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Impact of Reconstruction Algorithms and Gender-Associated Anatomy on Coronary Calcium Scoring with CT:

An Anthropomorphic Phantom Study

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Abstract

Rationale and Objectives—Different computed tomography imaging protocols and patient characteristics can impact the accuracy and precision of the calcium score and may lead to inconsistent patient treatment recommendations. The aim of this work was to determine the impact of reconstruction algorithm and gender characteristics on coronary artery calcium scoring based on a phantom study using computed tomography.

Materials and Methods—Four synthetic heart vessels with vessel diameters corresponding to female and male left main and left circumflex arteries containing calcification-mimicking materials (200–1000 HU) were inserted into a thorax phantom and were scanned with and without female breast plates (male and female phantoms, respectively). Ten scans were acquired and were reconstructed at 3-mm slices using filtered-back projection (FBP) and iterative reconstruction with medium and strong denoising (IR3 and IR5) algorithms. Agatston and calcium volume scores were estimated for each vessel. Calcium scores for each vessel and the total calcium score (summation of all four vessels) were compared between the two phantoms to quantify the impact of the breast plates and reconstruction parameters. Calcium scores were also compared among vessels of different diameters to investigate the impact of the vessel size.

Results—The calcium scores were significantly larger for FBP reconstruction (FBP > IR3 > IR5). Agatston scores (calcium volume score) for vessels in the male phantom scans were on average 4.8% (2.9%), 8.2% (7.1%), and 10.5% (9.4%) higher compared to those in the female phantom with FBP, IR3, and IR5, respectively, when exposure was conserved across phantoms. The total

calcium scores from the male phantom were significantly larger than those from the female phantom ($P < 0.05$). In general, calcium volume scores were underestimated (up to about 50%) for smaller vessels, especially when scanned in the female phantom.

Conclusions—Calcium scores significantly decreased with iterative reconstruction and tended to be underestimated for female anatomy (smaller vessels and presence of breast plates).

Keywords

Coronary calcium scoring; computed tomography; phantom study; gender differences; quantitative imaging; coronary imaging

INTRODUCTION

Cardiovascular disease is the leading cause of death in American women, and women have higher cardiovascular mortality rates compared to men (1). A common screening approach for intermediate risk patients is the identification of calcium in the coronary arteries using computed tomography (CT) (2,3). The calcium score is used as an overall indicator of coronary health, with higher scores indicating higher risk of coronary artery disease. In general, women have smaller, faster beating hearts, smaller arteries, and a different breast structure compared to men, which can potentially lead to differences in performing quantitative calcium scoring (4–6).

Research has been done to standardize and quantify coronary artery calcium in CT, accounting for patient differences. McCollough et al. reported a consensus standard for quantification of coronary artery calcium and reported standardized CT acquisition parameters to achieve comparable image noise, spatial resolution, and mass scores among patients of varying sizes (7). Willemink et al. recently compared calcium scoring with a smaller 300×200 mm and a larger 400×300 mm chest phantom in a multivendor phantom study (8). Willemink et al. showed that the calcium scores were systematically underestimated in a larger chest phantom. Willemink et al. stated that the results were relevant to women in the sense that the thorax attenuation of the women was similar to a larger chest.

The impact of iterative reconstruction (IR) algorithm on calcium scoring has also been a subject of recent studies in the literature. Gebhard et al. showed that the iterative algorithm ASIR (Adaptive Statistical Iterative Reconstruction, GE Healthcare) reduced noise but also decreased Agatston calcium scores (9). A similar conclusion was reached for the iterative algorithms SAFIRE (Sinogram Affirmed Iterative Reconstruction, Siemens healthcare) and ADMIRE (Advanced Modeled Iterative Reconstruction, Siemens healthcare) by Kurata et al. and McQuiston et al., respectively (10,11). Willemink et al. showed that IR resulted in a trend toward lower Agatston scores and calcification volumes for multiple vendor platforms compared to filtered-back projection (FBP) and suggested that caution should be taken for coronary calcium scoring with IR algorithms (12). Takahashi et al. found a significant decrease in maximum CT value and calcified plaque size in both patient and phantom studies with the iterative algorithm ASIR compared to FBP (13). However, Schindler et al. found that IR techniques (IRIS and SAFIRE [strength level not specified]) did not have a

substantial impact on the Agatston score (14). It is worth noting that for the high-density (800 mg HA/cm³) 5-mm calcium cylinder included in their phantom, Schindler et al. did find that IR algorithms yielded significantly lower Agatston scores compared to FBP.

However, none of the studies were dedicated to the examination of gender differences. The purpose of our study was to assess and compare coronary artery calcium scoring with CT between men and women and to investigate the impact of image reconstruction algorithms on calcium measurements through imaging of gender-specific anthropomorphic phantoms that incorporate both gender-based breast structure and vessel sizes.

METHODS

Anthropomorphic Phantom Materials

Four synthetic vessels were designed in our lab and were custom built (Fuyo Co., Tokyo, Japan). Each vessel contained three artificial stenoses with 9-mm lengths and 5-mm spacing (see Fig 1). Six calcium mimicking materials spanning 105–1000 HU at 120 kV were used to form the stenoses. Each stenosis was composed of two materials and on average blocked about half the vessel diameter (Fig 1). One stenosis mimicked a relatively low-density calcified plaque with a necrotic core (stenosis 1: nylon (MC901UB) [200 HU] and polybutylene terephthalate (PBT) [105 HU]), and the other two mimicked relatively hard calcified plaques (stenosis 2: polyether sulphone resin (PES) [400 HU] and polyether ether ketone resin (PEEK) [170 HU], stenosis 3: polyvinyl chloride (PVC) [1000 HU] and polyoxymethylene (PMG(G)) [450 HU]). The diameters of the two larger synthetic vessels (4.5 and 4.0 mm) were chosen to represent the average diameter of the left main artery in the average male and female (referred to as M-LM and F-LM), respectively (5). The diameters of two smaller synthetic vessels (3.4 and 2.9 mm) represented average diameters of the left circumflex artery in the average male and female (referred to as M-LCX and F-LCX), respectively.

The vessels, filled with water, were attached to the outside area of the heart in an anthropomorphic thorax phantom (Kyoto Kagaku Co., Tokyo, Japan) and wrapped with a butter–wax mixture (about –100 HU) to mimic the pericardium (Fig 2). Two anthropomorphic breast plates (CIRS Inc., Norfolk, VA) were attached on top of the thorax phantom to represent the female breast anatomy (Fig 2c). Imaging without the breast plates represented a smaller thorax attenuation, which roughly corresponds to a similarly sized male. The thorax phantoms with and without the breast plates are referred to as female phantom and male phantom, respectively, in the rest of the paper.

Imaging Protocol

The male phantom and female phantom with all four vessels inserted were scanned with a dual-source CT scanner (SOMATOM Force; Siemens Medical Solutions USA, Inc., Malvern, PA). Ten repeat scans were acquired using single-energy mode with repositioning of the phantom between each scan by a small random rotation. A simulated electrocardiogram signal (heart rate = 60 bpm) was used to trigger the scanner to work in retrospective electrocardiogram-trigger mode; however, the phantom was static and did

not incorporate any heart or lung motion. The scan parameters were tube voltage, 120 kV; tube current time product, 80 mAs (scanner's automatic dose module, CareDose, was turned off); collimation, 192×0.6 mm; pitch factor, 0.2; and rotation time, 330 ms. The acquisition protocols were selected based on protocols typically used in clinical practice and were based on the published consensus protocol for a medium-sized patient using a fixed tube current (7). We did not adjust the tube current time product and the automatic dose module was turned off for both male and female phantom scanning. Automatic exposure control (AEC) has been widely used in coronary artery CT angiography and has been found to substantially reduce the radiation dose (15). However, the benefit of AEC in a calcium score protocol is limited as tube current is already relatively low. Multicenter clinical trials, such as the Multi-Ethnic Study of Atherosclerosis, use fixed tube currents similar to this study to avoid vendor variation of AEC and unintended CTDI_{vol} changes. To maintain a fixed CTDI_{vol} and to allow for a direct comparison between male and female phantoms of basically the same size, we used a fixed tube current time product. This allowed us to directly measure the impact on calcium scoring when the breast plates were added in the female phantom.

Each scan was reconstructed at a 3-mm slice thickness with a 50% overlap using three image reconstruction algorithms: FBP, IR (ADMIRE, Siemens Medical Solutions USA, Inc.) with denoising strength 3 (IR3) and 5 (IR5). The 3-mm reconstructions were selected to again match calcium scoring protocols used in clinical practice. The field of view was 200 mm and the convolution kernel was a standard medium-smooth kernel Br36 (our rationale for using the Br36 kernel is discussed in the "Discussion"). In summary, 10 repeated scans were obtained for the male and female phantoms in single-energy mode and were reconstructed with three reconstruction algorithms.

Calcium Scoring

Calcium presence was quantified as Agatston and calcium volume scores using an in-house automated threshold-based segmentation algorithm. The Agatston score is based on the product of the weighted density score given the highest attenuation value and the area of the calcification. Calcifications were identified when the CT value of pixels within the vessel was above a standard threshold of 130 HU in more than two contiguous pixels. Note this definition is for CT images with a slice thickness equal to 3 mm (no overlapping). If the images are acquired with different slice thicknesses or with overlapping slices, a scaling factor must be applied to normalize the score (7). The calcium volume score was defined as the product of the number of voxels with a Hounsfield unit value higher than 130 HU and the volume of each voxel, measured in cubic millimeter.

The scores were estimated for each of the four vessels (M-LM, M-LCX, F-LM, and F-LCX) in each of the male and female phantom scans. We defined the total calcium score as the summation of the scores for all four vessels, and the male (female) calcium score for each vessel as the M-LM (F-LM) score or the M-LCX (F-LCX) score in the male and female phantoms, respectively.

Reference Standard

Each stenosis was scanned using high-resolution micro-CT (Scanco100 Medical μ CT; Scanco USA, Wayne, PA) and the reference standard for the volume of the volume score was obtained using the semiautomatic segmentation tool supplied with the microCT system's software suite. No reference standard was evaluated for the Agatston score due to the fact that the Agatston score does not correspond to a specific physical measurement.

Noise Measurement

Regions of interest of the same size ($15 \times 15 \times 15$ voxels) located at the center area within the heart region of the anthropomorphic phantom (a uniform region) were used to evaluate the noise in each set of scans. The standard deviations of the regions of interests were used as measures of the noise within each scan.

Statistical Analyses

The first analysis investigated the impact of CT reconstruction method on calcium scoring. Calcium scores for each imaging reconstruction method were reported as mean $\pm$ standard deviation. To evaluate if there was a statistical difference between scores in subgroups that resulted from different reconstruction algorithms, data were compared using the *t*-test with Bonferroni's correction for multiple comparisons. The Lilliefors test was used to test the normality of the data, as well as the other two analyses described next.

The second analysis focused on differences associated with gender-specific phantoms, characterized by the presence or absence of breast plates in the female and male phantoms, respectively. We calculated the concordance correlation coefficients (CCCs) for the calcium scores of each vessel from male and female phantoms and plotted Bland-Altman's plot for agreement analysis. Total calcium scores of the female and male phantoms were compared as well. Coefficients of variation were calculated to compare repeatability among repeated scans. Analysis of the total calcium scores of the female and male phantoms using one-way analysis of variance (ANOVA) was performed to determine whether there was a significant difference between the two phantoms. The average total score difference between the two phantoms was calculated for each imaging protocol.

Finally, we examined gender differences in terms of both the breast anatomy and vessel size, by comparing the female calcium scores, defined as the calcium scores for the two female-specific vessels in a female phantom scan, to the male calcium scores, defined in a similar manner for the male-specific vessels in a male phantom scan. Differences in gender-related factors, both anatomy and vessel size, were used as factors in a two-way ANOVA test. The vessels were categorized into two groups, small and large, which corresponded to F/M-LCX and F/M-LM, respectively. Note that, because the female and male calcium scores have different ground truths, the scores were converted into a relative score error before the analysis was conducted. In the present study, relative score error was defined as $\ln$

$\left(\frac{\text{Measured Score}}{\text{Reference Standard}} \right)$. Because the Agatston score is image-based and has no reference standard, it was not included as part of this analysis. All statistical analyses and the

segmentation algorithm were implemented using MATLAB (version 7.5.0, R2007b; MathWorks, Inc., Natick, MA).

RESULTS

Reference Standard for Calcium Stenosis Volume

The reference standard calcium volumes for F-LM, F-LCX, M-LM, and M-LCX were 137, 79, 149, and 84 mm³, respectively. The reference standard for the total calcium volume (sum of the F-LM, F-LCX, M-LM, and M-LCX scores) and the calcium volume for female vessels (sum of F-LM and F-LCX scores) and male vessels (sum of M-LM and M-LCX scores) was 449, 216, and 233 mm³, respectively.

Image Noise

The mean effective dose for the 10 repeated scans was equal to 1.22 ± 0.08 mSv (corresponding to CTDI_{vol}: 5.98 ± 0.4 mGy) (16). The noise levels for all imaging protocols are shown in Figure 3. Findings show that IR5 yielded the lowest noise level and FBP yielded the highest noise level. Overall, the images from the female phantom contained higher noise, in the order of +4.4, +3.6, and +2.9 HU on average for FBP, IR3, and IR5 compared to those of the male phantom, due to the presence of the breast plates.

Effect of Image Reconstruction Method on Calcium Score Estimation

Table 1 shows the total calcium scores of each of the male and female phantoms obtained for the three reconstruction algorithms. Results show that FBP yielded the highest and IR5 yielded the lowest Agatston and calcium volume scores. Figure 4 gives examples of the impact of the reconstruction algorithm on the calcium score. The differences among the three reconstruction algorithms were all statistically significant as verified by the *t*-test with Bonferroni's correction (one-sided, $P < 0.0167$). For the total calcium volume score, FBP-derived results with the 3-mm slice thickness were the closest to the reference standard. Overall, the total calcium scores varied substantially across the imaging reconstruction algorithms investigated in the present study. The total Agatston score ranged from 348 to 496 (348–477 for the female phantom and 374–496 for the male phantom), and the total calcium volume score ranged from 318 to 448 mm³ (318–445 mm³ for the female phantom and 341–448 mm³ for the male phantom).

Gender Impact

Figure 5 shows CT slices of the male and female phantoms at similar locations. These images were reconstructed using FBP. The figure shows that the female phantom has stronger streaking artifacts compared to the male phantom image due to the higher X-ray attenuation associated with the breast plates. Calcium scores for each vessel from the male phantom were highly correlated with that from the female phantom with CCC values of 0.989, 0.978, and 0.972 for the Agatston score with FBP, IR3, and IR5, and 0.992, 0.983, and 0.977 for calcium volume score with FBP, IR3, and IR5, respectively. The CCC values given previously were averages across the four vessels.

Figure 6 shows the mean score differences for the four vessels in Bland-Altman's plots. Note that the scores were log transformed and the results were converted to percentage for easier interpretation. In general, calcium scores were higher for the male phantom. The Agatston scores for vessels scanned in the male phantom were 4.8% (FBP), 8.2% (IR3), and 10.5% (IR5) higher compared to those in the female phantom. The calcium volume score for vessels scanned in the male phantom were 2.9% (FBP), 7.1% (IR3), and 9.4% (IR5) higher compared to those in the female phantom.

The total calcium scores of the male phantom varied less (ie, smaller coefficient of variance) than those of the female phantom as indicated in Table 2. Overall, the variance for the total score under each imaging condition was small (coefficient of variance within 0.9%–2.4%), indicating high repeatability for the calcium scoring tasks. ANOVA applied to the total Agatston and calcium volume scores showed that the measurements in the male and female phantoms were significantly different ($P < 0.05$). The mean total score of the male phantom was larger than that of the female phantom by 20 (FBP), 30 (IR3), and 36 (IR5), and 12 (FBP), 24 (IR3), and 28 (IR5) mm³ for Agatston and calcium volume scores, respectively (Fig 7).

In addition to the comparison of the total calcium score between the female and male phantoms, we also compared the female calcium volume score (female vessels in female phantom) to the male calcium volume score (male vessels in male phantom). We have normalized the calcium volume scores using the reference standard for calcium volume, as defined at the end of "Noise Measurement." Two-way ANOVA with interaction was applied to the relative score errors for male/female calcium volume scores as described in "Noise Measurement." Our results show that both the breastplate and vessel size significantly impacted the calcium scores. The trend was an underestimation of the calcium score when the vessel was small and imaged within the female phantom (Fig 8). There was also a trend for underestimating the calcium score when the image was reconstructed using an iterative algorithm.

DISCUSSION

In the present study, we have performed cardiac CT scans on gender-specific anthropomorphic phantoms. We investigated the impact of reconstruction algorithm, female anatomy (inclusion of breast plates), and vessel size on the accuracy and precision of calcium quantification based on calcium scores. Our findings show that the smaller vessels, the inclusion of female breast anatomy, and IR algorithm significantly impact calcium scoring. All of these factors tended to exacerbate the underestimation in calcium scores.

The influence of breast anatomy was expected because our female phantom corresponds to a somewhat larger patient because of the breast plates compared to the male phantom, and Willemink et al. observed the underestimations of calcium scores of phantoms of large-sized patients (8). The breast anatomy reduces the number of photons transported through the phantom and likely increases scatter somewhat with the fix exposure protocols used in our study. Therefore, the noise level increases, as shown in our noise level analysis. However, increasing noise may not by itself suggest a decrease in the average calcium scores, but it is

likely that higher noise will result in a smaller number of voxels being above the 130-HU threshold because of the higher variability in the values. This would then lead to a reduction in the calcium scores.

The influence of vessel size was expected to be a very important factor due to partial volume effects that can impact both the CT number and the estimation of the boundaries of the calcifications (17). We analyzed the effect of vessel size using the relative score error, which normalizes the calcium volume score by the reference standard. Under ideal imaging conditions (eg, absence of partial volume artifacts), the relative score error is expected to be invariant to calcium size. We found that smaller vessels and, as a result, smaller calcifications are influenced more by the partial volume effect than larger vessels and calcifications. Therefore, underestimation was more severe in the smaller vessels associated with women even though the percentage of occlusion was similar in both the male and female phantom scans. Based on our phantom results, it appears that these two factors are likely to compound the difficulty in accurately and precisely estimating calcium scores, and therefore cardiovascular risk, in women.

In the present work, the accuracy of the calcium score was found to be highly dependent on the image reconstruction algorithms. The differences in total calcium score across reconstruction algorithms in the present study were as large as ~150 for the Agatston score and ~130 mm³ for the calcium volume score, which could cause inconsistent risk interpretation. Our results show that the calcium scores are lower with IR compared to FBP, which are consistent with the literature, as summarized in the “Introduction.” The denoising process associated with IR impacted the CT attenuation values, especially for small structures with high density. We found that the ADMIRE algorithm yielded lower attenuation values on average for the calcium deposits compared to FBP and therefore reduced the area that met the threshold criterion for calcification. This led to lower calcium scores for IR compared to FBP. When stronger denoising was applied, the reduction in score was even more profound. In addition, we found that there was a complicated interaction between IR and the gender-specific phantoms. IR reduced the overall noise as well as the noise differences between the female and male phantoms, but the calcium score differences between the two phantoms were larger with IR compared to FBP. For instance, the Agatston (calcium volume) score for each vessel was on average reduced by 10.5% (9.4%) in the female phantom compared to the male phantom with IR5, whereas the reduction was 4.8% (2.9%) with FBP. Further investigation is needed to determine why the reduction of noise with IR does not result in a decrease in the calcium score differences between the male and female phantoms.

The conclusion from our study related to reconstruction algorithms is that care must be taken in switching from the FBP algorithms to iterative algorithms for calcium scoring because the differences may result in inconsistent risk classification. The calcium threshold and Agatston weighting factors used in the current clinics are defined based on FBP-reconstructed images. Therefore, to reduce/correct the differences that we observed between the FBP and IR algorithms, modifications to the calcium threshold or Agatston weighting factors, or a calibration technique developed across reconstruction algorithms, might be helpful. For example, instead of using 130 HU, one can use a fixed calcium hydroxyapatite

density threshold (100 mg/cm^3) as suggested by McCollough et al. (7). McCollough et al.'s study showed that this method reduced interscanner variability. The HU value for the 100 mg/cm^3 calcium hydroxyapatite could be obtained empirically before scanning or could be obtained using some type of pocket phantom imaged with the patient. The calibration process for the Agatston score might be more complicated because multiple thresholds are involved. We were aware of a set of new "Q" kernels (stand for quantitative) available on the Siemens scanner used in the present study. However, as shown in McQuiston et al., even with the use of a Qr36 kernel, a decreasing trend was observed from FBP to IR (11). We believe that our conclusion should likely hold for the newer Qr36 kernel as well based on McQuiston et al.'s work and some preliminary data we conducted during a pilot phase of the present study (11). As part of a pilot study, we reconstructed two repeated scans using three different convolution kernels, Br36, Bf36, and Qr36, respectively. We found the calcium scores for Bf36 and Qr36 were similar and were both about 30% lower than Br36. The reason we chose Br36 was that for the FBP with 3-mm slice thickness, the maximum CT value of each calcification and the resulting calcium volume score with Br36 was more consistent with the reference standard compared to the two other kernels.

Our phantom study has limitations. First, the phantom is static, such that no heart or lung motion is included. We plan to construct a dynamic heart phantom as a continuation of the present study to understand how cardiac motion impacts gender-based calcium scoring to further improve our understanding that calcium scoring varies between women and men. We will incorporate the fact that women have a faster heart rate on average. Second, the calcification materials used in the current study have attenuation values consistent with calcium but are not actually calcium, which is the reason we did not evaluate calcium mass scores. The construction of actual calcium (typically hydroxyapatite) into a complex shape is both difficult and costly. This is probably one of the reasons why, in most of the previous published phantom studies, calcifications were usually made into cylinders resulting in reduced complexity and realism compared to the clinical task. The design of our phantom was a trade-off between the material property of calcium and realistic shapes for the calcium deposits. Although using human calcified plaque specimens or in vivo data solves both issues, ground truth is hard to obtain, which adds difficulty in appropriately analyzing the score data. In addition, it can also be difficult to systematically examine the repeatability using in vivo data because of limitations in exposing patients to repeat CT exams. Third, our phantoms were only scanned using one CT scanner and the images were reconstructed using only one type of IR. Different vendors implement different IR algorithms (statistical-based, model-based, etc). As such, whether or not our conclusions will extended to different vendors needs further evaluation. Finally, we have compared FBP with a model-based IR algorithm using a single fixed dose. IR is often used for radiation dose reduction in practice. Additional work is needed to understand the impact of adjusting the dose such that FBP and IR generate images with similar noise levels and that the noise levels in the male and female phantoms are equalized. This type of study would allow a better understanding of the potential use of IR for calcium scoring at lower doses and its effect on gender-specific calcium scoring.

CONCLUSIONS

In conclusion, we have presented a phantom study investigating the effect of the image reconstruction method and gender differences with a state-of-the-art CT scanner. The results indicate that to obtain consistent calcium scores, not only does the imaging condition need to be standardized but also gender differences should be accounted for, due to the fact that the smaller vessels and the presence of the breast anatomy in women can substantially impact the precision and accuracy of calcium scoring.

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Figure 1.

Layout of the customized vessel phantom (Fuyo Co., Tokyo, Japan). Reference HU values for the materials were based on imaging of large samples of the materials (cylinder: 15 mm in diameter, 50 mm in length) placed in a water tank and scanned with a commercial computed tomography scanner at 120 kVp. HU, Hounsfield unit. MC901UB, nylon; PBT, polybutylene terephthalate; PES, polyether sulphone resin; PEEK, polyether ether ketone resin; PVC, polyvinyl chloride; POM(G), polyoxymethylene.

Figure 2.

(a) Picture of the four vessels wrapped in butter–wax mixture and Styrofoam. (b) Vessels (location indicated by the arrows) pictured inside the thorax phantom (F-LM cannot be observed in this view). (c) Female phantom (with the two synthetic breast plates attached to the chest) just before scanning. F-LCX, left circumflex artery in the average female; F-LM, left main artery in the average female; M-LCX, left circumflex artery in the average male; M-LM, left main artery in the average male.

Figure 3.

Box and whisker plots of noise levels of images obtained under each image reconstruction algorithm. Each box corresponds to results from 10 repeated scans using the same algorithm. *Blue and green colors* correspond to the male and female phantom, respectively. For each box, the *central red line* indicates the median, and the *bottom* and *top* edges of the box indicate the 25th and 75th percentiles. Outliers are indicated by a “+” symbol. FBP, filtered-back projection; HU, Hounsfield unit; IR3, iterative reconstruction with denoising strength 3; IR5, iterative reconstruction with denoising strength 5. (Color version of figure is available online.)

Figure 4.

Two examples of ROIs showing results from our calcium segmentation algorithm. (a) *Top to bottom*: a computed tomography slice with two ROIs marked by the *red squares* (FBP, with breast plates); a close-up view of a vessel within ROI-1; a close-up view of a vessel within ROI-2. (b) and (c) correspond to that reconstructed from IR3 and IR5, respectively. *Black contours* indicate a segmented calcium (> 130 HU). The reconstruction had an impact on the calcium boundary with the calcium area decreasing with IR3 and IR5 compared to FBP. FBP, filtered-back projection; HU, Hounsfield unit; IR3, iterative reconstruction with denoising strength 3; IR5, iterative reconstruction with denoising strength 5; ROI, region of interest. (Color version of figure is available online.)

Figure 5.

CT slice images of the female (*left*) and male (*right*) phantoms at similar locations. The *yellow arrow* on the *left* points to the presence of the breastplate, although most of the breastplate area is outside the field of view in this figure. The *red color* corresponds to regions with HU values greater than or equal to 130 HU. Note the *red highlighted areas* adjacent to the heart area correspond to calcium in the vessels. The images shown here were reconstructed using FBP and displayed using an intensity range of -1000 - 800 HU. FBP, filtered-back projection; HU, Hounsfield unit. (Color version of figure is available online.)

Figure 6.

Bland-Altman's plot for (a) Agatston scores or (b) calcium volume scores for each vessel scanned in the male and female phantoms. Scores were log transformed (natural log). *y*-axis: mean of corresponding scores; *y*-axis: score from the male phantom minus score from the female phantom. *Red lines*: mean of the differences; *green dashed lines*: upper and lower bounds for limit of agreement for all four vessels combined (± 1.96 standard deviation from the mean). FBP, filtered-back projection; F-LCX, left circumflex artery in the average female; F-LM, left main artery in the average female; IR3, iterative reconstruction with denoising strength 3; IR5, iterative reconstruction with denoising strength 5; M-LCX, left circumflex artery in the average male; M-LM, left main artery in the average male. (Color version of figure is available online.)

Figure 7.

Box and whisker plots of total scores from male and female phantoms from (a) FBP and (b) IR5. FBP, filtered-back projection; IR5, iterative reconstruction with denoising strength 5.

Figure 8.

Box and whisker plots for the relative calcium volume score errors for each vessel. *Left, middle, and right columns* in each block corresponds to FBP, IR3, and IR5 respectively. FBP, filtered-back projection; F-LCX, left circumflex artery in the average female; F-LM, left main artery in the average female; IR3, iterative reconstruction with denoising strength 3; IR5, iterative reconstruction with denoising strength 5; M-LCX, left circumflex artery in the average male; M-LM, left main artery in the average male.

TABLE 1

Total Agatston and Total Calcium Volume Scores* for Female and Male Phantoms

Total calcium score	Gender	FBP			IR3			IR5		
		Mean ± SD	Min, max		Mean ± SD	Min, max		Mean ± SD	Min, max	
Agatston score	Female	462 ± 8.3	451, 477		399 ± 8.4	390, 412		354 ± 7.6	348, 368	
	Male	482 ± 8.7	467, 496		429 ± 7.9	414, 441		390 ± 7.9	374, 399	
Calcium volume score	Female	427 ± 9.6	408, 445		369 ± 8.0	359, 387		326 ± 7.6	318, 340	
	Male	439 ± 7.9	425, 448		393 ± 7.9	379, 407		354 ± 7.0	341, 364	

FBP, filtered-back projection; IR3, iterative reconstruction with denoising strength 3; IR5, iterative reconstruction with denoising strength 5; SD, standard deviation.

* Reference standard for the total calcium volume score is 449 mm³.

TABLE 2

The Coefficients of Variations for the Agatston and Calcium Volume Scores Averaged Across the Reconstruction Algorithms and Slice Thicknesses

Coefficient of Variation	Agatston Score			Calcium Volume Score (mm ³)		
	FBP	IR3	IR5	FBP	IR3	IR5
Female	0.0180	0.0211	0.0216	0.0225	0.0218	0.0234
Male	0.0181	0.0184	0.0202	0.0180	0.0201	0.0197

FBP, filtered-back projection; IR3, iterative reconstruction with denoising strength 3; IR5, iterative reconstruction with denoising strength 5. The bold numbers indicate the lower coefficients of variation between the female and male phantom images.