The Anatomy of the Aortic Valvar Complex

Adapted from:

The Anatomy of the Aortic Valvar Complex

Mylotte D, Spicer DE, Sarwark AE, Backer CL, Anderson RH, Piazza N.

The Clinical Atlas of Transcatheter Aortic Valve Therapies, First Edition. Edited by Serruys PW, Windecker S, Thomas M, Bax J, Piazza N, van Mieghem N, Leon M.
2014 Europa Digital & Publishing.

INTRODUCTION

Half a millennium ago, Renaissance artist and scientist Leonardo da Vinci (1513) provided the first description of the structure and function of the aortic valvar complex.[1] da Vinci described how eddy currents generated by the sinuses of Valsalva approximated the aortic valvar leaflets in preparation for valvar closure. Some 500 years later, renewed interest in the anatomy of the aortic valvar complex has emerged in the light of the development and widespread adoption of transcatheter aortic valve implantation (TAVI). While there are several publications describing the anatomy of the aortic valvar complex,[2-4] few specifically focus on the unique challenges presented by TAVI.[5] Herein, we provide a detailed and comprehensive description of the anatomy of the aortic valvar complex as it pertains to TAVI.

ATTITUDINALLY APPROPRIATE NOMENCLATURE

In this chapter, we will describe all relevant cardiac structures according to their anatomical position within the chest, rather than the more traditional and somewhat confusing Valentine description.[6] Attitudinal anatomy becomes even more important when one considers that it corresponds to the 3-dimensional imaging techniques currently used to assess the aortic root for the purposes of TAVI.

THE AORTIC ROOT

The 'aortic root' refers to the aortic outflow tract from its entrance at the left ventricular outlet to its junction with the ascending portion of the aorta.[7] It is demarcated inferiorly by a virtual plane created by joining the basal attachment of the aortic valvar leaflets within the left ventricular outflow tract, and superiorly by the distal attachment of the leaflets at the sinutubular junction (**Figure 1**).[8] Within the root as thus defined, it is possible to recognise the sinuses of Valsalva, the sinutubular junction, the fibrous interleaflet triangles, and the semilunar valvar leaflets with their attachments in part to the ventricular and aortic walls, and in part to the aortic or anterior leaflet of the mitral valve (**Figure 2**). The root lies posterior and rightward relative to the subpulmonary infundibulum, with its circumference bordered anteriorly by the muscular left ventricle, and posteriorly by the orifices of the atrioventricular valves.

Figure 1. The aortic root

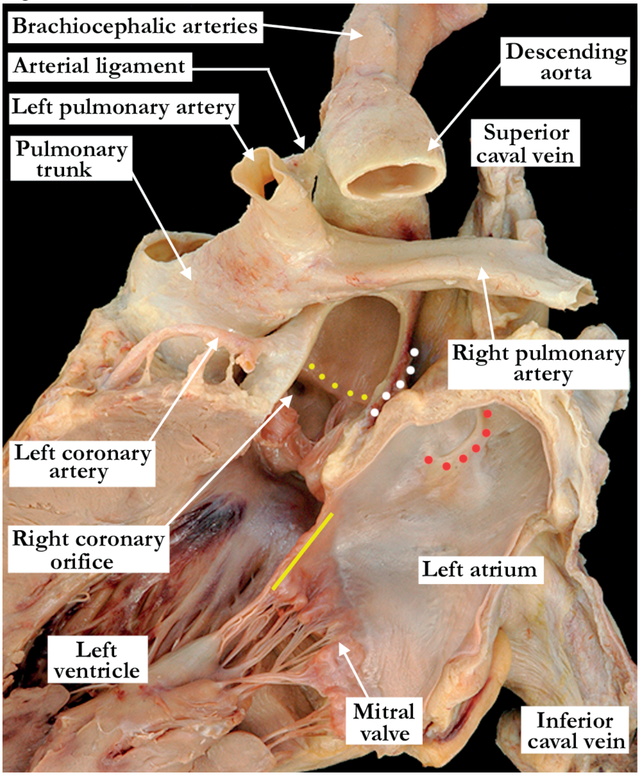

Figure 1. The left atrial and left ventricular walls along with the posterior wall of the aortic root have been removed to show the relationships of the structures surrounding the aortic root. Anteriorly the aortic root is bordered by the pulmonary trunk, the two arterial trunks spiralling as they leave the ventricular mass and exit the pericardial cavity. The pulmonary trunk bifurcates into the right and left pulmonary arteries and the arterial ligament extends from the base of the left pulmonary artery to the underside of the aortic arch. Adjacent to the pulmonary trunk and along its left posterior aspect, the left coronary artery arises from the aortic root and from the left facing or left coronary aortic sinus. The right facing or right coronary aortic sinus gives rise to the right coronary artery with the right coronary orifice arising just below the sinutubular junction in this specimen. The aortic root extends posterior and to the right of the pulmonary trunk with the distal most extension of the root marked by the sinutubular junction (yellow dots) and giving way to the tubular or ascending aorta. The ascending aorta then becomes the transverse aortic arch from which the brachiocephalic arteries arise. The area between the left subclavian artery, the most distal of the brachiocephalic arteries, and the arterial ligament is the aortic isthmus. The aortic isthmus then continues as the descending aorta. The right pulmonary artery crosses behind the ascending aorta on its way to the root of the right lung. The superior caval vein flanks the ascending aorta on the right. Within the left atrium, the horseshoe-like structure (red dots) marks the posterior aspect of the flap valve of the oval fossa where it overlaps the superior interatrial fold. The anterior wall of the right and left atrium lie adjacent to the aortic root and the space separating them is intrapericardial, known as the transverse sinus (white dots). The inlet of the left ventricle is guarded by the mitral valve with the anterior or aortic leaflet separating the inlet from the outlet component. This leaflet (yellow line) is in fibrous continuity with the aortic valve and forms an integral component of the supporting structures for the aortic root.

Figure 2. Aortic root

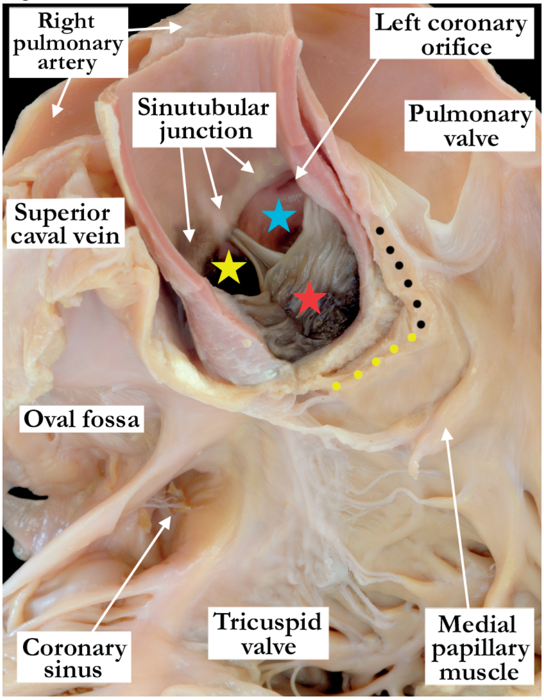

Figure 2. This is a simulated, oblique, subcostal echocardiographic view demonstrating the central position of the aortic root relative to the other cardiac valves. The aortic valve is to the right and posterior to the pulmonary valve that is supported by a complete, subpulmonary muscular infundibulum (black dots). Two leaflets of the aortic valve are immediately adjacent to the pulmonary trunk with those aortic sinuses typically giving rise to the coronary arteries. The red star marks the right hand facing sinus and gives origin to the right coronary artery while the left hand facing sinus (blue star) gives origin to the left main coronary artery. The yellow star marks the non-adjacent aortic sinus that has been referred to in the past as the non-coronary aortic sinus. Although rare, coronary arteries have been known to arise from this sinus, so the best reference to this sinus is non-adjacent. The leaflets of the aortic valve attach to the aortic wall at the sinutubular junction which is the distal most margin of the aortic root. On the anterior aspect of the aortic root lies the inner heart curvature which is at the junction of the subpulmonary infundibulum (black dots) and the parietal wall of the right ventricle, this area sometimes referred to as the ventriculo-infundibular fold (yellow dots). Note the close proximity of the right atrial musculature to the right of the aortic root.

AORTIC SINUSES

The regions corresponding to the luminal surface of the three bulges of the aortic root, which support their respective valvar leaflets, are known as the aortic sinuses of Valsalva (**Figure 3**). Usually, the right and left sinuses give rise to coronary arteries (right and left), while the third sinus does not. Because of this, the third sinus is usually described as the non-coronary sinus. On rare occasions, nonetheless, a coronary artery can arise from this third sinus. We prefer, therefore, to describe the sinuses as being right coronary; left coronary; and non-adjacent. The "non-adjacency" is considered relative to the sinuses of the pulmonary trunk. When considered attitudinally, the sinuses are located anteriorly (right coronary), leftward and posteriorly (left coronary), and rightward and posteriorly (non-adjacent) [7]. The mean diameter of the sinuses of Valsalva as measured with multidetector computed tomography (MDCT) was 32.4 ± 4.0 mm,[9] and was not significantly different between patients with and without aortic stenosis.[10]

Figure 3. Aortic sinuses

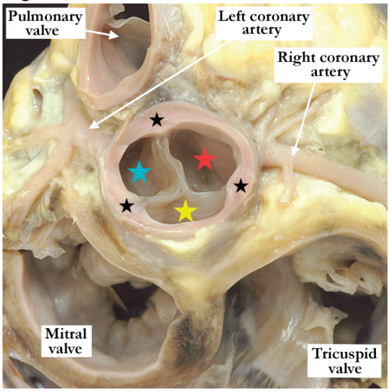

Figure 3. This close up view of the aortic root from the base of the heart demonstrates the relationship between the atrioventricular valves, the anterior wall of the atriums and the pulmonary trunk. The aortic root is located at the centre of the heart and is deeply wedged between the atrioventicular valves. The subpulmonary muscular infundibulum and the pulmonary trunk wrap around the anterior aspect of the aortic root. The two aortic sinuses that lie adjacent to the pulmonary trunk are called the right (red star) and left (blue star) facing sinuses, the right facing sinus typically giving rise to the right coronary artery and the left facing sinus the left coronary artery. The sinus marked by the yellow star is the non-adjacent sinus and is farthest from the pulmonary trunk. The zones of apposition between the three aortic valvar leaflets extend from the thickened areas within the aortic wall (black stars) to the central portion of the valvar orifice, this entire area marked as the commissure. In the past, only the areas at the black stars marking the attachment of the leaflets to the sinutubular junction were referred to as the commissures.

As the aortic root is a centrally located cardiac structure within the pericardial sac, rupture of the root or one of its sinuses during TAVI can result in direct communication with several different cardiac chambers.[7]

- Non-adjacent sinus: potential communication with the right or left atrium
- Left coronary sinus: potential communication with the left atrium or the transverse sinus (pericardial space).
- Right coronary sinus: potential communication with the right atrium or the right ventricular outflow tract.

As it exits the left ventricle, the aortic root angulates slightly towards the right and therefore overlies the superior aspect of the muscular ventricular septum and the right ventricle. Thus, aortic root rupture during TAVI can potentially also produce an interventricular septal communication.

SINUTUBULAR JUNCTION

The superior attachments of the aortic valvar leaflets demarcate the level of the sinutubular junction. This junction marks the exit of the aortic root, and the beginning of the ascending aorta (**Figures 2, 4**). Echocardiographic studies have demonstrated that the diameter of the sinutubular junction is significantly larger in patients with aortic stenosis than in normal patients.[10] MDCT data demonstrate that the maximal diameter of the sinutubular junction is 28.2 ± 3.2 mm, and that the mean distance between the basal attachment of the valvar leaflets and the sinutubular junction (sinutubular height) is 20.3 ± 3.3 mm.[9] The sinutubular ridge is prone to age-related atherosclerotic change and calcification.[11] The extent and location of such calcification should be considered when planning TAVI.

Figure 4. Sinutubular junction

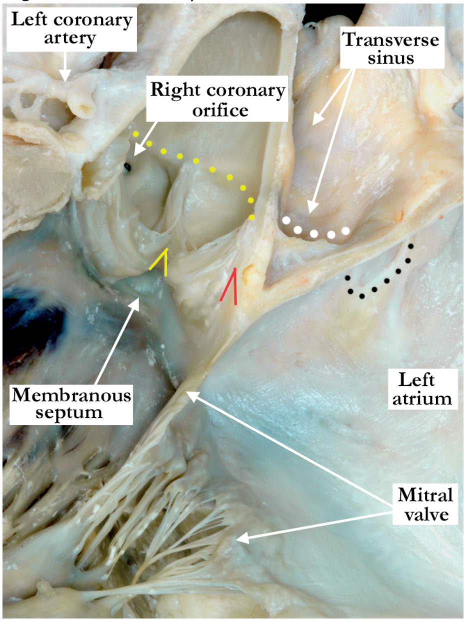

Figure 4. This long axis, close up view of the inlet and outlet components of the left ventricle highlights the relationship of the interleaflet triangles to the outside of the heart. The apex of the interleaflet triangles is the distal most extent of where the semilunar hinges of the leaflets join the sinutubular junction (yellow dots). The interleaflet triangle between the non-adjacent and the right coronary aortic sinus is illustrated with yellow lines. The red lines mark the interleaflet triangle between the non-adjacent and the left coronary aortic sinus, showing nicely how the distal extension of the interleaflet triangles separates the cranial extension of the aortic root from the pericardial cavity. The white dots mark the margin of the serous pericardium lining the transverse sinus. The serous pericardium reflects from the epicardial surface of the tubular aorta onto the anterior wall of the atrial chambers and incorporates a small area outside the heart, but within the pericardial cavity. The proximal aspect of two of the interleaflet triangles are in direct contact with the area of aorta to mitral fibrous continuity and are an integral part of the left and right fibrous trigones. Note the black dots which mark the horseshoe-like structure representing the overlapping of the flap valve of the oval fossa with the superior interatrial fold.

AORTIC LEAFLETS

The normal aortic valve is trifoliate (**Figure 5 A, B**). Each of the three leaflets has a semilunar attachment within the aortic root, and a free margin for coaptation with the other leaflets. At the level of the sinutubular junction, the semilunar hinges of adjacent leaflets come together to form the so-called commissures. If used literally, however, a "commissure" is a zone of apposition between adjacent structures. The true "commissures" within the valvar root, therefore, are the three zones of apposition between the leaflets extending from the so-called "commissures" to the valvar centroid. The leaflets themselves are slightly thicker towards their free margins. Interindividual and intraindividual variability with respect to the width and height of the leaflets is common.[12] The average width, measured between the peripheral zones of attachment along the sinus ridge, is 25.5 mm (**Figure 6**). The average height, measured from the base of the center of the leaflet to its free edge, is 14.1 mm (**Figure 5**). Coaptation along the zones of apposition occurs on the ventricular aspect of the leaflets, and involves the entire length of the free margin, taking place along approximately one third of the total leaflet depth. The central point of coaptation is thickened, and is known as the lunule. The leaflets are comprised of a fibrous core and underlying subendothelial fibroelastic layers. In the setting of severe aortic stenosis the

Figure 5. Normal trileaflet aortic valve leaflets
5A. Aortic view

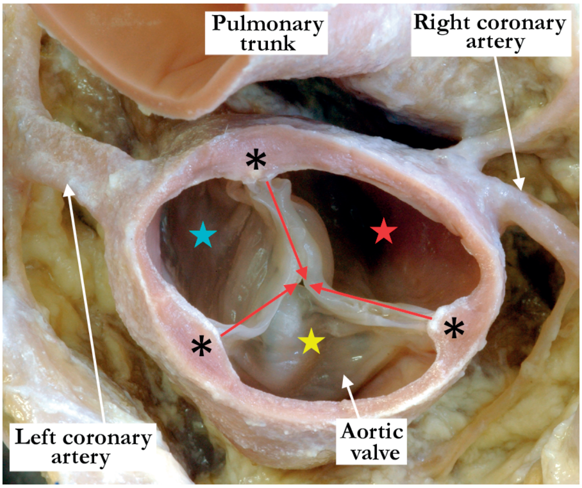

Figure 5A. This close up, short axis view from the base of the heart shows the normal aortic valve with two of the leaflets and aortic sinuses adjacent to the pulmonary trunk, the right (red star) aortic sinus typically gives rise to the right coronary artery and the left (blue star) aortic sinus the left coronary artery. The non-adjacent aortic sinus is represented by the yellow star. The zones of apposition (red arrows) between the leaflets extend from their attachments at the sinutubular junction (black stars) to the centre of the valvar orifice. Historically, it was only the peripheral attachments that were referred to as the commissures. Actually, it is the entirety of the zone of apposition that is the commissure.

5B. Ventricular view

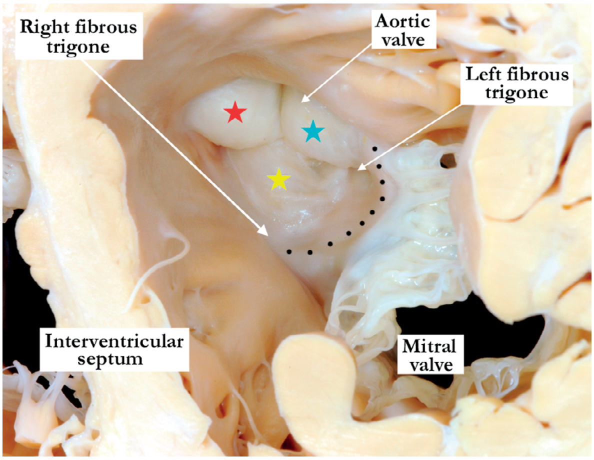

Figure 5B. The aortic to mitral fibrous continuity (black dots) and the aortic valve are viewed from the apex of the left ventricle. The mitral valve is supported by tendinous cords arising from the paired papillary muscles with no attachments to the ventricular septum. Within the left ventricle, the aortic root interposes between the mitral valve and the interventricular septum. The left ventricular outlet has a partially fibrous and partially muscular wall. Two of the leaflets that guard the outlet or aortic root are in fibrous continuity with the anterior or aortic leaflet of the mitral valve. These are the non-adjacent (yellow star) and the left (blue star) facing or left coronary leaflet with the third leaflet, the right (red star) facing or right coronary leaflet. The right and left fibrous trigones form the two ends of this fibrous continuity. The aortic root and mitral valve are anchored within the roof of the left ventricle where the fibrous trigones attach to the crest of the muscular ventricular septum. The fibrous trigones are thickened areas within the aortic to mitral fibrous continuity and the right fibrous trigone is continuous with the membranous septum. The right fibrous trigone and the membranous septum together form the central fibrous body.

Figure 6. Dimensions of aortic leaflets

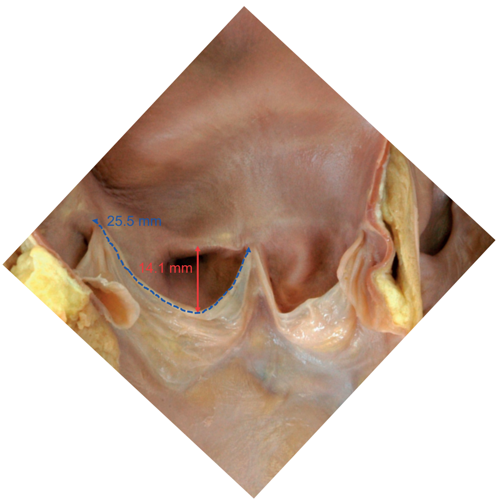

Figure 6. The average length and height of the aortic valve leaflets are 25.5 and 14.1 mm, respectively.

leaflets become thickened, heavily calcified, and non-compliant, with a resultant reduction in the orificial area for the systolic ejection of blood by the left ventricle (**Figure 7 A, B**).

Figure 7. Calcific aortic stenosis
7A. Aortic view

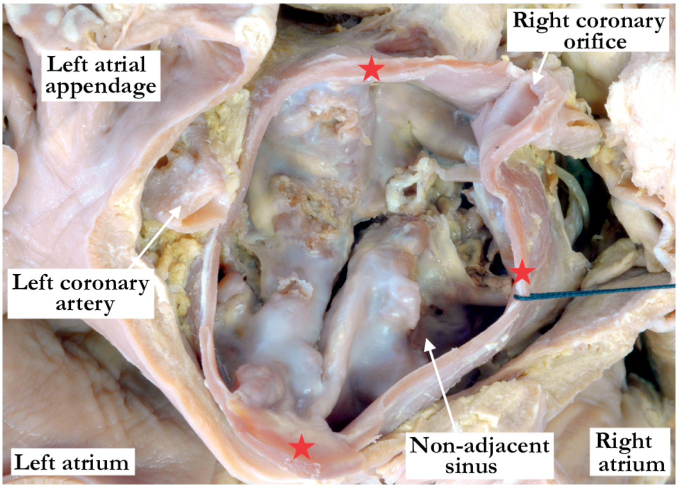

Figure 7A. The aortic root is viewed from the base of the heart and has been transected just below the sinutubular junction along the anterior most aspect. The aortic valvar leaflets are extremely thickened and are entirely calcified. The leaflets are non-compliant with only a small, slit-like, eccentric opening.
7B. Ventricular view.

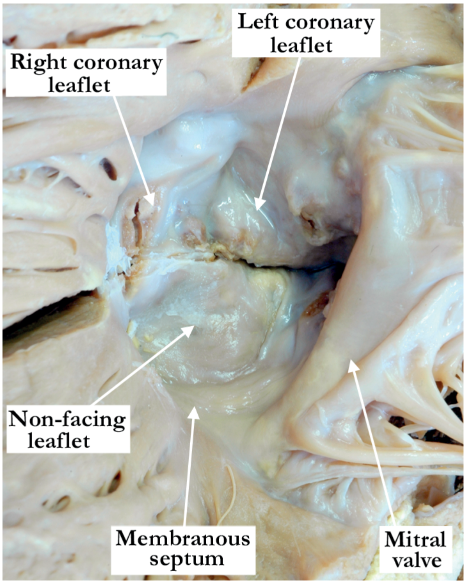

Figure 7B. This view is looking into the left ventricular outflow from the apex. The aorta to mitral fibrous continuity is thickened and has a redundant, shelf-like appearance secondary to the calcific nature of the aortic valvar leaflets. The leaflets are focally nodular and ulcerated with a slit-like, slightly eccentric opening. The normal semilunar nature of the leaflets and the overall anatomy of the aortic root have been disrupted.

The non-adjacent leaflet, and part of the left coronary leaflet, are in fibrous continuity with the aortic or anterior leaflet of the mitral valve. At either end, this area of fibrous continuity thickens to form the right and left fibrous trigones. The right fibrous trigone itself is then continuous with the membranous septum, and together these structures form the central fibrous body. When considered together, the fibrous trigones serve to anchor the aorto-mitral valvar unit to the roof of the left ventricle (**Figure 8**). Inadvertent low implantation of a transcatheter valve can therefore impinge on the aortic leaflet of the mitral valve, and yield mitral valve dysfunction.[13]

Figure 8. Ventricular aspect of aortic and mitral valves

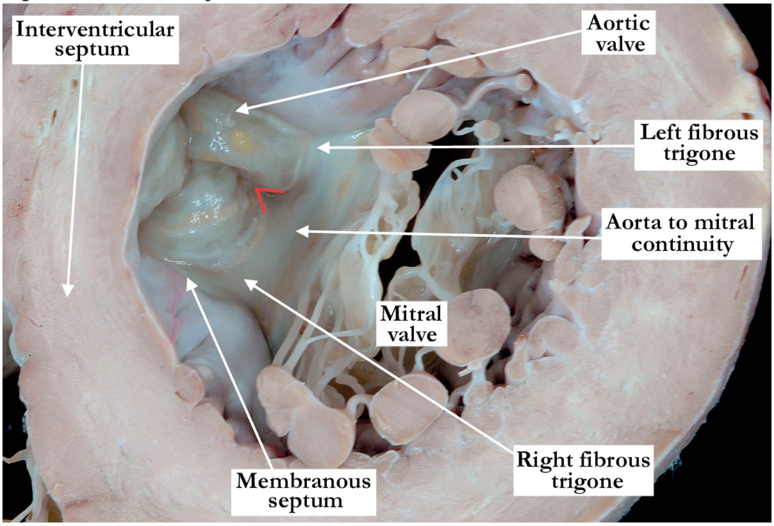

Figure 8. In this simulated, short axis, apical, echocardiographic view, the aortic root lies within the central portion of the heart and lifts the mitral valve away from the muscular, interventricular septum. The mitral valve is a bifoliate structure and is supported by paired papillary muscles with no cordal attachments to the septum. The aorta to mitral fibrous continuity supports approximately one third of the aortic root with the remaining two thirds supported by muscle. This area of fibrous continuity is quite strong and is supported by the thickened areas of the left and right fibrous trigones. The right and left fibrous trigones are easily seen at each end of the fibrous continuity with the interleaflet triangle (red lines) extending between the zones of apposition between the left aortic sinus and the non-adjacent aortic sinus. The non-adjacent sinus is entirely supported by the area of fibrous continuity between the aortic and mitral valves. The right fibrous trigone joins with the membranous septum at the base of the interleaflet triangle between the right aortic sinus and the non-adjacent sinus and forms the central fibrous body.

ANATOMY OF THE SO-CALLED "AORTIC ANNULUS"

The anatomic ventriculo-arterial junction is the transition point where left ventricular muscular tissue is replaced by the fibroelastic walls of the aortic valvar sinuses (**Figure 9**). Two of the aortic valvar leaflets cross this ventriculo-arterial junction, and take their basal origins from

Figure 9. Ventriculo-arterial junction

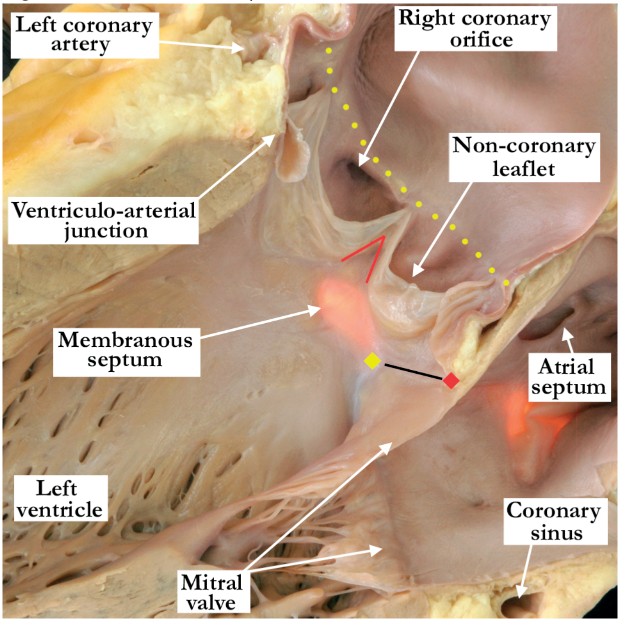

Figure 9. This is a close up, long axis view of the left ventricle and the aortic root. The aortic root is supported by partially fibrous and partially muscular walls with the anterior or aortic leaflet of the mitral valve in fibrous continuity with the aortic valve. This area of fibrous continuity (black line) involves the left and non-adjacent leaflets. The ends of this area of fibrous continuity are thickened and form the right (yellow diamond) and left (red diamond) fibrous trigones with the right fibrous trigone continuous with the membranous septum. These two components then form the central fibrous body. The attachments of the fibrous trigones to the crest of the musculature of the ventricular septum are what anchors the aortic root and the mitral valve within in the roof of the left ventricle. In the left ventricle, the aortic root interposes between the mitral valve and the septum. The anatomic ventriculo-arterial junction is in the area where the fibrocollagenous wall of the aorta is supported by the musculature of the parietal wall of the ventriculo-arterial junction. There is epicardial fat marking the outer aspect of this junction. The yellow dots mark the sinutubular junction which is the distal most extent of the aortic root. This area is typically represented by a discrete ridge between the aortic valvar sinuses and the tubular component of the aorta. The red lines represent a fibrous triangle between the right and non-adjacent aortic leaflets. These fibrous triangles extend between the semilunar hinge lines of the three aortic valvar leaflets to become the most distal extension of the ventricular outflow tract.

the muscular walls of the left ventricle (**Figure 10**). The semilunar hinge line of the coronary aortic leaflets, therefore, incorporates a small crescent of ventricular myocardium within the aortic sinuses. It is the virtual plane created by joining together the basal attachments of the leaflets that demarcates the frequently described "aortic annulus". It is this diameter of the entrance to the root that is important for the purposes of transcatheter aortic valve sizing.

There are three circular, and 1 crown-like, rings within the extent of the aortic root (**Figure 11**).[8] Since the leaflets are attached throughout the length of the root, it is their semilunar hinges which, in 3-dimensions, form the crown-like structure. The base of this crown is not a distinct anatomical structure, but is the virtual ring formed by joining the basal attachments of

Figure 10. Histology of the aortic root

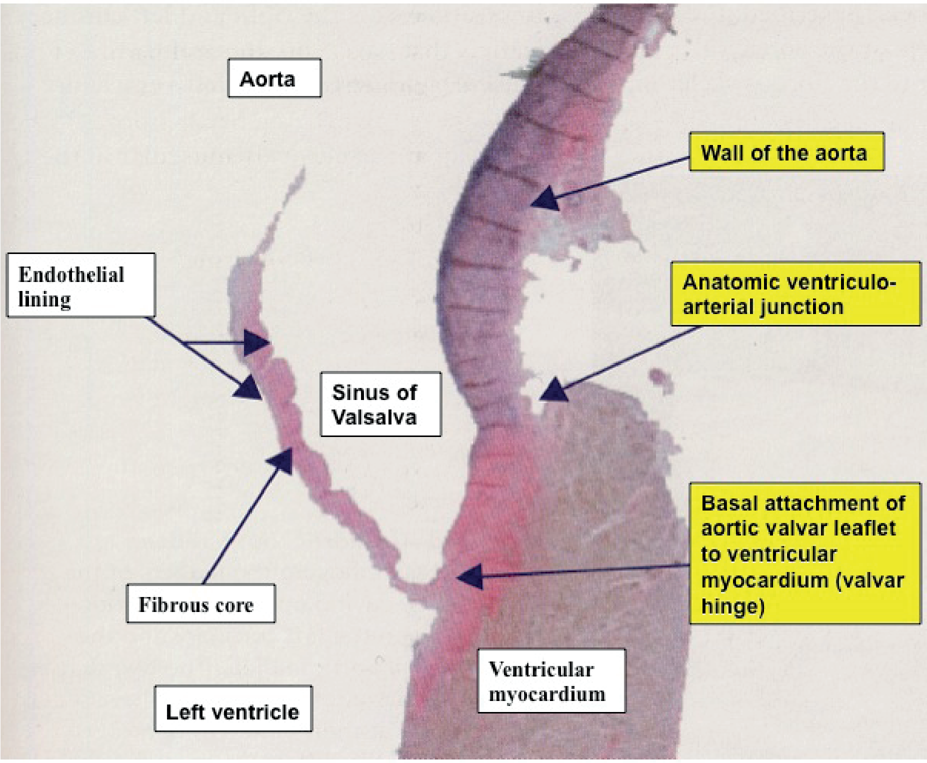

Figure 10. Histology of the aortic valvar complex shows the anatomic ventriculoarterial junction. Note that the basal attachment of the aortic valvar leaflets to the ventricular myocardium is proximal relative to the anatomic junction. The aortic leaflet displays and endothelial lining and a fibrous core.

the leaflets within the left ventricle. As discussed above, it is the diameter of this plane that is usually designated by echocardiographers as representing the valvar annulus. Many surgeons, in contrast, consider the crown-like construction to be the "annulus". The sinutubular junction forms the superior aspect of the crown and is a true anatomical ring. It is demarcated by the sinus ridge, the distal attachment points of the leaflets to the aortic root, and represents the most distal apposition zone between the aortic valve leaflets. Despite its true annular morphology, however, it is rarely, if ever, defined as the "annulus". The anatomic ventriculo-arterial junction also forms a ring between the base and superior aspects of the crown, but this locus is also not defined as the annulus.

Figure 11. The Aortic Rings

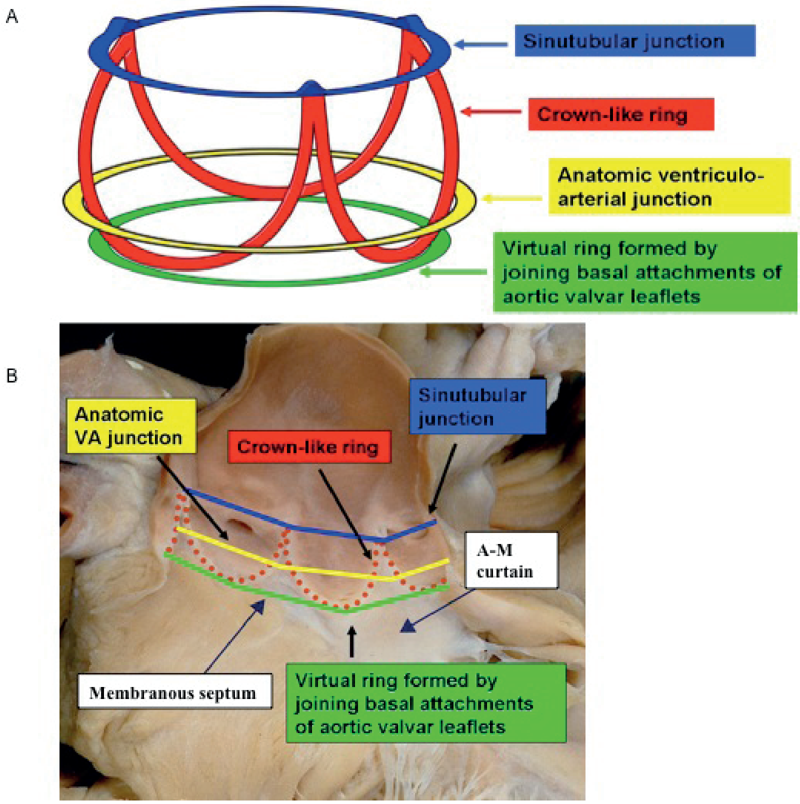

Figure 11. (A) Three-dimensional arrangement of the aortic root, which contains 3 circular "rings," but with the leaflets suspended within the root in crown-like fashion. **(B)** The leaflets have been removed from this specimen of the aortic root, showing the location of the 3 rings relative to the crown-like hinges of the leaflets. VA indicates ventriculoarterial; A-M, aortic-mitral.

AORTIC ROOT DIAMETERS

The shape of the aortic root is consistent, though its diameter can vary considerably. The diameter at its outlet, which is the level of the sinutubular junction, exceeds that at the level of its inlet at the virtual ring formed by the basal attachments of the leaflets by a ratio of 1.34 to 1.[14] Thus, the root has been described as a truncated cone. Importantly, the valvar complex is a dynamic structure, and its dimensions change according to the phases of the cardiac cycle, and with changes in pressure within the aortic root.[15, 16] The diameter of its entrance, the so-called aortic annulus, in particular, increases in diameter and decreases in eccentricity during ventricular systole.

Accurate measurement of the dimensions of the root is a critical component of successful transcatheter aortic valve implantation. Erroneous measurement of the aortic root (**Figure 12**) can lead to malposition or embolization of the prosthesis, paravalvar leak, rupture of the entrance to the root, and the potential for early structural degeneration of the leaflets. Several imaging modalities can be used for assessing the dimensions of the so-called annulus. The measurements of relevance include.[17]

Dimensions: maximal diameter, minimal diameter, mean, area, perimeter (circumference)

- Width of the Sinuses of Valsalva
- Height of the Sinuses of Valsalva
- Take-off height of the coronary arteries
- Width of the ascending aorta

Figure 12. Erroneous measurement of the aortic annulus diameters.

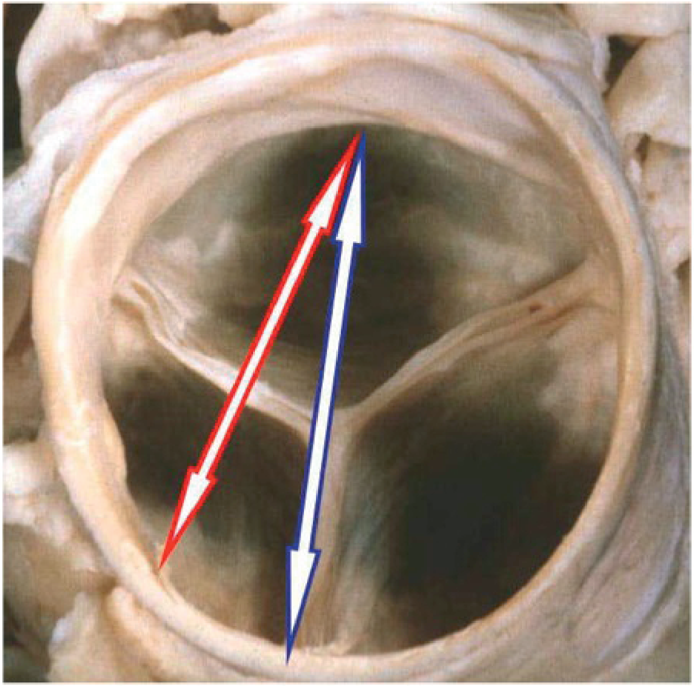

Figure 12. This basal short-axis view shows the closed aortic valve. The arrows demonstrate the potential hazard of 2-dimensional imaging techniques (echocardiography, contrast aortography) for measuring the "aortic valve annulus." Measurements made using the basal attachment of the leaflets do not transect the full diameter of the outflow tract but instead a tangent cut across the root.[18]

THE INTERLEAFLET FIBROUS TRIANGLES AND TRIGONES

The aortic root has several important boundary structures: the muscular and membranous interventricular septal components, the aortic or anterior mitral valvar leaflet, the area of aortic-to-mitral valvar continuity, and the two fibrous trigones. Approximately two thirds of the circumference of the lower part of the aortic root is connected to the muscular ventricular septum, with the remaining one third in fibrous continuity with the aortic leaflet of the mitral valve. As the semilunar attachments of the valve leaflets cross the anatomic ventriculo-arterial junction and merge distally to form the commissures, they leave three triangular wedges of tissue between their arcs (**Figure 13**). These triangles are known as the interleaflet fibrous triangles. The triangles are thinner, and less collagenous, than the surrounding sinusal walls. They therefore represent potential sites of root rupture during transcatheter valve implantation. The triangle between the left and right coronary sinuses lies immediately behind the free-standing right ventricular muscular infundibulum. The triangle between the right and non-adjacent leaflets is confluent with the membranous septum. The triangle between the left and non-adjacent leaflets lies along the area of aortic-mitral fibrous continuity.

The ends of the area of fibrous continuity are thickened to form the left and right fibrous trigones, with the right fibrous trigone contiguous with the triangle between the right and the non-adjacent sinuses. The trigones support and hinge the aortic-mitral valvar unit, thereby allowing these structures to be displaced during the cardiac cycle. The right fibrous trigone and the membranous ventricular septum together form the central fibrous body of the heart. This is the area within the heart where the membranous septum, the atrioventricular valves, and the aortic valve join in fibrous continuity.

Figure 13. The interleaflet fibrous triangles

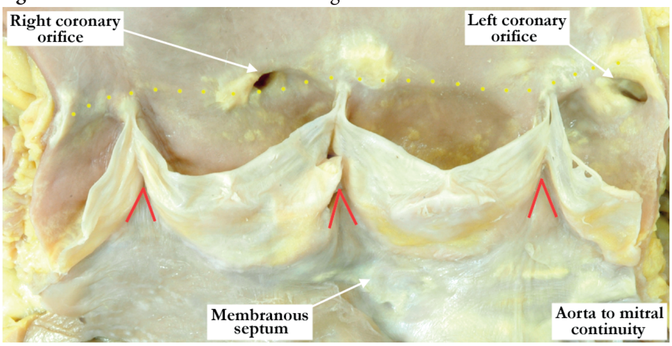

Figure 13. This diseased aortic valve has been opened through the mid portion of the left coronary aortic sinus. All of the aortic valve leaflets are thickened and focally calcified. There are calcific plaques at the sinutubular junction (yellow dots) and within the sinuses, especially in the area where the leaflets cross the anatomic ventriculo-arterial junction. The interleaflet triangles are marked with the red lines. The area of fibrous continuity between the aortic and mitral valves is thickened along with the membranous septum.

CORONARY ARTERIES

In the majority of cases, the coronary arteries arise from two separate orifices located within the left and right coronary aortic sinuses (**Figure 14**).[14, 19] Most arise below the sinutubular junction, although take-off at (9%) or above (22%) the junction is not uncommon.[20] Knowledge of the height of the coronary arteries with respect to the basal attachment of the native valve leaflets is important for those undertaking TAVI. Post-mortem examination of normal hearts show that the left and right coronary arteries arise on average 12.6±2.61 mm and 13.2±2.64 mm from the basal attachment of their respective leaflets.[21]

Figure 14. Origins of the coronary arteries

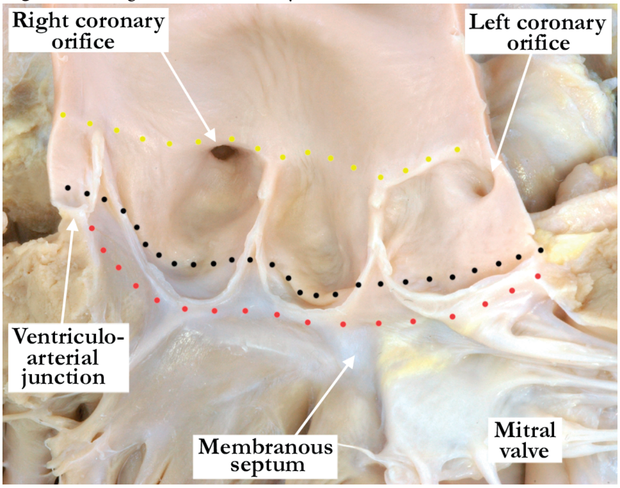

Figure 14. The aortic valvar leaflets have been removed from the intact aortic valve. This demonstrates three lines within the aortic root, the sinutubular junction (yellow dots), the anatomic ventriculo-arterial junction (black dots) and the line marking the most proximal portion of the aortic root (red dots). The sinutubular junction and the anatomic ventriculo-arterial junction form true lines within the aortic root. The line represented by the red dots is a virtual line and represents the proximal most attachment of the aortic valvar leaflets within the left ventricular outflow tract or aortic root. The aortic valvar leaflets cross the anatomic ventriculo-arterial junction at six points around the circumference of the valve, incorporating a crescent of muscle into the base of the sinus of the right coronary aortic leaflet and a portion of the left coronary aortic leaflet. Typically, the non-adjacent sinus has fibrous tissue in this area with fibrous tissue making up the remainder of the base of the left sinus. In this heart, the interleaflet triangle between the right coronary aortic sinus and the non-adjacent sinus is supported by muscle and does not reach the right fibrous trigone and the right-ward extent of the membranous septum.

Accurate assessment of the distance between the basal attachment point of the leaflets and the coronary arterial orifices is an important component of screening in advance of implantation, and procedural planning. All current prostheses available for transcatheter valve implantation are designed with a skirt of fabric or tissue sewn within the stent or frame in order to create a seal with the native aortic root and reduce paravalvar leak). If the origin of the coronary arteries is low within the sinuses of Valsalva, and/or the prosthesis is placed too high, the skirt can obstruct the arterial orifices and rapidly induce myocardial ischemia and haemodynamic collapse. An identical situation can be observed if deployment of the prosthesis displaces the native leaflets such that they cover that arterial orifices in patients with low lying coronary arteries.

Consequently, the height of the orifices within the sinuses should be assessed using multislice computed tomography.[9] According to the computed tomographic data, the mean distance from the basal attachment point of the leaflets to the orifices of the left coronary and right coronary arteries was 14.4±2.9 mm and 17.2±3.3 mm, respectively.[9] Although these measurements were similar in those with and without aortic stenosis, there was important variability that underscores the need for assessment in individual patients, the more so since the height of the orifice of the left coronary artery ranged from 7.1 to 22.7 mm.[9] The width of the sinuses of Valsalva has also been recognized to be an important determinant of potential arterial occlusion in the setting of transcatheter valve implantation. A minimum sinusal width is recommended in order to accommodate the redundant native aortic leaflets.

In cases where transcatheter valve implantation is being considered for treatment of a failing surgical bioprosthesis, it is important to know both the position (annular or supra-annular implantation) and design characteristics of the surgical prosthesis, as coronary arterial occlusion is more commonly described than when native aortic valves are being replaced by transcatheter valve implantation.[22]

RELATIONSHIP TO THE CONDUCTION SYSTEM

In the right atrium, the atrioventricular node is located within the triangle of Koch. The boundaries of this triangle are the tendon of Todaro, the orifice of the coronary sinus, and the attachment of the septal leaflet of the tricuspid valve (**Figure 15**). The hinge point of the septal leaflet of the tricuspid valve separates the membranous septum into its atrioventricular and interventricular components. It is the atrioventricular component of this membranous septum that forms the apex of the triangle of Koch, with the atrioventricular node found just inferior to the apex of this triangle.

The atrioventricular node continues as the bundle of His, which penetrates the atrioventricular component of the membranous septum, and runs superficially along the crest of the ventricular septum to give rise to the fascicles of the left bundle branch. The left bundle is closely related to the base of the interleaflet triangle between the right and non-adjacent and leaflets of the aortic valve, with the superior part of the bundle intimately related to the right coronary aortic leaflet (**Figure 16**).[23] Autopsy findings suggest that the average distance between the nadir of the non-adjacent aortic valve leaflet and the left bundle branch is 6.3±2.7 mm. Thus, the conduction axis is closely related to the subaortic apparatus, and can be injured during or after transcatheter valve implantation.

Figure 15. Triangle of Koch

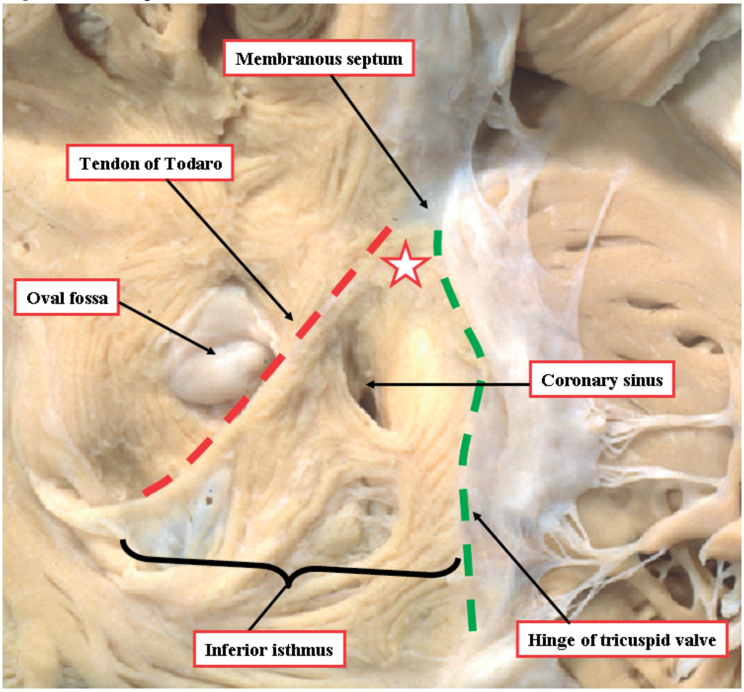

Figure 15. The heart is viewed from the right side, illustrating the component parts of the triangle of Koch.

Figure 16. Atrioventricular node

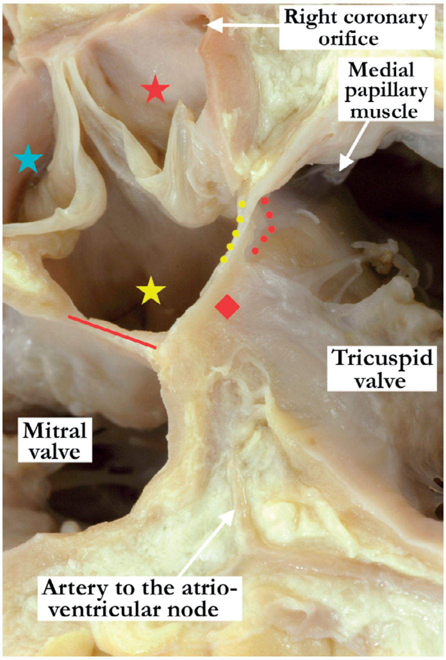

Figure 16. The atrial musculature has been removed along with the non-adjacent sinus of the aortic valve. The right (red star) and left (blue star) facing sinuses remain intact. The area of aortic to mitral fibrous continuity is marked by the red line and the image illustrates how the subaortic outflow tract is lifting the mitral valve away from the interventricular septum. On the opposite aspect a portion of the septal leaflet of the tricuspid valve has been removed to view the atrioventricular (yellow dots) and the interventricular (red dots) components of the membranous septum. This demonstrates the relationship between the base of the right interleaflet triangle, the right fibrous trigone and the membranous septum. The red diamond marks the site of the atrioventricular conduction axis. Note the artery to the atrioventricular node within the fat that interposes between the right and left atrial walls and the crest of the muscular ventricular septum at the base of the inferior interatrial fold.

ADDITIONAL SECTIONS

Bicuspid Aortic Valve

The aortic valve with two leaflets, usually said to be bicuspid, is the most commonly recognized form of adult congenital heart disease, estimated to occur in 1-2% of the general population [12, 24] (Figure 17). Compared to valves with three leaflets, those with only two leaflets are more likely to develop mid-life aortic stenosis or regurgitation. The majority of patients with such bicuspid valves will require valvar replacement during their lifetime [25]. This finding is thought to account for up to half of all surgical replacements of the aortic valve undertaken in adults [26]. The procedure also accounts for over one-fifth of the indications for aortic valvar replacement in octogenerians [27]. Traditionally, the finding of a valve with two leaflets has been considered a contraindication to transcatheter aortic valve implantation. The large and eccentric entrance of the root associated with the bicuspid valve, along with the extensive calcification and fibrosis of the aortic leaflets, and the not-infrequent requirement for replacement of the ascending aorta, all account for the reluctance to treating these patients percutaneously [28]. Although viewed traditionally as a contraindication, however, patients with bicuspid valves have been successfully treated by transcatheter valve implantation [29].

Figure 17. Bicuspid aortic valve

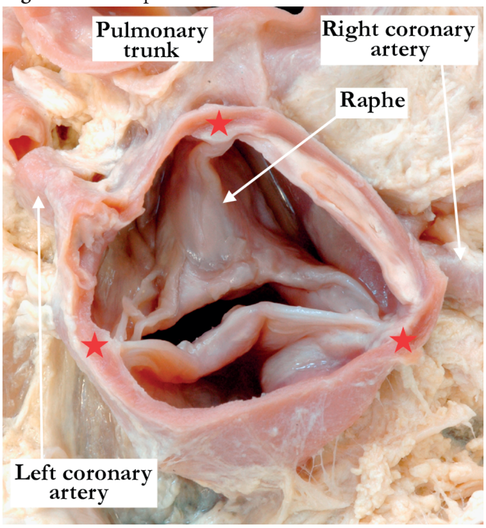

Figure 17. The aortic root is viewed from the arterial aspect and has been transected at the sinutubular junction. The aortic valve is bicuspid with an incomplete zone of apposition or raphe between the right and left facing sinuses. This area and the component parts of the aortic valvar leaflets, are thickened and somewhat rigid, preventing the leaflets from coapting in a normal fashion. The distal attachments of the zones of apposition are marked by the red stars and there is a plaque-like thickening within the aortic wall associated with the right facing sinus.

REFERENCES

1. Robicsek F. Leonardo da Vinci and the sinuses of Valsalva. *Ann Thorac Surg*. 1991;52:328-35.
2. Yacoub MH, Kilner PJ, Birks EJ and Misfeld M. The aortic outflow and root: a tale of dynamism and crosstalk. *Ann Thorac Surg*. 1999;68:S37-43.
3. Becker A. Surgical and pathological anatomy of the aortic valve and root. *Oper Tech Cardiac Thorac Surg* 1996;1:3-14.
4. Anderson RH, Razavi R and Taylor AM. Cardiac anatomy revisited. *J Anat*. 2004;205:159-77.
5. Piazza N, de Jaegere P, Schultz C, Becker AE, Serruys PW and Anderson RH. Anatomy of the aortic valvar complex and its implications for transcatheter implantation of the aortic valve. *Circ Cardiovasc Intervent*. 2008;1:74-81.
6. Anderson R and Kanani M. Mitral valve repair: critical analysis of the anatomy discussed. *Multimed Man Cardiothorac Surg*. 2007;2007.
7. Ho SY. Structure and anatomy of the aortic root. *Eur J Echocardiogr*. 2009;10:i3-10.
8. Anderson RH. Clinical anatomy of the aortic root. *Heart*. 2000;84:670-3.
9. Tops LF, Wood DA, Delgado V, Schuijf JD, Mayo JR, Pasupati S, Lamers FP, van der Wall EE, Schalij MJ, Webb JG and Bax JJ. Noninvasive evaluation of the aortic root with multislice computed tomography implications for transcatheter aortic valve replacement. *JACC Cardiovascular Imaging*. 2008;1:321-30.
10. Crawford MH and Roldan CA. Prevalence of aortic root dilatation and small aortic roots in valvular aortic stenosis. *Am J Cardiol*. 2001;87:1311-3.
11. Loukas M, Wartmann CT, Tubbs RS, Apaydin N, Louis RG, Jr., Easter L, Black B and Jordan R. The clinical anatomy of the sinutubular junction. *Anat Sci Int*. 2009;84:27-33.
12. Vollebergh FE and Becker AE. Minor congenital variations of cusp size in tricuspid aortic valves. Possible link with isolated aortic stenosis. *Br Heart J*. 1977;39:1006-11.
13. Wong DR, Boone RH, Thompson CR, Allard MF, Altwegg L, Carere RG, Cheung A, Ye J, Lichtenstein SV, Ling H and Webb JG. Mitral valve injury late after transcatheter aortic valve implantation. *J Thorac Cardiovasc Surg*. 2009;137:1547-9.
14. Reid K. The anatomy of the sinus of Valsalva. *Thorax*. 1970;25:79-85.
15. Swanson M and Clark RE. Dimensions and geometric relationships of the human aortic valve as a function of pressure. *Circ Res*. 1974;35:871-82.
16. Blanke P, Russe M, Leipsic J, Reinohl J, Ebersberger U, Suranyi P, Siepe M, Pache G, Langer M and Schoepf UJ. Conformational pulsatile changes of the aortic annulus: impact on prosthesis sizing by computed tomography for transcatheter aortic valve replacement. *JACC Cardiovasc Interv*. 2012;5:984-94.
17. Buellesfeld L, Stortecky S, Kalesan B, Gloekler S, Khattab AA, Nietlispach F, Delfine V, Huber C, Eberle B, Meier B, Wenaweser P and Windecker S. Aortic root dimensions among patients with severe aortic stenosis undergoing transcatheter aortic valve replacement. *JACC Cardiovasc Interv*. 2013;6:72-83.
18. Khalique OK, Kodali S, Paradis JM, Nazif TM, Williams MR, Einstein AJ, Pearson GD, Harjai K, Grubb K, George I, Leon MB and Hahn RT. Aortic Annular Sizing Using a Novel 3-Dimensional Echocardiographic Method: Utility and Comparison to Cardiac Computed Tomography. *Circ Cardiovasc Imaging*. 2013.
19. Turner K and Navaratnam V. The positions of coronary arterial ostia. *Clin Anat*. 1996;9:376-80.
20. Muriago M, Sheppard MN, Ho SY and Anderson RH. Location of the coronary arterial orifices in the normal heart. *Clin Anat*. 1997;10:297-302.
21. Cavalcanti JS, de Melo NC and de Vasconcelos RS. Morphometric and topographic study of coronary ostia. *Arq Bras Cardiol*. 2003;81:359-62, 355-8.

22. Mylotte D, Lange R, Martucci G and Piazza N. Transcatheter heart valve implantation for failing surgical bioprostheses: technical considerations and evidence for valve-in-valve procedures. *Heart*. 2013. 99: 960-7.
23. Tawara S. *Das Reizleitungssystem de Saugetierherzens: Eine Anatomichhisologische Studie uber das Atrioventricularbundel und die Purkinjeschen Faden*. Jena, Germany; 1906.
24. Edwards JE. The congenital bicuspid aortic valve. *Circulation*. 1961;23:485-8.
25. Lewin MB and Otto CM. The bicuspid aortic valve: adverse outcomes from infancy to old age. *Circulation*. 2005;111:832-4.
26. Roberts WC and Ko JM. Frequency by decades of unicuspid, bicuspid, and tricuspid aortic valves in adults having isolated aortic valve replacement for aortic stenosis, with or without associated aortic regurgitation. *Circulation*. 2005;111:920-5.
27. Roberts WC, Janning KG, Ko JM, Filardo G and Matter GJ. Frequency of congenitally bicuspid aortic valves in patients >/=80 years of age undergoing aortic valve replacement for aortic stenosis (with or without aortic regurgitation) and implications for transcatheter aortic valve implantation. *Am J Cardiol*. 2012;109:1632-6.
28. Himbert D, Pontnau F, Messika-Zeitoun D, Descoutures F, Detaint D, Cueff C, Sordi M, Laissy JP, Alkhoder S, Brochet E, Iung B, Depoix JP, Nataf P and Vahanian A. Feasibility and outcomes of transcatheter aortic valve implantation in high-risk patients with stenotic bicuspid aortic valves. *Am J Cardiol*. 2012;110:877-83.
29. Wijesinghe N, Ye J, Rodes-Cabau J, Cheung A, Velianou JL, Natarajan MK, Dumont E, Nietlispach F, Gurvitch R, Wood DA, Tay E and Webb JG. Transcatheter aortic valve implantation in patients with bicuspid aortic valve stenosis. *JACC Cardiovasc Interv*. 2010;3:1122-5.