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Research paper

Iterative beam-hardening correction with advanced modeled iterative reconstruction in low voltage CT coronary calcium scoring with tin filtration: Impact on coronary artery calcium quantification and image quality

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A B S T R A C T

Objective: We investigated the impact of iterative beam-hardening correction (IBHC) with advanced modeled iterative reconstruction (ADMIRE) of ultra-low radiation-dose tin filtered (Sn100 kVp) CACS acquisitions on image quality, calcium quantification, and risk classification.
Methods: CT data of 60 patients (55% male, age 62.3 ± 9.8years) who underwent a 3rd generation dual-source CACS scan using a prospectively ECG-triggered 100 kVp sequential acquisition protocol with tin filtration (Sn100 kVp) were reconstructed using IBHC with filtered back projection (FBP) and ADMIRE with strength levels of three and five. Image noise was calculated and Agatston scores were derived from all reconstructions. Image noise, Agatston score categories, and percentile-based cardiac risk categorization of the respective reconstruction techniques were compared.
Results: The mean estimated radiation dose equivalent of CACS acquisitions in the study population was 0.20 ± 0.07 mSv. Mean image noise significantly decreased with ADMIRE compared to FBP (both $p < 0.0001$). Agatston scores derived from the respective reconstructions were significantly different in a paired comparison (median [25th and 75th percentile]): FBP 34.7 [1.9, 153.6], ADMIRE 3 28.6 [1.1, 134.5], ADMIRE 5 22.7 [0.3, 116.8]; both $p < 0.0001$). Agatston score categories and cardiac risk categorization showed excellent agreement of ADMIRE 3 and ADMIRE 5 with FBP ($\kappa = 0.92$ [0.86–0.98] and $\kappa = 0.86$ [0.79–0.94]; $\kappa = 0.94$ [0.87–1.00] and $\kappa = 0.91$ [0.83–0.99]; however, modest cardiac risk reclassifications of 3% and 7% for ADMIRE 3 and ADMIRE 5, respectively, were observed.
Conclusion: Iterative reconstruction using IBHC ADMIRE in low voltage, ultra-low dose CACS with tin filtration significantly decreased image noise. However, it also reduced Agatston scores compared to FBP, which may have an impact on subsequent cardiac risk classification, although risk reclassification occurred only in a modest number of subjects.

1. Introduction

Coronary artery calcium is an important marker of atherosclerotic plaque burden, and a large body of evidence has accumulated

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Abbreviations

ADMIRE	Advanced modeled iterative reconstruction algorithm
ADIR	Adaptive iterative dose reduction
ASIR	Adaptive statistical iterative reconstruction
BMI	Body mass index
CACS	Coronary artery calcium scoring
CAD	Coronary artery disease
DSCT	Dual-source CT
FBP	Filtered back projection
HIR	Hybrid iterative reconstruction
IBHC	Iterative beam hardening correction
IMR	Iterative model reconstruction
IRIS	Iterative reconstruction in image space
SAFIRE	Sinogram-affirmed iterative reconstruction
SD	Standard deviation

supporting the value of the Agatston calcium score for cardiovascular risk stratification.[1,2] CT coronary artery calcium scoring (CACS) is mainly used as a screening test in *a priori* healthy subjects, and thus, should be performed with the lowest possible radiation dose. Recently introduced 3rd generation dual-source CT (DSCT) with tin filtration can reduce the radiation dose of CACS acquisitions.[3,4] The tin-filter absorbs low-energy x-rays in the range of 30 and 50 keV, which are mainly absorbed in the outer tissue layers of the patient without significantly contributing to the measured signal, effectively increasing the radiation dose efficiency of non-contrast scans. Furthermore, a recent clinical study using CT tin filtration with low voltage (Sn100 kVp) and filtered back projection (FBP) reconstruction demonstrated excellent accuracy in calcium detection and risk categorization while significantly reducing radiation dose compared with standard 120 kVp CACS acquisition.[3] However, differences in Agatston scores and a significant increase in image noise were observed with Sn100 kVp CACS acquisitions. Given the large body of data establishing cardiovascular risk for CACS reference values, any systematic error in calcium scoring is problematic. A preliminary study evaluating an iterative beam-hardening correction (IBHC) algorithm that restores the spectral response of the Sn100 kVp acquisition to that of a standard 120 kVp spectra has been evaluated and shown to largely overcome the systematic errors in calcium quantification; however, the Sn100 kVp FBP reconstructions still suffer from increased noise compared to standard 120 kVp spectra.[4] Various iterative reconstruction techniques in combination with electrocardiogram-controlled radiation dose modulation, use of prospective electrocardiogram-triggering, advanced acquisition techniques, such as high pitch acquisition and the lowering of the tube voltage have shown to be effective strategies to decrease radiation dose and image noise compared to standard FBP,[5–8] potentially mitigating the increased noise seen in Sn100 kVp acquisitions. Previous studies showed that CACS using iterative reconstruction techniques allowed for coronary calcium quantification similar to that of traditional FBP[9–11] albeit with systematically decreased calcium scores, potentially moving patients into a lower cardiac risk categorization.[12,13] There have been no studies to date evaluating iterative reconstruction techniques combined with IBHC algorithms, which in theory could overcome the increased noise and systematically decreased Agatston scores of low-dose Sn100 kVp CACS acquisitions.

Thus, we sought to investigate calcium quantification and image quality of low-dose CACS with tin filtration (Sn100 kVp) using advanced modeled iterative reconstruction (ADMIRE) and IBHC.

2. Material and methods

2.1. Study population

This single-center retrospective study was approved by the local Institutional Review Board and written informed consent was obtained from all patients. The study was performed in compliance with HIPAA regulations. Data of 64 patients who underwent a dedicated ECG-triggered 100 kVp calcium scan with tin filtration (Sn100 kVp) as part of a research study between February and May 2016 were retrospectively analyzed. Patients with known coronary artery disease (prior percutaneous stent implantation or coronary artery bypass grafting) were not eligible to participate. Further, we excluded patients with implanted mechanical prosthetic valves ($n = 2$) or cardiac devices ($n = 2$) to prevent imaging artifacts. Thus, a total of 60 patients were included for further analysis.

2.2. CT acquisition parameters and image reconstruction

CT acquisition was performed with a 3rd generation DSCT system (SOMATOM Force, Siemens Healthineers, Forchheim, Germany) equipped with a fully integrated circuit detector system (Stellar Infinity, Siemens) and two x-ray tubes (Vectron, Siemens Healthineers).

A dedicated prospectively ECG-triggered non-contrast calcium scoring dual source scan with tin filtration was performed on the scanner by means of special custom pack software. Tin filtration was used on both tubes in combination with a tube voltage of 100 kVp (Sn100 kVp) triggered at 40% (HR $\geq$ 80bpm) or 70% (HR < 80bpm) of the cardiac cycle with the following scan parameters: automated tube current modulation (CARE Dose4D, Siemens Healthineers) with a reference tube current of 300 mAs/rot, collimation: 42 $\times$ 1.2 mm, gantry rotation time 0.25s.

All studies were reconstructed with FBP and ADMIRE at a strength level of 3 and 5. For both FBP and the ADMIRE reconstructions, a dedicated iterative beam hardening correction (IBHC) based calcium material reconstruction was used, with a medium sharp convolution kernel (Qr36), 3.0 mm section thickness and increment of 1.5 mm. Typical reconstruction field of view (FOV) was 160 $\times$ 160 mm, depending on the patient anatomy, in a 512 $\times$ 512 pixel image matrix.

2.3. Image analysis of CACS datasets

For objective and subjective image analysis, the reconstructed image data sets were analyzed using dedicated post-processing evaluation software (syngo.via VB10 Calcium Scoring, Siemens Healthineers). The extent of coronary calcification was quantified on non-contrast scans by two independent observers. Both were blinded to patient characteristics and the imaging report. The extent of calcification, defined as a plaque with an area $\geq$1.03 mm^2, was determined using the Agatston score with a detection threshold of 130 HU.[14] To facilitate observer blinding, the minimum time between the evaluations of calcium on corresponding series was 1 week for both observers. The total Agatston score was recorded and values for the different reconstructions were compared. Agatston score categories were as follows: 0, 1–10, 11–100, 101–400, 401–1000, and >1000.[15] Accordingly, Agatston score percentile-based risk categorization was as follows: 0%, 1–25%, 26–50%, 51–75%, 76–95%, and >95%.[16] Signal and noise was determined as the standard deviation of HUs by placing a region of interest (1 cm^2) in the left ventricle. Consistent placement and size of the region of interest throughout all examinations was ensured by an intrinsic copy-paste function of the dedicated evaluation software. The mean and standard deviation of Hounsfield Units (HU) were recorded and the image noise was calculated by dividing