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Developing and Evaluating Virtual Cardiotomy for Preoperative Planning in Congenital Heart Disease

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Abstract. Careful preoperative planning is of outmost importance – in particular when considering complex corrective surgery on congenitally malformed hearts. As an aid to such decision-making we describe a system for virtual reconstruction of patient-specific morphology from 3D-capable imaging modalities such as MRI and CT. We introduce and illustrate the concept of virtual cardiotomy as a new tool to preoperatively evaluate the feasibility of different surgical strategies by investigating the anatomical spatial relations through any number of virtual incisions. We review the technical and clinical implementation of the various components of the system, namely 3D imaging, segmentation and reconstruction, visualization, and simulation of tissue elasticity. Finally we summarize the main findings from a recent evaluation study on 42 infants and children.

Keywords. preoperative planning, congenital heart disease, virtual cardiotomy

Introduction

As far back as in 1988 virtual models based on magnetic resonance imaging were introduced to visualize spatial relationships in patients with congenital heart disease [1]. Both magnetic resonance imaging and visualization techniques of the time suffered from severe limitations however, hindering the adoption of the techniques as clinically useful tools. In the last five years we have fortunately seen significant developments in both the imaging, visualization, and most recently surgical simulation techniques that, when combined, have facilitated a clinical implementation of real-time, interactive virtual cardiotomy for preoperative planning [2].

In this paper we review this development, specifically the necessary prerequisites to virtual cardiotomy, namely imaging, segmentation, 3D reconstruction, visualization, simulation of tissue deformation, and finally a clinical evaluation study demonstrating quantitatively the accuracy of the proposed method.

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1. Methods

1.1. Imaging

Any imaging modality capable of three-dimensional (3D) imaging can, at least in principle, be used to reconstruct patient-specific virtual models of the heart and major vessels. 3D echocardiography is emerging but does not (yet) offer the desired resolution and contrast for easy reconstruction. Both CT and MRI, on the other hand, can potentially provide high-resolution 3D data with excellent contrast between the blood pool and tissues [3-4]. At our institutions MRI is most often preferred over CT due to radiation concerns, as the risk of radiation-induced fatal cancer from pediatric CT is not negligible. We have however reconstructed complex anatomy from both modalities. Contrast-enhanced MR angiography is used routinely for 3D imaging and provides excellent preoperative information using multiplanar reconstruction (MPR), maximal intensity projection (MIP), or volume rendering – however strictly limited to vascular structures only [5]. Using instead an imaging sequence triggered to a short acquisition window in either systole or diastole, virtual models of *intra*-cardiac morphology can be reconstructed. A free-breathing, ECG-triggered, T2-prepared, 3D steady-state free precession (SSFP) whole-heart MRI sequence with a respiratory navigator was applied using a five-element cardiac coil and an acquisition window of 50–60 ms at resolution of 1.3^3 mm^3 isotropic voxels on a 1.5-T whole-body MRI scanner [4] (Philips Medical Systems, Best, The Netherlands). Data were either acquired during end-systole (heart rate >75 bpm) or end-diastole (heart rate<75 bpm).

1.2. Segmentation and reconstruction

To segment 3D imaging data we utilize commercial software (Cardiac3D, Systematic Software Engineering, Aarhus, Denmark). This software implements the watershed transform as described by Vincent and Soille [6]. To control the segmentation the user can interactively insert colored markers (e.g. blood = red, myocardium = green, background = black/transparent). To have full control of the resolution and visual appearance of the reconstructed models, the segmented volume is imported into dedicated in-house software, which builds a 3D surface model using the marching cubes algorithm, reduces the polygon count to a user defined level, and exports the model in a standard 3D format for viewing with a broad range of off-the-shelf visualization systems. Smoothing is applied both to the segmented volume before reconstruction and geometrically to the reconstructed surface. If the user is interested in visualizing the endocardial surface solely, it is sufficient to segment the blood pool in the data [7]. If the myocardium is the target of the reconstruction, naturally this must be segmented also. As an alternative to inspecting a reconstruction virtually, it can be reproduced physically using stereolithography [8].

1.3. Virtual cardiotomy

To provide an accurate "surgeon's view" of a given morphology/repair, e.g. to evaluate or compare the feasibility of a right atrium incision versus a right ventricular outflow incision for a given procedure, we developed the concept of virtual cardiotomy [2]: An incision can be made in any part of the tissue and the corresponding "flaps" pulled aside to reveal the exact spatial relations of the underlying structures. In order to

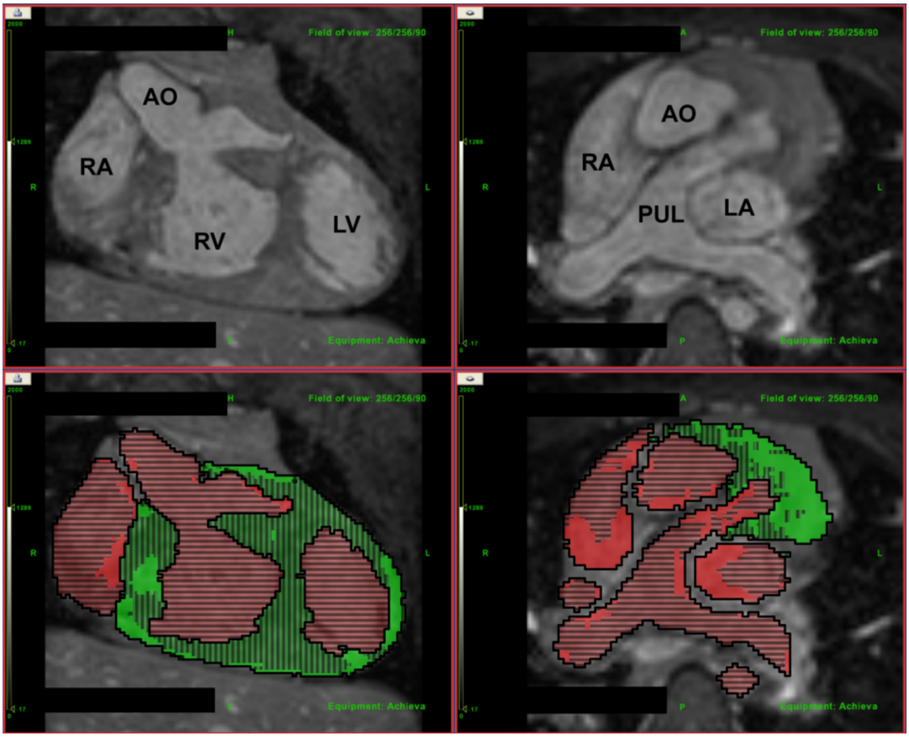

Figure 1. Image acquisition (top) and segmentation (bottom) from a three year-old girl with complete atrioventricular septal defect (AVSD), double outlet right ventricle (DORV), transposition of the great arteries (TGA), valvular and subvalvular pulmonary stenoses, and a left superior vena cava (LSVC). A coronal slice is presented to the left and a transversal slice on the right. *AO* aorta, *LA* left atrium, *LV* left ventricle, *PUL* main pulmonary artery, *RA* right atrium, *RV* right ventricle.

achieve a physically plausible simulation of the tissue deformation, it is necessary to obtain a *volumetric* model from the segmentation process, i.e. a segmentation of the myocardium but also an approximation of the vessel walls [9]. A requirement for an practicable simulation is that the user is able to interact with the model in real-time. This puts severe limitations both on the complexity of the reconstructed model (i.e. the number of discrete elements in the model) and on the biomechanical model used to simulate the elastic behavior. In recent years we have seen several techniques emerge, which are capable of real-time simulation of non-linear elasticity using parallel computation on commodity hardware, e.g. [10-12]. For this work a physical simulation based on a volumetric mass-spring-damper model was utilized [12]. A visualization technique, which maps a high-resolution surface mesh to the surface of a reduced resolution volumetric mesh used for physical simulation of tissue deformation, was utilized to ensure high visual quality of the simulation [13]. At present our target resolution for the simulation mesh is 40,000 nodes (with three degrees of freedom each), and the target resolution for the visualization mesh is 100,000 vertices.

1.4. Evaluation

The necessary segmentation time and the accuracy of the reconstructed models were evaluated quantitatively in a study containing 42 patients aged 0–10 years (average ±

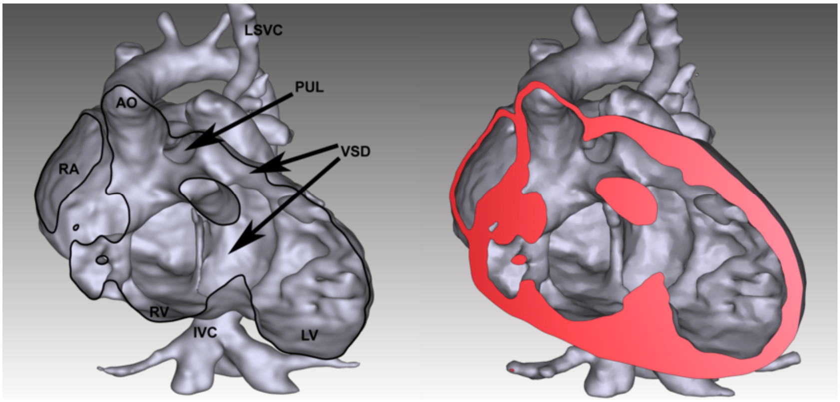

Figure 2. Reconstruction of the endocardium (left) and myocardium (right) of the patient described in Figure 1. A clipping plane is used to visualize spatial relations inside the heart. *AO* aorta, *IVC* inferior vena cava, *LSVC* left superior vena cava, *PUL* main pulmonary artery (origin), *LV* left ventricle, *RA* right atrium, *RV* right ventricle, *VSD* ventricular septal defect.

standard deviation: age 3±3 years, weight 13±9 kg, heart rate 96±21 bpm) [2]: In patients with diagnostic image quality the segmentation quality (and hereby the reconstruction accuracy) was independently graded 1–4 (4 = no discrepancies, 1 = misleading error) by two independent observers. Moreover, the feasibility of virtual cardiotomy was studied qualitatively in selected cases of *complex* congenital heart disease [2].

2. Results

Figure 1 shows the image quality obtained in a three year old girl with complex intra-cardiac malformations (selected from the study reported in [2]). Two reformatted slices are shown on the top and the corresponding segmentation at the bottom. A horizontal (red) shading pattern classifies the blood pool and a vertical (green) shading pattern classifies the myocardium. Voxels corresponding to either shading pattern was classified by the marker-driven semi-automated segmentation algorithm. Bright areas within a segmentation contour, on the other hand, correspond to voxels that were subsequently segmented manually. As reported in the evaluation study [2], the average segmentation time was 59 minutes and its quality graded with average scores of 3.5 and 3.6 by the two observers (with a maximum score of 4).

In Figure 2 the 3D reconstruction (corresponding to the patient from Figure 1) of the blood pool and myocardium is shown. A clipping plane was inserted in order to visualize the complex spatial relations inside the heart: The aortic outflow tract and the origin of the pulmonary artery are clearly visualized just above two ventricular septal defects.

While the depiction of the spatial relations in Figure 2 provides a much desired overview, it does not necessarily provide the surgeon with an exact picture of the limited visual field of view he would encounter during a specific procedure. In order to achieve a realistic view, the virtual cardiotomy simulator was used in Figure 3 to visualize the view from one potential incision – crossing from the aortic root into the right ventricle. The length of the incision was purposely exaggerated in this example to provide an illustration in which both ventricular septal defects are visible.

3. Discussion

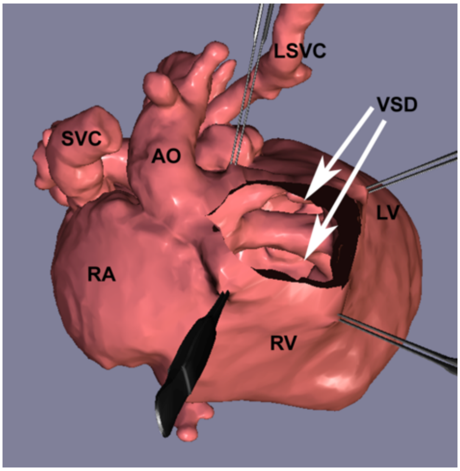

Figure 3. Virtual cardiotomy. A surgeon's view of the two ventricular septal defects (VSD) present in the patient described in figure 1. *AO* aorta, *LSVC* left superior vena cava, *LV* left ventricle, *RA* right atrium, *RV* right ventricle, *SVC* superior vena cava.

A broad spectrum of complex intra-cardiac malformations exists, for which preoperative planning is of outmost importance. The patient depicted in Figure 1-3 is a good example of a group of patients in which both the aorta and the main pulmonary artery originate from the right ventricle. The surgeon must estimate whether intra-cardiac routing of blood from the left ventricle to the aorta through the associated ventricular septal defect(s) is possible through an intracardiac tunnel, whether it is better (or necessary) to perform a switch operation of the main pulmonary artery and the aorta, or finally whether to resolve to a univentricular repair instead. The presented virtual cardiotomy simulator provides a valuable new tool to estimate preoperatively whether highly individual anatomy allows for a given procedure to be completed.

On the technical side, the computing power required to both visualize and compute tissue elasticity in real-time on complex morphologies such as the heart has only recently become available on commodity hardware. In this work we utilized the parallel computing capabilities of modern graphics hardware to achieve sufficient frame rates for smooth simulation. The overall behavior of the simulation can be defined as an engine in which: 1) a number of simulation steps are run – after which force feedback is rendered to a haptic device (simulation rates far exceeds 1000 Hz on the presented models), 2) after a number of repetitions of step 1 the model is visualized – deformed by the current configuration of the simulation mesh. When using such decoupling of the simulation and visualization meshes, it is important to establish a two-way mapping between the potentially different notions of time used in the two systems [14]: While the user interaction is performed in "real world time" the biomechanical simulation is steadily advancing "simulation time" and expects uniformly sampled input forces over time. This latter assumption is invalid in cases when the simulation is mixed non-uniformly with haptic rendering and visualization steps. Fortunately, at the cost of an unnoticeable delay in the interaction this problem can be overcome [14].

In conclusion, we presented a system in which accurate virtual reconstructions of patient-specific cardiac anatomy can be reconstructed in less than an hour from 3D MRI. Coupled with sophisticated visualization – including virtual cardiotomy – the presented work thus introduces a new clinically feasible non-invasive technique for improved preoperative planning in complex cases of congenital heart disease.

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