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Surface flattening of the human left atrium and proof-of-concept clinical applications☆

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ABSTRACT

Surface flattening in medical imaging has seen widespread use in neurology and more recently in cardiology to describe the left ventricle using the bull's-eye plot. The method is particularly useful to standardize the display of functional information derived from medical imaging and catheter-based measurements. We hypothesized that a similar approach could be possible for the more complex shape of the left atrium (LA) and that the surface flattening could be useful for the management of patients with atrial fibrillation (AF). We implemented an existing surface mesh parameterization approach to flatten and unfold 3D LA models. Mapping errors going from 2D to 3D and the inverse were investigated both qualitatively and quantitatively using synthetic data of regular shapes and computer tomography scans of an anthropomorphic phantom. Testing of the approach was carried out using data from 14 patients undergoing ablation treatment for AF. 3D LA meshes were obtained from magnetic resonance imaging and electroanatomical mapping systems. These were unfolded using the developed approach and used to demonstrate proof-of-concept applications, such as the display of scar information, electrical information and catheter position. The work carried out shows that the unfolding of complex cardiac structures, such as the LA, is feasible and has several potential clinical uses for the management of patients with AF.

1. Introduction

1.1. Background

Planar mapping or surface parameterization of three-dimensional (3D) meshes is a well studied problem in computer graphics [1]. It has a wide range of applications in various fields of science and engineering with the most important application being mapping textures to polygonal mesh models for enhancing their visual quality. Parameterizations are known to introduce distortions in either angles or areas and it is desirable that a mapping minimizes these distortions. An *isometric* mapping is one that preserves distances and is almost impossible to achieve for complex surfaces. Others such as *conformal* (angle-preserving) or *authalic* (area-preserving) are possible. Floater [2–4] produced several works in surface parameterization by extending a previously known geometrical theorem due to Tutte [5]. Floater's methods imposed fixed boundaries in the resulting parameterization. Free boundary parameterization methods have been proposed by Scheffer and de Sturler [6] and later by Levy et al. [7]. Desbrun et al. [8] employed conformal energy functions with linear solutions capable of both free and fixed boundary parameterization.

Surface parameterization has been applied to problems arising in medical image processing. Planar mapping of the cerebral cortex has important applications and have been proposed in Hurdal et al. [9], Haker et al. [10] and Gu et al. [11] for computing conformal maps. The use of Ricci flow in flattening the cortex has also been investigated [12]. More recently, planar maps have also been commonly used for registering images of the brain, e.g. [13]. A common technique is to map the cortex to a spherical surface. The sphere provides a standard platform for comparison before registration can be accomplished. This is the method implemented in FreeSurfer [14], a leading and widely used tool for brain surface reconstruction. However, FreeSurfer suffers from a severe computational burden

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causing it to be very slow. Most of the existing methods rely on some form of dimensionality reduction and this usually involves solving an eigen value problem. The size of the mesh can often be a limiting factor and there is usually a trade-off between speed and mesh size. Often this means decimating a mesh and thus lowering the resolution of the underlying data.

This manuscript concerns application of planar mapping to the heart. The use of this has been so far restricted to the relatively simply shaped left ventricle (LV). The LV myocardial wall is often transformed into a planar *bull's-eye* plot [15]. This is a polar plot of different sections of the wall that allows simplification and standardization. It can be particularly useful for visualization and reporting of functional information about the LV, such as wall motion, perfusion and distribution of scarring. The bull's-eye plot has been adopted by the American Heart Association as the standard way to represent the LV. In this manuscript we implement, validate and test planar mapping of the more complex left atrium (LA) to assist in the management of patients with atrial fibrillation (AF).

1.2. Clinical motivation

AF is the most common heart rhythm disturbance and originates in the LA. It affects approximately 2.3 million people in the USA [16]. Since it was shown that ectopic beats from within the pulmonary veins (PV) commonly initiate AF [17], catheter ablation strategies have evolved to electrically isolate the PVs from the LA body. By controlled destruction of cardiac tissue in a circumferential pattern around the left and right PV pairs, the PVs are electrically disconnected from the LA and therefore cannot influence atrial electrical behaviour. Although this treatment can provide a cure for many patients, arrhythmia recurrences are common, particularly in patients with persistent AF [18–20], leading to a repeat procedure in up to 50% of this challenging patient group to achieve the best clinical outcomes.

Recurrences of AF following a circumferential PV isolation procedure are invariably associated with recovery of PV to LA conduction which is dependent largely on a failure to achieve continuous and permanent lesions. Multiple factors influence the operator's ability to achieve such a lesion including, but not limited to, catheter stability, power, tissue thickness, contact and temperature achieved, force and duration of radiofrequency (RF) application, cardiac motion and local heat sink effect. Many of the factors impeding effective lesion delivery can be mitigated in part by operator experience but they certainly cannot be eliminated [21] as evidenced by high volume centres continuing to report levels of arrhythmia recurrence in excess of 10–15% at five years after ablation [19,20]. Clearly, there remains a need to identify ways in which improvements in ablation technique can lead to better clinical outcomes.

Catheter ablation procedures for AF are performed by cardiac electrophysiologists. The vast majority of cardiac electrophysiologists utilize an electroanatomical mapping system to guide the procedure [21]. Both the CARTO (Biosense Webster) and Velocity (St. Jude Medical) systems permit reconstruction of an anatomical representation of the LA, electrophysiological characterization of the chamber (voltage, activation time) and display in real-time of the catheter position within the chamber. 3D electroanatomical models of the target cardiac chambers obtained by live catheter tracking, pre-procedural imaging, such as magnetic resonance imaging (MRI) or computed tomography (CT), or a combination of both are used to guide the interventions. In these systems, 3D models displayed on a two-dimensional (2D) screen require frequent interaction from the end-user for displaying the current region of interest. We hypothesized that the use of planar mapping of the LA could assist in the display of the anatomical and functional information that is commonly used in the management of patients with AF.

1.3. Proposed work

In earlier work [22] that focused on planar mapping of the LV, we briefly demonstrated that a B-spline based LA flattening may be possible. In this work we investigate a surface flattening technique developed primarily for texture mapping in computer graphics [8] and apply it to flatten 3D LA meshes. The mathematical background is described in Section 2.1. We qualitatively and quantitatively validated the technique by application to synthetic data of regular shapes (Section 2.2.1) and to an anthropomorphic phantom imaged with CT (Section 2.2.2). Finally we test our method using 14 data sets from patients that underwent RF ablation for treatment of atrial fibrillation and use these data to demonstrate several proof-of-concept applications of the planar mapping (Section 2.2.3).

2. Methods

2.1. Mathematical framework for surface unfolding

We define here the problem of unfolding and flattening the LA mesh. Essentially this is a parameterization of a piece-wise mesh. Given a piecewise linear mesh M of the LA, the problem of mesh parameterization is to obtain a linear mapping φ between M and a planar triangulation $U \in \mathbb{R}^2$. The mapping is isomorphic meaning U must inherit the same intrinsic and structural properties as M. Mesh M is non-closed due to a cut made at the mitral valve annulus and contains holes at each ostium since the PVs must be truncated before the unfold. The 3D position of the ith vertex in the mesh is denoted by $\mathbf{x}_i = (x_i, y_i, z_i)^t$ and in the 2D mesh U as $\mathbf{u}_i = (u_i, v_i)^t$. The mapping φ creates a one-to-one correspondence between the 3D mesh and its 2D unfold, essentially flattening the mesh to a planar map.

Since the LA is an anatomical structure with some distinct anatomical features, such as the appendage, it is important to preserve, when unfolding, as much of the natural or *intrinsic* properties of the LA mesh as possible. The distortion measure E between M and U is a functional that takes in as input two triangulations and returns a real value:

$$E : T \times T \to \mathbb{R} \qquad (1)$$

This distortion measure evaluates how much the structural properties of the meshes are distorted due to the unfolding. In [8], a distortion measure was developed by ensuring a few basic properties are fulfilled by a predefined functional. The two most important properties relevant to LA meshes are listed here: (1) invariance due to rigid transformations of the mesh, and (2) preserves continuity due to finer triangulations. The former is important as two meshes exactly alike but having undergone rotations and translations must yield a zero distortion, thereby allowing the parameterization to be independent of any rigid transformations. The latter ensures that this discrete version of distortion (due to the discrete nature of LA meshes) converges to its continuous form as we get finer and finer triangulations of the mesh. We restrict our discussion of distortion measures to *1-ring neighbourhoods*. A 1-ring is a subset of the 3D LA mesh, consisting of a vertex and all its adjacent triangles. See Fig. 1 for an illustration of a 3D 1-ring neighbourhood with its corresponding unfold planar 2D 1-ring. The distortion measure and thus the parameterization, discussed further in this text, is one which preserves angles and areas of 1-ring neighbourhoods.

2.1.1. Angle-preservation

An angle-preserving (i.e. conformal) distortion measure can be developed by quantifying shape distortions of the mapping