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Anatomy and Function of Normal Aortic Valvular Complex

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Additional information is available at the end of the chapter

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1. Introduction

Recently, the interest in the anatomy of the normal aortic valve complex has augmented, mostly because of the increasing use of conservative surgical techniques for repairing or replacing cardiac valves. The knowledge of the anatomy also has important implications in the manufacture of prostheses that must conform to this anatomical configuration.

1.1. Historical perspective

The earliest documented interest in the anatomy of the aortic valvular complex stems from the Renaissance, with the description and drawings by Leonardo da Vinci. [1]

Leonardo da Vinci had an almost perfect understanding of the physiology of the human heart. But he had no inkling of the circulation of the blood, and the existence of one-way valves was incompatible with the ancient belief that the heart simply churned blood in and out of the ventricles, thus generating heat and 'vital spirit'. Unable to reconcile what he had observed with what he believed to be true, Leonardo reached an impasse. He became trapped in describing the motion of the blood through the valves in even more detail. And there, it seems, his anatomical work came to an end. [2]

The next anatomist to study the aortic valve was Andreas Vesalius. Then, for almost 400 years the study of the human heart was very sporadic and limited.

The 19th century brought in the era of anatomic dissection and the knowledge on the aortic valve grew wider. Henle was the first to introduce the term "arterial root". During the first

half of the 20th century the rise in autopsy rates in Europe and North America facilitated the study of cardiac anatomy. [3]



Figure 1. Leonardo da Vinci - The aortic valve, from the Royal Collection © Her Majesty Queen Elizabeth II - <http://www.royalcollection.org.uk/collection/919082/the-aortic-valve>

Nowadays the need to understand the anatomy of the aortic valve is crucial, therefore the books and articles devoted to this topic are numerous.

1.2. Definitions

There is still no consensus on the best way to describe the anatomy of the aortic root [4].

The term “aortic root” refers to the aortic valve from its position at the left ventricular outlet to its junction with the ascending portion of the aorta. [5] It is the direct continuation of the left ventricular outflow tract.

Aorto-ventricular junction refers to the junction between the left ventricular structures and the aortic valvular sinuses, this representing the anatomic junction, or the semilunar lines of attachment of the arterial valvular leaflets, this locus representing the haemodynamic ventriculo-arterial junction [4].

Annulus is conventionally described as the virtual ring, formed by joining the basal attachment points of the leaflets within the left ventricle.

Nodule of Arantius is the small fibrous mound that forms at the center of each leaflet when the closing edge meets the free edge.

Between the free and closing edges, to each side of the nodule are two crescent-shaped areas known as the lunulae, which represent the sites of cusp apposition during valve closure. [6]

1.3. Embryology

The development of the aortic valve complex is extremely complicated and not yet fully understood.

The heart begins as a single tube that separates into two tubes and begins to twist rightward onto itself, called "d" looping.

Cells from the primary cardiac crescent, formed bilaterally within the embryonic disc, migrate into the cervical region of the developing embryo to form the primary heart tube. With further growth, cells from a second cardiogenic area, located posterior to the dorsal wall of the developing pericardial cavity, migrate into the cardiac region. The cells from this secondary heart field populate the outflow tract and the aortic arches. [7]

The heart tube is composed of an outer layer of myocardium and an inner lining of endocardial cells, separated by an extensive extracellular matrix referred to as the cardiac jelly. After rightward looping of the heart, the cardiac jelly overlying the future atrioventricular canal and outflow tract expands into swellings known as cardiac cushions. [8]

Subsequent to looping, the outflow tract possesses a characteristic dog-leg bend which divides the outflow tract into proximal and distal portions.

The cushions contained within the myocardial wall go through significant changes. In addition to the cushions that have fused to separate the proximal outflow tract into prospective aortic and pulmonary components, two further intercalated cushions have grown in the opposite quadrants of the common outflow tract. Formation of cavities in the fused distal parts of the proximal cushions, along with similar cavitation in the intercalated cushions, now produces the primordiums of the arterial valvular leaflets and sinuses. These structures, therefore, are formed in the most distal part of the proximal outflow tract, immediately upstream relative to the developing sinotubular junction. The cavitation of the cushions leaves the central luminal part of each cushion to form the arterial valvular leaflets, with the peripheral part arterialising to form the wall of the supporting valvular sinuses. The rightward and inferior of the intercalated cushions forms one sinus of the aortic valve, while the opposite leftward and superior intercalated cushion forms the non-adjacent sinus of the pulmonary valve. The adjacent sinuses and valvular leaflets, in contrast, are excavated from the fused distal parts of the proximal cushions, with each of the two fused cushions forming one sinus and leaflet of the aortic valve, together with the adjacent sinus and leaflet of the pulmonary valve. [7]

The definitive fetal cardiac structure is developed by 8 weeks.

2. Histological structure

Function of normal heart valves is based on their properties of ensuring unidirectional blood flow without regurgitation. They open and close 40 million times a year and 3 billion times over a lifetime. This property depends on the mobility, pliability, and structural integrity of their leaflets. The competency of the aortic valvular complex depends on the stretching and molding of its 3 cusps to fill the orifice during the closed phase of the cardiac cycle. [9]

2.1. Dynamic relations between the aortic valvular complex and its histological structure

The substantial changes in size and shape of the valve cusps and leaflets that occur during the cardiac cycle are facilitated by a highly complex internal microarchitecture. The layered structure of the aortic valve is formed by: a dense collagenous layer close to the outflow surface, which provides the primary strength component, a central core of loose connective tissue, and an elastin layer below the inflow surface. The essential functional components of the heart valves comprises the valvular endothelial cells (VECs), the valvular interstitial cells (VICs), and extracellular matrix (ECM), including collagen, elastin and glycosaminoglycans. [9]

The major component of valve cusps is collagen, 43% to 55% (predominantly type I but also some type III) [10] and 11% elastin. The quantity, quality, and architecture of the valvular ECM, particularly collagen, elastin, and glycosaminoglycans, are the major determinants of not only the cyclical functional mechanics over the second-to-second periodicity of the cardiac cycle, but also the lifetime durability of a valve. The cells of the heart valves through complex cell-ECM interactions, transduce forces into molecular changes that mediate normal valve function and pathobiology. Through such mechanisms, healthy heart valves are able to maintain homeostasis, adapt to an altered stress state, and repair injury via connective tissue remodeling mediated by the synthesis, repair, and remodeling of the several ECM components. [9]

The most abundant cell type in the aortic valve are VICs. They are distributed throughout all of its layers, are crucial for valvular function [11] and synthesize the ECM. VICs mediate matrix remodeling and continuously repair functional damage to collagen and the other ECM components. As a response to injury VICs may translate from one phenotypic state to another during valvular homeostasis. The 5 distinct VIC phenotypes include embryonic progenitor endothelial/mesenchymal cells (eVICs), quiescent VICs (qVICs), activated VICs (aVICs), postdevelopmental/adult progenitor VICs (pVICs), and osteoblastic VICs (ob-VICs). [12] Adult heart valve VICs have characteristics of resting fibroblasts, are quiescent, without synthetic or destructive activity for extracellular matrix. They are activated by abrupt changes in the mechanical stress during intrauterine maturation. Once activated VICs can differentiate into a variety of other cell types, including myofibroblasts and osteoblasts. [11]

The blood-contacting surfaces of the aortic valve are lined by endothelial cells. VECs resemble to endothelial cells but evidence is increasing that VECs are phenotypically different from vascular endothelial cells elsewhere in the circulation, which is consistent with the increasing recognition of more widespread endothelial heterogeneity across circulatory sites,

[13] and the possibility that VECs may interact with VICs to maintain the integrity of valve tissues. [14] Evidence indicates that different transcriptional profiles are expressed by VECs on the opposite faces of a normal adult pig aortic valve and these may contribute to localization of early pathological aortic valve calcification [15]. Abnormal hemodynamic forces can cause tissue remodeling and inflammation which may lead to aortic valve diseases. [11]

2.2. Normal aortic valve development

An understanding of valve architecture and cellular changes that occur in cardiac valves during fetal development, maturation, and aging would provide mechanistic insights into the pathogenesis of congenital and acquired valve abnormalities and aid assessment of therapeutic strategies for valve disease. A study which performed quantitative histological assessment of 91 human semilunar valves obtained from second and third trimester fetus, neonates, children and normal adults found very interesting results. [16]

Valves must accommodate to substantial hemodynamic changes throughout lifetime. Large populations of VICs undergo phenotypic modulation to become activated myofibroblasts and return to quiescent fibroblasts during adaptive remodeling in response to changing environmental conditions. [17-19] VICs and VECs functions likely influence ECM synthesis and remodeling. Fetal valves possess a dynamic/adaptive structure and contain cells with an activated/immature phenotype. During postnatal life, activated cells gradually become quiescent, whereas collagen matures through increased fiber thickness and alignment. Fetal second-trimester semilunar (aortic and pulmonary) valves lack distinguishable layers, are composed primarily of proteoglycans, have no detectable elastin, small amounts of disorganized collagen, and are histologically identical. [20] Fetal valves structure differs, even late in gestation, from that of adult valves, which have a trilayered architecture with a highly specialized and functionally adapted ECM. The study demonstrated that fetal valves have much higher cellular densities than adult valves, associated with an increased cell proliferation-to-apoptosis ratio. VICs density was highest in the second trimester and decreased progressively throughout gestation and postnatally. Fetal VICs proliferation indices were likewise greater than those of adult valves. Valvular cell turnover is high during fetal development and continues at a low rate postnatally. [16]

They also demonstrated physiological activation of endothelial cells that consistently expressed high levels of SMemb, MMP-1, MMP-13, ICAM-1, and VCAM-1 in fetal and children's valves in contrast to adult valves. Valvular cells that are activated in utero undergo phenotypic changes at birth and gradually become quiescent, whereas collagen matures through increased fiber thickness and alignment. This suggests a progressive adaptation to the prevailing hemodynamic environment. [16]

3. Structure and anatomy of the aortic root

The aortic valve is the cardiac centerpiece and forms the bridge between the left ventricle and the ascending aorta. Its components are the sinuses of Valsalva, the fibrous interleaflet triangles, and the valvular leaflets themselves. [1]

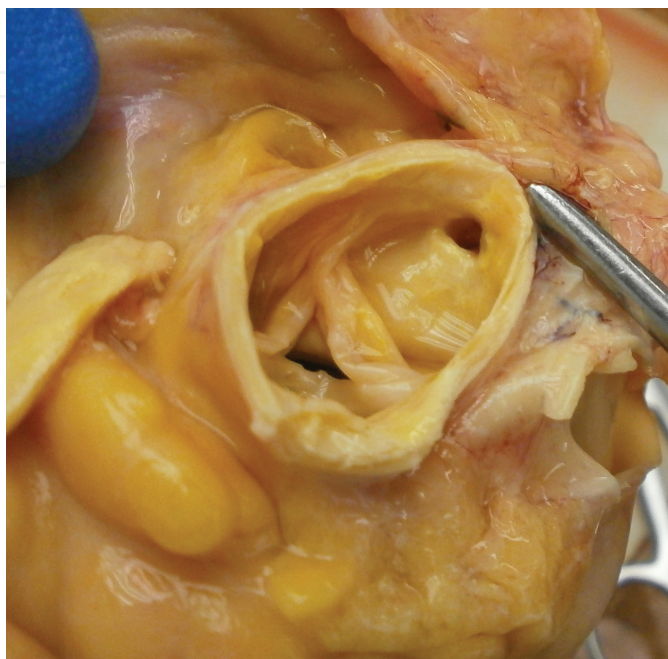


Figure 2. View of a dissected heart (the atrial chambers and the arterial trunks are removed). The heart is photographed from above. [4]

3.1. The “Annulus” controversy

When defined literally “annulus” refers to a little ring. The aortic root contains at least 3 circular rings and 1 crown-like ring. [21] The valvular leaflets are attached throughout the length of the root. Therefore, seen in 3 dimensions, the leaflets take the form of a 3-pronged coronet, with the hinges from the supporting ventricular structures forming the crown-like ring (Figure 1). The base of the crown is a virtual ring, commonly known as “annulus”. This plane represents the inlet from the left ventricular outflow tract into the aortic root and is the diameter that is typically analysed by the echocardiographer when providing measurements of the diameter of the annulus.

The controversy arises from the fact that on one hand there are multiple rings described and on the other hand, the term “annulus” appears to describe a circle, a fibrous ring on which the leaflets are inserted, but such a structure does not exist in the anatomy of the aortic valve. No consensus has been found yet.

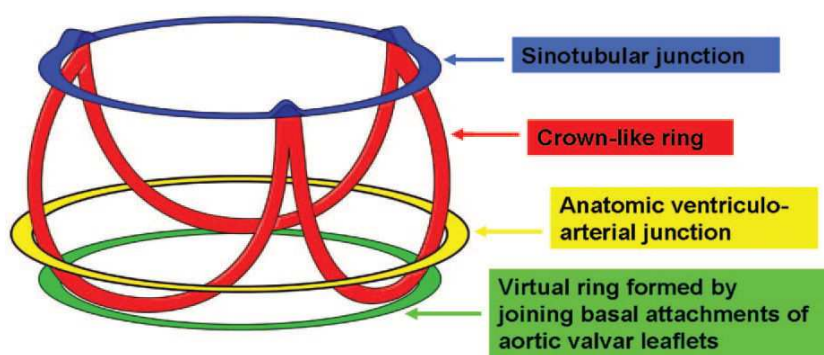


Figure 3. The “rings” of the aortic root [1]

3.2. Anatomic versus hemodynamic ventriculo-arterial junction

As we have shown in figure 3, there is a marked discrepancy between the circular anatomic junction and the semilunar hemodynamic junction. [22] The hemodynamic junction separates the root into those compartments exposed to aortic as opposed to left ventricular pressures. By virtue of the semilunar attachments of the leaflets, portions of the fibrous aortic root are exposed to ventricular pressures, these being the superior portions of the interleaflet triangles, whereas portions of the left ventricle are exposed to aortic pressures, these being the most basal portions within the sinus of Valsalva. [1]

3.3. Aortic sinuses, location of the coronary arteries and sinotubular junction

The spaces between the luminal surface of the three bulges on the aortic root and their respective valvular leaflets are known as the aortic sinuses of Valsalva. [5] The sinuses are named according to the arteries arising from within them (right, left, and noncoronary). The right sinus structures have the greatest dimensions followed by the non coronary sinus, and finally the left coronary sinus. [23]

Distance between the ostium and Valsalva's sinus		Sex	
		Male	Female
Left commissure	left coronary	9.7	9.3
	right coronary	11.2	10.7
Right commissure	left coronary	10.9	10.8
	right coronary	11.3	9.9
Bottom of the Valsalva's sinus	left coronary	13.4	13.0
	right coronary	15.0	13.8

Table 1. Mean values of the distances of the ostium and its relation to the corresponding Valsalva's sinus (in mm) in both sexes (adapted from [24])

In the majority of cases, the orifices of the coronary arteries arise within the 2 anterior sinuses of Valsalva, usually positioned just below the sinotubular junction, but are rarely centrally located. It is not unusual, however, for the arteries to be positioned superior relative to the sinotubular junction. Accessory coronary arterial orifices are found in the majority of the anterior aortic sinuses. [25]

Several studies emphasize on the importance of large variations of coronary ostia origins. Also, there are significant differences between in vivo and ex vivo measurements regarding the right coronary ostium. [26,27]

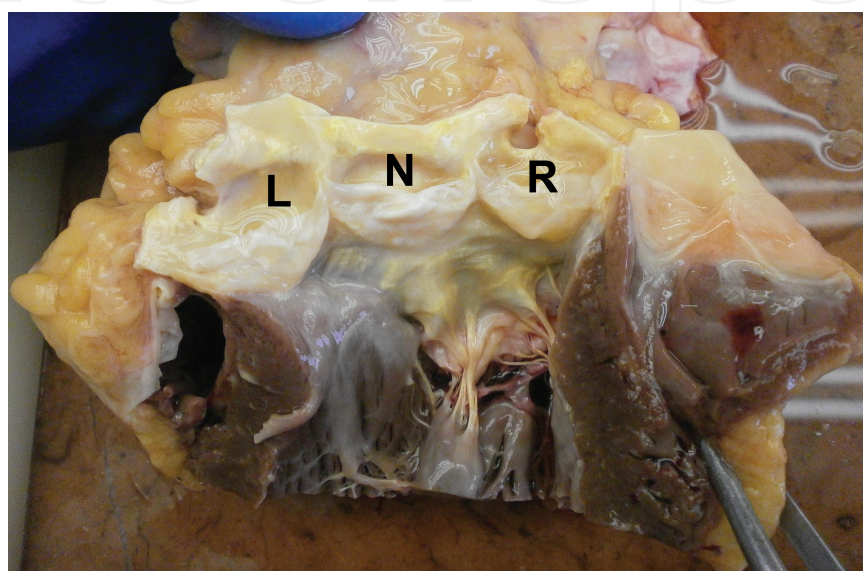


Figure 4. Left (L) and right (R) aortic sinuses that give origin to the main coronary arteries and the non-coronary (N) sinus. [5]

The superior border of the sinuses is the sinotubular junction (also known as the supra-aortic ridge). On the outside, the sinotubular junction is where the tubular portion of the aorta joins onto the sinusal portion. Inside, there is usually a slightly raised ridge of thickened aortic wall. But the sinotubular junction is not perfectly circular. It takes on the contour of the three sinuses, giving it a mildly trefoil or scalloped outline. [5]

A comparison between the circumferences measured at the level of the sinotubular junction and at the level of the aortic root base shows that the circumference of the sinotubular junction is 95% of the circumference measured at the aortic root base. [23]

3.4. Aortic valvular leaflets

The normal aortic valve has three leaflets. Each of the three leaflets has a free margin and a margin where it is attached in semilunar fashion to the aortic root. The maximal height of each leaflet is considerably less than that of its sinus on account of its scoop-shaped free margin. When the valve opens, the leaflets fall back into their sinuses without the potential of occluding any coronary orifice. The semilunar hingelines of adjacent leaflets meet at the level of the sinotubu-

lar junction, forming the commissures. The body of the leaflets are pliable and thin in the young, although its thickness is not uniform. With age, the leaflets become thicker and stiffer.

Each leaflet has a somewhat crimped surface facing the aorta and a smoother surface facing the ventricle. The leaflet is slightly thicker towards its free margin. On its ventricular surface is the zone of apposition, known as the lunulae, occupying the full width along the free margin and spanning approximately one-third of the depth of the leaflet. This is where the leaflet meets the adjacent leaflets during valvular closure. At the midportion of the lunulae, the ventricular surface is thickened to form the nodule of Arantius that extends along 60% of the inferior margin of the lunulae. When the valve is in closed position, the inferior margin of the lunulae meet together, separating blood in the left ventricular cavity from blood in the aorta. Fenestrations in the lunulae are common, especially in the elderly, but the valve remains competent because they are above the closure line. [5]

The leaflets have a core of fibrous tissue, with endothelial linings on their arterial and ventricular aspects. Their origin from the supporting left ventricular structures, where the ventricular components give rise to the fibroelastic walls of the aortic valvular sinuses, marks the anatomic ventriculo-arterial junction. Significantly, in those areas where the leaflets arise from the ventricular myocardium, their basal attachments are well below the level of the anatomic ventriculo-arterial junction. [1]

Leaflet	Measure	Sex	
		Male	Female
Left coronary	Leaflet height	15.2	14.9
	Lunulae width	4.6	4.3
	Lunulae length	30.7	29.3
	External intercommissural distance	25.4	23.5
	Internal Intercommissural distance	20.0	18.5
Right coronary	Leaflet height	15.2	14.5
	Lunulae width	4.4	4.2
	Lunulae length	30.4	27.9
	External intercommissural distance	24.5	23.8
	Internal Intercommissural distance	19.2	18.7
Noncoronary	Leaflet height	15.0	14.6
	Lunulae width	4.3	4.2
	Lunulae length	30.3	28.2
	External intercommissural distance	24.4	22.1
	Internal Intercommissural distance	20.1	19.1

Table 2. Mean values of the height of the leaflets and size of the lunulae (width and length) and internal intercommissural distances in mm in both sexes (adapted from [24])

Variations exist among individuals in the dimensions of the root, but in the same individual, there can be marked variations in all aspects of the dimensions of the individual leaflets, including the height, width, surface area and volume of each of the supporting sinuses of Valsalva. [28, 29, 30] A study of 200 normal hearts revealed that the average width, measured between the peripheral zones of attachment along the sinus ridge, for the right, the noncoronary, and the left coronary leaflets was 25.9, 25.5, and 25.0 mm, respectively. [28]

3.5. Interleaflet fibrous triangles

As a result of the semilunar attachment of the aortic valvular leaflets, there are 3 triangular extensions of the left ventricular outflow tract that reach to the level of the sinotubular junction. [31] These triangles, however, are formed not of ventricular myocardium but of the thinned fibrous walls of the aorta between the expanded sinuses of Valsalva. Their most apical regions represent areas of potential communication with the pericardial space or, in the case of the triangle between the right and left coronary aortic leaflets, with the plane of tissue interposed between the aorta and anteriorly located sleeve-like subpulmonary infundibulum. [1]

The triangles are thinner and less collagenous than the hingelines or the sinusal walls. These areas are potential sites of aneurysmal formation. [32]

3.6. The relationships of the aortic root

The aortic root is positioned to the right and posterior relative to the subpulmonary infundibulum. The leaflets of the aortic valve are attached only in part to the muscular walls of the left ventricle, since so as to fit the orifices of both aortic and mitral valves within the circular profile of the left ventricle, there is no muscle between them in the ventricular roof. The aortic root, furthermore, is wedged between the orifices of the two atrioventricular valves. The root is related to all four cardiac chambers. [4]

The plane of the aortic valve tilts inferiorly at an angle to the pulmonary valve. The nadirs of the aortic sinuses lie in a plane at an angle of 30° from the horizontal. [32] Thus, the arterial surface of the closed leaflets of the aortic valve is directed not only upwards but also rightward at an angle of at least 45° to the median plane. [33]

3.6.1. Relationship between the left ventricular outflow tract and the aortic root

The left ventricular outflow tract is composed of a muscular component and a more extensive fibrous component. The orientation of the outflow tract is known to change with aging. In individuals aged under 20 years, the angle varies between 135 and 180 degrees and the left ventricular outflow tract represents a more direct and straight extension into the aortic root. In hearts from individuals aged over 60 years, the angle varies between 90 and 120 degrees and the left ventricular outflow tract may not extend in straight fashion into the aortic root but rather in a rightward “dog leg”. [1]



Figure 5. A dissected atrioventricular junction viewed from above showing how the aortic valve wedges itself between the mitral and tricuspid valves (reproduced from <http://www.rjmatthewsmd.com>)

3.6.2. Interleaflet triangles and their relationship to the mitral valve and membranous septum

Guarding the left ventricular outflow tract, the aortic root also has an intimate relationship with the ventricular septum and the mitral valve. In attitudinal orientation, it is apparent that the aortic root leans rightward slightly, over the ventricular septum, to overly the right ventricle. In the elderly, the relationship between septal crest and aortic root changes to give a sigmoid-shaped ventricular septum. [4]

Relative to the aorta, the mitral valve is located posterior and to the left, the tricuspid valve is located inferiorly and to the right.

The ends of the area of fibrous continuity are thickened to form the left and right fibrous trigones. The interleaflet triangle between the noncoronary and left coronary leaflet is part of the area of fibrous continuity because the aortic-mitral curtain seen from within the left ventricular outflow tract represents the equivalent of the anterior mitral valvular annulus. The interleaflet triangle located between the right coronary and noncoronary aortic leaflets is confluent with the membranous septum. Together, the membranous septum and the right fibrous trigone 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. [1]

3.6.3. Relationship between the aortic valve and the conduction system

The atrioventricular node, located in the wall of the right atrium at the apex of the triangle of Koch, is relatively distant from the root. As the conduction axis, penetrates to the left, through the central fibrous body, however, it is positioned at the base of the interleaflet tri-

angle between the non- and right coronary aortic sinuses. Having penetrated through the fibrous plane providing atrioventricular insulation, the bundle then branches on the crest of the muscular ventricular septum, the left bundle branch fanning out on the smooth left ventricular side, while the cord-like right bundle branch penetrates back through the muscular septum, emerging on the septal surface in the environment of the medial papillary muscle (figure 6). [4]

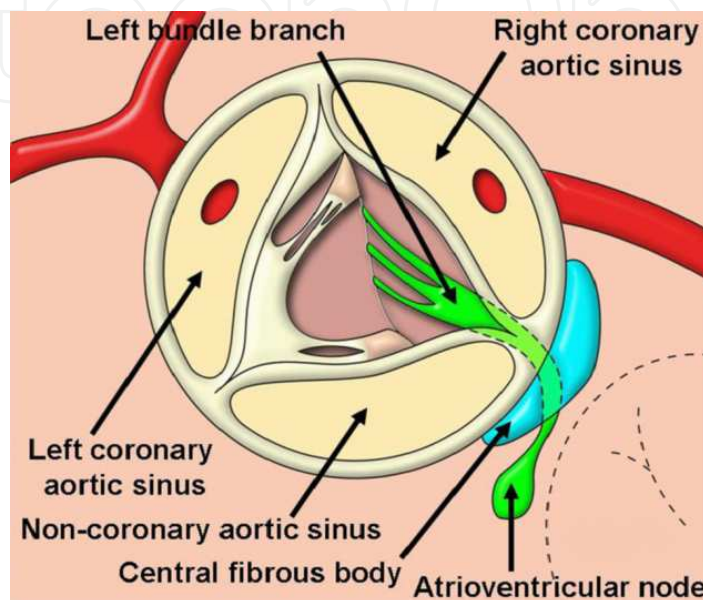


Figure 6. Aortic sinuses, coronary arteries and the the location of the atrioventricular conduction axis, as seen by looking down through the aortic root (schematic from [4])

4. Microscopic anatomy

The aortic valve is composed of different structures, each one with its own histological profile. The histology of the aortic root is characterized by a gradual shift from the primarily elastic aorta to the muscular ventricle. [31]

The annulus is a dense collagenous meshwork, in which elastic and collagenous fibrils and also neuronal structures are present. At the commissure level originate the collagen fibres of the intermediate layer, which are orientated in a radial fashion. Here, they do not only infiltrate the intima layer of the aortic root, but they also radiate into the media layer where they are anchored. The endothelial cells are separated by the basal layer from the elastic fibres and collagenous fibrils. The endothelial cells show microvilli at their surface, which increase the overall surface area for an increased exchange of substances.

The interleaflet triangles are different in their microscopic structure. The triangle between the left-coronary and non-coronary sinus forms part of the aortic-mitral valvular curtain, is histologically fibrous and equivalent to the mitral valve leaflet structure. The triangle be-

tween the non-coronary and the right-coronary aortic sinus is incorporated within the membranous part of the septum and is also made of fibrous tissue. In contrast, the triangle between the right-coronary and left-coronary sinus in the area of the subpulmonary infundibulum is supported by muscular tissue and only fibrous at its apex.

The sinuses are arranged with very different components, but the largest part of all the three sinuses is composed in a similar manner to the three layers of the aortic wall: tunica intima, tunica media and tunica externa (adventitia). The inner layer of the intima is composed of endothelial cells arranged in the direction of the vessel. The subendothelial connective tissue is arranged in the same manner as the endothelial cells. This layer is divided from the intima by the membrana elastica interna. The media is composed of circular arranged structures: smooth muscle cells, elastic fibres, collagen fibres type II and III and proteoglycans. The adventitia is the external layer. It is separated from the intima by the membrana elastica externa. Similar to the intima, the elements of the adventitia are arranged in a longitudinal fashion and composed of collagen fibres of type I. The sinotubular junction shows the same principal arrangement of tissue elements compared with the sinuses and the ascending aorta, but the diameter of the wall is thicker. [34]

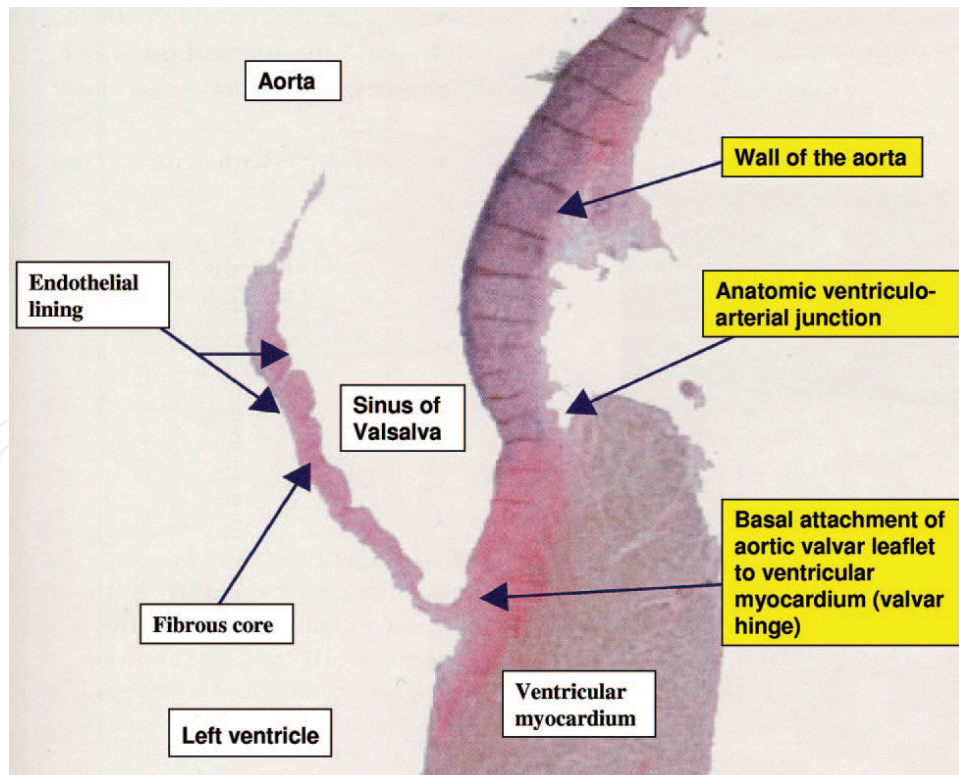


Figure 7. Histology of the aortic valvular complex [1]

The aortic valve leaflet is a three-layered structure (lamina ventricularis, lamina spongiosa and lamina fibrosa) composed of differing amounts of collagen, elastin, and glycosaminoglycans, that form a well-defined honeycomb or spongelike structure, suggesting that elastin forms a matrix that surrounds and links the collagen fiber bundles. [35] The leaflets are covered by a continuous layer of endothelial cells with a smooth surface on the ventricular side and numerous ridges on the arterial side. The arrangement of the endothelial cells is across, not in line with the direction of flow. [36]

5. Surgical anatomy

A thorough knowledge of the anatomy of the aortic valve and its relations to the surrounding cardiac structures is a prerequisite for the successful completion of the repair or replacement performed by the surgeon.

Surgical descriptions of the aortic root are not always similar with the anatomical descriptions, leading to a series of confusional data. Also the *in vivo* measurement of the valve components don't always correspond to the *ex vivo* measurements, in part due to the movement of the heart and its structures during the cardiac cycle.

By sequentially following the line of attachment of each leaflet, the relationship of the aortic valve to its surrounding structures can be clearly understood. Beginning posteriorly, the commissure between the noncoronary and left coronary leaflets is positioned along the area of aorto-mitral valvular continuity. The fibrous subaortic curtain is beneath this commissure. To the right of this commissure, the noncoronary leaflet is attached above the posterior diverticulum of the left ventricular outflow tract. Here the valve is related to the right atrial wall. As the attachment of the noncoronary leaflet ascends from its nadir toward the commissure between the noncoronary and right coronary leaflets, the line of attachment is directly above the portion of the atrial septum containing the atrioventricular node. The commissure between the noncoronary and right coronary leaflets is located directly above the penetrating atrioventricular bundle and the membranous ventricular septum. The attachment of the right coronary leaflet then descends across the central fibrous body before ascending to the commissure between the right and left coronary leaflets. Immediately beneath this commissure, the wall of the aorta forms the uppermost part of the subaortic outflow. An incision through this area passes into the space between the facing surfaces of the aorta and pulmonary trunk. As the facing left and right leaflets descend from this commissure, they are attached to the outlet muscular component of the left ventricle. Only a small part of this area in the normal heart is a true outlet septum, since both pulmonary and aortic valves are supported on their own sleeves of myocardium. Thus, although the outlet components of the right and left ventricle face each other, an incision below the aortic valve enters low into the infundibulum of the right ventricle. As the lateral part of the left coronary leaflet descends

from the facing commissure to the base of the sinus, it becomes the only part of the aortic valve that is not intimately related to another cardiac chamber. [37]

6. Ecocardiographic anatomy

The ability to record high-quality echocardiographic images and obtain accurate Doppler flow recordings are essential determinants of the overall value of the echocardiographic examination. As such, echocardiography is highly operator dependent. It is difficult to over-emphasize the critical role of the person who performs the imaging. To obtain a comprehensive and accurate echocardiogram, the echocardiographer must understand the anatomy and physiology of the aortic valve and have a thorough knowledge of the ultrasound equipment to optimize the quality of the recording. [38]

6.1. Transthoracic Echocardiography (TTE)

Anatomic evaluation of the aortic valve is based on a combination of short- and long-axis images to identify the number of leaflets, and to describe leaflet mobility, thickness, and calcification.

Two-dimensional imaging of the normal aortic valve in the parasternal long axis view demonstrates two leaflets (right and noncoronary), while the parasternal short axis demonstrates a symmetrical structure with three uniformly thin leaflets that open equally, forming a circular orifice during most of systole. During diastole, the normal leaflets form a three pointed star with a slight thickening or prominence at the central closing point formed by the aortic leaflet nodules, known as the nodules of Arantius. The three aortic valve leaflets may also be visualized in a subcostal view.

The aortic valve leaflets appear thin and delicate and may be difficult to visualize. In the long-axis view, the leaflets open rapidly in systole and appear as linear parallel lines close to the walls of the aorta. With the onset of diastole, they come together and are recorded as a faint linear density within the plane of the aortic annulus. Because the velocity of valve motion during opening and closing is high relative to the frame rate of most echocardiographic systems, the normal aortic valve is usually visualized either fully opened or closed but rarely in any intermediate position. In the basal short-axis view, the three aortic leaflets can be visualized within the annulus during diastole. The three lines of coaptation can be recorded, normally forming a Y (sometimes referred to as an inverted Mercedes-Benz sign). With the onset of systole, the leaflets open out of the imaging plane, providing a view of the aortic annulus. The short-axis perspective is most helpful to determine the number of leaflets and whether fusion of one or more commissures is present. In patients who are difficult to image, normal leaflets are so delicate that they are hard to visualize, generally an indication that they are morphologically normal. [38]

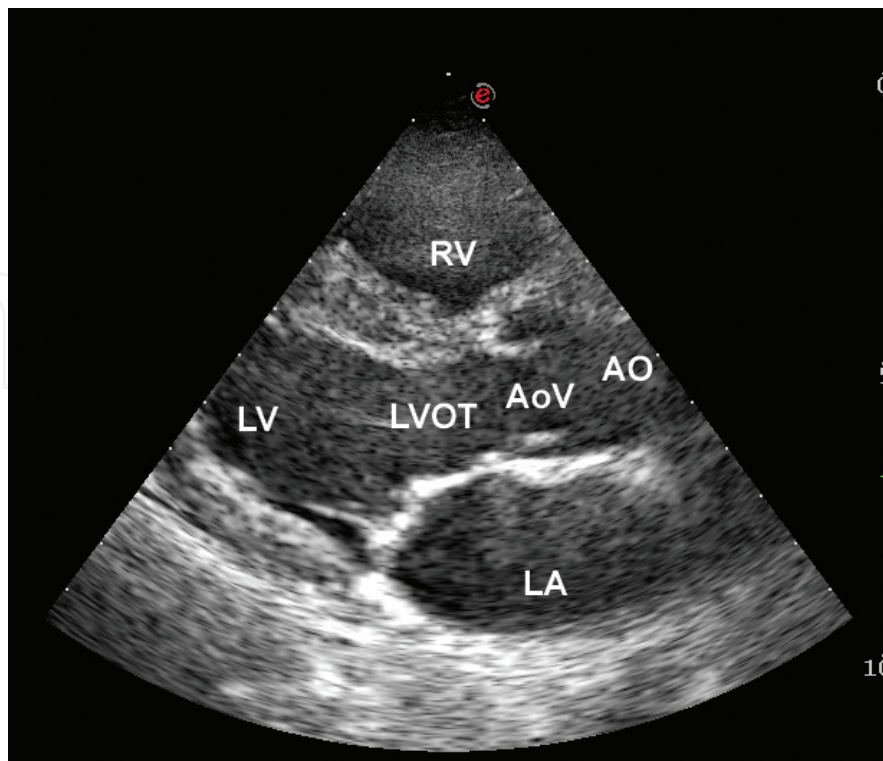


Figure 8. Transthoracic echocardiogram, parasternal long axis view. Aortic valve is open (author's collection).

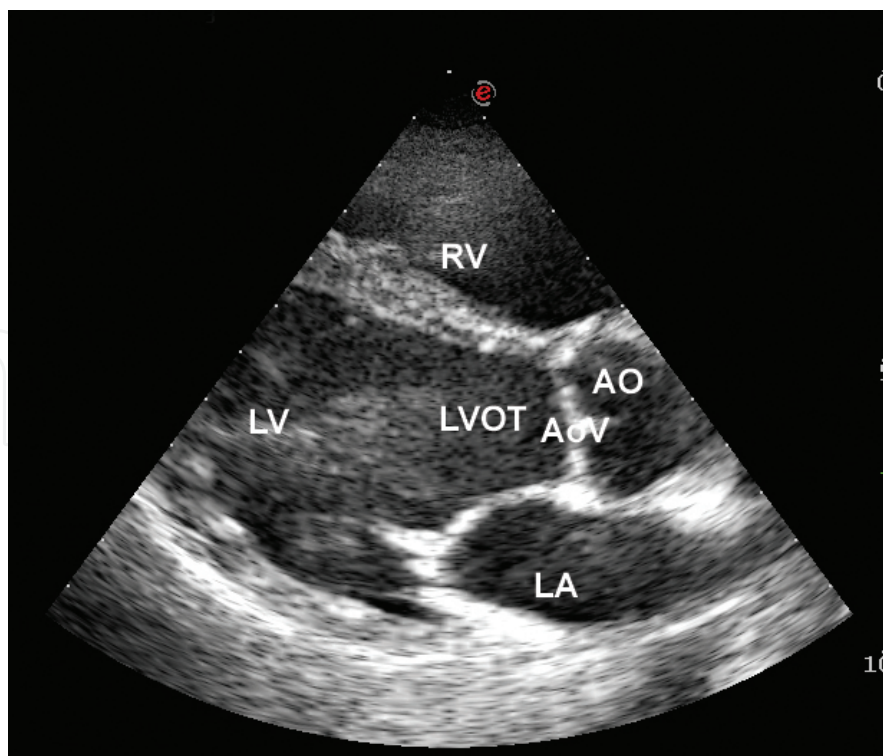


Figure 9. Transthoracic echocardiogram, parasternal long axis view. Aortic valve is closed (author's collection).

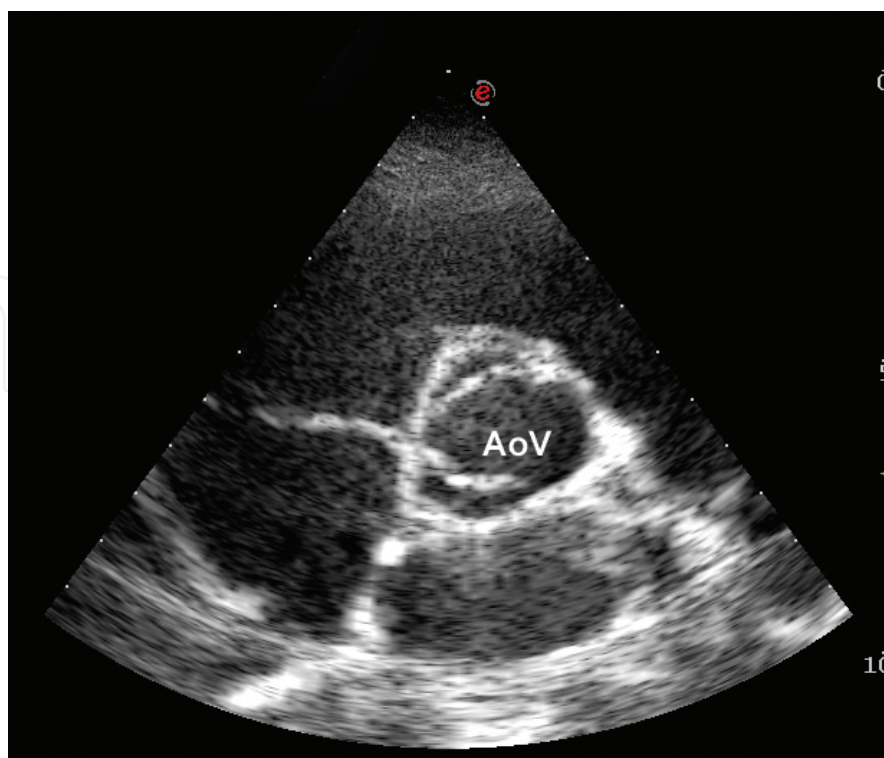


Figure 10. Transthoracic echocardiogram, suprasternal view. Aortic valve is open (author's collection).

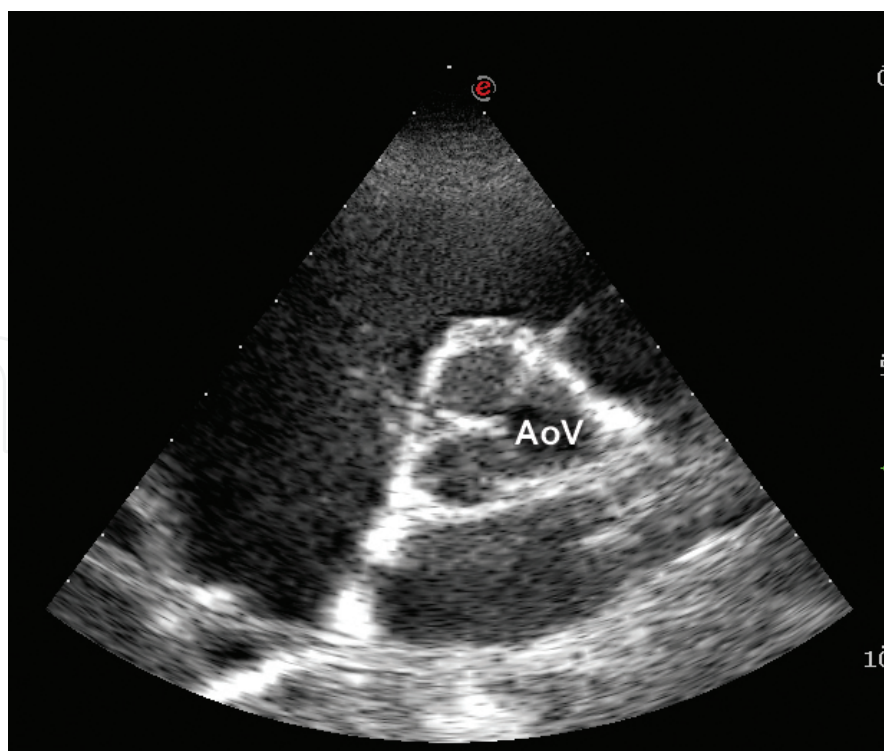


Figure 11. Transthoracic echocardiogram, suprasternal view. Aortic valve is closed (author's collection).

6.2. Transesophageal Echocardiography (TEE)

Transthoracic imaging usually is adequate, although TEE may be helpful when image quality is suboptimal.

To characterize the aortic valve using TEE, the valve should be imaged in short-axis view (the aortic valve can generally be visualized in a plane between 30 to 60° from the transverse 0°) and long-axis view (typically at 120 to 160° from transverse 0°).

The short-axis view is the only view that provides a simultaneous image of all three leaflets. The leaflet adjacent to the atrial septum is the noncoronary leaflet, the most anterior is the right coronary leaflet, and the other is the left coronary leaflet. The probe is withdrawn or anteflexed slightly to move the imaging plane superiorly through the sinuses of Valsalva to bring the right and left coronary ostia and then the sinotubular junction into view. The probe is then advanced to move the imaging plane through and then proximal to the AV annulus to produce a short axis view of the left ventricular outflow tract. The mid esophageal short-axis view at the level of the leaflets is used to measure the length of the free edges of the leaflets and the area of the aortic valve orifice by planimetry.

In the long axis view, the left ventricular outflow tract appears toward the left of the display and the proximal ascending aorta toward the right. The leaflet that appears anteriorly or toward the bottom of the display is always the right coronary, but the leaflet that appears posteriorly in this cross-section may be the left or the noncoronary, depending on the exact location of the imaging plane as it passes through the valve. The mid esophageal long-axis view is the best cross-section for assessing the size of the aortic root by measuring the diameters of the annulus, sinuses of Valsalva, sinotubular junction and proximal ascending aorta, adjusting the probe to maximize the internal diameter of these structures. The diameter of the annulus is measured during systole at the points of attachment of the aortic valve leaflets to the annulus and is normally between 1.8 and 2.5 cm.

The deep transgastric view is obtained by advancing the probe deep into the stomach and positioning the probe adjacent to the left ventricular apex. The exact position of the probe and transducer is more difficult to determine and control deep in the stomach, but some trial and error flexing, turning, advancing, withdrawing, and rotating of the probe develops this view in most patients. In the deep transgastric long-axis view, the aortic valve is located in the far field at the bottom of the display with the left ventricular outflow tract directed away from the transducer. Detailed assessment of valve anatomy is difficult in this view because the left ventricular outflow tract and aortic valve are so far from the transducer, but Doppler quantification of flow velocities through these structures is usually possible. [39]

The TEE examination is also performed intraoperative to refine and confirm preoperative diagnosis, to assess the etiology and severity of aortic valve disease, to measure the annulus and to prepare the surgeon for other alternatives.

6.3. Three-Dimensional Echocardiography (3DE)

3DE represents a major innovation in cardiovascular ultrasound. Advancements in computer and transducer technologies permit real-time 3DE acquisition and presentation of cardiac structures from any spatial point of view.

A complete 3D TTE exam requires multiple acquisitions from the parasternal, apical, subcostal, and suprasternal transducer positions. Because the volume-rendered 3D data set can be cropped to display a variety of intracardiac structures by choosing different cut planes as an alternative to “view” (referred to heart’s orientation to the body axis), “anatomic planes” (referred to the heart itself) can be used to describe image orientation. [40]

For the visualization of the aortic valve the 3DE TTE protocol is the parasternal long-axis view with and without color (narrow angle and zoomed acquisitions) and the 3DE TEE protocol is the 60° mid-esophageal, short-axis view with and without color (zoomed or full-volume acquisition) and the 120° mid-esophageal, long-axis view with and without color (zoomed or full-volume acquisition).

The common approaches for imaging the aortic valve by 3D TTE are from the parasternal and apical views. Three-dimensional data sets including the aortic root can be cropped and rotated for a dynamic 3D rendering of the aortic valve, which can be visualized from both the aortic and ventricular perspectives, as well as sliced in any desired longitudinal or oblique plane.

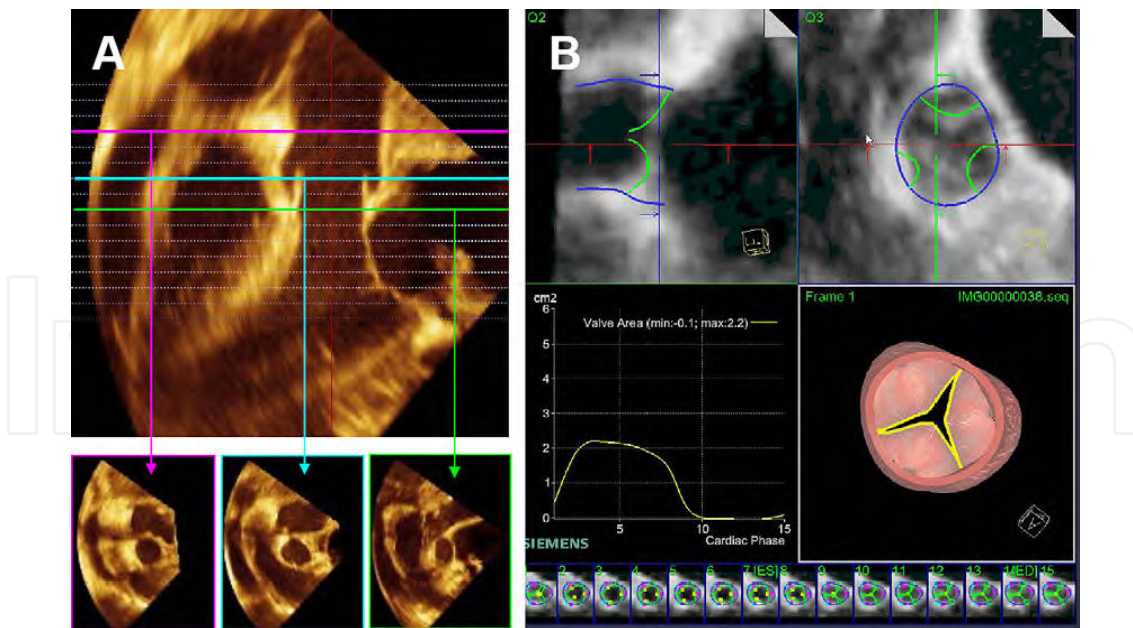


Figure 12. Three-dimensional TEE data set cropped to demonstrate the aorta in long axis (A, top). Using this image, in face views of the sinotubular junction (A, bottom left), sinus of Valsalva (A, bottom middle), and aortic annulus (A, bottom right) can be obtained for assessment. Dynamic, automatic tracking of the aortic valve leaflets (B, top left) and annulus (B, top right) can be performed, providing aortic valve area throughout the cardiac cycle (B, middle left and bottom strip). A model derived from the automated tracking is also produced (middle right). [41]

Real-Time 3D can be realized by obtaining a TEE 2D image of the aortic valve at either the 60° midesophageal, short-axis view or the 120° midesophageal, long-axis view. After the 2D image is optimized, narrow-angled acquisitions can be used to optimize the 3D image and to examine aortic valve and root anatomy. After acquisition, the aortic valve should be oriented with the right coronary cusp located inferiorly, regardless of whether the aortic or the left ventricular outflow tract perspective is presented.

Color Doppler 3D TEE imaging should also be performed to detect the initial appearance of flow at the onset of systole. [41]

7. Functional anatomy

The aortic root is a complex structure that requires analysis part by part but always remembering that all the parts contribute to form one functional unit, a three-dimensional structure adjoining distally to the aorta and proximally to the ventricle.

The aortic valve, like the pulmonary valve, has no tensor apparatus (i.e., chordae tendineae or papillary muscles). The commissures form tall, peaked spaces between the attachments of adjacent leaflets and attain the level of the aortic sinotubular junction, the ridge that separates the sinus and tubular portions of the ascending aorta. The functional aortic valve orifice can be at the sinotubular junction or proximal to it. [42]

The three half moon-shaped leaflets form pocket-like tissue flaps that are avascular. Just below the free edge of each leaflet is a ridgelike closing edge. At the center of each leaflet, the closing edge meets the free edge and forms the nodule of Arantius. Between the free and closing edges, to each side of the nodule are two crescent-shaped areas known as the lunulae, which represent the sites of leaflet apposition during valve closure. Lunular fenestrations, near the commissures are common and increase in size and incidence with age. [43] However, owing to their position distal to the closing edge, they rarely produce valvular incompetence. [42] When viewed from above, the linear distance along the closing edge of a leaflet is much greater than the straight-line distance between its two commissures. This extra length of leaflet tissue is necessary for nonstenotic opening and nonregurgitant closure of the valve. [6] Normally, the diameter of the aortic annulus at the hinge points of the aortic valve is about equal to the diameter of the ascending aorta at the sinotubular junction. [44] When the valve opens, the leaflets fall back into their sinuses without the potential of occluding any coronary orifice. The semilunar hingelines of adjacent leaflets meet at the level of the sinotubular junction, forming the commissures. The body of the leaflets are pliable and thin in the young, although its thickness is not uniform.

The commissure between the right and posterior aortic leaflets overlies the membranous septum and contacts the commissure between the anterior and septal leaflets of the tricuspid valve. The commissure between the right and left aortic leaflets contacts its corresponding pulmonary commissure and overlies the infundibular septum. The intervalvular fibrosa, at the commissure between the left and posterior aortic cusps, fuses the aortic valve to the anterior mitral leaflet. [6, 42]

A study of 100 formalin-fixed hearts from adult patients with normally functioning aortic valves found that the luminal area of the aorta at the sinotubular junction increased with age and with heart weight, where increased heart weight was attributed to systemic hypertension. [45] Volume-wise, the sinuses are largest when the valve closes, serving as reservoirs during ventricular diastole and allow filling of the coronary arteries.

When left ventricular pressure exceeds that in the aortic root, the valvular leaflets are pushed apart and fall back into their respective sinuses, allowing unimpeded ejection of blood. The orifices of the coronary arteries are commonly found close to the level of the sinotubular junction. [25]

8. Conclusion

In the new era of cardiac surgery, now more than ever, the need to further study the aortic valve complex anatomy and function is greater.

A thorough knowledge of the anatomy of the aortic valve and its relationships is essential to understanding aortic valve pathology and many congenital cardiac malformations. Also it is crucial for the diagnosis and treatment (both surgical and conservatory) of aortic valve pathology.

Accurate understanding of the anatomy of interest is of cardinal importance for the development of devices and treatment protocols. We emphasize the importance of considering anatomic variations in the development of treatments, an understanding of the intraindividual and interindividual variations that may exist can lead to refinements in current designs of valvular prostheses.

Although the aortic valve is the most intensely studied cardiac valve, there is still no consensus on how to describe its components and a universal terminology is yet to be found. The multidisciplinary approach will continue to be crucial in working through these challenges.

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