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Virtual Surgery for Conduit Reconstruction of the Right Ventricular Outflow Tract

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Abstract

Purpose—Virtual surgery involves the planning and simulation of surgical reconstruction using three-dimensional (3D) modeling based upon individual patient data, augmented by simulation of planned surgical alterations including implantation of devices or grafts. Here we describe a case in which virtual cardiac surgery aided us in determining the optimal conduit size to use for the reconstruction of the right ventricular outflow tract.

Description—The patient is a young adolescent male with a history of tetralogy of Fallot with pulmonary atresia, requiring right ventricle-to-pulmonary artery (RV-PA) conduit replacement. Utilizing preoperative magnetic resonance imaging data, virtual surgery was undertaken to construct his heart in 3D and to simulate the implantation of three different sizes of RV-PA conduit (18, 20, and 22 mm).

Evaluation—Virtual cardiac surgery allowed us to predict the ability to implant a conduit of a size that would likely remain adequate in the face of continued somatic growth and also allow for the possibility of transcatheter pulmonary valve implantation at some time in the future. Subsequently, the patient underwent uneventful conduit change surgery with implantation of a 22-mm Hancock valved conduit. As predicted, the intra-thoracic space was sufficient to accommodate the relatively large conduit size without geometric distortion or sternal compression.

Conclusion—Virtual cardiac surgery gives surgeons the ability to simulate the implantation of prostheses of different sizes in relation to the dimensions of a specific patient's own heart and thoracic cavity in 3D prior to surgery. This can be very helpful in predicting optimal conduit size, determining appropriate timing of surgery, and patient education.

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Declaration of Conflicting Interests

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Keywords

virtual surgery; right ventricle-to-pulmonary artery (RV-PA) conduit surgery; computer-aided design; 3D reconstruction

“Virtual surgery” involves using patient data, usually radiological images, to create patient-specific three-dimensional (3D) models, so that planned surgical procedures, such as the implantation of devices or grafts, can be carried out *in silico*, before the actual surgery. It has been used in several surgical specialties, notably orthognathic and craniofacial surgery,¹ but application to cardiac surgery has primarily addressed planned implantation of mechanical circulatory support devices. For congenital heart disease, 3D reconstruction of intracardiac anatomy² and 3D printing of physical models³ have been used for cardiac surgical planning, but the use of virtual cardiac surgery remains novel. Here we describe a case in which virtual cardiac surgery aided us in determining the optimal conduit size to use for the reconstruction of right ventricular outflow tract (RVOT).

The patient is a young adolescent male with a history of tetralogy of Fallot with pulmonary atresia. He was initially palliated with a left Blalock-Taussig shunt at two months of age and then a central shunt at six months. At the age of one year and four months, he underwent central pulmonary artery reconstruction and placement of an 8-mm pulmonary valve homograft as RV-PA conduit. Two months later (at the age of one year and six months), he underwent ventricular septal defect closure and placement of a 12-mm Hancock valved RV-PA conduit. Over the ensuing years, he has experienced satisfactory somatic growth and has progressively developed conduit stenosis. He has been monitored closely with serial echocardiograms as well as periodic evaluation with cardiac magnetic resonance imaging (MRI) studies. The RVOT pressure gradient on echocardiography at the age of 12 years and 1 month was 94 mm Hg (peak) and 58 mm Hg (mean). At the age of 12 years and 8 months, the patient underwent a cardiac MRI scan, which showed a right ventricular end-diastolic volume index of 83.2 mL/m² and a regurgitant fraction of 7.4%. Utilizing digital data from the MRI study, virtual surgery was undertaken to construct his heart in 3D and to simulate the implantation of three different sizes of RV-PA conduit (18, 20, and 22 mm; Figures 1 and 2). The 3D data and virtual surgery images were presented and discussed at the pediatric joint cardiology and cardiac surgery preoperative conference. Although conduit replacement was clearly indicated at this time on the basis of the estimated RVOT gradient and right ventricular pressure, it was reassuring to be able to simulate the geometry of conduit implantation with several sizes of device and predict the ability to implant a conduit of a size that would likely remain adequate in the face of continued somatic growth (anticipated adolescent growth spurt) and also allow for the possibility of transcatheter pulmonary valve (TPV) implantation at some time in the future. A recent long-term follow-up study of TPV replacement found that smaller TPVs are associated with a higher mean Doppler RVOT gradient at discharge and a high RVOT mean gradient at discharge is associated with TPV reintervention.⁴ Thus, a conduit with a larger diameter was better. Subsequent to this exercise, the patient underwent uneventful conduit change surgery with implantation of a 22-mm Hancock valved conduit at age 13 years and 2 months. As predicted by the virtual surgery simulation, the intrathoracic space was sufficient to accommodate the relatively

large conduit size without geometric distortion or sternal compression. Recovery was uneventful and he was discharged seven days after surgery.

Virtual cardiac surgery gives surgeons the ability to simulate the implantation of prostheses of different sizes in relation to the dimensions of a specific patient's own heart in 3D prior to surgery (Figure 1). This can be very helpful in predicting optimal conduit size. As one of the modes of conduit failure is chest wall compression, it is important to ensure there is enough space in the thorax prior to implantation. Thus, the relation of the virtual simulated conduit to the chest wall (Figure 2) is important. While we sometimes print 3D heart models of complex congenital heart disease for surgical planning and education, in this case, the anatomy of the heart itself is not complex. The images of the virtual simulated conduit superimposed on the patient's existing MRIs (Figure 2) are more useful than actual 3D printing to estimate the relation of the virtual simulated conduit to the chest wall.

Virtual cardiac surgery may also be helpful in determining appropriate timing of surgery. An example would be the case of a child with a moderate gradient across a previously implanted RV-PA conduit in combination with some degree of conduit valve regurgitation. Surgery in such a case would be elective, with numerous factors contributing to the determination of optimal timing. In light of the development of TPV replacement,⁵ there now exists considerable impetus to reduce the number of surgical RVOT procedures that may be required over a patient's lifetime by extending the functional life of an implanted valved conduit through the use of transcatheter devices. At the present time, the size (diameter) of the surgically implanted conduit is one of the principal determinants of the possibility of subsequent implantation of devices such as TPVs. The ability to predict surgical implantation of a conduit that is sufficiently large to assure a high likelihood of the possibility of eventual deployment of a TPV or similar device may be helpful to clinicians in determining the timing of surgical RVOT procedures that are elective.

With respect to the actual case illustrated in this report, the 4-mm difference in diameter between 18- and 22-mm RV-PA conduits may be physically quite small (approximately equal to the thickness of two coins), but the ability to implant a 22-mm conduit instead of an 18-mm conduit could mean one less major open-heart surgery for a pediatric patient with congenital heart disease. "Virtual conduit implantation" can be done using the patient's existing preoperative imaging data and does not cause any additional discomfort or inconvenience to the patient. Finally, it can be used as an educational tool for patients and parents as well as for clinical and academic discussions at preoperative conferences.

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Abbreviations and Acronyms

3D three dimensional

MRI	magnetic resonance imaging
RV-PA	right ventricle-to-pulmonary artery
RVOT	right ventricular outflow tract
TPV	transcatheter pulmonary valve

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Figure 1. Virtual right ventricle-to-pulmonary artery (RV-PA) conduit reconstruction surgery. A, Overview. B–D, Views of the RV-PA stenosis. E–G, Virtual surgery with three different sizes of conduits. Yellow: 18 mm, green: 20 mm, and red: 22 mm.

Figure 2. Virtual simulated right ventricle-to-pulmonary artery (RV-PA) conduit superimposed on the patient's existing magnetic resonance imaging (MRI). These images are useful to estimate the relation of the virtual simulated conduit to the chest wall. A–F, Sagittal plane. G–J, Transverse plane. Blue arrowheads: inner chest wall; yellow: 18 mm, green: 20 mm, and red: 22 mm.