Revisiting the anatomy of the right ventricle in the light of knowledge of its development

Crucean, Adrian; Spicer, Diane e.; Tretter, Justin t.; Mohun, Timothy j.; Anderson, Robert h.

DOI:
10.1111/joa.13960

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (Harvard):
Crucean, A, Spicer, DE, Tretter, JT, Mohun, TJ & Anderson, RH 2023, 'Revisiting the anatomy of the right ventricle in the light of knowledge of its development', *Journal of Anatomy*, pp. 1-15. https://doi.org/10.1111/joa.13960

Received: 4 March 2023 | Revised: 18 September 2023 | Accepted: 19 September 2023

DOI: 10.1111/joa.13960

Journal of Anatomy ANATOMICAL SOCIETY WILEY

REVIEW ARTICLE

Revisiting the anatomy of the right ventricle in the light of knowledge of its development

Adrian Crucean[1] | Diane E. Spicer[2] | Justin T. Tretter[3] | Timothy J. Mohun[4] | Robert H. Anderson[5]

[1]Department of Paediatric Cardiac Surgery, Birmingham Women's and Children's Hospital, Birmingham, UK

[2]Congenital Heart Center, All Children's Hospital, St Petersberg, Florida, USA

[3]Department of Pediatric Cardiology, Cleveland Clinic Children's, and the Heart, Vascular, and Thoracic Institute, Cleveland Clinic, Cleveland, Ohio, USA

[4]The Crick Institute, London, UK

[5]Biosciences Institute, Newcastle University, Newcastle-upon-Tyne, UK

Correspondence
Adrian Crucean, Department of Paediatric Cardiac Surgery, Birmingham Women's and Children's Hospital, Birmingham, UK.
Email: adrian.crucean@nhs.net

Abstract

Controversies continue regarding several aspects of the anatomy of the morphologically right ventricle. There is disagreement as to whether the ventricle should be assessed in bipartite or tripartite fashion, and the number of leaflets to be found in the tricuspid valve. In particular, there is no agreement as to whether a muscular outlet septum is present in the normally constructed heart, nor how many septal components are to be found during normal development. Resolving these issues is of potential significance to those investigating and treating children with congenitally malformed hearts. With all these issues in mind, we have revisited our own experience in investigating the development and morphology of the normal right ventricle. To assess development, we have examined a large number of datasets, prepared by both standard and episcopic microscopy, from human and murine embryos. In terms of gross anatomy, we have compared dissections of normal autopsied hearts with virtual dissections of datasets prepared using computed tomography. Our developmental and postnatal studies, taken together, confirm that the ventricle is best assessed in tripartite fashion, with the three parts representing its inlet, apical trabecular, and outlet components. The ventricular septum, however, has only muscular and membranous components. The muscular part incorporates a small component derived from the muscularised fused proximal outflow cushions, but this part cannot be distinguished from the much larger part that is incorporated within the free-standing muscular infundibular sleeve. We confirm that the tricuspid valve itself has three components, which are located inferiorly, septally, and antero-superiorly.

KEYWORDS
interventricular communication, pulmonary root, tricuspid valve, tripartite ventricular description, ventricular development

1 | INTRODUCTION

As has been stated on several previous occasions, the right ventricle is very much the poor relation of its left ventricular counterpart (Ho & Nihoyannopoulos, 2006; Stubbs et al., 2023; Wang et al., 2019). This does not detract, however, from its integral role in supporting the normal pulmonary circulation. In terms of its anatomy, it is more complex in many ways when compared to its partner, not least because its outflow valve is almost always supported by a free-standing infundibular sleeve (Merrick et al., 2000; Stamm et al., 1998). This feature leads to potential problems in describing the components of the sleeve, since if it is recognised as being free-standing, it is obviously separated in its entirety from the adjacent components of the left ventricle. The potential controversies relate not only to the pulmonary valve and its supporting infundibulum. Discussions continue, for example, as to whether the tricuspid valve truly possesses three leaflets (Hołda et al., 2019; Schlossbauer et al., 2021; Tretter et al., 2016; Victor & Nayak, 1994). As pointed out in an earlier review (Muresian, 2016), it has also been debated as to whether the ventricle itself possesses two (Kumar et al., 1997; Van Praagh et al., 1979, 1989) or three (Ho & Nihoyannopoulos, 2006; Mori et al., 2019; Muresian, 2016; Wang et al., 2019) parts. Those arguing for the bipartite approach suggest that the apical part, which accounts for the third component in the tripartite model, can itself be considered to possess inlet and apical extensions (Kumar et al., 1997; Van Praagh et al., 1979). All of these issues are of significance to those diagnosing and treating children with congenitally malformed hearts.

In this regard, much of the evidence cited by the proponents of both of these approaches has depended on inferences made from cardiac development (Anderson et al., 2014; Anderson, Tretter, et al., 2019; Van Praagh et al., 1979, 1989). It is appropriate, therefore, to revisit the descriptions of anatomy on the basis of newer evidence now available concerning development. This is even more relevant now, since the evidence can be provided by interrogation of three-dimensional datasets available for the key stages in both human and murine embryos. In this review, therefore, we will show how the recent evidence regarding development sheds new light on the previous controversies relating, first, to the morphology of the subpulmonary infundibulum, second to the number of leaflets of the tricuspid valve, and third to the components of the ventricle itself. We will reinforce our descriptions by using virtual dissections of computed tomographic datasets obtained in the clinical setting. We will refer to the right ventricle in its accepted morphological definition (Muresian, 2016), but describe it on the basis of its attitudinally correct position with regard to the rest of the cardiac mass and the thoracic cavity (Anderson et al., 2013). Such descriptions are obviously enhanced by the ability to make the virtual dissections from datasets obtained during life. There is growing acceptance that it is now appropriate to use English words and syntax for the purposes of description, even though "Terminologia Anatomica" retains Latin terms as the starting point of anatomical categorisation (Chmielewski, 2020). The use of eponyms is discouraged in the anatomical listings, but it is unlikely they will disappear.

2 | DEVELOPMENT OF THE RIGHT VENTRICLE

The evidence regarding cardiac development depends very much on the material available for study. We have based our interpretations on the examination of datasets from both human and murine hearts, prepared using the three-dimensional technique of high-resolution episcopic microscopy (Mohun & Weninger, 2012; Table 1). All the datasets were prepared by Dr Mohun while he was working at the Crick Institute, and were prepared following all the ethical guidelines

TABLE 1 Specimens examined.

Human hearts	Episcopic	Histologic	Murine hearts	Episcopic
Carnegie stage 11	0	3	Embryonic day 10.5	17
Carnegie stage 12	1	2	Embryonic day 11.5	31
Carnegie stage 13	3	4	Embryonic day 12.5	12
Carnegie stage 14	5	8	Embryonic day 13.5	11
Carnegie stage 15	4	3	Embryonic day 14.5	8
Carnegie stage 16	3	9	Embryonic day 15.5	12
Carnegie stage 17	1	6		
Carnegie stage 18	0	4		
Carnegie stage 19	0	3		
Carnegie stage 20	1	0		
Carnegie stage 21	0	4		
Carnegie stage 22	0	1		
Carnegie stage 23	0	1		

Note: The numbers show the specimens examined for each of the stages. The histological datasets were provided by the Human Developmental Biology Resource.

established by the Institute. Some of the murine hearts had been genetically manipulated using Cre technology so as to demonstrate myocardium using the gene *Xmlc2*, and the lineage from the second heart field using the *Islet-1* gene. For the human hearts, we have supplemented the material by interrogation of additional datasets prepared by standard serial histological sectioning. All these datasets were contained within the archive of the Human Developmental Biology Resource <hdbr@ncl.ac.uk> and have been prepared in accordance with the protocols of the resource (Gerrelli et al., 2015). A number of datasets studied for each of the relevant stages, covering the time from the formation of the ventricular loop to the closure of the embryonic interventricular communication, are also shown in the Table. Although there are minimal differences between the human and murine hearts, such as the presence of a persistent left superior caval vein in the mouse, and lack of any interventricular membranous septum, we have previously established that the morphological arrangements are basically comparable. The minimal differences do not impact on the descriptions of the morphologically right ventricle. The murine right ventricle has been shown to be tripartite by the end of the late fetal period, with a trifoliate atrioventricular valve (Webb et al., 1996).

The first indication of the development of the right and left ventricle is seen subsequent to looping of the primary heart tube (Hikspoors et al., 2022). This occurs at Carnegie stage 11 in the human, which is at the start of the fifth week of development subsequent to fertilisation. In the mouse, it is well underway on embryonic day 10.5. The images provided for the different stages of development show the temporal changes to be comparable in the human and murine hearts. The first change is heralded by the emergence of trabeculations from the outer curvature of the ventricular loop. The trabeculations of the developing left ventricle grow from the inlet of the loop, with those of the right ventricle growing from the outlet part. Concomitant with the formation of the trabeculations, it also becomes possible to observe the first signs of the formation of the ventricular septum separating the apical components of the ventricular cavities (Figure 1).

At these initial stages, the atrioventricular canal is supported exclusively by the part of the primary heart tube from which is ballooning the developing apical part of the left ventricle. At the same stage, the outflow tract is supported entirely above the ballooning apical component of the developing right ventricle. At these stages, therefore, the developing left ventricle, while receiving the entirety of the outlet from the developing atrial chambers, lacks any outlet other than the primary interventricular communication. The developing right ventricle, in contrast, has its inlet provided by the embryonic interventricular communication, but is supporting the entirety of the outlet of the developing heart. The right ventricle achieves its own inlet component subsequent to expansion of the atrioventricular canal. This involves remodelling of the primary interventricular communication (Lamers et al., 1992). The channel then remaining between the developing ventricles becomes the secondary foramen. It is ongoing remodelling of the secondary foramen that then provides the developing left ventricle with its outlet component. The first stage of the remodelling, which produces the inlet of the right ventricle, has become evident by Carnegie stage 15 in the human heart. This is at the beginning of the sixth week after fertilisation. The comparable stages in murine development are seen during embryonic day 11.5. The key process is rightward expansion of the atrioventricular canal (Figure 2). This process is followed by the fusion of the cushions contained within the atrioventricular canal. Fusion of the cushions produces the primordiums for the development of the future tricuspid and mitral valvar orifices. Subsequent to the expansion, the atrioventricular canal myocardium itself is transformed into the distal margins of the myocardial walls of the developing atrial chambers (Figure 3a,c). By this stage of development, cushions formed within the outflow tract have fused in its middle parts and have also fused with a protrusion that grew from the dorsal wall of the aortic sac (Anderson et al., 2012). Growth of the protrusion has separated the non-myocardial distal outflow tract into the intrapericardial arterial trunks. It is the distal major cushions occupying the middle part of the outflow tract, however, that fuse to produce, along with the additional intercalated valvar swellings, the primordiums of the developing aortic and pulmonary roots. At Carnegie stage 16, however, the proximal parts of these cushions have still to fuse (Figure 3b,d). It is ongoing fusion of the proximal cushions during embryonic day 12.5 in the mouse, and at Carnegie stage 17 in the human heart, which represents the next stage of development.

The fusion of the proximal cushions serves to build a partition in the basal part of the cavity of the right ventricle. This creates a tunnel between the aortic root and the cavity of the left ventricle, with the aortic root itself still at this stage supported exclusively above the cavity of the right ventricle. The persisting secondary part of the initial embryonic interventricular communication then becomes the entrance from the left ventricle to the subaortic outflow tract. As the proximal outflow cushions fuse to create the tunnel between the aortic root and the left ventricle, a channel still remains between the aortic root and the cavity of the right ventricle. This aorto-right ventricular channel, which can be considered to represent the tertiary interventricular communication, is subsequently closed by the rightward margins of the atrioventricular cushions, thus completing the process of ventricular septation (Figure 4b). The components of the cushions closing the foramen were described by Odgers as tubercles (Odgers, 1938).

Having closed the foramen between the aortic root and the right ventricle, the tubercles of the atrioventricular cushions will become the membranous septum. This permits still further remodelling of the newly created left ventricular outflow tract, such that the aortic root is eventually insinuated between the developing mitral valve and the muscular ventricular septum. With this transfer of the aortic root into the left ventricle, which takes place during the early part of fetal development in the human heart, and subsequent to E14.5 in the murine heart, the inferior part of the muscular septum becomes interposed between the inlet of the right and the outlet of the left ventricles (Figure 4d). During these processes, the proximal outflow cushions have undergone myocardialisation (van den Hoff et al., 1999; van den Hoff &

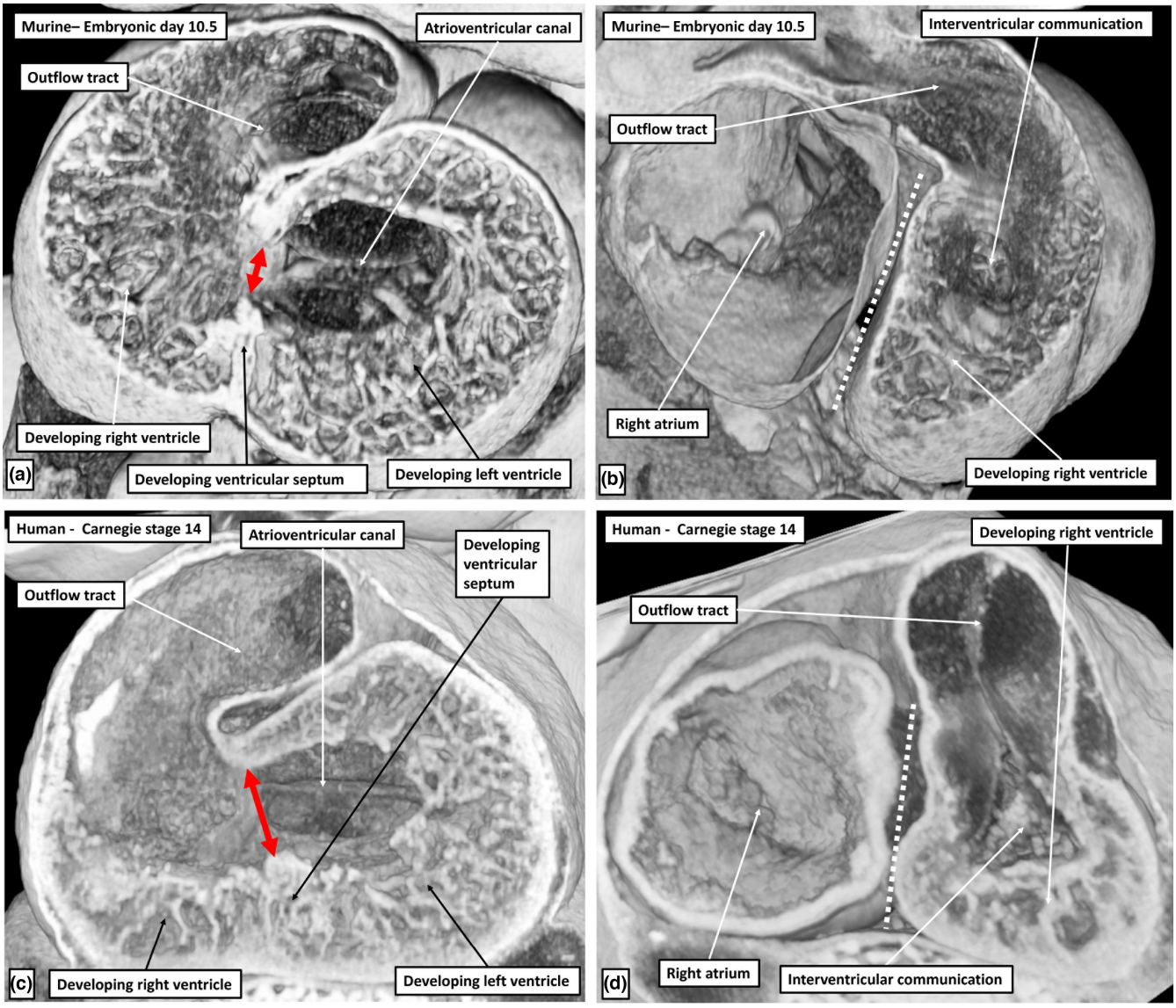

FIGURE 1 The sections are taken from episcopic datasets of a mouse heart at embryonic day 10.5 (a, b), and a human dataset at Carnegie stage 14 (c, d). (a) and (c) are sections across the ventricular loop, while (b) and (d) are oblique sections from the same datasets showing the relations of the apical part of the developing right ventricle and the right atrium. The double-headed black arrow shows the primary interventricular communication. The dotted white lines emphasise the lack of a direct inlet to the developing right ventricle.

Wessels, 2020). The myocardialised shell of the fused mass, producing the roof of the right ventricle (Figure 4b), becomes the free-standing subpulmonary infundibulum (Figures 4c and 5a). As part of the process of remodelling, the core of the fused cushion mass attenuates to produce an area of fibroadipose tissue that interposes between the newly formed infundibulum and the developing sinuses of the aortic root (Figure 4c). The septal attachment of the muscularised shelf is then incorporated into the crest of the apical muscular septum (Figure 5b). The components of the shelf forming the ventricular roof then become the supraventricular crest, separating the cavity of the right ventricle from the aortic root (Figure 4c). Subsequent to these processes, it is not possible to identify a muscular outlet septum as a discrete entity separate from the crest of the muscular ventricular septum. The definitive ventricular septum, therefore, is made up of the initial muscular component, formed between the developing apical ventricular components; the integrated part of the muscularised proximal cushions, which supports the developing right and left aortic coronary valvar sinuses; and the membranous septum, which was derived from the tubercles of the atrioventricular cushions. During these processes, the initial atrioventricular canal myocardium, which served as a connecting component during development, has become converted into the distal margins of the walls of the right and left atrial chambers. The proximal parts of the outflow tract, in contrast, have been incorporated into the ventricles as their own separate outflow tracts. In this regard, the aortic root, at the end of the embryonic period of development, and subsequent to its transfer to the left ventricle, is also supported initially by

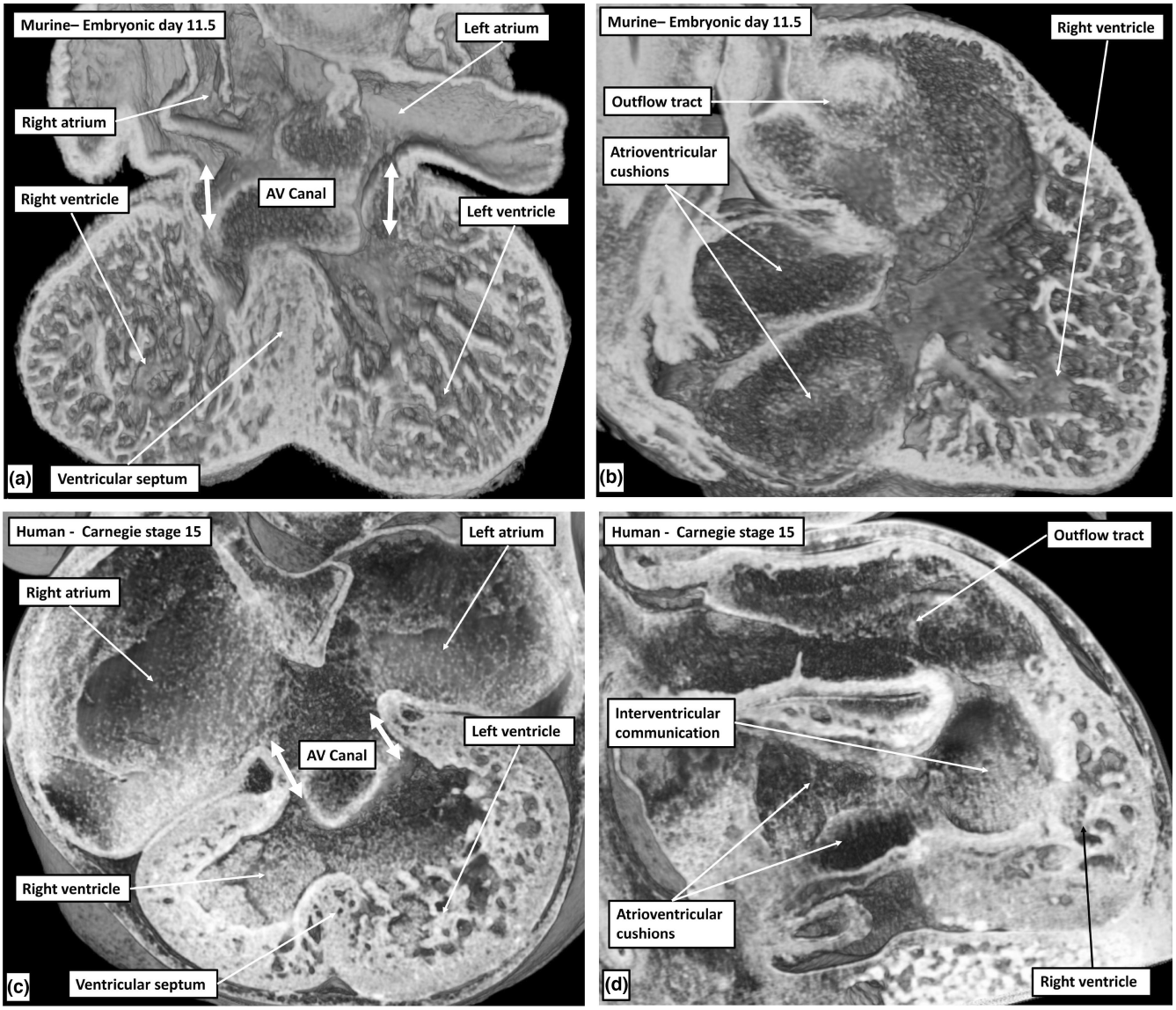

FIGURE 2 The images again show sections from episcopic datasets prepared from murine (a, b) and human (c, d) hearts. The developing mouse was at embryonic day 11.5, while the human specimen was graded at Carnegie stage 15. (a) and (c) show "four-chamber" sections, while (b) and (d) are orthogonal cuts through the same datasets across the right side of the atrioventricular junction, which has expanded so as to provide direct communication between the cavities of the right atrium and the developing right ventricle. The entirety of the outflow tract, however, remains supported by the developing right ventricle. It is now possible to recognise the atrioventricular canal myocardium (double headed while arrow) and the proximal, intermediate, and distal parts of the outflow tract.

a completely muscular infundibulum (Figure 5b). Only during the initial weeks of fetal life in the human heart does the myocardial inner heart curvature attenuate and becomes converted into fibrous tissue, forming the area of fibrous continuity between the leaflets of the aortic and mitral valves. The precise timing of these changes remains to be determined.

During the changes described above, there have also been marked changes in the make-up of the ventricular walls. As already described, the apical component of the ventricle is formed initially by ballooning from the outlet of the ventricular loop (Figure 1). When the atrioventricular canal has expanded rightwards to provide the developing ventricle with its inlet component, the walls are largely made up of the ventricular trabeculations, with the compact parts of the walls being very thin (Figure 2). Even at the stage at which the aorto-right ventricular communication is closed by the tubercles of the atrioventricular cushions, the trabeculations still form the larger part of the thickness of the ventricular walls (Figure 4b). Shortly after closure of the interventricular foramen, there is rapid growth of the compact component of the ventricular walls (Figure 4c). The thickening of the compact component of the ventricular walls occurs concomitant with the establishment of the coronary arterial circulation from the aortic root. The increasing thickness of the compact layer is also accompanied by the coalescence of the previously existing trabeculations. These then form the papillary muscles of the tricuspid valve, together with the extensive strap known as the septomarginal trabeculation, which reinforces the surface of the ventricular

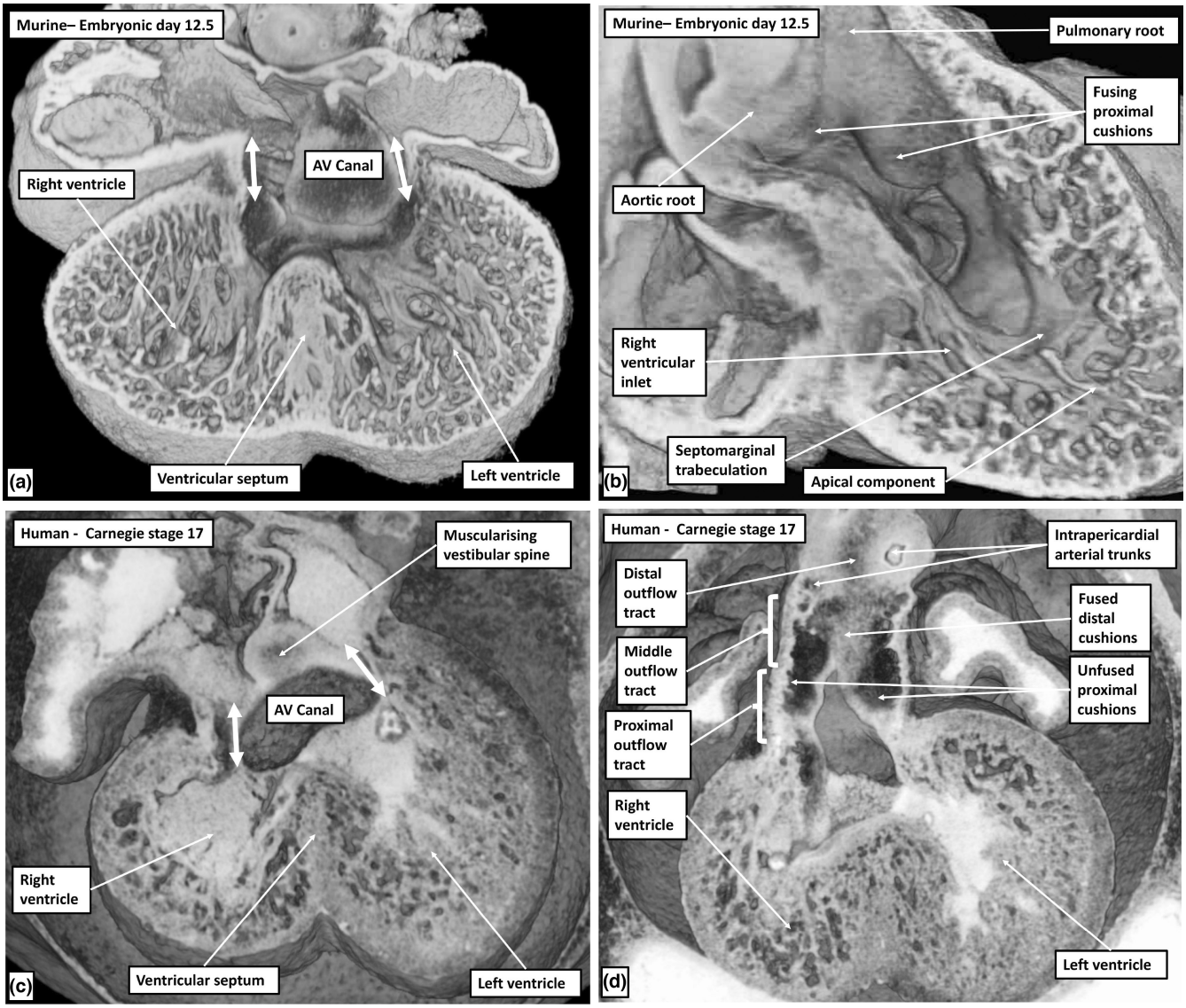

FIGURE 3 The images show sections through episcopic datasets from a mouse at embryonic day 12.5 (a, b) and a human heart at Carnegie stage 17 (c, d). The murine sections show a four-chamber cut (a) and an oblique cut through the developing outflow tract (b), which still remains supported exclusively by the developing right ventricle. The proximal parts of the outflow cushions are now fusing so as to build a shelf in the roof of the right ventricle. Comparable images for the human heart are both taken in four-chamber planes. The cut through the outflow tract (d) shows well the three parts of the developing outflow tract, with the major cushions already fused in the middle part, but yet to fuse in the proximal part. The lack of proximal fusion is also seen in (b), showing the murine arrangement. Note that the atrioventricular canal myocardium is becoming sequestrated to form the vestibules of the developing right and left atrial chambers, which have been separated by fusion of the primary septum with the atrial margins of the atrioventricular cushions. (c) Also shows the muscularising vestibular spine, which will form the buttress of the atrial septum.

septum, and the septoparietal trabeculations, which extend from the anterior margin of the septomarginal trabeculation to reach the parietal ventricular wall (Figure 4c). One of the septoparietal trabeculations retains its continuity with the anterior papillary muscle of the tricuspid valve and is known as the moderator band. At the time ventricular septation is completed, the primordium septal leaflet of the tricuspid valve, formed by fusion of the rightward margins of the atrioventricular cushions that wrapped across the muscular ventricular septum, has still to be delaminated from the surface of the muscular ventricular septum. At the same stage of development, an additional cushion has formed within the parietal wall of the right atrioventricular junction. It is subsequent expansion of the right junction, again subsequent to the closure of the interventricular communication, that sets the scene for the formation of the antero-superior and inferior leaflets of the tricuspid valve (Jongbloed at al., 2005; Kanani et al., 2005; Lamers et al., 1995; Mall, 1912; Odgers, 1939). The precise details of remodelling of the mural cushion to produce the antero-superior and inferior leaflets, however, remain to be elucidated. Already at birth in the mouse, nonetheless, it is possible to recognise the three leaflets of the tricuspid valve (Figure 6).

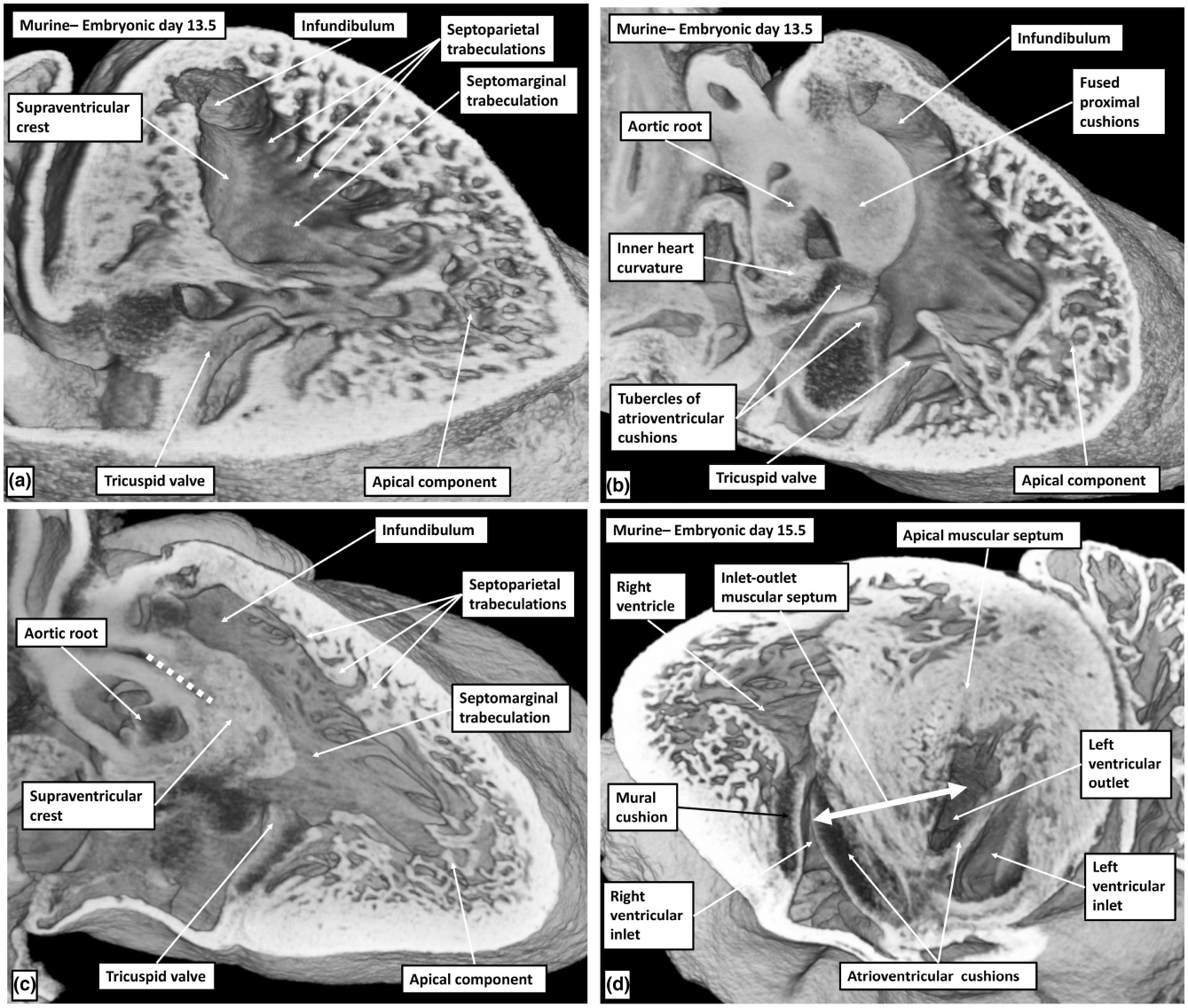

FIGURE 4 All of these images are from sections derived from murine datasets. (a) and (b) show the arrangement at embryonic day 13.5. The proximal cushions have fused to build the shelf in the roof of the right ventricle (a), while tubercles from the rightward margins of the atrioventricular cushions are closing the persisting foramen between the left ventricular outflow tract and the right ventricle (b). At this stage, the inner heart curvature, or ventriculo-infundibular fold, interposes between the developing leaflets of the tricuspid and aortic valves. By embryonic day 15.5, as shown in (c) and (d), the right ventricle has achieved its definitive form. The proximal cushions have muscularised and separated from the aortic root to form the free-standing infundibular sleeve (c). The ventriculo-infundibular fold now separates the leaflets of the tricuspid and pulmonary valves. The short axis cut in (d) shows how the aortic root has now become insinuated between the mitral valve and the muscular ventricular septum subsequent to remodelling of the secondary interventricular communication, with the inferior part of the muscular septum now forming a partition between the inlet of the right and the outlet of the left ventricles.

3 | THE ANATOMY OF THE DEFINITIVE RIGHT VENTRICLE

Although termed the "right ventricle", the chamber is positioned, for the most part, anteriorly relative to its morphologically left partner (Figure 7). It is for this reason, along with the fact that it does not always occupy its normal position, that it is best termed the morphologically right ventricle. For the purposes of our current discussion, however, we can simply describe it as the right ventricle, albeit noting that its components should be described in attitudinally appropriate fashion (Anderson et al., 2013). On the basis of the knowledge of the tripartite development as described above, it is now possible to provide a simple account of its definitive components. It is also the case that, as for the developmental changes, the morphological arrangements are essentially comparable in the human and murine hearts. We will illustrate the features as seen in the human heart. The myocardial components of the chamber extend from the atrioventricular junction to the pulmonary root (Figure 8). The atrioventricular junction is formed throughout by the fibroadipose tissues that separate the distal extent of the atrial walls from the crest of

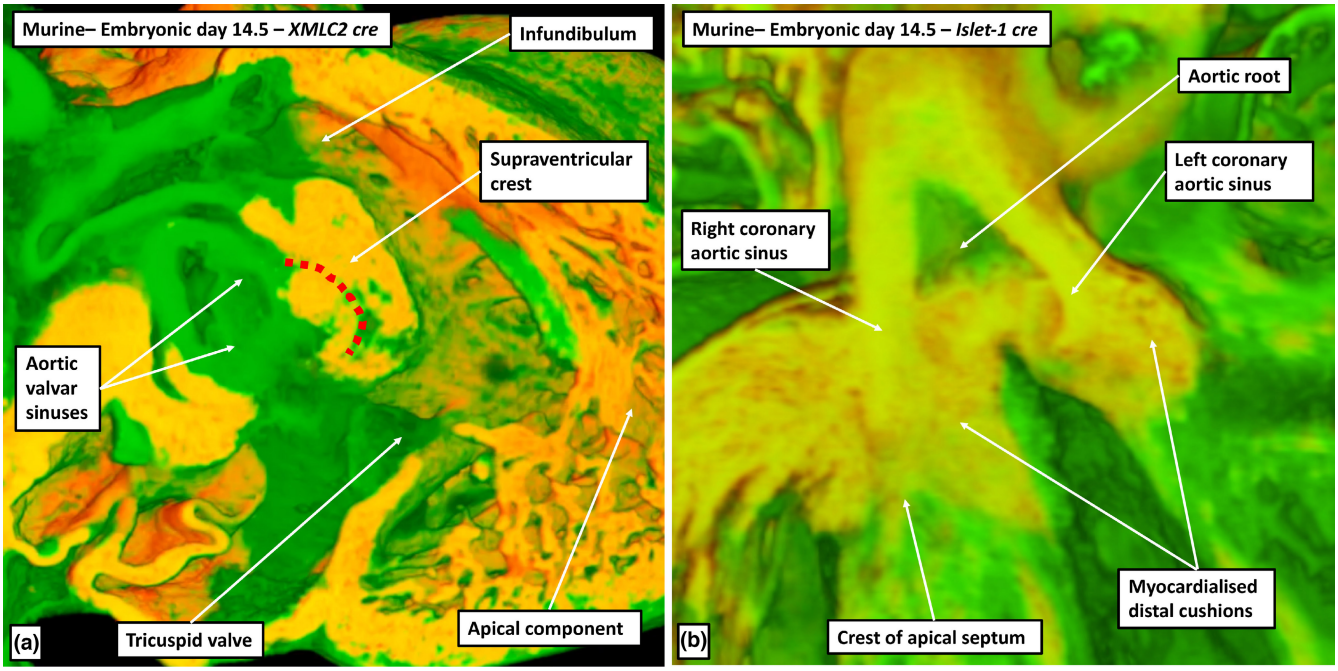

FIGURE 5 The images are taken from murine datasets in which the mouse, during development, was programmed using Cre technology to reveal the presence, in (a), of the gene producing the myocardial light chain proteins (*XMLC2*), and in (b) the *Islet-1* gene, which marks the second heart field. Both panels are from murine embryos sacrificed at embryonic day 14.5. The yellow areas in (a) show myocardium, while in (b), they show the tissues derived from the developing outflow tract, specifically by muscularisation of the distal cushion supporting the developing adjacent leaflets of the aortic valve.

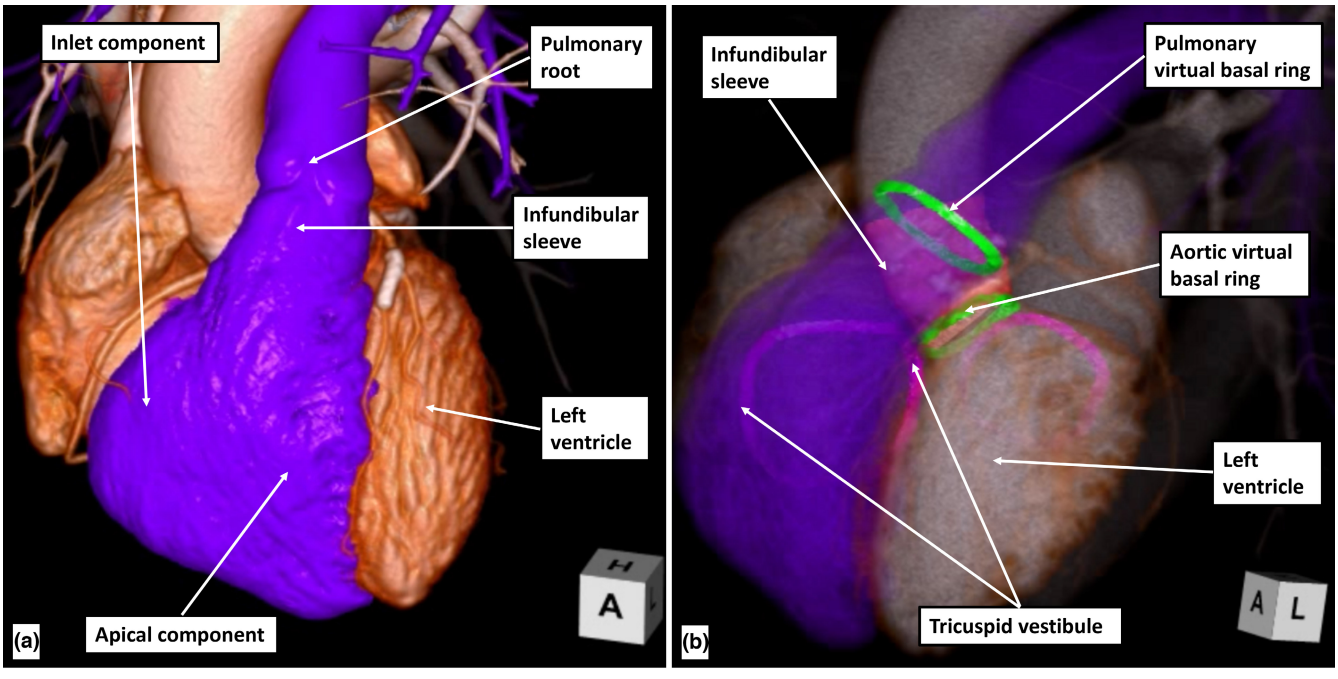

FIGURE 6 The images are from a computerised tomographic dataset of a normal human heart. In (a), the right ventricle has been coloured purple. In (b), the virtual basal rings of both arterial roots have been marked in green, and the vestibules of the atrioventricular valves marked in pink. The boxes show the location of the heart relative to the bodily coordinates, with A showing anterior, and L showing left.

the ventricular myocardial mass. There is no obvious "annulus" to be found within the junction in the sense of a fibrous ring interposed between the atrial and ventricular myocardial masses. Instead, the leaflets of the tricuspid valve are hinged from the ventricular walls and the septum at the level of the insulating plane provided by the fibroadipose tissues within the junction. The ventriculo-arterial

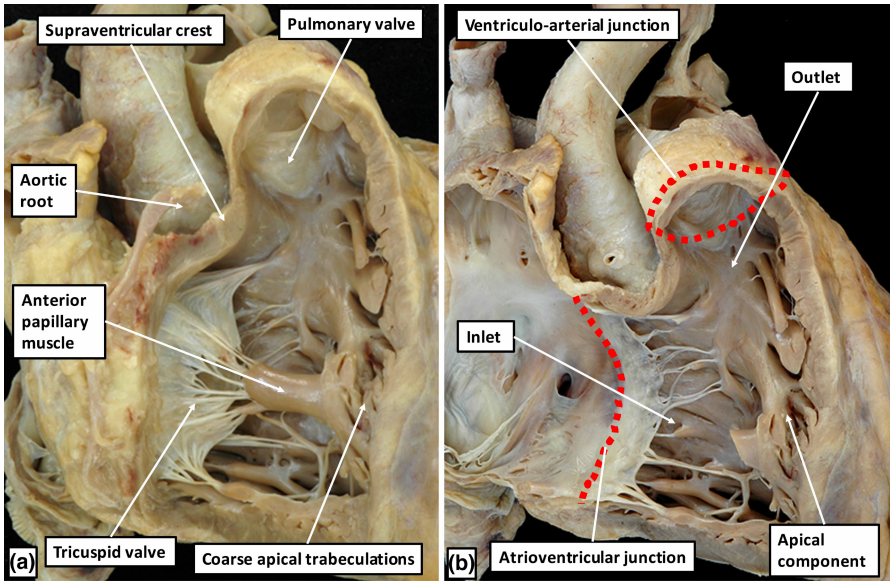

FIGURE 7 The images show the extent and make-up of the definitive right ventricle. (a) Shows the view of the ventricular cavity subsequent to removal of its parietal wall. The tricuspid valve is seen guarding its inlet, with the pulmonary valve guarding the outlet. The ventricle wraps itself around the aortic root, having a trabeculated outer curvature, and a smooth inner curvature forming the supraventricular crest. (b) Shows the arrangement having cut across the atrioventricular junction, but with the ventriculo-arterial junction remaining intact.

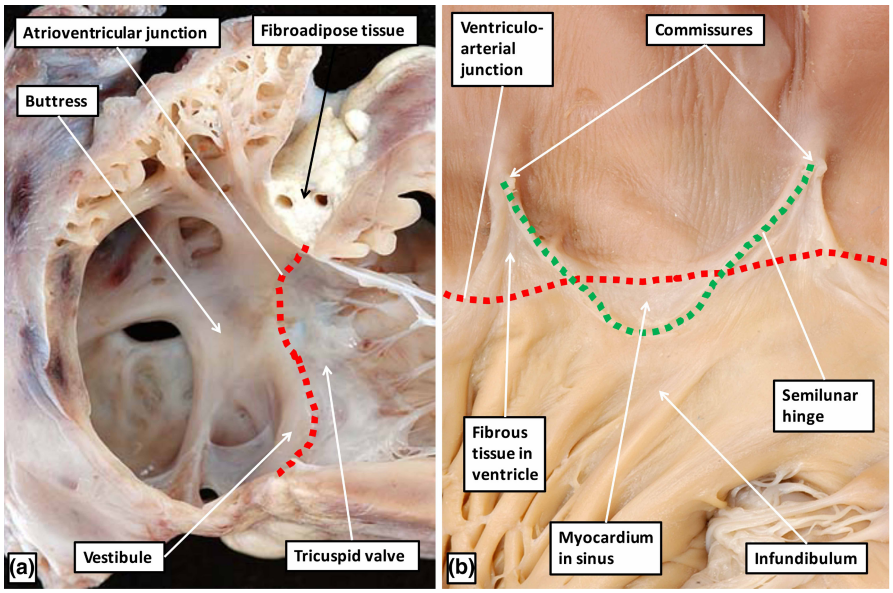

FIGURE 8 The images show the arrangement of the atrioventricular (a) and the ventriculo-arterial (b) junctions, which delineate the extent of the right ventricle. As shown in (a), the junction at atrioventricular level is formed by fibro-adipose tissues interposed between the atrial vestibules and the crest of the ventricular mass. At the level of the ventriculo-arterial junction, because of the location of the semilunar hinge of the pulmonary valvar leaflets, crescents of myocardium are incorporated at the bases of each of the valvar sinuses, while fibrous tissue of the pulmonary trunk forms interleaflet triangles that extend distally to the level of the sinutubular junction.

junction, in contrast, is much more complex. This is because the semilunar hinges of the three leaflets of the pulmonary valve each cross the anatomic junction between the right ventricular myocardium and the fibro-elastic walls of the sinuses of the pulmonary trunk (Figure 9). The ventricular cavity, therefore, extends between the semilunar hinges of the pulmonary valve to reach the sinutubular junction. This arrangement itself then differs from the junction found between the left ventricular myocardium and the aortic root. Such a myocardial–arterial junction in the left ventricle is found only at the bases of the two sinuses of the root that give rise to the coronary arteries. As with the right ventricle, nonetheless, the left ventricular cavity extends between the hinges of the semilunar leaflets to reach the aortic sinutubular junction. It is the presence of the complete free-standing muscular sleeve supporting all three sinuses

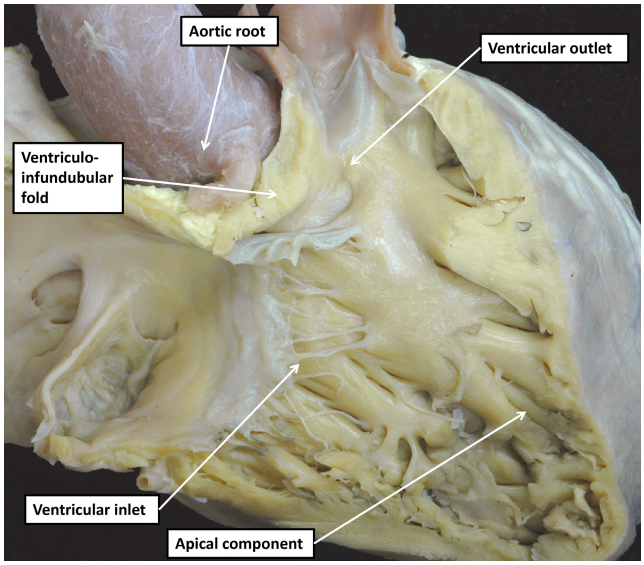

FIGURE 9 The image shows how the right ventricle, when defined as extending from the atrioventricular to the ventriculo-arterial junctions, can be described as possessing an inlet component, extending from the atrioventricular junction to the distal extent of the tension apparatus of the tricuspid valve, an apical component occupying the outer curvature of the ventricular mass, and an outlet component formed by the free-standing muscular subpulmonary infundibular sleeve. The ventricle wraps itself round the aortic root, with the inner curvature of the ventricular mass forming the ventriculo-infundibular fold. The inlet and outlet components come together at the level of the membranous part of the ventricular septum, not seen in this image, but shown in Figure 8.

of the pulmonary root within the right ventricle (Figure 7b) that underlies the feasibility of the Ross procedure (Merrick et al., 2000).

When assessed on the basis of its extent of its walls extending between the atrioventricular and sinutubular junctions, the ventricle can be described as possessing functional inlet, apical trabecular, and outlet components, although there are no discrete anatomical boundaries between the parts (Figures 5a and 10). The inlet component surrounds and supports the tricuspid valve. It extends from the atrioventricular junction to the distal extent of the valvar tension apparatus. The bases of the papillary muscles forming this distal boundary are themselves continuous with the apical trabeculations. Beyond the distal attachments, the coarsely trabeculated ventricular component occupies the outer curvature of the ventricular cavity. The ventricular walls then continue basally as a free-standing myocardial sleeve, which forms the subpulmonary infundibulum (Figure 5b). The inlet, apical, and outlet components thus radiate out from the central area of the ventricular base. This is occupied by the membranous part of the septum. When assessed from the left side, the membranous septum fills the base of the interleaflet triangle separating the non-coronary and right coronary sinuses of the aortic root. In terms of its size, the membranous septum is tiny compared to the bulk of the muscular septum (Figure 10a). The muscular septum itself interposes for its greater part between the apical components of the ventricles. It is a curved structure. Inferiorly, however, it separates the inlet of the right from the outlet of the left ventricle (Anderson, 2017; Figure 10b). The lack of any muscular septum interposed between the ventricular inlets reflects not only the wedging of the aortic root between the mitral valve and the septum but also the presence of a deep infero-septal recess in the left ventricle (Figure 10). This space interposes between the aortic (anterior) leaflet of the mitral valve and the left ventricular septal endocardial surface (Tretter et al., 2021, 2022). The space is roofed by an area of fibrous continuity between the leaflets of the mitral and tricuspid valves. This area, which is part of the so-called central fibrous body, provides the support for the antero-inferior buttress of the atrial septum. The distal part of the ventricular cavity is formed by the free-standing infundibular sleeve, which posteriorly separates the cavity of the infundibulum from the aortic root (Figure 11a). Hence, the normal ventricular septum lacks any anatomically discrete outlet component (Anderson, Tretter, et al., 2019; Figure 11b). It is the presence of the free-standing sleeve that lifts the leaflets of the pulmonary valve away from the base of the ventricular mass (Figure 5b). As already emphasised, it is this feature which makes possible the Ross procedure (Merrick et al., 2000).

The ventricular inlet surrounds and supports the leaflets of the tricuspid valve. As already discussed, there is no discrete "annulus", in the sense of a complete ring-like fibrous cord, supporting these leaflets at the level of the atrioventricular junction. Instead, the leaflets are hinged on the crest of the ventricular walls and the septum. In the area of the septum, the superior part of the septal leaflet is hinged by the fibrous plate that provide continuity, at the base of the atrial septum, between the septal leaflet of the tricuspid valve and the aortic (anterior) leaflet of the mitral valve. The fibrous plate forms the roof of the infero-septal recess. Again as already emphasised, the fibrous plate is part of the central fibrous body, which also includes the membranous septum and the right fibrous trigone. The latter structure is the rightward end of the area of fibrous continuity in the roof of the left ventricle between the leaflets of the aortic valve and the aortic (anterior) leaflet of the mitral valve. The skirt of fibrous tissues forming the leaflets of the tricuspid valve itself, as the name suggests, closes in trifoliate fashion. When assessed in attitudinally appropriate fashion, the leaflets are located septally, inferiorly, and antero-superiorly. They guard the comparable parts of the right atrioventricular junction (Tretter et al., 2016; Figure 12). The most prominent papillary muscle of the tricuspid valve, the anterior muscle, is most frequently attached to, and supports, the middle of the antero-superior leaflet. In other instances, it provides tendinous cords for both the antero-superior and inferior leaflets of the valve. The zone of apposition between the antero-superior leaflet, which is the largest leaflet of the valve, and the septal leaflet is supported by the characteristic medial papillary muscle. This structure is also known as the conal papillary muscle, the papillary muscle of the septum, or the muscle of Lancisi (Figure 13). There is marked variability in its size, the location of its insertion to the septum, the number of its heads, and even its presence or absence. In many individuals, furthermore, there can be an additional muscle supporting this zone of apposition. Irrespective of the variation, the muscle, or muscles,

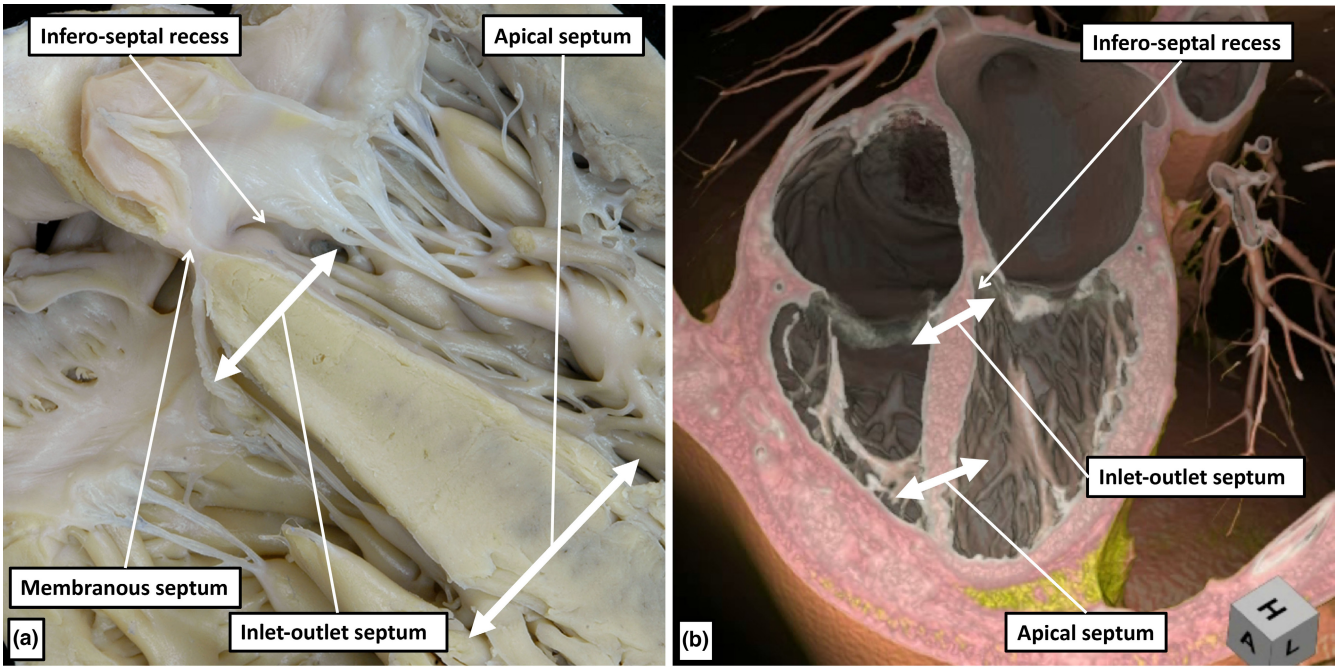

FIGURE 10 (a) Is a four-chamber section through the interleaflet triangle separating the non-coronary and right coronary sinuses of the aortic root. It shows the small size of the membranous parts of the ventricular septum. By virtue of the wedging the aortic root between the mitral valve and the septum, the section also shows how the inferior part of the muscular septum interposes between the inlet of the right and the outlet of the left ventricles, extending apically to separate the apical components. These features are also shown in (b), taken from a clinical computed tomographic dataset prepared to show a normal heart.

arises from the caudal limb of the septomarginal trabeculation. The septal leaflet itself has multiple tendinous cords attaching it directly to the inferior part of the ventricular septum. These septal attachments are the most consistent feature of the tricuspid valve. There is usually a smaller inferior papillary muscle supporting the zone of apposition between the inferior and septal leaflets, although this muscle is frequently duplicated (Tretter et al., 2016).

The apical component of the ventricle is dominated by its coarse trabeculations, which occupy the entirety of the ventricular outer curvature (Figure 5a). During development, some of the trabeculations have coalesced to form the papillary muscles of the tricuspid valve, and additional trabecular structures. One of these latter structures is particularly well formed. It reinforces the surface of the septum, and is known as the septomarginal trabeculation, or the septal band (Figure 13). It has an obvious body, which extends along the septal surface to the apex, where it gives rise to the most prominent of the septoparietal trabeculations. This trabeculation, known as the moderator band, however, is but one of the series of septoparietal trabeculations. The cranial of these myocardial bundles is found at the mouth of the infundibulum. At the ventricular base, the septomarginal trabeculation itself divides into cranial and caudal limbs. These clasp the inner curvature of the right ventricle. This fold, well described as being a part of the supraventricular crest, or crista supraventricularis, separates the leaflets of the tricuspid and pulmonary valves. Its distal component forms part of the free-standing infundibulum, specifically the part directly adjacent to the aortic root (Figure 11a). The cranial limb of the septomarginal trabeculation usually extends within the free-standing infundibular sleeve to reach the base of the leaflets of the pulmonary valve (Figure 13). The caudal limb extends towards the membranous septum. Reinforcing the right ventricular aspect of the crest of the muscular septum, which forms the cranial margin of the membranous septum, the caudal limb gives rise to the medial papillary muscle.

The pulmonary valve itself has three leaflets. Each leaflet is supported proximally by the free-standing infundibular sleeve. Their characteristic feature is the crossing of their semilunar hinges over the myocardial–arterial junction (Figure 9b). This results in crescents of ventricular myocardium being incorporated at the base of each of the pulmonary valvar sinuses. Fibrous arterial tissues then fill the interleaflet triangles between the sinuses, albeit enclosing the distal parts of the ventricular cavity. They extend between the pulmonary valvar sinuses to the level of the sinutubular junction. It is the sinutubular junction, therefore, which marks the distal extent of the ventricular cavity when the leaflets of the pulmonary valve are in their closed positions.

4 | DISCUSSION

Questions might be asked as to whether our review is provided for those teaching human anatomy, or for the many investigators who now use the mouse as a model for the investigation of disease processes. We hope that our account will be of value for practitioners in all these fields. Although there are subtle differences in the

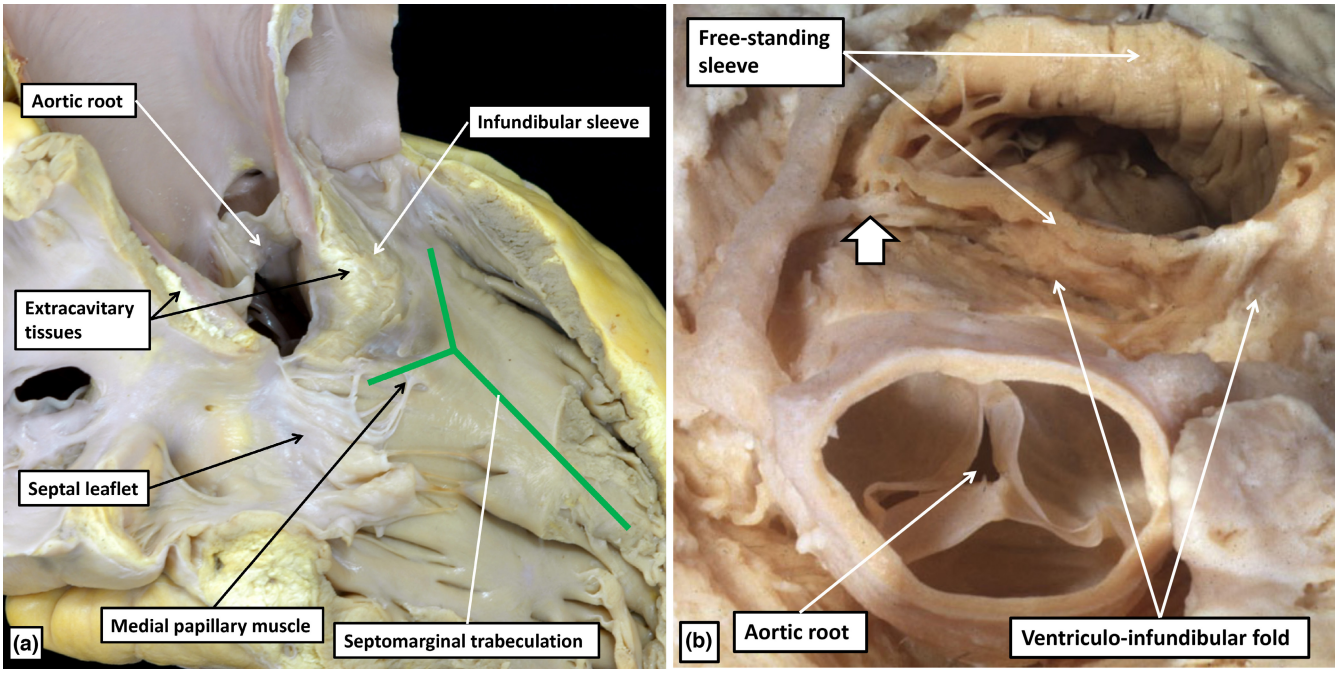

FIGURE 11 (a) Shows a dissection of the outflow tract of the right ventricle in which the free-standing infundibular sleeve has been cut back to show the extracavitary tissues that interpose between the cavity of the right ventricle and the sinuses of the aortic root. The right coronary aortic sinus has also been removed. The green "Y" shows the body and limbs of the septomarginal trabeculation. The dissection in (b), using a different heart, shows how the pulmonary root can be removed from the base of the right ventricle, exposing the free-standing infundibular sleeve. The base of the ventricular mass is photographed from the atrial aspect. The white arrow with black borders shows the first septal perforating branch of the anterior interventricular artery.

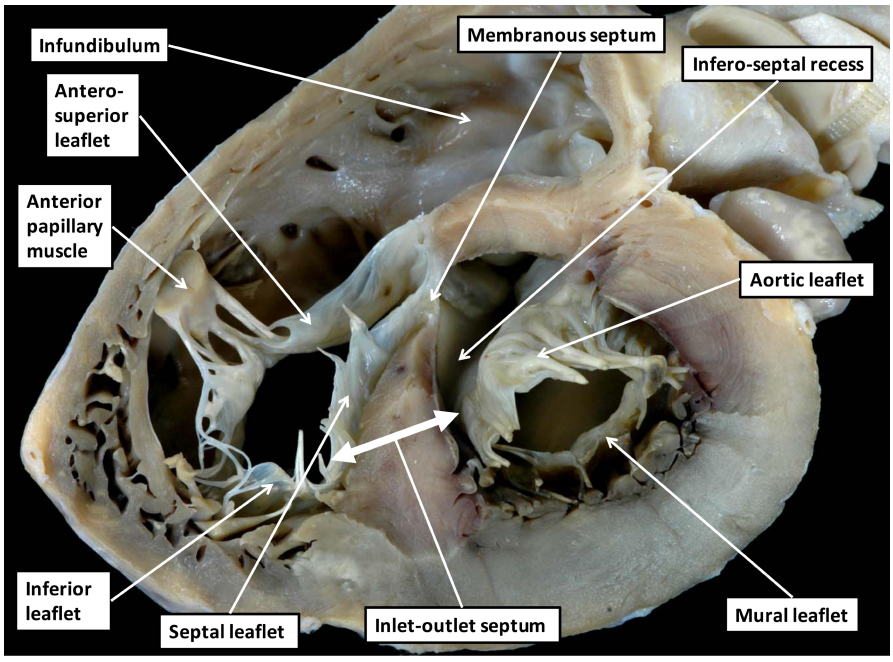

FIGURE 12 The image shows a short axis cut of the ventricular mass viewed from the aspect of the ventricular apexes, with the heart positioned in attitudinally appropriate fashion. The cut shows how the membranous septum is formed at the junction of the ventricular inlet and outlet components. It shows well the fashion in which the infero-septal recess of the aortic root interposes between the aortic leaflets of the aortic valve and the left ventricular septal surface. The mural leaflet of the mitral valve lacks any attachment to the septum. The tricuspid valve can be seen to close in trifoliate fashion, with the leaflets occupying antero-superior, septal, and inferior positions.

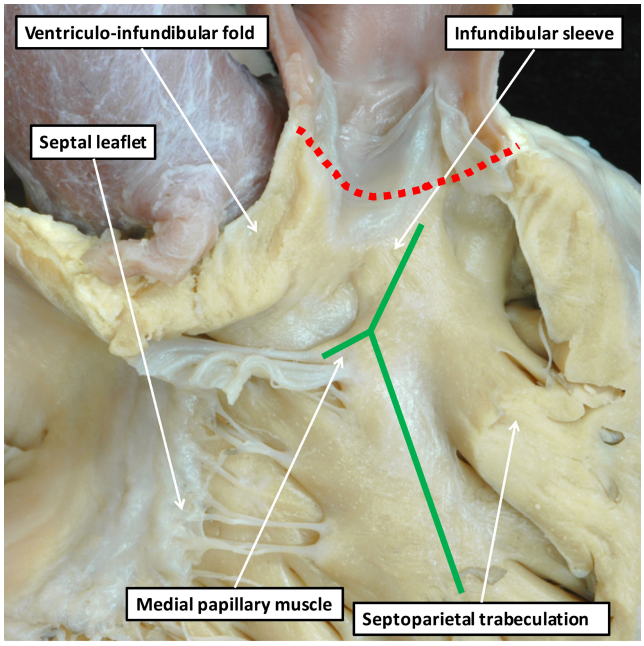

FIGURE 13 The image is a magnified view of the outlet of the right ventricle in the heart also shown in Figure 9. This image shows the location of the medial papillary muscle, along with the tendinous cords attaching the septal leaflet to the ventricular septum. It also shows the location of the prominent septal trabeculation known as the septomarginal trabeculation or the septal band. The green lines show the long body, and the characteristic cranial and caudal limbs of the trabeculation. The ventriculo-infundibular fold, representing the inner heart curvature, inserts between the limbs of the trabeculation. In this heart, the cranial limb is confluent with a prominent septoparietal trabeculation. The image shows well how the semilunar hinges of the leaflets of the pulmonary valve cross the anatomic ventriculo-arterial junction (red dashed line).

postnatal morphology of the human and murine hearts, the similarities of the developmental processes are sufficiently coherent to permit direct comparisons between the two species. As we emphasised in our introduction, the right ventricle has usually been seen as the poor relation of its left ventricular counterpart (Ho & Nihoyannopoulos, 2006; Stubbs et al., 2023; Wang et al., 2019). It was initially described as possessing two rather than three components. The muscular septum interposing between its cavity and that of the left ventricle, furthermore, was suggested, on developmental grounds, to have four components (Kumar et al., 1997; Van Praagh et al., 1979, 1989). These components were said to represent the septum of the atrioventricular canal, the sinus septum, and the proximal and distal parts of a "conal" septum (Van Praagh et al., 1989). The developmental evidence underscoring this hypothesis was not described in any detail. The evidence now available from interrogation of three-dimensional datasets provided from both human and mouse developing hearts, as summarised in our review, offers no support for these suggestions. On the contrary, the evidence shows that there is but a solitary muscular septum. This is formed as the ventricular apical components "balloon" from the primary heart tube (Anderson, Tretter, et al., 2019; Christoffels et al., 2000). There is, nonetheless, a myocardial septum of the atrioventricular canal. This is formed by muscularisation of the vestibular spine (Anderson, Tretter, et al., 2019; Jensen et al., 2017). As this structure becomes the antero-inferior buttress of the oval fossa, it is the true second atrial septum (Jensen et al., 2017). As with the myocardium of the atrioventricular canal itself, which serves to connect the atrial and ventricular components of the heart during initial development, it is eventually sequestered within the atrial component subsequent to the formation of the atrioventricular junctions. During development, there is also a septum dividing the proximal part of the developing outflow tract into its subaortic and subpulmonary components (Anderson, Tretter, et al., 2019). This structure is formed by fusion and subsequent muscularisation of the proximal parts of the cushions that spiral throughout the outflow tract during development (van den Hoff et al., 1999; van den Hoff & Wessels, 2020). By the end of the process of septation, this myocardialised shelf, formed from the proximal cushions, has become the larger part of the free-standing muscular subpulmonary infundibular sleeve. In consequence, there is no anatomically discrete conal, outlet, or infundibular septum to be found in the normal heart (Anderson, Tretter, et al., 2019). We used to argue that it was possible to dissect between the limbs of the septomarginal trabeculation so as to produce a channel between the right and left ventricles. This remains the case, but the myocardium removed also includes the crest of the apical muscular septum and the overlying caudal limb of the septomarginal trabeculation (Figure 5b).

It was the presence, during development, of the atrioventricular canal, and of the conus, or proximal outflow tract, which prompted the suggestion that, in addition to the atrial, ventricular, and arterial segments, the heart itself possessed "connecting segments" (Van Praagh, 2000). As the episcopic datasets show, these components do serve, during development, to connect together the major cardiac segments (Anderson, 2017). Subsequent to the completion of septation, the atrioventricular canal myocardium is incorporated into the atrial chambers as the vestibules of the atrioventricular valves. The "conus", if considered equivalent to the proximal part of the outflow tract, is separated by fusion of the proximal cushions to become the ventricular outflow tracts. The definitive ventricular myocardial mass, therefore, extends between the atrioventricular and the distal myocardial–arterial junctions. Each ventricle within the mass, in both functional and anatomical respects, can then be described as possessing inlet, apical, and outlet components (Goor & Lillehei, 1975). Such a tripartite approach is entirely consistent with the development sequence of ventricular formation. Each of the ventricles is initially formed with an apical component, which "balloons" from the outer curvature of the primary heart tube. The inlet of the right ventricle at this initial stage is the primary interventricular foramen. It obtains its own inlet subsequent to expansion of the atrioventricular canal. Since it balloons from the outlet part of the loop, however, the ventricle initially supports the entirety of the outflow tract.

With ongoing remodelling of the interventricular foramen, the ventricle cedes one of the outlet components to the left ventricle (Anderson, Spicer, et al., 2019). The tripartite approach to ventricular development and description, however, does not apply to the septum, which has only muscular and membranous components.

The developmental evidence now provides cogent explanations for the formation of the components of the supraventricular crest, also known as the crista supraventricularis. There is a degree of ambiguity in this regard in the use of "supraventricular". The structure in question is above the cavity of the right ventricle, forming the wall of the infundibulum adjacent to the aortic root. There is agreement that the crest should be considered separate from the septomarginal trabeculation or septal band (Anderson et al., 1977; Van Praagh, 2000). Part of the crest exists from the outset of development, being interposed between the atrioventricular canal and the outflow tract. This part is the initial inner heart curvature, or ventriculo-infundibular fold. At this initial stage of development, however, the fold interposes between the forming leaflets of the tricuspid and aortic valves. Subsequent to commitment of the aortic root to the left ventricle, the initial inner curvature merges with the component of the free-standing infundibular sleeve produced by muscularisation of the proximal outflow cushions. The muscularising proximal cushions themselves are continuous with the muscularising distal cushions, which support the developing leaflets of the pulmonary valve adjacent to the aortic root. The definitive ventriculo-infundibular fold of the right ventricle, therefore, part of the supraventricular crest, is a compound entity. It is made up of the initial inner heart curvature, the part of the infundibular sleeve derived from the proximal cushions, and the parts formed by muscularisation of the distal outflow cushions. It is the overall supraventricular crest that, at times, has been described as the parietal band (Anderson et al., 1977). The septal band, or septomarginal trabeculation, is formed by consolidation of the trabeculations that, during the initial stages of development, form the larger part of the initial ventricular walls. The consolidation of these initial trabeculations, which continue to grow along with the compact part of the ventricular walls, produces not only the prominent septomarginal trabeculation but also the multiple septoparietal trabeculations, which extend from its anterior margin. The trabeculations also consolidate to form the papillary muscles supporting the leaflets of the tricuspid valve.

The number of leaflets to be found with the tricuspid valve has also been a controversial issue. The evidence available from development, as yet, does not help in resolving this issue, since the inferior and antero-superior leaflets are formed by remodelling of the initial mural cushion formed within the developing right atrioventricular junction (Figure 6). The arguments depend very much on the criteria used to define the leaflets. When the skirt of leaflet tissue is observed during ventricular systole, it closes in trifoliate fashion in both the human and murine hearts. The components of the closing valve can then be seen, with the heart viewed in attitudinally appropriate position, to occupy inferior, septal, and antero-superior positions within the atrioventricular junction. It is certainly the case that, when each of these component parts is assessed in isolation, they can show subunits. This does not detract from the fact that the overall skirt closes in trifoliate fashion, permitting always the recognition of the three major leaflets.

Taken together, the findings now available in terms of cardiac development provide the means to arbitrate the controversies that previously abounded with regard to the right ventricle. The features now revealed by the clinical three-dimensional imaging techniques lend still further support for the definitions and descriptive terms that can appropriately be based on our current knowledge of cardiac development.

AUTHOR CONTRIBUTIONS

All authors discussed in advance the topics to be discussed, and how best to address them. Dr Adrian Crucean took the lead in determining the material to be presented. Mrs Diane E. Spicer prepared the anatomical dissections, which were then supplemented by the virtual dissections of the clinical datasets by Dr Justin T. Tretter. Professor Robert H. Anderson was responsible for analysing the datasets available from the human and murine embryos. All authors were involved in writing the manuscript and agreeing on the draft prepared for submission.

FUNDING INFORMATION

Preparation of the review received no direct funding.

CONFLICT OF INTEREST STATEMENT

None of the authors have interests to declare.

DATA AVAILABILITY STATEMENT

I confirm, AC.

ORCID

Adrian Crucean https://orcid.org/0000-0001-7655-1990
Robert H. Anderson https://orcid.org/0000-0001-5163-9021

REFERENCES

Anderson, R.H. (2017) Has the congenitally malformed heart changed its face? Journey from understanding morphology to surgical cure in congenital heart disease. *Circulation Research*, 120(6), 901–903.

Anderson, R.H., Becker, A.E. & Van Mierop, L.H. (1977) What should we call the'crista'? *Heart*, 39(8), 856–859.

Anderson, R.H., Chaudhry, B., Mohun, T.J., Bamforth, S.D., Hoyland, D., Phillips, H.M. et al. (2012) Normal and abnormal development of the intrapericardial arterial trunks in humans and mice. *Cardiovascular Research*, 95(1), 108–115.

Anderson, R.H., Spicer, D.E., Brown, N.A. & Mohun, T.J. (2014) The development of septation in the four-chambered heart. *The Anatomical Record*, 297(8), 1414–1429.

Anderson, R.H., Spicer, D.E., Hlavacek, A.J., Hill, A. & Loukas, M. (2013) Describing the cardiac components—attitudinally appropriate nomenclature. *Journal of Cardiovascular Translational Research*, 6, 118–123.

Anderson, R.H., Spicer, D.E., Mohun, T.J., Hikspoors, J.P. & Lamers, W.H. (2019) Remodeling of the embryonic interventricular communication in regard to the description and classification of ventricular septal defects. *The Anatomical Record*, 302(1), 19–31.

Anderson, R.H., Tretter, J.T., Spicer, D.E. & Mori, S. (2019) The fate of the outflow tract septal complex in relation to the classification of ventricular septal defects. *Journal of Cardiovascular Development and Disease*, 6(1), 9.

Chmielewski, P.P. (2020) New Terminologia Anatomica highlights the importance of clinical anatomy. *Folia Morphologica*, 79(1), 15–20.

Christoffels, V.M., Habets, P.E., Franco, D., Campione, M., de Jong, F., Lamers, W.H. et al. (2000) Chamber formation and morphogenesis in the developing mammalian heart. *Developmental Biology*, 223(2), 266–278.

Gerrelli, D., Lisgo, S., Copp, A.J. & Lindsay, S. (2015) Enabling research with human embryonic and fetal tissue resources. *Development*, 142(18), 3073–3076.

Goor, D.A. & Lillehei, C.W. (1975) *Congenital malformations of the heart*. New York: Grune & Stratton, pp. 1–37.

Hikspoors, J.P., Kruepunga, N., Mommen, G.M., Köhler, S.E., Anderson, R.H. & Lamers, W.H. (2022) A pictorial account of the human embryonic heart between 3.5 and 8 weeks of development. *Communications Biology*, 5(1), 226.

Ho, S.Y. & Nihoyannopoulos, P. (2006) Anatomy, echocardiography, and normal right ventricular dimensions. *Heart*, 92(suppl 1), i2–i13.

Hołda, M.K., Zhingre Sanchez, J.D., Bateman, M.G. & Iaizzo, P.A. (2019) Right atrioventricular valve leaflet morphology redefined: implications for transcatheter repair procedures. *JACC: Cardiovascular Interventions*, 12(2), 169–178.

Jensen, B., Spicer, D.E., Sheppard, M.N. & Anderson, R.H. (2017) Development of the atrial septum in relation to postnatal anatomy and interatrial communications. *Heart*, 103(6), 456–462.

Jongbloed, M.R.M., Wijffels, M.C.E.F., Schalij, M.J., Blom, N.A., Poelmann, R.E., Van Der Laarse, A. et al. (2005) Development of the right ventricular inflow tract and moderator band: a possible morphological and functional explanation for Mahaim tachycardia. *Circulation Research*, 96(7), 776–783.

Kanani, M., Moorman, A.F., Cook, A.C., Webb, S., Brown, N.A., Lamers, W.H. et al. (2005) Development of the atrioventricular valves: clinicomorphological correlations. *The Annals of Thoracic Surgery*, 79(5), 1797–1804.

Kumar, K., Lock, J.E. & Geva, T. (1997) Apical muscular ventricular septal defects between the left ventricle and the right ventricular infundibulum: diagnostic and interventional considerations. *Circulation*, 95(5), 1207–1213.

Lamers, W.H., Virágh, S., Wessels, A., Moorman, A.F. & Anderson, R.H. (1995) Formation of the tricuspid valve in the human heart. *Circulation*, 91(1), 111–121.

Lamers, W.H., Wessels, A., Verbeek, F.J., Moorman, A.F., Virágh, S., Wenink, A.C. et al. (1992) New findings concerning ventricular septation in the human heart. Implications for maldevelopment. *Circulation*, 86(4), 1194–1205.

Mall, F.P. (1912) On the development of the human heart. *American Journal of Anatomy*, 13(3), 249–298.

Merrick, A.F., Yacoub, M.H., Ho, S.Y. & Anderson, R.H. (2000) Anatomy of the muscular subpulmonary infundibulum with regard to the Ross procedure. *The Annals of Thoracic Surgery*, 69(2), 556–561.

Mohun, T.J. & Weninger, W.J. (2012) Embedding embryos for high-resolution episcopic microscopy (HREM). *Cold Spring Harbor Protocols*, 2012(6), pdb-prot069583.

Mori, S., Tretter, J.T., Spicer, D.E., Bolender, D.L. & Anderson, R.H. (2019) What is the real cardiac anatomy? *Clinical Anatomy*, 32(3), 288–309.

Muresian, H. (2016) The clinical anatomy of the right ventricle. *Clinical Anatomy*, 29(3), 380–398.

Odgers, P.N.B. (1938) The development of the pars membranacea septi in the human heart. *Journal of Anatomy*, 72(2), 247–259.

Odgers, P.N.B. (1939) The development of the atrio-ventricular valves in man. *Journal of Anatomy*, 73(4), 643–657.

Schlossbauer, S.A., Faletra, F.F., Paiocchi, V.L., Leo, L.A., Franciosi, G., Bonanni, M. et al. (2021) Multimodality imaging of the anatomy of tricuspid valve. *Journal of Cardiovascular Development and Disease*, 8(9), 107.

Stamm, C., Anderson, R.H. & Ho, S.Y. (1998) Clinical anatomy of the normal pulmonary root compared with that in isolated pulmonary valvular stenosis. *Journal of the American College of Cardiology*, 31(6), 1420–1425.

Stubbs, H., MacLellan, A., Lua, S., Dormand, H. & Church, C. (2023) The right ventricle under pressure: anatomy and imaging in sickness and health. *Journal of Anatomy*, 242(1), 17–28.

Tretter, J.T., Izawa, Y., Spicer, D.E., Okada, K., Anderson, R.H., Quintessenza, J.A. et al. (2021) Understanding the aortic root using computed tomographic assessment: a potential pathway to improved customized surgical repair. *Circulation: Cardiovascular Imaging*, 14(11), e013134.

Tretter, J.T., Sarwark, A.E., Anderson, R.H. & Spicer, D.E. (2016) Assessment of the anatomical variation to be found in the normal tricuspid valve. *Clinical Anatomy*, 29(3), 399–407.

Tretter, J.T., Spicer, D.E., Sánchez-Quintana, D., Back Sternick, E., Farré, J. & Anderson, R.H. (2022) Miniseries 1—Part III: 'Behind the scenes' in the triangle of Koch. *EP Europace*, 24(3), 455–463.

van den Hoff, M.J., Moorman, A.F., Ruijter, J.M., Lamers, W.H., Bennington, R.W., Markwald, R.R. et al. (1999) Myocardialization of the cardiac outflow tract. *Developmental Biology*, 212(2), 477–490.

van den Hoff, M.J. & Wessels, A. (2020) Muscularization of the mesenchymal outlet septum during cardiac development. *Journal of Cardiovascular Development and Disease*, 7(4), 51.

Van Praagh, R. (2000) Nomenclature and classification: morphologic and segmental approach to diagnosis. In: Moller, J.H., Hoffman, J.I.E. (Eds.) *Pediatric cardiovascular medicine*. New York: Churchill Livingstone, pp. 275–288.

Van Praagh, R., Geva, T. & Kreutzer, J. (1989) Ventricular septal defects: how shall we describe, name and classify them? *Journal of the American College of Cardiology*, 14(5), 1298–1299.

Van Praagh, R., Plett, J.A. & Van Praagh, S.T. (1979) Single ventricle. Pathology, embryology, terminology and classification. *Herz*, 4(2), 113–150.

Victor, S. & Nayak, V.M. (1994) The tricuspid valve is bicuspid. *The Journal of Heart Valve Disease*, 3(1), 27–36.

Wang, J.M.H., Rai, R., Carrasco, M., Sam-Odusina, T., Salandy, S., Gielecki, J. et al. (2019) An anatomical review of the right ventricle. *Translational Research in Anatomy*, 17, 100049.

Webb, S., Brown, N.A. & Anderson, R.H. (1996) The structure of the mouse heart in late fetal stages. *Anatomy and Embryology*, 194, 37–47.

How to cite this article: Crucean, A., Spicer, D.E., Tretter, J.T., Mohun, T.J. & Anderson, R.H. (2023) Revisiting the anatomy of the right ventricle in the light of knowledge of its development. *Journal of Anatomy*, 00, 1–15. Available from: https://doi.org/10.1111/joa.13960