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# Ventriculo-aortic junction in human root. A geometric approach☆

Nil Grousson*, Khee-Hiang Lim, Hou-Sen Lim, Ean-Tat Ooi, Sidney L.H. Salgues, Joon-Hock Yeo, Wolfgang A. Goetz

*Physiological Laboratory, School of Mechanical and Aerospace Engineering, Nanyang Technological University, Block N3.1-B2a-01, 50 Nanyang Avenue, Singapore 639798, Singapore*

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**Abstract**

With advances in tissue engineering and improvement of surgical techniques, stentless biological valves and valve-sparing procedures have become alternatives to traditional aortic valve replacement with stented bioprostheses or mechanical valves. New surgical techniques preserve the advantages of native valves but require better understanding of the anatomical structure of the aortic root. Silicone rubber was injected in fresh aortic roots of nine human cadavers under the physiological closing pressure of 80 mmHg. The casts reproduced every detail of the aortic root anatomy and were used to digitize 27 leaflet attachment lines (LALs) of the aortic valves. LALs were normalized and described with a mathematical model. LALs were found to follow a pattern with the right coronary being the largest followed by the non-coronary and then the left coronary. During diastole, the aortic valve LAL can be described by an intersection between a created tube and an extruded parabolic surface. This geometrical definition of the LAL during end diastole gives a better understanding of the aortic root anatomy and could be useful for heart valve design and improvement of aortic valve reconstruction technique.


*Keywords:* Anatomy; Mathematical model; Aortic valve; Sinus of Valsalva; Geometrical construction

## 1. Introduction

In recent years, there has been a trend towards stentless biological valves (Silberman et al., 1998; Williams et al., 1999; Doss et al., 2005) and valve-sparing procedures (David et al., 2001; Hopkins, 2003). The intention is to create a more physiological valve substitute allowing dynamic root expansion during the systolic phase of the cardiac cycle while maintaining physiological fluid dynamics.

Although the stentless bioprostheses are attached directly to the aortic annulus to overcome stent related problems such as leaflet calcification (Thubrikar et al., 1983) and non-physiologic blood flow pattern (Marquez et al., 2001), they present a new problem for valve designers. With the absence of a scaffold, the stentless prostheses must closely match the native Sinus of Valsalva and annulus. Close matching is important to avoid distortion of the leaflets and is critical for valve functioning. Therefore, the leaflet attachment line (LAL) is an area of special interest for valve designers and cardiac surgeons performing valve-sparing procedures.

Although many studies (Mercer et al., 1973; Swanson and Clark, 1974; Thubrikar, 1989; Choo et al., 1999) from the early seventies to the present investigated the geometry of the aortic valve structure, most of them focused exclusively on the geometry of the leaflet body and the Sinus of Valsalva. Only a few studies described the aortic LAL. Thubrikar (1989) postulated that the leaflet–sinus assembly fuses in a circular shape, while Swanson and Clark (1974) described it as an intersection of the cylindrical contour of the leaflet with a flat plane forming an ellipsoidal shape. This implies that the attachment profile is elliptical. However, a similar analysis by Mercer et al. (1973) concluded that the profile is parabolic. All these

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*Corresponding author. Tel.: +65 67905500; fax: +65 67924062.
*E-mail addresses:* nil_grousson@yahoo.fr (N. Grousson), mjhyeo@ntu.edu.sg (J.-H. Yeo).

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**Nomenclature**

LAL leaflet attachment line
$\phi_c$, $\phi_b$ commissural and basal diameters
$\pi_c$, $\pi_b$ commissural and basal planes
$\alpha_{bc}$ aortic root tilting angle
$\pi_{ni}$ $(i = n, r, l)$ (i.e. $\pi_{nn}$, $\pi_{nr}$, $\pi_{nl}$) perpendicular leaflet planes ($\pi_{ni} \perp \pi_c$)
$\beta_{ij}$ $(i,j = n, r, l;\ i \neq j)$ (i.e. $\beta_{nr}$, $\beta_{rl}$, $\beta_{ln}$) angles between $\pi_{ni}$ and $\pi_{nj}$
$\pi_i$ $(i = n, r, l)$ (i.e. $\pi_n$, $\pi_r$, $\pi_l$) LAL tilting planes
$M_i$ $(i = n, r, l)$ (i.e. $M_n$, $M_r$, $M_l$) lowest point of a LAL
$\alpha_i$ $(i = n, r, l)$ (i.e. $\alpha_n$, $\alpha_r$, $\alpha_l$) LAL tilting angle
$\angle$ angle
$\cap$ intersection
$(O, XYZ)$ or $(O, XY)$ Cartesian coordinate system in reference to $\phi_c$
$W_i$ $(i = n, r, l)$ (i.e. $W_n$, $W_r$, $W_l$) commissural width
$H_i$ $(i = n, r, l)$ (i.e. $H_n$, $H_r$, $H_l$) Sinus of Valsalva height
$C_i$ $(i = n, r, l)$ (i.e. $C_n$, $C_r$, $C_l$) circle matching the projection of the LAL
$r_i$ radius of circle $C_i$
$\text{Cyl}_i$ $(i = n, r, l)$ (i.e. $\text{Cyl}_n$, $\text{Cyl}_r$, $\text{Cyl}_l$) constructed cylinder passing through $C_i$
$c_i$ distance between $\text{Cyl}_i$-axis and inter-commissural axis
$\theta_i$ first angle leading the coordinate system transformation
$\varphi_i$ second angle leading the coordinate system transformation
$\zeta_i$ $\alpha_i + \theta_i$, orientation of the tube in relation to the plane $\pi_i$
$F_i$ $(i = n, r, l)$ (i.e. $F_n$, $F_r$, $F_l$) function of the LAL projection curve fitting

early studies assumed that all sinuses of the aortic root were of the same size and omitted considerations of aortic root asymmetry. Later, it has been shown that the aortic root is asymmetrical with the non-coronary sinus volume and height, being bigger than the right and then the left (Choo et al., 1999).

New insights into the importance of anatomic asymmetry of the aortic root emphasize the need to give a precise and reproducible description of the asymmetric LAL in human.

## 2. Method

Nine fresh (within 24 h after death) human aortic roots (Malay cadavers, $36 \pm 5$ years, two women, seven men, height $170 \pm 15$ cm, weight $76 \pm 28$ kg, body surface area $1.878 \pm 0.552\,\text{m}^2$) were provided by Singapore Mortuary @ HSA (Centre for Forensic Medicine, Health Sciences Authority, Singapore). The use for research was approved by Singapore General Hospital Committee. Soft silastic E RTV silicone rubber (Dow Corning Corporation Midland, MI, USA) was injected into the aortic root with the aortic leaflets closed at a pressure of 80 mmHg. These silicone rubber casts were then copied to hard SG95 resin casts (MCP-HEK Tooling Gmbh, Frankfurt, Germany) to eliminate error due to user-related pressure variations on the probe while digitization of the soft rubber casts.

### 2.1. Digitization of the LAL

Casts were digitized using a FARO Arm 3D digitizer (FARO Technologies Inc., Lake Mary, FL, USA) to obtain nine 3D coordinates for each LAL at all three sinuses (non-coronary, right coronary and left coronary). Each LAL was digitized three times using the FARO Arm and the points obtained from each LAL were averaged. The 3D B-spline curves were plotted through the averaged points, using Surfacer (Imageware Inc., Ann Arbor, MI, USA). The point data were merged using 3D CAD modeling software, Pro/Engineer (Parametric Technology Corporation, Waltham, MA, USA).

### 2.2. Processing of the LAL

Commissural and basal diameters (respectively, $\phi_c$ and $\phi_b$, Fig. 1 and Table 1) were measured by constructing two circles, one at the commissural level (passing through the highest point of the LAL) and the other one at the base of the aortic root (passing through the lowest points of the LAL and $M_i$, Fig. 1). Diameters were confirmed by direct

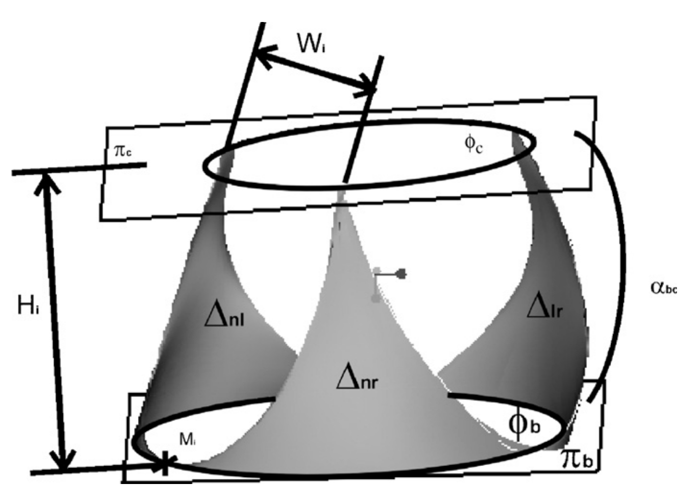


Fig. 1. Commissural and basal diameters $\phi_c$ and $\phi_b$ and the reference planes $\pi_c$ and $\pi_b$. Inter-leaflet triangle between left- and right- ($\Delta_{lr}$), inter-left-leaflet triangle between non- and left- ($\Delta_{nl}$) and inter-leaflet triangle between non- and right-coronary sinus ($\Delta_{nr}$). The angle $\alpha_{bc}$ between the two reference planes $\pi_c$ and $\pi_b$. Lowest point of a LAL ($M_i$), commissural width ($W_i$) and Sinus of Valsalva height ($H_i$).