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Feasible scan timing for 320-row coronary CT angiography generated by the time to peak in the ascending aorta

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ABSTRACT

Purpose: A 320-row CT scanner can briefly scan the entire heart. Therefore, the feasible scan timing is required. The aim of this study was to propose a refined method for feasible scan timing for coronary CT angiography (CCTA) using a time-density curve of the ascending aorta (AAo).

Methods: One-hundred and twenty-nine patients were prospectively enrolled. All patients were performed test-bolus method. For the initial 65 patients, the scan timing was determined as a 3.0 s delay at the peak time in the AAo, which was defined as the conventional protocol (COV-P). For the next 64 patients, a scan timing of 1.0, 3.0, or 5.0 s delay was determined according to the interval from the contrast media arrival to peak time in the AAo, which was defined as the arrival to peak protocol (AP-P). The optimal scan timing was identified by the measurement of CT number in the left atrium, left ventricle, AAo, and descending aorta. The coronary enhancement and heterogeneity were compared between the two protocols.

Results: The optimal scan timing was significantly higher in the AP-P than in the COV-P (85.9% vs. 61.5%, $p = 0.0017$). The CT number in the left circumflex artery (LCX) was significantly higher in the AP-P than the COV-P (344.5 Hounsfield units vs. 316.3 Hounsfield units, $p = 0.0484$). The heterogeneous index of the LCX was significantly greater for the COV-P than the AP-P (-36.8 vs. -25.8, $p = 0.0028$).

Conclusions: The AP-P can be used to determine the optimal scan timing for CCTA and contributes to stable coronary enhancement.

1. Introduction

Coronary computed tomography angiography (CCTA) is a well-known and reliable method for the diagnosis of coronary artery disease [1–4]. To achieve adequate diagnostic performance for CCTA, a test-bolus [5,6] or bolus-tracking [7–9] technique is generally used for the administration of contrast media (CM). The bolus-tracking technique can adjust the scan timing by capturing the time point at which the aortic enhancement reaches a set threshold, but it is not certain that the scan can be performed at the aortic peak enhancement time. When a short CM injection duration (10 s or less) is used, the aortic peak enhancement time does not coincide with the injection duration [10], and therefore the bolus-tracking technique is not suitable in such cases. On the other hand, since the test-bolus technique can predict the peak enhancement time, it is useful when a shorter CM injection duration is used.

The scan timing on the CCTA can be determined by the delay time from the aortic peak time on the test-bolus data according to Bae's theory [10]. The formula in Bae's theory is adapted when the duration of CM injection on the actual scan is shorter than the time to peak aortic enhancement on the test-bolus injection. The majority of CCTA examinations coincide with this situation. A scanner with a 320-row detector can briefly scan the entire heart over a single cardiac cycle [11–13]. Meanwhile, in cases when the administrated test-bolus flow is extremely early or late, we have found that the feasible scan timing in 320-row CCTA is not accurately determined based on Bae's theory. In such cases, an inaccurate determination may result in an insufficient enhancement for evaluating the coronary artery disease. The

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theoretical delay time is determined using only the injection duration, and therefore we considered that another approach using an index of CM flow for the feasible scan timing is required. The aim of the present study was thus to propose a new method for determining the feasible scan timing for 320-row CCTA using test-bolus data, and to investigate the validity of this method by comparing its results with those of the conventional method based on Bae's theory.

2. Materials and methods

This study received institutional review board approval, and the requirement for prior informed consent was waived. This study involved the evaluation of prospective data obtained as a part of routine care.

2.1. Patient population

Data from 129 consecutive patients who had undergone CCTA with 320-row CT (Aquilion ONE ViSION Edition; Toshiba Medical Systems, Otawara, Japan) between August 2015 and June 2016 were prospectively analyzed. All patients had been clinically referred for an assessment of known or suspected coronary artery disease. All patients met one of two criteria: (1) they had been scanned with a single volume scan (i.e., an axial scan), or (2) they had been scanned with multicycle volume scans for a heart rate of ≥75 beats per minute (bpm) or for atrial fibrillation, followed by additional image reconstruction using half-scan reconstruction (phase of 75% in the first cardiac cycle) for the analysis.

The exclusion criteria were as follows: (1) patients scanned with helical scanning, and (2) patients scanned with a wide-volume scan over 160 mm in the craniocaudal direction (e.g., postoperative coronary artery bypass graft). The patients' characteristics are summarized in Table 1.

2.2. Test-bolus and CCTA protocols

In all patients, the CM iopamidol-370 (Iopamiron; Bayer HealthCare, Osaka, Japan) was delivered through a 20-gauge cannula in the right antecubital vein, using a power injector (Dual Shot GX 7; Nemoto-Kyorindo, Tokyo). The CM dose was tailored to the patient's body weight, and the test-bolus method was performed immediately before the CCTA. For the CCTA, CM at 0.7 ml/kg body weight was administered over a fixed injection duration of 10.0 s. For the test-bolus examination, the injection duration was fixed at 4.0 s, and the injection rate was set to be equivalent to that in the CCTA. In both examinations, CM administration was followed by the injection of 30 ml saline at the same rate as used for the CM injection.

The test-bolus examinations were performed using prospectively ECG-triggered axial scanning for the ascending aorta (AAo) at the left main trunk level in mid-diastole for 15–25 cardiac cycles during a 20.0 s period starting from 7.0 s after the initiation of the bolus injection of the CM with an inspiratory breath-hold [14]. The scan parameters were as follows: tube potential, 80 kV; tube current, 60 mA; rotation time, 0.275 s; detector configuration, 0.5 mm; scan length, 20 mm; and reconstructed field of view, 200 mm. All patients received sublingual nitroglycerin 5 min prior to the scanning and did not receive beta-blockers.

After the test-bolus examination, the CCTA was performed under an inspiratory breath-hold. The scan parameters were as follows: tube potential, 120 kV; tube current, automatic exposure control (noise level, standard deviation 20; reconstructed slice thickness, 0.5 mm); rotation time, 0.275 s; detector configuration, 0.5 mm; scan length, 128–160 mm; and reconstructed field of view, 160–200 mm. The scan length and reconstructed field of view were determined depending on the patient's physique.

Table 1
Baseline demographic data for each protocol.

	COV-P	AP-P
No. of patients	65	64
Male/female	33/32	41/23
Age (years)	63.3 ± 13.2	68.8 ± 13.1
Weight (kg)	60.9 ± 11.6	62.0 ± 12.9
Height (cm)	160.2 ± 8.8	160.7 ± 9.4
Body mass index (kg/m^2)	23.7 ± 3.9	24.0 ± 4.5
Heart rate (bpm)	62.5 ± 11.2	65.5 ± 12.0
Contrast media (ml)	42.6 ± 8.1	43.4 ± 9.0

Unless otherwise specified, the data are the means ± standard deviation.

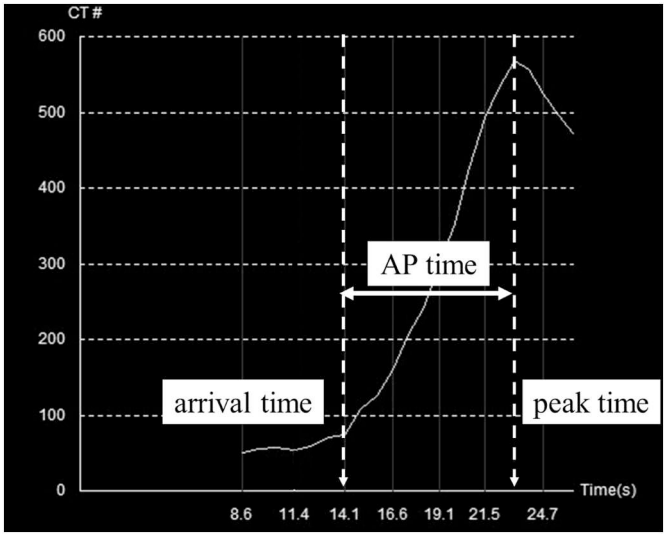

Fig. 1. Time density curve (TDC) of the ascending aorta at the test bolus. AP time was calculated using the time interval between the contrast media arrival time and the aortic peak time from the TDC.

2.3. Determination of scan timing

For the initial 65 patients, the conventional test-bolus protocol (COV-P) using a TDC of AAo at the left main trunk level was performed. The scan timing was fixed at 3.0 s after the peak enhancement time in AAo according to Bae's theory [10]. For the next 64 patients, a new protocol was performed using the interval time between the CM arrival time and the aortic peak time (AP time) from the TDC of the test-bolus data (AP-P; Fig. 1). The CM arrival time was defined as the initial point of increase in the CT number of AAo from the baseline. The scan timing was determined to follow three patterns: 1) a delay time of 5.0 s from the aortic peak time at the AP time of < 6.0 s; 2) a delay time of 3.0 s from the aortic peak time at the AP time of 6.0 s to 10.0 s; and 3) a delay time of 1.0 s from the aortic peak time at the AP time of > 10.0 s [15].

2.4. Definition of optimal scan timing and analysis of AP time in COV-P

The CT numbers for AAo and the descending aorta (DAo) at the left main trunk level, the left atrium (LA), and the left ventricle (LV) were measured on the axial images of CCTA data. The optimal scan timing (AAo group) was defined as follows: 1) a CT number difference of < 40 Hounsfield units (HU) between AAo and LA or LV and between AAo and DAo; and 2) a higher CT number in AAo than in either LA/LV or DAo. The suboptimal scan timing was defined as a lower CT number in AAo than in either LA/LV or DAo, and a CT number difference of > 40 HU between AAo and LA/LV (LA/LV group) and between AAo and DAo (DAo group). We analyzed the AP time of the CCTA patients who underwent COV-P.

Table 2
Prevalence of each group in COV-P and AP-P CCTA.

	Scan timing	Group	COV-P	AP-P	p value
Prevalence (%) (No. of patients)	Optimal	AAo	61.5 (40/65)	85.9 (55/64)	0.0017
	Suboptimal	LA/LV	18.5 (12/65)	6.3 (4/64)	0.00354
		DAo	20.0 (13/65)	7.8 (5/64)	0.0458

AAo: ascending aorta, AP-P: arrival to peak protocol, COV-P: conventional protocol, DAo: descending aorta, LA: left atrium, LV: left ventricle.

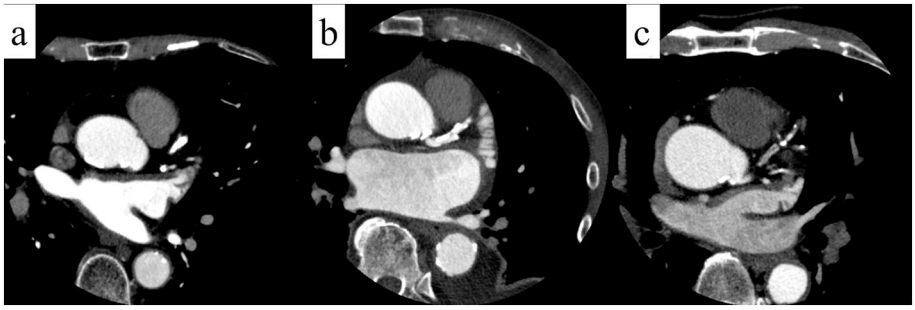

Fig. 2. Axial images at the level of the left main trunk of the patients who underwent coronary CT angiography with the test-bolus method.
(a) An image of LA/LV group showing the early scan timing (suboptimal). The maximum CT number is observed at the left atrium.
(b) An image of AAo group showing the optimal scan timing. The maximum CT number is observed at the ascending aorta compared to the other areas of the heart.
(c) An image of DAo group showing the late scan timing (suboptimal). The maximum CT number is observed at the descending aorta.

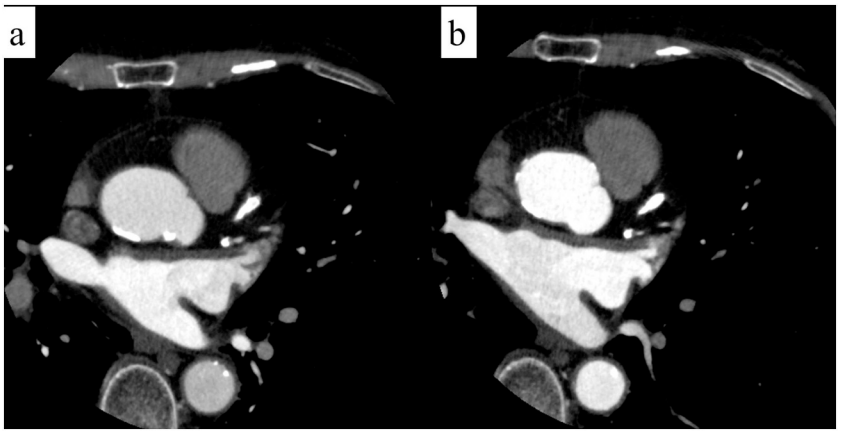

Fig. 3. Axial images obtained before and after percutaneous coronary intervention in a 63-year-old woman.
(a) A CCTA image acquired under COV-P is shown (body weight, 37.0 kg; CM dose, 25 ml; heart rate, 60 bpm). The maximum CT number was observed at the left atrium. (b) A CCTA image acquired under AP-P is shown (body weight, 43.0 kg; CM dose, 30 ml; heart rate, 61 bpm). The maximum CT number was observed at the ascending aorta.

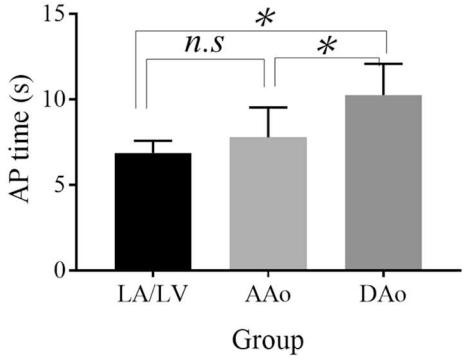

Fig. 4. AP time of the time density curve analysis in the initial 65 patients who underwent the conventional test-bolus protocol (COV-P).
Bar graph showing the calculated AP time of the time density curve analysis in the initial 65 patients who underwent the conventional test-bolus protocol (COV-P). The AP times of the LA/LV, AAo, and DAo groups were 6.9 ± 0.7 s, 7.8 ± 1.8 s, and 10.3 ± 1.8 s, respectively. *: $p < 0.0001$; n.s.: not significant.

2.5. Evaluation of coronary arterial enhancement

Based on the American Heart Association 17-segment model, the CT numbers for the right coronary artery (RCA) #1, #2, and #3, LMT #5, left anterior descending (LAD) #6, #7, and #8, and left circumflex (LCX) #11 and #13 were measured. Heterogeneity of coronary enhancement was defined as the slope of the linear regression equation of the CT number from the proximal to distal sites of the coronary artery. The heterogeneity of RCA, LAD, and LCX was calculated in each case.

2.6. Statistical analysis

Continuous data are expressed as the mean ± standard deviation (SD). The prevalence of optimal and suboptimal scan timing was analyzed by chi-squared test. To compare the AP-time values among the three patient groups, we used a one-way analysis of variance followed by Tukey's test. For comparison of the mean CT number of the AAo and coronary arteries between COV-P and AP-P, we used an unpaired *t*-test. Comparison of the heterogeneity of the coronary arteries' enhancement was analyzed with the unpaired *t*-test. Values of $p < 0.05$ were considered significant. These analyses were performed using GraphPad Prism, version 7.01 (GraphPad Software, La Jolla, CA, USA).

3. Results

3.1. Prevalence of optimal scan timing

The prevalence of optimal scan timing in patients who underwent AP-P was significantly increased compared to that of the CCTA patients who underwent COV-P ($p = 0.0017$) (Table 2). Among the 65 CCTA patients who underwent COV-P, 40 patients (61.5%) belonged to the

Table 3
Prevalence of each delay time in 64 patients who underwent AP-P (arrival to peak protocol).

			Delay time		
	Scan timing	Group	5 s	3 s	1 s
Prevalence (%) (No. of patients)	Optimal	AAo	71.4 (10/14)	95.1 (39/41)	66.7 (6/9)
	Suboptimal	LA/LV	14.2 (2/14)	2.4 (1/41)	11.1 (1/9)
		DAo	14.2 (2/14)	2.4 (1/41)	22.2 (2/9)

AAo: ascending aorta, DAo: descending aorta, LA: left atrium, LV: left ventricle.

Table 4
CT number of the ascending aorta and coronary arteries.

CT number (HU)	Segment no.	COV-P	AP-P	p value
Ascending aorta		432.1 ± 74.3	423.4 ± 68.5	n.s
Right coronary artery	#1	424 ± 76.4	416.4 ± 70.9	n.s
	#2	404 ± 69.7	403.1 ± 72.8	n.s
	#3	386.8 ± 82.0	375.4 ± 77.7	n.s
Left main trunk	#5	418.4 ± 72.7	411.5 ± 76.8	n.s
Left anterior	#6	403.6 ± 75.5	399.1 ± 80.2	n.s
descending	#7	402.2 ± 72.4	385.2 ± 64.2	n.s
	#8	334.9 ± 71.5	342.9 ± 65.5	n.s
Left circumflex	#11	395.1 ± 75.7	390.9 ± 75.3	n.s
	#13	316.3 ± 78.7	344.5 ± 81.58	0.0484

Data are the means ± standard deviation.
AP-P: arrival to peak protocol, COV-P: conventional protocol, n.s: not significant.

AAo group, which had optimal scan timing. Twelve and 13 of these 65 patients had suboptimal scan timing and belonged to the LA/LV group and the DAo group, respectively. Among the 64 patients who underwent CCTA with AP-P, 55 patients (85.9%) belonged to the AAo group and nine patients belonged to the suboptimal scan timing group (four patients in the LA/LV group and five in the DAo group). The results for a representative patient are shown in Figs. 2, 3.

3.2. AP time in COV-P

In the initial 65 patients, the AP time was 6.9 ± 0.7 s for the LA/LV group, 7.8 ± 1.8 s for the AAo group, and 10.3 ± 1.8 s for the DAo group, respectively (Fig. 4). The AP time was significantly greater for the DAo group than the AAo and LA/LV groups ($p < 0.0001$).

3.3. Required delay time in patients under AP-P

Among the 64 patients who underwent CCTA under the AP-P were 14 patients (21.9%) with a delay time of 5 s, 41 patients (64.1%) with a delay time of 3 s, and 9 patients (14.1%) with a delay time of 1 s (Table 3). About one-third of patients were divided into 5 s or 1 s delay time groups. Ten of the 14 patients (71.4%) with 5 s delay and 6 of the 9 patients (66.7%) with 1 s delay were judged to have optimal scan timing (Table 3). Furthermore, 95.1% of patients with a 3 s delay had optimal scan timing.

3.4. Coronary arterial enhancement

Comparison of the mean CT number at the AAo revealed that there was no significant difference between the values obtained using the COV-P and AP-P (Table 4). A higher CT number was observed in segment #13 at the LCX of the patients who underwent the AP-P compared to the patients who underwent the COV-P ($p = 0.0484$). In each of the other segments of the coronary arteries, there was no significant difference between the values obtained using the COV-P and AP-P (Table 4).

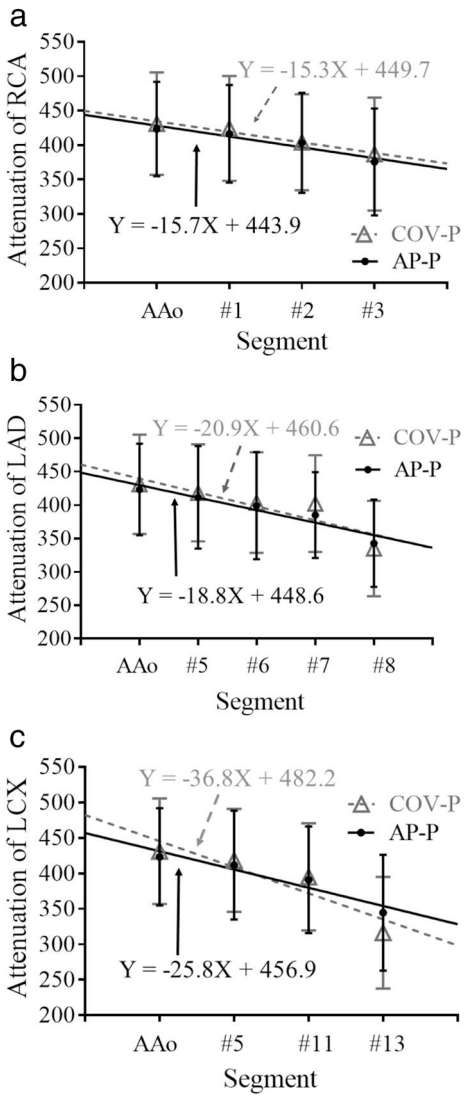

Fig. 5. Coronary-CT number slope from the proximal to distal segment of the coronary arteries as determined by linear regression analysis.
(a) Right coronary artery (RCA), (b) left anterior descending artery (LAD), (c) left circumflex (LCX). The solid lines indicate the mean CT number slope of the patients who underwent CCTA with AP-P. The dashed lines indicate the mean CT number slope of the patients who underwent CCTA with the COV-P.

3.5. Heterogeneity of coronary enhancement

The coronary CT number slope of LCX from the proximal to distal sites was significantly more gentle in CCTA patients who underwent AP-P compared to that of patients who underwent COV-P ($p = 0.0028$) (Fig. 5). In the linear regression slope of RCA and LAD, there was no significant difference between the COV-P and AP-P (Table 5).

Table 5
Slope of the linear regression equation from the proximal to distal sites of the coronary artery's CT number.

Coronary artery	COV-P	AP-P	p value
Right coronary artery	−15.3 ± 22.3	−15.7 ± 18.5	n.s
Left anterior descending	−20.9 ± 16.9	−18.8 ± 12.6	n.s
Left circumflex	−36.8 ± 21.7	−25.8 ± 19.3	0.0028

Data are the means ± standard deviation.
AP-P: arrival to peak protocol, COV-P: conventional protocol.

4. Discussion

Our present findings suggest that the protocol using the AP time at the test bolus and the new index technique (AP-P) achieved a higher prevalence of optimal scan timing compared to the conventional technique during CCTA on 320-row CT. Use of the AP-P technique could achieve suppression of the interpatient variability of the vascular peak time. We focused on the AP time as a new index for the determination of scan timing because the AP time is a part of the estimated cardiac output, which links to the interpatient variability of the vascular peak time and enhancement [16–18]. In Fig. 4, the AP time indicated the necessity of further adjustment for the delay time. Cases with shorter AP time require a longer delay time than the theoretical delay time, and vice versa. These results are considered to represent the iodine concentration due to the relationship between injection duration and cardiac output [15]. Therefore, our scan timing prediction using AP time could correct for the effect of the cardiac output. The AP time is independent of vascular resistance at the injection site or the dilution and slowing of the CM during the venous passage [19]. Konno et al. adapted the cardiac output obtained from test-bolus data sets to the injection rate of the CM and reported a formula for optimal enhancement in CCTA [20]. Fleischmann reported a simulated TDC based on mathematical analysis using a simple additive model [21]. However, it is difficult for an operator to obtain the simulated TDC on the CT console after test bolus in an expeditious manner. Our technique is a robust post-processing procedure, and it is not dependent on the operator's experience.

In the initial 65 patients with COV-P, there was no significant difference in the body mass index (22.1, 23.8, and 24.6) or heart rate (63.7, 63, and 60 bpm) among the LA/LV, AAo, and DAo groups. Therefore, the suboptimal or optimal scan in COV-P is not related to the individual's physiological condition. AP-P is useful for providing adequate scan timing for 320-CCTA without an additional procedure, such as application of the CM or radiation. Prospectively ECG-triggered axial scanning for a test bolus was applied in the present study [14]. The accurate measurement of the AP time requires a temporal resolution of sub-milliseconds per phase. However, the accuracy of the commonly used regular time tracking is limited in sub-millisecond scans. Use of prospectively ECG-triggered axial scanning is thus an essential technique when using the AP-P method.

As indicated in Table 3, the use of AP-P resulted in a higher prevalence of the optimal scan timing in all three delay time groups. The advantage of AP-P is that it corrects the peak enhancement time for coronary arteries in CT examinations using a short injection duration (around 10 s) [18]. Consequently, AP-P can reduce the failure cases relating to the scan timing in coronary CT angiography with 320-row CT.

The average CT number of the AAo in the COV-P and AP-P group was > 400 HU, which was a sufficient level of enhancement for CCTA, as a previous study also reported [22]. Among the initial 65 patients with COV-P, there were 3 patients (4.6%) who had an AAo CT number of < 300 HU, which is an insufficient enhancement level for CCTA. In contrast, all patients in the AP-P group achieved an AAo CT number of over 300 HU. This result constitutes an advantage of AP-P over COV-P. The feasible scan timing can allow a reduction of the dose of the CM [17]. This is because the scanner can scan the entire heart within 0.28 s over a single cardiac cycle, and does not require an extra amount of contrast media to keep the contrast enhancement correspondent with the scan time. Accordingly, our AP-P can be used to optimize the CM dose. Moreover, AP-P improved the homogeneity of the coronary arterial enhancement compared to the COV-P. In particular, the LCX, which is a smaller coronary artery than the RCA or LAD, was strongly affected by the influence of the CM filling. Funama et al. reported that the transluminal attenuation-gradient was affected by scan timing after CM injection and by cardiac output [23]. In order to improve the detection of the gradient of luminal contrast attenuation between the proximal and distal portions, they recommended that the scan timing at the peak enhancement should be avoided, unlike in the CCTA. Therefore, our index of the prediction for the aortic peak enhancement time could also be useful for the clinical setting of transluminal attenuation-gradient scanning.

We acknowledge the following limitations of this study. First, we did not assess the diagnostic ability of the CCTA using our technique, and thus additional studies will be needed to investigate the effect of our approach on the diagnostic ability. Second, the study was limited to patients scanned with a single cardiac cycle or CCTA performed with half-scan reconstruction from multicycle scanning data. Further studies are needed to investigate whether our results also apply to patients with multicycle reconstruction for a scan length over 160 mm or higher heart rates. Third, the injection durations of the CM as the test bolus and full bolus for the CCTA in this study were fixed (4.0 and 10.0 s, respectively). If our proposed method is to be adopted for use with another injection duration, further studies of the delay time will be needed.

5. Conclusions

In conclusion, we propose a new index using the AP time at the AAo obtained from test-bolus data to optimize the scan timing for 320-row CCTA. With the use of the corrected delay time based on the AP time at the ascending aorta from the test-bolus data, we achieved feasible scan timing and improved the homogeneity of the coronary arterial enhancement in 320-row CCTA much more frequently compared to the conventional CCTA.

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