Rapid Prototyping
A New Tool in Understanding and Treating Structural Heart Disease

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Abstract—As the appreciation of structural heart disease in children and adults has increased and as catheter-based closure procedures are now being performed in clinical practice, cardiovascular physicians have multiple compelling new reasons to better understand cardiac anatomic and spatial relationships. Current 2-dimensional imaging techniques remain limited both in their ability to represent the complex 3-dimensional relationships present in structural heart disease and in their capacity to adequately facilitate often complex corrective procedures. This review discusses the cardiovascular applications of rapid prototyping, a new technology that may not only play a significant role in the planning of catheter-based interventions but also may serve as a valuable educational tool to enhance the medical community’s understanding of the many forms of structural heart disease. (Circulation. 2008;117:2388-2394.)

Key Words: computed tomography ■ heart defects, congenital ■ heart septal defects ■ percutaneous closure ■ rapid prototyping

Cardiovascular physicians and engineers have multiple compelling new reasons to better understand cardiac anatomic spatial relationships. First, congenital heart disease in children and adults has increased the appreciation of intracardiac shunt lesions and other anatomy-based lesions. In the last several years, there has been a dramatic increase in the number of both approved and investigative catheter-based therapies for congenital as well as acquired structural heart disease that involve both modification of structures and implantation of novel devices. Second, innovative cardiac valve interventions require an advanced understanding of spatial relationships and an ability to effectively navigate delivery systems within cardiac chambers. Finally, therapeutic intracardiac procedures in electrophysiology require an in-depth understanding of 3-dimensional (3D) relationships of cardiac structures to effectively perform both simple and complex ablation procedures.

Fortunately, each of these new therapies has been accompanied by advances in medical imaging modalities that permit a more accurate, noninvasive assessment of cardiac defects. Current 2-dimensional (2D) imaging techniques, however, fall short both in representing the complex 3D relationships present in structural heart disease and adequately facilitating often complex corrective procedures. The physician must instead integrate the 2D images in his/her mind and conceptually extract the relevant 3D relationships. Although computer graphics allow for 3D representations of cardiac structures using processed 2D images from modalities such as ultrasound and multidetector computed tomography (CT), these representations remain limited by their overall lack of realism, dependence on computer workstations for visualization, and inability to be tangibly manipulated. The recent development of rapid prototyping, a method by which 2D images are processed into 3D physical models, has provided a new way for physicians and engineers to more clearly understand complex spatial relationships while effectively predicting potential procedural complexities by allowing operators to physically visualize device-anatomy orientation in 3D space. Rapid prototyping represents a new technology that likely will play a significant role in the patient-specific planning of catheter-based interventions and may also serve as a method by which to enhance the medical community’s overall understanding of the many forms of structural heart disease.

Introduction to Rapid Prototyping
Rapid prototyping is a process by which 3D computerized surface models are converted into physical models. The technology was originally developed for use by the manufacturing industry to design components for numerous products, including automobiles, aircraft, and computers. In these industrial applications, the technology was used primarily to both evaluate the ease of future product assembly and assess the feasibility of manufacturing newly designed products before implementing large-scale fabrication. With the unique capabilities afforded by modern imaging modalities such as multidetector CT, magnetic resonance imaging (MRI), and 3D echocardiography, the use of rapid prototyping has begun an expansion into medical applications in which it may serve to directly affect patient care. Specifically, the technology has been invaluable in medical disciplines in which disease management relies heavily on a thorough understanding of...
complex anatomic structures and has been shown to improve diagnostic accuracy, assist in preoperative planning, and enhance the teaching of patients, students, and physicians.

Medical rapid prototyping was first utilized in 1990 when investigators used CT source image data to produce a model of cranial bone anatomy displaying full internal detail. Since that time, the development of medical rapid prototyping has been facilitated by advances in medical imaging technology, computer hardware, and 3D image processing software. For many years, the technology was applied almost exclusively to create models and manufacture implants of bony structures in a range of medical specialties, including oral and maxillofacial surgery, neurosurgery, and orthopedics. As rapid prototyping advanced, it was further utilized in various disciplines to create models of vasculature structures in the brain and periphery.

Historically, preserved hearts obtained at autopsy were used to teach anatomy and provide insight to physicians exploring new operative procedures and engineers designing new devices. In addition, 3D models of these specimens could be created by paraffin wax or silicone casting. These methods, however, were time-consuming, could only be performed on postmortem specimens, and involved a process necessitating the destruction of the casted heart. From a practical standpoint, neither autopsy hearts nor cardiac pathologists are readily available for most clinicians. Furthermore, the autopsy specimens may or may not have anatomy similar to that of the patient for whom clinical care is being planned. Finally, cardiac chambers in autopsy specimens are either collapsed or frozen at end diastole or end systole depending on the fixative, which inevitably leads to alterations of essential 3D spatial relations.

Standard 2D imaging modalities (echocardiography, fluoroscopy, angiography, and planar images from multidetector CT and MRI), although widely available and undeniably valuable in the evaluation of and planning for most surgical and interventional procedures, remain limited in their ability to clearly represent the complex 3D spatial relationships present in structural heart disease. Cardiac imaging has only recently made the transformation of 2D data sets into 3D and 4-dimensional computerized reconstructions a routine process, thereby providing the necessary input data for cardiovascular rapid prototyping. In fact, preliminary investigations into the cardiovascular application of rapid prototyping have already demonstrated remarkable potential, assisting in the development of new cardiac support devices and implantation of artificial valves and facilitating both preoperative and intraoperative orientation during corrective surgery for congenital abnormalities. As our understanding of the technology continues to advance, rapid prototyping is emerging as a viable tool that can be employed in the care, management, and treatment of patients with a variety of cardiovascular syndromes and anomalies.

**Rapid Prototyping of Cardiac Models**

Currently, no standardized process exists by which to transform 2D cardiac image data into a physical model. To date, a wide array of algorithms have been successfully applied in an investigative fashion with a variety of source image data including digital photographs of pathological specimens, multidector CT, MRI, and echocardiography. In our research laboratory, we used cardiac CT angiography (CTA) images as the source data for rapid prototyping of cardiac models. CT acquisition is performed on a Philips Brilliance 40-slice CT scanner (Philips Medical Systems, Netherlands) that has a gantry speed of 420 ms and an absolute slice resolution of 0.625 mm. Patients are administered intravenous β-blockers as needed to achieve heart rates of 60 to 75 bpm to minimize motion artifact during image acquisition. Images are obtained in a 250-cm field of view from the pulmonary artery through the inferior border of the heart during a dual-phase intravenous injection of 100 to 150 mL of iodinated contrast (350 to 370 mg) infused at 5 mL/s followed by a 40-mL saline injection infused at 4 mL/s. In addition, all images are acquired with the use of both ECG multiphase gating technology and a single breath-hold technique.

The CTA images are subsequently processed with the use of several software packages ranging from those used for Digital Imaging and Communications in Medicine viewing to others that were originally designed for application in computer animation, video game creation, and other advanced graphic applications. The multistep imaging process begins as 2D cross-sectional images are imported into an advanced open-source Digital Imaging and Communications in Medicine viewer with built-in image processing software (OsiriX; Antoine Rosset, University of Geneva; Osman Ratib, University of California at Los Angeles). With the use of OsiriX, a traditional volumetric cardiac CT reconstruction is generated to capture enhanced detail for focal anatomic areas, including intracardiac defects and ventricular chamber detail (eg, trabeculations, papillary muscles). Once a volumetric reconstruction of the region of interest has been performed, a polygon surface mesh model is generated from this volume model with threshold settings for optimal inner wall extraction. In addition, a second polygon mesh is generated to encompass the exterior surface (Figure 1).

The second step in image processing involves the use of advanced 3D animation software (Softimage XSI; Softimage Co, Montreal, Quebec, Canada) to define exterior contours from the exterior polygon surface mesh model created in
OsiriX. This stage of processing begins by defining a target object (the polygon surface model created in OsiriX), skin object (highly subdivided primitive polygon cube) surrounding the target object, and reference object (small polygon sphere placed in the center of the secondary object). The skin object is subsequently deformed in a shrink-wrapping process toward the target object, with the reference object used as a center point toward which the shrinking vectors are directed. When a predetermined threshold on the polygon surface model is encountered during the deformation process, the shrink-wrapping process is stopped (Figure 2). This newly warped polygon model is exported as a clean polygon model based on the original CT-derived surface model.

The final steps in processing involve correcting errant points from the shrink-wrapping process and averaging away remaining noise with the use of advanced 3D modeling and rendering software (Modo 301; Luxology, LLC, San Mateo, Calif). This final editing stage requires expert clinical and anatomic knowledge of each patient because a wide array of structural heart anomalies significantly deviating from conventional cardiovascular anatomy may be present. A polygonal modeling program is subsequently used to merge inner and outer surfaces, cut away “viewing windows,” and correct any residual polygon mesh errors. Finally, the model surface is tessellated with a smoothing algorithm to generate the final, high-resolution (=500 000 or more polygons) structure that is exported as a stereolithography (.stl) file for 3D printing.

Methods of Rapid Prototyping
The rapid prototyping technology used in medicine is defined as either subtractive or additive depending on the printing method used.1 The only subtractive technique used in medical applications is milling, in which the shape of the model is milled from a block of material (either polyurethane or other foam product). Although low in cost, milling is limited in producing models that define surface anatomy alone with overall poor geometric accuracy.

The most common additive technologies used in medicine are selective laser sintering, fused deposition modeling, multijet modeling/3D printing, and stereolithography. Selective laser sintering (3-D Systems Inc, Rock Hill, SC) uses a high-power laser (eg, carbon dioxide laser) to fuse small particles of plastic, metal, or ceramic powders into a 3D object. The laser selectively fuses a pattern into the surface of a thermoplastic powder bed by scanning cross sections generated from the computer-aided design file of the computerized 3D surface model. After a cross section is scanned and laser fused, the powder bed is lowered by 1 layer of thickness, a new layer of thermoplastic powder is applied on top, and the process is repeated. Selective laser sintering has the ability to utilize a variety of thermoplastic powders and has a high geometric accuracy but is generally higher in cost than other additive methods.

In fused deposition modeling (Stratasys Inc, Eden Prairie, Minn), a plastic filament (typically acrylonitrile butadiene styrene polymer) is forced through a heated extrusion nozzle that melts the filament, moves in both a horizontal and vertical direction as guided by the computer-aided design software, and deposits a layer of material that hardens immediately on extrusion. A separate water-soluble material is used for making temporary support structures while the manufacturing is in progress. The process is repeated layer by layer until the model is complete. Fused deposition modeling demonstrates excellent geometric accuracy because the
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The assistence of ultrasonic agitation.

The following cases illustrate how our laboratory has utilized physical models in preinterventional procedure planning.

Case 1: Congenital Muscular VSD

A 30-year-old man was referred for percutaneous closure of a congenital muscular VSD. A transeosophageal echocardiogram confirmed the presence of a VSD in the mid inferoseptal region with Doppler color flow consistent with bidirectional shunting. A cardiac CTA was performed to better assess the size and location of the VSD and demonstrated a large inferoseptal VSD measuring 14×12 mm. Rapid prototyping using the patient’s CTA as source image data was performed, generating a 3D physical model that clearly defined the VSD anatomy and spatial orientation to surrounding structures. On the basis of the physical model, it was thought that a 12-mm Amplatzer (AGA Medical, Golden Valley, Minn) muscular VSD occluder device would not interfere with aortic, mitral, or tricuspid valve function. Finally, placement of various catheters from the superior vena cava, inferior vena cava, and retrograde aortic approaches was simulated with the physical model used as a guide, revealing that the optimal approach to crossing the VSD (ie, minimizing catheter bending or kinking while maximizing utilization of the catheter’s primary and secondary bends) would be with a Judkins right-4 (JR-4) diagnostic catheter from the retrograde aortic approach (Figure 3A). The patient subsequently underwent an uncomplicated percutaneous VSD closure through the right internal jugular vein approach with the use of a 12-mm Amplatzer muscular VSD occluder device (Figure 3B and 3C).

Figure 3. Physical model application in a congenital muscular VSD. A, Mode of crossing the VSD (arrowhead) with a JR-4 diagnostic catheter via retrograde approach. B, Delivery catheter (arrow) pathway to the VSD (arrowhead) via the superior vena cava (SVC) approach. C, View from the right atrium (RA) into the right ventricle illustrating a prominent septal curvature (arrowheads) and subsequent Amplatzer muscular VSD occluder device orientation (arrow). Ao indicates aorta; PV, pulmonary vein; PA, pulmonary artery; LV, left ventricle; IVC, inferior vena cava; and LA, left atrium.

Preliminary Experience With Rapid Prototyping

Since beginning our exploration into the cardiovascular applications of rapid prototyping 10 months ago, we have produced 10 physical models based on CTA source images from adult patients referred for percutaneous procedures. The cases include the following diagnoses: post–myocardial infarction ventricular septal defect (VSD) with surgical patch dehiscence, unoperated post–myocardial infarction VSD, congenital muscular VSD, complex atrial septal defect (ASD), periprosthetic mitral valve leak, and acquired VSD after aortic valve replacement. We have also successfully created a physical model of a thoracic aorta in a patient with a large pseudoaneurysm and multiple aortic ulcerations requiring endovascular repair. The estimated processing time required to create an .stl file from CTA source image data varied greatly from 48 to 120 hours, although processing time decreased dramatically as experience with the development software increased. The average print time of each model on a Dimension 1200 series printer (Stratasys, Inc, Eden Prairie, Minn) employing fused deposition modeling was 60 hours.

The model is made of plastic (or in some cases metal), is extremely durable, and can be sterilized for use in the operative setting. Build times, however, are long (up to or beyond 24 hours, depending on the size of the object) and also involve the time-consuming process of removing the support structures in a heated sodium hydroxide solution with the assistance of ultrasonic agitation.

Multijet modeling or 3D printing (Z Corporation, Burlington, Mass) essentially works like a normal ink-jet printer but in 3D space. In this process, layers of fine powder (either plaster or resins) are selectively bonded by printing a water-based adhesive from the ink-jet printhead in the shape of each cross section as determined by the computer-aided design file. Each layer quickly hardens, and the process is repeated until the model is complete. 3D printing is generally recognized as the fastest additive method of rapid prototyping (with production times generally <7 hours, depending on the object’s size) and is the only technology that accommodates the printing of full-color prototypes. Compared with other additive methods (eg, selective laser sintering), however, 3D printing results in models that are generally less geometrically accurate, not as mechanically strong, and completely opaque.

In stereolithography, models are built through layer-by-layer polymerization of a photosensitive resin. A computer-controlled laser generates an ultraviolet beam that draws on the surface of a pool of resin stimulating the instantaneous local polymerization of the liquid resin in the outlined pattern. A movable platform lowers the newly formed layer, thereby exposing a new layer of photosensitive resin, and the process is repeated until the model is complete. Advantages (ie, high geometric accuracy) and disadvantages (ie, long build times, requirement of support structures, high cost) of stereolithography are similar to those seen in fused deposition modeling and selective laser sintering, although stereolithography offers the additional advantage of generating transparent models.
A post-VSD closure left ventricular angiogram demonstrated no evidence of left to right flow.

Case 2: Fenestrated ASD With Large Atrial Septal Aneurysm

A 50-year-old woman was referred for percutaneous ASD closure. A transesophageal echocardiogram confirmed the presence of an atrial septal aneurysm but also revealed the presence of multiple defects with predominately left-to-right shunting. Subsequent invasive evaluation with intracardiac echocardiography revealed multiple small fenestrations, a separate patent foramen ovale, and a bulging, aneurysmal septum, making full characterization of the anatomy difficult. A cardiac CTA revealed a 27×24-mm atrial septal aneurysm with multiple fenestrations and normal pulmonary vein anatomy. Rapid prototyping was performed with the patient’s CTA used as source image data, yielding a physical model that clearly illustrated both the atrial septal aneurysm bulging into the right atrium as well as the quantity, size, and spatial orientation of the septal fenestrations and patent foramen ovale. The model also showed that a 35-mm Amplatzer Cribriform device would successfully cover all fenestrations if its center waist was placed across the central-most fenestration. This central fenestration faced inferiorly and slightly to the left as opposed to the normal plane of secundum ASDs, which are typically oriented slightly inferiorly and rightward. By placing various catheters into the model, it was established that crossing the central fenestration would require an angulated catheter such as a JR-4 diagnostic catheter, which could be advanced toward the tricuspid valve and then turned upward to cross the defect (Figure 4A). Furthermore, because of the size of the aneurysm and the location of the central fenestration, it was anticipated that although device placement would not fully correct the bulging nature of the aneurysm, it also would not interfere with tricuspid valve inflow. The patient subsequently underwent an uncomplicated percutaneous closure procedure with the use of a 35-mm Cribriform occluder, catheter shapes, and navigation strategy as illustrated by the use of the physical model (Figure 4B).

Case 3: Prosthetic Mitral Valve Perivalvular Leak

A 72-year-old man was referred for percutaneous closure of a severe periprosthetic leak on the posteromedial aspect of a mitral valve bioprosthesis. A cardiac CTA was performed and revealed a 12×16-mm periprosthetic valvular defect. To better define the spatial orientation of the defect in regard to both surrounding anatomic structures and the prosthetic valve struts, rapid prototyping was performed with the patient’s CTA used as the source image data. Using the physical model as a guide, the operators determined that a transseptally placed delivery catheter would need to transverse a greater distance to cross the periprosthetic defect than it would need to cross the mitral valve alone. Furthermore, it was revealed that an acute angle would need to be negotiated to cross the defect. With the physical model used as a reference for device sizing, a 10-mm Amplatzer atrial septal occluder device was believed suitable to achieve defect closure without compromising surrounding anatomic or valvular structures and function. Placement of a sample device in the physical model revealed that the left ventricular disc would overlap the sewing ring and abut one of the struts of the bioprosthesis; however, it was determined that implantation of significantly larger devices would result in physical deformation of the left ventricular disc of the atrial septal occluder device (Figure 5). The patient subsequently underwent successful percutaneous closure of the periprosthetic defect with an 11-mm Amplatzer atrial septal occluder device that successfully covered the periprosthetic defect with immediate resolution of pulmonary vein flow reversal during systole. Immediately after the procedure, transesophageal echocardiography demonstrated a

Figure 4. Physical model application in a fenestrated ASD. A, View from the right ventricular (RV) apex through the tricuspid valve annulus (arrowheads) demonstrating the course and angulation of a JR-4 diagnostic catheter (arrows) required to cross the central-most defect on an aneurysmal interatrial septum. B, Close-up of the left atrial disc of an Amplatzer 35-mm Cribriform ASD occluder device (arrow) demonstrating no obstruction of the mitral valve annulus (arrowheads). Ao indicates aorta; LV, left ventricle; and PV, pulmonary veins.

Figure 5. Physical model view from the left ventricular (LV) lateral wall of an Amplatzer atrial septal occluder device (arrow) through a prosthetic mitral perivalvular defect. The physical model demonstrated that placement of an occluder device would not interfere with adjacent prosthetic valve struts (arrowheads). RV indicates right ventricle.
broad, low-velocity, residual “splay” of color Doppler flow through the device.

After the procedure, however, the patient developed transfusion-requiring hemolysis and pigment-induced nephropathy with renal failure. This rare complication has been reported in isolated cases of percutaneous VSD closure with Amplatz devices.25 The patient subsequently underwent an uncomplicated surgical defect repair that involved sewing a Gore-Tex patch over the left atrial side of the existing Amplatz device, leading to complete resolution of pigment-induced nephropathy.

Case 4: Thoracic Aortic Pseudoaneurysm and Ulcerations
A 69-year-old man underwent a high-resolution CT scan revealing a large paramediastinal mass that was thought to be either a saccular aortic aneurysm or a parenchymal mass. A subsequent CT aortogram confirmed the presence of a large left-sided superior mediastinal mass that most likely represented focal aortic rupture with pseudoaneurysm formation and a contained hematoma. Multifocal penetrating aortic ulcers involving both the mid and distal segments of the thoracic aorta were noted as well (Figure 6A). Rapid prototyping using the patient’s CT aortogram as source image data was performed, generating a 3D physical model that delineated both the number and locations of the aortic pseudoaneurysm and ulcerations as well as the diffuse and irregular contour of the descending thoracic aorta consistent with scattered foci of calcified plaque. The patient subsequently underwent an uncomplicated placement of a 31-mm-diameter by 15-mm-length Gore TAG thoracic endoprosthesis (W.L. Gore and Associates, Newark, Del) covering both the origin of the pseudoaneurysm and the proximal and mid thoracic aortic ulcerations (Figure 6B).

Current Limitations
A potential barrier to the widespread acceptance of using this evolving technology in the management and treatment of cardiovascular disease is the limited ability to study the presumed improved clinical outcomes by using physical models in a randomized, controlled fashion. To date, our description of the utility of rapid prototyping has been limited to anecdotal case studies, although we have utilized the technology in both very complex (ie, percutaneous VSD closure after failed surgical patch repair) and unique clinical circumstances (ie, percutaneous closure of a prosthetic perivalvular defect), with each case presenting an array of technical challenges not addressed by its predecessor. In addition, although we have thus far evaluated the utility of physical models by comparing their use with retrospective assessments of anecdotal cases not involving the use of physical models, we acknowledge that using historical controls as a basis for comparison is itself a source of controversy because it is often difficult to account for specific variables such as operator learning curves.

Our preliminary experience with rapid prototyping has been promising and indicates that the creation of physical models from CT source image data using rapid prototyping technology is feasible and valuable from both educational and procedural perspectives. Although our research laboratory has thus far exclusively used CT source image data for rapid prototyping, we have since begun investigating the feasibility of utilizing the same processing algorithm with MRI source image data. In the future, we anticipate applying the same principles discussed in this review to a broader array of imaging modalities including MRI and 3D echocardiography. Finally, given that cardiovascular rapid prototyping remains an evolving technology currently in the early developmental stages, its access remains limited to a select number of research facilities worldwide. As our understanding of both rapid prototyping and its applications in cardiovascular medicine continue to evolve, however, we anticipate that rapid prototyping will one day be as readily available as are current imaging modalities to all practitioners evaluating and treating patients with heart disease.

Conclusion
Advances in medical imaging and device technology are changing the way in which physicians are approaching the
care of patients with structural heart disease. This new technology review discusses the continued evolution of rapid prototyping technology and provides an initial experience with anecdotals of the manner in which rapid prototyping can be used in the care of patients with structural heart disease.

The clinical ramifications of rapid prototyping in structural heart disease are widespread. As described earlier, physical models allow surgeons and interventional cardiologists to appreciate potential procedural difficulties, assess the likelihood of success or failure, and select appropriate equipment and devices for use. From an industrial perspective, patient-specific physical models may be of particular value in the preclinical development of new medical devices by accurately portray spatial relationships and device/anatomy fitting in a spectrum of diseased hearts from patients who could be candidates for the new treatment. They may also be used in the analysis of procedural failures and adverse events, as well as in the training of investigators and clinicians after device approval. Finally, by allowing information to be conveyed in both visual and tactile forms, rapid prototyping exhibits limitless promise on an educational level. By enhancing the anatomic and pathological understanding of cardiac defects and helping to clarify the aims and limitations of corrective surgery and percutaneous procedures, physical models can enrich patients’, students’, and physicians’ understanding of structural heart disease with the ultimate result of enhancing the level of care provided to this growing subset of adult patients.

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Disclosures

None.

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