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Development of new anatomy reconstruction software to localize cardiac isochrones to the cardiac surface from the 12 lead ECG

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Abstract Non-invasive electrocardiographic imaging (ECGI) of the cardiac muscle can help the pre-procedure planning of the ablation of ventricular arrhythmias by reducing the time to localize the origin. Our non-invasive ECGI system, the cardiac isochrone positioning system (CIPS), requires non-intersecting meshes of the heart, lungs and torso. However, software to reconstruct the meshes of the heart, lungs and torso with the capability to check and prevent these intersections is currently lacking. Consequently the reconstruction of a patient specific model with realistic atrial and ventricular wall thickness and incorporating blood cavities, lungs and torso usually requires additional several days of manual work. Therefore new software was developed that checks and prevents any intersections, and thus enables the use of accurate reconstructed anatomical models within CIPS. In this preliminary study we investigated the accuracy of the created patient specific anatomical models from MRI or CT. During the manual segmentation of the MRI data the boundaries of the relevant tissues are determined. The resulting contour lines are used to automatically morph reference meshes of the heart, lungs or torso to match the boundaries of the morphed tissue. Five patients were included in the study; models of the heart, lungs and torso were reconstructed from standard cardiac MRI images. The accuracy was determined by computing the distance between the segmentation contours and the morphed meshes. The average accuracy of the reconstructed cardiac geometry was within 2 mm with respect to the manual segmentation contours on the MRI images. Derived wall volumes and left ventricular wall thickness were within the range reported in literature. For each reconstructed heart model the anatomical heart axis was computed using the automatically determined anatomical landmarks of the left apex and the mitral valve. The accuracy of the reconstructed heart models was well within the accuracy of the used medical image data (pixel size < 1.5 mm). For the lungs and torso the number of triangles in the mesh was reduced, thus decreasing the accuracy of the reconstructed mesh. A novel software tool has been introduced, which is able to reconstruct accurate cardiac anatomical models from MRI or CT within only a few hours. This new anatomical reconstruction tool might reduce the modeling errors within the cardiac isochrone positioning system and thus enable the clinical application of CIPS to localize the PVC/VT focus to the ventricular myocardium from only the standard 12 lead ECG.

Keywords: Anatomical models; ECGI; Inverse problem; Patient specific models

Introduction

Recently we have introduced the non-invasive cardiac isochrone positioning system (CIPS) that is able to localize PVC from the standard 12 lead using a patient specific volume conductor model derived from MRI [1,2]. In our research the volume conductor model meshes are used by the boundary element method (BEM) to relate the simulated electrical cardiac activity by means of the equivalent double layer [3,4] to the measured ECG at the electrodes on the torso surface [5,6]. To compute this transfer function the BEM requires non-intersecting triangulated surface meshes of the atria and ventricles (i.e. the left and right endocardium and the epicardium), blood cavities, lungs, and torso.

Several commercial (e.g. Amira, www.vsg3d.com) and open source software (e.g. seg3d [7], cleaver [8]) packages

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are available to create anatomical models of the heart, lungs and torso, using different image segmentation methods to reconstruct the myocardial meshes from MRI or CT images. Examples of segmentation methods are 3D active shape models [9] and active appearance models (AAM) [10]. A limitation of these segmentation based reconstruction techniques is that they heavily rely on image quality, which is frequently far from optimal in clinical practice, for instance 1) the amount of fat limiting the detection of the right ventricular wall, 2) intermittent failure in ECG triggering of the MRI sequence and 3) the movement of the contracting heart. Consequently the reconstructed myocardial heart surfaces are often intersecting, i.e. intersections occur between the endo- and epicardial surface or between the reconstructed blood cavities or lungs and the heart surfaces. None of the available software tools is able to detect and prevent the intersections between the reconstructed geometries. As a consequence the reconstruction process may take several days due to the tedious manual correction of the geometries derived from the image segmentation.

Therefore we have created a new software tool, *CIPS anatomy*, which is able to localize and prevent such intersections within the volume conductor model. The system morphs an existing reference model of the heart into a patient specific one. In this preliminary study the accuracy of the reconstructed models is investigated and discussed in relation to the used image data and the purpose of the models, i.e. the localization of the PVC origin.

The use of a reference model of the heart has several advantages, as the internal structure of the heart is maintained. That is, the mesh vertices describing the valves in the reference model are still part of the same valve in the patient specific model of the heart. Thus the orientation and position of the individual valvular plane can easily be computed for each patient specific heart. In this paper a 3D to 2D mapping algorithm is proposed using the computation of the anatomical heart axis. This patient specific anatomical heart axis can be computed automatically due to the maintained anatomical relations originating from the reference heart model. The proposed 2D mapping of the ventricles divides ventricles into segments comparable to the 17 segment left ventricular model used in imaging [11]. For the localization of PVC, however, the 2D model is adapted to include also a mapping of the right ventricle and specifically the left and right outflow tract areas as many PVCs are originating from these regions [12–14].

Methods

New software was developed, *CIPS anatomy*, capable of morphing a reference heart into a patient specific heart from DICOM images, either MRI or CT in origin. In this approach a reference heart model is used to morph toward the patient specific cardiac anatomy. The following steps are identified:

- Segmentation of the relevant tissues, i.e. determine the boundaries of epicardium, endocardium, blood vessels, lungs, and torso.
- Moving the reference heart model within the segmentation countour lines of the boundaries.
- Morphing the positioned reference heart model to the local contours.
- Reconstruction of the remaining tissues, e.g. lungs, torso.

Segmentation

The reconstruction of the patient specific heart model requires the identification of the left and right of the atrial and ventricular endocardial surface and the epicardium of the ventricle. The identification of the boundaries of these cardiac tissues in the DICOM images is referred to as segmentation. Although open source segmentation tools are available, e.g. seg3d [7] or Osirix [15], we used an integrated manual segmentation approach in our software, *CIPS anatomy*. The software draws contour splines through the manual identified boundary points on the DICOM image. Each cardiac related contour spline was sampled at 5 mm distances, and at 10 mm distances for lungs and torso splines. The manual approach was needed because our morphing software required a separate labeling of the left and right atrial and ventricular endocardial boundaries (Fig. 1). As the atrial wall is too thin to be detected reliably, only the atrial blood cavities are segmented (Fig. 1). The aortic valve and pulmonary valve locations are identified in the segmentation by the transition between left endocardium and aorta, respectively right endocardium and pulmonary artery. In a similar way the tricuspid valve and mitral valve are located between the atrial and ventricular cavity contour points. Finally also the lungs and torso are segmented. The major drawback of the manual approach is that it is still time consuming, on average 1–2 hours per patient.

Initial reference heart positioning

The reference heart was labeled in accordance with the segmentation labeling, i.e. of 7 cardiac components; (1–3) the ventricular left and right endocardium and epicardium, (4–5) the atrial left and right endocardium, (6) the aorta, and (7) the pulmonary artery. The labeling enables the identification of valve planes in the model. For each valve a plane is fitted through the points connecting two types of tissue, as an example; the tricuspid valve is fitted through the mesh points connected to both right atrial and ventricular endocardium.

In the first step of the algorithm the optimal position of the heart chambers was determined by an iterative procedure that minimizes the distance between the blood cavity segmentation contour points and the meshes of the left and right blood cavities. During the first step the internal structure of the heart meshes is maintained, i.e. the complete set cardiac meshes are shifted, scaled and/or rotated (Fig. 1). In the second step the heart is positioned such that the computed valvular planes of model and match plane described by the contour points, i.e. the heart was positioned such that atrial, aortic and pulmonary artery contour points were above the model fitted valves and the ventricular contour points below. This process is very fast and takes approximately 10–20 seconds.

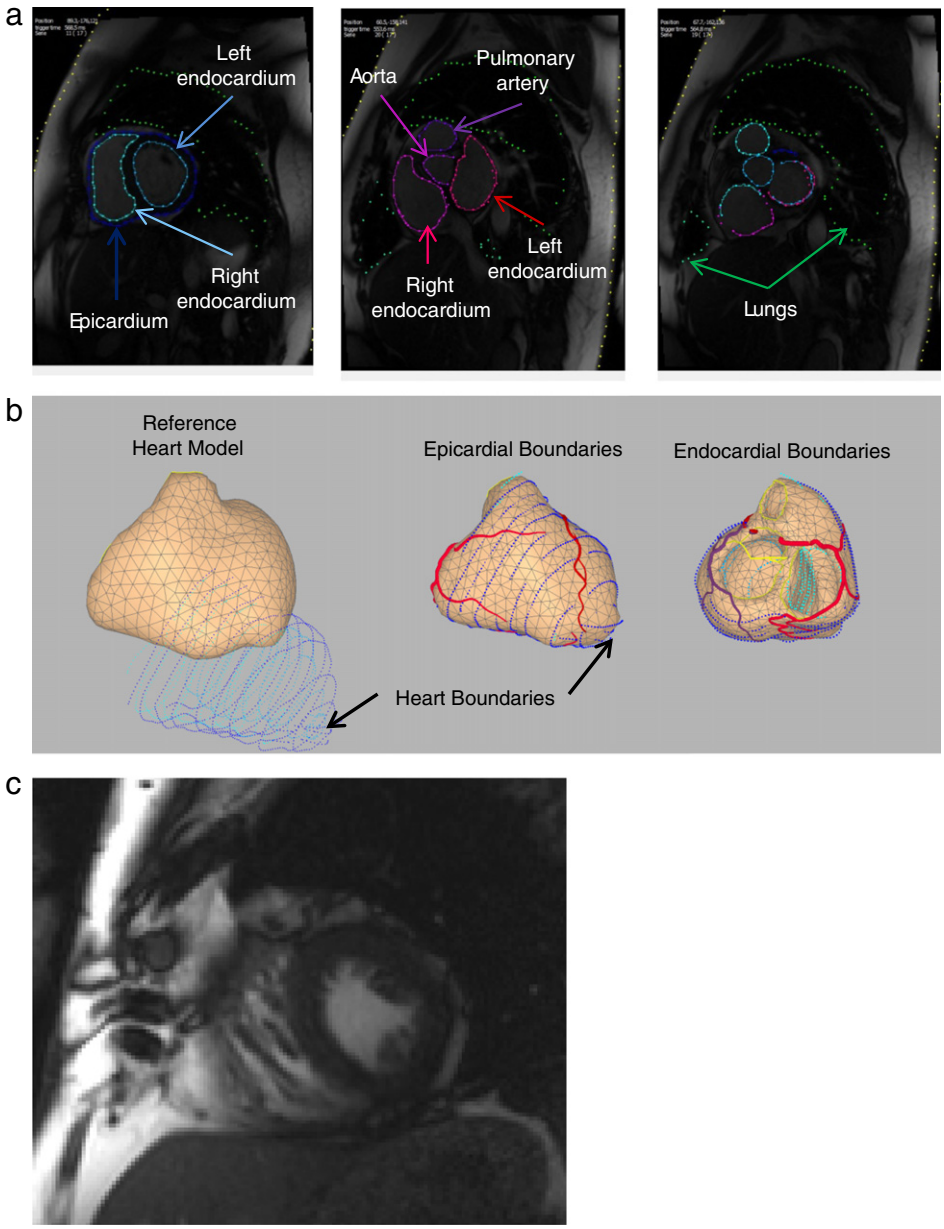

Fig. 1. a) The top panels show the segmentation of the relevant tissues to build the model of the heart, blood cavities, lungs and torso. b) Bottom left panel; the reference heart with the ventricular contour points as created from the MRI segmentation, right panels: after morphing the heart to the reference heart to the contour points. The epicardial surface is morphed toward the epicardial contour points, the left and right endocardium to the respective labeled contour points. c) Example of the interference of epicardial fat blurring the right lateral wall.

Automatic morphing heart model

To obtain the patient specific model of the heart, the mesh needs to match the image contour points as close as possible. Therefore a morphing algorithm based on Hu et al. [16] is used to adapt the position of the individual mesh vertices of the ventricles. This iterative algorithm interpolates the parameterization and geometry information of meshes by adapting the vertex positions such that the distance between contour points and mesh surface is minimized while keeping the local surface smooth (minimization of the Laplacian) and the individual triangle surfaces as equal as possible. The displacement of a vertex, however, can result in cross sections of the connected triangles with triangles of another mesh or another part of the same mesh. Therefore an algorithm is used to limit the proposed displacement preventing cross sections, eventually without moving the individual vertex. Consequently this limiting algorithm can prevent the morphing of the mesh locally. In these situations the software allows the user to manually morph the locale geometries. A major advantage of morphing a reference model is that algorithm can handle the spatial sparseness of MRI data and smooths up to a certain extent the frequently occurring shifts between different MRI cross sections. A manual/visual inspection of the morphed models is, however, always required. As mentioned before the software allows for these corrections. Depending on the required manual correction this whole process takes between 5 and 15 minutes.

Table 1
Demographics of the 5 patients in this study; gender, age and weight.

Patient ID	Gender	Age [years]	Weight [kg]	Average LV wall thickness [mm]	Volume [mm^3]	Heart axis angles [°]		
						X axis	Y axis	Z axis
1	F	26	53	8.7	185	69	133	130
2	F	57	60	8.6	149	66	140	120
3	M	52	138	15.1	258	38	123	106
4	M	52	93	10.9	218	52	131	115
5	M	75	76	8.7	144	57	136	115

The average left wall thickness, cardiac wall volume and heart axis orientation expressed in angles to the positive X-, Y-, and Z axis are derived from the patient specific ventricular mesh.

Automatic morphing remaining tissues; lungs and torso

Some of the recorded cardiac MRI data did only contain the cardiac scan without a full torso scan. In that case the existing reference torso and lung geometries are manually positioned and adapted to the limited number of segmentation contour point. When enough data are available to reconstruct the torso and lungs automatically the contour points are meshed and checked for intersections with the heart geometry and corrected manually when necessary (Fig. 1b). The decision to automatically morph the lungs and torso is currently determined by the user, as no algorithms are available to determine whether enough data are available.

Clinical representation of the cardiac anatomy

This 3D computer model can be sliced in any 2D plane to be matched to any clinical image, like echo, MRI or CT. We developed a computer program that uses the anatomical heart axis usually derived from the 2D clinical images. Using a reconstructed 3D model the anatomical axis can be computed from the anatomical heart model landmarks. The anatomical axis is computed by: 1) fitting a plane through the vertices building the mitral annulus, 2) project all endocardial points on this valve plane and 3) compute the basal heart axis position by taking the average of the projected points as the position of the plane. Step 3 accounts for hearts that are more spherical, which have caused the bulging of the anterior, posterior and free wall. Consequently the center of the projected endocardial points moves toward the lateral wall. 4) Finally the heart axis is computed as the 3D vector between the mid-basal heart axis position and the most distant endocardial vertex relative to this basal point. For each patient the heart axis was computed, resulting in an angle between the X, Y, and Z-axis. The X-axis is defined as the posterior to anterior line, the Y axis as the right lateral to left lateral line and the Z axis as the line from feet to head.

This anatomical heart axis plane is now used to automatically create 4 left and 3 right ventricular cross-planes: the valvular or basal plane, mid basal plane, an apical plane and the apex itself (see Fig. 3). Each left ventricular level, except the apex and the outflow regions, is divided in 5 regions, an anterior region, 2 septal regions, an inferior and a lateral one.

For idiopathic PVC and VT localization the valve plane is the most relevant one, as the majority originates from the left and right outflow tract region. Therefore this region is subdivided accordingly (see Fig. 3), respectively left and right coronary cusp for the left outflow tract and for the RVOT, the lateral and posterior septum.

Results

Five subjects who underwent radiofrequency (RF) ablation of symptomatic idiopathic PVCs were included in the study (Table 1). Each patient signed an informed consent and the study was approved by the UCLA Institutional Review Board (#14-000837). For each patient the cardiac anatomy was reconstructed from a clinical cardiac MRI scan. There were 2 female and 3 male patients, and the age ranged from 26 years to 75 years. The total time to reconstruct the heart and torso models for these 5 subjects ranged from 1.5 to 2.2 hours with a median of 1.9 hours.

Due to several errors in the MRI data, manual corrections were needed for all patients. Several error sources were identified; the relative thin wall of the right ventricle can under some circumstances prevent the detection of the myocardial boundaries in the MRI data. As an example we show in Fig. 1c the MRI of patient 3. In this image the right ventricular epicardial and endocardial boundaries are difficult to separate due to large amount of epicardial fat which has a similar intensity as the blood in the right cavity. Other artifacts involved errors were related to the ECG triggering of the MRI, for instance frequent PVCs or T-wave detection instead of a QRS resulting in a different contractile state of the heart relative to the 'normal QRS'. Also different breathing patterns of the patient can shift the MRI heart position [17]. These errors probably contributed to the observation that the cardiac contour points on a short axis

Table 2
The distance between the contour points and the geometry (mean ± standard deviation and maximum between brackets).

Patient ID	Ventricles			Left lung			Right lung		
	[mm]		# vertices	[mm]		# vertices	[mm]		# vertices
1	1.9	±1.2 (13)	1283	3.1	±3.2 (14)	720	3.8	±4.5 (24)	711
2	1.9	±2.0 (14)	1492	2.1	±2.5 (14)	693	4.0	±7.4 (37)	594
3	2.5	±2.4 (17)	1128	5.7	±4.7 (28)	432	6.2	±5.9 (32)	462
4	1.7	±1.7 (10)	1421	6.4	±5.3 (27)	459	4.0	±4.2 (29)	582
5	2.1	±1.8 (15)	1334	4.6	±4.1 (30)	630	5.1	±4.7 (24)	693

The minimum distance was for all geometries close to zero (<0.1 mm). For the ventricles the distance was computed between the epicardial contour points and the epicardium respectively the endocardial points and surfaces.

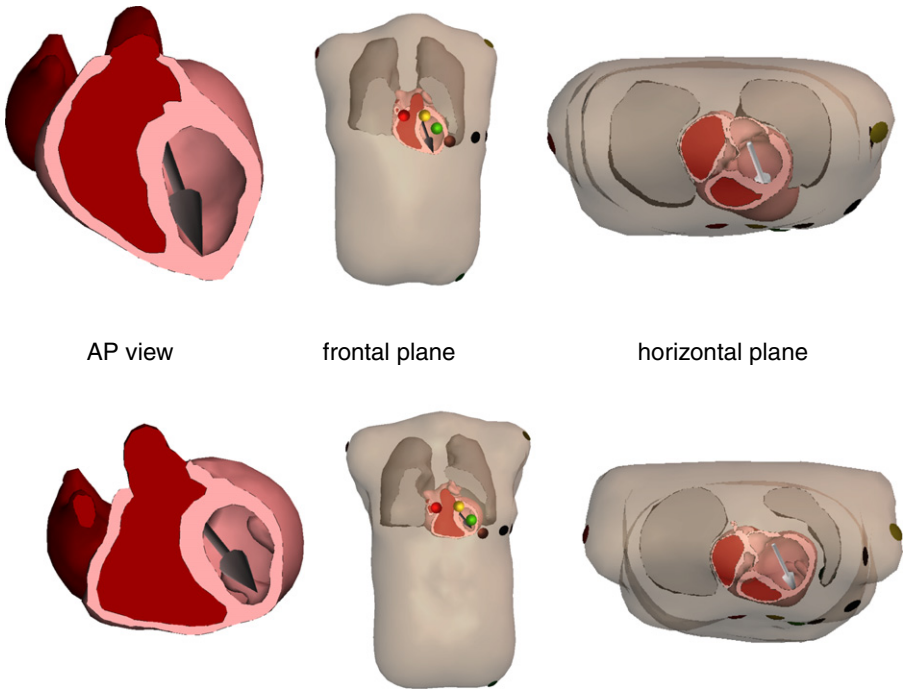

Fig. 2. Two examples of the resulting automatic computation heart axis computation; top row patient 1, bottom row patient 2 (Table 2). Three different views on the models; 1) AP view on the heart with the heart axis arrow in the left cavity. 2) In the middle the frontal view with the 12 lead ECG electrodes positioned according to the standard, and 3) the horizontal plane with ECG electrodes.

Code	description
LAB	Anterior Base
LASB	Anterior Septal Base
LISB	Inferior Septal Base
LIB	Inferior Base
LLB	Basal lateral
LAM	Anterior Mid
LASM	Anterior Septal Mid
LPSM	Inferior Septal Mid
LIM	Mid inferior
LLM	Mid lateral
LAA	Apical anterior
LASA	Apical septal
LISA	Inferior Septal Apex
LIA	Inferior Apex
LLA	Lateral Apex
LA	Apex

SPM	Superior Papillary muscle
IPM	Inferior Papillary muscle
ROLS	RVOT Left Septum
RORS	RVOT Right Septum
ROA	RVOT Anterior
ROL	RVOT Lateral
RLB	Right lateral base
RIB	Right inferior base
RSB	Right septal base
RAM	Right anterior mid
RLM	Right mid lateral
RIM	Right inferior mid
RSM	Right septal mid
RA	Right apex

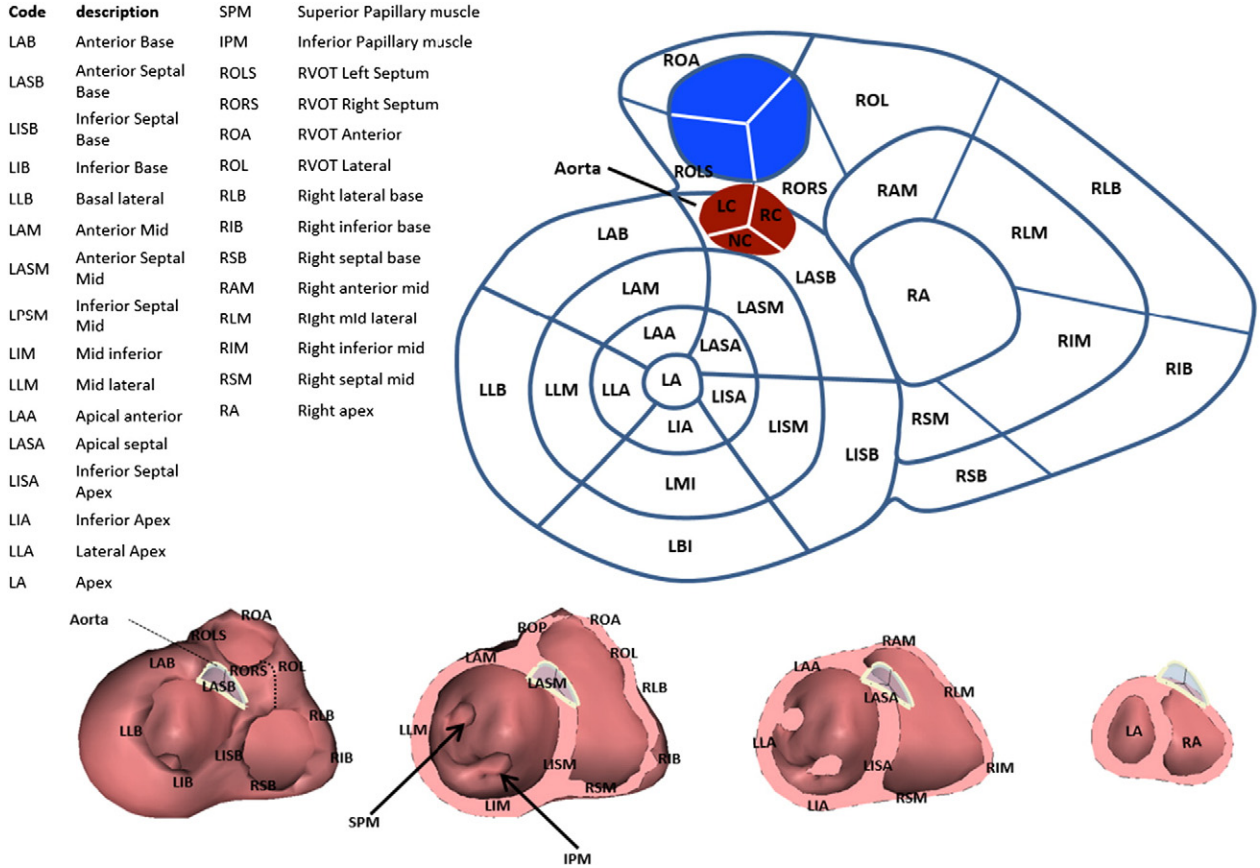

Fig. 3. Creation of cardiac regions and the relation of these regions to the patient specific cardiac anatomy. The cross planes of the heart models on the bottom are created along the computed heart axis (see Fig. 2; patient 2). The projected anatomical planes are patient specific and related both to the left and right ventricles. The left ventricle has been divided in 5 segments, because the accuracy of the PVC localization using the 12 lead ECG to the posterior and lateral wall is limited. The right ventricular apex is usually higher than the left apex. For patients whom this is not the case the right ventricular apical region will be enlarged using this patient specific projection method.

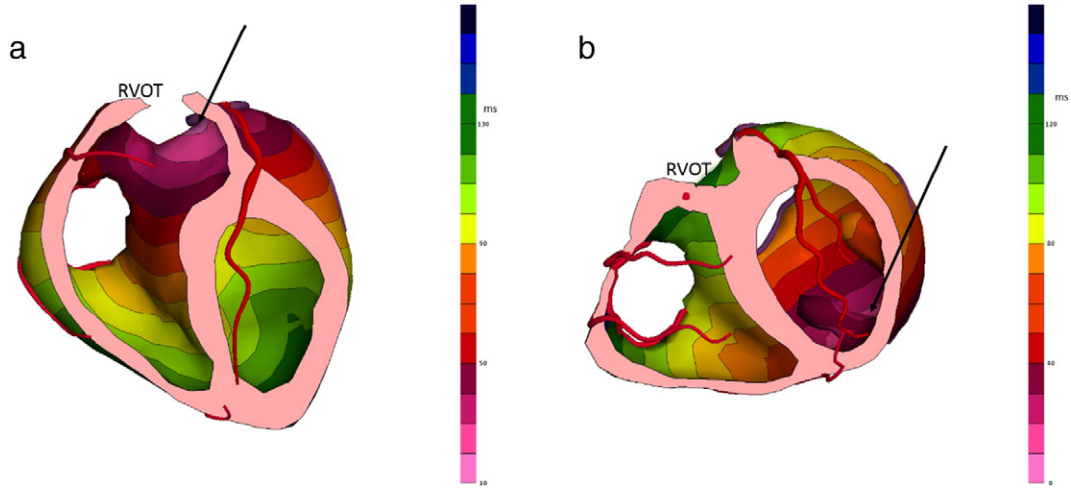

Fig. 4. The activation timing as estimated by CIPS for patient 1 (panel a) and patient 2 (panel b). The PVC location can be derived from this activation timing, i.e. for patient 1 the RVOT left septum region and for patient 2 the inferior papillary muscle. The arrow points to the estimated PVC location to the cardiac anatomy. For orientation purposes the RVOT is indicated as well as the arteries. For both panels the heart is in a sliced AP orientation, showing both endocardial and epicardial surfaces. Isochrones are shown every 10 ms.

MRI image almost never exactly coincided with the contour points on a long axis cardiac image. When morphing the lungs and torso, cross sections between lungs and heart were prevented by limiting the morphing displacement of the lung and torso vertices.

The accuracy of the resulting reconstructions was evaluated by projection distances of the tissue specific contour points on the respective surface of the geometries and computed (see Table 2). For the ventricles the average projected contour point distance was 2.0 ± 1.8 mm and for the lungs was 4.3 ± 4.7 mm. The pixel size of the MRI images ranged from 1.4 to 1.9 mm, which relates the mesh accuracy to 1–1.4 pixels for the heart and 2–3 pixels for the lungs.

Considerable differences were found in the computed heart axis orientations (see 2 examples in Fig. 2). A maximum difference in heart orientation was found between patients 1 and 3 with an angle between both heart axes of 63°. We also compared the heart axis with the normal vector of the short axis MRI images, which represents the heart axis as estimated by the MRI operator. We found an average difference between operators defined heart axis and computed heart axis of 7° for the X axis, 8° for the Y axis and −2° for the Z axis. Using the heart axis (Fig. 2) a 2D representation was computed from each 3D model as shown in Fig. 3 for patient 2.

Discussion

In this paper we introduced a novel software tool to create accurate models of the heart, lungs, and torso from medical images such as MRI or CT. The tool is able to reconstruct the ventricular myocardium accurately with an average error of 1–1.4 pixels for the heart and 2–3 pixels for the lungs (see Table 2). The purpose of these models is to use them in the cardiac isochrone positioning system (CIPS), to localize the PVC to the cardiac anatomy [6]. As an example the positioned isochrones on the cardiac surface are shown for the first two patients in Fig. 4. CIPS requires the models to compute a patient specific transfer function between ECG electrodes and cardiac anatomy [1]. The achieved model accuracy is well within the set goal to localize the origins of PVCs to the correct region of the cardiac anatomy (Fig. 3).

The accuracy of the meshes generated by MRI is influenced by several factors. One of the major limitations of MRI is the fact that the heart is spatially sparsely sampled, and the distance between MRI images usually is about 5–8 mm. Moreover several artifacts influence MRI data quality; 1) breathing, 2) ECG triggering, and 3) specific technical issues related to the MRI machine. Given these error sources the achieved accuracy of the models is high. Increasing the number of vertices used in the mesh might reduce the reconstruction errors, as is indicated when comparing the errors and number of vertices in ventricular and the lung geometries (Table 2). However this has not been further investigated due to limitations of the memory management of the used computer system (CIPS anatomy is a Windows 32 bit application). Future algorithm developments will aim to limit the manual inspection and rework due to the measurement errors.

The computed heart axis was majorly used to automatically divide the heart in different regions. The proposed method to compute the heart axis captures the whole anatomy, without any human interaction. The method to compute the heart axis is only possible because the mitral and aortic valve can be determined from the reference model. This valve relation within the heart model stays fixed during the whole patient specific morphing process, yet another advantage of the use of such reference model. The initial results of this study show that the computed heart axis is in general agreement with the clinically determined heart axis. A larger database is required to determine a more precise relationship between clinically determined and computed heart axis.

The computed heart axis was used to automatically compute patient specific cross sections of the heart at 4 levels to create an easy to interpret visualization 2D view of the

patient's heart. The 2D projection method has been optimized for the localization of PVC, therefore the 2D projection does not only contain the left ventricle, but also a mapping of the right ventricular regions. The link to the 3D cardiac anatomy still allows for detailed inspection of the left and right outflow tract areas where many of the PVCs originate from [12–14]. Thus the combined 2D/3D view can support the clinical interpretation of the CIPS results, i.e. the global PVC origin location can be rapidly interpreted from the 2D view, whereas the 3D view allows for the inspection of the anatomical location. Because the 3D projection to a 2D plane is computed the regions indicated in this 2D plane related directly to the 3D cardiac anatomy. This method can also be used to display other parameters such as scar tissue or ischemic regions while keeping the direct link to the original 3D model and the underlying MRI or CT.

In addition to project the heart from 3D to 2D, the frontal and horizontal plane of the whole thorax can be used to visualize the ECG electrode – heart relation, key for understanding the waveforms of the ECG (Fig. 2). These kinds of models and derived visualizations might be useful in the education of the ECG interpretation and the influence of ECG electrode misplacement.

The achieved accuracy of models might improve the accuracy of the PVC localization of the cardiac isochrone positioning system, as modeling errors can be significantly reduced by this new software tool. The importance of the accurate anatomical models needs to be proven using various levels of details in the used models within the cardiac isochrone positioning system.

Limitations

This preliminary study is lacking validation of the reconstructed anatomical meshes. Such validation requires the comparison of meshes generated by different available segmentation and meshing tools. This, however, requires a vast amount of knowledge and experience of these software packages which is not available in our group. Such comparison thus would require the involvement of different research groups meshing the models from the same data. Based on such study the accuracy of the reconstructed meshes can be determined, especially when using CT data with a high spatial density compared to the sparse MRI data used in the current study.

Conclusion

We have shown that our new CIPS-anatomy software was able to reconstruct the cardiac anatomy within the accuracy determined by the MRI (1–1.4 pixels). The achieved accuracy of heart models can improve the accuracy of the PVC localization of the cardiac isochrone positioning system, as modeling errors are reduced. Additionally, this may improve the efficiency of PVC and VT localization in clinical ablation procedures, and ultimately the success and safety of the procedure.

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