

# The Influence of Reconstruction Algorithm and Heart Rate on Coronary Artery Image Quality and Stenosis Detection at 64-Detector Cardiac CT

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## Index terms:

Computed tomography (CT)  
Reconstruction  
Algorithm  
Phantom  
Coronary artery angiography

DOI:10.3348/kjr.2009.10.3.227

*Korean J Radiol* 2009; 10: 227-234

Received July 1, 2008; accepted  
after revision November 24, 2008.

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**Objective:** We wanted to evaluate the impact of two reconstruction algorithms (halfscan and multisector) on the image quality and the accuracy of measuring the severity of coronary stenoses by using a pulsating cardiac phantom with different heart rates (HRs).

**Materials and Methods:** Simulated coronary arteries with different stenotic severities (25, 50, 75%) and different luminal diameters (3, 4, 5 mm) were scanned with a fixed pitch of 0.16 and a 0.35 second gantry rotation time on a 64-slice multidetector CT. Both reconstruction algorithms (halfscan and multisector) were applied to HRs of 40–120 beats per minute (bpm) at 10 bpm intervals. Three experienced radiologists visually assessed the image quality and they manually measured the stenotic severity.

**Results:** Fewer measurement errors occurred with multisector reconstruction ( $p = 0.05$ ), a slower HR ( $p < 0.001$ ) and a larger luminal diameter ( $p = 0.014$ ); measurement errors were not related with the observers or the stenotic severity. There was no significant difference in measurements as for the reconstruction algorithms below an HR of 70 bpm. More nonassessable segments were visualized with halfscan reconstruction ( $p = 0.004$ ) and higher HRs ( $p < 0.001$ ). Halfscan reconstruction had better quality scores when the HR was below 60 bpm, while multisector reconstruction had better quality scores when the HR was above 90 bpm. For the HRs between 60 and 90 bpm, both reconstruction modes had similar quality scores. With excluding the nonassessable segments, both reconstruction algorithms achieved a similar mean measured stenotic severity and similar standard deviations.

**Conclusion:** At a higher HR (above 90 bpm), multisector reconstruction had better temporal resolution, fewer nonassessable segments, better quality scores and better accuracy of measuring the stenotic severity in this phantom study.

**N**on-invasively evaluating coronary arterial stenoses is a major challenge for multidetector computed tomography (MDCT). There have been rapid advances of the electrocardiographic (ECG) gated cardiac CT scanning systems and techniques, including more detector rows and the advanced postprocessing software, and CT coronary angiography can now be performed at normal heart rates (HRs) with high sensitivity and specificity for detecting significant coronary stenoses (1–3). The recently introduced 64-detector MDCT allows using a sub-second gantry rotation speed. The 2 major reconstruction algorithms for CT coronary angiography are the halfscan algorithm and the multisector algorithm. The multisector reconstruction algorithm retrospectively reconstructs images from different cardiac cycles (two to five) and this could theoretically reduce the effective temporal resolu-

tion to a minimum of 65 ms, while the halfscan algorithm reconstructs images from a single cardiac cycle. The multisector reconstruction algorithm usually achieves better temporal resolution than the standard halfscan reconstruction algorithm does (4). The combination of fast gantry rotation and the multisector algorithm is expected to improve the performance of coronary CT angiography at higher HRs. Using a pulsating cardiac phantom, we investigate the influence of HR on the two reconstruction algorithms for the image quality, the number of nonassessable segments and the accuracy of detecting stenoses on a 64-slice MDCT.

## MATERIALS AND METHODS

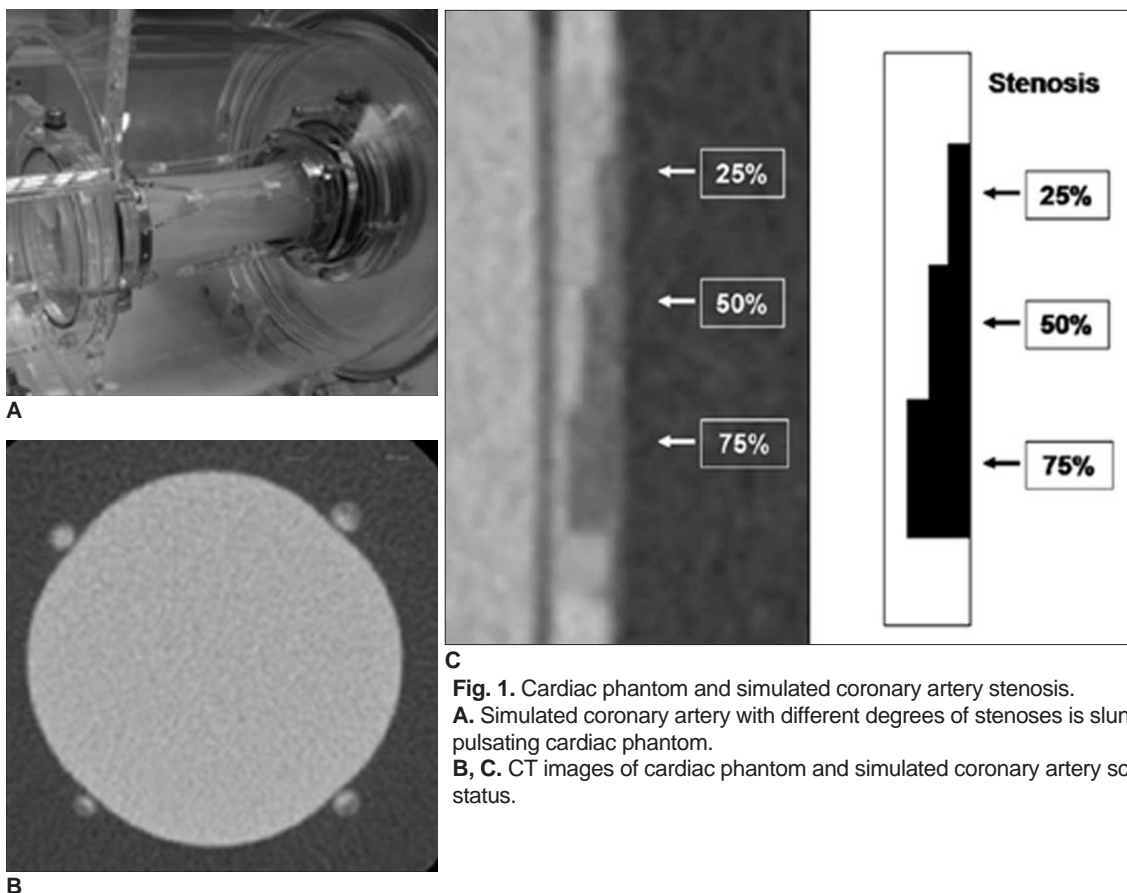
### Cardiac Phantom

The phantom consisted of 5 components; the driver, the control, the support, the balloon phantom and the ECG. The phantom's end-diastolic phase, with the longest motion-free periods, was designed at 85% of the R-R interval despite of the changes of the HR. Different sized acrylic tubes (3, 4 and 5 mm) were used to simulate coronary arteries. Inside them, artificial plaques (+ 100 Hounsfield unit [HU]) simulated different degrees of

stenosis (0, 25, 50 and 75%). These tubes were attached to the surface of a pulsating cardiac phantom (Fuyo Co., Tokyo, Japan) to simulate real heart motion. We diluted iodinated contrast medium (Angiografin, 306 mg I/ml, Schering AG, Berlin, Germany) with distilled water to a density of about 330 HU, and then we filled the cardiac phantom and the simulated coronary arteries with it (Fig. 1).

### Multidetector CT and Reconstruction

The pulsating cardiac phantom equipped with the simulated coronary arteries was scanned with a 64-slice MDCT (LightSpeed VCT; GE Medical Systems, Milwaukee, WI). First, we scanned the cardiac phantom with static scanning to confirm the lumen size and the degree of stenosis in the simulate coronary arteries. We then scanned the phantom with an ECG-gated cardiac helical scan. The scan protocol was 120 kV, 600 mA, 0.35 second/rotation, a 0.625 mm slice-thickness, a 0.625 mm slice interval, a 0.16 fixed pitch factor and a 50 cm field of view (FOV) for both the static and cardiac helical scanning. The phantom and the simulated coronary arteries were scanned at 9 different HRs: 40, 50, 60, 70, 80, 90, 100, 110 and 120 beats per minute (bpm). Both reconstruction



**Fig. 1.** Cardiac phantom and simulated coronary artery stenosis.

**A.** Simulated coronary artery with different degrees of stenoses is slung on surface of pulsating cardiac phantom.

**B, C.** CT images of cardiac phantom and simulated coronary artery scanned at static status.

algorithms, the halfscan reconstruction (single sector reconstruction, Snapshot Segment) and the multisector reconstruction (two sector reconstruction, Snapshot Burst), were applied to the 9 different HRs with the reconstructed phase at 85% of the R-R interval of the diastolic cardiac cycle of the phantom. In this study, we choose a two-sector reconstruction algorithm instead of a four-sector reconstruction algorithm because the number of sectors used for image reconstruction in the multisector reconstruction is fluctuant (5). The CT scanner will automatically adjust the number of sector used according to the HR. If the four-sector reconstruction algorithm was chosen, then the number of sectors used may oscillate between one to four sectors depending on the HR. A two-sector reconstruction algorithm was used in this study to ensure that the number of sectors used at higher HRs was constant.

The effective temporal resolution (175 msec) is half of the gantry rotation time (GRT, 350 msec) in the halfscan reconstruction, but actually the time required for one image acquisition includes the time gantry rotation for 180° plus a beam fan angle (approximately 30–60°). So, the temporal window is approximately around 60–66% of the GRT for the halfscan reconstruction. In the multisector reconstruction with the M segment, the effective temporal resolution varies between GRT/2 and GRT/2M (6–9).

**Image Quality and Data Analysis**

There was a total of 324 segments of the simulated coronary arteries to be analyzed ([3 segments with differ-

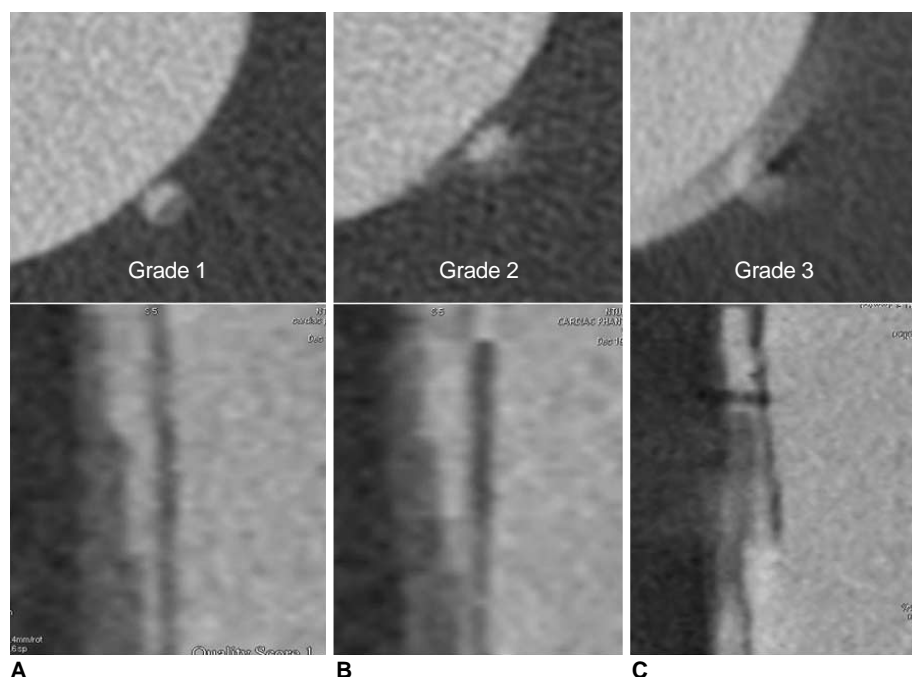
ent degrees of stenosis + 1 non-stenotic segment] × 3 different sizes of acrylic tubes × 9 different HRs × 3 observers). Analysis was performed on an AW workstation (AW 4.3, GE Medical Systems, Milwaukee, WI) by three experienced radiologists who were kept blinded to the luminal diameters, the degree of stenosis, the HR and the reconstruction algorithm. The images were segmented and then presented to the radiologists independently. The radiologists measured the diameter of the patent lumen from each segmented image, instead of the stenotic rate. By doing this, the radiologist could not know the actual diameter of each segment since the stenotic and nonstenotic segments were separately presented. The images were reviewed with a fixed viewing window of 800/200 (WW/WL) and a viewing FOV of 3.2 cm. The axial images and the multiplanar reformatted images along the coronary axis were read. An average luminal diameter was obtained from three manual measurements of each segment. The degree of stenosis was finally calculated after collecting all the data.

The degree of stenosis (%) was calculated as:

$$\frac{(\text{the luminal diameter at the nonstenotic segment} - \text{the luminal diameter at the stenotic segment}) \times 100\%}{\text{the luminal diameter at the nonstenotic segment}}$$

The CT scans were interpreted independently by three board-certified radiologists.

Image quality was recorded on a 3-point scale. Grade 1 equals a good quality image without artifacts, grade 2 equals an acceptable quality image with mild motion



**Fig. 2.** Image quality score.  
**A.** Grade 1 equals good quality without artifacts.  
**B.** Grade 2 equals acceptable quality with mild motion artifacts.  
**C.** Grade 3 equals nondiagnostic quality with significant motion artifacts.

artifacts that do not interfere with the diagnosis and grade 3 equals a nondiagnostic, poor quality image with significant motion artifacts (Fig. 2). The readers' scores were averaged for each segment. Paired *t* tests were used to analyze the differences in image quality. *P* value less than 0.05 were considered to indicate a significant difference.

**Assessable and Nonassessable Segments**

Segments with a quality score of 3 were defined as nonassessable segments due to the nondiagnostic image quality, and the segments with a quality score of 1 or 2 were defined as assessable segments. Both the numbers of nonassessable segments and the measurement error, defined as the relative error, of all the segments were recorded. The definition of relative error will be further discussed in the results section. The correlations between the number of nonassessable segments, the relative error and the reconstruction algorithm, HR, luminal diameter, stenotic severity and observers were analyzed.

**RESULTS**

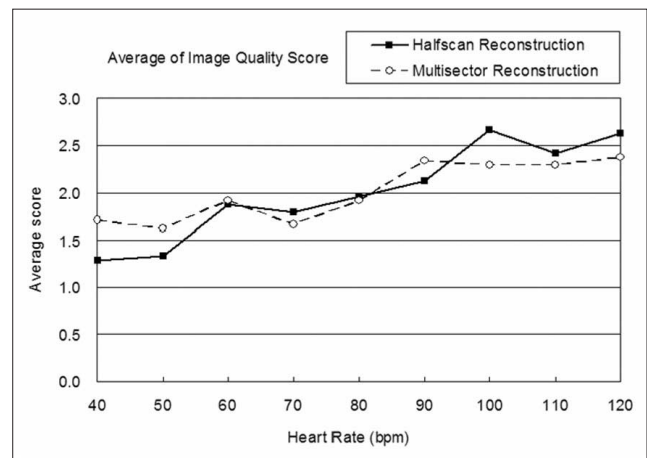
**Temporal Window**

At an HR of 40 and 50 bpm, the temporal window was 227 ms for both the halfscan and multisector reconstructions, so the fan angle in our study was about 53.5°. With an increasing HR (60–120 bpm), the temporal window improved in the multisector reconstruction with the best temporal window being 127 ms, while the temporal window in the halfscan reconstruction remained unchanged at 227 ms (Fig. 3).

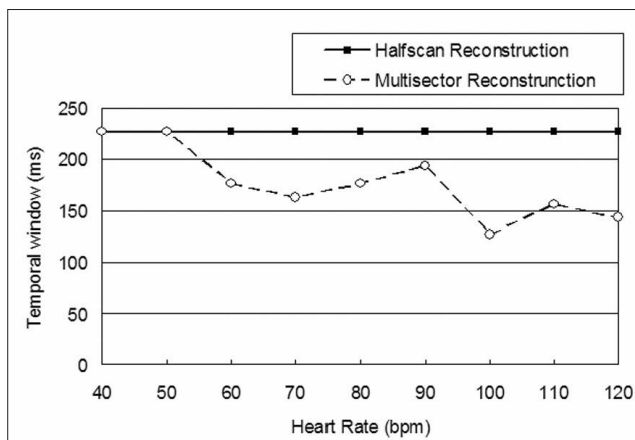
**Image Quality Score**

In our study, a lower score equates with better image

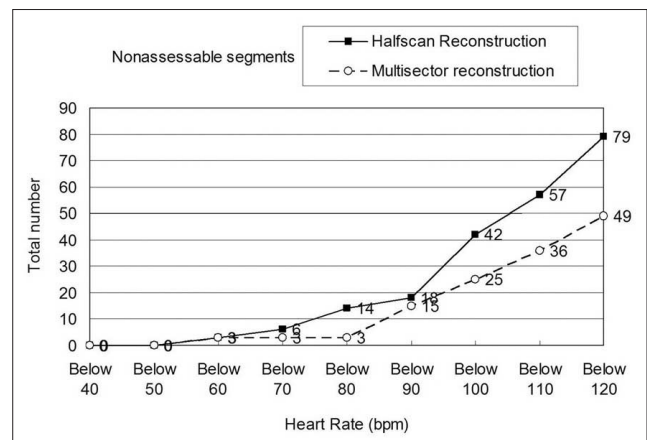
quality. At HRs below 60 bpm, the halfscan reconstruction achieved a better image quality than the multisector reconstruction did. In contrast, at HRs above 70 bpm (70–120 bpm), the multisector reconstruction achieved better image quality than the halfscan reconstruction did, except for a paradoxical reverse phenomenon at an HR of 90 bpm (Fig. 4). At an HR of 90 bpm, the halfscan reconstruction performed better than the multisector reconstruction despite of the tendency for a better performance of multisector reconstruction at higher HRs. Even so, at the intersection HR of 60–80 bpm, the two reconstruction algorithms provided equally good images. In summary, multisector reconstruction achieved better or equally good image quality at an HR higher than 60 bpm.



**Fig. 4.** Image quality score is average of scores given by three radiologists. At heart rate between 60 and 90 bpm, both reconstruction algorithms achieved similar quality scores. At other rates, halfscan reconstruction scored better at lower heart rates and multisector reconstruction scored better at high heart rates. Paradoxical reversal was noted at heart rate of 90 bpm.



**Fig. 3.** Temporal window shows waveform improvement with heart rate above 60 bpm and it ranges between 127 and 227 msec in multisector reconstruction algorithm, but it does not change in halfscan reconstruction.



**Fig. 5.** Summation of nonassessable segments by heart rate. Multisector reconstruction results in fewer nonassessable segments, and especially at higher heart rates. This trend is most obvious above heart rate of 80 bpm.

**Nonassessable Segments**

The number of nonassessable segments increased with an increasing HR for both algorithms. The trend for an increasing number of nonassessable segments with an increasing HR was more obvious for the halfscan than for the multisector reconstruction algorithm. For the 324 segments, 79 (24.4%) halfscan segments were nonassessable and 49 (15.1%) multisector segments were nonassessable. This advantage of multisector reconstruction was conspicuous above an HR of 80 bpm (Fig. 5). On the logistic regression analysis, the number of nonassessable segments was correlated with the reconstruction algorithm ( $p = 0.004$ ) and HR ( $p < 0.001$ ), but not with the luminal diameter, the degree of stenosis and the observer.

**The Accuracy of Detecting Stenosis**

With excluding the nonassessable segments, we found no significant difference between the reconstruction algorithms for the accuracy of measuring the degree of stenosis (Fig. 6).

We also used the relative error to analyze the accuracy of measuring the degree of stenosis according to the following equation:

$$\text{Relative error (\%)} = \frac{(\text{the measured degree of stenosis} - \text{the true degree of stenosis}) \times 100\%}{\text{true degree of stenosis}}$$

So less relative error represented better accuracy.

When analyzing the accuracy of stenosis detection, also referred to as the relative error, both the assessable and nonassessable segments should be included. Because the relative error of the nonassessable segments is measureless, we have to make an assumption for the relative error of the nonassessable segments. The relative error of the nonassessable segments could be presumed to be a variable degree of error (100, 150 and 200%) because the relative error of the assessable segments varies from 0 to 196% and the relative error of the nonassessable segments should be presumed to be greater than that of the assess-

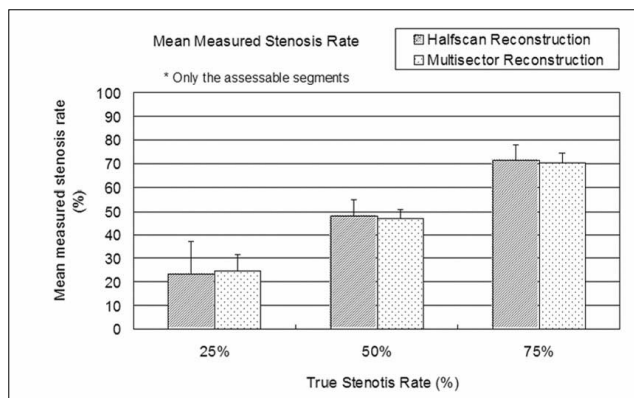
**Table 1. Correlation of Relative Error (Representing Accuracy of Stenosis Detection) with Luminal Diameter, Stenotic Severity, Observer, Reconstruction Mode and Heart Rate**

Variables	X = 100%	X = 150%	X = 200%
Luminal diameter	0.012*	0.014	0.017
Stenotic severity	0.929	0.282	0.098
Observer	0.192	0.269	0.322
Reconstruction mode	0.024	0.005	0.002
Heart rate	0.000	0.000	0.000

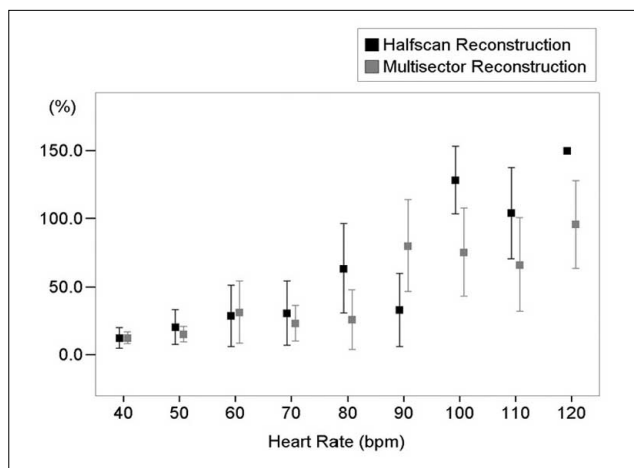
Note.— X = Presumed relative error of nonassessable segments  
 \*Number represents  $p$  value

able ones. On the linear regression analysis, better accuracy of stenosis detection (a smaller relative error) was correlated with multisector reconstruction, slower HRs and a larger luminal diameter, and it was not correlated with the degree of stenosis and the observer (Table 1). For example, at presumed 150% error of the nonassessable segment, better accuracy was correlated with multisector reconstruction ( $p = 0.005$ ), slower HRs ( $p < 0.001$ ) and larger luminal diameter ( $p = 0.014$ ), and it was not correlated with the degree of stenosis and the observer. Despite of the variable degree of the assumptive relative error of the nonassessable segments, the correlation remained the same.

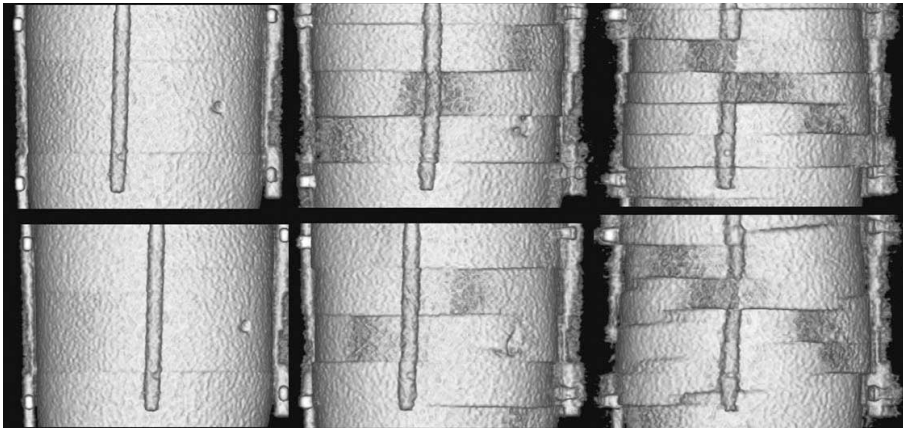
At HR of 40–70 bpm; both reconstruction algorithms achieved a similar relative error. However, multisector reconstruction achieved a better performance at an HR



**Fig. 6.** Excluding nonassessable segments, there is no significant difference between reconstruction algorithms for mean measured stenotic severity and standard deviation.



**Fig. 7.** Relative errors of both assessable and nonassessable segments were analyzed. At heart rates from 40 to 70 bpm, there are similar small measurement errors with using both reconstruction algorithms. Multisector reconstruction achieved better performance at heart rate above 80 bpm, except at heart rate of 90 bpm.



**Fig. 8.** Upper images: volume rendering images of halfscan reconstruction at heart rates of 40, 80 and 120 bpm (left to right). Lower images: volume rendering images of multisector reconstruction at heart rates of 40, 80 and 120 bpm (left to right). There is fewer cardiac motion related banding artifacts noted on multisector reconstruction, and especially at higher heart rates.

above 80 bpm, except at an HR of 90 bpm (Fig. 7).

### Artifact

The volume rendering images of the two reconstruction algorithms at different HRs showed the better performance of the multisector reconstruction algorithm at higher HRs (Fig. 8). There was less cardiac motion related to banding artifacts for the multisector reconstruction algorithm, and especially at higher HRs.

## DISCUSSION

The temporal resolution of MDCT with using the halfscan reconstruction algorithm has improved (6–9) and this permits reliable assessment of the main coronary branches in patients with HRs below 65 bpm (10, 11). However, the temporal resolution of the gated reconstruction images is of major concern when considering the heart because the motion of the coronary arteries can reach up to 69.5 mm/s during the cardiac cycle (10). So we confirmed that even for an HR below 65, the halfscan algorithm provided better image quality than the multisector reconstruction algorithm did. When HRs are faster, the temporal resolution of the halfscan reconstruction algorithm will be too long for a motion-free image. The multisector reconstruction algorithm retrospectively composes images from different cardiac cycles (two to five), which theoretically could significantly reduce the effective temporal resolution (12). Thus, marked improvement of the effective temporal resolution theoretically achieves better image quality at faster HRs. But the maximum benefit for temporal resolution occurs when the gantry rotation and cardiac motion are fully asynchronous, which depends on the relationship between the HR and the pitch (13–15), so the image quality of both reconstruction algorithms will degrade with heart rates higher than 90 bpm, as was our result. A successful multisector

reconstruction also requires no misregistration due to arrhythmia or a changing HR (16). Coronary artery visualization and analysis requires high resolution. However, it cannot be expected that the coronary artery returns to exactly the same position from one cardiac cycle to the next. This may probably slightly blur the images and thus reduce the image quality. One disadvantage of multisector reconstruction is the nonconstant improvement of the temporal resolution because of synchronous gantry rotation and the cardiac cycle; this also explains the paradoxical reverse, at an HR of 90 bpm, of both the image quality (Fig. 4) and the accuracy of stenosis detection (Fig. 7), as was shown in our study. Similar results were reported in a 32-patient study that found better image quality with an HR > 75 bpm than with an HR of 65–75 bpm (17), though the temporal resolution, HR, GRT and pitch were different from that of our current study. Another disadvantage of multisector reconstruction is the higher radiation exposure required at a lower pitch for obtaining high spatial resolution, and this radiation exposure is estimated to be 30% higher than that of the halfscan reconstruction (18). There might be a certain degree of ethical concern for the unnecessary radiation dose if a lower pitch is routinely used for low HR patients for both the halfscan and multisector reconstructions. Using ECG-pulsed tube current modulation should be considered to decrease the radiation dose (19).

Two studies (4, 20) have reported a decreased image quality with using halfscan reconstruction in MDCT units when the HR exceeds 65 bpm in phantoms and patients. One of these studies reported that an increase in image quality by multisector reconstruction when the HR exceeds 65 bpm (variable gantry rotational speed and variable pitch values) leads to a significant increase in imaging time with using 4-detector MDCT (4). Another study reported better sensitivity, specificity, accuracy and fewer nonassessable segments with multisegment reconstruction

versus halfscan reconstruction with using a 16-slice CT scanner in 34 patients with normal HRs (21). The same group latter reported better diagnostic accuracy and longer vessel lengths that were free of motion artifacts with multisector reconstruction in all HR groups (< 65 bpm, 65–74 bpm and > 74 bpm) on 16-slice MDCT in a study of 126 patients (22). In a 32-patient study (17), there was no significant improvement in image quality in any of the HR groups with employing dual-segment reconstruction versus halfscan reconstruction and using 64-detector MDCT. They proposed that the temporal resolution (165 ms) using 64-detector MDCT and halfscan reconstruction was similar to the temporal resolution (approximately 160 ms) using 16-detector MDCT and multisector reconstruction (17). In another similar 40-patient study with HRs that ranged from 61 to 87 bpm (23), there was no significant difference of the single- and two-segment reconstruction algorithms in the number of visible segments and the quality scores. Better image quality was observed for two-segment reconstruction only at a certain HR range in that study. However, our phantom study on a 64-detector MDCT demonstrated that multisector reconstruction achieved better or equally good image quality at an HR higher than 60 bpm (Fig. 4) and better or equally good diagnostic accuracy for all the HR groups (Fig. 7), except at an HR of 90 bpm. The diagnostic accuracy was significantly better for the multisector reconstruction than that for the halfscan reconstruction at HRs of 80, 100, 110 and 120 bpm. This differences could have resulted from the lack of inter-heart beat variability in our study or the limited number of patients with a high HR in their studies (17, 23).

One advantage of our study was that the true degree of stenosis in the simulated coronary arteries was assured and this was also confirmed by static scanning. This method should be more accurate than 2-plane coronary angiography, and more objective than expensive intracoronary ultrasound (24). Another advantage was that the HRs in our study were well controlled by the pulsating cardiac phantom, and so we avoided the confounders of unexpected arrhythmia or changing HRs due to contrast medium injection and the vagal tone during breath-hold or that was due to anxiety. However, this was also a limitation, since it means our results cannot reflect the reality of clinical settings. Since our phantom had rigid vessel walls, it cannot be a good emulation of a real heart in terms of the rate of wall motion, as well as the actual distortion of the epicardial surface. In addition, a simulated coronary stenosis excludes artifacts from calcium plaque, making it less close to the real pathology seen in clinical settings. Finally, the diameters of our simulated coronary arteries (3–5 mm) do not fully represent the range of diameters of

the true main coronary arteries (1.46–6.09 mm) (25), nor do they represent the scenario of eccentric stenoses.

According to our study, multisector reconstruction achieved equally good or better diagnostic accuracy for all the HR groups and at least equally good image quality at an HR higher than 60 bpm. The application of multisector reconstruction for HRs between 60 and 80 bpm is acceptable, and the application of multisector reconstruction for the group with higher HRs would be beneficial. However, the reproducibility of our results should be confirmed in the setting of inter-heart beat variability.

In conclusion, our study results showed that at higher HRs, multisector reconstruction in a 64-detector MDCT achieved better temporal resolution, fewer nonassessable segments, better image quality, less cardiac motion related banding artifacts and less error in measuring the degree of stenosis.

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