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Realistic Simulation of Regional Myocardial Perfusion Defects for Cardiac SPECT Studies

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Abstract

The current 3D XCAT phantom allows users to manually define the regional myocardial perfusion defect (MPD) as a simple pie-shaped wedge region with reduced activity level in the myocardium of left ventricle. To more accurately and realistically model the MPD, we have developed a new regional MPD model for the 3D XCAT phantom for myocardial perfusion SPECT (MP-SPECT) studies based on the location and the severity of the stenosis in a computer generated coronary arterial tree. First, we generated a detailed coronary arterial tree by extending the large proximal branches segmented from patient CT images to cover the whole heart using an iterative rule-based algorithm. Second, we determined the affected downstream vascular segments of a given stenosis. Third, we computed the activity of each myocardial region as a function of the inverse-distance-weighted average of the flow of the neighboring vascular segments. Fourth, we generated a series of bull's-eye maps of MP-SPECT images of different coronary artery stenosis scenarios. Fifth, we had expert physician readers to qualitatively assess the bull's-eye maps based on their similarity to typical clinical cases in terms of the shape, the extent, and the severity of the MPDs. Their input was used to iteratively revise the coronary artery tree model so that the MPDs were closely matched to those found in bull's-eye maps from patient studies. Finally, from our simulated MP-SPECT images, we observed that (1) the locations of the MPDs caused by stenoses at different main arteries were different largely according to their vascular territories, (2) a stenosis at a proximal branch produced a larger MPD than the one at a distal branch, and (3) a more severe stenosis produced a larger MPD than the less severe one. These observations were consistent to

those found in clinical cases. Therefore, this new regional MPD model has enhanced the generation of realistic pathological MP-SPECT images using the XCAT phantom. When combining with the mechanical model of the myocardium, the new model can be extended for the simulation of 4D gated MP-SPECT simulation of a pathological heart with both perfusion and motion defects.

I. Introduction

The 4D eXtended CArdiac-Torso (XCAT) phantoms [1] is a new extended version of the 4D NCAT phantom, a digital anthropomorphic phantom that has been widely used in medical imaging research to evaluate different medical imaging instrumentation and technologies. The 4D XCAT phantom models the entire human body and provides highly detailed anatomy and physiologically realistic respiratory and cardiac motion models. Also, the XCAT phantom allows modeling of pathological heart with a regional myocardial perfusion defect (MPD). The defect can be manually defined as a low activity pie-shaped wedge region within left ventricle myocardium for myocardial perfusion SPECT (MP-SPECT) studies [2]. The parameters needed to define the MPD include the location of the defect center, the azimuthal angular width of the defect and its extent along the long-axis of the heart. However, as shown in Figure 1, the location, shape, and extent of the defined MPD is not clinically realistic.

We have developed an improved simulation tool to realistically model regional MPDs for the 4D XCAT phantom for MP-SPECT studies based on the location and the severity of the stenosis in the computer generated coronary arterial tree.

II. METHODS

A. Computer Generated Coronary Arterial Tree

The 3D version of the 4D XCAT phantom has the proximal large branches of the coronary arterial tree, which was segmented from clinical CT data. To extend the initial large branches to cover the whole heart, we have previously developed an iterative rule-based generation method based on morphometric, anatomic, and bifurcation properties of normal coronary arterial trees [3]. The generation method, including self avoidance and boundary avoidance algorithms, guided the growth directions of the daughter segments at each bifurcation. The rules were summarized as follows:

1. two daughter branches are produced for each parent Branch;
2. the daughter branches lie in the branching plane;
3. the flow rate of the parent branch is conserved after branching;
4. the diameters of the daughter branches are statistically determined by the connectivity probability and nominal diameters of the morphometric data;
5. the flow-dividing ratio and branching angles are determined by the diameters of the daughter branches;

6. the branch length of a given order is determined statistically by a “scaled” nominal length of the morphometric data;
7. the larger branches (order 9 or larger) are confined to the subepicardial and septal layers and the smaller branches are allowed to penetrate into the myocardium layer;
8. the combined branching vector is determined by the self avoidance and boundary avoidance algorithms; and
9. the normal vector of the branching plane is calculated from the parent branch vector and the combined branching vector.

The algorithm generated two daughter segments at each bifurcation point as outlined above and iterated until segments of the largest six orders were constructed. A coronary arterial tree model, including the left anterior descending (LAD), left circumflex (LCX), and right coronary artery (RCA), was generated using the scheme. The generated coronary arterial tree including branches down to the designated order 10, order 8, and order 6 are shown in Fig. 2 (a), (b) and (c), respectively. The model of the coronary arterial tree with the six largest branches had vessel diameters down to 120 μ m, consisted of 3940, 1232, and 3902 segments for the LAD, LCX, and RCA, respectively.

However, we found that the coronary arterial tree, generated by the original generation rules and from the original data, suffered a number of pitfalls in achieving good realism. We have iteratively improved the rules, the anatomic and morphometric data, and the relevant parameters based on the feedback from physicians. For instance, we improved the generation rules by allowing large branches to grow into septal layer, enhanced the anatomic details by modeling atrioventricular openings and septal layer, and properly scaled the morphometric data for human coronary arterial tree. This iterative improvement process on the coronary artery tree model with the aid of the physicians will be reported in a separate publication.

B. Generation of MPD

We adopted the coronary artery segment numbering convention used by bypass angioplasty revascularization investigation (BARI) in accordance with the American College of Cardiology (ACC) and the American Heart Association (AHA) guidelines for coronary angiography [4]. In this paper, we placed stenoses at the “proximal right coronary artery segment (RCA1)”, the “proximal LAD artery segment (LAD12)”, the “proximal circumflex artery segment (LCX 18)”, the “mid-LAD artery segment (LAD 13)”, and the “first diagonal branch segment (LAD 15)”.

The detailed coronary arterial tree was systemically extended from the initial large coronary arteries, as described above. Thus, the parent-daughter connection relationship of the whole coronary arterial tree was fully known. Given the specific location of the stenotic artery segment, the affected downstream vascular segments were determined by iteratively tracing down the arterial tree. The affected downstream vascular segments suffered from the reduction of blood flow due to the stenosis in the proximal segment. The distance from each branch in the arterial tree for each myocardial region was determined. Neighboring branches were identified as affected if their distances were within a predefined effective perfusion

range. The activity of each myocardial voxel was computed as a function of inverse-distance-weighted average of the flow of these neighboring vascular segments.

C. MP-SPECT Simulation

The 3D XCAT phantom can be used to simulate the radioactivity distribution of a typical Tc-99m Sestamibi patient study in MP-SPECT. The generated phantom was stored in a 256 by 256 by 256 array with a pixel size and slice thickness of 0.156 cm. SPECT projection data were generated from the phantoms using an analytical projector with a parallel-hole low-energy high-resolution collimator. A complete projection dataset over the typical 180 degree arc from 45° LPO to 45° RAO was generated. Then, the projection images were collapsed to 128 by 128 matrices, and scaled to represent clinical count level. Poisson noise was added to the scaled projection data which were reconstructed using 3D filtered-back projection reconstruction method followed by Butterworth post-filter. The SPECT images were reoriented to the short-axis orientation and their corresponding bull's-eye maps were computed.

D. Evaluation by Expert Readers

Three different MP-SPECT studies were performed to evaluate the realism of our MPD models based on the coronary artery tree. In the first study, we studied the effect of the stenoses in different main arteries for the cases with severe stenoses in “RCA1”, “LAD12” and “LCX18”. In the second study, we studied the effect of the proximity of the stenoses for the cases with severe stenosis in “LAD12”, “LAD13” and “LAD 15”. In the third study, we studied the effect of the severity of the stenoses for the cases with mild, moderate, and severe stenoses in LAD 12. Three expert readers (2 M.D./Ph.D.'s and 1 M.D.) qualitatively assessed the bull's-eye maps of these MP-SPECT images on their similarity to typical clinical data in terms of the location, shape, extent, and delineation of the regional MPDs.

III. RESULTS AND DISCUSSIONS

In study 1, as shown in the bull's eye maps of the simulated MP-SPECT (Figure 3) images, the locations and extents of the MPDs caused by the stenoses at LAD12, LCX18 and RCA1 were different largely according to their vascular territories. The LAD12 stenosis caused an anterolateral defect, the LCX18 stenosis caused a lateral defect, and RCA1 caused an inferoseptal defect. We observed clear delineations between the MPDs of the stenoses of different arteries and the irregular shapes and smooth transition at the border zones of the defects.

In study 2, stenoses in more distal LAD13 (Figure 4(a)) and LAD15 (Figure 4(b)), produced smaller MPDs than the one in the proximal LAD12 (Figure 3(a)). The LAD13 stenosis caused an antero-septal defect whereas the LAD15 stenosis caused an anterolateral defect. Similar to study 1, we observed clear delineation, irregular shape and smooth transition properties from the generated MP-SPECT. In study 3, the locations of the defects were not affected by the severity of stenoses (mild, moderate, and severe) located in the same arterial segment (in this case, LAD12) as shown in Figure 3(a) and Figure 5. The extent and the severity of the defect increased with the severity of the stenosis. Overall, based on the

evaluation by the expert readers, these bull's eye maps were consistent to those found in clinical MP-SPECT cases in term of the location, shape, extent and severity of these MPDs.

IV. CONCLUSION

We concluded that the new regional MPD model for the 3D XCAT phantom has enhanced the generation of realistic MP-SPECT based on stenoses in the coronary arterial tree. When combining with mechanical model of the beating heart, the new model can be extended for the simulation of 4D gated MP-SPECT data of a pathological heart with both perfusion and motion defects.

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(a) Pie-shaped wedge definition

(b) Bull's eye map

Fig. 1.
Regional MPD defined by original XCAT heart phantom

(a) Order 10 to 11

(b) Order 8 to 11

(c) Order 6 to 11

Fig. 2.
Computer generated coronary arterial tree at different levels of detail

(a) Stenosis at LAD12 (severe stenosis)

(b) Stenosis at LCX18 (severe stenosis)

(c) Stenosis at RCA1 (severe stenosis)

Fig. 3.

Simulation results of study 1. Left column: Computer generated coronary arterial tree (Red: Normal; Dark Purple: Downstream of severe stenosis); Right column: Bull's eye map of simulated MP SPECT image with MPD defined by the new perfusion heart model

(a) Stenosis at LAD13 (severe stenosis)

(b) Stenosis at LAD15 (severe stenosis)

Fig. 4.

Simulation results of study 2. Left column: Computer generated coronary arterial tree (Red: Normal; Dark Purple: Downstream of severe stenosis); Right column: Bull's eye map of simulated MP SPECT image with MPD defined by new perfusion heart model

(a) Stenosis at LAD12 (moderate stenosis)

(b) Stenosis at LAD12 (mild stenosis)

Fig. 5.

Simulation results of study 3. Left column: Computer generated coronary arterial tree (Red: Normal; Light Purple\Purple\Dark Purple: Downstream of mild\moderate\severe stenosis); Right column: Bull's eye map of simulated MP SPECT image with MPD defined by new perfusion heart model