Optimization of scan timing for aortic computed tomographic angiography using the test bolus injection technique

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Abstract

Background: With fast computed tomography (CT), it is possible for the scanning to outpace the contrast medium bolus during aortic CT angiography (CTA).

Purpose: To evaluate the effectiveness of a new method for reducing the risk of outpacing in which the scan start timing (*ST*) and speed can be estimated from the peak enhancement time measured at the femoral artery using a single test bolus injection (femoral artery test injection method [FTI method]).

Material and Methods: In 30 cases of aortic CTA, we measured the time to peak enhancement at the femoral artery (T_{PF}) and the ascending aorta (T_{PA}) with test-bolus injection performed twice in each examination. From the resultant linear relationship between T_{PF} and transit time ($TT = T_{PF} - T_{PA}$), we developed a method for determining the *ST* and *TT* from T_{PF}. One hundred patients were assigned to two groups: FTI and bolus tracking (BT), each with 50 patients. CT values were measured in main vessels (ascending aorta, descending aorta, femoral artery). The CT values of the vessels and the rate of cases with more than 300 HU (good cases) were compared between the two groups.

Results: The enhancement in the FTI method was significantly higher than that of the BT method (average CT values: FTI, 388.3 ± 52.4; BT, 281.2 ± 59.1; $P < 0.001$). The rates of good cases for FTI and BT were 86.0% and 46.0%, respectively.

Conclusion: The FTI method was very effective in reducing the risk of outpacing of the contrast medium transit in aortic CTA without the need for an additional contrast medium dose.

Keywords

Computed tomography (CT), vascular, CT angiography, test-bolus injection, bolus tracking

Introduction

With multi-slice computed tomography (CT) scanners, long-range CT scans with short scan times (high speeds) and high longitudinal resolutions are now possible (1–3), and the image quality of CT angiography (CTA) by intravenous contrast medium injection has been improved (4–7). However, it is still possible for scanning to outpace the contrast medium bolus, especially in aortic CTA examination, before it reaches the end point of the scan range, owing to the high-speed nature of the scan (8,9). For such cases, the image quality of aortic CTA scans is degraded, with low attenuations in the aorta. It is well known from preceding studies that coexisting cardiovascular disorders and aneurysms may slow the blood flow speed in the aorta. Thereby, in patients with such

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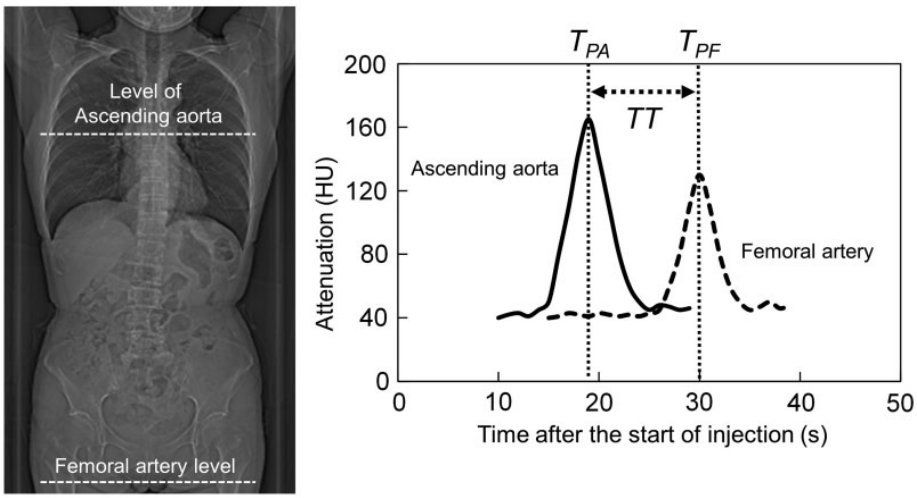

Fig. 1. Measurement points of T_{PA} and T_{PF} (times to peak enhancement at femoral artery and ascending aorta, respectively) and examples of attenuation curves. T_{PF} and T_{PA} were measured in two independent test bolus monitoring procedures before the main bolus.

diseases, the risk of the outpacing might be increased.

The most frequently used bolus timing techniques are the test-bolus injection method (TI method) (10,11) and the bolus tracking method (BT method) (10,12–14). These methods are useful to determine the scan delay for optimal scan start timing; however, they cannot reduce the risk of outpacing the contrast medium transition, because they naturally do not provide any information to optimize the scan speed corresponding to the contrast medium transit time in the aorta.

To reduce the risk of outpacing and simultaneously obtain sufficient enhancement for aortic CTA, we devised a method that enables estimation of the contrast medium transit time in the aorta using the peak enhancement time at the femoral artery measured with only one test-bolus injection (femoral artery test injection method [FTI method]). The purpose of this study was to evaluate the effectiveness of our FTI method compared with the BT method.

Material and Methods

Pre-investigation for measuring transit time

We performed a pre-investigation directly measuring the contrast medium transit times in the aorta by using double test-bolus injections executed during aortic CTA examinations. The study protocols were approved by the local ethics board, and informed consent was obtained from each participant. In the CTA examination, the peak enhancement times at the femoral artery (T_{PF}) and the ascending aorta (T_{PA}) were measured with the first test-bolus injection and subsequent second bolus injection, respectively, both performed before the main-bolus injection (Fig. 1).

Table 1. Patient characteristics of *TT* measurements.

Patients (*n*)	30
Male, female	19, 11
Age (years)	67.5 ± 12.6
Body weight (kg)	60.6 ± 10.7
Body height (cm)	163.3 ± 7.7
Aortic aneurysm	9 (30%)
Aortic dissection	6 (20%)
Other (normal, post operation, including)	15 (50%)

Thirty consecutive patients (19 men, 11 women; mean age, 67.5 years; age range, 35–89 years) were enrolled in this pre-investigation. Patient characteristics are summarized in Table 1. In all patients, iopamidol at a concentration of 300 mg of I/mL (Iopamiron 300; Bayer Healthcare, Osaka, Japan) was delivered via a 20-gauge catheter inserted into an antecubital vein and a power injector (DUAL SHOT GX; Nemoto Kyorindo, Tokyo, Japan). Contrast material dose was tailored to the patients' body weight. Contrast material volume and injection duration, respectively, were 60 mg I/kg and 3 s for the test bolus, and 300 mg I/kg and 15 s for the main angiographic bolus. With both protocols, contrast material administration was followed by administration of 30mL of a saline solution delivered at the same injection rate as for the contrast material. The monitoring levels along the femoral artery and ascending aorta were set to the levels of the pubic

symphysis and tracheal bifurcation, respectively. All CT scans were performed on a 64-slice CT scanner (SOMATOM Sensation 64; Siemens Medical Systems, Forchheim, Germany). Both monitoring scans for the T_{PF} and T_{PA} measurements were performed with interval scans each with 120 kV and 20 mAs, and scan start times were set to 15 and 10 s after the beginning of the intravenous injections, respectively. The two (right and left) femoral and ascending aortic artery time-attenuation curves were generated at circular regions of interest (ROIs) within the respective vessels in CT images from each patient. From the time-attenuation curves, the T_{PA} and T_{PF} (average of right T_{PF} and left T_{PF}) were measured, and the transit time between the ascending aorta and femoral artery (TT) was then calculated by $T_{PF} - T_{PA}$.

Because T_{PA} and T_{PF} are sequential time points, if both indicators could be measured in a single test bolus transit, we assumed that the predicted TT, TT' could then be estimated from only T_{PF} by the approximation function $TT' = f(T_{PF})$, which could be estimated from the measured relationship between T_{PF} and TT ($T_{PF} - T_{PA}$).

Fig. 2 shows plots of measured T_{PF} versus TT in 30 aortic CTA examinations. A highly positive linear correlation between T_{PF} and TT ($r = 0.869$, $P < 0.01$) was indicated. Thereby, the relationship between T_{PF} and TT' was given by

$$TT' = 0.652\, T_{PF} - 5.902 \quad (1)$$

Thus, we assumed that the scan start timing (ST) could also be estimated from the T_{PF} using the following relationship:

$$ST = T_{PF} - TT' + k \quad (2)$$

where k is the injection duration difference between the test and main-boluses. According to a known relation between the peak time and the injection duration (15–17), the peak time depends upon the injection duration, and the longer injection duration, the more delayed the peak time. Therefore, the true T_{PF} for the main-bolus is delayed by k. Because T_{PA} was not well correlated ($r = 0.296$, $P < 0.01$) with TT, as shown in Fig. 3, we demonstrated that T_{PA} could not be used for the TT estimation.

Procedure for the FTI method

Fig. 4 shows the outline procedure for the FTI method proposed in this paper. T_{PF} was measured by a test-bolus injection performed before the main-bolus injection, and then TT' and ST were calculated using equations (1) and (2). Subsequently, the scan time (table feed speed) for the main-bolus was adjusted by the rotation speed and pitch factor settings to agree with the calculated contrast medium transit time. Scanning for the main-bolus was then performed with the estimated ST and scan duration equal to TT'.

Comparison of the FTI method and the BT method

Patients: To validate the FTI method, we compared the enhancement abilities of the FTI and BT methods, which were used for aortic CTA examinations. One hundred consecutive patients (39 men, 61 women;

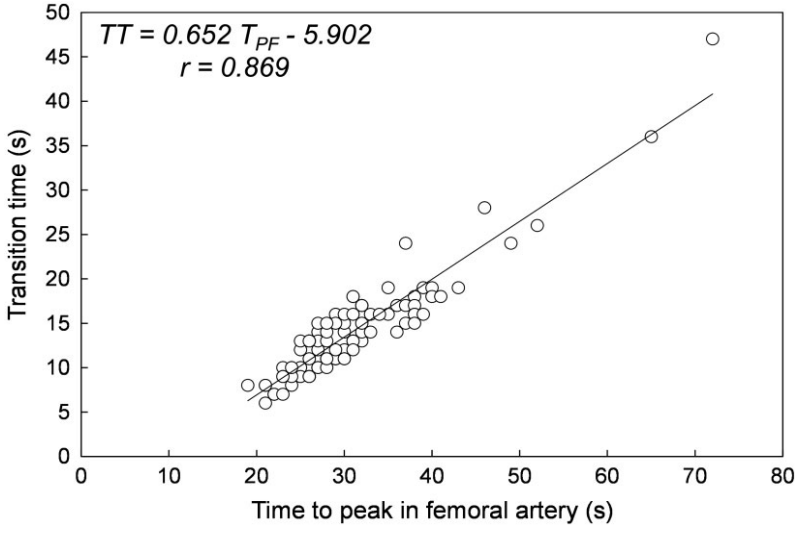

Fig. 2. Plots of T_{PF} versus TT (contrast medium transit time in aorta, calculated by $T_{PF} - T_{PA}$) and regression line. A highly positive correlation between T_{PF} and TT was indicated ($P < 0.01$).

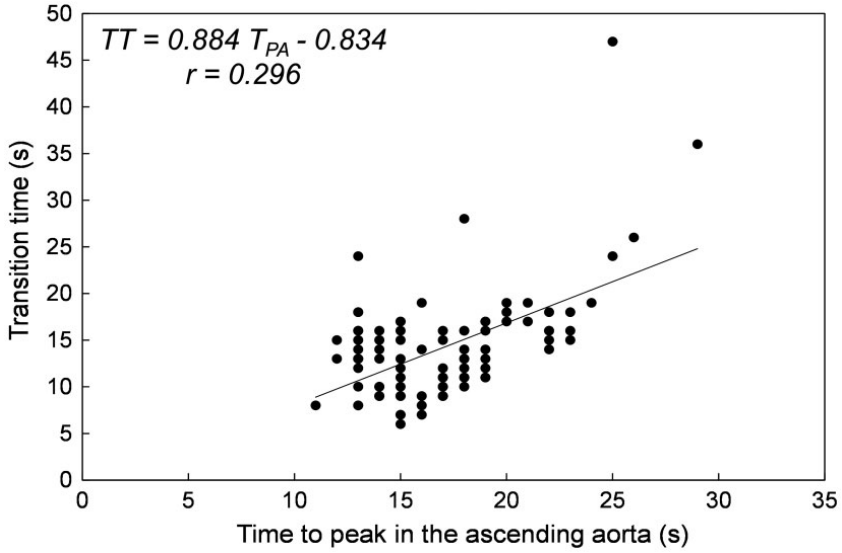

Fig. 3. Plots of T_{PA} versus *TT* and regression line. T_{PA} was not well correlated with *TT*.

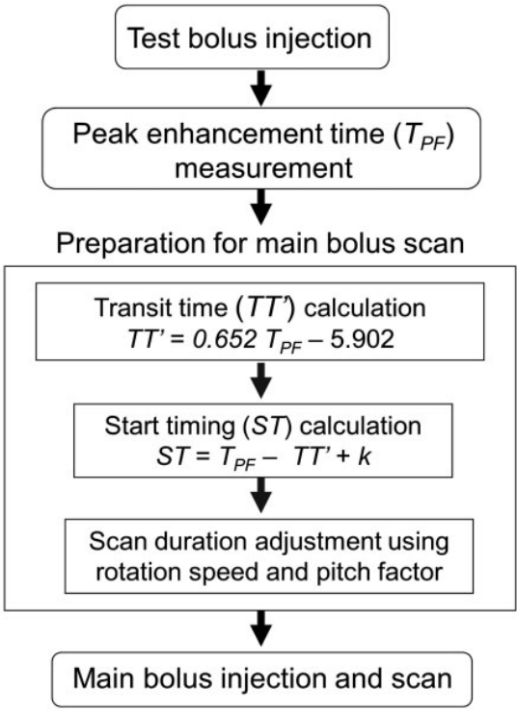

Fig. 4. Outline procedure of FTI method.

mean age, 67 years; age range, 42–83 years) were examined. We assigned each protocol in alternating sequence, such that every other patient (FTI method group, 50 patients; BT method group, 50 patients) received the same (FTI or BT) protocol. Patient characteristics, including age, weight, and aortic disease for both groups are presented in Table 2. For these patient characteristics, no significant differences were observed between groups.

Parameters for investigation: Scan, reconstruction, and contrast medium injection parameters for FTI and BT methods are presented in Table 3. The trigger

Table 2. Patient backgrounds of the FTI and BT method groups.

	FTI method	BT method
Patients (*n*)	50	50
Male, female	21, 29	18, 32
Age (years)	69.5 ± 10.2	66.2 ± 9.4
Body weight (kg)	62.1 ± 10.6	61.2 ± 8.8
Body height (cm)	159.9 ± 8.9	160.9 ± 7.1
Aortic aneurysm	14 (28%)	16 (32%)
Aortic dissection	20 (40%)	20 (40%)
Other diseases (including normal)	16 (32%)	14 (28%)

threshold for the BT method at the ascending aorta was set at 120 HU. The duration between the trigger and the scan start was 5 s, equal to the time for which the patient was instructed to hold their breath. Each contrast medium administration was followed by 30mL of saline solution at the same injection rate as for the contrast material.

As the injection durations of the test and main-boluses for the FTI method were 3 s and 15 s, respectively, the k-factor in the equation (2) was set to 12 (15 – 3). The range between levels of the sternoclavicular joint (superior margin of aortic arch) and the upper edge of the pubic symphysis was scanned in the craniocaudal direction for each main-bolus injection.

The ranges of pitch factor and rotation time used for the FTI method were 0.45–1.5 and 0.33–1.0, respectively. In cases where the scan duration was not able to be precisely adjusted to TT', the scan duration was set to the nearest value larger than TT'.

Table 3. Scan, reconstruction, and contrast medium injection parameters for FTI and BT method.

	FTI method		BT method	
	Test bolus scan	Main scan	Monitoring scan	Main scan
Tube voltage (kV)	120	120	120	120
Reference mAs *	20	200	20	200
Rotation time (s/rot.)	0.5	Variable (0.33–1.0)	0.5	0.5
Scan delay time (s)	15	Variable	10	Variable
Detector configuration	1 × 5 mm	64 × 0.6 mm	1 × 5 mm	64 × 0.6 mm
Pitch factor	NA	Variable (0.45–1.5)	NA	1.0
Slice thickness	5.0	5.0	5.0	5.0
Reconstruction kernel	B31f	B31f	B31f	B31f
CM concentration (mgI/mL)	300	300	300	300
CM dose (mgI/kg)	60	300	NA	300
Injection duration (s)	3	15	NA	15

*mAs setting of CT automatic exposure control system. CM, contrast medium; NA, not applicable.

Assessment of contrast enhancement: Arterial CT values for contrast enhancement were measured for each patient. ROIs were placed in the ascending aorta at the level of the tracheal branch (AAo), at the descending aorta at the level of the first lumbar vertebra (DAo), and in the right and left femoral arteries at the level of the pubic symphysis. The two ROI values in the femoral arteries were averaged into one ROI value (FA). Cases in which the CT values of all of the three ROIs were 300 HU or greater were classified as "good cases", because an aorta enhancement of 300 HU or higher is required if aortic side branches are to be visualized (18). Thus, cases with CT values less than 300 HU in at least one ROI were classified as "poor cases". Significance differences between the FTI and BT methods were evaluated with the Mann-Whitney *U* test at $P < 0.01$. SPSS version 11 software (IBM Corporation, Armonk, NY, USA) was used for the statistical analysis.

Results

Fig. 5 shows box plots of mean CT values over the three ROIs (AAo, DAo, and FA) for the FTI and BT methods. The all-mean CT value of the FTI method was significantly higher than that of the BT method (388.3 ± 52.4 HU for the FTI method and 281.2 ± 59.1 HU for the BT method, $P < 0.001$). The mean CT values for the three ROIs presented in Table 4 also indicated significant improvements with the FTI method ($P < 0.05$). Though no significant CT value differences between the three ROIs were observed in both methods ($P > 0.05$), the FA/CT value drop from AAo of the BT method (13.9%) was higher than that of the FTI group (4.6%). Fig. 6 represents the maximum intensity projection image examples for the good and poor cases, respectively. In the poor cases in the FTI method, though the enhancement at the ascending aorta was not sufficient, as shown in Fig. 6c, the mean CT value for the group of 279 HU was close to the minimum threshold level for a "good case" (300 HU). Especially in the poor cases using the BT method, enhancement differences between the upper and lower regions of the aorta due to outpacing of the CT scan were notable. Table 5 provides means and standard deviations of the CT values of the three ROIs, scan start times, and scan durations for good cases and poor cases using the FTI method. From the sufficient ROI values at the femoral artery, we found that the outpacing problem for aortic CTA was mostly overcome, even for the poor cases. The scan start timings and scan durations of the poor cases were significantly delayed and longer, respectively, compared with those of the good cases ($P < 0.01$ for both). Rates of "good cases" for the FTI and BT methods were 86.0% and 46.0%, respectively. The mean CT values of the good cases in the BT group and the poor cases in the FTI group were 340.66 ± 25.69 HU and 342.51 ± 22.66 HU, respectively, and there were no significant differences between them ($P = 0.916$).

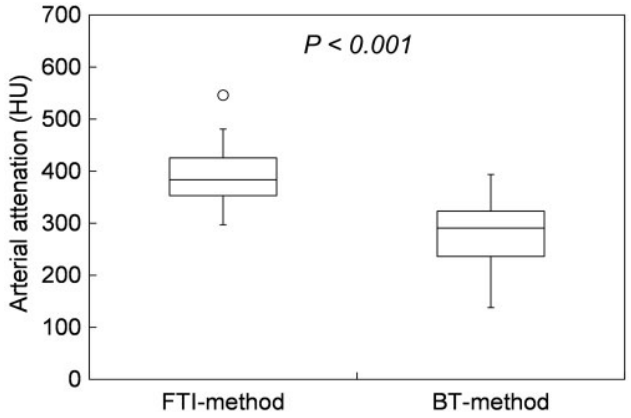

Fig. 5. Box plots of mean CT values over three ROIs (AAo, DAo, and FA) for FTI methods.

Table 4. Means and standard deviations of CT values of three ROIs for FTI and BT methods.

	FTI method	BT method	*P* value
Ascending aorta (HU)	391.7 ± 58.6	299.7 ± 64.1	<0.05
Descending aorta (HU)	399.5 ± 51.0	285.7 ± 64.5	<0.05
Femoral artery (HU)	373.8 ± 56.4	258.2 ± 75.1	<0.05

Table 5. Means and standard deviations of CT values for good cases and poor cases in FTI method.

	Good case	Poor case	*P* value
Ascending aorta (HU)	404.3 ± 59.9	289.7 ± 7.1	<0.01
Descending aorta (HU)	386.6 ± 53.9	342.2 ± 36.5	<0.05
Femoral artery (HU)	376.4 ± 54.9	357.2 ± 44.5	0.22
Scan start time (s)	28.4 ± 1.9	36.9 ± 3.8	<0.01
Scan duration (s)	13.7 ± 3.6	29.6 ± 7.1	<0.01

Discussion

The extent of this type of CT examination is very long, and the contrast medium bolus transit speed is very variable among individuals. According to a report by Fleischmann and Rubin, transit speeds between the aorta and popliteal artery were in the range of 29–177 mm/s for patients with peripheral arterial occlusive disease (PAOD), who potentially have a lower blood flow speed than normal patients (8). Nakaya et al. also reported that aorto-popliteal bolus transit speeds for 42 patients with vascular diseases such as PAOD, abdominal aortic aneurysm, and aortitis were in the range of 34.2–136.7 mm/s (9). Scan speeds of current clinical scanners with 64–128 detector-rows (32–80mm detector full widths) were in the range of approximately 50–130 mm/s with assumed conditions of a pitch factor of 0.8 and a rotation speed of 0.5 s. Assuming that the speed range in the region of aortic CTA (longitudinal range: just above the aortic arch to the femoral heads) is similar to that of aorto-popliteal bolus transit, the possibility for current MSCT scanners outpacing the contrast medium transit in aortic CTA also then becomes higher with increases in scan speeds. To reduce the risk of outpacing, Fleischmann and Rubin proposed a method with extended injection duration, combined with a reduction in acquisition speed or an increased scanning delay (8). This method might impair the contrast medium dose saving, maintaining sufficient enhancement, which is one of the features of the current high-speed MSCT systems, because an increase in the contrast medium dose is unavoidable in this approach. Therefore, even if the extension of injection duration combined with the delayed scan start is effective to reduce the risk of outpacing, the increase in contrast medium dose is problematic in terms of the risk of renal dysfunction caused by the contrast medium injection (19–21).

One option to cope with this problem would be to measure ascending aorta and femoral artery arrival times in every individual and to adjust the acquisition speed according to the *TT* estimated by the two measured arrival times. Laswed et al. measured the aorto-popliteal bolus transit speed by using a single test-bolus injection and two sequential low-dose dynamic acquisitions, and the CTA scan speed was optimized using the estimated *TT* (22). However, quick table transition and scan preparation between the ascending aorta and femoral artery may not be possible depending on the MSCT system. Because the estimated transit speed in the aorta measured in our investigation was in the range of 12.8–82.1 mm/s, the scan speed could be successfully adjusted to achieve the desired scan duration with a reasonable pitch factor range (0.45–1.5) and rotation time range (0.33–1.0 s) for the MSCT system we used. As the maximum speed of 177 mm/s reported by Fleischmann and Rubin was impossible for our MSCT system, with a maximum speed of 87.3 mm/s, for cases with such high transit speeds, longer injection durations might be needed to achieve sufficient enhancement. Thus, increases in contrast medium dose are unavoidable in such cases. However, as the maximum scan speeds of recent 64-slice MSCT systems with 40-mm detector full widths, which are becoming more widespread,

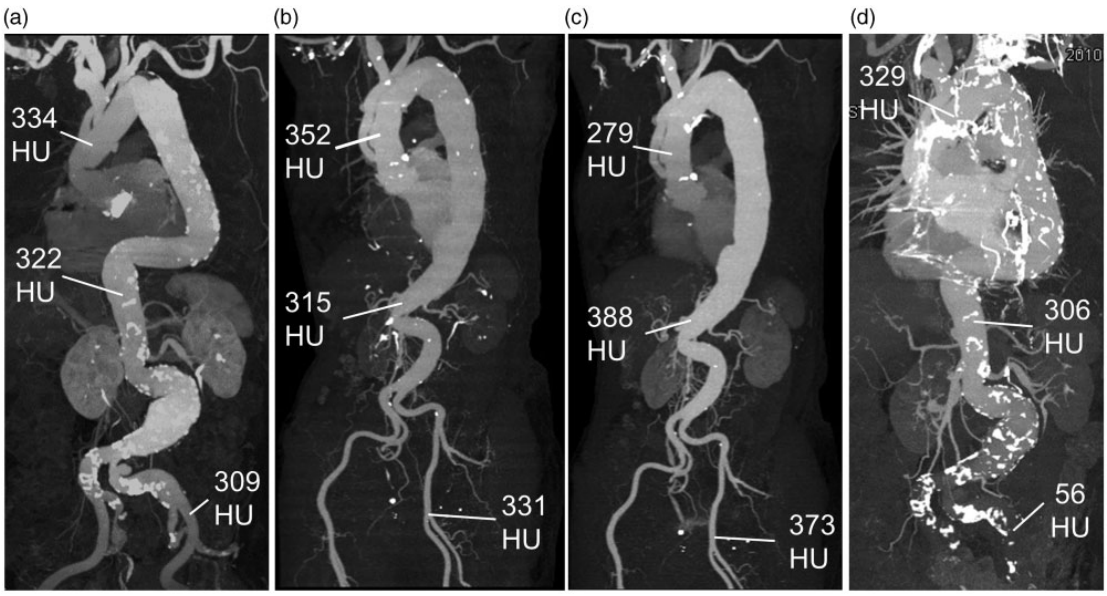

Fig. 6. Maximum intensity projection image examples of good cases for (a) FTI method and (b) BT method; poor cases for (c) FTI method and (d) BT method. Respective scan start times/scan durations (s) were (a) 34.0/30.1, (b) 25.0/9.3, (c) 27.0/30.2, and, (d) 35.0/17.8.

reach approximately 180 mm/s, the FTI method can be safely performed without increasing contrast medium dose using such MSCT systems.

In all of the poor contrast enhancement cases (7 cases) for the FTI method, the ROI values at the ascending aorta were less than 300HU (289.7 ± 7.1 HU), while other ROIs in all cases presented sufficient values more than 300HU (DAo range, 302.5–398.1 HU; FA range, 309.4–448.3 HU). The average *TT* of poor cases with the FTI method was 29.6 ± 7.1 s, which is much longer than the 13.7 ± 3.6 s of good cases, as shown in Table 5. Thus, the difference between the actual scan timing at the ascending aorta and the estimated *ST* became longer in all poor cases. To prevent this problem, the injection duration should be prolonged according to the scan timing difference between the upper edge of the aortic arch and the lower ascending aorta. In this study, we used the contrast medium at low concentrations (300 mg I/mL). Thus, the use of higher concentrations might affect the results of our study. However, it seems that the significantly low CT values (minimum of 60.6 HU) at the femoral arteries in the poor cases of BT method would not be improved to more than 300HU even by using higher concentrations.

The FTI method has some drawbacks. This method cannot be applied to patients with bilateral complete occlusions of the femoral arteries due to diseases such as arteriosclerosis obliterans or aortic dissection involving femoral arteries. Moreover, in cases of short *TT*, the corresponding high scan speeds may require higher pitch factors which can address the deterioration of image quality (23,24). However because the 64-slice MSCT systems with 40-mm detector full widths, which are wider than that of the MSCT we used in this study, are becoming standard, it is possible to manage the fast blood flow without using excessive pitch factors that cause image quality deterioration.

Our study had several limitations. First, the number and selection of participants in our study population may not have ensured that it was representative of the entire population of patients with aortic disease. Moreover, though the FTI method requires only one time test-bolus monitoring, the procedures in this method may not be simple in that the peak time measurement at the femoral artery, estimation of the *ST* (*TT'*), and scan speed adjustment are needed before main-bolus scanning.

In conclusion, the FTI method, which can determine the correct scan start timing and speed for aortic CTA from only a single test-bolus monitoring at the femoral artery, was very effective for reducing the risk of contrast medium transit outpacing and simultaneously improving contrast enhancement without the need for an additional radiation dose compared with the BT and TI methods.

Declaration of conflicting interests

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