Electron Beam CT versus 16-slice Spiral CT: How Accurately Can We Measure Coronary Artery Calcium Volume?

Objective: The purpose of this study is to investigate how accurately we can measure CAC volume using electron beam computed tomography (CT) and 16-slice spiral CT.
Materials and Methods: CAC models with known volume attached to a cardiac phantom were scanned. The error of measurement, variability between measured and real volumes and inter-scan measurement variability were obtained. For spiral CT, 7 different parameters; i.e. (1) slice-thickness (0.625mm, 1.25mm and 2.5mm), (2) retrospective spiral electrocardiograph (ECG)-gated or prospective axial ECG-triggering, (3) overlapping or non-overlapping, were included.
Results: The error of measurement was 15% on electron beam CT and 8-20% on spiral CT. CAC volumes were underestimated in 92% and overestimated in 8% of the electron beam CT scans. Volumes were underestimated in 79%, correct in 5% and overestimated in 16% of the spiral CT scans. The best measurement and the least variability was observed on 0.625mm retrospective spiral ECG-gated CT (error of 8%), a significant result (t-test: $p<0.01$) when compared with electron beam CT.
Conclusion: CAC volume measurement on CT scanners may be significantly different and often underestimates the real volume of CAC. For precise evaluation of CAC volume, thin-slice retrospective spiral ECG-gated scan using a spiral CT scanner is desirable.

The risk of myocardial infarction and sudden cardiac death is related to the coronary artery calcium (CAC) score [1,2] as defined by electron beam CT. The score is the product of volume and density of calcification as defined by Agatston [3]. Monitoring CAC is suggested to assess the progression or regression of coronary atherosclerosis, thereby documenting a risk factor which might suggest future medical intervention [4,5]. Originally, Agatston score and then volume [6] and mass [7] scoring were introduced for the quantification of CAC. However, whether CT quantification of moving CAC reflects actual CAC volume remains a matter for debate. The purpose of this study is to assess measurement accuracy by quantification of CAC models with known volume, attached to a cardiac phantom.

Materials and Methods:

An originally designed cardiac phantom, consisting of 5 components: driver, control, support, rubber balloon phantom and an ECG, was used. The phantom, mimicking the left ventricle, was filled with a mixture of water and contrast medium (58HU) to simulate non-contrast blood, and was submerged in corn oil (-118HU) simulating epicardial and pericardial fat. For CAC models, putty (501HU) with 2 sizes/volumes: 3mm/30mm^3 and 5mm/50mm^3 was packed inside rubber tubes (mimicking coronary arteries) attached to the balloon surface (Fig. 1).

For heart rate sequences, 1) low heart rate (60bpm), 2) high heart rate (85bpm), 3) high heart rate (85bpm) with shifting and 4) arrhythmia sequences were set (Fig. 2).

The ends of the balloon were stabilized to a fixed support at a distance of 10cm. However, deformity of the balloon resulted in some through-plane motion of the

calcium models themselves. The volumes of the balloon phantom were approximately 100 and 200ml at the systolic and diastolic phases, respectively. The diastolic phase of the phantom corresponded to around 80% of the R-R interval, however the duration of the diastolic phase was inconstant, depending on the heart rate.

Three sequential CT scans were repeated using both an electron beam CT scanner (C-150 XL; Imatron, South San Francisco, CA) and a 16-slice spiral CT scanner (LightSpeed Ultrafast 16; GE Medical Systems, Waukesha, WI). The scan was performed at three different starting points for the table (-1, 0 and +1mm) in order to determine the effect of the position of the 'patient' on the scoring result (to mimic interscan variability).

Electron Beam CT Protocol

The standard electron beam CT protocol used was as follows; 100msec acquisition time, 35-40 continuous gapless slices of 3mm thickness, 130kV, 625mA. The single-section mode images were obtained by ECG-triggered to 80% of the R-R interval. Image reconstruction was performed with a 512 x 512 pixel matrix using a sharp reconstruction kernel. The display field was 18cm.

Retrospective ECG-gated spiral CT protocol

Volumetric data of the phantom were obtained by helical mode with scan parameters of 0.625mm collimation width x 16 detectors, gantry rotation speeds of 0.5 (sequence 1, 4) and 0.6 (sequence 2, 3) sec/rotation, 120kV and 100mA. The pitch was set to 0.275, enabling for multisector reconstruction (where pitch is defined as table feed per gantry rotation divided by the total x-ray beam width (NxT) where N is the number of active DAS channels and T is the single DAS channel width). Multisector reconstruction

means that images, to improve temporal resolution, are retrospectively reconstructed by combining some (n=2 to 4) adjacent cardiac cycles [8]. Four kinds of reconstructions were created; (1) 0.625mm thickness images with 0.625mm increment, (2) 1.25mm/1.25mm, (3) 2.5mm/1.25mm; i.e. overlapping reconstruction and (4) 2.5mm/2.5mm. The center of the temporal window was set to 80% of the R-R interval. The matrix size and field of view were the same as for the electron beam CT protocol, and the reconstruction kernel was standard. Almost all spiral CT images had a temporal resolution from 100 to 250msec, although the temporal resolution achieved by multisector reconstruction differed according to the heart rate and the number of cardiac cycles used for image reconstruction.

Prospective ECG-triggering axial CT protocol

Axial images with thickness of 0.625mm, 1.25mm and 2.5mm were scanned at prospective triggering so that the center of the temporal window corresponded to 80% of the R-R interval. Scanning parameters of a gantry rotation speed 0.5 sec/rotation, 120kV and 100mA were used. The matrix size and field of view were the same as for the electron beam CT protocol, and the reconstruction kernel was standard. Temporal resolution was 250msec.

Phantom scan and reconstruction on electron beam CT and 16-slice CT is summarized in Table 1.

Error of measurement and variability between measured and real volumes

We measured volume (not the 'so called' calcium volume score) of the calcium models. In the measurement, volume score [6] was used, with the calcium detection

threshold set to half the CT value of the calcium model (250HU). With this setting, if more than half of a pixel included calcium, the volume score became positive, and if less than half, this led to a negative measurement. This concept, strictly speaking, is justified when calcium is surrounded by water (CT value zero). In this study however, apart from calcium materials, pixels might include a part or all parts of the surrounding structure, i.e. a mixture of water and contrast medium, corn oil and rubber tube. The error of measurement and variability of the measured volume were calculated using the following equation:

Error = abs(measurement – real volume) / real volume

Variability = 2 x abs(measurement – real volume) / (measurement + real volume).

This was performed on each of the three sequential scans for the calcium models and the results were compared between CT protocols as well as between calcium sizes. It was tested to see whether calcium had been under or overestimated. The calcium models were also scanned in a static state.

Inter-scan variability

The inter-scan variability was calculated using the following equation:

Inter-scan variability = 2 x abs(S1 – S2) / (S1 + S2)

where S1 is CAC score on the first scan. This was calculated between scan1 and scan2, scan2 and scan3 and between scan3 and scan1.

Statistical Analysis:

For statistical analysis, t-tests were used to determine differences in variability. P-values < 0.05 were considered to identify significant differences.

Results:

In a static state, error of measurement was 5% on electron beam CT and 2-6% on spiral CT. The best measurement was observed on 0.625mm spiral CT.

Error of measurement on electron beam CT and spiral CT is shown (Fig. 3). The error on electron beam CT was 15%. On 16-slice spiral CT scanner, the error was different between scan protocols (8% to 20%). The error of 8% on 0.625mm spiral CT and 9% on 1.25mm spiral CT was significantly lower than that on electron beam CT ($p<0.01$, 0.02).

Variability between measured and real volumes for calcium, and inter-scan variability is shown (Fig. 4). The variability between measured and real volumes was 16% on electron beam CT and 8-24% on spiral CT. The inter-scan variability was 12% on electron beam CT and 8-26% on spiral CT. The best results were obtained from 0.625mm spiral CT, both on the variability between real and measured volumes (8%) and inter-scan variability (8%).

Figure 5 shows the type of scan taken and whether the resulting measurement was an underestimation, correct or an overestimation. In 92% on electron beam CT and 63 to 100% (79% in overall) on spiral CT, CT measurement resulted in underestimation.

When compared between 3mm and 5mm calcium models, variability between measured and real volumes in the 3mm model was significantly higher than that in the 5mm model (Fig. 6).

Discussion:

There are many studies on inter-scan variability in CAC measurement, however

variability between real CAC volume and that measured on CT has not received much focus due to its not being assessable in vivo. We have found only one phantom study [9] calculating 'volume score' [6] of calcified plaques with known volumes.

Factors influencing inter-scan variability on CAC measurement reported are as follows; partial volume effect [10], the use of the step function in the Agatston method to quantitate calcium [11], coronary artery motion [12], image noise [13], field inhomogeneity [7], lack of calibration [14], total volume of CAC [15], scoring parameters [16], etc. In the current study, factors contributing to improving measurement accuracy on spiral CT are thinner slice thickness and use of retrospective spiral ECG-gated scan. These also act in reducing variability between measured and real volumes and inter-scan variability [17, 18]. This is explainable as related to factors, partial volume effect and coronary artery motion; i.e. temporal resolution.

Despite relatively low inter-scan variability (10%), the level of measurement error (14%) on 2.5mm overlapping spiral CT seems to be important as it may lead to an inappropriate assignment in CAC risk stratification [19, 20]. Our result is different from that attained by Kopp et al. which, using a 4-slice spiral CT scanner (2.5mm thickness with 1mm increment), showed very good accordance. The reason for this is not clear, however. One possibility considered is that our heart rate protocols included shift and arrhythmia sequences which produce more through-plane motion of calcium than stable heart rates do. In addition, on multisector reconstruction, which we used, small variations in heart rate are an important factor for optimizing temporal resolution [21]. We were also surprised by strong the similarity between 'volume score' and real volume in the study by Kopp et al.. This is because it is emphasized by Ulzheimer et al. [18]

that volume score does not correspond to a real physical measurement as it strongly depends on the thresholds used.

Schlosser et al. suggest that motion may result in smearing artifacts and an underestimation of the score [22]. In most scans, our results support this theory. However, correct or overestimation of calcium volume existed in a minor number of cases. This indicates it is not adequate to hypothesize that real CAC volume is higher than what is actually measured on CT.

Variability between measured and real volumes was higher in the 3mm model scan. This seems to be explainable mainly by partial volume effect. Inter-scan variability of the Agatston score on electron beam CT is also known to be high on a low-score group [5].

The CAC models used in the current study do not have the exact properties as a real CAC in vivo. The putty material we used has a regular shape, homogenous density and greater x-ray absorption. The reason we selected such models was that our main purpose was to evaluate measurement accuracy rather than test inter-scan variability. Furthermore, putty was place inside the tube rather than into or on the wall of the tube, as is the case with CAC in vivo.

The setting of threshold may affect volume measurement. In the current study, we set the CAC threshold to half the CT value of the calcium model which is measured on spiral CT. A recent study [23] shows that image attenuation values vary by CT scanners, therefore highlighting the importance of the use of calibration phantoms. However, the fact that error of measurement was only 5% in a static state on electron beam CT and that this was comparable to those on spiral CT, seems to suggest that the threshold

factor is not considered to have a significant effect.

We do not imply that we propose to change the CAC quantification approach; i.e. measuring actual CAC volume instead of Agatston, volume score and mass score. Absolute volume measurement is never possible in vivo. What is most important is validating a reproducible technique which can predict cardiac events.

Although the best measurement and the least variability was observed on 0.625mm retrospective spiral ECG-gated CT, it brings it with the most radiation exposure to maintain the image quality needed, which is an important factor in CAC scoring [13]. Determination of slice thickness and reduction of the tube current or voltage should be validated in further clinical studies.'

One limitation of our study is that we did not test 1.5mm-thickness on electron beam CT. Different from the electron beam CT scanner we used, a new generation electron beam CT scanner is able to cover a whole heart using 1.5mm-thickness. This, of course, is expected to improve measurement accuracy.

In conclusion, we need to be aware of the fact that CAC volume measurement on either electron beam or spiral CT may be significantly different and often underestimates real CAC volume. For precise evaluation of CAC volume, thin-slice retrospective spiral ECG-gated scan using a spiral CT scanner is desirable.

References:

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Figure Legends

Fig. 1 Cardiac phantom

Picture shows two sizes of CAC models packed inside rubber tubes (mimicking coronary arteries) and attached to the balloon surface.

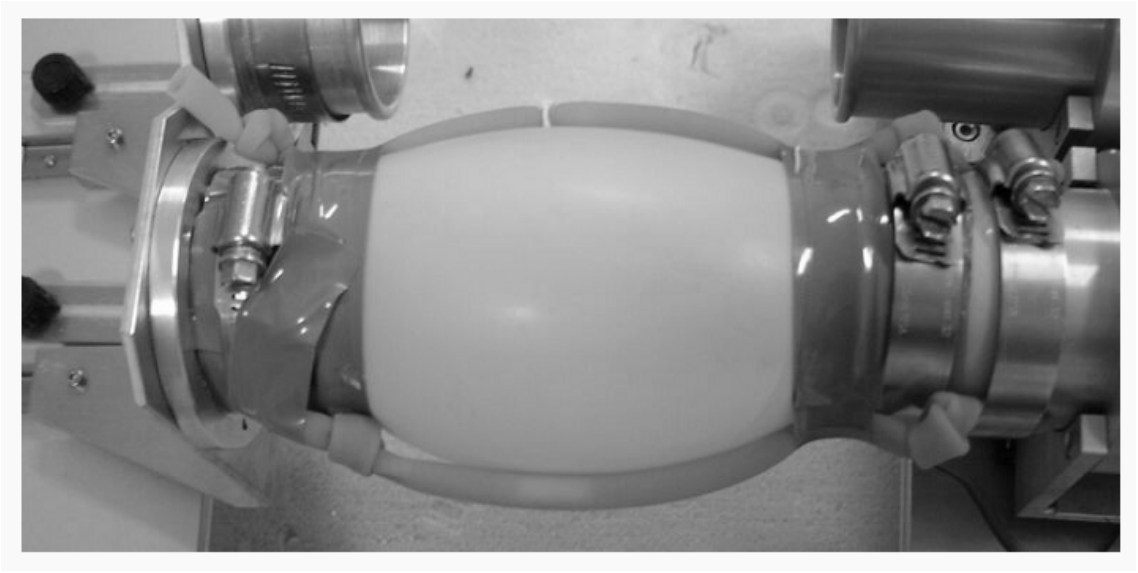

Fig. 2　Heart rate sequences

Graph shows the four types of heart rate sequences used in the study; 1) low heart rate (60bpm), 2) high heart rate (85bpm), 3) high heart rate (85bpm) with shifting and 4) arrhythmia.

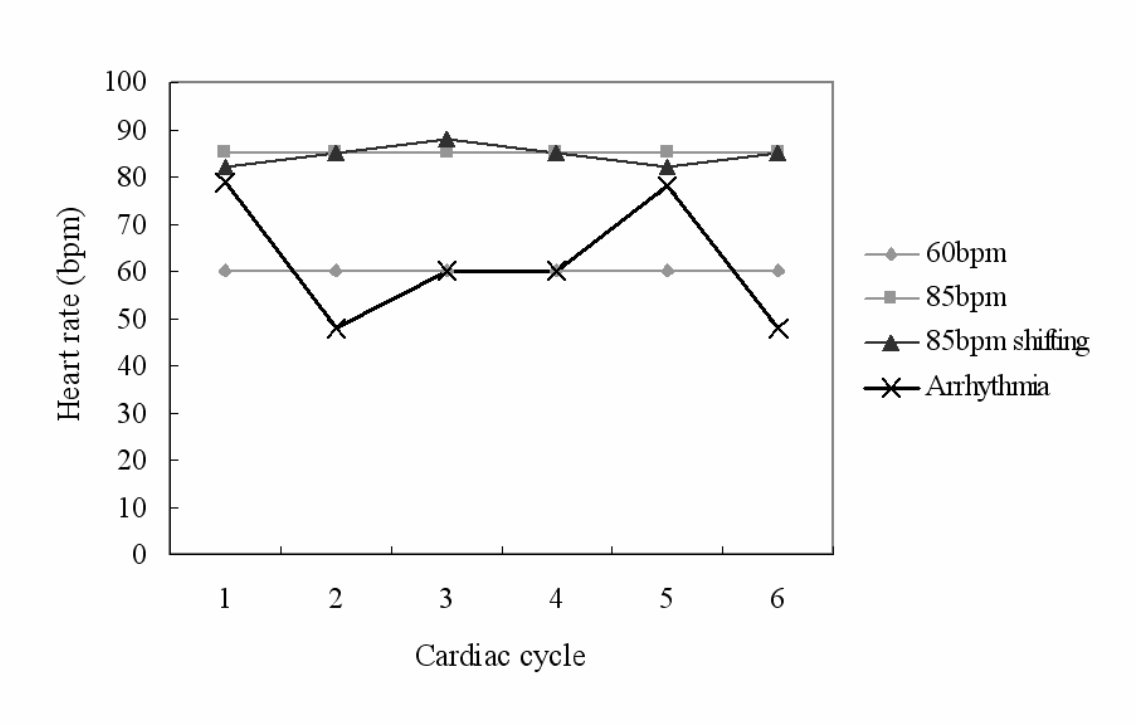

Fig. 3　Error of measurement

Graph shows the error of measurement (%) on electron beam CT and 16-slice spiral CT scanners. The error was 8% on 0.625mm spiral CT and 9% on 1.25mm spiral CT, significantly lower than 15% on electron beam CT ($p<0.01$, 0.02).

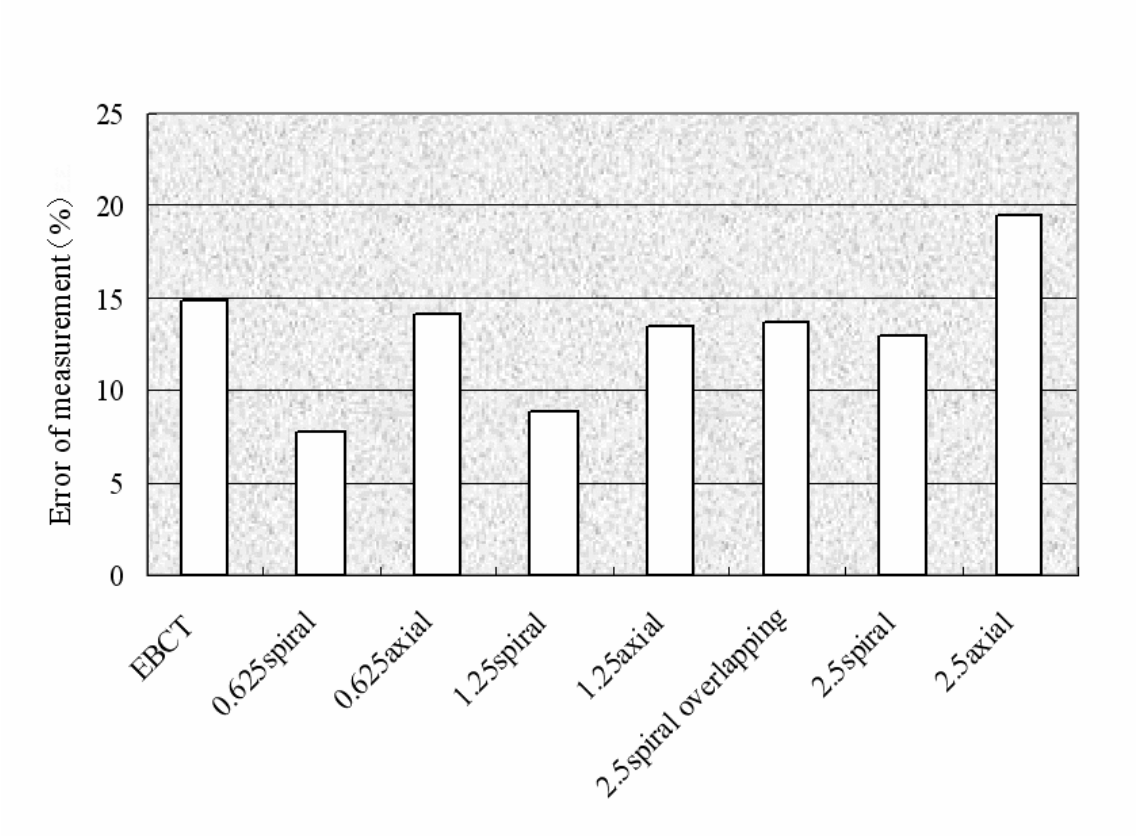

Fig. 4　Variability between measured and real volumes and inter-scan variability

Graph shows variability (%) between measured and real volumes (white bars) and inter-scan variability (gray bars). Thinner slice thickness and use of retrospective spiral ECG-gated scan are factors in reducing both variabilities. Variability between measured and real volumes tended to be higher than inter-scan variability on electron beam CT (p=0.07) and 2.5mm overlapping spiral CT (p=0.07).

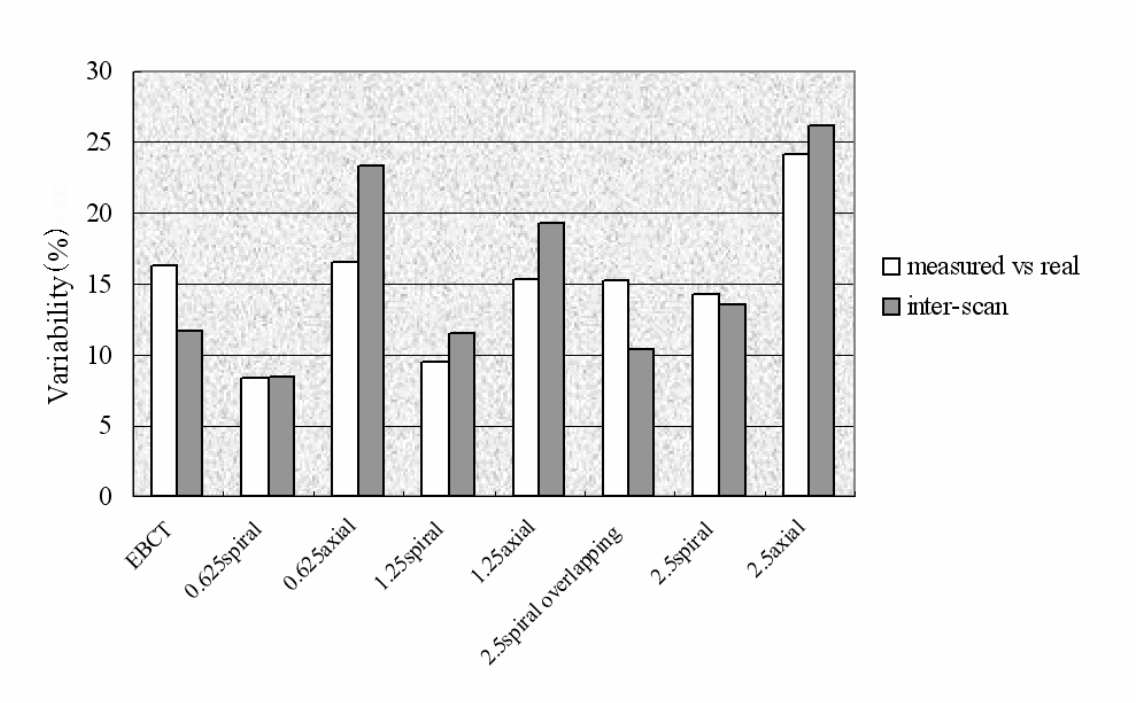

Fig. 5　Estimation of calcium volume on CT

Graph shows underestimation (white bars) and overestimation (gray bars) in CAC volume measurement. CT often underestimates the real volume of CAC. The sum of underestimation and overestimation ratios does not come to 100% in some of the CT protocols that have the correct measurement.

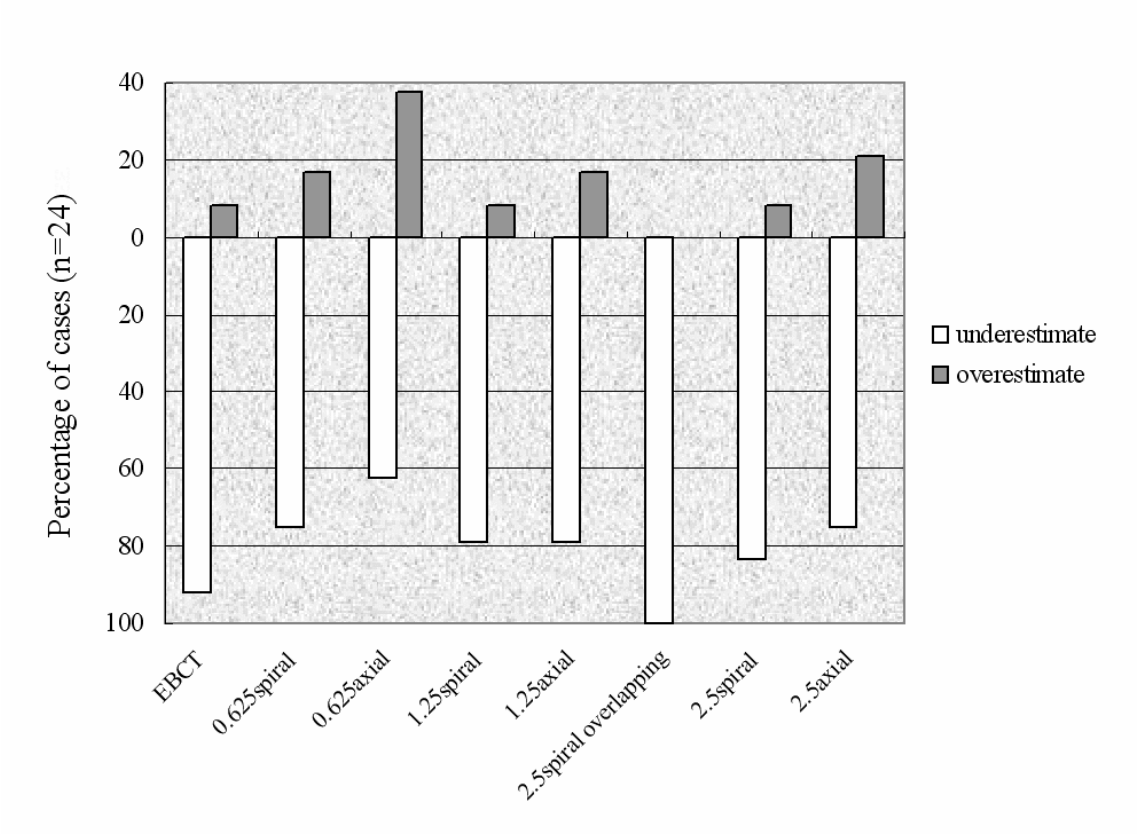

Fig. 6　3mm vs 5mm calcium models in variability between real and measured volume

Graph shows variability (%) between real and measured volumes in 3mm calcium models (white bars) is higher than that in 5mm models (gray bars), and reached a significant level ($p<0.05$) on spiral CT.

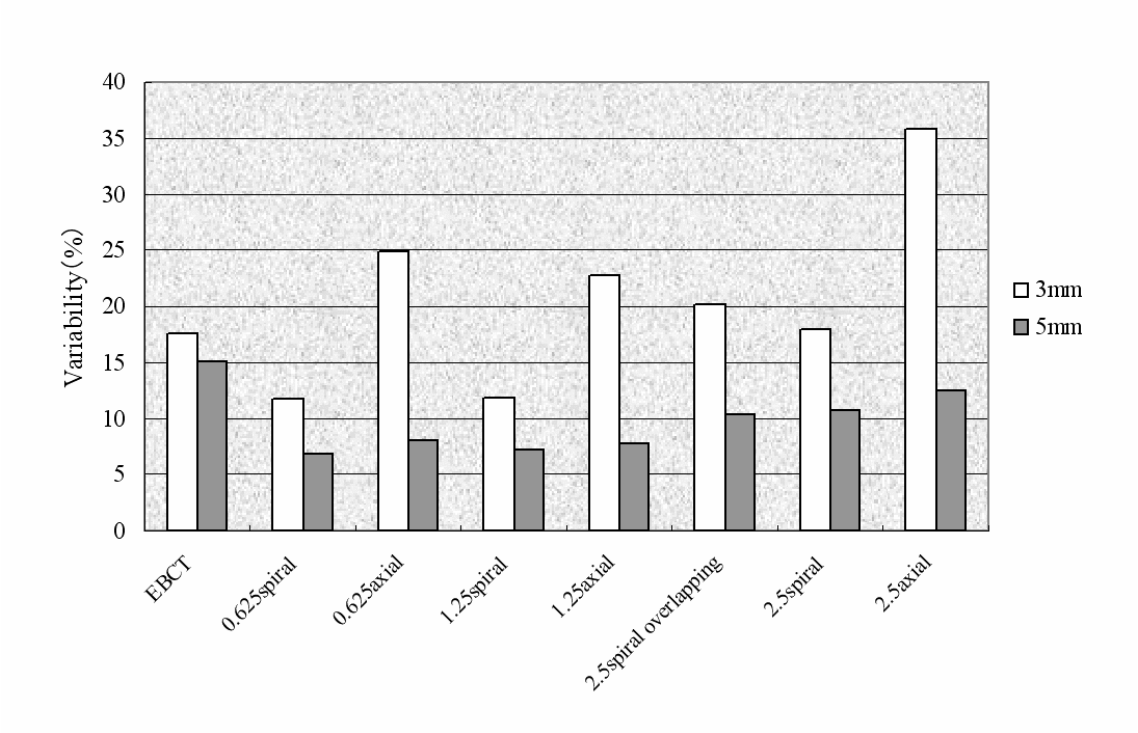

Table 1: Summary of phantom scan and reconstruction on electron beam CT and 16-slice CT

No. of phantom	1
No. of CAC models	2 (3mm/30mm3 and 5mm/50mm3, putty)
No. of heart rate curves per scan	4 (60, 85 , 85 shifting and arrythmia; in bpm)
No. of scans per protocol	3 (home position = -1, 0 and +1 mm)
No. of protocols	8 1 on EBCT: 3/3mm 4 on MSCT Retrospective: 0.625/0.625mm, 1.25/1.25mm, 2.5/1.25mm, 2.5/2.5mm 3 on MSCT Prospective: 0.625mm, 1.25mm, 2.5mm

No. Number, CAC. coronary artery calcium
EBCT. electron beam CT, MSCT. multi slice (16-slice) CT