Revisiting the Anatomy of the Living Heart
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An understanding of the complexity of cardiac anatomy is required by all who seek, in the setting of cardiac disease, to interpret the images confronting them. Although the mysteries of cardiac structure have been extensively addressed, significant gaps continue to exist between the descriptions provided by morphologists and by those working in the clinical setting. In part, this reflects the limitations in providing 3D visualization of such a complicated organ. Current 3D imaging technology now permits visualization of the cardiac components using datasets obtained in the living individual. These advances, furthermore, demonstrate the anatomy in the setting of the heart as imaged within the thorax. It has been failure to describe the heart as it lies within the thorax that remains a major deficiency of many morphologists relying on the dissecting room to provide the gold standard. Describing the heart in an attitudinally appropriate fashion, a basic rule of clinical anatomy, creates the necessary bridges between anatomists and clinicians. The rapid progression of cardiac interventional techniques, furthermore, emphasizes the need to revisit cardiac anatomy using a multidisciplinary approach. In this review, therefore, we illustrate the advantages of an attitudinally correct approach to cardiac anatomy. We then focus on the morphology of the arterial roots, revealing the accuracy that can now be achieved by clinicians using datasets obtained during life. (Circ J 2016; 80: 24–33)

Key Words: Arterial roots; Attitudinally correct nomenclature; Clinical anatomy; Computed tomography; Heart

There is no question that, in term of its morphology, the heart is remarkably complex. A precise understanding of cardiac anatomy, nonetheless, is a prerequisite for those who seek to understand cardiac function, not only in the normal heart, but the more so when the heart is diseased. Detailed accounts of cardiac anatomy are proven, but even the best of these existing accounts, based on dissections of autopsied hearts, have limitations when used as the basis for understanding the architecture and relationships of the components of the living heart. The 2D images obtained using autopsied hearts can be difficult for clinical cardiologists to understand, particularly if the specimens themselves have been prepared and displayed in a non-clinical fashion.

In this respect, the rapid recent developments in clinical imaging can now serve to bridge the gap between morphologists and clinical cardiologists, specifically the gap between the anatomy of the autopsied heart and that observed in the living individual. Those using clinical imaging have now shown that even the most nuanced of cardiac anatomy can be revealed.1–3 It can now justifiably be argued that such features are demonstrated with even greater accuracy during life than in the autopsy room.4 This means that investigations using techniques such as multidetector computed tomography can now provide the new gold standard.5 There is then an even more pressing reason for considering the imaging analysis of the living heart as providing the new gold standard. When described on the basis of reconstructed 3D datasets, the software used shows the precise relationships of the cardiac components within the thorax. The various structures can then be described in an attitudinally appropriate fashion, a basic rule of clinical anatomy.6–8 Only when the cardiac components are described as seen during life will clinicians intuitively communicate in an entirely logical fashion. This is now the more important in the light of the rapid progress made in cardiac interventional techniques.9–13

The time is ripe, therefore, to revisit clinical anatomy on the basis of the multidisciplinary approach now achieved using the cooperated effort of anatomists, cardiologists, and radiologists.1,2,14–16 In this review, we begin by discussing how cardiologists can now reconstruct the images provided by computed tomography so as to put the heart back into the thorax. We then show that, having achieved this goal, it is optimal to describe the structures observed in an attitudinally appropriate fashion. Finally, we focus in greater detail on the structure of the arterial roots, demonstrating the exquisite detail that is now at the fingertips of all clinicians preparing datasets using 3D imaging techniques such as computed tomography.
Acquisition of Images and Reconstruction for Cardiac Anatomy

All features of normal cardiac anatomy can now readily be reconstructed using the volume datasets routinely collected from adult patients who undergo ECG-gated and contrast-enhanced coronary arterial computed tomographic angiography. Such datasets can be obtained by all who have access to commercially available multidetector-row computed tomographic scanners. The images can be reconstructed using either maximum or minimum intensity projection, combined with multiplanar reconstruction and appropriate volume-rendering. In the images to be shown in our review, selected structures were reconstructed and colored separately on the basis of the attenuation value determined prior to merging. It is possible to make cuts in any direction to provide merged volume-rendered images. All our images were obtained and manipulated using a commercially available workstation (Ziostation 2 ver. 2.4.0.3.; Ziosoft Inc., Tokyo, Japan).

In addition to the reconstructions that are routinely made using such workstations, several additional methods can be used comprehensively to demonstrate the 3D anatomy, depending on the focus of attention and the structures selected for rendering. So-called “dye-cast” imaging, for example, can be used to extract a chosen cardiac chamber, or indeed all the cardiac chambers (Figure 1). This approach is comparable to conventional dye-casting as used when modelling autopsied hearts. Although this technique demonstrates well the relationship between the chambers (Figure 1), the technique shows only the cavities of the cardiac components, with walls and septa not reconstructed in these images.

It is the use of virtual dissection that permits retraction of the chambers enhanced using dye-casting, thus visualizing the walls and septa. Each segmented structure can then be selectively colored, or made transparent, to make the images more comprehensive. These images are obviously of far greater value for interventional cardiologists, because it is the walls and partitions that are their main targets (Figure 2).

But because the spatial resolution of the 3D image provided by virtual dissection is frequently lower than that of the 2D multiplanar images used for reconstruction, thin structures such as valvar leaflets are not well visualized in the volume-rendered image (Figure 2). This limitation can be circumvented by converting the plane-cut surface of the volume-rendered image into the 2D multiplanar image used for reconstruction. It is also possible to create shells by extracting only the surfaces of the volume of interest. The latter technique proves useful when recognizing the outlook of the structure by freely adjusting transparency. Combining these methodologies, and others such as multi-data fusion, makes it possible to create images of sufficient quality to fully appreciate the anatomy of the living heart. In this way, clinicians can now show that proper demonstration of the mysteries of cardiac anatomy is no longer confined to those who work in the dissecting room or the autopsy suite.5,17

The Attitudinally Correct Approach to Cardiac Anatomy

The first rule that medical students are taught when they begin their studies of human anatomy is that all structures are described as they are positioned in the body, the individual considered as standing upright and facing the observer in the so-called “anatomical” position. It remains a mystery as to why this rule is followed when describing every structure or organ within the body except the heart. Thus, for centuries, those who have studied cardiac anatomy have approached the organ as seen when removed from the body and positioned upon its apex: the so-called Valentine position. It is such studies that have provided the existing gold standard for...
understanding the interrelationships of the cardiac components. Important as such studies have been, they nonetheless have their shortcomings. It is only in the Valentine position that the allegedly right chambers are seen to the right of their purportedly left-sided partners. As we have shown in Figure 1, in reality the right atrium and right ventricle are positioned anteriorly relative to the left atrium and ventricle. It is true that a strip of the left ventricle forms the left-sided border of the cardiac silhouette, but all that is seen of the left atrium, when the heart is viewed frontally in its attitudinally appropriate position, is the tip of the left atrial appendage (Figure 1). One study of cardiac anatomy in the autopsy room, nonetheless, truly provides the existing gold standard. This is because the importance of the attitudinally appropriate approach was the essence of the dissections illustrated by McAlpine in his superb Atlas, which contains multiple 2D images showing cardiac structures in their orientation as seen in life. When the senior author produced a similar Atlas, he and his colleague stressed the importance of such attitudinally appropriate anatomy, but then ignored their own recommendations in the larger part of their book. The configuration and alignment of the components of the heart, nonetheless, can vary markedly within the thorax during the cardiac cycle, and there can be marked individual variability. Because of such variations, it is important to appreciate the standard orientation of the normal heart, as such knowledge is fundamental in implementing the diagnostic and therapeutic processes in clinical cardiology. Data is currently limited with regard to the average 3D orientation of the living heart. In our data obtained from 100 adult patients consecutively undergoing coronary arterial computed tomography, with a mean age of 64.3±15.5 years, just under two-fifths of whom were female, the mean angles of the 3D anatomical axis, defined as the longitudinal axis from the center of the mitral orifice to the left ventricular apex, as projected on the frontal, horizontal, and left lateral planes, were 52.3±12.0°, 48.7±9.5°, and 34.0±11.2°, respectively (Figure 3).

Thus far, it has been conventional to describe the rotation of the heart in the frontal, horizontal, and lateral planes. We suggest that it is also necessary to note any rotation in the atroventricular plane along the longitudinal axis, this representing the short axis of the ventricular mass as viewed from the apex of the left ventricle (Figure 3, Lower right panel). When considering individual variation, such an approach permits the rotation of the heart to be considered along its anteroposterior or sagittal, supero-inferior or vertical, right-left or transverse, and longitudinal axes. At present, it is frequent to find terms such as “vertical heart”, and “clockwise rotation” being used routinely but ambiguously. If assessed along the axes shown in Figure 3, then vertical rotation can be assessed along the anteroposterior axis (Figure 3, Upper left panel), but should then be differentiated from dorsal rotation along the right-left axis (Figure 3, Lower left panel). In similar fashion, clockwise rotation along the longitudinal axis (Figure 3, Lower right panel) should be differentiated from leftward rotation along the supero-inferior axis (Figure 3, Upper right panel). In the field of electrocardiography, rotation along the supero-inferior axis is conventionally expressed as clockwise rotation, as opposed to counterclockwise rotation being used to define the position of the transitional zone. In the field of echocardiography, it is pulsatile rotation along the longitudinal axis of the heart that is currently expressed as torsion, or twisting as opposed to untwisting.

It was the report of the working group convened by the European Society of Cardiology and the North American Society of Pacing and Electrophysiology that emphasized the incorrectness of many of the names currently used to describe the cardiac components. Despite the time that has passed since the publication of their report, many of these names still retain their popularity, despite their incorrectness. Thus, it is
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The problems afflicting current conventional descriptions of the atrioventricular valves, reflecting the ongoing popularity of the Valentine position for cardiac description, again come to the fore when considering ECG nomenclature. The logic underscoring Einthoven’s description of his triangle was based firmly on the fact that the recordings are made and analyzed with the subject presumed to occupy the anatomical position. It is the so-called Valentine nomenclature that decrees that the “right” bundle branch supplies the “right” ventricle, in fact located anteriorly, while the “left” bundle branch ramifies in the posteriorly located “left” ventricle. Appreciation of the discrepancies between the Valentine and attitudinal orientations explains the paradox whereby so-called “right” bundle branch block manifests as anterior axis deviation, revealed by the presence of an R-wave in lead V1 of the precordial leads, with “left” bundle branch block becoming manifest as a posterior axis deviation, with an S-wave in lead V1. In similar fashion, it can then be appreciated why so-called “left anterior” fascicle hemi-block manifests as superior axis deviation, with an S-wave in limb lead aVF, and “left posterior” fascicle hemi-block as inferior axis deviation, showing an R-wave in limb lead aVF, combined with posterior axis deviation revealed by an S-wave in lead V1 of the precordial leads. Leads V1 and V2 are appropriately called the precordial leads when assessed for intrinsic slowness of conduction, as is commonly the case.

While it is beyond question that blockage of the artery produces inferior myocardial infarction, would not understanding for future generations of clinicians be facilitated if the artery were now described in the attitudinally appropriate fashion? The same goes for not only the leaflets, but particularly the papillary muscles, of the atrioventricular valves. When considered relative to the overall arrangement of the cardiac base, the leaflets of the mitral valve are best described as being aortic and mural, although anterior and posterior are approximately accurate. When we assess the locations of the papillary muscles that support the 2 ends of the zone of apposition between the leaflets, however, there can be little question that they are located inferomedially and superolaterally (Figure 4, Right panel). In similar fashion, attention to the orifice of the tricuspid valves shows that its leaflets guard anterosuperior, inferior, and septal components of the right atrioventricular junction, with the septal rather than the inferior leaflet being positioned posteriorly when considered relative to the thoracic coordinates.

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with the subject occupying the anatomical position, whereas there is no justification for considering them as “right” precordial leads, which is necessary when using the Valentine approach.

When promoting the value of attitudinally correct nomenclature, based on anatomical position, we do recognize that the right and left ventricles, and right and left atria, are unlikely ever to change their names. Those describing these chambers in the setting of the congenitally malformed heart, nonetheless, intuitively recognize the problems currently existing by describing the “morphologically” right ventricle, or appropriate chamber. For incomplete ventricles, or arterial trunks, they then describe their position relative to the bodily coordinates. On this basis, therefore, we submit that there is every reason to rename the papillary muscles and the valvar leaflets according to their locations within the heart. Increasing use of 3D imaging techniques will inexorably point to the problems created by the current nomenclature, despite its ongoing popularity. The same is true for the inferior interventricular coronary artery. Time will tell whether our aspirations are fulfilled. In our opinion, nonetheless, understanding would be made so much simpler for future generations of medical students and trainee cardiologists by the adoption of the attitudinally appropriate approach.

**Virtual Dissection of the Arterial Roots**

Problems with describing the arterial roots exist not only with postnatal, but also with prenatal anatomy. When considering development, use of conventional terms such as “conus” and “truncus” create problems in even accounting for the arterial roots, which develop in the middle of the outflow tract. From the stance of development, therefore, a strong case can be made for assessing the changes in terms of the proximal, intermediate, and distal components of the developing outflow tract. It then becomes an easy matter to appreciate that the arterial roots are formed and develop within the intermediate part of the tract, with the proximal part providing the subvalvar ventricular outflows, and the distal part the intrapericardial arterial trunks. When relating these developmental events to postnatal anatomy, note should be taken that the distal parts of the outflow cushions, which initially separate the intermediate component of the tract into the aortic and pulmonary roots, along with the core of the proximal cushions, lose their septal location as an extracardiac tissue plane is produced to separate the aortic root from the subpulmonary infundibulum. During this process, the surface of the proximal outflow cushions muscularizes to form the free-standing infundibular sleeve. The cushions themselves fuse with the crest of the muscular ventricular septum, thus walling the developing aortic root into the left ventricle. It is the presence of the infundibular sleeve that permits the entirety of the pulmonary root to be removed and used as an aortic autograft in the Ross procedure. Equally important in the developmental process is the wedging of the aortic root between the developing mitral valve and the muscular ventricular septum. Subsequent to the wedging, the postero-inferior part of the muscular ventricular septum separates the
inlet of the right ventricle not from the inlet, but from the outlet of the left ventricle (Figure 6).

These processes provide the explanation of why, in the normal heart, the cushions form no discernible muscular outlet septum, even though they have functioned as septal entities during embryogenesis. Muscularization of the cushions produces a discrete muscular outlet septum only when ventricular septation is incomplete.\textsuperscript{16,35,36} The location of the postero-inferior part of the muscular ventricular septum, furthermore, separating the inlet of the right from the outlet of the left ventricle (Figure 6), explains why there is no component of the muscular ventricular septum that can be considered to represent an “atrioventricular canal septum”, as has been suggested by some authorities.\textsuperscript{37} In the postnatal heart, the ventricular septum has membranous and muscular components, with the muscular part derived exclusively from the primary muscular ventricular septum.\textsuperscript{38} This evidence acquired from examination of developing hearts also explains the known location of the atroventricular conduction axis, positioned astride the crest of the muscular ventricular septum.\textsuperscript{39}

Many of the difficulties that continue to exist with regard to understanding the postnatal anatomy of the aortic and pulmonary roots relate to lack of consensus regarding the best use of words. As appropriately stated by the German surgeons who conducted a world-wide survey, the current situation is a true Tower of Babel.\textsuperscript{40} As was revealed by their questionnaire, the term “cusp” is used indiscriminately, with no consensus as to whether it describes the valvar leaflets or their supporting sinuses. Our own belief is that, if anatomy is to be properly appreciated, and understood by morphologists and clinicians, words should be used in their everyday meaning, just as we believe that there is no excuse to ignore the “anatomical position” when describing cardiac relationships. In this respect, a “cusp” is an elevation, or else describes the crossing point of 2 curves, so it would be better applied to the components of the roots currently described as the “commissures” (Figure 7, Left panel). We prefer to describe the component of the arterial wall supporting the moving component as the sinus, and to account for the free-moving part itself as the valvar leaflet, thus obviating the need to use “cusp” at all. Recognizing on the basis of usage that “commissure” is unlikely to disappear from the lexicon, we also suggest that it is necessary to recognize the zones of apposition between the adjacent leaflets (Figure 7, Right panel).

The zones of apposition, which must close in competent fashion to ensure valvar competence, extend from the peripheral attachments of the leaflets at the sinutubular junctions to the centroids of the valvar orifices (Figure 7, Right panel). Virtual dissection also reveals the semilunar attachments of the valvar leaflets (Figures 5, 7). When reconstructed, the hinge lines take the form of a 3-pointed coronet, which extends between the sinutubular junction and the virtual plane of the basal ring, with the latter identified by echocardiographers as the valvar annulus. The virtual dissection then serves to confirm the lack of any discrete anatomic entity producing the alleged annulus.\textsuperscript{28,41,42} This line is more accurately described as the diameter of the entrance to the arterial roots (Figure 5, Right panel). The virtual dissection also shows how the semilunar hinges cross the anatomic ventriculo-arterial junction, incorporating crescents of myocardium at the bases of the coronary aortic valvar sinuses (Figure 7). Such myocardial crescents are found at the bases of all 3 sinuses of the pulmo-
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The interventricular component of the membranous septum itself is also of interest, because if deficient, this is the site of the commonest variant of ventricular septal defect. Its location is demonstrated with exquisite accuracy by virtual dissection (Figure 8, Right panel), which confirms that the ventriculo-infundibular fold crosses the interleaflet triangle on its right ventricular aspect, continuing anteriorly to form the posterior component of the supraventricular crest. The anterocranial component of the crest, anterior to the site of the right coronary aortic sinus, is then formed by the free-standing muscular infundibular sleeve (Figure 5, Right panel). There are no anatomic boundaries between the components of the supraventricular crest derived from the inner heart curvature as opposed to the free-standing subpulmonary infundibulum, the latter formed by muscularization of the proximal outflow cushions. It is the infundibular component that inserts at the crotch of the septomarginal trabeculation, between its superior and inferior limbs. As shown by virtual dissection (Figure 8, Right panel), the superior limb extends toward the left sinus of the pulmonary valve, while the inferior limb borders the interventricular component of the membranous septum. The dissection also reveals well the origin of the medial papillary muscle of the tricuspid valve from the inferior limb.

**Revisiting the Anatomy of the Heart Using Computed Tomography**

It has previously been shown that sophisticated cross-sectional images of an autopsied heart could be obtained using computed tomography, the heart being prepared as far as possible to simulate the clinical situation. As we hope we have demonstrated in our review, these images of the autopsied heart can now be matched by interrogation of the living heart. We submit that, because of its excellent temporal and spatial resolutions, computed tomography should now be recognized as the gold standard for analysis of the anatomy of the living heart. Indeed, we would go further, because the ability to dissect the datasets available in every desired plane makes the technique the gold standard for delineating the subtle details of all aspects of cardiac anatomy.

All clinicians with access to standard computed tomographic scanners, furthermore, have the capacity, when using appropriate software, to match the images we have produced.

It is difficult to reconstruct what is not known. It is optimal, therefore, that those undertaking such reconstructions should possess a suitable knowledge of previous descriptions of basic cardiac anatomy and embryology. We recognize that it is such studies that, to date, have provided the existing gold standard. The perceptive investigator, nonetheless, will recognize the hurdles that are placed in the race for understanding by use of
Figure 7. Virtual dissections, again made from datasets acquired from patients undergoing assessment of coronary arterial disease, show the salient features of the arterial roots. (Left) The semilunar hinges (yellow dotted lines) of the arterial valvar leaflets extend distally to the sinutubular junction (black dotted line), but arise proximal to the anatomic ventriculo-arterial junction. Because of this proximal attachment, the myocardium of the crest of the muscular ventricular septum is incorporated at the base of the coronary aortic leaflets; this image shows the right coronary aortic leaflet. The red oval shows the crossing of the 2 curved lines at the sinutubular junction; if described literally, this point would be a cusp, but it is conventionally described as the valvar commissure. (Right) Short-axis view of the aortic valve from the arterial aspect. The black double-headed arrows show the 3 zones of apposition of the valvar leaflets. The yellow circles show their peripheral attachments at the sinutubular junction, the so-called commissures. The red stars show the crescents of myocardium incorporated into the base of both the coronary aortic sinuses (see Left panel).

Figure 8. Virtual dissections show the components of the supraventricular crest and its relationship to the septomarginal trabeculation. (Left) Removal of the right coronary aortic valve sinus, and superimposing the location of the membranous part of the septum. The dotted lines show the landmarks to the triangle of Koch. (Right) Removal of the anterior wall of the right ventricle.
non-attitudinally derived nomenclature. Appropriate interpretation of images obtained using conventional axial slices is also fundamental. We then acknowledge that, despite its excellent temporal and spatial resolution, and its wide field of view, any study obtained using computed tomography must be justified in view of the risk of radiation. Even though the current high-end 3rd-generation dual-source scanners are capable of providing optimal images with extremely low doses of radiation, and with minimal use of contrast, the procedure is free neither of radiation exposure nor use of contrast material. Furthermore, to provide images suitable for analysis in an attitudinally appropriate fashion, the attention needs to be paid to the individual supine, holding the breath at deep inspiration, and elevating both arms. This posture in itself may influence the intrathoracic morphology. The quality of the images obtained for optimal reconstruction also depends on various factors, including body weight, the characteristics of the equipment used, the scanning protocols, various artifacts, cardiac function, basic heart rhythm and rate, and the density and volume of the required contrast. Although each image used in the presented figures could have been prepared by any clinician with patience and dedication, it is a team approach, involving cardiac radiologists and technologists that produces optimal results.27

Conclusions
The increasing use of interventional cardiac procedures has emphasized the ongoing need for profound knowledge of 3D cardiac anatomy. Our own knowledge of cardiac anatomy continues to expand, and has been facilitated by investigations derived by virtual dissection of computed tomographic datasets.4,14,15,16 As yet, the value of such investigations has not been fully appreciated. It is continuing multidisciplinary work in this field, such as we have described in our review, that will surely bridge the gap between anatomists, cardiologists, and radiologists, serving to enhance the clinical application of the extensive insights obtained from an understanding of the basic anatomy. It was more than a decade ago that the promise of the rapidly progressing imaging modalities was recognized, and the invitation given to cardiac anatomists to keep abreast of these remarkable achievements in 3D imaging of the living heart.28 Now, when using a multidisciplinary approach, the subtle nuances of the cardiac anatomy can be demonstrated with even better accuracy during life than in the autopsy room. It is our opinion that the time has now come to reset the gold standard for the visualization of clinically pertinent cardiac anatomy.5

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Conflicts of Interest
None.

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