Surgical Anatomy of the Aortic Valve and Root

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## Disclosure

<table>
<thead>
<tr>
<th>Company</th>
<th>Role</th>
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<tbody>
<tr>
<td>Medtronic, Inc</td>
<td>PI Clinical Trials</td>
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<td>WL Gore &amp; Associates</td>
<td>PI Clinical Trials</td>
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<td>Bolton Medical</td>
<td>PI Clinical Trials</td>
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Understanding AV and Root Geometry

\[ \tan \left( \frac{\alpha + \theta}{2} \right) = \frac{H - H_s}{\frac{R_c}{2}} = a \; ; \; \alpha + \frac{\theta}{2} = \tan^{-1} a \]

\[ \theta + \alpha = 90 + \beta \]

\[ \theta = 90 + \beta - \tan^{-1} a \]

\[ \beta = 180 + 2\beta - 2\tan^{-1} \left( \frac{H - H_s}{\frac{R_c}{2}} \right) \]

\[ X_s = AB - AC \]

\[ \cos \alpha = \cos \left( 90 + \beta - \theta \right) \]

\[ = \cos \left( 90 + \beta - 180 - 2\beta + 2\tan^{-1} a \right) \]

\[ = -\sin \left( \beta - 2\tan^{-1} a \right) \]

\[ X_s = \frac{H}{\cos \beta} + \frac{R_b}{\sin \beta} - 2\tan^{-1} \left( \frac{H - H_s}{\frac{R_c}{2}} \right) \]

\[ \left( \frac{L_d}{2} \right)^2 = R_c^2 + \left( \frac{R_c}{2} \right)^2 \]

\[ L_d = 2 \cdot R_c^2 + \frac{R_c}{2} \]

\[ L_s = \frac{H - X_s - CF}{2} \]

\[ CF = R_b \tan \alpha \]

\[ = R_b \left( 90 + \beta - \theta \right) \]

\[ = R_b \left( 90 + \beta - 180 - 2\beta + 2\tan^{-1} a \right) \]

\[ = R_b \left( 2\tan^{-1} a - \beta - 90 \right) \]

\[ L_d = 2 \cdot R_c^3 + \left( \frac{H - X_s - R_b \tan \alpha}{\frac{R_b}{2}} \right) \left( \frac{H - H_s}{\frac{R_c}{2}} \right) - \left( \beta - 90 \right)^2 \]

\[ \frac{R}{\sin \theta} = \frac{R_c}{\sin 2\theta} \]

\[ L_s = 2 \pi R \cdot \left( \frac{360 - 4\gamma}{360} \right) \]

\[ \frac{R}{\sin \theta} = \frac{R_c}{\sin 2\theta} \]

\[ \tan \gamma = \frac{\frac{R_c}{2} \left( 90 + \beta - \theta \right)}{R_b + H \tan \beta - \frac{R_c}{2}} \]

\[ \gamma = \tan^{-1} \left( \frac{R_c}{2 \cdot R_b + 2H \tan \beta - \frac{R_c}{2}} \right) \]

\[ L_s = \frac{\left( \frac{R_c}{R_b} \right) - 2\tan^{-1} \left( \frac{R_s}{2 \cdot R_b + 2H \tan \beta - \frac{R_c}{2}} \right)}{2 \tan^{-1} \left( \frac{R_c}{2 \cdot R_b + 2H \tan \beta - \frac{R_c}{2}} \right)} \]

Understanding AV and Root Geometry
RIDICULOUS

The Aortic Root

A Dynamic Structure
5 Key Components:

- Sino-Tubular Junction
- Sinuses of Valsalva
- Annulus
- Sub Aortic Segment
- Aortic Leaflets
What is the definition of aortic root?

Root extends from the basal attachments of the aortic valve leaflets (green line) to the sinutubular junction (blue line).
Surgical Anatomy

- Aortic root is anchored between the pulmonary root anteriorly and mitral and tricuspid posteriorly.
- Fibrous skeleton of the heart.

Diastole shown

Carpentier’s Reconstructive Valve Surgery Ch 5, 2010
Aortic Root: Crown and 3 “Rings”

1: Sinutubular Junction

2: Anatomic ventriculo-aortic junction

3: Virtual basal ring “echo” annulus

“Crown” formed by attachment of semilunar valve leaflets

Slide courtesy of Nicolo Piazza, MD
Anderson MMCTS 2006
Sinuses of Valsalva

- Membranous septum
- Posteromedial trigone
- Mitral valve
- Anterolateral trigone
- Aorto-mitral curtain
Annulus

Scallop-shaped fibrous structure attached to the trigones the aorto- mitral curtain and the muscular and membranous septa.
Aortic Root Function

Early systole  Late systole  Diastole
Sinuses of Valsalva

Collagen $\rightarrow$ Elastin

- More collagen at base
- Progressive increase in elastic lamellae superiorly as approach sinutubular junction
Sinuses of Valsalva

- When pressurized, the sinutubular junction is larger than that of annulus
  - 1 : 1.3 ratio of diameters
- When not under pressure, the annulus is larger than sinutubular junction
  - 1 : 1.15 ratio of diameters
“The aortic sinuses have no effective on valve competence, but are important in reducing mechanical stress on the aortic cusps during the cardiac cycles by creating eddies and currents between the cusps and the sinus walls.”

T. David Nat. Rev. Cardiol 2013

Furukawa ATS 1999
Bellhouse Nature 1968
De Paulis ATS 2001
Aybek JHVD 2005
Sinuses of Valsalva
Sinuses of Valsalva

- Sinotubular junction
- Sinus of Valsalva
- Annulus
Force (stress) = Pressure \times Area
Vertical Force Equilibrium

\[ A = \pi r^2 \]

\[ p(\pi r^2) = \sigma_1(2\pi r t) \]

\[ \sigma_1 = \frac{pr}{2t} \]
The Sinuses of Valsalva

<table>
<thead>
<tr>
<th>Coronary Artery Positions</th>
<th>Distance from nadir (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right coronary sinus</td>
<td>18.8 (1.8) * Largest</td>
</tr>
<tr>
<td>Non-coronary sinus</td>
<td>17.4 (1.9) *</td>
</tr>
<tr>
<td>Left coronary sinus</td>
<td>15.2 (1.8) * Smallest</td>
</tr>
</tbody>
</table>

Coronary ostia positions. Distances from nadir in millimeters From A. Carpentier
# Aortic Root: Coronary Ostia

## Considerable Variation

<table>
<thead>
<tr>
<th></th>
<th>LCA</th>
<th>RCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-Mortem (n=51)</td>
<td>12.6 ± 2.6 mm</td>
<td>13.2 ± 2.6 mm</td>
</tr>
<tr>
<td>Arq Bras Cardio 2003;81:359</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSCT (n=169)</td>
<td>14.4 ± 2.9 mm</td>
<td>17.2 ± 3.3 mm</td>
</tr>
<tr>
<td>JACC Img 2008;1:321-330</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angiography (n=63)</td>
<td>13.6 ± 2.2 mm</td>
<td>15.7 ± 2.3 mm</td>
</tr>
<tr>
<td>Rotterdam experience</td>
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</table>

Nicolo Piazza, MD Anderson MMCTS 2006
Sub Aortic Segment

- Left coronary artery
- Right coronary artery
- Membranous septum
- Non-coronary sinus
- Mitral valve
- Tricuspid valve
- AV node
- Left bundle branch
- Right fibrous trigone
Valve Leaflet Properties

- Fibrous core (spongiosa and fibrosa) covered by fibroelastic layer on arterial and ventricular sides
- Less elastin than ascending aorta but surprisingly elastic
- Loose gelatinous layer, the spongiosa, is sandwiched by two fibrous layers
- Permits folding & unfolding

Ventricularis → Preload
Compliant, dense sheet of elastic fibers

Fibrosa → Tensile Strength
Circumferentially oriented collagen fibers

Spongiosa → Flexibility
Loose connective tissue: permits “shearing”

Vesely · J Biomechanics 1998 [Image]
Tseng · Acta Biomaterialia 2011
Anatomic Variants

1. Unicuspid

2. Bicuspid

3. Quadricuspid

4. Penticuspid

Images: Rubin EJCTS 2009

Godefroid Eur J Echo 2006

Wang 2010 ATS
Range of Morphology: Leaflets

Equal cusps & commissures

Unequal cusps & Equal commissures

Unequal commissures & cusps

Roberts Circulation 1970; 42: 91-97
Aortic Valve Disease

**Stenosis**
Most prevalent AV disease
2% of persons > 65 yrs have frank disease
Carabello Lancet 2009

Calcification  Rheumatic  Congenital

**Regurgitation**
~5 per 10,000 persons per yr
Medline

Dilated root may also dissect
~3 per 10,000 persons per yr
Hagan JAMA 2000
## Functional Classification: Aortic Regurgitation

<table>
<thead>
<tr>
<th>AI Class</th>
<th>Type I</th>
<th>Type II</th>
<th>Type III</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Normal cusp motion with FAA dilatation or cusp perforation</td>
<td>Cusp Prolapse</td>
<td>Cusp Restriction</td>
</tr>
<tr>
<td></td>
<td>Ia</td>
<td>Ib</td>
<td>Ic</td>
</tr>
<tr>
<td>Mechanism</td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
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### Repair Techniques

<table>
<thead>
<tr>
<th>Repair Techniques (Primary)</th>
<th>STJ remodeling</th>
<th>Aortic Valve sparing: Reimplantation or Remodeling with SCA</th>
<th>Patch Repair</th>
<th>Prolapse Repair</th>
<th>Leaflet Repair</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ascending aortic graft</td>
<td>Reimplantation or Remodeling with SCA</td>
<td>SCA</td>
<td>Plication Triangular resection Free margin Resuspension Patch</td>
<td>Shaving Decalcification Patch</td>
</tr>
<tr>
<td>(Secondary)</td>
<td>SCA</td>
<td>STJ Annuloplasty</td>
<td>SCA</td>
<td>SCA</td>
<td>SCA</td>
</tr>
</tbody>
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- FAA=functional aortic annulus
- STJ=sinutubular junction
- SCA=subcommissural annuloplasty

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de Kerchove and El Khoury ACS 2013
Bicuspid Aortic Valves

- Most common congenital cardiovascular defect
- 0.9% to 2% prevalence
  - 3-6 million US citizens
  - Males affected 4:1
- Genes involved include *NOTCH 1* and *ACTA2*
- Majority of BAV patients develop complications over time
  - Stenosis, regurgitation, or both
  - Aortic dilatation/dissection possible
- Cause of about 50% of adult aortic valve stenosis
- Dilatation of aorta not uncommon
  - Responsible for more morbidity and mortality than all other congenital disorders combined

“crown” shape of bicuspid (top) differs from normal tricuspid (bottom) shape
Valve Opening: 2-cusp vs 3-cusp

Robicsek, Ann Thorac Surg 2004
Circumference = $2 \pi r \approx 6r$
Sievers Classification of Bicuspid Aortic Valves

- **Type O: No Raphe**
- **Type 1: 1 Raphe**
- **Type 2: 2 Raphes**

<table>
<thead>
<tr>
<th>main category: number of raphes</th>
<th>lat</th>
<th>ap</th>
<th>L - R</th>
<th>R - N</th>
<th>N - L</th>
<th>L - R / R - N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. subcategory: spatial position of cusps in Type 0 and raphes in Types 1 and 2</td>
<td>13 (4)</td>
<td>7 (2)</td>
<td>216 (71)</td>
<td>45 (15)</td>
<td>8 (3)</td>
<td>14 (5)</td>
</tr>
<tr>
<td>2. subcategory: Valvular Function</td>
<td>I</td>
<td>S</td>
<td>B (I + S)</td>
<td>No</td>
<td></td>
<td></td>
</tr>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 (2)</td>
<td>1 (0.3)</td>
<td>79 (26)</td>
<td>22 (7)</td>
<td>3 (1)</td>
<td>6 (2)</td>
</tr>
<tr>
<td></td>
<td>7 (2)</td>
<td>5 (2)</td>
<td>119 (39)</td>
<td>15 (5)</td>
<td>3 (1)</td>
<td>6 (2)</td>
</tr>
<tr>
<td></td>
<td>1 (0.3)</td>
<td>15 (5)</td>
<td>7 (2)</td>
<td>2 (1)</td>
<td>2 (1)</td>
<td></td>
</tr>
</tbody>
</table>

Sievers 2007; 304 Surgical specimens and OR collected over 5 years
Fazel/Miller Classification

BAV Aortopathy

13% Aortic Root
14% Tubular Aorta
28% Tubular Aorta/Arch
45% Diffuse

64 patients from surgical and radiological databases; 4 clusters of aortopathy observed

Fazel 2008 JTCVS
Bicuspid aortic valve is the most common congenital heart defect in adults, affecting 1.3% of the population worldwide, and is responsible for more deaths and complications than the combined effects of all the other congenital heart defects. Although aortic stenosis and regurgitation are the most common complications of a bicuspid aortic valve, dilatation of any or all segments of the proximal aorta from the aortic root to the aortic arch, called bicuspid aortopathy, is also present in approximately 50% of affected persons. Accumulating evidence suggests that the pattern of aortic dilatation in persons with a bicuspid aortic valve is diverse, possibly reflecting heterogeneity in molecular, rheologic, and clinical features. This article provides a brief overview of the basic principles, recent advances, and recommendations for the treatment of adults with bicuspid aortopathy.

Wall stress differs by fusion pattern
R-L: Right anterior wall of ascending aorta
Wall stress differs by fusion pattern
R-N: Posterior wall, affects arch?
There is no substitute for knowing the anatomy and physiologic function
Obrigado!

South America’s Biggest City: SAO PAULO BRAZIL