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Ultra-low dose quantitative CT myocardial perfusion imaging with sparse-view dynamic acquisition and image reconstruction: A feasibility study

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ABSTRACT

Purpose: We implemented and validated a compressed sensing (CS) based algorithm for reconstructing dynamic contrast-enhanced (DCE) CT images of the heart from sparsely sampled X-ray projections.
Methods: DCE CT imaging of the heart was performed on five normal and ischemic pigs after contrast injection. DCE images were reconstructed with filtered backprojection (FBP) and CS from all projections (984-view) and 1/3 of all projections (328-view), and with CS from 1/4 of all projections (246-view). Myocardial perfusion (MP) measurements with each protocol were compared to those with the reference 984-view FBP protocol.
Results: Both the 984-view CS and 328-view CS protocols were in good agreements with the reference protocol. The Pearson correlation coefficients of 984-view CS and 328-view CS determined from linear regression analyses were 0.98 and 0.99 respectively. The corresponding mean biases of MP measurement determined from Bland-Altman analyses were 2.7 and 1.2 ml/min/100 g. When only 328 projections were used for image reconstruction, CS was more accurate than FBP for MP measurement with respect to 984-view FBP. However, CS failed to generate MP maps comparable to those with 984-view FBP when only 246 projections were used for image reconstruction.
Conclusion: DCE heart images reconstructed from one-third of a full projection set with CS were minimally affected by aliasing artifacts, leading to accurate MP measurements with the effective dose reduced to just 33% of conventional full-view FBP method. The proposed CS sparse-view image reconstruction method could facilitate the implementation of sparse-view dynamic acquisition for ultra-low dose CT MP imaging.

1. Introduction

Over the past decade, the advent of slip-ring and multi-slice technology has enabled coronary computed tomography angiography (CCTA) to emerge as a viable imaging modality for the anatomic assessment of coronary artery disease (CAD) [1–3], particularly in excluding CAD in patients with acute chest pain [4]. However, the specificity and positive predictive value of CCTA for detecting functionally significant coronary artery stenosis have been modest [5–7]. To address this shortcoming of CCTA, CT myocardial perfusion (MP) imaging has become an intense focus of recent cardiac CT research [8]. Combining CCTA and CT-MP imaging allows comprehensive anatomic and physiological evaluation of CAD with a single imaging modality, which is useful for the diagnosis and patient management [7,9,10].

Quantitative CT-MP imaging requires repeated scanning of the heart over a short duration of time (~30 s) after contrast administration to monitor the first-pass of contrast in the myocardium. One method for reducing radiation dose of a CT-MP study is sparse-view dynamic acquisition, in which X-ray projections are sparsely acquired in each gantry

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rotation. However, the resulting aliasing artifacts in the images reconstructed with filtered backprojection (FBP) could lead to inaccurate MP measurement. Compressed sensing (CS) is a signal processing technique that was initially proposed for sparse signal recovery [11,12]. It was later shown that CS can be used to reconstruct CT anatomic images from much fewer X-ray projections than what the Nyquist-Shannon theorem dictates for FBP [13–15]. We herein investigated the effectiveness of CS image reconstruction in sparse-view DCE CT acquisition for MP measurement. In porcine CT-MP studies, DCE heart images of five normal and ischemic pigs were reconstructed with a CS based algorithm from a subset of full projections to simulate the sparse-view dynamic acquisition scenario. The resulting MP measurements were compared to those obtained from the conventional full-view FBP protocol to determine the bias and correlation of the CS based CT MP values. The usefulness of the proposed sparse-view protocols to assess myocardial ischemia was also demonstrated in a CT MP study of a patient with known CAD.

2. Methods

2.1. Implementation of CS based CT image reconstruction

The rationale of CS image reconstruction with sparsely sampled X-ray projections is based on the fact that a CT image of an animal or a patient usually contains just a few inhomogeneous regions. Theoretically, by properly exploring the sparsity of edges (boundaries) in a CT image, very few projections are required to reconstruct the image with sufficient quality. CS algorithms for recovering sparse signals from very few linear measurements have been discussed extensively elsewhere [11–16], and a brief overview of our implementation of CS for reconstructing DCE heart images is provided below (the detailed algorithm is provided in Appendix A).

In the context of CS, CT image reconstruction can be formulated as a constrained optimization problem:

$$\min_i \sum_i \|\boldsymbol{D}_i \boldsymbol{x}\|, \qquad \text{s.t. } \boldsymbol{Ax} = \boldsymbol{p} \tag{1}$$

where $\boldsymbol{x}$ is the image vector (attenuation coefficients of the imaged object), $\boldsymbol{D}_i\boldsymbol{x}$ is the discreet gradient of $\boldsymbol{x}$, $\boldsymbol{p}$ is the collection of all projections, $\boldsymbol{A}$ is the design system that relates $\boldsymbol{x}$ to $\boldsymbol{p}$, and $\|.\|$ refers to the l_2-norm. The solution of $\boldsymbol{x}$ in Eq. (1) can be obtained from heuristic approaches such as gradient decent (greedy) algorithms, l_1 minimization or total variation (TV) minimization [15]. We have employed the TV minimization for our studies owing to its superior ability to preserve edges [15,17] and reduce the spillover of highly-attenuating objects to the surrounding area (i.e. reduce the partial volume effect in the myocardium adjacent to the contrast-filled heart chambers). These features are particularly crucial for CT-MP studies. The TV minimization in Eq. (1) can be solved by using the augmented Lagrangian multiplier (ALM) method [18]:

$$\mathcal{L}_A(\boldsymbol{x}, \boldsymbol{\lambda}, \mu) = \sum_i \|\boldsymbol{D}_i \boldsymbol{x}\| - \boldsymbol{\lambda}^T(\boldsymbol{Ax} - \boldsymbol{p}) + \frac{\mu}{2}\|\boldsymbol{Ax} - \boldsymbol{p}\|_2^2 \tag{2}$$

where $\mathcal{L}_A(.)$ is the augmented Lagrangian function, $\boldsymbol{\lambda}$ is a vector of Lagrangian multipliers, μ is a penalty parameter, and T is the transpose operator. Due to the ill-conditioning of the CT problem [17], the classic Lagrangian function, $\sum_i \|\boldsymbol{D}_i\boldsymbol{x}\| - \boldsymbol{\lambda}^T(\boldsymbol{Ax} - \boldsymbol{p})$, is augmented with a quadratic penalty (regularization) term, $\frac{\mu}{2}\|\boldsymbol{Ax} - \boldsymbol{p}\|_2^2$, to reduce error propagation in presence of noise. While both the l_1 norm ($\|.\|$, least absolute derivation) and l_2 norm ($\|.\|_2$, least squares) can be used for the regularization, we chose to use the l_2 norm for this purpose due to the fact that it is computationally efficient and offers a unique solution. The ALM method first minimizes $\mathcal{L}_A(\boldsymbol{x}, \boldsymbol{\lambda}, \mu)$ with respect to $\boldsymbol{x}$ while keeping $\boldsymbol{\lambda}$ fixed. The $\boldsymbol{\lambda}$ is then updated based on the initial solution, and these steps are repeated iteratively until a convergence criterion is satisfied [15,19].

2.2. Experiments

2.2.1. Pig CT-MP studies

2.2.1.1. Data acquisition. We investigated the proposed low dose image reconstruction method for quantitative CT-MP imaging in five 40–50 kg farm pigs. The animal studies were approved by the institution's animal research ethics review board. Two pigs had myocardial infarction induced in the apical wall of the myocardium using a catheter-based method. In this procedure, the distal left anterior descending (LAD) artery (below the 2nd diagonal branch) was transiently occluded with a balloon catheter for 1 h followed by reperfusion. The other three pigs were normal and without infarction. These pigs collectively provided a wide spectrum of myocardial tissue, from normal to ischemic or infarcted, for the validation of the proposed CS sparse-view reconstruction method.

In each CT-MP study, the pig was placed in either a supine or lateral position on the CT scanner table. Anesthesia was induced with intramuscular injection of 2–3 ml solution of Telazol (Tiletamine, Zoetis Services LLC, United States) reconstituted with Rompun (Xylazine, BayerDVM, United States). The pig was intubated and mechanically ventilated with a large animal ventilator (model 613, Harvard Apparatus, United States). Two sequential DCE scans were then performed. Prior to each DCE scan, iodinated contrast agent (iohexol 300 mgI/ml) was injected into an ear vein at 3 ml/s and at a dosage of 0.7 ml per kg body weight. The ventilator was turned off to minimize breathing motion during the DCE scanning period. Using a GE Healthcare 64-slice CT750 HD scanner set for prospective ECG-triggered scanning, a 4 cm section of the heart covering the largest cross-section of the left ventricle was scanned 3 to 4 s after contrast injection and then at mid-diastole alternate heart beats for a total of ~25 images. The scan settings used a full 360° projection acquisition with 140 kVp, 80 mA, 8 × 5 mm collimation and 0.35 s gantry rotation period.

2.2.1.2. Image reconstruction. All the X-ray projections acquired from the pig studies were beam-hardening corrected prior to image reconstruction using a desktop computer equipped with a 64 GB RAM memory and an Intel(R) Core (TM) i7-3820 3.60 GHz CPU. DCE heart images were reconstructed with FBP and CS from all the measured projections (984 views) and 1/3 of all projections (328 views). Image reconstruction with CS was repeated using only 1/4 of all projections (246 views). Thus, there were a total of five sets of DCE heart images reconstructed for perfusion analysis (i.e. 984-view FBP, 984-view CS, 328-view FBP, 328-view CS and 246-view CS). All the simulated sparse-view projection sets were evenly distributed over 360°.

2.2.1.3. Image analysis. Each set of DCE heart images was analyzed using a proprietary CT Perfusion software (GE Healthcare) to generate MP maps. The CT-MP values measured with each protocol were compared to those with the full-view FBP protocol in the lateral, apical and septal wall of the myocardium over four to five consecutive 5-mm slices using Bland-Altman and linear regression analyses. There were a total of 67 myocardial regions in five pigs for comparison. Bland-Altman analysis was used to determine the mean bias of each CS protocol from the reference full-view FBP method. Point estimates were presented as mean and limits of agreement were presented as 95% confidence intervals (CI).

To assess the image quality associated with each reconstruction scheme, the standard deviation of image value (SD) was measured in four regions of interest (ROIs) in a DCE heart image: two in the back muscle region and two in the air region adjacent to the porcine body (Fig. 1). Each ROI was 1 cm in diameter. The SD reflects the magnitude of fluctuation in CT number in the image due to the presence of image noise and/or streak artifact.

2.2.2. Patient CT-MP study

2.2.2.1. Data acquisition. The proposed low-dose method was also tested in a CAD patient enrolled in a CT-MP imaging trial approved by the institution's human ethics review board. Iodinated contrast (Iopamidol 370) was injected intravenously at 5 ml/s and a dosage of 0.7 ml per kg body weight, 3–4 s before the myocardium was imaged at rest using a similar prospectively ECG triggered dynamic scanning protocol to the animal studies: 140 kVp, 50 mA, 8 × 5 mm collimation and 0.35 s gantry rotation period. CT-MP imaging

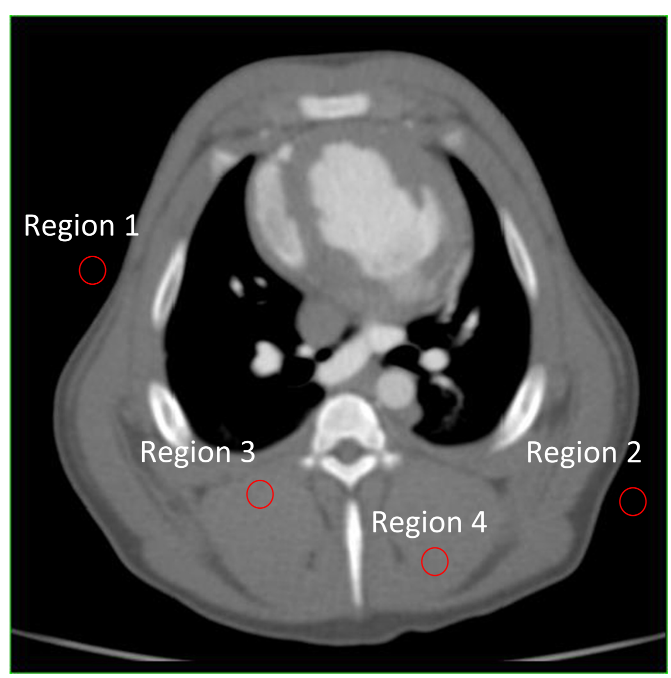

Fig. 1. Image noise and artifact associated with the five image reconstruction protocols were compared in four regions of interest (regions 1 to 4) in the DCE heart images.

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