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Generation and Evaluation of a Simultaneous Cardiac and Respiratory Gated Rb-82 PET Simulation

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Abstract

The goal is to generate and evaluate a simulated 4D Rb-82 PET dataset that realistically models simultaneous respiratory and cardiac motions for use to study the effects of the motions and their compensation using various gating schemes. Normal cardiac and respiratory (C&R) motions were simulated separately using the realistic 4D XCAT phantoms. The C&R motion cycles were divided into 24 and 48 equally-spaced time points, respectively. The simultaneous dual motions were modeled by 24×48 phantoms with different combinations of C&R motion phases. Almost noise-free projections of the heart, blood pool, lungs, liver, stomach, spleen, and the remaining body were simulated separately using the combined SimSET and GATE Monte Carlo simulation program which is 12 times faster than GATE alone. The projections were scaled and combined to simulate a typical Rb-82 myocardial perfusion (MP) PET patient study. The no gating, 6-frame respiratory gating only, 8-frame cardiac gating only, and simultaneous 6-frame respiratory and 8-frame cardiac gating schemes were applied. Each gated projection dataset was reconstructed using a 2D OS-EM without and with attenuation correction (AC) using an averaged and gated attenuation maps. The reconstructed images were evaluated in terms of artifactual non-uniformity in the MP polar map. Significant artifactual non-uniformity was found in the MP polar map over all gating scheme without AC. With AC, the artifactual decreases in both the anterior and inferior

regions were reduced with respiratory gating. Cardiac motion alone did not cause significant artifactual non-uniformity. In addition, the combination of dual gating and AC using the gated attenuation map provided the most uniform MP polar map. We demonstrated the flexibility and utility of the 4D XCAT phantom set with simultaneous C&R motions. It is a powerful tool to study motion effects on MP PET studies and to evaluate C&R gating schemes, AC and quantitative 4D PET image reconstruction methods.

I. Background

Cardiac and respiratory motions are well-known as major sources of image degradation and artifacts in PET myocardial perfusion imaging. Attenuation and its improper correction can also contribute to additional image artifacts. Figure 1 represents the effect of motion and attenuation. To study any correction method, the effect caused by motion should be analyzed first.

The goal of this study is to generate and evaluate a simulated 4D Rb-82 PET projection dataset that realistically models simultaneous cardiac and respiratory motions for use to study the effects of the motions and their compensation using various gating schemes on the myocardial perfusion PET imaging.

II. Methods

The experiment and data analysis methods are summarized at the Figure 2.

Normal cardiac and respiratory motions were simulated separately using the realistic 4D XCAT (eXtended Cardiac Torso) phantoms [1]. The cardiac and respiratory motion cycles were divided into 24 and 48 equally-spaced time points (time-gating methods), respectively. The cardiac and respiratory cycles were assumed to be 1.0 and 5.0 seconds, respectively. Maximum extent of diaphragm due to respiratory motion was assumed to be 2.0 cm. The simultaneous dual motions were modeled by 24×48 phantoms with different combinations of cardiac and respiratory motion phases. Almost noise-free projections of the heart, blood pool, lungs, liver, stomach, spleen, and the remaining body were simulated separately as figure 3.

The combined SimSET and GATE Monte Carlo simulation program which is about 12 times faster than GATE alone ($256 \times 256 \times 67$, XCAT attenuation map, heart-only Rb-82 source, regularMatrix) is used [2–4]. The imaging geometry and characteristics of a GE RX PET system was used in the simulation [5]. The GE RX PET camera consists of 24 rings and 630 crystals per a ring. Axial and transaxial field of view were 15.7 and 70 cm, respectively. True and scatter events were stored and no random events were simulated. A total of 96 billion of positron decay events were generated for “almost noise-free.” simulation of each phantom. The simulated PET projections have about 10 times higher coefficient of variance (CoV) than that found in clinical data. The projections from different tissue organs were scaled and combined to simulate a typical Rb-82 myocardial perfusion (MP) PET patient study.

The 24×48 simulated projection frames were grouped into 6 respiratory amplitude- and 8 cardiac time-gated frames for the [no gating], [6-frame respiratory gating only], [8-frame cardiac gating only], and [simultaneous 6-frame respiratory and 8-frame cardiac gating] schemes as shown in table 1 [6]. The amount of respiratory and cardiac motions and the grouping into 6 equal-amplitude respiratory frames and 8 equal-time cardiac frames are represented in Figure 4.

Each gated projection dataset was reconstructed using a 3D OS-EM algorithm of a modified STIR (Software for Tomographic Image Reconstruction) [7]. The sinogram were rebinned using SSRB (single-slice rebinning) with ring difference 5 and reconstructed using OS-EM with 42 updates (21 subsets, 15 projections/subset). Three attenuation corrections (AC) methods, including (1) no attenuation correction, (2) attenuation correction using an averaged attenuation map, and (3) attenuation correction using a series of matched respiratory gated attenuation maps, were compared. Reconstructed images were post-filtered using a Butterworth low-pass filter (4th order, 0.21 cycle/pixel).

The reconstructed images were evaluated as myocardial perfusion (MP) polar map [8]. The MP polar map is widely used in the analysis of MP SPECT images. Reconstructed images were re-oriented into the short-axis images of the left ventricle (LV). From each of the series of short-axis images shown in Figs. 5(a) and (b), substitute of the pixel value along each angular ray with its maximum pixel, resize and form the 2D MP polar map as shown in Fig. 5(c).

III. Results

Figures 6(a) and (b) show the MP polar maps of the LV with no cardiac and respiratory gating, and without and with attenuation correction (AC), respectively. They show the predominant image artifact caused by attenuation especially by the liver. In Figure 6(b) with AC, artifactual decrease in both the anterior and inferior regions is shown. [From results shown in Figures 7 and 8, the artifact is primarily due to respiratory motion.]

Figure 7(a) shows the predominate attenuation artifact without AC on the polar map from cardiac gated MP PET images. Figures 7(b) and (c) shows the MP polar maps obtained with two AC methods demonstrating that although the magnitude of the artifact is much reduced, the artifact pattern is similar. Also, they show that the use of an average attenuation map is effective in AC.

Figure 8(a) shows the predominate attenuation artifact without AC on the polar map from respiratory gated MP PET images. Figures 8(b) and (c) with AC demonstrate the respiratory motion artifact shown in Figure 6(b) is much reduced with respiratory gating. Also, they show an average attenuation map is effective in AC.

Figure 9(a) shows the predominate attenuation artifact without AC on the polar map from dual respiratory & cardiac gated images. Figures 9(b) and (c) with AC demonstrate the respiratory motion artifact shown in Figure 6(b) is much reduced with both respiratory and cardiac gating. Also, they show the matched dual-gate attenuation map is the most effective in AC.

IV. Conclusions

We demonstrated the flexibility and utility of the 4D XCAT phantom set with simultaneous respiratory and cardiac motions. It was a powerful tool to study the motion effects on MP PET images and to evaluate individual and dual respiratory and cardiac gating schemes, attenuation correction, and quantitative 4D PET image reconstruction methods.

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Fig. 1.

Sample short-axis myocardial SPECT images reconstructed from MC simulation. (a) Sample image obtained without cardiac and respiratory motions and attenuation effect. Compared with (a), (b) sample image showing blurring due to respiratory motion in the up-down direction without any motion correction, and (c) sample image showing artifactual decrease of activity at the septal and inferior of the LV wall due to attenuation without attenuation correction.

Fig. 2.
Flowchart of experiment and data analysis methods.

Fig. 3.
The 4D XCAT phantoms showing 7 tissue organs. Each organ (indicated in red) was simulated separately and merged later.

Fig. 4.

Changes of (a) diaphragm motion and (b) LV volume of the 4D XCAT phantom as function of time frame number. The 24 respiratory and 48 cardiac data set (green circle) were grouped into 6 amplitude (horizontal lines) and 8 time (vertical lines) frames, respectively.

Fig. 5.

The generation of the MP polar map starts with a series of (a) short-axis MP images that are perpendicular to the axis of (b) the vertical long-axis image and resized appropriately to form (c) the 2D MP polar map.

Fig. 6.
MP polar map with no gating (a) without and (b) with AC.

Fig. 7. MP polar maps obtained with cardiac gating only and (a) without and (b) with AC using averaged attenuation map, and (c) with AC using matched respiratory gated attenuation maps. The upper and lower rows of polar maps are obtained at end-of-diastole (ED) phase and end-of-systole (ES) phase, respectively.

Fig. 8.

MP polar maps obtained with respiratory gating only and (a) without and (b) with AC using an averaged attenuation map, and (c) with AC using matched respiratory gated attenuation maps. The upper and lower polar maps are obtained at end-of-exhalation (EX) phase and end-of-inhalation (EI) phase, respectively.

Fig. 9.

MP polar maps obtained with dual respiratory and cardiac gating and (a) without and (b) with AC using averaged attenuation map, and (c) with AC using matched dual-gate attenuation maps. Within each case, sample MP polar maps were obtained at end-of-exhalation (EX) & end-of-diastole (ED) (left-upper), at end-of-exhalation (EX) & end-of-systole (ES) (right-upper), at end-of-inhalation (EI) & end-of-diastole (ED) (left-lower), and at end-of-inhalation (EI) & end-of-systole (ES) (right-lower).

Table I

The four different gating schemes used in the study

	Respiratory Gating	Cardiac Gating
1	No gating	No gating
2	6 amplitude gates	No gating
3	No gating	6 time gates
4	6 amplitude gates	6 time gates