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The clinical anatomy of tetralogy of Fallot

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IT IS NOW WELL OVER ONE HUNDRED YEARS SINCE Arthur Louis Etienne Fallot showed that four discrete morphologic abnormalities co-existed in the majority of patients he had autopsied with "la maladie bleu",[1] or cyanosis as we now describe it. The lesions he identified were an interventricular communication, subpulmonary stenosis, biventricular origin of the aortic valve, and right ventricular hypertrophy. We now know that the combination of these anomalies had been recognised long before Fallot's epochal description. Indeed, it is Neils Stensen, the Danish monk who also described the parotid duct, who is usually acknowledged as being the first to describe the entity that we now call tetralogy of Fallot.[2] Cases were certainly described by John Hunter,[2] whilst with the benefit of hindsight, we can see an unequivocal example illustrated by the Baron von Rokitansky[3] in his ground-breaking atlas (Fig. 1).

Although the combination of anomalies makes up one of the most characteristic of congenital cardiac malformations, the entity of tetralogy has proved remarkably contentious. There are various ways to describe the abnormal muscle bundles that surround the interventricular communication and produce the substrate for subpulmonary obstruction.[4–6] Arguments have raged concerning the dimensions of the narrowed subpulmonary infundibulum.[5,6] Debate still continues concerning the relationship between tetralogy and hearts having a double outlet ventriculoarterial connection, or alignment.[7,8] In this review, we will attempt to shed light on all these contentious issues, showing how many of the controversies reflect use of different nomenclatures as opposed to variations in observations. We will also show how some of the issues can be clarified by findings from the developing human heart.[9] Some of the problems, nonetheless, reflect the desire to compare the findings in tetralogy of Fallot with those seen in the normal heart.[5,6] We will commence our review, therefore, with an analysis of the structure of the normal outflow tracts, showing how logical description of the various components[10] is essential if we are to understand the abnormal situation seen in tetralogy.

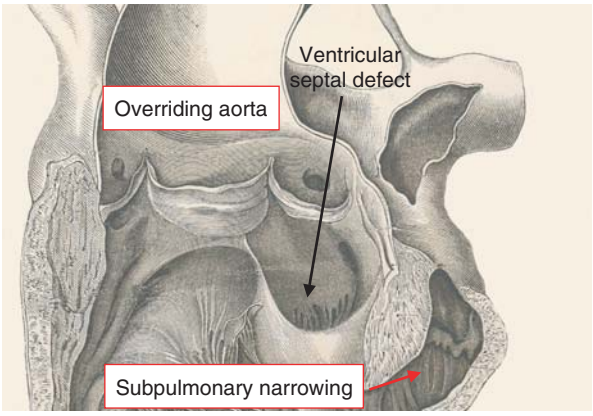

Figure 1.
This etching, taken from the atlas of Von Rokitansky, shows the unequivocal features of the lesion we now call tetralogy of Fallot. Compare with Figure 12.

Structure of the normal outflow tracts

The outflow tracts of the two ventricles differ in that, in the right ventricle, the leaflets of the pulmonary valve are supported by a complete muscular infundibulum, whilst in the left ventricle, two of the leaflets of the aortic valve are in fibrous continuity with the

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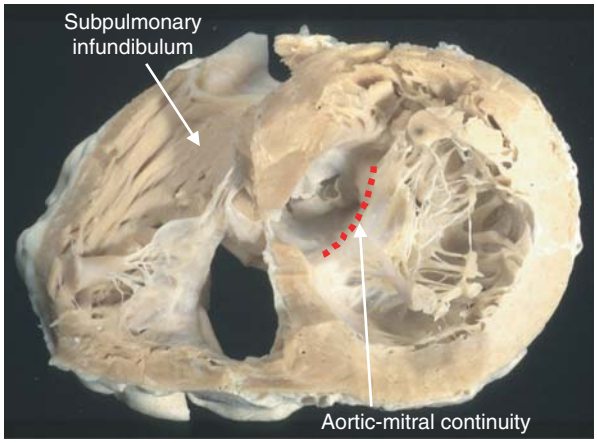

Figure 2.
This short axis section of the normal heart is prepared to replicate the left anterior oblique projection, and is viewed from the apical aspect. It shows the muscular right ventricular infundibulum interposed between the leaflets of the pulmonary and tricuspid valves, with fibrous continuity between the aortic and mitral valvar leaflets in the roof of the left ventricle.

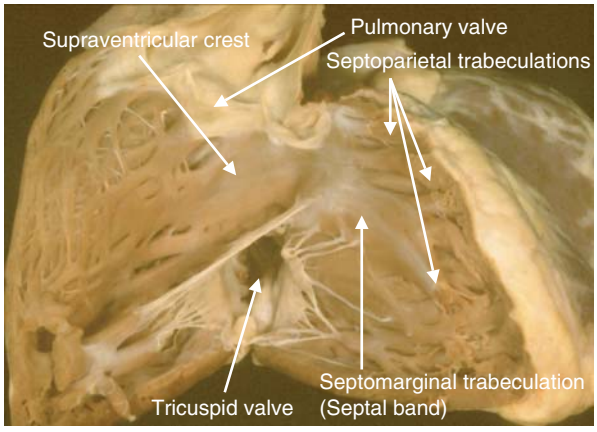

Figure 3.
The normal right ventricle has been opened to reveal its septal surface. Note the supraventricular crest inserting between the limbs of the septomarginal trabeculation, with the septoparietal trabeculations extending from the anterior edge of the septal trabeculation.

aortic leaflet of the mitral valve (Fig. 2). Thus, when viewed from the aspect of the right ventricle, an extensive muscular crest separates the leaflets of the tricuspid and pulmonary valves. This is the supraventricular crest, or "crista supraventricularis" (Fig. 3). The crest itself inserts into the septal aspect of the ventricle between the limbs of a prominent septal trabeculation, variously known as the septal band or the septomarginal trabeculation, albeit that the line of insertion between these parts is better developed in some normal hearts than other. This septal trabeculation usually has a body that divided cranially into two limbs, with the crest inserting

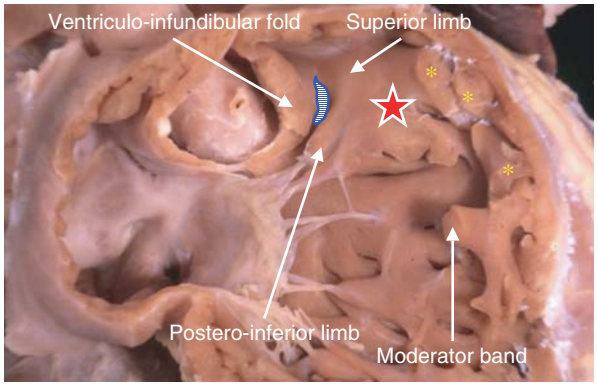

Figure 4.
In this normal heart, it is possible to see the limbs of the septomarginal trabeculation (red star) clasping the ventriculo-infundibular fold. The small area between the limbs shown by the blue crescent can be dissected to gain entrance to the left ventricle. It represents the muscular outlet septum but cannot be distinguished anatomically from the remainder of the supraventricular crest. Note the septoparietal trabeculations (yellow asterisks) extending from the anterior margin of the septal trabeculation. One trabeculation is prominent, and runs to the anterior papillary muscle. This is the moderator band.

between the limbs (Fig. 4). The cranial limb extends basally, and supports the leaflets of the pulmonary valve. The caudal limb runs beneath the membranous septum, and usually gives rise to the medial papillary muscle of the tricuspid valve. The body of the trabeculation extends towards the apex, where it breaks up to become continuous with the coarse apical trabeculations of the right ventricle. A series of further trabeculations, however, arise from the anterior surface of the septal trabeculation and run to the parietal wall of the ventricle, with one of these bundles being prominent as the moderator band, which runs to join the anterior papillary muscle of the tricuspid valve. The overall series of bundles represent the septoparietal trabeculations.[11] Careful dissection then reveals that the supraventricular crest has three component parts. The part of the muscle immediately between the limbs of the septal trabeculation can be removed so as to create a communication with the left ventricle. This small part, therefore, is a muscular outlet septum (Fig. 4). The larger part of the crest, however, is no more than the inner curvature of the parietal wall of the right ventricle, separating the cavity of the right ventricle from the transverse sinus and the right coronary artery (Fig. 5). The basal part of the crest is that supporting the leaflets of the pulmonary valve, and this is the complete sleeve of muscular infundibulum that permits removal of the pulmonary valve as an autograft for use in the Ross procedure (Fig. 6). The overall arrangement of the muscle bundles in the normal heart, therefore, is as shown in Figure 7. In terms of nomenclature, and for comparison with tetralogy of Fallot, it is necessary to

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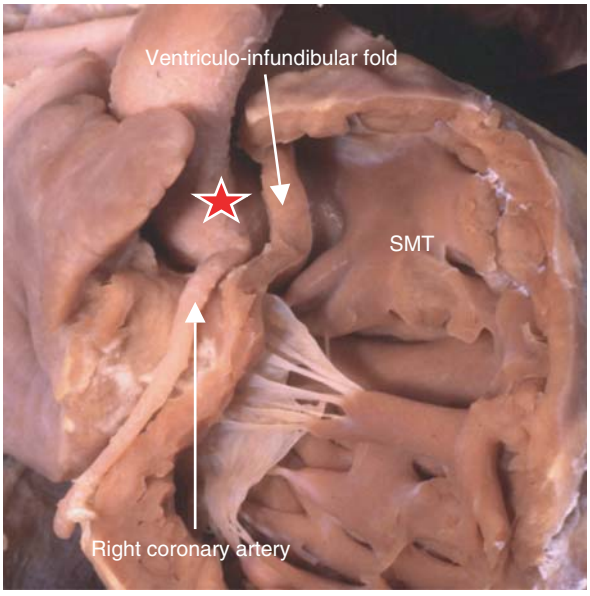

Figure 5.
This dissection of the heart shown in Figure 4 reveals that the larger part of the supraventricular crest is the parietal wall of the right ventricle, termed the ventriculo-infundibular fold, which separates the ventricular cavity from the transverse sinus of the pericardium (red star) and the right coronary artery running within the right atrioventricular groove. SMT: septomarginal trabeculation.

differentiate between the component parts of the normal supraventricular crest.[10] Some simply describe the crest as the "parietal band".[5] As we will see, however, the components of this band spring apart in the setting of tetralogy.[12] Thus, it is better to identify specifically the small part of the normal crest that separates the cavities of the right and left ventricle. This can then be described as the muscular outlet septum, or conal septum. This is separate from the inner heart curvature separating the leaflets of the tricuspid and pulmonary valves, which is the ventriculo-infundibular fold. Some call this "parietal band 2".[13] The basal part of the ventriculo-infundibular fold then becomes an integral part of the free-standing sleeve of subpulmonary infundibular musculature. The distinction between these two parts is also important for full appreciation of the arrangement seen in tetralogy of Fallot.

Development of the outflow tracts

Consideration of the way that the aorta is committed to the left ventricle during normal cardiac development[9] can now shed considerable light on the differences in structure between the normal heart and tetralogy of Fallot. Initially, the developing outflow tract of the heart is supported exclusively by the right ventricle. The outflow tract itself, initially with exclusively muscular walls, can be divided by an obvious

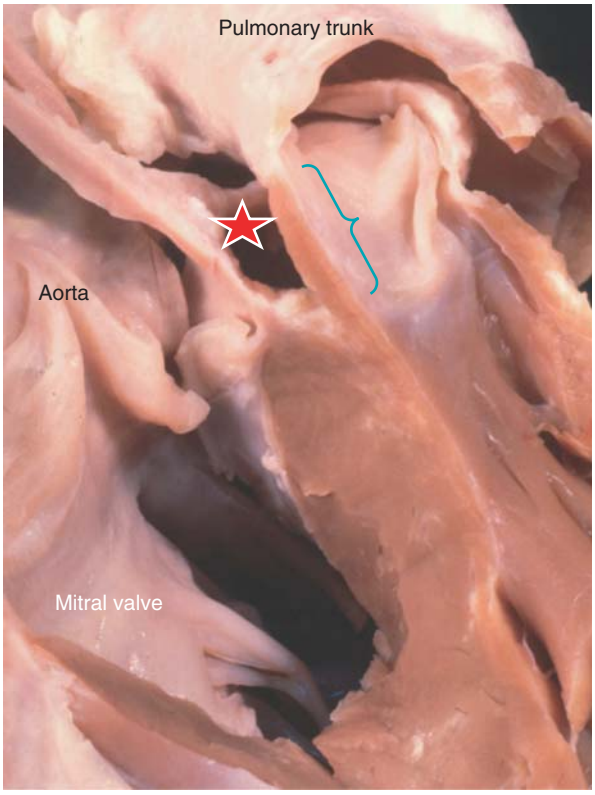

Figure 6.
This section across the ventricular septum reveals the sleeve of free-standing infundibular musculature (green bracket) that lifts the leaflets of the pulmonary valve away from the base of the right ventricle, making possible the Ross procedure. Note the tissue plane (red star) between the infundibulum and the aortic root.

dog-leg bend into proximal and distal portion (Fig. 8). The distal part is divided by fusion of outflow ridges, or cushions, to form the intrapericardial components of the arterial trunks. The pulmonary and aortic valvar sinuses, along with the valvar leaflets, are then sculpted at the level of the bend. The most proximal part of the outflow tract will produce the ventricular outflow tracts, and initially the musculature of the inner heart curve continues to separate the primordiums of the developing arterial valves from the forming leaflets of the atrioventricular valves, even when the aorta is becoming committed to the left ventricle (Fig. 9). It is the fusion of the most proximal parts of the outflow cushions to each other, and also to the crest of the muscular ventricular septum and the rightward tubercles of the atrioventricular cushions, which commits the aorta to the left ventricle. At the time of fusion of the most proximal parts of the cushions, the fused tissue mass still hangs in comma fashion above the cavity of the right ventricle. As this mass fuses with the primary ventricular septum and the atrioventricular cushions (Fig. 10), it muscularises and slides over the developing aortic root to become the free-standing subpulmonary infundibulum

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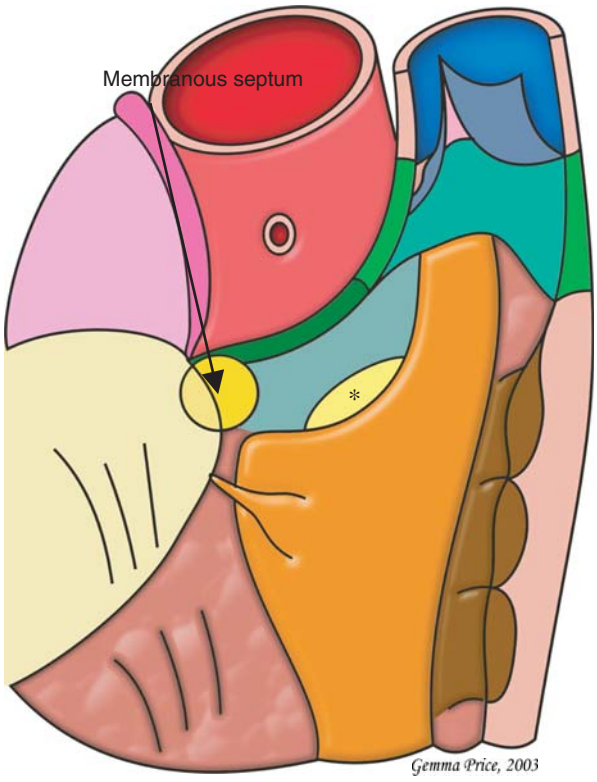

Figure 7.
The diagram shows the building blocks of the right ventricular outflow tract. The septomarginal trabeculation, or septal band, is shown in orange, with the septoparietal trabeculations coloured brown. The cut edge of the ventriculo-infundibular fold, making up the larger part of the supraventricular crest, is shown in dark green, with the subpulmonary infundibulum in brighter green. The part of the crest that can be removed to enter the left ventricle, representing the muscular outlet septum is shown by the asterisked yellow lozenge.

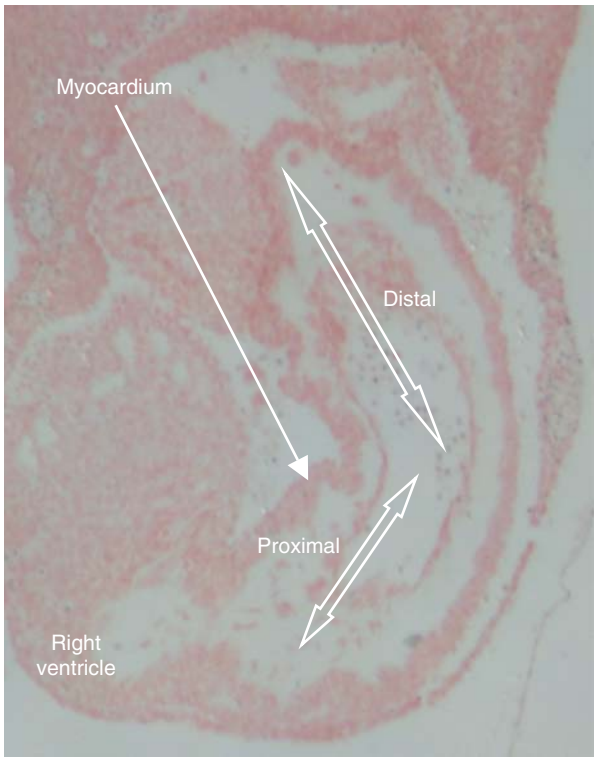

Figure 8.
This section through a human embryo at Carnegie stage 15, taken in the frontal plane, shows how the developing outflow tract initially has exclusively muscular walls, and is divided by an obvious bend into proximal and distal components.

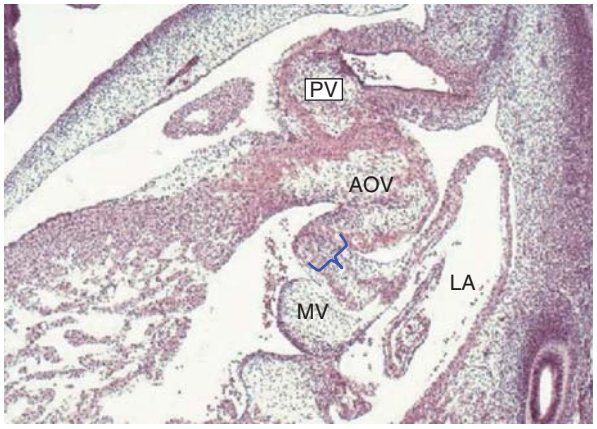

Figure 9.
This section through a human embryo at Carnegie stage 18, taken in the sagittal plane, shows how the musculature of the inner heart curvature (blue bracket) separates the developing primordiums of the aortic (AOV) and mitral (MV) valves. PV: pulmonary valve; LA: left atrium.

(Fig. 11). The precise mechanisms underscoring this transformation from intracardiac septum to free-standing infundibulum have still to be determined. In terms of the relationship to the remainder of the heart, however, the part of the muscularised cushions that persists as an interventricular septum is far less significant after formation of the free-standing infundibulum than was the case prior to closure of the embryonic interventricular communication (compare Figs 10 and 11). The interventricular communication itself is closed by the fusion of the most proximal part of the mesenchymal mass with the atrioventricular cushions, and this part of the septum remains fibrous as the membranous septum. Prior to fusion of the outflow cushions with the muscular ventricular septum, however, the developing heart retains an affinity with tetralogy of Fallot in that there is an interventricular communication, and the aortic valve retains its connections in both right and left ventricles. During normal development, however, there is no subpulmonary obstruction. The reasons why the cushion mass might be deviated in antero-cephalad fashion to produce tetralogy have still to be established, but the potential for such transformation is self-evident.

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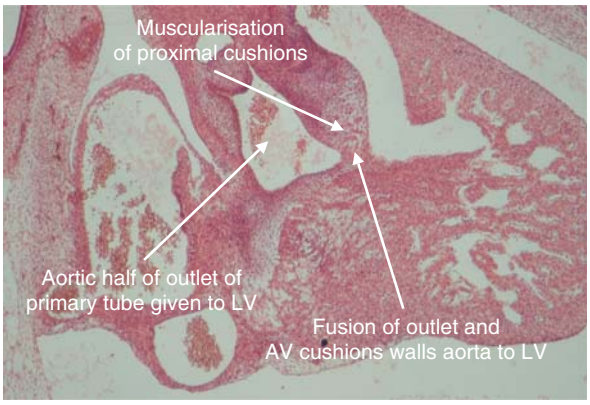

Figure 10.
This section of another human embryo at Carnegie stage 18 shows how the proximal end of the outflow cushions is fusing with the muscular septum so as to wall the aorta into the left ventricle, and at the same time undergoing muscularisation.

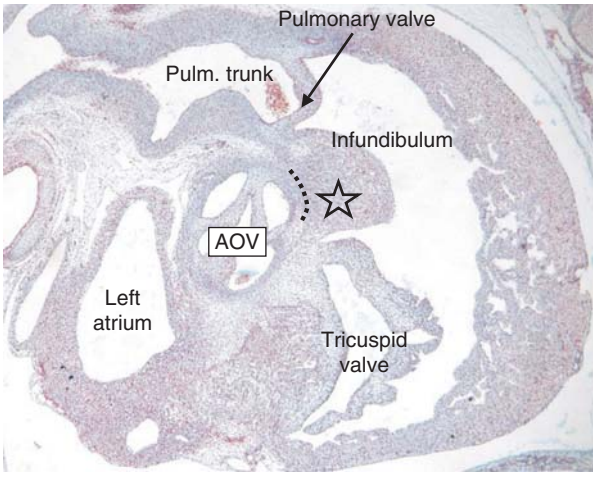

Figure 11.
This section of another human embryo at the stage just after the completion of ventricular septation shows how the muscularised proximal ends of the outflow cushions are becoming converted into the subpulmonary infundibulum (star). With further development, a plane will develop along the dotted line between the infundibulum and the aortic root, which now contains the leaflets of the aortic valve (AOV).

Clinical anatomy of tetralogy of Fallot

The essential difference between tetralogy of Fallot and the normal heart is that, in tetralogy, the components of the supraventricular crest have sprung apart, each element retaining its own individuality. One of us (RHA) had initially thought that the essence of tetralogy was antero-cephalad deviation of the muscular outlet septum relative to the limbs of the septomarginal trabeculation.[12] We now know that, whilst antero-cephalad deviation of the outlet septum, or its fibrous remnant, is indeed one of the cardinal features of tetralogy (Fig. 12), this feature in isolation

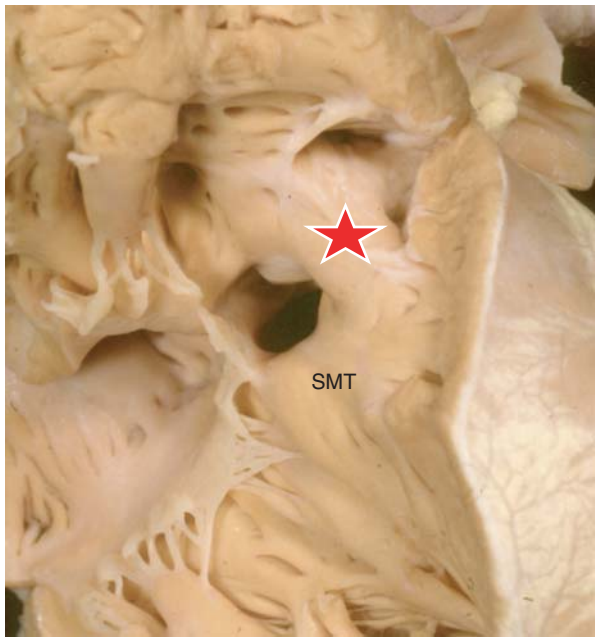

Figure 12.
As shown in this specimen, the cardinal feature of tetralogy of Fallot is antero-cephalad deviation of the outlet septum (red star) relative to the limbs of the septomarginal trabeculation (SMT).

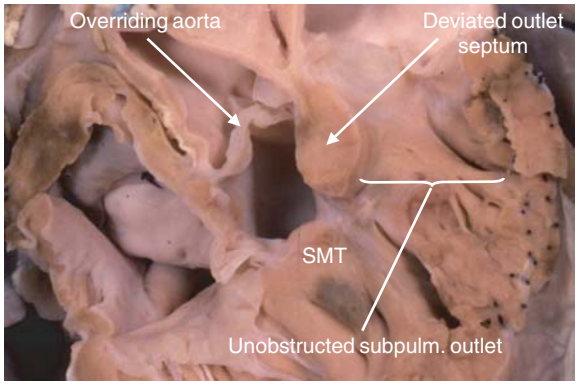

Figure 13.
As shown in this example of the so-called Eisenmenger ventricular septal defect, sectioned to replicate the subcostal oblique echocardiographic plane, antero-cephalad deviation of the outlet septum in isolation, that is in the absence of a small subpulmonary infundibulum, is insufficient to produce the phenotypic features of tetralogy of Fallot. SMT: septomarginal trabeculation.

is not sufficient to produce the abnormal pathology. This is because the outlet septum can be deviated in antero-cephalad fashion, along with extensive biventricular connection of the aortic valve, when there is no subpulmonary stenosis. This combination is seen in the so-called "Eisenmenger ventricular septal defect" (Fig. 13). An elegant study by the group from Leiden demonstrated the quantitative affinity between the Eisenmenger defect and tetralogy of Fallot.[14]

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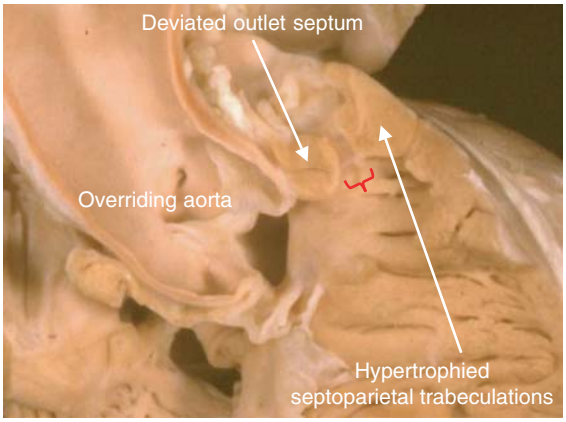

Figure 14.
As shown in this specimen sectioned for comparison to Figure 13, it is also necessary to have hypertrophy of the septoparietal trabeculations and a small diameter to the subpulmonary infundibulum resulting in or in addition to deviation of the muscular outlet septum to produce the phenotype of tetralogy of Fallot.

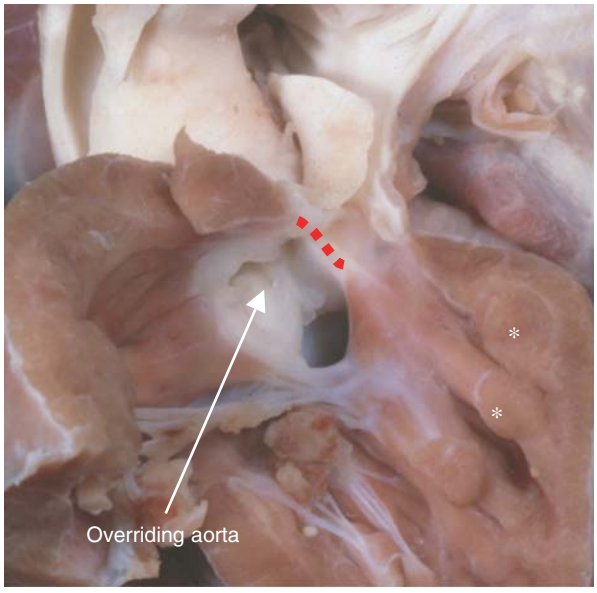

Figure 15.
In this specimen, the outlet septum is represented by a fibrous raphe between the leaflets of the overriding aortic valve and the pulmonary valve (red dotted line). The presence of the hypertrophied septoparietal trabeculations (asterisks) show the affinity to tetralogy of Fallot. The ventricular septal defect is doubly committed and juxta-arterial.

The other essential feature to produce tetralogy, in addition to antero-cephalad deviation of the muscular outlet septum, is hypertrophy of the septoparietal trabeculations, or conal free wall (Fig. 14). Such hypertrophy is seen even when the outlet septum itself is represented only by a fibrous remnant, seen when the interventricular communication is doubly committed (Fig. 15). One of us (PMW) subscribes to the hypothesis that the essence of tetralogy is the presence of a small subpulmonary infundibulum or conus, along with a normally sized subaortic area in the absence of a conus, this combination in itself resulting in the antero-superior, or antero-cephalad, deviation of the infundibular septum.

Although the deviation of the outlet septum, and the hypertrophy of the septoparietal trabeculations, are found in all examples of tetralogy, and can be considered the essential phenotypic features, there is then marked individual variability to be found in the other features. This can be summarised in terms of variability in the borders of the interventricular communication, differences in the extent of commitment of the aortic valve to the right ventricle, and variations in the length and structure of the subpulmonary infundibulum. Also important is the presence of associated malformations. We will discuss each of these items in greater detail.

Variability in the morphology of the interventricular communication

"Interventricular communication" is a better term to describe the hole between the ventricles than "ventricular septal defect", because there is still debate as to the plane of space that constitutes the "septal defect". Part of the essence of tetralogy is the biventricular connection of the leaflets of the aortic valve. This means that the muscular outlet septum is exclusively a right ventricular structure (Fig. 12). There is, therefore, a cone of space subtended beneath the leaflets of the aortic valve that overrides the crest of the muscular ventricular septum (Fig. 16). Relative to this cone of space, the true interventricular communication is the direct upward continuation of the plane of the muscular ventricular septum. This plane, however, transects the undersurface of the leaflets of the overriding aortic valve, and this is not the space that is closed by the surgeon to commit the aorta to the left ventricle. The plane of space of clinical importance is the right ventricular margin of the subtended cone. This right ventricular margin shows marked and significant variability in its superior and postero-inferior margins. In about four-fifths of patients, the superior margin will be the muscular outlet septum, while the postero-inferior margin is made up of an area of fibrous continuity between the tricuspid, aortic, and mitral valves (Fig. 17). Oftentimes, this area is reinforced by a fibrous flap representing the interventricular component of the membranous septum, whilst the atrioventricular component of the membranous septum is incorporated in the area of fibrous continuity. Because this space surrounds and incorporates the area of the membranous septum, the defect itself can justifiably be considered to be perimembranous.[9] The defect can also be termed a conal

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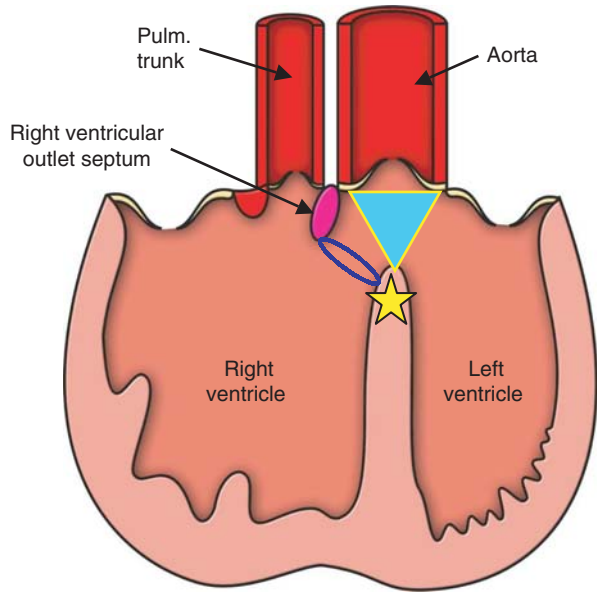

Figure 16.
The diagram shows the cone of space (triangle) subtended between the leaflets of the overriding aortic valve and the crest of the ventricular septum (star). Note that, in this setting, the outlet septum (green) is exclusively a right ventricular structure. It is the right ventricular margin of the cone of space (red oval) that is closed by the surgeon so as to reconnect the aorta with the left ventricle. This is the border that shows significant anatomic variability (see Figs 12, 17 and 18).

septal malalignment defect. The significance of this is that, unlike the most common perimembranous type of defect, namely the typical "conoventricular" defect, malalignment defects are more anterior, and do not have attachments of the cords of the tricuspid valve at their margins, nor are they partially covered by the tricuspid valvar leaflets. In about one-fifth of such patients, however, the postero-inferior margin of the defect is made of muscle rather than fibrous tissue (Fig. 18). This is because the ventriculo-infundibular fold, interposing between the leaflets of the tricuspid and aortic valves, fuses with the posterior limb of the septomarginal trabeculation. This is important clinically because the muscle bar thus formed protects the atrioventricular conduction axis.[12] If sufficiently large, sutures can be placed all along this muscular margin without fear of damaging the conduction tissues. The defect, therefore, whilst still being a conal septal malalignment defect, possesses a muscular postero-inferior rim, thus distinguishing it from the malalignment defect that is perimembranous.

The third variation in the borders of the defect is to be found in the superior margin. As already stated, in most patients this margin is formed by the muscular outlet septum (Fig. 12). In a very small proportion of Caucasian patients, but in larger proportions of patients from the Far East, South America, and

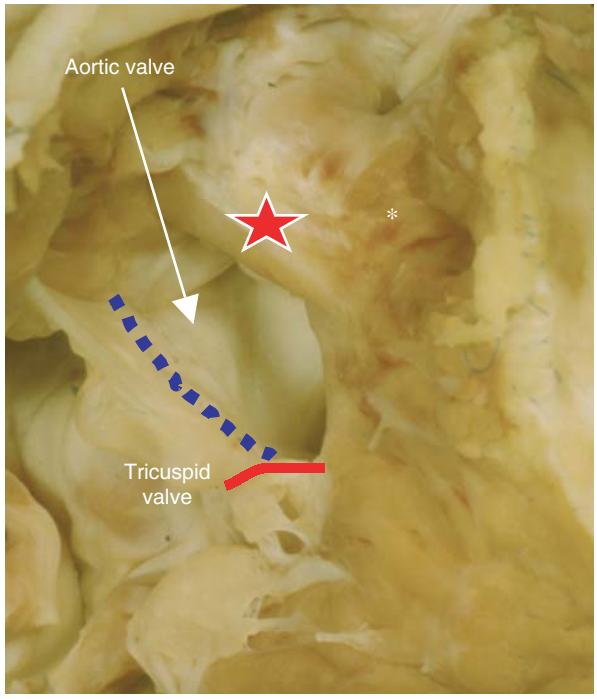

Figure 17.
In this specimen, the roof of the ventricular septal defect is the deviated outlet septum (red star). Note the resection of the septoparietal trabeculations (asterisk). The postero-inferior border is made up of an extensive area of fibrous continuity between the leaflets of the aortic and tricuspid valves (blue dotted line). The conduction axis (red line) is at risk in the postero-inferior margin.

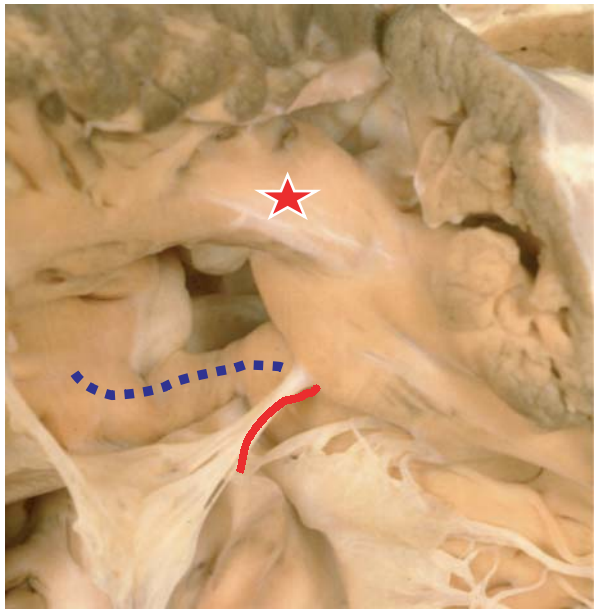

Figure 18.
In this specimen, the postero-inferior limb of the septomarginal trabeculation has fused with the ventriculo-infundibular fold, producing a muscular postero-inferior rim to the defect (blue dotted line) that protects the conduction axis (red line). Note that the outlet septum is still deviated in antero-cephalad direction so that the defect remains conoventricular, termed malalignment type by some (compare with Fig. 17).

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Mexico, this rim is made up of a fibrous raphe between the leaflets of the aortic and pulmonary valves, the muscular outlet septum having failed to develop (Fig. 15). The defect is therefore doubly committed and juxta-arterial, or can be described as representing conal septal malalignment in association with conal septal hypoplasia. Some describe this defect as being "supracristal". This term is inappropriate, however, since the essential component of the "crista", the muscular outlet septum, has failed to develop in this setting. The relationship of the defect to the septomarginal trabeculation, or septal band, is exactly the same as in the other forms of conal septal malalignment. The doubly committed defect itself can be perimembranous or have a muscular postero-inferior rim depending on the degree of formation of the ventriculo-infundibular fold and its fusion with the posterior limb of the septomarginal trabeculation. In the past, one of us (RHA) argued that, since the muscular outlet septum was absent in this defect, it should not be considered as part of tetralogy of Fallot.[15] We now recognise that this concept was misfounded, since the primordium of the outlet septum is clearly present in the doubly committed defect, but has failed to muscularise.

Variation in commitment of the aorta to the right ventricle

This, perhaps, remains the most contentious point with regard to description of tetralogy of Fallot. To some of us, tetralogy of Fallot represents a lesion diagnosed on the basis of its morphology. Double outlet is no more than a description of a particular ventriculo-arterial connection or alignment, and does not, therefore, describe any individual entity.[7] Within this philosophical approach, there is no logical reason why tetralogy of Fallot should not co-exist with a double outlet connection, or alignment, whenever more than half of the circumference of the aortic valve is supported by right ventricular rather than left ventricular structures. And analysis of a large series of cases with the phenotypic features of tetralogy shows that such arrangement is far from rare.[12] On the other hand, some authorities argue that double outlet should only be described when both arterial valves not only arise predominantly from the right ventricle, but are also supported in their entirety by complete muscular infundibulums.[8] This approach, of course, transgresses the important philosophical principle established by Van Praagh et al., and dubbed the "Morphological method", which states that one variable morphological feature should not be defined on the basis of a second feature that is itself variable. One of us (PMW) considers double outlet right ventricle to represent one type of ventriculo-arterial alignment, whereas tetralogy of Fallot is deemed to be one conotruncal anomaly produced by a small subpulmonary conus, with a normally sized subaortic area in the absence of an infundibulum or conus, in the setting of the ventriculo-arterial alignment termed "normally aligned great arteries". The other major conotruncal anomaly with normally aligned great arteries is that seen commonly with interrupted aortic arch, and in some cases of ventricular septal defect accompanied by hypoplasia of the aortic arch, namely a small subaortic area with no conus but a normal subpulmonary area with a conus. Within this concept, the ventriculo-arterial alignment of double outlet right ventricle can itself be associated with a number of conotruncal anomalies, including bilateral conuses of equal size; bilateral conuses with a small subaortic conus as seen in the so-called Taussig-Bing type, often with hypoplasia of the aortic arch; bilateral conuses with small subpulmonary conus, giving double outlet of the "tetralogy" type; a subpulmonary conus only with fibrous continuity between the leaflets of the tricuspid and aortic valves, as often seen with mitral atresia; a subaortic conus only, with fibrous continuity between the leaflets of the mitral and pulmonary valves but with pulmonary trunk clearly above the right ventricle, sometimes with straddling mitral valve; and a host of other conal abnormalities. All of the above, however, may be considered semantic, and not as important as the practical difference between tetralogy of Fallot with fibrous continuity between the leaflets of the mitral and aortic valves, and what some of us call the "tetralogy" type of double outlet right ventricle with mitral-aortic discontinuity. In the former, repair never results in obstruction to the left ventricular outlet, whereas in the latter it frequently does, due to the fact that the muscle between the mitral and aortic valves, together with the remaining borders of the interventricular communication, completes a ring of muscle. This ring of muscle may hypertrophy over time after intraventricular repair using a baffle, resulting in obstruction to the outflow from the left ventricle.

Cases do exist with muscular separation between the leaflets of the aortic and mitral valve and the unequivocal outflow morphology of tetralogy (Fig. 19), but they are rare.

Morphology of the subpulmonary infundibulum

As we have discussed, the essence of tetralogy of Fallot is a "squeeze" produced between the deviated muscular outlet septum or its fibrous remnant, and the hypertrophied septoparietal trabeculations (Fig. 14). In those with a muscular outlet septum, the majority of patients, this then produces a narrowed muscular

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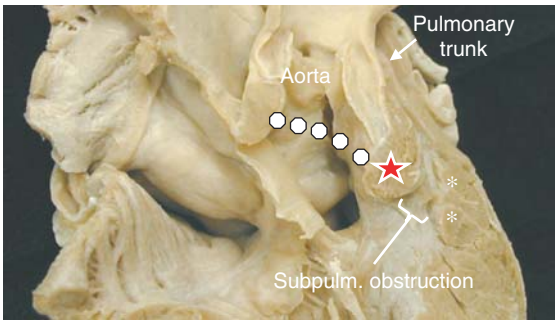

Figure 19.
In this specimen, the antero-cephalad deviation of the outlet septum (star) combined with hypertrophy of the septoparietal trabeculations (asterisk), combined with overriding of the aortic valve, fulfil the criterions for description as tetralogy of Fallot. Note, however, that there is a muscular infundibulum separating the leaflets of the aortic and mitral valves. In this specimen, therefore, tetralogy of Fallot co-exists with double outlet right ventricle, or, as one of us (PMW) would say, there is the tetralogy type of double outlet right ventricle.

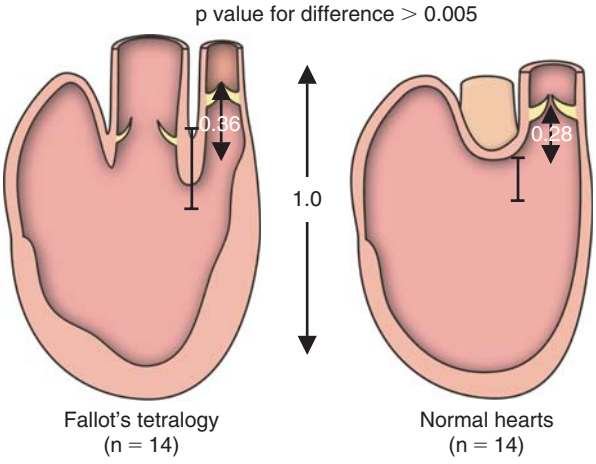

Figure 20.
This cartoon summarises the measurements made by Becker et al.[6] When assessed in series of cases, the infundibulum is significantly longer in the setting of tetralogy than in the normal heart, although it can be short in individual cases.

orifice to the subpulmonary infundibulum. Since the septal component of the subpulmonary infundibulum itself can be completely lacking in those patients with the doubly committed defect, it is not surprising that examination of large series of autopsied specimens reveals marked variation in the length of the subpulmonary infundibulum, and also in the thickness of the muscular outlet septum.[12] When series of specimens are measured, however, and compared to the ratio of infundibular length as seen in the normal heart relative to the overall length of the right ventricle (Fig. 20), the subpulmonary infundibulum in tetralogy is found to be longer than normal.[6,16] It is incorrect, therefore, to argue that the infundibulum is "too short" in the setting of tetralogy.[5] The infundibulum certainly has reduced volume compared to normal, and is unequivocally narrow, but in the majority of hearts, it is longer when compared to the arrangement seen in the normal heart. The mouth of the infundibulum, however, is but one of the potential narrowings in the pulmonary outflow tract. The pulmonary valve itself can be additionally stenotic, and has only two leaflets in the majority of cases, whilst further narrowing can be found at the sinutubular junction or within the pulmonary arteries, particularly in the left pulmonary artery at the site of origin of the arterial duct, if such a structure is present or ligamentous.

Associated malformations

Any lesions that can, potentially, co-exist with tetralogy must be anticipated to be present. Some are sufficiently frequent to warrant positive exclusion. A right-sided aortic arch is present in up to one-third of patients. Anomalous origin of the anterior interventricular artery from the right coronary artery is found in perhaps one-twentieth of cases, and is of obvious surgical significance. Perhaps the most significant feature of surgical importance, however, is the presence of pulmonary atresia rather than stenosis. This variant makes up the majority of cases of "pulmonary atresia with ventricular septal defect". It is important because virtually all those examples with pulmonary arterial flow derived from systemic-to-pulmonary collateral arteries have the intracardiac anatomy of tetralogy or one of its variants.[17] Tetralogy of Fallot with pulmonary atresia can also co-exist with other origins of pulmonary arterial blood, such as the arterial duct, or rarer forms such as aortopulmonary windows, but it is the subset with systemic-to-collateral arteries that are most important. Space precludes a detailed analysis of these hearts, but the key is to determine the proportion of the pulmonary vasculature supplied by the collateral arteries, and its connection with the intrapericardial pulmonary arteries, if indeed such arteries are present.[18] Other significant associated malformations include a second muscular inlet ventricular septal defect, atrioventricular septal defect with common atrioventricular junction, or canal, and straddling and overriding of the tricuspid valve.

Conclusions

It is now possible to identify strict morphological criterions for the diagnosis of tetralogy of Fallot, namely antero-cephalad deviation of the muscular outlet septum or its remnant relative to the septomarginal trabeculation, or septal band, coupled with

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hypertrophy of the septo-parietal trabeculations or a small subpulmonary infundibulum or conus. Even within this strict morphological definition, however, as previously emphasised by Lev and Eckner,[4] no two specimens are identical. It is identification of the morphological variations within this phenotypic framework, therefore, that provides the key to accurate clinical diagnosis. These variations include the differences in the margins of the ventricular septal defect, the extent of aortic override, and the precise anatomic substrates for pulmonary obstruction. Also important are the number and nature of associated malformations. If approached in this fashion, then those semantic differences that persist are of relatively minor significance.

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References

1. Fallot A. Contribution a l'anatomie pathologique de la maladie bleue (cyanose cardiaque). Marseille Med 1888; 25: 77–93.
2. Marquis RM. Longevity and the early history of the tetralogy of Fallot. Br Med J 1956; i: 819–822.
3. von Rokitansky CF. Die Defecte der Scheidewande des Herzens. Pathologisch-Anatomisch Wilhelm Braumuller, Vienna, 1875, pp 27–29.
4. Lev M, Eckner FAO. The pathologic anatomy of tetralogy of Fallot and its variants. Dis Chest 1964; 45: 251–261.
5. Van Praagh R, Van Praagh S, Nebesar RA, et al. Tetralogy of Fallot: underdevelopment of the pulmonary infundibulum and its sequelae. Report of a case with cor triatriatum and pulmonary sequestration. Am J Cardiol 1970; 26: 25–33.
6. Becker AE, Connor M, Anderson RH. Tetralogy of Fallot: a morphometric and geometric study. Am J Cardiol 1975; 35: 402–412.
7. Wilcox BR, Ho SY, Macartney FJ, et al. Surgical anatomy of double-outlet right ventricle with situs solitus and atrioventricular concordance. J Thorac Cardiovasc Surg 1981; 82: 405–417.
8. Van Praagh R. Nomenclature and classification: Morphologic and segmental approach to diagnosis. In: Moller JH, Hoffman JIE (eds). Pediatric Cardiovascular Medicine. Churchill Livingstone, New York, NY, USA, 2000, pp 275–288.
9. Anderson RH, Webb S, Brown NA, Lamers WH, Moorman AFM. The development of the heart: (3) Formation of the ventricular outflow tracts, arterial valves, and intrapericardial arterial trunks. Heart 2003; 89: 1111–1118.
10. Anderson RH, Becker AE, Van Mierop LHS. What should we call the "crista"? Br Heart J 1977; 39: 856–859.
11. Goor DA, Lillehei CW. Congenital Malformations of the Heart. Grune and Stratton, New York, 1975, pp 1–37.
12. Anderson RH, Allwork SP, Ho SY, Lenox CC, Zuberbuhler JR. Surgical anatomy of tetralogy of Fallot. J Thorac Cardiovasc Surg 1981; 81: 887–896.
13. Lev M, Bharati S, Meng CCL, et al. A concept of double-outlet right ventricle. J Thorac Cardiovasc Surg 1972; 64: 271–281.
14. Oppenheimer-Dekker A, Gittenberger-de Groot AC, Bartelings MM, et al. Abnormal architecture of the ventricles in hearts with an overriding aortic valve and a perimembranous ventricular septal defect ("Eisenmenger VSD"). Int J Cardiol 1985; 9: 341–355.
15. Griffin ML, Sullivan ID, Anderson RH, Macartney FJ. Doubly committed subarterial ventricular septal defect: new morphological criteria with echocardiographic and angiocardiographic correlation. Br Heart J 1988; 59: 474–479.
16. Howell CE, Ho SY, Anderson RH, Elliott MJ. Variations within the fibrous skeleton and ventricular outflow tracts in tetralogy of Fallot. Ann Thorac Surg 1990; 50: 450–457.
17. Anderson RH, Devine WA, del Nido P. The surgical anatomy of tetralogy of Fallot with pulmonary atresia rather than pulmonary stenosis. J Card Surg 1991; 6: 41–59.
18. Ho SY, Catani G, Seo JW. Arterial supply to the lungs in tetralogy of Fallot with pulmonary atresia or critical pulmonary stenosis. Cardiol Young 1992; 2: 65–72.