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Directional analysis of cardiac motion field from gated fluorodeoxyglucose PET images using the Discrete Helmholtz Hodge Decomposition

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ABSTRACT

Objectives: Extract directional information related to left ventricular (LV) rotation and torsion from a 4D PET motion field using the Discrete Helmholtz Hodge Decomposition (DHHD).
Materials and methods: Synthetic motion fields were created using superposition of rotational and radial field components and cardiac fields produced using optical flow from a control and patient image. These were decomposed into curl-free (CF) and divergence-free (DF) components using the DHHD.
Results: Synthetic radial components were present in the CF field and synthetic rotational components in the DF field, with each retaining its center position, direction of motion and diameter after decomposition. Direction of rotation at apex and base for the control field were in opposite directions during systole, reversing during diastole. The patient DF field had little overall rotation with several small rotators.
Conclusions: The decomposition of the LV motion field into directional components could assist quantification of LV torsion, but further processing stages seem necessary.

1. Introduction

Cardiovascular diseases (CVDs) represent a significant risk of death. An estimated 17.7 million people died from CVDs in 2015, which is 31% of global deaths, according to the World Health Organization) (WHO, 2017). Since CVDs can cause a change to normal cardiac motion, quantification and analysis of the cardiac motion field may assist in diagnosis.

Various characteristics of ventricular wall motion determine the efficiency of left ventricular (LV) function. Buckberg (2004), according to Notomi et al. (2005), notes that recent research in clinical cardiac mechanics has moved away from short (SAX) and long axis (LAX) ventricular function and LV ejection fraction to three-dimensional ventricular deformation studies, which include investigations of LV torsion. Torsion can be defined as the difference in rotation between the LV apex and base. Burns et al. (2008), investigating the torsion present in normal cardiac function, conclude that quantification of torsion may provide insights into myocardial dysfunction and help predict response to treatment. Sengupta et al. (2008) investigate LV twist mechanics and summarize clinical applications of LV torsion for diagnosis of specific diseases, including coronary artery disease, valvular heart disease and hypertrophic cardiomyopathy. As an example, van Dalen et al. (2011) evaluate rigid-body rotation (RBR), where the base and apex of the LV rotate in the same direction and at similar angular velocities, in individuals with Noncompaction Cardiomyopathy (NCC), a rare and inherited congenital disease that can cause alterations of the normal twisting motion in the LV (van Dalen and Geleijnse, 2013). They found that RBR can be a predictor of this condition and conclude that it is an objective, quantitative and reproducible criterion.

In previous work, we quantified the 4D (3D + time) cardiac motion vector field from gated positron emission tomography (PET) images, and then used the magnitude of the motion field to calculate the LV Kinetic Energy Index (KE*f*) (Sims et al., 2015; Gutierrez et al., 2003). While KE*f* can provide global and regional information about cardiac function, directional information from the vectors is not used. A possible method to determine LV torsion is to decompose the motion field into contractions, expansions, rotations and translations.

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The use of PET images for motion quantification makes an interesting research proposal. The PET image is functional, meaning that it shows metabolic processes through the movement and distribution of a radiopharmaceutical in the body, and parts of the heart with lesions tend to have lower absorption of the radiopharmaceutical. Motion analysis in PET images therefore combines functional information, in terms of absorption of radiopharmaceutical, with cardiac motility, producing a unique result. However, PET images have low resolution, voxels of width 4mm in the proposed study, which can impact accuracy in motion quantification compared to modalities such as CT.

The application of optical flow techniques to 4D PET images results in a dense 4D LV motion field. Previous work in cardiac motion analysis from nuclear medicine images has used a transformation of velocity vectors from Cartesian to spherical polar coordinates (Rebelo et al., 2010), enabling cardiac expansion and contraction to be analyzed separately from rotation. However, the origin and alignment of the coordinate axes must be placed manually, resulting in operator-induced error. Further, these components of motion may not be oriented with respect to a single axis or center, leading to distortion or omission of the directional information. It might also be argued that the LV is not spherical in form, so the scheme cannot be fully representative of the motion field over the entire LV.

We propose that there may be significant contraction or rotation of individual regions of the myocardium, particularly in pathological cases, where the center of motion may not coincide with the LV centroid. Notomi et al. (2005) quantify the LV rotational field from a cardiac motion field derived from speckle tracking by resolving vectors along the midmyocardial line; while this avoids assumptions about fixed LV geometry, the approach would still mix regional and global components.

Visualization of flow fields has been intensely studied in many areas of engineering. Polthier and Preuss (2000) describe an approach for characterization of flow topology through the analysis of singularities, i.e. the centers of

We have shown previously (Sims et al., 2016) how the DHHD can be used to decompose synthetic 4D cardiac motion fields into radial, rotational and translational components, simulating motion fields from nuclear medicine, generated by the Extended Cardiac Torso Phantom (v2.0) (XCAT) (Segars et al., 2010). Since these fields are noise-free and very well behaved, created from position vectors generated by the phantom rather than using optical flow, there is a clear separation into radial and rotational component fields. The objective of the proposed study is to demonstrate the capability of the DHHD to extract directional information relating to contraction, expansion and rotation of the left ventricle from a cardiac motion field estimated from 4D (3D + time) PET images using optical flow techniques and to evaluate the resulting rotational motion field components as a source for calculating LV torsion.

2. Materials and methods

2.1. Materials

The following motion fields were generated and used as input vector fields for the DHHD.

2.1.1. Creation of synthetic motion field components

Motion field components were created on a grid of size $55 \times 55 \times 55$. A field consisting of pure radial motion, F_{RAD}, was created by forming a 3D Gaussian scalar potential, ϕ, according to Eq. (1a), then applying the gradient operator and normalizing as shown in Eq. (1b). The values of x, y and z in Eq. (1a) refer to positions on the integer grid, with x_c, y_c, z_c defining the center of the potential,

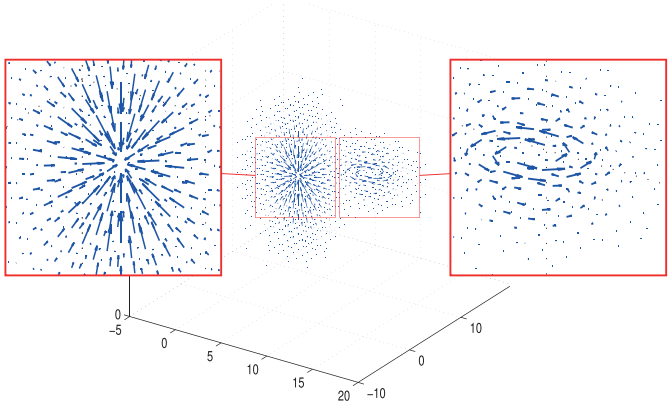

Fig. 1. Example superposition of 3D radial and rotational motion field components.

and σ, the standard deviation, defining the smoothness and extent of the motion field in the domain. Sinks or sources were created by taking the gradient of a positive or negative potential respectively. A field consisting of pure rotation around an axis parallel to the z-axis, F_{ROT}, was formed using a vector potential, $(0, 0, \phi)$, then applying the curl operator and normalizing as shown in Eq. (1c). Counter-clockwise or clockwise rotations in the xy plane, as seen from above, were created from positive or negative potentials respectively. Fig. 1 shows an example 3D motion field consisting of a sink and counter-clockwise rotation.

$$\phi = e^{-\frac{1}{2\sigma^2}[(x-x_c)^2+(y-y_c)^2+(z-z_c)^2]} \tag{1a}$$

$$F_{CF} = \frac{\nabla\phi}{\max(|\nabla\phi|)} \tag{1b}$$

$$F_{DF} = \frac{\nabla \times (0, 0, \phi)}{\max(|\nabla \times (0, 0, \phi)|)} \tag{1c}$$

In order to demonstrate the DHHD, a complex synthetic 3D input motion field was created by forming and superposing four motion field components, each with $\phi = 5.0$. Motion centers were at the following locations in a $55 \times 55 \times 55$ grid: (i) sink at (20,20,28); (ii) source at (34,34,28); (iii) clockwise rotation in xy plane at (20,34,28); (iv) counter-clockwise rotation in xy plane at (34,20,28). A slice through this motion field at $z = 28$ is shown in Fig. 2, where the field is shown as viewed from above (along the line of decreasing z).

2.1.2. Quantification of motion field from 4D FDG PET gated images

A set of 4D FDG PET gated images were obtained, acquired at the Department of Nuclear Medicine and Molecular Imaging (DNMMI) at the Heart Institute, HC-FMUSP, Sao Paulo, Brazil, using a Philips Gemini TF 64 TOF PET/CT scanner (series number 7535, Manufactured Jan 2012 by Philips Medical Systems (Cleveland) Inc., Cleveland, OH, USA). Permission for use of the images in this project was granted under Ethics Committee protocol number 0030/11. The images have 16 frames per cardiac cycle, volumes of $128 \times 128 \times 128$ voxels, and pixel width and slice depth 0.4 cm. The set of 31 images contained 8 controls, individuals with normal cardiac function, with the remainder being patients with different degrees of NCC. All individuals in the trial were put on a special diet and had fasted for at least 6 h prior to the start of the study. The quantity of FDG was sufficient to acquire an adequate image in individuals with normal function and patients. In order to perform an analysis with the best available data, an expert cardiologist selected a single control image based on visual assessment of cardiac motion and considerations from other tests performed at the time of imaging. This was denominated image N, a female, aged

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