Journal of Biomechanics 39 (2006) 2665–2672

JOURNAL OF BIOMECHANICS

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Geometric modeling of functional trileaflet aortic valves: Development and clinical applications

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Accepted 19 August 2005

Abstract

The dimensions of the aortic valve components condition its ability to prevent blood from flowing back into the heart. While the theoretical parameters for best trileaflet valve performance have already been established, an effective approach to describe other less optimal, but functional models has been lacking. Our goal was to establish a method to determine by how much the dimensions of the aortic valve components can vary while still maintaining proper function. Measurements were made on silicone rubber casts of human aortic valves to document the range of dimensional variability encountered in normal adult valves. Analytical equations were written to describe a fully three-dimensional geometric model of a trileaflet valve in both the open and closed positions. A complete set of analytical, numerical and graphical tools was developed to explore a range of component dimensions within functional aortic valves. A list of geometric guidelines was established to ensure safe operation of the valve during the cardiac cycle, with practical safety margins. The geometry-based model presented here allows determining quickly if a certain set of valve component dimensions results in a functional valve. This is of great interest to designers of new prosthetic heart valve models, as well as to surgeons involved in valve-sparing surgery.

Keywords: Aortic valve; Dimensions; Geometric modeling; Valve-sparing operation

1. Introduction

The aortic valve is located between the left ventricle of the heart and the aorta, which distributes blood to the whole body. The aortic valve is made of three moving flaps called leaflets that come together in the center of the valve to close it. The leaflets are attached inside a conduit, the base of the aorta called the aortic root. The aortic root balloons out around the leaflets' attachments, creating the three aortic sinuses (Fig. 1). It is well recognized that the geometry of the aortic valve has an important bearing on its ability to carry out its function, namely, to prevent the blood ejected into the aorta from flowing back to the left ventricle (Kunzelman et al., 1994). Furukawa et al., 1999 recently demonstrated that the dilation of the aortic root could lead to valve leakage (insufficiency), as the leaflets become too small to close the valve.

The geometry of the aortic leaflet in particular and the aortic valve in general has received considerable attention (Swanson and Clark, 1974; Trenkner et al., 1976; Mercer et al., 1973). Thubrikar (1990) explored the design of trileaflet valves such as the aortic valve to ensure optimal performance. Specifically, geometric criteria were defined to guarantee appropriate sealing (coaptation) of the leaflets in closed position, a proper valve height-to-diameter ratio to minimize dead space, no folds in the leaflets and minimum leaflet flexion to

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doi:10.1016/j.jbiomech.2005.08.012

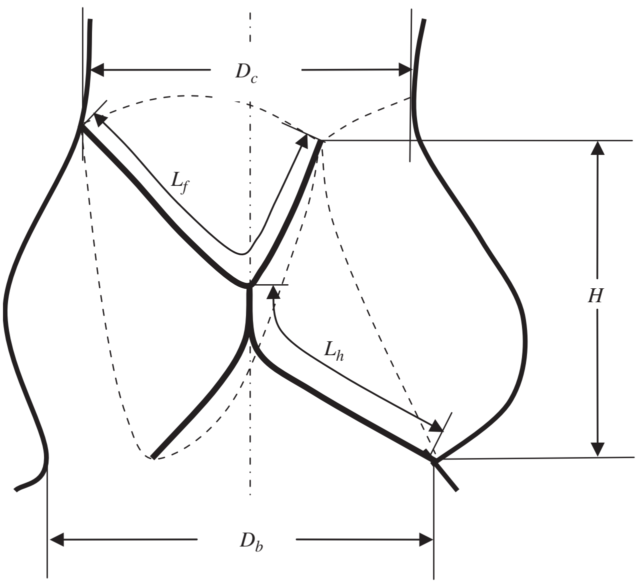

Fig. 1. Drawing of the aortic valve showing the side view of one leaflet. D_b: diameter of the base, D_c: diameter of the commissures, H: valve height, L_f: leaflet free-edge length, L_h: leaflet height.

make the use of energy as efficient as possible. Following this approach, given say the diameter at the base of the valve, one valve geometry satisfies the criteria chosen for optimization. This framework provides extremely valuable insight but is somewhat too rigid to accommodate the dimensional variability observed in normally functioning valves (Swanson and Clark, 1974).

Cardiac surgeons have long recognized the importance of scaling valve design to suit their specific needs, especially when they wish to restore functional dimensions in a patient's leaky valve, in the so-called valve-sparing procedure (David, 2002). Yet, as the variability in valve design has not been properly elucidated and described in a model, only master surgeons dare attempt valve sparing in spite of its numerous advantages over valve replacement. Therefore, the basic question as to what dimensions of the valve components are safe and acceptable is still open and deserves a second look. This is also a natural complement to the considerable efforts currently devoted towards the development of new polymers and engineered tissues for more efficient and longer lasting prosthetic valves.

A direct geometric approach to address the problem would be to use computer-assisted design (CAD) programs to establish if a given set of dimensions does result in a valve that can effectively open and close. However, this turns out to be a lengthy and demanding process, because the Boolean operations involved in the geometric construction of the valve combine poorly with parameterization, and make it counter productive for the study of a wide range of dimensions.

The objective of the present study was to propose alternative tools for the geometric analysis of trileaflet valves such as the aortic valve. First, in order to document the dimensional variability observed in normally functioning human aortic valves, measurements were made from silicone rubber molds of normal human adult aortic valves. Then, to incorporate dimensional variability in geometric modeling, an analytical approach was adopted to implement basic design principles and determine which dimensions are satisfactory and which are not. The equations developed were implemented in an easy-to-use computer program. Finally, parameterized visualization tools were developed to represent the three-dimensional geometry of the valves and confirm their adequacy.

2. Methods

2.1. Geometry and assumptions

Geometric modeling of a complex structure such as the aortic valve calls for simplifying assumptions to make the approach tractable. First, it is assumed that the three leaflets are identical in size and properties, and lie at 120° from each other in the circumferential direction of the valve. Fig. 1 shows a longitudinal cross-section of the aortic valve in closed position, with a side view of one leaflet to the right. Represented are the primary parameters that can be used to define the valve dimensions: D_b, the diameter of the base; D_c, the diameter of the top of the commissures—the aortic root wall regions where two leaflets insert side-by-side along parallel lines; H, the valve height; L_f, the leaflet free-edge length and L_h, the leaflet height. It is hypothesized that the planes going through the base of the valve and the top of the commissures are parallel. Most importantly, it is further considered that the dimensions of the valve components do not change significantly enough during the cardiac cycle that their variation should be accounted for in a first-order analysis.

2.2. Dimensional measurements in human aortic valves

To quantify the dimensional variability observed in normally functioning human aortic valves, measurements were made from silicone rubber molds of 15 normal human adult aortic roots cast at 80 mmHg pressure, with the valves in closed position. The cryopreserved roots were provided by tissue bank Lifenet (Virginia Beach, VA) and were available for other ongoing studies at the Heineman laboratory. Dimensions D_b, D_c and the aortic sinus height (which varies similarly to H in normal valves) were measured directly from the molds, while L_f and L_h were measured after the sinus-leaflet units were cut away from the aortic