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Myocardial signal density levels and beam-hardening artifact attenuation using dual-energy computed tomography☆

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ABSTRACT

The assessment of myocardial perfusion using single-energy (SE) imaging is influenced by beam-hardening artifacts (BHA). We sought to explore the ability of dual-energy (DE) imaging to attenuate the presence of BHA. Myocardial signal density (SD) was evaluated in 2240 myocardial segments (112 for each energy level) and in 320 American Heart Association segments among the SE group. Compared to DE reconstructions at the best energy level, SE acquisitions showed no significant differences overall regarding myocardial SD or signal-to-noise ratio. The segments most commonly affected by BHA showed significantly lower myocardial SD at the lowest energy levels, progressively normalizing at higher energy levels.

1. Introduction

The evaluation of myocardial perfusion imaging by means of multidetector computed tomography (CT) has earned interest during the past decade and shows promise to provide a significant incremental value over coronary computed tomography angiography (CCTA) [1–5]. The growing need to assess the physiological impact of a given atherosclerotic lesion is supported by the relatively poor relationship between the degree of stenosis and the presence of ischemia [6,7].

Several ex vivo and in vivo studies provide a robust proof of concept, with a close correlation between contrast kinetics of gadolinium-based agents in magnetic resonance imaging and iodinated contrast agents in CT [8,9]. Myocardial CT perfusion (CTP) has been validated in a number of clinical scenarios, including the evaluation of patients with low to intermediate likelihood of coronary artery disease (CAD), as well as for the triage of patients with acute chest pain [3,4,9].

Notwithstanding, the assessment of CTP using conventional single-energy (SE) acquisitions is influenced by the presence of beam-hardening artifacts (BHA) [10,11]. These artifacts are related to the polychromatic nature of X-rays and to the energy-dependency of X-ray attenuation, and lead to a significant drop in attenuation levels in areas adjacent to highly enhanced structures, commonly resembling perfusion defects in certain left ventricular segments during CCTA [11]. Dual-energy (DE) CT imaging appears as an intriguing technique for CTP, mainly driven by its ability to obtain synthesized monochromatic image reconstructions that might attenuate some of the aforementioned technical issues [5,12]. We therefore sought to explore the ability of DE CTP to mitigate the presence of BHA.

2. Materials and methods

The present study was a single-center, investigator-driven, observational study that involved consecutive patients without a history of CAD who were referred for CCTA evaluation at our institution due to atypical chest pain and evidence of a normal stress-rest single-photon emission CT within the previous 3 months. All patients included were >18 years old; in sinus rhythm; able to maintain a breath-hold for ≥15 s; and without a history of contrast-related allergy, renal failure, or hemodynamic instability. Additional exclusion criteria comprised a body mass index >32 kg/m^2 or a history of previous myocardial infarction, percutaneous or surgical coronary revascularization, severe valve disease, chronic heart failure, chronic obstructive pulmonary disease, or high-degree atrioventricular block. Patients with diabetes, left ventricular hypertrophy, and obstructive (≥50% stenosis) atherosclerotic coronary lesions were also excluded. In addition, patients with intrascan mild heart rhythm abnormalities leading to motion artifacts such as premature

Abbreviations: SE, single energy; DE, dual energy; CTP, computed tomography perfusion; SD, signal density; BHA, beam-hardening artifacts; CCTA, coronary computed tomography angiography; CAD, coronary artery disease.

☆ We declare that Drs. Patricia Carrascosa and Ricardo C. Cury provided consultant work for GE Healthcare in the past 12 months. There are no competing interests related to the manuscript for any of the other authors.

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beats and heart rate <40 bpm were excluded. Two cohorts of patients were sequentially included. The study group was acquired using DE scan; and the control group, using conventional SE scan.

3. Image acquisition

Patients with a heart rate of more than 65 bpm received 50 mg metoprolol orally or 5 mg intravenous propralonol if needed in order to achieve a target heart rate of less than 60 bpm.

Patients were scanned using a DE scanner equipped with gemstone detectors with fast primary speed and low afterglow designed for spectral imaging (Discovery HD 750; GE Medical Systems, Milwaukee, WI, USA). All scans were performed using prospective electrocardiogram gating using a 100-ms padding centered at 75% of the cardiac cycle. Other scanner-related parameters were a collimation width of 0.625 mm and a slice interval of 0.625 mm. Maximum tube voltage and current of SE scans were adjusted according to the body habitus (100 kV or 120 kV for patients with body mass index <30 kg/m^2 or larger, respectively).

DE imaging was performed by rapid switching (0.3–0.5 ms) between low and high tube potentials (80–140 kV) from a single source, thereby allowing the reconstruction of low- and high-energy projections and generation of monochromatic image reconstructions with 10-keV increments from 40 to 140 keV. Iterative reconstruction was performed in all cases at 40% adaptive statistical iterative reconstruction. For DE acquisitions, 60 keV is so far the lowest monoenergetic level available for the reconstruction of images utilizing an iterative reconstruction algorithm. A dual-phase protocol with 50–70 ml of iodinated contrast (iobitridol; Xenetix 350, Guerbet, France) followed by a 30–40-ml saline flush was injected through an arm vein. A bolus tracking technique was used to synchronize the arrival of contrast at the level of the coronary arteries with the start of the scan. Image acquisition was performed after sublingual administration of 2.5–5 mg of isosorbide dinitrate.

The institution's Ethics Committee approved the study protocol, which complied with the Declaration of Helsinki, and written informed consent was obtained from all patients.

4. Myocardial perfusion analysis

CCTA image analysis was performed off-line on a dedicated workstation using a commercially available dedicated software tool (AW 4.6; GE Healthcare). Two experienced observers (PC, GRG) were randomly assigned to independently analyze patients of either of the two groups. CT images were analyzed at mid diastole using a smooth filter in axial planes and multiplanar reconstructions. Short-axis views were obtained initially using 5-mm average multiplanar reconstructions from base to apex, with the full dataset available for the reader. Using standardized regions of interest of 10 to 20 mm^2, myocardial signal density (SD) and noise (standard deviation of myocardial SD) were determined for every segment according to the American Heart Association (AHA) 17-segment myocardial model [13]. AHA segment 17 corresponding to the left ventricular apex was excluded from the analysis since it encompasses a thin myocardial wall and is therefore prone to measurement error. Left ventricular and right ventricular chamber mean SDs were evaluated at basal, mid, and apical short axis.

Measurements among the DE group were performed at different energy levels ranging from 40 to 100 keV. SD ratio, which is highly related to myocardial blood flow measured by microspheres, was determined as previously described: myocardial SD/left ventricular blood pool SD (at the corresponding level; basal, mid, or apical) [14]. Myocardial SD, SD ratio, and signal-to-noise ratio were evaluated at every AHA segment.

CT effective radiation dose was derived by multiplying the dose–length product with the weighting (k) value of 0.014 mSv/mGy/cm for chest examinations, as suggested by the Society of Cardiovascular Computed Tomography [15].

5. Statistical analysis

Discrete variables are presented as counts and percentages; and continuous variables, as mean±standard deviation. Comparisons among groups were performed using paired-samples t test, independent-samples t test, analysis of variance (ANOVA), χ^2 tests, or Fisher's Exact Tests, as indicated. Post hoc comparisons were explored using least significant difference tests. We explored correlations between the basal inferolateral (BIL) segment SD, previously established as the most common location of BHA [11], and variables thought to be related to the presence of BHA using Spearman correlation coefficients. The agreement between observers for the identification of BHA was assessed using the Kappa coefficient. A two-sided P value of less than .05 indicated statistical significance. Statistical analyses were performed with use of SPSS software, version 22 (Chicago, IL, USA).

6. Results

Forty patients constituted the study population (DE group, $n=20$; SE group, $n=20$). The mean age was 59.6±12.0 years, and 28 (70%) were male. Demographical characteristics were similar between groups, as well as the heart rate and the effective radiation dose (Table 1).

Myocardial SD levels were evaluated in 2240 AHA myocardial segments (112 for each energy level from 40 to 100 keV at 10-keV intervals) among the DE group and in 320 AHA segments in the SE group.

7. Myocardial SD levels using DE and SE imaging

Among the DE group, myocardial SD levels and myocardial SD ratio were higher at low energy levels, with significantly lower SD levels at increasing energy levels (Tables 2 and 3, and Figs. 1 and 3). In turn, myocardial signal-to-noise ratio was not significantly influenced by the energy level applied, although 70 keV was identified as the energy level with the best overall signal-to-noise ratio (Table 4). Compared to DE reconstructions at 70 keV, SE acquisitions showed no significant differences overall regarding myocardial SD levels or signal-to-noise ratio, whereas a number of segments showed lower SD ratio among the SE group (Fig. 2).

8. Effect on BHA

Among the SE group, a total of 35/320 segments (10.9%) were identified as BHA by both observers (kappa 0.82; $P<.0001$), whereas among the DE group, a total of 42/320 segments (13.1%) were identified as BHA by both observers (kappa 0.83; $P<.0001$).

On a per-patient level, 18 (90%) patients among the SE group showed at least one segment with BHA, most commonly located at the BIL (65%)

Table 1
Demographical characteristics

	DE ($n=20$)	SE ($n=20$)	P
Age (years±S.D.)	60.8±9.9	58.5±14.3	.56
Male, n (%)	12 (60%)	16 (80%)	.30
Hypertension, n (%)	12 (60%)	10 (50%)	.75
Hypercholesterolemia, n (%)	11 (55%)	10 (50%)	.99
Previous smoking, n (%)	7 (35%)	2 (10%)	.13
Body mass index (kg/m^2±S.D.)	27.9±3.2	27.8±3.9	.88
Heart rate (bpm±S.D.)	63.3±5.8	63.1±5.4	.93
Effective dose (mSv±S.D.)	3.1±0.4	3.3±0.7	.34

Comparisons performed using Fisher's Exact Test.