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Universal ventricular coordinates: A generic framework for describing position within the heart and transferring data

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ABSTRACT

Being able to map a particular set of cardiac ventricles to a generic topologically equivalent representation has many applications, including facilitating comparison of different hearts, as well as mapping quantities and structures of interest between them. In this paper we describe Universal Ventricular Coordinates (UVC), which can be used to describe position within any biventricular heart. UVC comprise four unique coordinates that we have chosen to be intuitive, well defined, and relevant for physiological descriptions. We describe how to determine these coordinates for any volumetric mesh by illustrating how to properly assign boundary conditions and utilize solutions to Laplace's equation. Using UVC, we transferred scalar, vector, and tensor data between four unstructured ventricular meshes from three different species. Performing the mappings was very fast, on the order of a few minutes, since mesh nodes were searched in a KD tree. Distance errors in mapping mesh nodes back and forth between meshes were less than the size of an element. Analytically derived fiber directions were also mapped across meshes and compared, showing $< 5°$ difference over most of the ventricles. The ability to transfer gradients was also demonstrated. Topologically variable structures, like papillary muscles, required further definition outside of the UVC framework. In conclusion, UVC can aid in transferring many types of data between different biventricular geometries.

1. Introduction

The ventricles of mammalian hearts share many common characteristics. These include a biventricular geometry, Purkinje system (PS), and helical myocardial fiber orientation (Streeter et al., 1969). They also express electrical heterogeneity with respect to transmural (Lou et al., 2011; Sabir et al., 2007), apicobasal (Janse et al., 2012), and left-right gradients (Pandit et al., 2011; Volders et al., 1999).

It is recognized that describing such scalar, vector, and tensor data on a generic heart framework is important, especially in the clinical context. This prompted the American Heart Association to define a standard 17 sector map over a decade ago (Cerqueira et al., 2002). However, it can be difficult to accurately transfer high-resolution data and compare results between vastly different heart geometries. This difficulty arises from the highly variable size and relative proportion of hearts within the same species or between different species.

Modern day methods for mapping ventricular data between hearts are namely based on large deformation diffeomorphic metric mapping (LDDMM) applied to anatomical data from magnetic resonance imaging (MRI) and computed tomography scans (Beg et al., 2005). LDDMM has shown success for mapping myocardial fiber orientation (Vadakkumpadan et al., 2012) and anatomical positioning (Miller et al., 2014) between hearts. However, several drawbacks have limited LDDMM's widespread use to a large array of other problems. For example, LDDMM works directly with voxelized image data and is computationally demanding (hours) when the template and target hearts are of significantly different resolu-

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tions, particularly if at least one of the data sets has a submillimeter resolution. This makes transferring large quantities of data between histology, imaging, and computer models extremely daunting. Furthermore, unstructured meshes, which are extensively used for electromechanical modeling, need to be converted back and forth between an image stack format. This significantly increases the storage and processing time for LDDMM, as well as introduces sampling errors at the surfaces of the mesh.

We propose a novel global positioning system for three-dimensional biventricular heart geometries to overcome the limitations of LDDMM. Accordingly, we define a set of generic ventricular coordinates to define position within any biventricular heart that takes only minutes to formulate on <12 central processing units (CPU), even for mesh resolutions at the submillimeter scale that require significant input/output. The method also works equally well for regular or irregular meshes.

To help foster more expansive data sharing, the coordinates are intuitive so that experimentalists can easily estimate them for their data, which also facilitates transferring experimental data directly to computer modeling studies. Furthermore, the coordinates vary smoothly in space so that they can be used as arguments to functions that assign myocardial properties based on position. Finally, despite geometries which can be quite different, subjectivity is minimized when assigning the coordinates so that interobserver variability is reduced.

To develop our UVC, we build upon aspects from previous computational cardiac modeling studies. To determine position in the left ventricular (LV) geometry for mechanical simulations, Costa et al. (1996) used prolate spheroidal coordinates. For the purpose of assigning action potential heterogeneity in a biventricular mesh for electrocardiogram genesis, Potse et al. (2006) used minimal distance parameterizations between epicardial and endocardial surfaces to define the myocardial transmural direction, and Keller et al. (2012) extended this approach to define the apicobasal direction. Bayer et al. (2012) parameterized the same transmural and apicobasal directions in biventricular geometries for assigning rule-based myocardial fiber orientation, but they determined these directions more accurately from solutions to Laplace's equation instead of minimal distance. Paun et al. (2017) also followed a Laplace approach for mapping complex endocardial anatomy. Despite these developments, none provide a complete parameterization for arbitrary biventricular geometries, particularly for the septum and its junction with the LV, right ventricle (RV), and apex.

In this article, we first present the rationale and methods for determining UVC for arbitrary volumetric heart meshes. We then demonstrate how to use UVC for transferring scalar, vector, and tensor data between different biventricular meshes. To evaluate the algorithm's performance, we analyze errors associated with the transformation process. The results from this new approach show great promise for its widespread use to determine unique positioning in the heart and facilitate the transfer of data between hearts.

2. Methods

2.1. UVC rationale

Position is described within arbitrary ventricles by a combination of four parameters called Universal Ventricular Coordinates (UVC). As mentioned in the introduction, the rationale for UVC is based on how clinical and experimental studies define spatial data within the ventricles. Accordingly, the first coordinate of UVC, $\mathfrak{z}$, represents the distance traveled along the long axis of the ventricles from the apex to the base. The second coordinate of UVC, ρ, is the distance from the endocardium to epicardium, i.e. transmurality. The third coordinate of UVC, ϕ, is the circumferential distance around the long axis of the LV and RV. The ϕ is necessary to distinguish between the posterior and anterior regions of the ventricles in $\mathfrak{z}$ and ρ. The final coordinate, ν, distinguishes between the LV and RV for the other three coordinates of UVC. In the following sections, necessary user inputs and UVC are discussed in detail utilizing the biventricular human mesh described in Moreno et al. (2011), Bayer et al. (2016).

2.2. User inputs for UVC

To compute UVC, the user must first provide the following inputs: (i) a single epicardial apex surface point; (ii) a single LV endocardial surface point; (iii) a single RV septal surface point; and (iv) the surface points representing the ventricular base at the atrioventricular junction. The rest of the algorithm is fully automatic, with only one tolerance (T_{SEPT}) to adjust for optimal results. T_{SEPT} defines the RV septal surface and is described later in more detail.

With the user inputs above, the following surfaces are obtained to compute UVC in a biventricular mesh.

1. Base
2. Epicardium
3. LV endocardium
4. RV endocardium
5. RV septum

The process of obtaining each surface is as follows. For a volumetric mesh, the entire surface is known by identifying all element faces not shared by another tissue element. On this surface, the user defines the base, which then leaves three distinct isolated regions: the epicardium; LV endocardium; and RV endocardium. The epicardial surface is identified by finding the surface containing the epicardial apex point (input by the user). The LV endocardium is identified by finding the endocardial surface containing the LV endocardial surface point (input by the user) with the third remaining surface labeled as RV endocardium. The RV endocardium is further subdivided into its septal and free wall endocardial regions using the change in the surface normal at the interface between the RV septum and endocardium. More specifically, starting from the user input septal node on the RV surface, the algorithm defines each connected element as endocardium and then grows the region by looking at surface normals. If the normal of a surface element under consideration does not differ by more than the tolerance T_{SEPT} from its neighboring element, it is added to the region. A T_{SEPT} of 0.05 for the dot product of neighboring normals is used for all meshes in this study. In the case the resolution of the mesh is too low to detect prominent changes in surface normals at the junction of the RV septum with the free wall, manual segmentation would be straightforward given the oversimplified geometry at such resolutions. Manual intervention may also be used for the base input if it is difficult to define automatically using simple numerical approaches.

2.3. Separating the ventricles at the LV-RV junction

To facilitate the computation of UVC, the LV, RV, and LV-RV junction domains are identified in the biventricular geometry. Accordingly, the boundary conditions shown in Fig. 1A are assigned to the surfaces of the biventricular mesh, where ϕ =0 on the LV endocardium, ϕ =0.5 on the RV septum, and ϕ =1 on the RV endocardium. Solving Laplace's equation using these Dirichlet boundary conditions gives the solution shown in Fig. 1B. Using this scalar field, the LV is defined by all scalar values ≤ 0.5 (Fig. 1C) and the RV by all scalar values >0.5 (Fig. 1D).

2.4. Apicobasal coordinate - $\mathfrak{z}$

The apicobasal direction from the apex to base of the ventricles is represented with the coordinate $\mathfrak{z}$ following the approach