23 Virtual Surgery in Congenital Heart Disease

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Teaching, diagnosing, and planning of therapy in patients with complex structural cardiovascular heart disease require profound understanding of the three-dimensional (3D) nature of cardiovascular structures in these patients. To obtain such understanding, modern imaging modalities provide high-resolution two-dimensional (2D), three-dimensional (3D), and sometimes even time-resolved 3D imaging of the cardiovascular anatomy of the chest. When 3D structures need to be understood based on 2D images, a 3D model is a very helpful tool to visualize and to understand the often complex 3D structures [1].

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In combination with the availability of virtual models of congenital heart disease (CHD), techniques for computer-based simulation of cardiac interventions have enabled early clinical exploration of the emerging concept of virtual surgery [2, 3]. This chapter serves as an introduction to virtual surgery for patient-specific preoperative planning and teaching of cardiovascular anatomy and interventions for clinicians. The chapter is mainly based on the discussion of a few examples. An overview of the underlying imaging and data-processing techniques is provided.

Figure 23.1 depicts the generic setup. Using computer-simulation techniques the user can rotate and investigate the cardiac anatomy. Two haptic devices provide both positional and rotational freedom during interaction as well as force feedback. The heart of the virtual patient is a reconstruction based on a 3D scan, in this case from magnetic resonance imaging. In Figure 23.2 the ventricular portion of the heart is zoomed. A ventricular septal defect (VSD) is visualized from a surgeon's view. In the following paragraphs the simulation of structural cardiovascular disease for preoperative planning and surgical training is discussed.

Planning of interventions in patients with CHD, in particular surgical procedures, can be very difficult. Often surgical decisions are based on previous experience and therefore the result is very often operator dependent. Patient-specific virtual surgery simulation could improve the surgeon's or interventionalist's preoperative planning and training opportunities, therefore reducing the risk of cardiothoracic interventions

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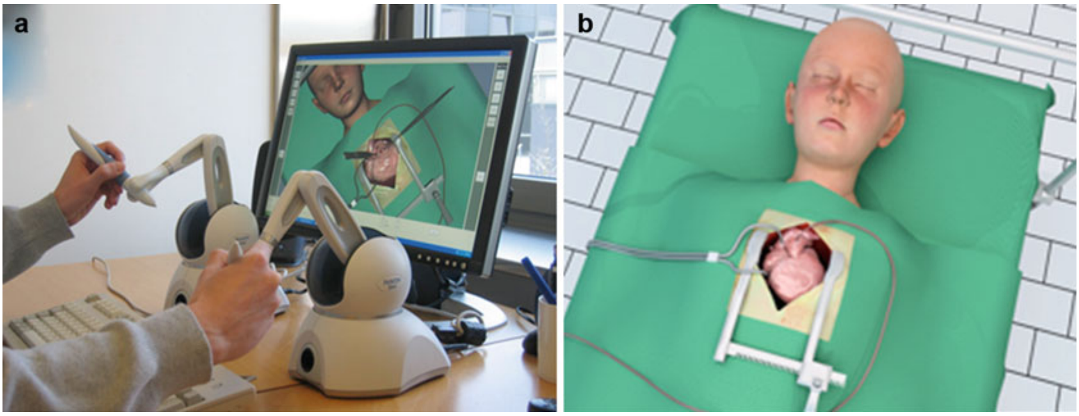

Fig. 23.1 Haptic devices for interactive manipulation of anatomical structures reconstructed from three-dimensional (3D) datasets. The operator can interactively rotate and dissect a virtual specimen to study the anatomy in detail. The corresponding forces are felt through the haptic devices (**a**). A virtual patient in the operating theatre, with a heart reconstructed from a 3D MRI dataset (**b**)

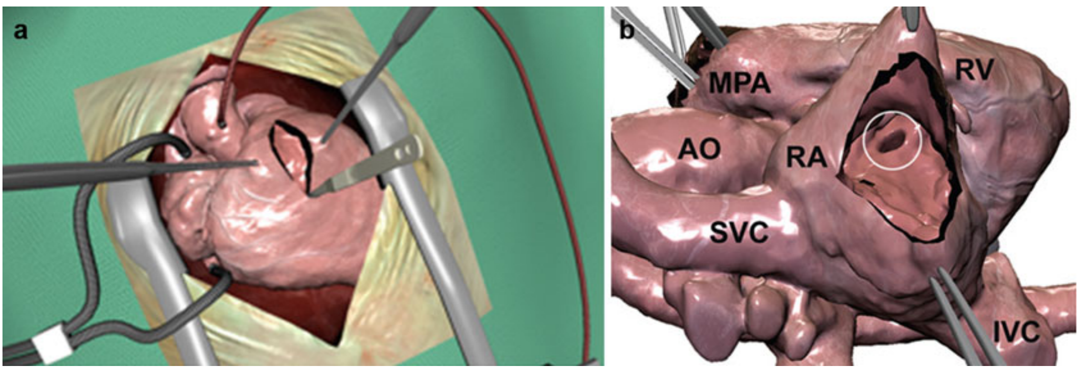

Fig. 23.2 Magnified view of the virtual patient from Fig. 23.1 in a full rendering of the surgical setting (**a**). Only the heart is visualized in (**b**) depicting a ventricular septal defect (VSD, *circle*). The heart was reconstructed from a 3D MRI dataset. It can be manipulated by lifting, rotation, dissection, insertion of a virtual patch, etc. using the devices displayed in Fig. 23.1. The corresponding forces to the virtual manipulations, such as performing a myocardial incision and traction of myocardial tissue using a forceps, are transmitted to the user via the haptic devices (Fig. 23.1a). *AO* aorta, *IVC* inferior vena cava, *MPA* main pulmonary artery, *RA* right atrium, *RV* right ventricle, *SVC* superior vena cava

and improve outcome. Using simulation, the optimal interventional strategy can be planned in advance and different approaches can be discussed with colleagues from other institutions with different grades of experience. The 3D model is a useful communication tool that enables the pediatric cardiac surgeon or interventionalist to discuss interventional strategies. Instead of discussing treatment options purely based on 2D imaging and 3D renderings of the extracardiac anatomy, patient-specific virtual surgery provides the surgeon with a useful tool to communicate the surgical view of the intra- and extracardiac morphology and allows testing of different strategies to repair a cardiovascular defect.

So far heart specimens were essential to understand the various complex pathologies in patients with congenital heart disease. Studies in the pathology laboratory are only possible in a few institutions worldwide, and the number of these rare specimens is very limited. A combination of virtual and physical reproduction of anatomical specimens in conjunction with demonstration of modern imaging techniques could be ideal for

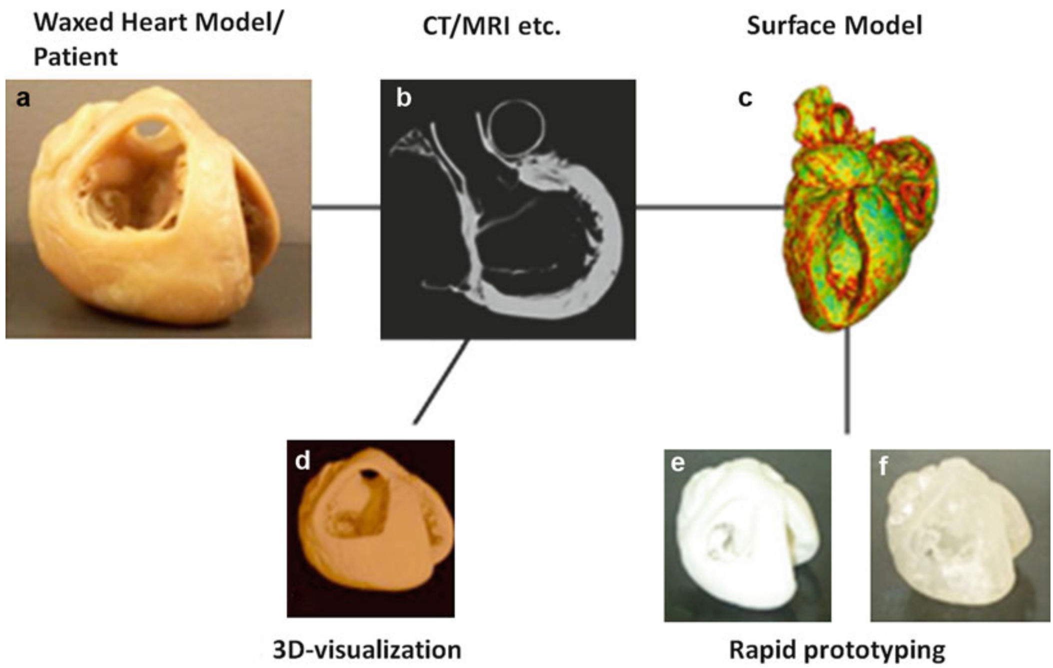

Fig. 23.3 A schematic overview of the production process from a specimen (**a**) via imaging (**b**) to virtual reconstruction (**d**) and physical reproduction using rapid prototyping (**e**, **f**) after creation of a STL file (**c**). Computed tomography was used as the imaging modality in this example, but other 3D imaging techniques can be used in the production process as well

training in the clinical environment. As outlined in Fig. 23.3, virtual reconstruction and physical reproduction using rapid prototyping is a very interesting concept in this respect. Virtual cardiotomy could be a cost-effective supplementary technique to rapid prototyping. Different types of incisions and interventional procedures can be tested and demonstrated independently of the level of experience of the operator and without any risk for the patient. As the models are patient specific, personalized treatment strategies can be developed using this technology.

From Imaging to 3D Modeling

As a prerequisite of virtual surgery, three steps are required:

1. Image acquisition
2. Image segmentation
3. Three-dimensional modeling

A visual illustration of these three steps is provided in Fig. 23.3 and a dedicated section for each step is provided below. The description is intended as an overview of one possible approach to obtain a model suitable for virtual surgery.

It is important to understand that each of these steps is some kind of interpretation of the image data and therefore some errors may be introduced in comparison to the original anatomical structure. These errors can be minimized by improved image quality, e.g., by raising image resolution and improving contrast. In case of virtual surgery, which is performed to predict exact results of a surgical procedure, these errors must be considered when evaluating surgical outcome. Because of this surgeons and interventionalists should be critical of simulation results and be prepared for variations during the actual procedure.

Image Acquisition

The initial step towards obtaining an accurate model for simulation of virtual surgery is acquisition of an image dataset with high resolution and contrast for optimal 3D modeling of the morphology of the congenital heart defect. Frequently an end-diastolic scan is preferred from a surgeon's point of view, as it is closest to the state of the heart on the heart-lung machine [4]. However, the dynamic component of a beating heart is not displayed with this approach. Novel 3D techniques allow acquisition of at least two cardiac phases within one cardiac cycle (end systole and mid diastole) [5]. A complete time-resolved dataset of the cardiac cycle would be ideal [6]. Each individual phase could then be segmented and the results of an intervention could be modeled on a beating heart model.

The present chapter focuses on the concept of virtual interventions in open-heart surgery. Therefore it is assumed that a single-phase three-dimensional (3D) scan in end diastole should be sufficient. Currently multidetector computed tomography (MDCT) or magnetic resonance imaging (MRI) is used for a 3D virtual surgery dataset. MRI as a radiation-free and noninvasive method is most commonly used in patients with CHD in clinical routine. Therefore our examples in this book chapter are based on MRI datasets.

3D MRI

A range of publications is dedicated to 3D MRI. Early research focused on delineating the vasculature structures using contrast-enhanced imaging [7, 8]. As data are usually acquired within one breath hold, ECG triggering is not used to shorten data acquisition time. Therefore intracardiac structures are not imaged adequately. Respiratory-gated and ECG-triggered sequences allow the acquisition of whole-heart MRI datasets suitable for segmental morphological analysis [5, 9]. It was initially evaluated in adolescents and adults with congenital heart disease [4]. After further technical developments, now intracardiac structures in infants and children can be imaged and used for 3D modeling [5, 10]. Recently new intravascular contrast agents have enabled contrast-enhanced imaging triggered to the cardiac cycle. These improvements enable 3D MRI to be acquired in all age groups in clinically acceptable time frames [11, 12]. Figure 23.4a illustrates the current standard image quality obtainable for the dataset underlying the 3D reconstruction demonstrated in Figs. 23.1 and 23.2.

Image Segmentation

Tissue and blood pool need to be segmented to create suitable models for virtual surgery. With the current sequences used, the vessel walls are indistinguishable from the blood lumen and surrounding tissue. Therefore the myocardium and blood pool are segmented. Vessel walls are created by software unless the blood pool is already bordered by the myocardium.

It is out of the scope of this chapter to discuss various segmentation algorithms. For the present work a marker-based segmentation algorithm was applied [1]. The user inserts a number of colored markers in the blood pool, myocardium, and background, respectively. One color is dedicated for each category. From this input the software

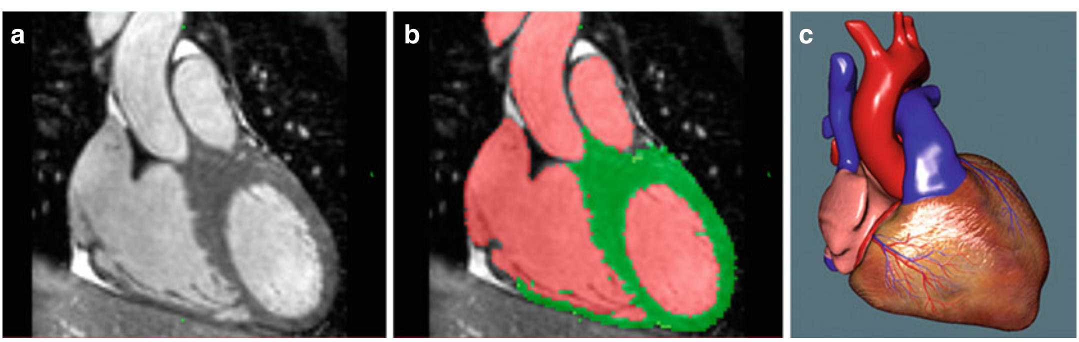

Fig. 23.4 A three-step process to create a model for virtual surgery is shown: 3D imaging (**a**), semiautomatic segmentation (**b**), and 3D reconstruction of a virtual model for visualization and simulation (**c**)

computes and visualizes a corresponding segmentation in real time. This procedure can be carried out in just a few minutes, assuming a reasonable image quality has been obtained. Unfortunately it is usually more time consuming to subsequently verify and manually correct residual segmentation errors. A previous study showed that about 1 h for segmentation was required for a suitable model for surgical simulation [3]. Improvements of segmentation software, image contrast, and resolution will reduce the time for creating models for virtual surgery. Figure 23.4b shows a segmented slice corresponding to the non-segmented slice seen on the left (Fig. 23.4a). With this software the segmentation is done in 3D and *not* slice by slice to reduce the time for preparation of the virtual surgery model. The blood pool is colored in red and the myocardium in green (Fig. 23.4b).

3D Modeling

Proceeding to the 3D modeling step, two scenarios should be distinguished:

- Patient-specific preoperative planning
- Generic modeling for training and teaching

A brief section is dedicated to each scenario outlined below. The simulation of realistic tissue deformation behavior in response to surgical tools is required for both scenarios. This needs to be interactive and in real time. Haptic feedback from freely movable tools in 3D is preferred (Fig. 23.1a). A fundamental requirement of virtual surgery is the possibility of making arbitrary tissue incisions. The underlying technical foundation to the system discussed below has been published [13].

Patient-Specific Modeling

Once the segmentation of the morphological scan has been completed, it can be exported into the simulator, which automatically sets up a simulation environment such as the one depicted in Figs. 23.1 and 23.2. In the next section the applicability of the system will be discussed.

It might be necessary to preprocess the data structure of a 3D model, i.e., the mesh, to achieve reliable results from the simulation or to speed up the simulation itself for real-time purposes. Preprocessing ranges from reducing overly sampled parts of a 3D model to completely resampling a raw, initially highly sampled model. Even during a simulation 3D models have to adapt to their meshes, e.g., to allow for arbitrary incisions, in which case, the data structure has to be aligned along these incisions. This technical aspect is particularly important since automatic modifications of the data structure are the third source for errors referred to the original anatomical structure after image acquisition and segmentation.

Generic Modeling

To define a convincing new training or teaching environment, further processing is advisable. As a demonstration model we scanned a volunteer and constructed a 3D model of his heart and major vessels [2]. Some desired morphological defects were manually introduced, specifically two atrial septal defects (ASDs) and two ventricular septal defects (VSDs). An option of dynamically configuring whether these defects should all be present for a given simulation session was implemented. A graphical artist was employed to colorize the models and enhance their visual appearance. An example of such visual model enhancement is provided in Fig. 23.4c. The significant effort to create these realistic models is justified by their unlimited and universal use.

Virtual Surgery Examples

Preoperative Planning

Congenital heart disease often has complex intra- and extracardiac malformations, which need to be addressed individually by a specific surgical or interventional approach. The surgeon needs to be able to view all cardiovascular structures of interest to plan the incision and the operative strategy to achieve optimal results. There is further a need for the surgeon to interact with the dataset to try out different types of surgical techniques including the design of patches to produce optimal surgical results.

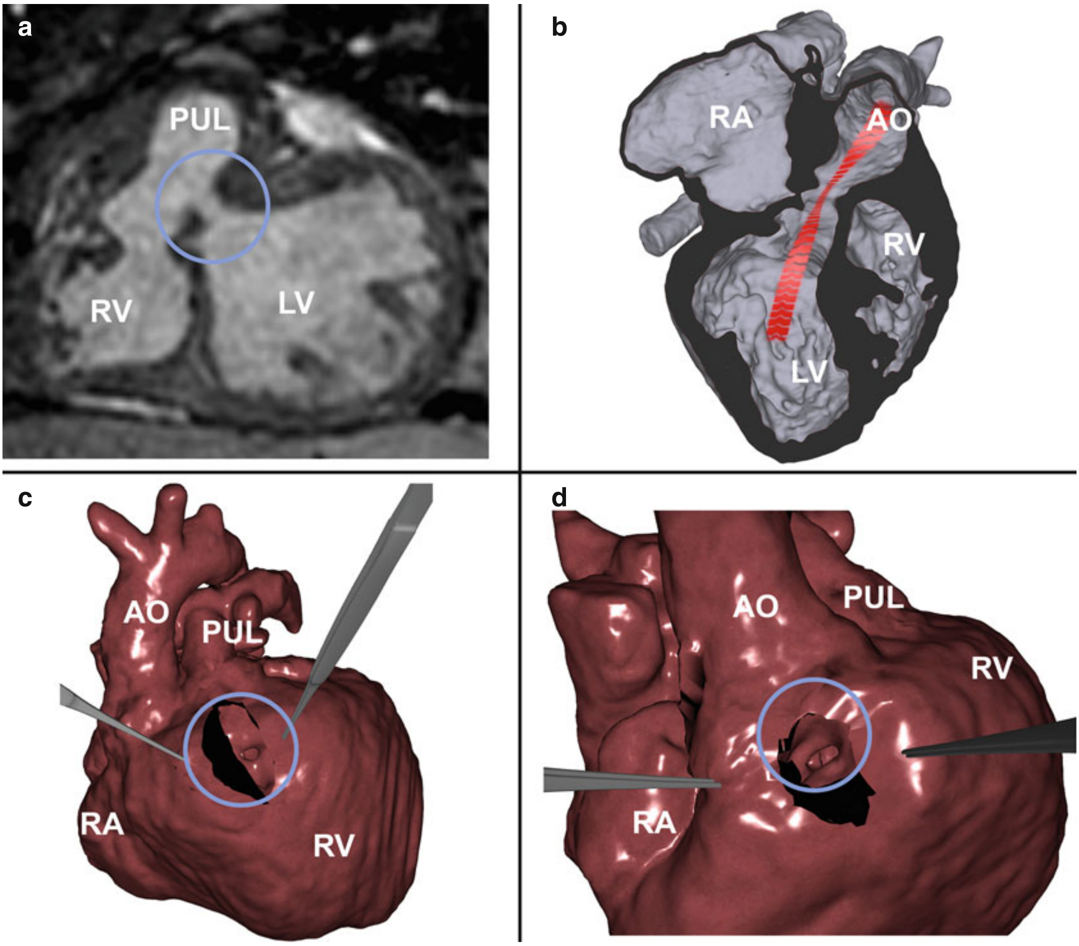

Fig. 23.5 Post-surgical 3D visualization and simulation from a MRI data set of a 10-year-old girl after an intraventricular repair of a double-outlet-right ventricle (*DORV*) is shown. The aorta was to the right of the pulmonary artery in a side-by-side position. Two baffle leakages and a narrow baffle pathway from the left ventricle to the aorta were imaged postoperatively. (**a**) Oblique slice from the 3D MRI data set depicting the larger sub-pulmonary baffle leakage (*circle*). (**b**) 3D visualization of the baffle pathway from the left ventricle to the aorta (*red arrow*). (**c**) An incision in the sub-pulmonary region reveals the exact 3D position of the larger residual baffle leakage (*circle*). (**d**) An incision in the sub-aortic region shows the narrow baffle pathway (*circle*) from the left ventricle to the aorta. *AO* aorta, *LV* left ventricle, *PUL* pulmonary artery, *RA* right atrium, *RV* right ventricle

Figures 23.5 and 23.6 provide two examples of virtual cardiotomy to illustrate what can be achieved using this tool. Figure 23.5 shows a patient with double-outlet right ventricle (DORV) after an intracardiac baffle repair connecting the left ventricle to the aorta and the right ventricle to the pulmonary artery. This is a challenging operation even for an experienced surgeon [14]. The 3D visualization and simulation tools were used to evaluate the post-surgical outcome. An oblique reformatting of the 3D MRI reveals a residual sub-pulmonary baffle leakage (Fig. 23.5a). The precise position of this baffle leakage is visualized with a virtual incision in the right ventricle (Fig. 23.5c). The passage of blood through the baffle is visualized in Fig. 23.5b, d. The red arrow (Fig. 23.5b) indicates the path through the baffle from the left ventricle to the aorta. The virtual incision (Fig. 23.5d) in the sub-aortic region demonstrates the narrow intraventricular pathway from the left ventricle to the aorta.

Figure 23.6 compares the operative situs of a patient with a VSD with the virtual model to prove the suitability but also the limitations of this tool.

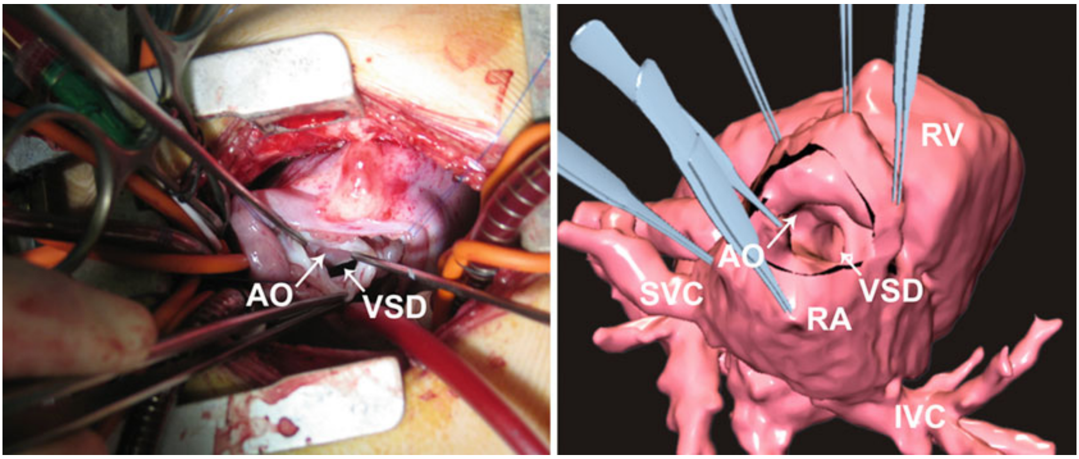

Fig. 23.6 Surgical image (*left*) and virtual cardiotomy (*right*) in a 1-year-old child with a ventricular septal defect. An incision in the right atrium gives access to the defect, which is located just below the aortic outflow tract. *IVC* inferior vena cava, *RA* right atrium, *RV* right ventricle, *SVC* superior vena cava, *VSD* ventricular septal defect

Predictive Simulation

In the context of cardiovascular surgery, predictive simulation is a recently emerging field. First examples regarding the extracardiac vasculature can be found in the literature [15, 16]. The challenge of predictive simulation systems is to behave as physically correct as possible to provide reliable previews of outcomes for different surgical approaches. This slight shift of focus entails several requirements and opportunities for such simulation systems. Rather than simulating surgical tools controlled in real time through haptic input devices for virtual operations, such a simulation system can be considered to be the tool itself.

A surgeon, already experienced in incising and suturing, is supposed to interact on a higher level with the software, e.g., by just indicating incisions or choosing incisions, which should be sutured automatically. Solely the result is of interest to be able to evaluate different approaches for an intervention. While the simple interaction is done in real time, e.g., by clicking on a static 3D model, the resulting deformations are simulated directly afterwards without strong real-time requirements. This allows the simulation to utilize very sophisticated mathematical models for accurately predicting the outcome or proposing optimal patch shapes for most promising results regarding blood flow for example.

Figure 23.7 shows an early prototype of a predictive simulation system for interventions in patients with malformed extracardiac vasculature [16]. Different approaches to correct a patient with coarctation of the aorta are simulated. In the future this may lead to better results in these patients as different surgical approaches can virtually be tested and the best result can be predicted. In this case the surgeon would then choose the technique providing the best result based on the recommendations of the modeling tool. It is very important that the physician who is actually performing the procedure makes the final decision.

Training and Teaching

How virtual surgery can support training, teaching, and clinical medicine and therefore improve patient outcome is outlined below. The approach for training and teaching has a different focus than the clinical setup, but many of the technical considerations are similar. Data can be acquired from heart specimens using high-resolution computed tomography to obtain optimal imaging results [17, 18]. Models can be post-processed by an artist to obtain most realistic results of the cardiac morphology, which needs to be demonstrated. Time for reconstructing these models is not as crucial as in the clinical setup, and many of

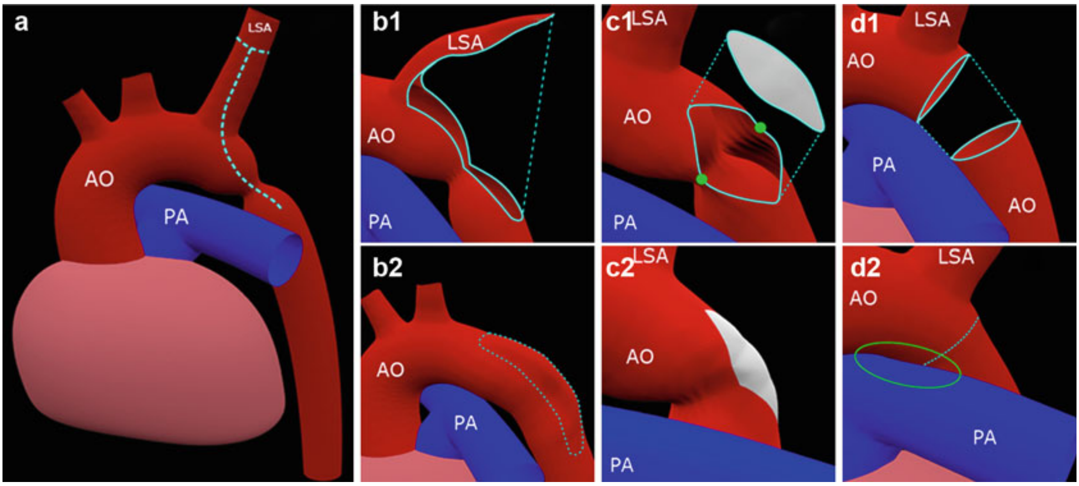

Fig. 23.7 A prototype for preoperative planning of surgery of coarctation of the aortic arch is shown (**a**). Deformations caused by different interventions are simulated: before and after a subclavian flap aortoplasty (**b**), patch aortoplasty (**c**), and an end-to-end anastomosis (**d**) (From Kislinskiy et al. [16] with permission)

the specimens used are more a template for a typical form of congenital heart disease rather than a very specific patient model.

For clinical purposes the heart of the patient needs to be imaged as precisely as possible prior to surgery. The time required for segmentation and preparing the model should be within reasonable time limits to make it applicable in a clinical setup in a cost-effective way. The models produced need to be evaluated regarding their reliability to depict the relevant structures of the intracardiac anatomy to enable optimal surgical results.

Because of further developments in imaging technology and computer hardware and software, it can be expected that this technology will be an essential part in teaching and training, research, and clinical medicine with the final goal to improve patient outcome.

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