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Reproducibility of coronary calcium quantification in repeat examinations with retrospectively ECG-gated multisection spiral CT

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Abstract High reproducibility is a key requirement for coronary calcium scoring in follow-up examinations. We investigated the inter-examination reproducibility of calcium scoring with retrospectively ECG-gated multisection spiral CT (MSCT). Fifty patients were examined twice with MSCT. Slices were reconstructed with retrospective ECG gating in the diastolic phase with 3-mm slice width and up to 125-ms temporal resolution. We calculated the Agatston score, calcium volume with and without isotropic interpolation, and calcium mass, and derived the mean and median variability. We investigated the change of variability with use of 3-mm non-overlapping and overlapping increments (2, 1.5, 1 mm). Use of overlapping increment results in considerably reduced interscan variability. We observed a minimum mean variability of 12% and a minimum median variability of 9% for the Agatston score. For volume and mass quantification we obtained a minimum mean variability of 7.5% and a minimum median variability of 5%. Multisection spiral CT enables coronary calcium quantification with high reproducibility in follow-up examinations mainly founded on image data with reduced partial-volume errors due to overlapping increment.

Keywords Cardiac CT · Multisection spiral CT · Coronary calcium · Agatston score · Calcium volume · Calcium mass

Introduction

Electron-beam CT scanning (EBCT) has been established as a non-invasive imaging modality for the detection and quantification of coronary calcium by using the Agatston scoring algorithm [1]. With EBCT scanning, typically 3-mm thick slices are acquired contiguously with prospective ECG triggering in mid-diastole and an exposure time of 100 ms per slice. An effective radiation exposure of approximately 0.9 mSv was reported for this protocol [2].

The amount of coronary calcification may be used as a marker for the total atherosclerotic plaque burden [3]. Variable amounts of calcification may indicate regression or progression of atherosclerosis and coronary artery disease (CAD) [4]. The normal progression of coronary calcification is approximately represented by 14–27% (average 24%, [5]) increase of the calcium score per year that may be enhanced up to 33–48% for patients with significant coronary disease [6, 7]. Various studies have shown that progression of coronary calcifi-

cation is decelerated (<10% per year) in patients under statin therapy [8]. For reliable monitoring of the progression of coronary disease via measurement of coronary calcification, the error between successive examinations must be considerably smaller than the expected change of calcified plaque burden; thus, high accuracy and reproducibility of the calcium score measurement with interscan variability below 10% are crucial for reliable detection of small changes within a reasonable follow-up interval.

The interscan reproducibility of EBCT scanning has been shown to have poor to fair values ranging from 14 to 51% mean variability depending on scan technique and scoring method [4, 9, 10]. High variability is particularly present for small amounts of calcification. Recently, alternative quantitative volumetric scoring methods have been developed that have improved interscan reproducibility [11]. Partial-volume errors introduced by contiguous acquisition with 3-mm slice width, long breathhold times of 25–40 s, and image artifacts due to inconsistent ECG triggering for arrhythmic heart rates have been identified as the main variability factors [2].

Recently, mechanical multi-slice CT systems (MSCT) with simultaneous acquisition of four slices, 0.5-s scanner rotation, and 125-ms maximum temporal resolution provided by special reconstruction algorithms have become available for cardiac CT scanning [12, 13]. The first studies have shown a high correlation of MSCT with prospectively ECG-triggered acquisition and 250-ms effective exposure time compared with EBCT for the detection of coronary calcification using the Agatston- and volumetric scoring methods [14]; however, it has also been shown that a higher degree of coronary motion artifacts may be present with MSCT due to reduced temporal resolution with 250-ms effective exposure time.

Multislice CT with retrospective ECG gating enables continuous volume coverage with acquisition of overlapping slices and substantially faster volume coverage compared with ECG triggering. Phantom studies and experimental patient studies have shown that non-overlapping sequential scanning is an important contributor to the interscan variability of Agatston- and volumetric calcium scores due to partial-volume errors in plaque registration [15, 16]. These studies could demonstrate that ECG-gated volume coverage with MSCT and overlapping image reconstruction improves the reproducibility of coronary calcium quantification especially for small plaques in comparison with EBCT with ECG-triggered sequential acquisition [15].

Thus, some of the most important factors to the interscan variability of coronary calcium scoring can potentially be suppressed to a large extent by MSCT using retrospective ECG gating; therefore, the purpose of the presented study was to investigate a potential improvement of interscan variability in repeat coronary calcium scans with this technique.

Materials and methods

The reproducibility of coronary calcium scoring with MSCT was evaluated in a clinical study based on 50 consecutive patients (42 men, 8 women; age range 36–85 years, mean age 59.9 years, ±9.8 years standard deviation) who were examined twice with MSCT using ECG-gated spiral scanning. Written informed consent was obtained from each patient after the nature of the procedure had been fully explained. The study protocol was approved by the internal review board of the clinical institutions that performed the clinical examinations and the federal board of radiation protection.

The patients that were included in this study were referred to the department because of a suspicion of coronary artery disease either by clinical symptoms or because of the presence of cardiovascular risk factors. Patients with known arrhythmia and patients with stents were not excluded from the study. Coronary stents were identified and excluded during the scoring process. The second scan was performed within 3–5 min after the first scan with repositioning of the patient. The MSCT data was acquired on a Somatom Volume Zoom with "HeartView CT" application (Siemens, Forchheim, Germany) with 4×2.5-mm collimation, 120 kV, 100 mA (133 mAs effective), 0.5-s rotation time, and pitch 1.5 (feed 7.5 mm/s; pitch is defined as table feed per full rotation normalized to the width of one slice of the multislice detector). With this protocol the 12-cm scan range of heart is covered in 16-s scan time. Effective patient dose per scan was determined with 2.6 mSv for men and 3.4 mSv for women (Software Windose, Scanditronix, Wellhoefer Inc., Erlangen, Germany). Images were reconstructed with the ACV algorithm [13] in diastole with 3-mm slice width and up to 125-ms temporal resolution dependent on heart rate. A medium sharp convolution kernel ("B35f", 50% value of the modulation transfer function ≈4 cm^{-1}, no edge enhancement) was used that provides a maximum in-plane resolution of approximately 9 lp/cm. Optimum image quality by means of minimization of motion artifacts can be achieved with retrospectively ECG-gated image reconstruction in different phases of the cardiac cycle for left coronary artery tree (i.e., left main: LM; left artery descending: LAD; and circumflex: CX) and right coronary artery tree (right coronary artery: RCA) [17, 18]. The optimal reconstruction position within the cardiac cycle was determined from reconstruction for two representative axial levels containing the proximal LAD (segments 6, 7) and the middle segment of the RCA (segment 2) at 35, 40, 45, 50, 55, 60, 65, and 70% of the cardiac cycle. From these images only those two time points with least motion artifacts of the RCA, on the one hand, and of LM, LAD, and CX, on the other hand, were chosen for reconstruction of the complete volume; thus, two image data sets were reconstructed per scan and evaluated separately. One image data set was reconstructed for scoring of the RCA and the second one for scoring of the LM, LAD, and CX. Individual extra-systolic heart beat was eliminated prior to ECG-gated reconstruction if gapless reconstruction could be assured by a maximum distance of 1500 ms between two consecutive R-waves that was not exceeded.

Calcified lesions were identified based on a Hounsfield threshold of 130 HU for all applied scoring methods. The Agatston scoring algorithm [1] has been developed for sequential image data and needs modification if overlapping slice data is processed. We used the intuitive approach to calculate normalized scores *AgN* where the sum of the scores of the individual plaques *n* is multiplied with the ratio of image reconstruction increment *Inc* and slice-width **SW** (Eq. (1)). The normalized score *AgN* is identical with the traditional Agatston score for *Inc*=*SW*=3 mm.

$$AgN = \frac{Inc}{SW} \sum_{n} Area(n) \cdot CoFactor(n). \quad (1)$$

Due to the non-linear weighting operation with the variable integer *CoFactor* (=1–4 according to Agatston et al. [1], depending on

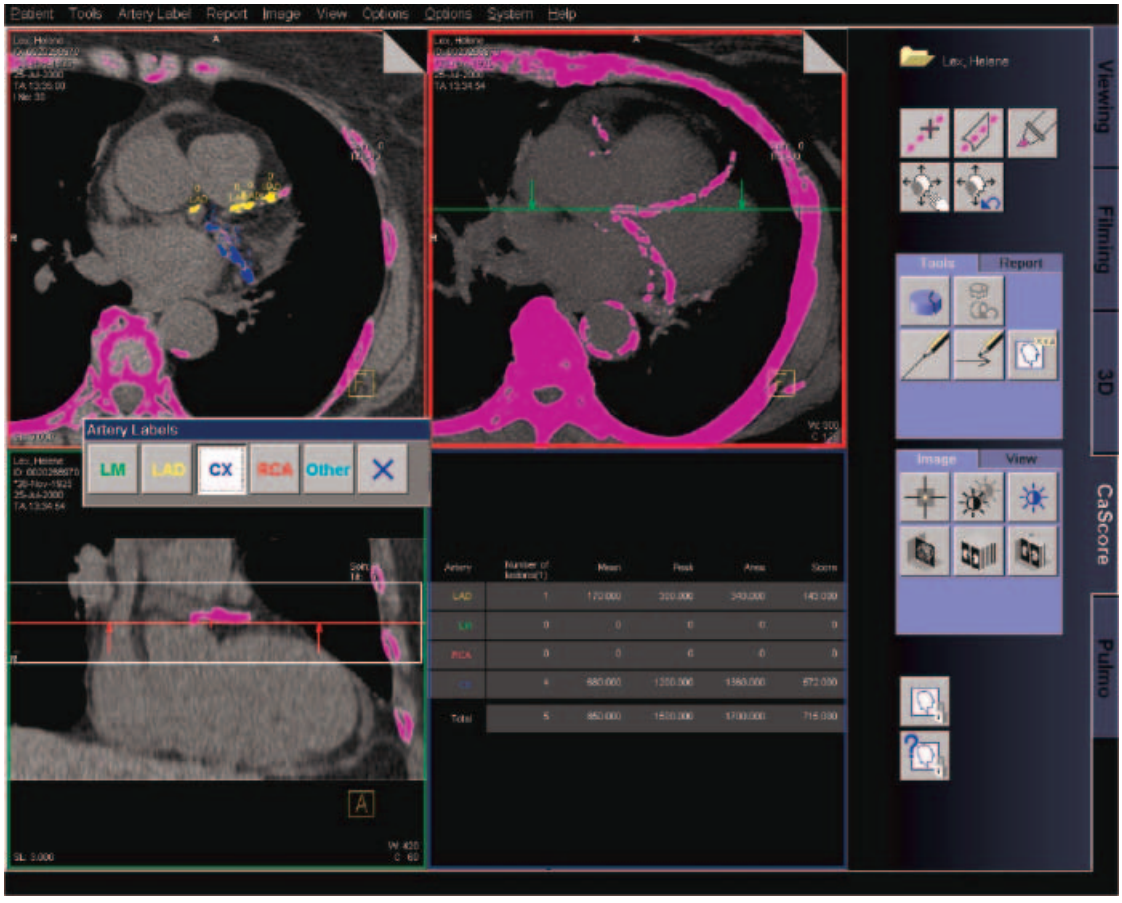


Fig. 1 Presentation of the platform used for Agatston-based, volumetric and mass quantification of coronary calcification ("syngo Calcium Scoring", Volume Wizard, Siemens, Forchheim, Germany). Lesions exceeding the calcium threshold of 130 HU are identified with 3D-based picking and viewing tools and are assigned to the different coronary arteries: left main (*LM*); left artery descending (*LAD*); circumflex (*CX*); and right coronary artery (RCA). Measurement and score values are displayed and reported in table format

peak attenuation in plaque deposit) the Agatston score can be very prone to variations.

Alternative volumetric quantification algorithms have been developed that can process sequential as well as overlapping image data of different slice width and provide volume equivalents (in cubic millimeters) of calcified plaques. Non-linear operations are eliminated that may increase interscan variability. Isotropic interpolation procedures in between adjacent image slices can be used to reduce the influence of partial-volume errors for improved reproducibility [11].

In our study we calculated a conventional volume *Vol* (Eq. (2)) and a volume Vol_I with continuous (isotropic) interpolation (Eq. (3)) as proposed by Callister et al. [11].

$$Vol = \sum_n Vol(n) = \sum_n Area(n) \cdot Inc \tag{2a}$$

$$Vol_I = \sum_n Vol_I(n) = \sum_n Area(n) \cdot Inc \cdot W_I(n). \tag{2b}$$

For the conventional volume quantification a volume *Vol(n)* was calculated for every individual lesion *n* from the total area of a lesion that is multiplied with the image increment *Inc*. The isotropic interpolation factor $W_I(n)$ takes information from the adjacent slices into account and modifies the contribution of a single image voxel to the volume of an individual lesion *n*. $W_I(n)$ may be greater or smaller than 1 depending on the propagation of a lesion in the scan direction. Also voxels that were not identified as part of a lesion due to a Hounsfield value <130 may contribute to the volume of the lesion if corresponding voxels at the same image position in the adjacent slice have a high contribution.

It has been proposed to expand volumetric quantification of coronary calcium to absolute mass quantification that can cope with different scanner properties and protocol variations via phantom calibration methods [19]. It could be shown in phantom experiments that calcium mass quantification is more robust to motion artifacts than Agatston scoring and calcium volume quantification [20] and may therefore be more reproducible. Calcium mass can be calculated in milligrams via multiplication of the volume of a lesion with a density factor ρ of the lesion that is derived from the mean Hounsfield value in the plaque that linearly depends on the mean density (in milligrams per cubic millimeter).

$$Mass = \sum_n Mass(n) = \sum_n Area(n) \cdot Inc \cdot \rho(MeanHU(n)). \tag{3a}$$

$$Mass_I = \sum_n Mass_I(n) = \sum_n Area(n) \cdot Inc \cdot W_I(n) \cdot \rho(MeanHU(n)). \tag{3b}$$

In our study we determined the calibration function $\rho(MeanHU)$ using a standardization phantom (Institute of Medical Physics, Erlangen, Germany; and QRM GmbH, Möhrendorf, Germany).

$$\rho(MeanHU(n)) = 0.84\frac{mg}{cm^3 HU}(MeanHU(n) - HU_{Water}) \quad (3c)$$

All scores were calculated using commercially available software ("syngo Calcium Scoring", Volume Wizard, Siemens, Forchheim, Germany; Fig. 1).

As a measure for interscan reproducibility we derived the mean variability σ_{mean} (Eq. (4a)) and the median variability σ_{median} (Eq. (4b)) for the total scores of the two examinations. The scan data was reconstructed by two independent examiners (T.F. and B.O.) and image data was evaluated by two independent observers (A.F.K. and R.F.).

$$\sigma_{mean} = \frac{1}{N_P}\sum_{i=1}^{i=N_P}\frac{2\,|Score_1(i) - Score_2(i)|}{(Score_1(i) + Score_2(i))}. \quad (4a)$$

$$\sigma_{median} = \underset{i=1\ldots N_P}{Median}\left(\frac{2\,|Score_1(i) - Score_2(i)|}{(Score_1(i) + Score_2(i))}\right). \quad (4b)$$

N_P=50 represents the total number of patients. Each patient is characterized with the index **i**.

We compared the variability of scores with 3-mm non-overlapping increment with scores based on overlapping increments of 2, 1.5, and 1 mm. The Agatston scores derived from the first scan of each patient reconstructed with 3-mm slice width and 3-mm increment without normalization for slice increment were used to categorize the score of the patients. A separate evaluation of the variability was performed for a patient subgroup with low to mild scores (*AgN* with 3-mm increment <100) who are more prone to inconsistency and variability than high scores. In addition, we investigated whether reconstruction increment has an influence on the total score values. We therefore compared the mean values including standard deviations and the median values of all total scores from both acquisitions that were determined with the same scoring algorithm but with different increments 3, 2, 1.5, and 1 mm; thus, 100 scores from 50 patients (two acquisitions for each patient) were used to evaluate each scoring algorithm for each image increment.

For statistical analysis, *t*-tests were used to examine differences in variability and score values for different scoring protocols within the patient group. *p*-values <0.05 were considered to identify significant differences.

Results

We observed mean heart rates between 51 and 96 bpm (67.2 bpm mean heart rate, ±12.9 bpm standard deviation) during the scans for the 50 patients and 100 acquisitions. Eighteen patients showed mean heart rates >70 bpm during one or both scans and 4 patients showed substantial heart rate changes with standard deviation >±5 bpm during one or both scans.

Based on the categorization with the Agatston scores derived from the first scan that was reconstructed with 3-mm slice width and 3-mm increment, low, mild, moderate, and severe calcifications were found in the examined patient cohort. Three patients did show no calcification, 3 patients had an Agatston score from 1 to 10 (low), 15 patients from 11 to 100 (mild), 14 patients from 101 to 400 (moderate), and 15 patients more than 400 (severe). Figure 2 shows very good correlation of the Agatston scores (*r*=0.987) derived from the two scans based on image data with 3-mm increment.

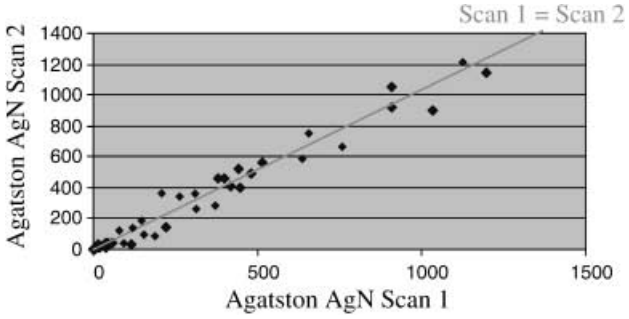


Fig. 2 Correlation diagram showing the agreement of the calcium measurements derived from two consecutive examinations. The diagram for the Agatston scores is based on non-overlapping image data (3-mm slice width and 3-mm increment) and shows good agreement and correlation of the two scans. Different extent of calcification from low (Agatston score *AgN*<10) to severe (Agatston score *AgN*>400) is present within the examined patient group

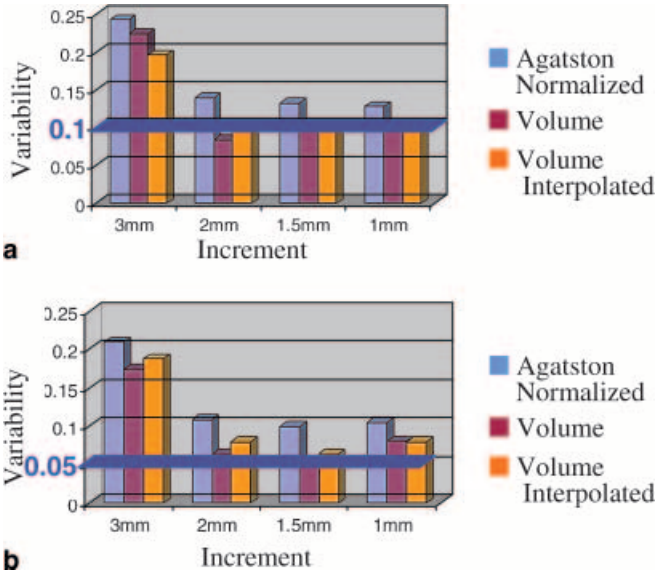


Fig. 3a, b Mean and median interscan variability dependent on image reconstruction increment for Agatston scoring and volume quantification (conventional volume, isotropic interpolated volume). **a** Mean interscan variability and **b** median interscan variability are presented for the entire patient group. Image reconstruction with slice overlap provides substantial improvement of interscan reproducibility with mean variability down to 8% and median variability down to 5%. Median variability is consistently lower than mean variability

Similar to presented phantom studies [15] we found a strong influence of the image reconstruction increment on the interscan variability. For the entire patient group the mean variability σ_{mean} equals 23% for Agatston score *AgN*, 21% for conventional volume *Vol*, and 18% for interpolated volume Vol_I when using non-overlapping increment 3 mm (Fig. 3a). A considerable reduction can be achieved with overlapping increment (*AgN* 12%, *Vol* 8%,

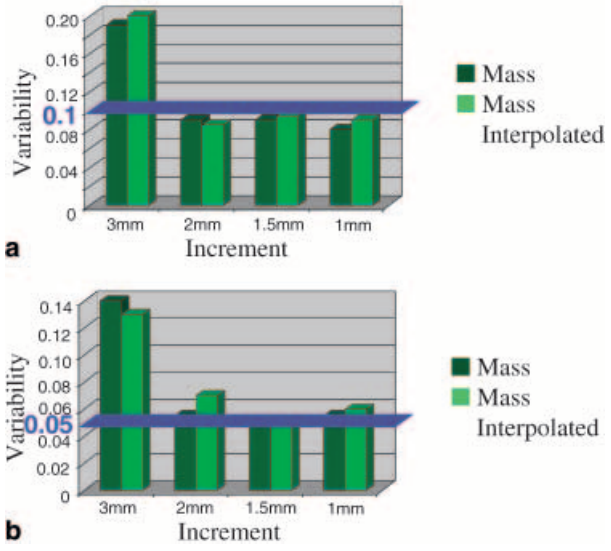


Fig. 4a, b Mean and median interscan variability dependent on image reconstruction increment for mass quantification (conventional mass, isotropic interpolated mass). **a** Mean interscan variability and **b** median interscan variability are presented for the entire patient group. Image reconstruction with slice overlap provides substantial improvement of interscan reproducibility with mean variability down to 7.5% and median variability down to 5%. Median variability is consistently lower than mean variability

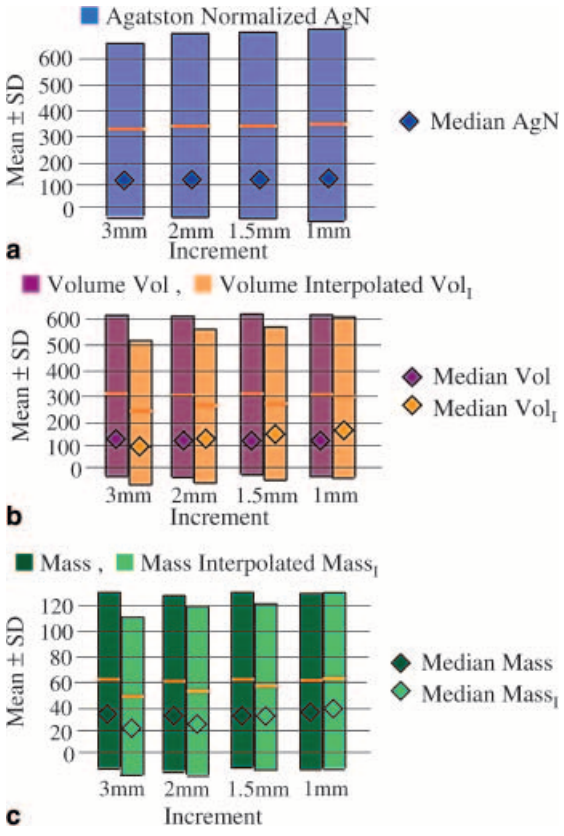


Fig. 5a–c Mean values including standard deviations and median values derived from 100 patient examinations for the different calcium quantification algorithms (Agatston score, conventional volume, isotropic interpolated volume, conventional mass, isotropic interpolated mass), dependent on reconstruction increment. Mean and median values of **a** Agatston score *AgN*, **b** conventional volume *Vol*, and **c** conventional mass *Mass* do not show substantial changes for different reconstruction increment. Mean and median values of **b** isotropic interpolated volume Vol_I and **c** isotropic interpolated mass $Mass_I$, however, increase with reduced image increment

Vol_I 9%) with $p<0.01$ (Fig. 3a). No substantial difference of the variability can be observed for increment 1 mm, 1.5 mm, and 2 mm (*AgN* 12–13%, *Vol* 8–10%, Vol_I 9–10%; $p>0.05$). Conventional volume and interpolated volume show very comparable behavior. Considerably higher mean variability is present for the patient subgroup with low to mild calcification if image data with non-overlapping increment is used (*AgN* 42%, *Vol* 34%, Vol_I 33%). Also for this group overlapping increment has high impact on the reduction of variability (*AgN* 16–21%, *Vol* 12–14%, Vol_I 12–16%) with $p<0.01$. Especially for low scores both conventional and isotropic interpolated volume provides improved reproducibility compared with Agatston scoring ($p<0.05$).

Median variability of Agatston scoring and volume is consistently lower than mean variability (Fig. 3b), as very high variability that may be present for very low scores has less influence. Also the median variability is reduced with overlapping image increment. A minimum median variability of 5% is observed for the total patient group (*AgN* 9–10%, *Vol* 5–8%, Vol_I 6–8%) and 7% for the subgroup with low to mild calcification (*AgN* 9–12%, *Vol* 7–10%, Vol_I 7–10%; $p<0.01$). Conventional volume and interpolated volume show also comparable median variability. The Agatston score consistently shows highest median variability ($p<0.05$). Also for the median variability the degree of overlap that is present for the increments 2, 1.5, and 1 mm has no strong influence ($p>0.05$).

The analysis of mean and median variability was also carried out for mass without and with isotropic interpolation. For the entire patient group the mean variability σ_{mean} was 19% for conventional mass *Mass* and 20% for interpolated mass $Mass_I$ when using non-overlapping increment 3 mm (Fig. 4a). We also observed a considerable reduction with overlapping increment (*Mass* 7.5–9%, $Mass_I$ 8–9.5%) with $p<0.01$ (Fig. 4a). Mean variability in the patient subgroup with low to mild calcification was 29% for *Mass* and 30% for $Mass_I$. The mean variability could be reduced with overlapping increment to 11–14% for *Mass* and to 11–15% for $Mass_I$ ($p<0.01$). With overlapping image increment a minimum median variability of 5% is observed with mass for the total patient group (*Mass* 5–6%, $Mass_I$ 5.5–7%) and 7% for the subgroup with low to mild calcification (*Mass* 7–8.5%, $Mass_I$ 7–9%; $p<0.01$; Fig. 4b). Also for the median variability of mass the degree of overlap that is present for

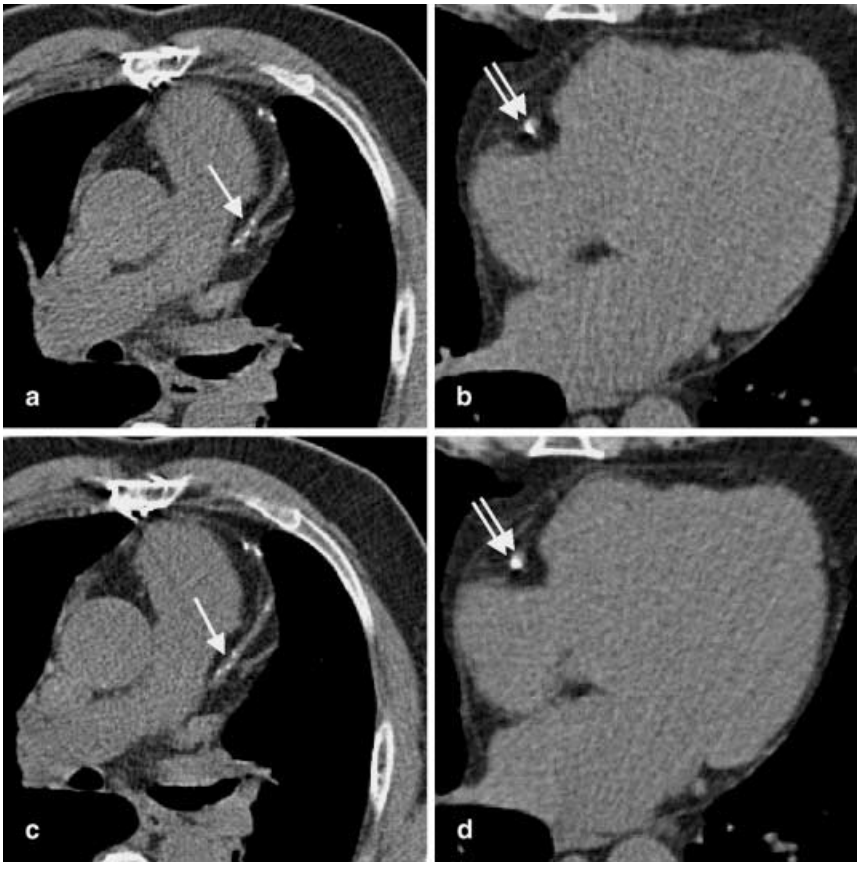


Fig. 6a–d Case example for repeat scan examinations in a patient with moderate coronary calcification and low and regular heart rate of 63 bpm. Scan parameters: 0.5-s rotation; 120 kV; 100 mA; 133 mAs effective; 4×2.5-mm collimation; 7.5-mm/s table feed; 3-mm slice width; 1.5-mm slice increment; 250 ms temporal resolution; reconstruction for left coronary tree at 55% and for right coronary tree at 55%. Score, location, and morphology of small calcified lesions in **a** LAD (*arrow*) and **b** RCA (*double arrow*) which were detected in **a**, **b** scan 1 can be accurately reproduced in **c**, **d** scan 2. Scan 1 (**a**, **b**): *AgN*=105; *Vol*=83 mm^3; Vol_I=78 mm^3; Mass=23 mg; $Mass_I$=21 mg. Scan 2 (**c**, **d**): *AgN*=118; *Vol*=87 mm^3; Vol_I=81 mm^3; Mass=25 mg; $Mass_I$=24 mg

the increments 2, 1.5, and 1 mm has no strong or statistical influence (p>0.05).

Mass quantification without and with isotropic interpolation showed slightly improved reproducibility compared with volumetric quantification and also significantly better reproducibility than Agatston scoring (p<0.05).

Overlapping images improves scoring reproducibility but systematic dependencies in relation to non-overlapping images have to be analyzed. For Agatston scoring, conventional volume, and conventional mass the mean value of all scores from all patients and both acquisitions, including the standard deviation, did not show remarkable variations for different reconstruction increments (Mean: *AgN* 310–316, *Vol* 308–312 mm^3, *Mass* 60–62 mg; Fig. 5). The median values were lower in absolute value but also very consistent for different reconstruction increments (Median: *AgN* 110–115, *Vol* 112–115 mm^3, *Mass* 36–38 mg). For the interpolated volume and interpolated mass, however, mean and median value are higher for low image increment. They increase from Mean(Vol_I)=261 mm^3, Median(Vol_I)=100 mm^3, Mean($Mass_I$)=49 mg, and Median($Mass_I$)=21 mg for 3-mm image increment to Mean(Vol_I)=302 mm^3, Median(Vol_I)=171 mm^3, Mean($Mass_I$)=62 mg, and Median($Mass_I$)=40 mg for 1-mm increment (p<0.001). Agatston-, conventional volume, and conventional mass do not show systematic differences depending on the image increment, interpolated volume, and interpolated mass; however, they systematically provide lower values for small image overlap.

Some representative case examples for repeat scan examinations are presented in (Figs. 6, 7, 8). Score, location, and morphology of small calcified lesions can be accurately reproduced for both moderate heart rates (Fig. 6: 63 bpm mean heart rate, ±2 bpm standard deviation) and higher heart rates (Fig. 7: 96 bpm mean heart rate, ±3 bpm standard deviation). For both examples the interscan variability is lower than 5%. Higher variability may be present for patients with low total score, high heart rates, and arrhythmic changes during the scan where motion may be present especially in the RCA (Fig. 8: 89 bpm mean heart rate, ±6 bpm standard deviation); however, the calcifications can still be identified and reproduced in both scans.

Discussion

Our study shows that MSCT with half-second scanner rotation using ECG-gated spiral scanning can provide continuous volume image data with appropriate temporal resolution within short breath-hold times for coronary

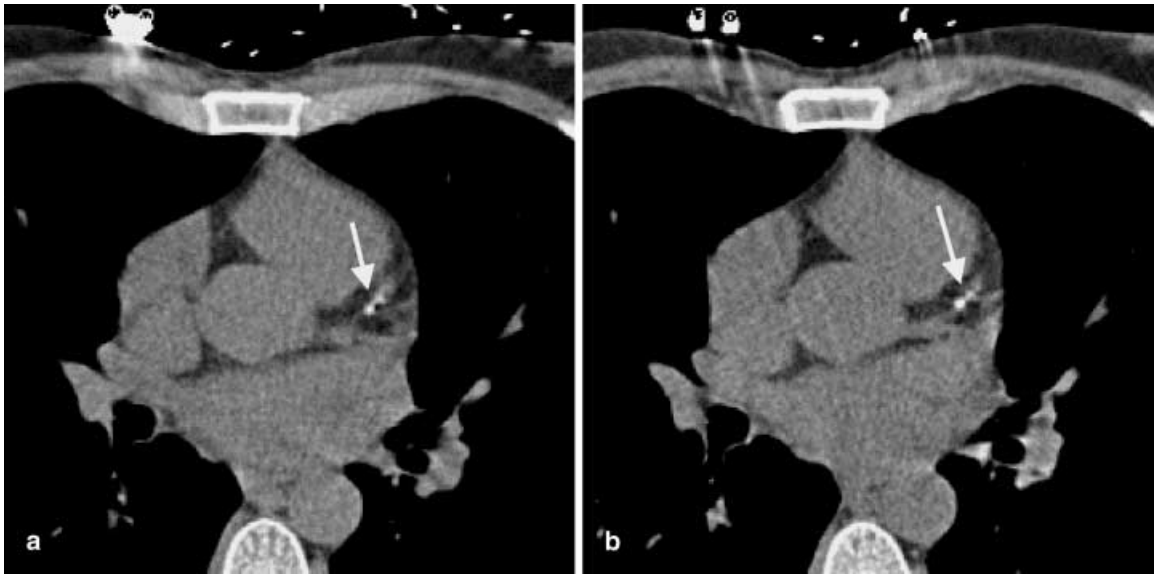
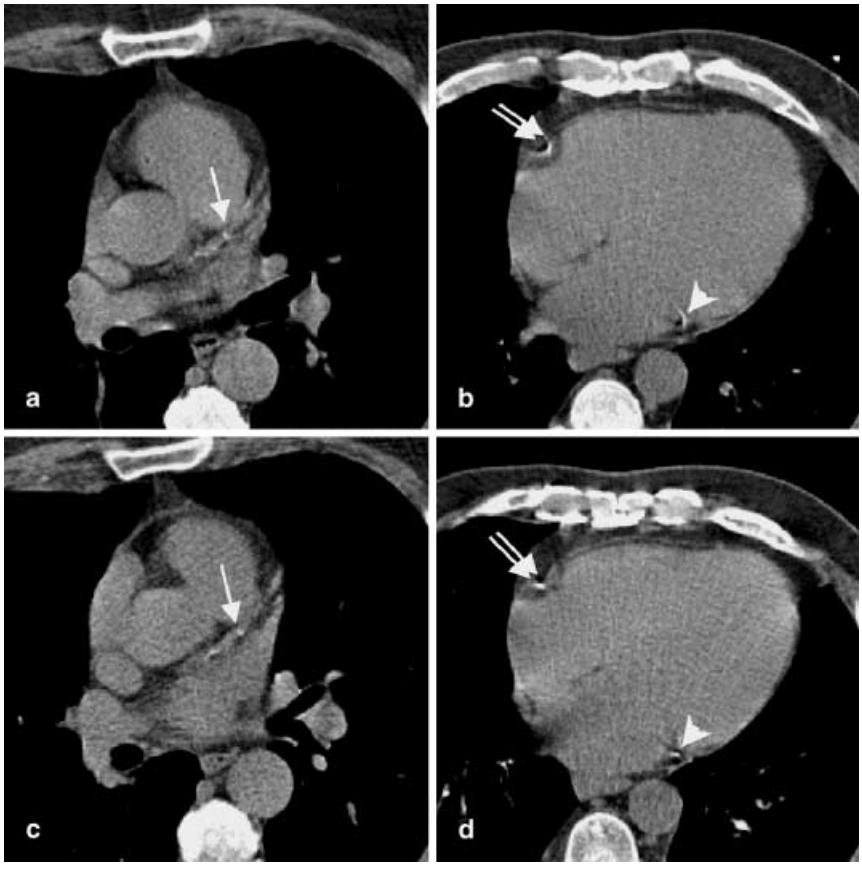


Fig. 7a, b Case example for repeat scan examinations in a patient with mild coronary calcification and high but regular heart rate of 96 bpm. Scan parameters: 0.5-s rotation; 120 kV; 100 mA; 133 mAs effective; 4×2.5-mm collimation; 7.5-mm/s table feed; 3-mm slice width; 1.5-mm slice increment; 125–145 ms temporal resolution depending on heart rate; reconstruction for left coronary tree at 55% and for right coronary tree at 45%. Score, location, and morphology of small calcified lesions in **a** LAD (*arrow*) which were detected in **a** scan 1 can be accurately reproduced in **b** scan 2. Scan 1 (**a**): *AgN*=26; *Vol*=34 mm^3; Vol_I=28 mm^3; Mass=5.0 mg; $Mass_I$=4.5 mg. Scan 2 (**b**): *AgN*=29; *Vol*=32 mm^3; Vol_I=25 mm^3; Mass=4.7 mg; $Mass_I$=4.1 mg

Fig. 8a–d Case example for repeat scan examinations in a patient with mild coronary calcification and high and irregular heart rate with 89 bpm mean heart rate (±6 bpm standard deviation). Examination parameters: 0.5-s rotation; 120 kV; 100 mA; 133 mAs effective; 4×2.5-mm collimation; 7.5-mm/s table feed; 3-mm slice width; 1.5-mm slice increment; 130–200 ms temporal resolution depending on heart rate; reconstruction for left coronary tree at 50% and for right coronary tree at 40%. Higher variability and motion is present but calcifications in **a** LAD (*arrow*), **b** RCA (*double arrow*), and **b** CX (*arrowhead*) which were detected in **a**, **b** scan 1 can also be identified and evaluated in **c**, **d** scan 2. Scoring of CX calcification was not performed based on displayed images (**b**, **d**) which are optimized for display of the right coronary tree. Scan 1 (**a**, **b**): *AgN*=40; *Vol*=56 mm^3; Vol_I=42 mm^3; Mass=9.6 mg; $Mass_I$=8.1 mg. Scan 2 (**c**, **d**): *AgN*=14; *Vol*=33 mm^3; Vol_I=24 mm^3; Mass=5.4 mg; $Mass_I$=4.6 mg



calcium scoring with high reproducibility. A mean variability down to 8% and a median variability down to 5% could be obtained with overlapping image data for our cohort of 50 patients who showed a wide range of heart rates and degree of calcification. The patient group included 18 patients with heart rate more than 70 bpm and 18 patients with low and mild calcification. Also for the patient subgroup with low and mild calcification we could demonstrate a mean variability down to 12% and a median variability down to 7%.

The low variability was found to be due mainly to a reduction of partial-volume errors with overlapping slice increment. Additional factors may be the absence of patient breathing and reduced sensitivity to heart rate changes with retrospective ECG gating. Our results indicate that the Agatston scoring algorithm can also be applied to overlapping slice data when using appropriate normalization factors for the slice reconstruction increment. With appropriate normalization the score values are consistent for different image reconstruction increment.

However, volume and mass quantification with moderate slice overlap from 33 to 50% (increment 2 or 1.5 mm for slice width 3 mm) have been shown to provide the best reproducibility. The reproducibility of volume and mass with isotropic interpolation is comparable to conventional volume and mass without isotropic interpolation for slice data with appropriate slice overlap.

The best consistency of volume and mass could be achieved with conventional algorithms without use of isotropic interpolation. With isotropic interpolation the values seem to depend on the image reconstruction increment and are statistically significantly lower for reconstruction increments with low degree of slice overlap. This effect may make routine use of volume and mass with isotropic interpolation difficult but could be eliminated by strict standardization of reconstruction parameters; however, the influence of this systematic effect on clinical validity needs to be further investigated and evaluated in targeted clinical trials.

Due to the high reproducibility which was demonstrated in this study, MSCT with ECG-gated spiral acquisition in combination with quantitative volumetric calcium evaluation may be a reliable tool to monitor coronary calcification in follow-up examinations, e.g. to evaluate progression of CAD in patients undergoing aggressive lipid-lowering medication therapy [8]. With a mean interscan variability of less than 10% also small changes of calcified plaque burden may be detectable within reasonable follow-up intervals of 1 year.

An obvious trade-off of the discussed MSCT examination technique using retrospective ECG gating is the considerably increased radiation exposure compared with ECG-triggered scan protocols with MSCT or EBCT. The relatively high radiation of ≥2.6 mSv is caused by continuous X-ray exposure and data acquisition at low and highly overlapping spiral pitch [21]; however, with the recently introduced technique of ECG-controlled tube output modulation the effective patient exposure can be reduced by ≈40–50% for ECG-gated spiral scanning with MSCT without remarkable compromises on image quality [21, 22]. The effective radiation exposure can then be reduced to <1.5 mSv for men and to <2 mSv for women for the protocol in this study. This new technique was not available at the time of this study but will be routinely used for future evaluation.

With the advent of multiple MSCT scanners from different manufacturers and with the ongoing development of MSCT systems and protocols with increased number of slices, increased spatial resolution and increased temporal resolution cross-technology quality control standards and calibration methods gain importance. At present, only calcium mass quantification allows for consideration of calibration functions for different scanners and scan protocols [19, 23]; thus, with the ongoing development of CT technology calcium mass quantification based on standardized scan and evaluation protocols should be considered as the calcium quantification method of choice.

In the near future mechanical 16-slice CT scanners with increased rotation speeds will become available [24] and will allow for coronary calcium scanning with increased temporal resolution and ≈8-s breath-hold time. Scans of the heart with submillimeter slices will be possible in breath-hold times of ≈16 s. With increased temporal resolution, image quality may be less sensitive to the selection of reconstruction phase in the cardiac cycle and thus the work flow to obtain optimal image quality with minimal motion artifacts may be simplified. With this development further improvements of sensitivity and reproducibility of quantification of coronary calcification with mechanical multislice CT is expected.

Conclusion

Retrospectively ECG-gated MSCT with four-slice acquisition and half-second scanner rotation enables coronary calcium quantification with high reproducibility based on image data reconstructed with overlapping image increment to reduce partial-volume errors. Patient-individual and vessel-individual selection of the reconstruction phase in the cardiac cycle provide minimization of motion artifacts and thus optimization of reproducibility in a patient group where heart rate is not controlled and higher heart rate can be present.

By using appropriate normalization Agatston scoring can also be applied to image data sets with overlapping image increment. Best reproducibility with interscan variability down to 5% can be achieved by using volume and mass quantification with 3-mm slice width and 1.5- to 2-mm image increment. Volume and mass quantification with isotropic interpolation do not show improved reproducibility. Calcium mass quantification shows

slightly improved reproducibility compared with calcium volume quantification and should become the preferred coronary calcium measurements as it allows, in addition, cross-calibration for different scanner technology and scan protocols.

Retrospectively ECG-gated spiral MSCT demonstrates substantially improved reproducibility compared with prospectively ECG-triggered MSCT at the expense of higher radiation exposure; however, developments are underway that provide significant reduction of radiation exposure with retrospective ECG gating, via ECG-controlled modulation of the tube output.

With interscan variability below 10%, the presented MSCT imaging procedure to quantify coronary calcium may be used to monitor progression of coronary calcification, which should be investigated in future studies.

Future developments of MSCT scanner technology with increased number of slices and increased rotation speed promise further improvements of sensitivity and reproducibility of quantification of coronary calcification.

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