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Computation of Calcium Score with Dual Energy CT: A Phantom Study

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Abstract

Dual energy computed tomography (DECT) improves material and tissue characterization compared to single energy CT (SECT); we sought to validate coronary calcium quantification in advancing cardiovascular DECT. In an anthropomorphic phantom, agreement between measurements was excellent, and Bland-Altman analysis demonstrated minimal bias. Compared to the known calcium mass for each phantom, calcium mass by DECT was highly accurate. Noncontrast DECT yields accurate calcium measures, and warrants consideration in cardiac protocols for additional tissue characterizations.

Keywords

calcification; calcium score; computed tomography; dual energy; phantom

Introduction

Dual energy computed tomography (DECT) technology has the potential to improve tissue characterization compared to single energy CT (SECT) by leveraging energy-dependent differences in x-ray attenuation of different materials¹. Emerging cardiac applications include characterization of coronary atherosclerotic plaques² and visualization of myocardial perfusion defects³.

Noncontrast cardiac SECT is a well-established and widely used technique for the detection and quantification of coronary artery calcification⁴. DECT could theoretically offer more detailed plaque characterization, providing that it also delivered reliable coronary calcium

detection and quantification. It is, however, unknown whether DECT-based calcium scoring would provide a suitable alternative to calcium scoring obtained with standard SECT protocols. Prior studies have compared DECT and SECT calcium scoring techniques using ex vivo samples and in patients. However, they did not compare measurements to known values⁵. We addressed the issue of clinical applicability of DECT calcium scoring techniques by using 1) an anthropomorphic coronary calcium phantom 2) a well-validated clinical workflow to obtain calcium measurements. In this study we investigated the feasibility of calcium quantification by DECT using a coronary calcium phantom, testing the hypothesis that calcium measurements by DECT are equivalent to known values and values measured using SECT.

Materials and Methods

An anthropomorphic cardiac CT phantom (QRM GmbH, Moehrendorf Germany) consisting of materials that mimic the CT density and attenuation properties of human thorax with variable calcium inserts was used to perform all experiments. Inserts consisted of varying density and amount of calcium hydroxyapatite (HA), the primary form of calcium in atherosclerotic plaque. Three phantoms, each containing nine inserts plus a large calibration insert, were used for imaging⁶(Fig. 1).

Imaging Parameters

CT calcium score images were acquired in both single and dual energy (GSI) modes on a 64-slice multi-detector, single source scanner (GE Healthcare). Tube current for both single and dual energy acquisitions was 250 mA. Tube voltage and gantry rotation time were 120 kVp and 0.35s, respectively, for single energy acquisitions. Dual energy imaging was performed using rapid switching of a single x-ray source between tube voltages of 80 and 140 kVp; gantry rotation duration was 0.8s. A simulated waveform of 70 beats-per-minute was used for all acquisitions.

Post-Processing

Dual energy acquisitions were reconstructed into 70 keV monochromatic images, to most closely simulate a 120 kVp SECT acquisition (AW Software, GE Healthcare, Waukesha, WI)⁷. SECT and monochromatic images were then exported to previously validated software for analysis (AQi, TeraRecon, Foster City CA).

Regions-of-interest (ROIs) were drawn to encompass the known location of each phantom calcification in both the monochromatic (DECT) images and SECT acquisitions. A calcified lesion is an area of 3 or more connected pixels with a CT number of > 130 HU⁸. With the AQi software 6 lesions were detected per phantom. Mean CT number, Agatston score, and volume scores were recorded.

Mass Score calculation

Calcium mass score from monochromatic images (m_i) were calculated as the product of the corresponding mean CT number (CT_i), volume score (V_i) and a calibration factor c , which relates CT number, CT_{known} , to a known lesion calcium density, ρ_{HA} (Equations 1, 2).

$$m_i = cCT_i V_i \quad [\text{Eq 1}]$$

$$c = \frac{\rho_{HA}}{CT_{known}} \quad [\text{Eq 2}]$$

To calculate the calibration factor, the CT_{known} was obtained from the large calibration insert in the SECT image. The calibration factor was calculated from the SECT image to avoid possible biases that could be present in the DECT images. Three separate calibration factors were obtained, one from each phantom, and then averaged to eliminate the effect of bias as density changes.

Calcium mass for each lesion was calculated as the product of measured lesion volume, mean CT number and calibration factor⁶.

Statistical Analysis

Concordance correlation coefficients⁹ were calculated to examine the agreement between the DECT calculated and true mass values and the agreement between DECT and SECT acquisitions for Agatston scores. Bland-Altman analysis¹⁰ was conducted to identify the differences between the DECT calculated and true mass values and between DECT and SECT Agatston scores, as well as to identify any systemic bias in DECT measurements. Linear regression analysis was performed to produce a predictive model of the SECT Agatston calcium score using the DECT-based score. All statistical analyses were performed using Matlab r2013a (Mathworks, Natick, MA) and Stata 13.0 (Stata Corporation, College Station, TX).

Results

DECT-calculated mass (range: 1.5 to 92.2 mg) and true mass (range: 4.2 to 78.5 mg) demonstrated excellent agreement with a concordance correlation coefficient of 0.99 (95% confidence interval, CI: 0.99, 1.0). Bland-Altman analysis demonstrated a mean difference between calculated and true mass of 0.03 mg with 95% limits of agreement (LoA) of -10.7 mg and +10.6 mg (Fig. 2).

Agatston calcium scores (*A*) ranged from 11.1 to 261.7 using SECT. A range of 5.72 to 282.9 was obtained using DECT. Excellent agreement between the calcium scores calculated from single and dual energy acquisitions was indicated by a concordance correlation coefficient of 0.98 (95% CI: 0.96, 1.00). Bland-Altman analysis demonstrated excellent agreement between single and dual energy calcium scores, a mean difference of 5.93 agatston units was detected with a 95% LoA of -21.84 and +33.69 agatston units (Fig. 2). Linear regression analysis (Fig. 3) yielded the following equation (Eq. 3) to predict a SECT-derived Agatston calcium score from a DECT-based score.

$$Score_{SE} = 0.89 * Score_{DE} + 5.1 \quad [\text{Eq 3}]$$

Radiation doses

Radiation dose was 4.6 and 10.14 Gy for the single and dual energy scans, respectively.

Discussion

In an anthropomorphic phantom with a range of calcium contents similar to those seen in human coronary artery atherosclerosis, we have derived a method to convert calcium scores acquired by a DECT-based technique to the conventional SECT-acquired values. Furthermore we have shown that noncontrast DECT is capable of yielding equivalent estimates of calcium score and mass to those obtained by conventional SECT.

It is interesting to note the slight differences between single and dual energy calculated Agatston score, requiring a correction factor. We note that the Agatston score is calculated based on the size and density, in Hounsfield units, of calcifications. Since Hounsfield units are proportional to the energy of x-ray photons used, we speculate that low vs. high energy photons used in DECT yield slight differences between the true and predicted single energy densities of calcifications. Nonetheless, DECT-derived calcium scores showed excellent agreement without significant bias compared to SECT-derived scores. Estimated radiation exposure was expectedly higher, but within the range accepted for protocols such as CT perfusion and other advanced cardiac applications.

With increasing interest in DECT for its potential utility in refining CT-based tissue characterization, validation of coronary artery calcium quantification is an essential step towards incorporation of DECT into clinical cardiac CT protocols. Further studies advancing coronary plaque characterization with DECT in patients referred for CCT are warranted.

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References

1. Bolus DN. Dual-energy computed tomographic scanners: principles, comparisons, and contrasts. *Journal of computer assisted tomography*. 2013; 37:944–947. [PubMed: 24270117]
2. Vliegenthart R, et al. Dual-energy CT of the heart. *AJR. American journal of roentgenology*. 2012; 199:S54–63. [PubMed: 23097168]
3. Danad I, Fayad ZA, Willemink MJ, Min JK. New Applications of Cardiac Computed Tomography: Dual-Energy, Spectral, and Molecular CT Imaging. *JACC. Cardiovascular imaging*. 2015; 8:710–723. [PubMed: 26068288]
4. Agatston AS, et al. Quantification of coronary artery calcium using ultrafast computed tomography. *Journal of the American College of Cardiology*. 1990; 15:827–832. [PubMed: 2407762]
5. Yamak D, et al. Coronary calcium quantification using contrast-enhanced dual-energy computed tomography scans. *Journal of applied clinical medical physics / American College of Medical Physics*. 2013; 14:4014.

6. McCollough CH, et al. Coronary artery calcium: a multi-institutional, multimanufacturer international standard for quantification at cardiac CT. *Radiology*. 2007; 243:527–538. [PubMed: 17456875]
7. Carrascosa, Patricia M.; RCC; García, Mario J.; Leipsic, Jonathon A., editors. *Dual Energy CT in Cardiovascular Imaging*. Springer International Publishing; Switzerland: 2015.
8. Moselewski F, et al. Calcium concentration of individual coronary calcified plaques as measured by multidetector row computed tomography. *Circulation*. 2005; 111:3236–3241. [PubMed: 15956133]
9. Lin LI. A concordance correlation coefficient to evaluate reproducibility. *Biometrics*. 1989; 45:255–268. [PubMed: 2720055]
10. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*. 1986; 1:307–310. [PubMed: 2868172]

Figure 1.

a) DECT image of cardiac phantom is shown. b) A diagram of the anthropomorphic cardiac phantom used for all experiments is shown. The 15mm lesion is a calibration insert and its density can be 800,400 or 200 mg/cm³.

Figure 2. Calcification mass from known phantom values and dual energy acquisitions were compared using Bland-Altman analysis.

Figure 3.

Calcification Agatston score from single and dual energy acquisitions were compared using Bland-Altman (a) and regression analysis (b). Bland-Altman plots show mean and 95% confidence limits of agreement with solid blue and dotted red lines, respectively. The regression plot shows best-fit line in red.