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Optimal image reconstruction phase at low and high heart rates in dual-source CT coronary angiography

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Abstract

The purpose of this study was to determine the cardiac phase having the highest coronary sharpness for low and high heart rate patients scanned with dual source CT (DSCT) and to compare coronary image sharpness over different cardiac phases. DSCT coronary CT scans for 30 low heart rate (≤ 70 beats per minute- bpm) and 30 high heart rate (>70 bpm) patients were reconstructed into different cardiac phases, starting at 30% and increasing at 5% increments until 70%. A blinded observer graded image sharpness per coronary segment, from which sharpness scores were produced for the right (RCA), left main (LM), left anterior descending (LAD), and circumflex (Cx) coronary arteries. For each coronary artery, the phase with maximal image sharpness was identified with repeated measures analysis of variance. Comparison of coronary sharpness between low and high heart rate patients was made using generalized estimating equations. For low heart rates the highest sharpness scores for all four vessels (RCA, LM, LAD, and Cx) were at the 65 or 70% phase, which are end-diastolic cardiac phases. For high heart rates the highest sharpness scores were between the 35 and 45% phases, which are end-systolic phases. Low heart rate patients had higher coronary sharpness at most cardiac phases; however, patients with high heart rates had higher coronary sharpness in the 45% phase for all four vessels ($P < 0.0001$). Using DSCT scanning, optimal image sharpness is obtained in end-diastole at low heart rates and in end-systole in high heart rates.

Keywords

Tomography; X-ray computed; Reproducibility of results; Radiographic image enhancement; Dual-source CT; CT coronary angiography; artifact; Motion artifact; Image quality; ECG gating

Introduction

The introduction of dual source CT (DSCT) scanners has made coronary CT angiography (CTA) very robust. With half-scan reconstruction, an effective temporal resolution of 83 ms can be achieved [1], allowing patients to be scanned with no beta-blocker premedication [2, 3].

However, the optimal cardiac phase for DSCT coronary reconstruction and its relationship to heart rate is not known. This is important because several radiation dose-reduction techniques

depend on predicting the optimal cardiac reconstruction phase before scanning. To date, the limited literature on this topic has produced conflicting results.

Two studies found that with DSCT, end-diastolic reconstructions were optimal in low heart rate patients (<70 beats per minute), but end-systolic reconstructions were preferable in high heart rate patients [4,5]. Another found no relationship to heart rate and motion artifact [6], while a third found that end-diastole was superior in both low and high heart rate patients [7].

Therefore, the purpose of this study was to determine the cardiac phase having the highest subjective coronary image sharpness (least motion artifact) for low heart rate and high heart rate patients. The second purpose was to compare coronary image sharpness in images obtained with DSCT scanners in patients at low heart rates and high heart rates in order to determine over which phases of the cardiac cycle coronary image sharpness was superior for each.

Materials and methods

Patient selection

Institutional Review Board approval was obtained, and patient information collected in compliance with Health Insurance Portability and Accountability Act regulations. 30 consecutive patients, who had undergone clinically indicated DSCT coronary CTA and who had a mean heart rate ≤ 70 beats per minute (bpm) at the time of scanning, were included. In addition, 30 separate patients, who had also undergone clinically indicated DSCT coronary CTA but who had a mean heart rate > 70 bpm at the time of scanning, were included, for a total of 60 patients. Heart rate information was obtained from the electrocardiographic gating information from the scanner. Patients who had undergone previous coronary artery bypass grafting were excluded to avoid artifacts from clips and difficulty in evaluating poorly opacifying native vessels. Patients who had not given consent for use of their medical records for retrospective research were excluded.

Demographic information

A nurse reviewed patient medical records for patient age, gender, height and weight at the time of CT scanning. Height and weight were converted to body mass index (BMI).

CT acquisition

All CT scans were performed on a DSCT scanner (Siemens Definition, Siemens Medical Solutions, Forchheim, Germany). The CT parameters were as follows: tube potential = 120 kV, tube rotation = 0.33 s, acquisition mode = 64×0.6 mm, reconstruction slice width = 0.75 mm, reconstruction slice interval = 0.4 mm, kernel = B26f, field of view = 25 cm. ECG-based tube current modulation was enabled. Pitch varied with heart rate. Tube current was set based on the left-to-right width of the patient as measured at the dome of the liver on the scout image (Table 1).

Contrast material was injected through a peripheral intravenous line (IV) using a dual head power injector (Stellant D, Medrad Inc, Indianola, PA). Non-iodinated contrast material (Visipaque 320, Amersham Health Inc, Princeton, NJ, FDA approved) was injected at a rate that varied with patient weight as follows: patients weighing less than 50 kg were injected at 4 ml/s, 50–100 kg at 5 ml/s, and > 100 kg at 6 ml/s.

The manufacturer's bolus tracking software (CAREbolus, Siemens Medical Systems), was used with a region-of-interest (ROI) placed over the ascending aorta. Immediately prior to contrast injection patients received a one time dose of sublingual (SL) nitroglycerin 0.4 mg. No beta blockade or other heart rate altering medications were given.

Contrast was injected as follows. First, a bolus of contrast was delivered, the volume of which was calculated by the following formula: $(\text{scan time} + 7) \times \text{injection rate} = \text{contrast volume}$. So for a patient with a 13 s scan time and an injection rate of 5 ml/s, the initial bolus of contrast would be $(13 + 7) \times 5 = 100$ ml. Using the dual head capability of the power injector, this initial bolus was immediately followed by 40 ml mixture of 30% contrast/70% saline, which was then followed by 10 ml of saline.

CT reconstruction

For each patient the DSCT scans were reconstructed into 9 image series each at a different phase in the cardiac cycle starting at 30% and increasing at 5% increments until 70%. Phases from 0–25% to 75–100% were not reconstructed because those phases fell outside the window during which the ECG-based tube current modulation used the full tube current. The nominal temporal resolution was 83 ms.

Each series was given a separate, randomized anonymous identification number. The images contained no information regarding patient identification or phase of the cardiac cycle.

Image analysis

Images were reviewed by one observer with 7 years experience as a board-certified Radiologists specializing in cardiac imaging. For each series, the reader was blind to patient information, the patient's heart rate, and the phase of the cardiac cycle for which the images in that series had been reconstructed.

The reader used the American Heart Association 15 segment model [8] (Fig. 1) to score the coronary arteries. For each segment, the reader gave a subjective score of coronary image sharpness from 0 to 4, with 0 representing minimal vessel sharpness (maximal motion artifact) and 4 representing maximal vessel sharpness (Table 2). The sharpness score assigned to a coronary segment represented the part of the coronary segment with the lowest sharpness/maximal motion artifact.

Using the American Heart Association 15 segment model, the coronary segments were then grouped into four coronary vessels: the right coronary artery (RCA), the left main coronary (LM), the left anterior descending coronary artery (LAD), and the circumflex coronary artery (Cx). For each vessel, the image sharpness score of the vessel was the average of the scores of the segments comprising the vessel.

Segments 1–4 represented the RCA. For patients with left dominance, only segments 1–3 were used. Segment 5 was the LM. Segments 6, 7, 8 represented the LAD. Segments 11, 12, 13 represented the Cx. The remaining segments (9, 10, 14, 15) represent diagonals, the second obtuse marginal, and the posterior descending in a left dominant system, which are inconsistently present or inconsistently visualized and were not included as parts of the LAD or Cx for the purposes of this analysis.

Statistical analysis

Summary statistics were reported for patient demographics (age, gender, body mass index, heart rate) for low versus high heart rate patients and comparisons were made using two sample *t*-test for continuous variables and Fisher's exact test for categorical variables.

Graphical analysis was done to display the pattern of coronary image sharpness for each of the 4 coronary arteries at various reconstruction phases in the cardiac cycle for low heart-rate and high heart-rate patients. This graphical approach also allowed us to visually assess the cardiac phases with best coronary image sharpness. Repeated measures analysis of variance was used

to identify the phase of cardiac cycle that had maximal coronary sharpness. The phase with maximum sharpness was compared to other phases in a pair-wise manner using paired *t*-test. The phase(s) that were not significantly different from the “best” phase identified were reported. This was done separately for high and low heart rate groups.

Comparison of coronary sharpness between the patients with high versus low heart rate was made using generalized estimating equations to account for the correlation associated with measurements within the same patient but at different phases of the cardiac cycle, and also adjusting for age, gender, and BMI. The analysis was performed separately for each of the 4 coronary arteries (RCA, LM, LAD, Cx). Graphical analysis was also done to display the pattern of coronary sharpness for each of the 4 coronary artery types at various phases of cardiac cycles for low heart-rate and high heart-rate patients.

Results

Demographics

Mean heart rate for low heart rate patients was 58.1 ± 8.2 bpm and for the high heart rate patients was 82.3 ± 8.5 bpm ($P < 0.001$). Low and high heart rate patients were similar in age (57.0 ± 10.1 years, 55.6 ± 11.4 years, respectively, $P = 0.64$) and body mass index (27.9 ± 3.9 , 28.2 ± 5.7 , respectively, $P = 0.78$) But there were significantly more male patients in the low heart rate group (19 males, 11 females) than the high heart rate group (7 males, 23 females). $P < 0.001$.

Best phase for low and high heart rate

For low heart rate patients the highest sharpness scores for all four vessels (RCA, LM, LAD, and Cx) were at the 65 or 70% phase of the cardiac cycle, which are end-diastolic cardiac phases. For high heart rate patients the highest sharpness scores were between the 35 and 45% phase, which are end-systolic phases. The exception was the left main for which 35, 40, and also 60% (a diastolic phase) were not statistically different from each other. The phases with maximal coronary image sharpness are summarized in Table 3.

Comparing low heart rate and high heart rate coronary sharpness per phase

The per phase comparison between low and high heart rate images sharpness are summarized in Table 4.

Overall, the low heart rate patients had higher coronary sharpness at most cardiac phases, and in particular had statistically significantly higher image sharpness at cardiac phases from 55 to 70% (diastolic phases) for all four coronary arteries ($P < 0.0001$). Low heart rate patients also had significantly higher coronary sharpness in the RCA, LAD, and Cx in some early systolic reconstructions (30–35%).

However, patients with high heart rates had statistically significantly higher coronary sharpness in the 45% cardiac phase for all four vessels ($P < 0.0001$) and higher coronary sharpness at the 40% for three of four coronary arteries: RCA ($P = 0.0008$), LAD ($P = 0.0006$) and Cx ($P < 0.0001$). The 40–45% cardiac phases correspond to end-systole. An example of the higher coronary sharpness in systolic phases in a high heart rate patient is shown in Fig. 2. Graphical display of coronary sharpness compared to heart rate is shown in Figs. 3, 4, 5 and 6.

Discussion

In this study, we found that in patients with low heart rates imaged using DSCT, the highest coronary sharpness (least motion artifact) occurred in end-diastolic reconstructions for all four

vessels (RCA, LM, LAD, Cx). However, for patients with high heart rates, the best coronary image sharpness occurred in the end-systolic reconstructions. When coronary sharpness at each reconstruction phase was directly compared between low and high heart rate patients, low heart rate patients had higher coronary sharpness in early systolic and all diastolic cardiac phases. However, high-heart rate patients had higher coronary sharpness than low heart rate patients in the end-systolic cardiac phases (40–45%).

Coronary motion throughout the cardiac cycle explains these findings. In the cardiac cycle there are two relatively quiescent phases, one in end-systole and one in end-diastole. In patients with low heart rates, the end-diastolic quiescent phase is longer and is associated with more slowly moving coronary arteries than the end-systolic quiescent phase [9]. Thus, in low heart rate patients, end-diastole is the part of the cardiac cycle with the best coronary image sharpness (least motion artifact).

However, when the heart rate increases, end-diastole becomes shorter and coronary motion during end-diastole becomes more rapid. Meanwhile, the length of end-systole changes little, so that in high heart rate patients end-systole is the portion of the cardiac cycle with the least motion [9]. The exception is the left main, which experiences less motion than other vessels and whose image sharpness changes less than the others. Here a 60% (diastolic) phase was equivalent to end-systolic reconstructions.

These findings are significant because a variety of radiation dose-reduction techniques exist in which optimal tube current is used only during selected parts of the cardiac cycle [10]. This requires the user to select the optimal cardiac reconstruction phase before scanning. Our findings suggest that end-diastolic phases should be chosen for patients with heart rates ≤ 70 bpm and end-systolic phases for patients with heart rates > 70 bpm.

Our findings are similar to studies by Wintersperger [11] and Leshka [12], which used 64-detector scanners and the studies by Weustink [5] and Seifarth [4], which used DSCT scanners. These studies found that in low heart rate patients, end-diastolic reconstructions were optimal, but in high heart rate patients, end-systolic reconstructions were optimal.

However, our findings are at odds with a previous study of 64-detector scanners by Leschka [13] and a separate study of DSCT also by Leschka [7], which found in both low and high heart rate groups that diastolic cardiac phases were the optimal for reconstruction; though they did find that as heart rate increased the amount of motion artifact on the systolic images became closer to that of the diastolic images [7]. The reason for the difference between our study and those of Leschka are unclear, but our study and those of Leschka do confirm that in DSCT, at high heart rates, systolic phase images take on greater importance. Application of dose-reduction techniques should take this into account.

The second finding of our study was that when comparing high heart rate and low heart rate patients, the high heart rate patients had higher image sharpness at end-systole than low heart rate patients had at end-systole; though the best overall image sharpness was in low heart rate patients in diastole. The reason why high heart rate patients could have higher image sharpness at any cardiac phase is unclear. It is possible the higher heart rate patients had more regular duration of end-systole than the lower heart rate patients, leading to better image quality at end-systole. Further investigation into the reasons behind this difference could be helpful in finding methods for improving image sharpness and decreasing motion artifact in the future.

There are several limitations to this study. First, we studied only the phases of the cardiac cycle from 30 to 70%. The patients were scanned with ECG-based tube current modulation set for maximal tube current in the cardiac phases from 30 to 70%. The remaining cardiac phases were acquired with low tube current and were therefore noisier than the 30–70% reconstructions,

which would have confounded comparisons of image sharpness/motion artifact. However, most previous studies have shown that images outside this range are low-sharpness/high-motion and therefore this should not affect the results of the study [7].

A second limitation is that the high and low heart rate groups had different percentages of males and females, though age, and BMI did not differ between groups. It is theoretically possible that coronary motion within the cardiac cycle could be different between men and women, which is why we adjusted our results for gender, as well as age and BMI.

A third limitation is that we did not account for heart rate variability. Patients with premature ventricular contractions or other irregular beats would have less sharp images. A systematic difference in heart rate variability between groups could have theoretically affected the results of this study.

A fourth limitation is that coronary image sharpness was assessed subjectively, which introduces the possibility of bias into the study. However, other studies assessing image quality over the cardiac cycle have used similar subjective scoring systems [4,5,7,11–13].

In conclusion, using DSCT scanning at low heart rates, optimal image sharpness is obtained in end-diastole. In high heart rate patients, optimal image sharpness is obtained in end-systole. This should be taken into account when using dose reduction techniques that limit the useable phases of the cardiac cycle.

References

1. Flohr TG, McCollough CH, Bruder H, Petersilka M, Gruber K, Suss C, Grasruck M, Stierstorfer K, Krauss B, Raupach R, Primak AN, Kuttner A, Achenbach S, Becker C, Kopp A, Ohnesorge BM. First performance evaluation of a dual-source CT (DSCT) system. *Eur Radiol* 2006;16(2):256–268. [PubMed: 16341833]
2. Heuschmid M, Burgstahler C, Reimann A, Brodoefel H, Mysal I, Haeberle E, Tsiflikas I, Claussen CD, Kopp AF, Schroeder S. Usefulness of noninvasive cardiac imaging using dual-source computed tomography in an unselected population with high prevalence of coronary artery disease. *Am J Cardiol* 2007;100(4):587–592. [PubMed: 17697811]
3. Weustink AC, Meijboom WB, Mollet NR, Otsuka M, Pugliese F, van Mieghem C, Malago R, van Pelt N, Dijk-shoorn ML, Cademartiri F, Krestin GP, de Feyter PJ. Reliable high-speed coronary computed tomography in symptomatic patients. *J Am Coll Cardiol* 2007;50(8):786–794. [PubMed: 17707184]
4. Seifarth H, Wienbeck S, Pusken M, Juergens KU, Maintz D, Vahlhaus C, Heindel W, Fischbach R. Optimal systolic and diastolic reconstruction windows for coronary CT angiography using dual-source CT. *AJR Am J Roentgenol* 2007;189(6):1317–1323. [PubMed: 18029865]
5. Weustink AC, Mollet NR, Pugliese F, Meijboom WB, Nieman K, Heijnenbroek-Kal MH, Flohr TG, Neefjes LA, Cademartiri F, de Feyter PJ, Krestin GP. Optimal electrocardiographic pulsing windows and heart rate: effect on image quality and radiation exposure at dual-source coronary CT angiography. *Radiology* 2008;248(3):792–798. [PubMed: 18710975]
6. Matt D, Scheffel H, Leschka S, Flohr TG, Marincek B, Kaufmann PA, Alkadhi H. Dual-source CT coronary angiography: image quality, mean heart rate, and heart rate variability. *AJR Am J Roentgenol* 2007;189(3):567–573. [PubMed: 17715102]
7. Leschka S, Scheffel H, Desbiolles L, Plass A, Gaemperli O, Valenta I, Husmann L, Flohr TG, Genoni M, Marincek B, Kaufmann PA, Alkadhi H. Image quality and reconstruction intervals of dual-source CT coronary angiography: recommendations for ECG-pulsing windowing. *Invest Radiol* 2007;42(8):543–549. [PubMed: 17620936]
8. Austen WG, Edwards JE, Frye RL, Gensini GG, Gott VL, Griffith LS, McGoon DC, Murphy ML, Roe BB. A reporting system on patients evaluated for coronary artery disease. Report of the ad hoc committee for grading of coronary artery disease, council on cardiovascular surgery, American Heart Association. *Circulation* 1975;51(4 suppl):5–40. [PubMed: 1116248]

9. Husmann L, Leschka S, Desbiolles L, Schepis T, Gaemperli O, Seifert B, Cattin P, Frauenfelder T, Flohr TG, Marincek B, Kaufmann PA, Alkadhi H. Coronary artery motion and cardiac phases: dependency on heart rate—implications for CT image reconstruction. *Radiology* 2007;245(2):567–576. [PubMed: 17848683]
10. Stolzmann P, Scheffel H, Schertler T, Frauenfelder T, Leschka S, Husmann L, Flohr TG, Marincek B, Kaufmann PA, Alkadhi H. Radiation dose estimates in dual-source computed tomography coronary angiography. *Eur Radiol* 2008;18(3):592–599. [PubMed: 17909816]
11. Wintersperger BJ, Nikolaou K, von Ziegler F, Johnson T, Rist C, Leber A, Flohr T, Knez A, Reiser MF, Becker CR. Image quality, motion artifacts, and reconstruction timing of 64-slice coronary computed tomography angiography with 0.33-second rotation speed. *Invest Radiol* 2006;41(5):436–442. [PubMed: 16625106]
12. Leschka S, Wildermuth S, Boehm T, Desbiolles L, Husmann L, Plass A, Koepfli P, Schepis T, Marincek B, Kaufmann PA, Alkadhi H. Noninvasive coronary angiography with 64-section CT: effect of average heart rate and heart rate variability on image quality. *Radiology* 2006;241(2):378–385. [PubMed: 16966483]
13. Leschka S, Husmann L, Desbiolles LM, Gaemperli O, Schepis T, Koepfli P, Boehm T, Marincek B, Kaufmann PA, Alkadhi H. Optimal image reconstruction intervals for non-invasive coronary angiography with 64-slice CT. *Eur Radiol* 2006;16(9):1964–1972. [PubMed: 16699752]

Fig. 1.
American heart association 15 segment model

Fig. 2. 65-year-old woman with chest pain. Axial DSCT images obtained in **a** diastole (60% of the R–R interval) and **b** systole (40% of the R–R interval) in a patient with heart rate >70 beats per minute show better image sharpness in systole

Fig. 3.
Right coronary artery sharpness vs. cardiac phase

Fig. 4.
Left main sharpness vs. cardiac phase

Fig. 5.
Left anterior descending coronary artery sharpness vs. cardiac phase

Fig. 6.
Circumflex coronary artery sharpness vs. cardiac phase

Table 1

Patient size specific technique chart to determine appropriate mAs

Patient width at level of dome of the liver	mAs/rotation
20.0–24.9 cm	90
25.0–29.9 cm	120
30.0–34.9 cm	170
35.0–39.9 cm	240
40.0–44.9 cm	340
45.0–50.0 cm	415

Table 2

Coronary image sharpness scoring

Coronary sharpness score	Description
4—Excellent	Coronary walls are sharp and well-defined with no blurring.
3—Good	Calcifications in a segment show little or no streak Coronary walls may be blurred but lumen is clearly discernible and separate from the surrounding fat. Calcifications present may have small amount of streak
2—Fair	Vessel walls may show mild streaking from motion, but a defined lumen is identifiable. Calcifications may show mild streaking beyond the lumen of the vessel
1—Poor	Severe streaking comprising more than 50% of the vessel lumen. Calcifications may streak beyond the vessel walls
0—Extremely poor	No definable lumen. If in cross section, vessel appears only as a blur. Vessels that run in plane may appear as multiple vessels. Calcifications do not appear as defined points

Table 3

Cardiac phases with maximal coronary sharpness

	Phase with maximal image sharpness (mean sharpness score)	All phases not significantly different from phase with maximal image sharpness (mean sharpness score) ^a
<i>High heart rate</i>		
RCA	40% (2.09)	45% (2.09)
LM	35% (2.90)	40% (2.77) and 60% (2.87)
LAD	35% (2.48)	40% (2.23)
CX	40% (2.27)	45% (2.08)
<i>Low heart rate</i>		
RCA	70% (2.90)	65% (2.76)
LM	65% (3.33)	70% (3.31)
LAD	70% (2.67)	65% (2.60)
Cx	70% (2.71)	65% (2.71)

^a All phases not listed were significantly different from phase with maximal sharpness

Table 4

Coronary image sharpness at low and high heart rate by coronary artery adjusted for age, gender, and body mass index

Cardiac phase (%)	RCA		LM		LAD		CX	
	Estimate (SE) ^a	P-value	Estimate (SE) ^a	P-value	Estimate (SE) ^a	P-value	Estimate (SE) ^a	P-value
30	1.09 (0.15)	<0.0001	0.28 (0.28)	0.33	-0.03 (0.15)	0.86	0.77 (0.16)	<0.0001
35	0.60 (0.15)	<0.0001	-0.50 (0.28)	0.08	-0.52 (0.15)	0.0006	-0.15 (0.16)	0.37
40	-0.46 (0.15)	0.0025	-0.43 (0.29)	0.14	-0.46 (0.15)	0.0030	-0.77 (0.17)	<0.0001
45	-0.89 (0.15)	<0.0001	-1.10 (0.28)	0.0001	-0.83 (0.15)	<0.0001	-1.13 (0.16)	<0.0001
50	-0.04 (0.15)	0.80	0.24 (0.28)	0.40	0.02 (0.15)	0.88	0.28 (0.16)	0.084
55	0.91 (0.15)	<0.0001	1.24 (0.28)	<0.0001	0.61 (0.15)	<0.001	1.37 (0.16)	<0.0001
60	1.51 (0.15)	<0.0001	1.79 (0.28)	<0.0001	1.07 (0.15)	<0.001	1.62 (0.17)	<0.0001
65	1.79 (0.15)	<0.0001	1.43 (0.28)	<0.0001	0.82 (0.15)	<0.001	1.19 (0.16)	<0.0001
70	1.55 (0.15)	<0.0001	1.12 (0.28)	<0.0001	0.67 (0.15)	<0.001	0.93 (0.16)	<0.0001

^a A positive estimate means that the coronary sharpness score was higher (better) for low heart rate. A negative score means the coronary sharpness score was higher (better) for the high heart rate. SE standard error of the estimate