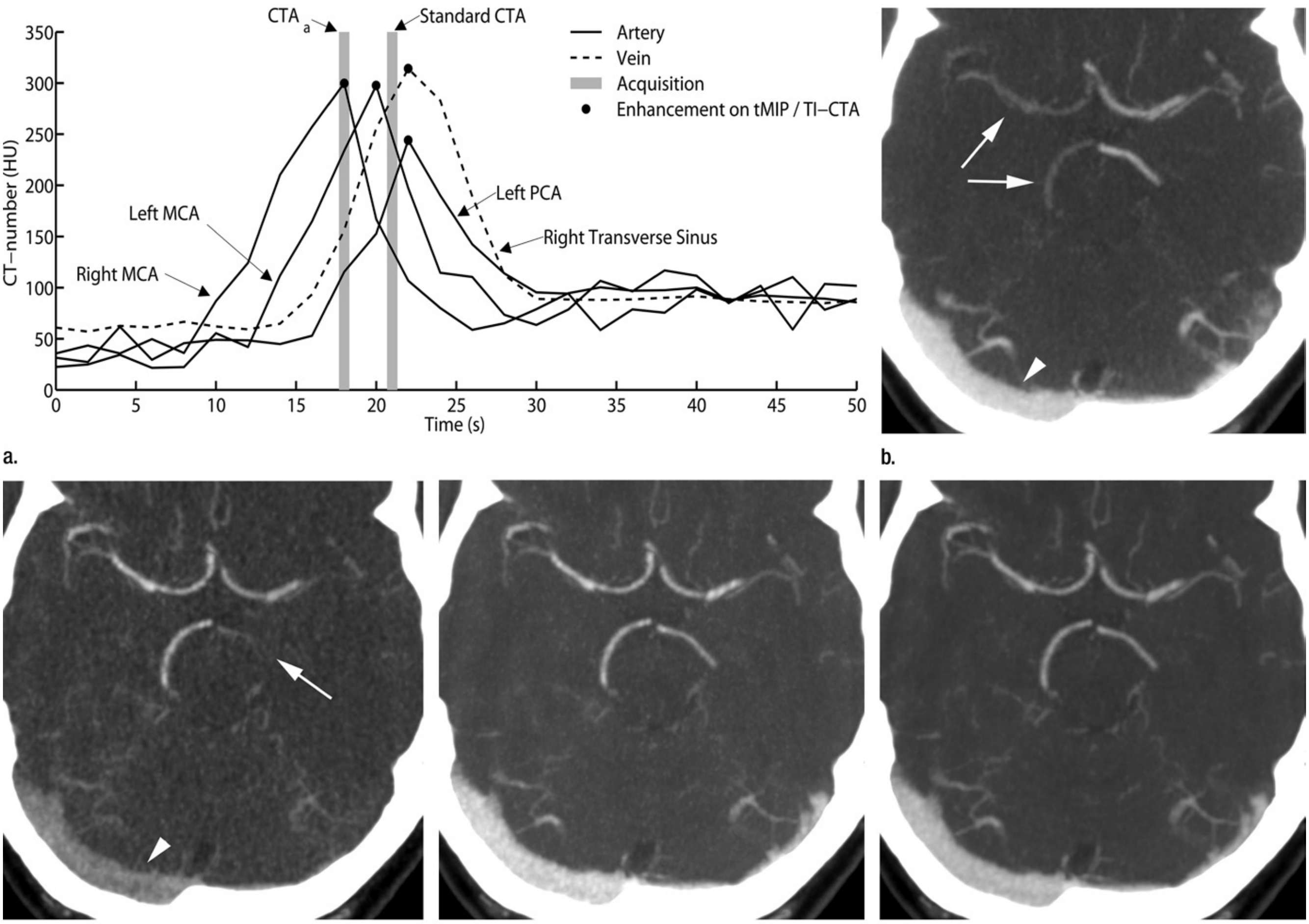


**Figure 1:** Images show effect of delayed contrast material arrival in a 44-year-old woman with a bilateral fetal variant of the posterior cerebral artery who had left-sided internal carotid artery dissection with collateral filling and distal left posterior cerebral artery occlusion. **(a)** Time-attenuation curves of the right middle cerebral artery *(MCA)*, left middle cerebral artery, left posterior cerebral artery *(PCA),* and right transverse sinus. *CTA* = CT angiography, $CTA_a$ = dynamic CT angiography, *TI-CTA* = TI CT angiography. **(b)** Standard CT angiographic image. (CT angiography is timed at the left middle cerebral artery at approximately 21 seconds). **(c)** Dynamic CT angiographic image obtained in the arterial phase at 18 seconds. **(d)** tMIP CT angiographic image. **(e)** TI CT angiographic image. In **a**, standard CT angiography and the arterial phase of dynamic CT angiography show contrast enhancement at one moment in time (bars). Since arteries need not be enhanced simultaneously, arterial enhancement (arrows) may vary on standard CT angiographic images and dynamic CT angiographic images acquired in the arterial phase. In **d** and **e**, maximal enhancement over time is seen, resulting in timing-invariant angiography with high enhancement of arteries and veins. Arteriovenous overlap will result in partial venous enhancement at standard CT angiography and the arterial phase of dynamic CT angiography (arrowheads) (window center, 150 HU; window width, 500 HU; maximum intensity projection, 5 mm).

However, the filter does not operate in the spatial domain, so spatial resolution of the images is not affected. Given optimized filter settings, TI CT should combine the good noise properties of standard CT angiography with the timing invariance of tMIP CT angiography.

### Filter Optimization for TI CT angiography

For TI CT angiography, we first determined the optimum setting of the Gaussian filter to maximize the contrast-to-noise ratio (CNR) in the circle of Willis. The filter strength along the temporal axis is described as the standard deviation of the Gaussian filter (measured in seconds). We calculated CNR in various vessels of the circle of Willis for filter strengths varying from 1 to 6 seconds in 0.25-second steps.

An experienced observer (E.J.S.) manually placed 10 regions of interest (ROIs) in the circle of Willis of every patient by using tMIP CT angiographic images. Five of these vascular ROIs were placed in medium arteries (≥2 mm diameter), and five were placed in small arteries (<2 mm diameter). A reference ROI of 25 × 25 mm was placed in a homogeneous region in the white matter of one occipital lobe.

The positions of these ROIs were stored for each patient so that measurement of average CT numbers ± standard deviation could be performed automatically as the filter strength was varied. Vascular contrast and CNR were determined per ROI for all filter strengths. Vascular contrast was defined as the arterial enhancement (average CT number in vascular ROI) minus the parenchymal enhancement (average CT number in reference ROI), and CNR was defined as the vascular contrast divided by the image noise (standard deviation of CT numbers in the reference ROI). To be able to better compare the effect of filtering between the various vessels, we defined relative CNR as the CNR of filtered tMIP CT angiography divided by the CNR of nonfiltered tMIP CT angiography.

### Statistical Analysis of Optimal Filter Strength

The optimal filter strength was determined in each of the 10 vascular ROIs per patient. It was defined as the filter strength that yielded maximal relative CNR. We calculated median and interquartile range for the optimum filter strength across the 250 vascular ROIs of all patients and performed the same calculations separately for medium and small arteries (125 ROIs each). Average vascular contrast, image noise, and relative CNR were determined separately for medium and small arteries and for all arteries together.

Statistical equivalence between the optimal temporal filter strengths of medium and small arteries was tested with the two-tailed Mann-Whitney test ($P \leq .05$). Optimal relative CNR was compared between medium and small arteries by using an independent two-sample two-tailed $t$ test (unequal variance, $P \leq .01$). Earlier, normality had been tested with the Kolmogorov-Smirnov test ($P > .05$).

### Comparison of TI CT Angiography, tMIP CT Angiography, Arterial Phase Dynamic CT Angiography, and Standard CT Angiography

We compared image quality of standard CT angiography with that of dynamic CT angiography performed in the arterial phase, unfiltered tMIP CT angiography, and TI CT angiography. TI CT angiography was calculated by using a single filter setting that was determined from the median optimum filter strength across all arteries.

Vascular contrast, image noise, and CNR were determined for each technique by using the same ROIs that were used for filter optimization and corresponding ROIs at identical locations for standard CT angiography.

For visual evaluation, four clinical observers (one neuroradiologist [I.C.v.d.S.], two radiology residents [J.W.D, A.D.H.], and one researcher with more than 2.5 years of experience in the evaluation of CT angiography examinations [T.v.S.]) were individually presented with random and blinded pairs of images acquired with the various CT angiographic techniques. All possible pairwise comparisons of the four CT angiographic techniques (six combinations for each of the 25 patients) were presented to the observers. The sequence in which image pairs were presented was randomized with respect to patients and imaging technique. To determine intraobserver variability, these 150 pairs were presented twice to all observers (with new randomization). To reduce potential sources of bias, the observers were not informed about which and how many angiographic techniques were compared. Images were scored for *(a)* vascular noise (noise affecting vasculature), *(b)* vascular contour (sharpness of the definition of the vascular contour), *(c)* detail visibility of medium arteries (middle cerebral artery segment 1, anterior cerebral artery segment 1, and posterior cerebral artery segment 1), *(d)* detail visibility of small arteries (anterior communicating artery, posterior communicating artery, and middle cerebral artery segment 3), *(e)* venous superimposition (superimposition of venous structures that are disturbing when evaluating the circle of Willis) and *(f)* overall image quality. Scoring was performed at the four-dimensional research workstation by using a three-point scale (better, equal, or worse image quality). The observers were instructed to select a preferred image when possible and to score images as equal only if they could not make a decision.

### Statistical Analysis of Comparison Study

Vascular contrast, image noise, and CNR measurements were tested for statistical equivalence with a paired per-patient two-tailed $t$ test. A $P$ value of less than .05 was considered to indicate a significant difference. Statistical analyses were performed by using software (SPSS, version 16.0; SPSS, Chicago, Ill).

Observer scores from the visual evaluation were expressed as the overall percentage of cases (with range between observations) in which one technique was found to be better than, equal to, or worse than another technique. Inter- and intraobserver agreement were determined by using κ statistics with correction for chance when scored on a three-point scale. Intraobserver κ values were calculated for each observer individually (four κ values), and interobserver κ values were calculated for each observer pair (24 κ values). Inter- and intraobserver agreement were expressed as mean κ value between observers with the accompanying range. A κ value of 0.81–1.00 indicated very good agreement; a κ value of 0.61–0.80, good agreement; a κ value of 0.41–0.60, moderate agreement; a κ value of 0.21–0.40, fair agreement; and a κ value of 0.20 or lower, poor agreement (12).

## Results

### Patient Group

After meeting the inclusion criteria, 36 consecutive patients were selected from the clinical database. Of these patients, six were excluded because of metal artifacts, three were excluded because of severe motion artifacts on CT perfusion images resulting from motion during scanning, and two were excluded because of severe interscan motion during CT perfusion that resulted in nonoverlapping volumes. The remaining 25 patients in this study had an

**Table 1**

**Results of Contrast-to-Noise Measurements**

| Measurement | Standard CT Angiography | Dynamic CT Angiography in the Arterial Phase | tMIP CT Angiography | TI CT Angiography |
|---|---|---|---|---|
| Vascular contrast (HU) | 170.6 ± 57.1 | 204.0 ± 51.5*† | 181.2 ± 50.2† | 173.8 ± 45.6 |
| Image noise (HU) | 13.5 ± 1.3† | 21.1 ± 2.5*† | 11.8 ± 1.1*† | 9.7 ± 1.0* |
| CNR | 12.6 ± 4.2† | 9.8 ± 2.9*† | 15.5 ± 4.6*† | 17.9 ± 4.7* |

Note.—Data are means ± standard deviations. TI CT angiography was found to have the highest CNR and lowest image noise when compared with dynamic CT angiography in the arterial phase, tMIP CT angiography, and standard CT angiography at vascular contrast similar to standard CT angiography (P = .69). P values were calculated on a per-patient basis with a two-tailed paired t test (P < .001).

* Significant difference compared with CT angiography.

† Significant difference compared with TI CT angiography.

average age of 60 years ± 17 and consisted of 15 men (60%) and 10 women (40%).

## Filter Optimization

Figure 2 displays the vascular contrast, image noise, and relative CNR as a function of the temporal filter strength. As expected, both vascular contrast and image noise decrease with increasing filter strength. However, we found that at modest filtering, the reduction of image noise was more pronounced than the reduction of vascular contrast. Because CNR is the ratio of vascular contrast to image noise, CNR increases with modest filtering. In contrast, with strong filtering, the decline in vascular contrast dominates and CNR decreases (Fig 2). For our protocol, the optimal filter strength (the standard deviation of the temporal Gaussian filter at which CNR was maximal) was 1.5 seconds (interquartile range, 1.5–2.0 seconds). This optimal filter strength was identical for medium and small arteries, and their increase in CNR was similar ($P = .21$). Averaged over all vessels, image noise decreased 18% while vascular enhancement decreased only by 3% at optimized temporal filtering. This resulted in an 18% increase in CNR compared with unfiltered tMIP CT angiography.

Given these results, the temporal filter strength of TI CT angiography for the comparison study was fixed at 1.5 seconds. Typically, reconstruction of TI CT angiography took 24 seconds on a standard personal computer with a 2.66-GHz quad CPU Core2 processor.

**Figure 2**

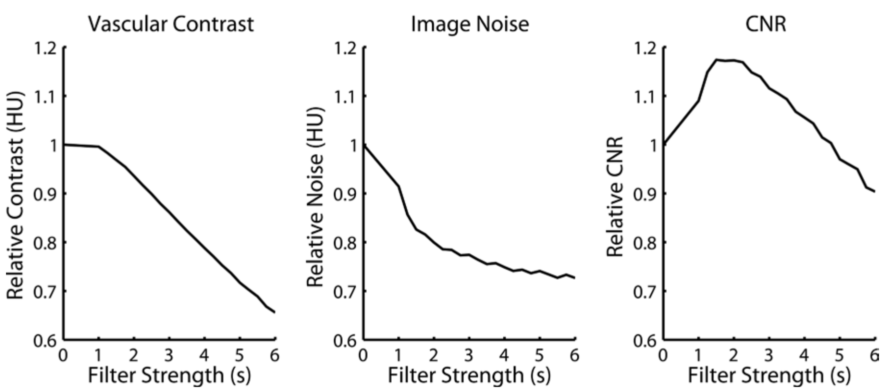


**Figure 2:** Graphs show results of temporal filter optimization (average across all arteries). Modest temporal filtering results in an increase in CNR since reduction of image noise is more pronounced than reduction of vascular contrast. Optimal temporal filter strength was defined at maximal CNR and was found at a filter strength of 1.5 seconds in our protocol. Optimal filter strength was independent of vessel size and varied little between patients.

## Comparison Study

Table 1 shows the results of the CNR measurements, and Table 2 and Figure 3 show the results of visual evaluation for the various CT angiographic techniques. TI CT angiography was found to have higher CNR (17.9 vs 12.6, 43% higher, $P < .01$) and lower image noise (9.7 HU vs 13.5 HU, 28% lower, $P < .01$) at similar vascular contrast as compared with standard CT angiography ($P = .69$). TI CT angiography was also rated to have less vascular noise (80.5% of cases; range, 60.0%–96.0%), better vascular contour (84.0% of cases; range, 68.0%–96.0%), better detail visibility of medium arteries (84.0% of cases; range, 72.0%–96.0%), better detail visibility of small arteries (85.0% of cases; range, 72.0%–96.0%), and better overall image quality (84.5% of cases; range, 72.0%–96.0%) than standard CT angiography. For this, overall the observers had good inter- and intraobserver agreement. On a case-by-case basis, in only one patient was standard CT angiography rated superior to TI CT angiography in the majo. (This was due to contrast agent injection difficulties.) The arterial phase of dynamic CT angiography was found to be inferior with respect to CNR (9.8 vs 12.6, 22% decrease, $P < .01$) and image noise (21.1 HU vs 13.5 HU, 56% increase, $P < .01$) but had higher vascular contrast (204.0 HU vs 170.6 HU, 20% increase, $P < .01$) than standard CT angiography.

**Figure 3**

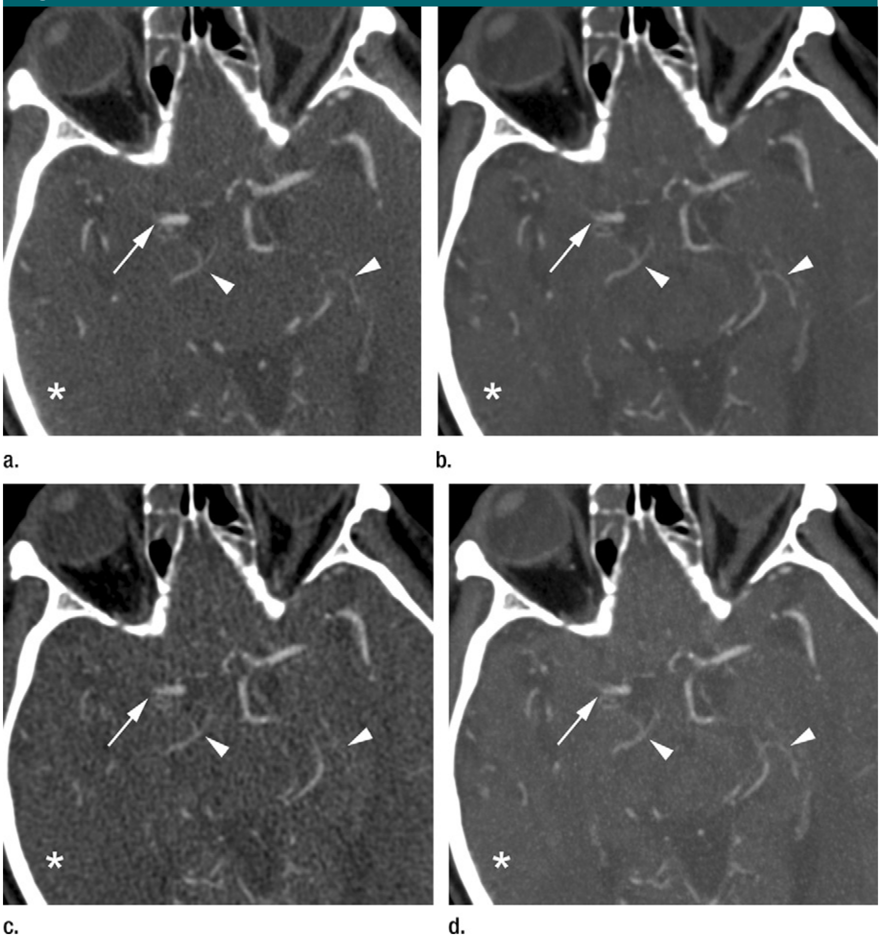


**Figure 3:** Comparison of **(a)** standard CT angiography, **(b)** TI CT angiography, **(c)** the arterial phase of dynamic CT angiography, and **(d)** tMIP CT angiography in a 76-year-old man with a right-sided middle cerebral artery occlusion (arrow). CNR, image noise (*), vascular noise, vascular contour, detail visibility of small and medium arteries, and overall image quality of TI CT angiography were superior to those of standard CT angiography, tMIP CT angiography, and the arterial phase of dynamic CT angiography at a vascular contrast that was similar to that of standard CT angiography. Venous enhancement (arrowheads) was present for all CT angiographic techniques (window center, 150 HU; window width, 500 HU; maximum intensity projection, 5 mm).

The arterial phase of dynamic CT angiography was also rated to have more vascular noise (95.5% of cases; range, 88.0%–100.0%), worse vascular contour (92.0% of cases; range, 84.0%–100.0%), worse detail visibility of medium (91.0% of cases; range, 76.0%–100.0%) and small (91.5% of cases; range, 84.0%–100.0%) arteries, and worse overall image quality (92.5% of cases; range, 80.0%–100.0%) than standard CT angiog raphy. For this, overall the observers had very good inter- and intraobserver agreement. Compared with tMIP CT angiography, the optimized temporal filtering in TI CT angiography resulted in improved image quality with superior CNR (17.9 vs 15.5, 18% increase, $P < .01$) and image noise (9.7 HU vs 11.8 HU, 18% decrease, $P < .01$) at only minor loss of vascular contrast (173.8 HU vs 181.2 HU, 3% decrease, $P < .01$). TI CT angiography was rated superior in nearly all cases (on average, 95%) with very good inter- and intraobserver agreement. Standard CT angiography and tMIP CT angiography were rated similarly; CT angiography was superior in about half of cases, and inter- and intraobserver agreement were only moderate and fair, respectively. For all combinations of techniques, venous superimposition was rated with poor interobserver agreement. For example, when comparing TI CT angiography with standard CT angiography, one observer rated venous superimposition to be superior at standard CT angiography in all cases, while another observer preferred TI CT angiography in 96% of cases. Intraobserver agreement, however, apart from one observer, varied from good to very good.

## Discussion

This study was performed to develop and test a simple and robust technique with which to reconstruct high-quality CT angiographic findings from CT perfusion data. We found that modest temporal filtering results in an increase in CNR compared with nonfiltered tMIP CT angiography because the reduction of image noise is more pronounced than the reduction of vascular contrast. Furthermore, we calculated the optimal filter strength individually for a large number of small and medium arteries and found little overall variation in optimal filter strength. In fact, the optimal filter strength appeared to be independent of artery size and varied little between patients with use of a fixed injection protocol. Thus, rather than define an optimal filter strength for each patient or vessel, an identical temporal filter strength could be chosen for all patients without jeopardizing image quality. This makes the technique fast and fully automatic. Our results further show that TI CT angiography has an image quality that is superior to the other angiographic techniques with respect to CNR, image noise, vascular noise, vascular contour, detail visibility of small and medium arteries, and overall image quality, while arterial enhancement is similar to standard CT angiography. These findings suggest that TI CT angiography could replace additional CT angiography if the vasculature of interest is within the volume scanned at CT perfusion.

**Table 2**

**Results of Visual Evaluation**

| | | | | |
|---|---|---|---|---|
| **A: TI CT Angiography vs Standard CT Angiography** | | | | |
| | TI CT Angiography Better (%)* | Equal (%)* | Interobserver Agreement† | Intraobserver Agreement† |
| Vascular noise | 80.5 (60.0–96.0) | 1.0 (0.0–4.0) | 0.59 (0.28–0.94) | 0.66 (0.34–1.00) |
| Vascular contour | 84.0 (68.0–96.0) | 1.0 (0.0–4.0) | 0.69 (0.46–1.00) | 0.73 (0.46–1.00) |
| Details | | | | |
| Medium arteries | 84.0 (72.0–96.0) | 1.0 (0.0–8.0) | 0.71 (0.46–0.94) | 0.72 (0.46–1.00) |
| Small arteries | 85.0 (72.0–96.0) | 1.0 (0.0–8.0) | 0.71 (0.46–1.00) | 0.72 (0.46–1.00) |
| Venous superimposition | 47.0 (0.0–96.0) | 17.0 (0.0–52.0) | −0.03 (−0.50 to 0.64) | 0.67 (0.28–1.00) |
| Overall image quality | 84.5 (72.0–96.0) | 0.0 (0.0–0.0) | 0.71 (0.46–0.94) | 0.75 (0.46–1.00) |
| **B: TI CT Angiography vs Arterial Phase of Dynamic CT Angiography** | | | | |
| | CT Angiography Better (%)* | Equal (%)* | Interobserver Agreement† | Intraobserver Agreement† |
| Vascular noise | 99.0 (96.0–100.0) | 1.0 (0.0–4.0) | 0.97 (0.88–1.00) | 0.97 (0.94–1.00) |
| Vascular contour | 99.5 (96.0–100.0) | 0.0 (0.0–0.0) | 0.99 (0.94–1.00) | 0.99 (0.94–1.00) |
| Details | | | | |
| Medium arteries | 100.0 (100.0–100.0) | 0.0 (0.0–0.0) | 1.00 (1.00–1.00) | 1.00 (1.00–1.00) |
| Small arteries | 100.0 (100.0–100.0) | 0.0 (0.0–0.0) | 1.00 (1.00–1.00) | 1.00 (1.00–1.00) |
| Venous superimposition | 56.0 (0.0–100.0) | 5.5 (0.0–24.0) | 0.01 (−0.50 to 1.00) | 0.76 (0.10–1.00) |
| Overall image quality | 100.0 (100.0–100.0) | 0.0 (0.0–0.0) | 1.00 (1.00–1.00) | 1.00 (1.00–1.00) |
| **C: TI CT Angiography vs tMIP CT Angiography** | | | | |
| | TI CT Angiography Better (%)* | Equal (%)* | Interobserver Agreement† | Intraobserver Agreement† |
| Vascular noise | 95.0 (88.0–100.0) | 2.0 (0.0–4.0) | 0.87 (0.70–1.00) | 0.87 (0.82–0.94) |
| Vascular contour | 94.5 (84.0–100.0) | 1.0 (0.0–4.0) | 0.85 (0.70–1.00) | 0.87 (0.76–1.00) |
| Details | | | | |
| Medium arteries | 95.5 (88.0–100.0) | 1.5 (0.0–4.0) | 0.87 (0.70–1.00) | 0.87 (0.82–0.94) |
| Small arteries | 95.0 (88.0–100.0) | 2.0 (0.0–4.0) | 0.86 (0.70–0.94) | 0.85 (0.76–0.94) |
| Venous superimposition | 50.0 (0.0–100.0) | 32.5 (0.0–100.0) | −0.08 (−0.50 to 0.94) | 0.51 (0.04–0.76) |
| Overall image quality | 95.0 (88.0–100.0) | 1.5 (0.0–4.0) | 0.86 (0.64–1.00) | 0.85 (0.76–0.76) |
| **D: Standard CT Angiography vs Arterial Phase of Dynamic CT Angiography** | | | | |
| | CT Angiography Better (%)* | Equal (%)* | Interobserver Agreement† | Intraobserver Agreement† |
| Vascular noise | 95.5 (88.0–100.0) | 1.0 (0.0–4.0) | 0.87 (0.70–1.00) | 0.91 (0.88–1.00) |
| Vascular contour | 92.0 (84.0–100.0) | 0.0 (0.0–0.0) | 0.80 (0.70–0.94) | 0.85 (0.76–1.00) |
| Details | | | | |
| Medium arteries | 91.0 (76.0–100.0) | 1.0 (0.0–4.0) | 0.80 (0.64–1.00) | 0.85 (0.76–0.94) |
| Small arteries | 91.5 (84.0–100.0) | 1.0 (0.0–4.0) | 0.81 (0.70–1.00) | 0.90 (0.76–0.94) |
| Venous superimposition | 55.0 (0.0–100.0) | 14.0 (0.0–40.0) | 0.06 (−0.50 to 0.82) | 0.52 (0.22–0.88) |
| Overall image quality | 92.5 (80.0–100.0) | 0.0 (0.0–0.0) | 0.83 (0.70–1.00) | 0.87 (0.76–0.94) |
| **E: Standard CT Angiography vs tMIP CT Angiography** | | | | |
| | TI CT Angiography Better (%)* | Equal (%)* | Interobserver Agreement† | Intraobserver Agreement† |
| Vascular noise | 53.0 (16.0–68.0) | 6.0 (0.0–16.0) | 0.26 (0.10–0.58) | 0.42 (0.22–0.52) |
| Vascular contour | 45.5 (12.0–68.0) | 3.0 (0.0–8.0) | 0.25 (−0.14 to 0.52) | 0.45 (0.1–0.88) |
| Details | | | | |
| Medium arteries | 50.0 (12.0–68.0) | 5.5 (0.0–24.0) | 0.25 (−0.02 to 0.52) | 0.42 (0.28–0.52) |
| Small arteries | 48.0 (12.0–68.0) | 3.5 (0.0–8.0) | 0.27 (−0.08 to 0.58) | 0.45 (0.34–0.52) |
| Venous superimposition | 40.5 (4.0–64.0) | 22.0 (0.0–52.0) | −0.05 (–0.44 to 0.34) | 0.28 (−0.08 to 0.46) |

Table 2 (continues)

Our results also show that the quality of images acquired with dynamic CT angiography during the arterial phase is inferior to the quality of images acquired with standard CT angiography and substantially lower than that of images acquired with TI CT angiography. Because the arterial phase of dynamic CT angiography represents the image quality of dynamic CT angiography, our findings suggest that TI CT angiography is superior in the evaluation

**Table 2 (continued)**

**Results of Visual Evaluation**

| | | | | |
|---|---|---|---|---|
| E: Standard CT Angiography vs tMIP CT Angiography | | | | |
| Overall image quality | 48.5 (12.0–68.0) | 5.0 (0.0–24.0) | 0.25 (−0.14 to 0.58) | 0.42 (0.22–0.52) |
| F: tMIP CT Angiography vs Arterial Phase of Dynamic CT Angiography | | | | |
| | tMIP CT Angiography Better (%)* | Equal (%)* | Interobserver Agreement† | Intraobserver Agreement† |
| Vascular noise | 95.5 (84.0–100.0) | 3.5 (0.0–16.0) | 0.87 (0.70–1.00) | 0.87 (0.64–1.00) |
| Vascular contour | 97.0 (84.0–100.0) | 0.5 (0.0–4.0) | 0.91 (0.70–1.00) | 0.94 (0.76–1.00) |
| Details | | | | |
| Medium arteries | 98.5 (96.0–100.0) | 0.0 (0.0–0.0) | 0.96 (0.88–1.00) | 0.99 (0.94–1.00) |
| Small arteries | 98.5 (96.0–100.0) | 0.0 (0.0–0.0) | 0.96 (0.88–1.00) | 0.96 (0.94–1.00) |
| Venous superimposition | 55.0 (0.0–100.0) | 11.0 (0.0–36.0) | −0.02 (−0.50 to 0.94) | 0.63 (−0.14 to 1.00) |
| Overall image quality | 98.5 (96.0–100.0) | 0.0 (0.0–0.0) | 0.96 (0.88–1.00) | 0.99 (0.94–1.00) |

* Data are percentages of cases in which one CT angiography technique was rated better than or equal to another technique. Data in parentheses are ranges between observations.

† Data are the average inter- and intraobserver agreement. Data in parentheses are ranges between observers.

of vascular morphology. Nevertheless, dynamic CT angiography yields complementary information about contrast material arrival in the various portions of the cerebral vasculature.

Visualization of small cerebral arteries depends on optimal arterial enhancement. This enhancement builds up over a few seconds after contrast material arrival and depends on various factors, including contrast material injection protocol and circulatory factors related to the individual patient (13). Venous enhancement in the brain starts early and usually is already visible at the time of maximal arterial enhancement. In case of delayed enhancement of an artery, for example, due to an obstruction in an afferent vessel, maximal enhancement occurs later and at a time when venous enhancement is even more pronounced. Our results show that venous enhancement occurs during standard CT angiography and even in the phase of maximal arterial enhancement during dynamic CT angiography. Others have found similar results (3,5,13). We have defined venous superimposition as superimposition of venous structures that are disturbing when evaluating the circle of Willis. We found that rating venous superposition appears to be highly subjective and variable between observers. The good intraobserver agreement, however, suggests that observers have their own subjective understanding of when venous enhancement disturbs their evaluation of the circle of Willis. Although venous enhancement can be distracting in the evaluation of the arteries, the good venous display of TI CT angiography also enables one to detect venous abnormalities, such as aberrant veins or venous thrombosis.

Correction for motion between images acquired over time is a requisite in CT perfusion to be able to derive perfusion maps, such as the cerebral blood volume, cerebral blood flow, and mean transit time, as well as reconstruction of TI CT angiographic images. In general, patient motion between examinations over time can be corrected by using image registration. However, in severe cases, image registration may fail. With our proprietary software, a small number of patients included in this study were not registered. Inaccurate registration due to vascular motion would result in vascular blurring. To evaluate this potential limitation, we included sharpness of the definition of the vascular contour in our evaluation. We found that the vascular contour in TI CT angiography was rated superior to that in standard CT angiography and the other techniques. In addition to motion between examinations, motion during image acquisition will result in motion artifacts that cannot be corrected. In this study, a few patients were excluded because of obvious motion artifacts. We excluded images with metal artifacts since these artifacts would hamper filter optimization and visual evaluation (for both TI CT angiography and standard CT angiography). In general, TI CT angiography does not add restrictions to CT perfusion imaging. In other words, if perfusion imaging is successful, TI CT angiographic images can be reconstructed.

Our study had several limitations. First, standard CT angiography and CT perfusion could not be evaluated with identical acquisition and reconstruction parameters. CT angiography was performed at 120 kVp whereas CT perfusion was performed at 80 kVp. This reflects current practice at many institutions. However, use of low–peak-voltage acquisitions for CT angiography might have increased enhancement of the arteries and improved CNR of standard CT angiography (14), making the found differences less striking. Second, the precise strength of the temporal filter used to generate TI CT angiography might be influenced by factors that affect the noise of individual CT images acquired during CT perfusion and that affect the shape of the time-attenuation curve (cardiac output and injection protocol). In our study, we did not further examine this issue but focused instead on the question of whether the technique can provide image quality superior to that provided by currently used CT angiographic techniques. Third, TI CT angiography is currently not available on commercial workstations but can be easily implemented with commercial software.

In conclusion, TI CT angiography is a simple and robust technique for the evaluation of vascular morphology that yields superior image quality when compared with the image quality of standard CT angiography or dynamic CT angiography of the brain. If CT perfusion has been performed, it is unnecessary to perform additional CT angiography of the brain, thereby reducing the total radiation dose and the amount of contrast material needed.

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