4D RECONSTRUCTION FOR DUAL CARDIAC-RESPIRATORY GATED SPECT

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ABSTRACT

Cardiac gated SPECT is an important clinical tool for assessment of both myocardial perfusion and ventricular function. Spatiotemporal (aka 4D) reconstruction has been demonstrated to be effective for suppressing the increased noise in cardiac gated SPECT. In this work, we propose a joint 4D reconstruction approach to accommodate the different respiratory phases in a dual cardiac-respiratory gating scheme in order to combat the artifacts of respiratory motion in cardiac SPECT. The proposed approach is to exploit the correlation in the signal component among both the cardiac and respiratory phases in the acquired data. In our experiments we evaluated the approach using simulated SPECT imaging with the 4D NCAT phantom and Tc-99m labeled Sestamibi as the imaging agent. Our results demonstrate that the proposed approach could effectively suppress the artifacts caused by respiratory motion in the reconstruction.

Index Terms*--Dual-gated SPECT, 4D reconstruction, respiratory gating.*

1. INTRODUCTION

Single photon emission computed tomography (SPECT) is widely used for myocardial disease diagnosis, which can provide important information about both myocardial perfusion and ventricular function [1]. However, SPECT images are known to suffer from a number of degrading factors, including reduced spatial resolution due to blur associated with both cardiac and respiratory motion [2].

To combat the blurring effect of cardiac motion, cardiac gated SPECT is often used, in which the data acquisition is divided into several time intervals in the cardiac cycle according to the ECG signal and images are reconstructed for the individual intervals (called gates). Gated SPECT can provide valuable diagnostic information such as ejection fraction, wall motion and wall thickening. However, gated images are also known to suffer from significantly increased noise due to the reduced counts in the individual intervals. In the literature there have been many efforts aimed to improve the quality of gated images using spatiotemporal processing techniques, e.g., [3-5]. Recently we developed a spatiotemporal (termed 4D) approach, and demonstrated that it could significantly reduce the noise and improve the accuracy of the reconstruction in gated SPECT [6,7].

Cardiac gated SPECT still suffers from artifacts caused by respiratory motion, which could lead to inaccuracy in both functional analyses of the left ventricle (LV) and regional myocardial perfusion [8]. There are several studies in the literature on respiratory gated SPECT [8-10]. In respiratory gating, image acquisition is performed during a portion of the respiratory cycle in which the extent of motion of the heart and diaphragm is reduced, thereby reducing the respiratory motion blur [8,10]. Respiratory gating can be achieved by phase gating or magnitude gating [11]. As with cardiac gating, respiratory gated SPECT also suffers from increased noise levels. To reduce the increased noise, one approach is to first estimate the respiratory motion from the reconstructed individual respiratory gates, and then correct for the respiratory motion in the reconstructed images [12].

In this work, we investigate a joint reconstruction approach to combat the effect of respiratory motion in cardiac gated SPECT by utilizing both cardiac and respiratory gating (i.e., dual gating). We extend our previously developed 4D reconstruction approach for cardiac gating such that it can also accommodate the different respiratory phases. Our goal is to exploit the correlation in the signal component among both the cardiac and respiratory phases. In our experiments we demonstrate that such a reconstruction scheme can significantly improve the reconstruction of the left ventricular wall when measured with several quantitative metrics.

We note that respiratory gating has been studied for correction of respiratory motion in other modalities such as PET or PET/CT [13,14]. However, to our best knowledge, the proposed joint reconstruction approach has not been previously exploited in SPECT, largely due to the challenge of significantly lowered data counts associated with both cardiac and respiratory gating.

2. METHODS

Below we first describe the imaging model in dual cardiac-respiratory gated SPECT, and then present our

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4D reconstruction scheme. Afterward, we provide a description of the experiments and evaluation methods.

2.1 SPECT imaging model with dual gating

In dual gated imaging, the data acquisition is synchronized with both the ECG signal and the respiratory period [13, 14]. Accordingly, the acquired data can be re-binned for different respiratory and cardiac phases. This is described by the following model:

$$E[g_{r,k}] = Hf_{r,k} + s_{r,k}, \quad k = 1,...,K, r = 1,...,R \qquad (1)$$

where $g_{r,k}$ and $f_{r,k}$ are vectors representing the acquired data (sinogram) and original image, respectively, during respiratory phase r and cardiac gate k, $s_{r,k}$ is the corresponding scatter component, K and R are the numbers of cardiac and respiratory phases, respectively. In (1), H is the system matrix describing the imaging process, and $E[\cdot]$ is the expectation operator.

Our objective is to reconstruct a cardiac gated sequence $\{f_{r,k},\ k = 1,...,K\}$ with respect to a chosen reference respiratory phase $r = r_0$ so that it is free from respiratory distortion. Conceptually, this could be accomplished by directly inverting the imaging equation in (1). However, such an approach would suffer from significantly increased noise due to the fact that the acquired counts are now further divided over both the respiratory phases and cardiac gates. Alternatively, to reduce the noise effect, one could simply sum the data over the respiratory phases for each cardiac gate by ignoring the respiratory motion, as is done in conventional cardiac gated SPECT; of course, this would lead to respiratory distortion. Below we propose a joint reconstruction approach by collectively utilizing all the acquired data over the different respiratory phases and cardiac gates.

2.2 4D reconstruction for dual gated SPECT

Our goal is to explore the correlation of the image signal among the different respiratory phases and cardiac gates. In the proposed approach, we first describe the different respiratory phases by a motion model with respect to a reference respiratory phase r_0, and describe the acquired data in terms of this reference phase. The cardiac gated images are then reconstructed with respect to this reference phase through statistical estimation.

Without loss of generality, let $r_0 = 1$ be the reference respiratory phase. The cardiac gated images $f_{r,k}$ in other respiratory phases are modeled with respect to their counterparts in the reference respiratory phase as:

$$f_{r,k} = T_r f_{1,k} \qquad (2)$$

where T_r is the motion operator between respiratory phase r and the reference phase. Then we can rewrite (1) as:

$$E[g_{r,k}] = HT_r f_{1,k} + s_{r,k}, \quad k = 1,...,K, r = 1,...,R \qquad (3)$$

Our goal is to reconstruct the cardiac gated sequence $\{f_{1,k},\ k = 1,...,K\}$ from (3). In this work we seek a joint estimation approach, which is described below.

Specifically, let $\mathbf{G}$ denote the collection of acquired data over all the respiratory phases and cardiac gates, i.e., $\mathbf{G} \equiv [g_{1,1}^T,...,g_{R,1}^T,g_{1,2}^T,...,g_{R,2}^T,...,g_{1,K}^T,...,g_{R,K}^T]$. Similarly, let $\mathbf{F}_1 \equiv [f_{1,1}^T,...,f_{1,K}^T]$, a vector denoting the gated sequence. Then we seek the solution as

$$\hat{\mathbf{F}}_1 = \arg\max_{\mathbf{F}_1}\{\log p(\mathbf{G} \mid \mathbf{F}_1) + \log p(\mathbf{F}_1)\} \qquad (4)$$

where $p(\mathbf{G} \mid \mathbf{F}_1)$ is the likelihood function of $\mathbf{G}$ parameterized by $\mathbf{F}_1$, and $p(\mathbf{F}_1)$ is a prior on $\mathbf{F}_1$. Under the independence of the acquired data among the different gates, the likelihood term $p(\mathbf{G} \mid \mathbf{F}_1)$ can be written in terms of the individual gates as

$$\log p(\mathbf{G} \mid \mathbf{F}_1) = \sum_{r=1}^{R}\sum_{k=1}^{K} \log p(g_{r,k} \mid f_{1,k}) \qquad (5)$$

where the likelihood term $p(g_{r,k} \mid f_{1,k})$ is defined through (3). In this study the Poisson likelihood is used.

The prior term $p(\mathbf{F}_1)$ in (4) is defined in a separable Gibbs prior as follows:

$$p(\mathbf{F}_1) \propto \exp[-\beta_s U_s(\mathbf{F}_1) - \beta_t U_t(\mathbf{F}_1)] \qquad (6)$$

where $U_s(\mathbf{F}_1)$ is an energy term defined to enforce spatial smoothing within individual gates, $U_t(\mathbf{F}_1)$ is an energy term to enforce smoothing along the motion trajectories across the different gates, β_s and β_t are their corresponding scalar weighting factors. Such a prior was previously used for 4D reconstruction of cardiac gated SPECT [7].

In our experiments, the modified BSREM algorithm [15] was applied for the optimization problem in (4) as previously in cardiac gated 4D [7]. Owing to space limitation, the specific detail of this algorithm is omitted here. Both the respiratory motion in the imaging model in (2) and cardiac motion required in the prior in (6) were determined from the image data, as explained in the next section.

2.3 Simulated imaging and reconstruction scheme

2.3.1 Data acquisition

The 4D NCAT 2.0 phantom [18] was used to generate the source and attenuation distribution. To better simulate the continuous nature of data acquisition, a set of 3D source images was first generated over 80 equally spaced time intervals during a complete respiratory cycle with both cardiac and respiratory motion. Afterward these images were grouped and averaged into 40 equally spaced gate intervals (Fig. 1(a)). The extent of diaphragm motion was

2 cm, and the extent of the AP expansion of the chest was 1.2 cm. The respiratory cycle and cardiac cycle were 5 sec and 1 sec, respectively.

For data acquisition, the SIMIND Monte Carlo package [19] was used to simulate gated SPECT imaging with Tc-99m labeled Sestamibi as the imaging agent and with the Picker Prism3000 with low-energy high-resolution (LEHR) collimator as the imaging system. The projection matrix was 64 by 64 with a pixel size 0.634 cm, and 64 angular projection sets were collected. Two energy windows were used: the photopeak window was 20% (28 keV) centered at 140 keV, and a 3.5 keV window abutted to the lower side of the photopeak window for scatter correction. Poisson noise was introduced at a level of 8 million total acquired counts as in a typical clinical acquisition for a Tc-99m labeled Sestamibi study. For scatter correction, the scatter component was estimated using the TEW method [19] and included in the likelihood function. A total of 30 different noise realizations were simulated for the purpose of quantitative evaluation.

2.3.2 Reconstruction scheme

For image reconstruction, the 40 gate intervals were rebinned into 8 cardiac gates and 10 temporal respiratory phases such that each respiratory phase corresponds to 4 cardiac gates as in Fig. 1(a). Subsequently, by exploiting the symmetry in the respiratory cycle, the 10 respiratory phases were further paired into 5 groups such that the two phases in each pair correspond to the same diaphragm height. This is illustrated in Fig. 1(b), where the rebinned data are laid out for the different cardiac cycle and respiratory gates in the form of a matrix. This effectively yields R=5 respiratory gates accordingly to the amplitude of diaphragm motion. The amplitude gate with the least motion (i.e., around 0) was used as the reference phase for reconstruction.

In the experiments we used a translational model for the myocardium across the different respiratory phases, and an optical flow model for the cardiac motion between the cardiac gates. While simple, a translational model was previously demonstrated to be effective for respiratory correction in cardiac SPECT owing to its limited resolution [12]. Of course, it is expected that a more elaborate motion model such as an affine model or a deformable model [16-17] could potentially be more beneficial, but we leave it for future investigation, as the main purpose of this study is to demonstrate the feasibility of our proposed joint reconstruction approach.

Specifically, to determine the motion operator T_r for the respiratory gates, the different cardiac gates within each respiratory gate were first averaged, (i.e., vertically in Fig.1 (b)), for the purpose of reducing the noise level. Afterward, a preliminary reconstruction of the myocardium was obtained for each respiratory gate. The myocardium was then segmented out based on the intensity using a region growing method, and its center of gravity was used to determine the parameters in T_r. Next, the cardiac gates of each respiratory phase were registered with respect to the reference respiratory phase and averaged to obtain a preliminary reconstruction. The optical flow method was then applied to these cardiac gates to estimate the cardiac motion field as in [6,7].

2.4 Evaluation

To quantify the accuracy of the reconstructed myocardium, we compute the root mean-squared-error (MSE) of a volumetric region containing the entire myocardium, which is defined as:

$$\text{MSE} = \frac{1}{K}\sum_{k=1}^{K}\left(\frac{\left\|f_k - \tilde{f}_k\right\|_{ROI}^2}{M}\right)^{\frac{1}{2}} \tag{7}$$

where f_k and $\tilde{f}_k$ denote the reference and reconstructed images, respectively, for cardiac gate k, and ROI denotes the volumetric region with pixel number of M.

To analyze the effect of respiratory motion, we examine the extent of spatial blurring on the LV wall by plotting its reconstructed intensity profiles. Moreover, we also investigate its temporal blurring on gated images by plotting the regional time activity curve (TAC) of the LV.

As reference, the cardiac gated images are also reconstructed from the noiseless projection data (without attenuation and scatter) with no respiratory motion. These images represent the ideal case of what would be obtainable if the imaging system were free from these degrading factors. It is referred to as Ideal. For comparison, we also applied 4D reconstruction of the gated images without correcting for the respiratory motion (referred to as 4D-cardiac), in which the respiratory gates were summed up for each cardiac gate.

3. RESULTS AND DISCUSSIONS

In Fig. 2, we show the MSE results obtained by the proposed 4D reconstruction algorithm with different values of temporal parameter β_t as in (6); the spatial parameter was kept as $\beta_s = 0$ in order to reduce the amount of spatial blur based on our previous 4D studies [7]. These results were averaged by 30 noise realizations. Note that in Fig. 2 the setting $\beta_t = 0$ corresponds to the case of ML reconstruction without temporal smoothing. As can be seen, the MSE was greatly reduced with increased temporal smoothing, with the best MSE=7.34 obtained at $\beta_t = 0.002$. This setting was used in subsequent analyses of the results.

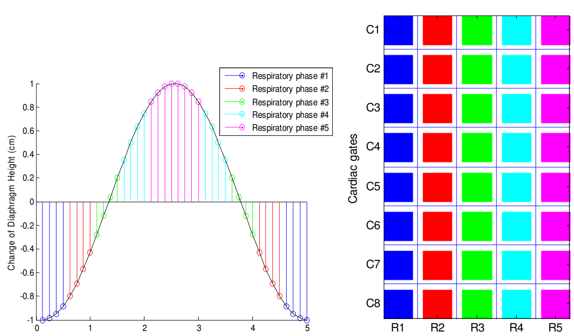
To analyze the temporal blurring effect, in Fig. 3 we show the regional TAC in the reconstruction for an ROI located near the LV wall boundary obtained by 4D-dual; for comparison, results are also shown for 4D without respiratory correction (4D-cardiac). As can be seen, the bias was notably increased in 4D-cardiac due to respiratory motion blurring.

To demonstrate the spatial blurring on the LV wall, we show in Fig. 4 the intensity profile for a cross-section through the LV obtained by the proposed method (4D-dual); for comparison, the results are also show for 4D without respiratory correction (4D-cardiac). These results were averaged from 30 noise realizations. As can be seen, the bias level was greatly reduced (hence less blurring) along the LV wall (particularly the section between pixels 10 and 13) in 4D-dual compared to 4D-cardiac; without respiratory correction, 4D-cardiac suffered from severe distortion compared with Ideal.

Finally, we show in Fig. 5 a set of reconstructed images for several cardiac gates from a typical noise realization by different methods. It is noted that the LV wall in the different gates is markedly improved in 4D-dual and much closer to that of Ideal; in comparison, the LV wall in 4D-cardiac suffers from significant blurring.

4. CONCLUSION

In order to reduce both cardiac and respiratory motion blur, we developed a joint 4D reconstruction approach for dual gated cardiac SPECT imaging. The results from simulated data show that the proposed approach could improve the image quality by both reducing the noise level and suppressing the motion blur. Encouraged by these results, in future work we plan to further develop this approach by incorporating a more elaborate respiratory motion model and test it with clinical acquisitions.



(a) (b)

Fig 1. (a) A respiratory cycle is divided into into 40 equally spaced time intervals and 10 equally-spaced respiratoy phases. The respiratory phases are paired into 5 gates according to the amplitude of the diaphragm height; (b) the respiratory-cardiac intervals are arranged into 5 respiratory and 8 cardiac gates.

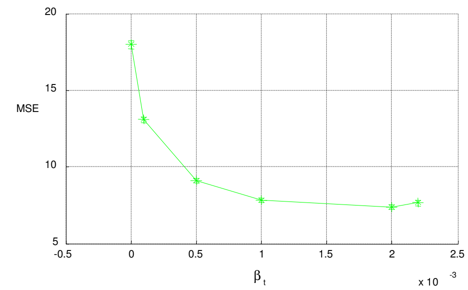


Fig 2. MSE of proposed 4D reconstruction of LV volume.

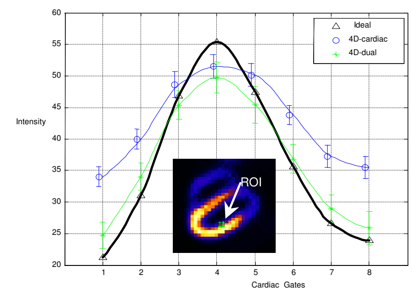


Fig. 3 Reconstructed TAC for an ROI near the boundary of LV.

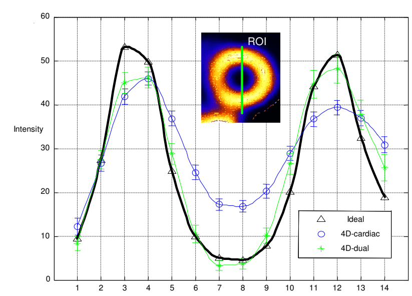


Fig. 4. Reconstructed intensity profile for a cross-section through the LV in short-axis view.

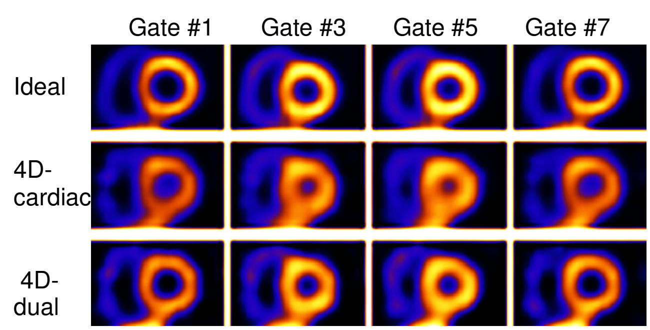


Fig. 5 Short axis view of reconstruction images of different cardiac gates.

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