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AMPLIFYING ART OF VALVE DESIGN BY SCIENCE

To the Editor:

Percutaneous pulmonary valve implantation has become one of the most promising surgical strategies for performing dysfunctional right ventricle–pulmonary artery continuity reconstruction. Size limitations of the currently available valves for percutaneous pulmonary valve implantation application, however, hinder the treatment of many patients.¹ Kan and colleagues² have proposed a design for handmade trileaflet-valved conduits with minimal size restriction and developed a tool to be used by surgeons to obtain optimal parameters before operation.

Such handmade expanded polytetrafluoroethylene (ePTFE) trileaflet conduits have been implanted in the pulmonary position since 1997 and have shown acceptable functional durability and expected performance, maintaining valve motion for as long as 10 years.³ Kan¹ further used the commercialized stent graft as the scaffold for compositing handmade trileaflet ePTFE valved conduits. Major vendors recommend selecting an oversized (10%-20%) stent graft to avoid later migration.¹ The diameter of the valve root, D' , determined by computed tomography or magnetic resonance imaging and the commissural coaptation height, H_1 , of the free edge of the valve leaflet are the only 2 parameters with which surgeons must be concerned (Figure 1, A).¹ Once determined, a thin ePTFE membrane is trimmed into a semilunar tricuspid shape.¹ Hammer and del Nido⁴ disclosed valuable information: the free edge of a single leaflet

is both stretched and pulled downward from the commissures at peak diastole; this note inspired us to reconsider the possible influence from height adjustment of the free edge.

From stress-stretch study⁵ and published anatomic study,⁶ while the aortic leaflet and attachment stresses reach maximum values at valve closure, the downward angle of the free edge, ϕ (Figure 1, B), has been reported to be approximately 35°, and ϕ decreased from 34° to 24° when diastolic pressure increased from 80 mm Hg to 120 mm Hg. The ePTFE trileaflet conduits implanted in the pulmonary position should have a similar yet smaller angle change. The commissural coaptation height (H_1) of the free edge of the valve leaflet should therefore be adjusted significantly to have adequate commissural surface to prevent pulmonary regurgitation. Accordingly, in Kan's design, a jotting template of a handmade leaflet consists of geometric parabola details, including lower curved line, C_1 , and upper curved line, C_2 . In terms of valve leaflet opening (Figure 1, C), an endoscope inspection camera was deployed into a mock circulation loop, mounted with either a tissue valve (Epic; St. Jude Medical Inc, St Paul, Minn) or an ePTFE-valved conduit, to monitor valve motion. The video clips clearly showed that the trileaflet ePTFE-valve conduit's performance was not inferior to that of the commercial tissue valve.² The computer-aided design procedure developed by Kan and colleagues¹ in the article sheds light on the quantitative method to be the bridge from 2-dimensional handcrafted art to 3-dimensional computer-aided design science.

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FIGURE 1. Handmade trileaflet valve design and its clinical application. A, Optimal design procedure. B, The downward angle of the free edge, ϕ . C, Comparison of a tissue valve (Epic; St. Jude Medical Inc, St Paul, Minn) and an expanded polytetrafluoroethylene valved conduit in the cardiac cycle.

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INNOVATION AND SCIENCE: THE FUTURE OF VALVE DESIGN

Reply to the Editor:

Designing semilunar valves in children has been a constantly evolving and at the same time challenging field for both the clinicians and the engineers involved. Recent approaches embraced include analytic methods based on engineering principles promising a more scientific and precision-based approach. This requires a solid understanding of the precise mechanisms of normal valve operation, but superimposed on this is the constantly changing environment of the valve due to the growing child, a change of hemodynamics, or a disease process that evolves over time.

This article by Chen and colleagues¹ is another example of attempting to advance the science of designing valves using an analytic approach and engineering principles for which they need to be congratulated. They used a commercial stent graft as the scaffold for compositing handmade tri-leaflet expanded polytetrafluoroethylene valved conduits.

The work by Chen and colleagues¹ takes steps toward understanding the relationship between the 2-dimensional shape of the valve leaflets and the closed and loaded 3-dimensional shape of the valve for a given material using a computer-aided design. Understanding this relationship is essential for developing a repeatable procedure for valve reconstruction that achieves predictable valve function postoperatively. On the other hand, achieving predictable long-term valve function requires an understanding of several more complicated relationships. For example, the range of normal working stresses in the reconstructed valve and adjacent tissues must be known and related to the loads at which these materials and tissues fail. We are just beginning to compare the working stresses in the reconstructed valve with the stresses at which valve reconstruction materials fail,² although this work just scratches the surface. Tissue stresses are also hypothesized to drive long-term biological responses, such as calcification and fibrosis, to valve reconstruction materials. Considerable work lies ahead to quantify these relationships so that they can be used to directly drive design. Finally, in the pediatric patient, repairing a valve with long-term durability requires

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understanding of and strategy for accommodating patient growth. Several preliminary concepts have been proposed to address the challenge of growth accommodating valve repair,^{3,4} but, again, much work remains to be done.

Pushing the frontiers in valve reconstruction requires both innovation and application of science, analytic methods, and engineering principles, combined with an understanding of the way the tissues and materials used behave over time. The final test of such designs still remains the human body itself and the unique ways it handles both the design of such valves and the tissues of which they are composed. Although clinicians, surgeons, and engineers have pushed the frontiers in this field, it is the harmonious and synergistic efforts of all that will push the field to the next level and the future of precision designed medicine.

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