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Systematic Approach to Malalignment Type Ventricular Septal Defects

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ABSTRACT: Various congenital heart diseases are associated with malalignment of a part of the ventricular septum. Most commonly, the outlet septum is malaligned toward the right or left ventricle. Less commonly, the whole or a major part of the ventricular septum is malaligned in relation to the atrial septal plane. Although the pathological conditions associated with ventricular septal malalignment have been well recognized, the descriptions are often confusing and sometimes incorrect. In this pictorial essay, we introduce our systematic approach to the assessment of malalignment type ventricular septal defects with typical case examples. The systematic approach comprises description of the essential features of malalignment, including the following: (1) the malaligned part of the ventricular septum, (2) the reference structure, (3) the mechanism of malalignment, (4) the direction of malalignment, and (5) the severity of malalignment.

Key Words: double outlet right ventricle ■ malalignment ■ overriding ■ straddling ■ ventricular septal defect

A ventricular septal defect (VSD) may occur in isolation as a simple punched-out hole in an otherwise normally formed ventricular septum. A VSD may also occur with various degrees of malalignment involving a component of the ventricular septum whereby an arterial or atrioventricular valve or valves override the resultant defective ventricular septum.¹⁻³ Most frequently, the outlet septum is malaligned in relation to the rest of the ventricular septum. Less frequently, the whole or a major part of the ventricular septum is malaligned in relation to the atrial septal plane.⁴⁻⁹ Finally, both atrial and ventricular septa can be grossly malaligned as if they were twisted along the long axis of the heart.¹⁰⁻¹³ The VSDs in such conditions can be described collectively as malalignment type VSDs. The concept of septal malalignment is particularly helpful in defining the characteristics of the VSD and the types of the atrioventricular and ventriculoarterial connections in hearts with overriding of an atrioventricular or arterial valve. The pathologic conditions that are associated with malalignment type VSD include the following:

1. Anterior malalignment of the outlet septum relative to the rest of the ventricular septum.
 - Tetralogy of Fallot (case 1).
 - Eisenmenger VSD (case 2).
 - Tetralogy type of double outlet right ventricle.
 - VSD type of double outlet right ventricle (case 2).
 - Double outlet right ventricle with subpulmonary VSD (cases 3 and 4).
2. Posterior malalignment of the outlet septum relative to the rest of the ventricular septum.
 - So-called coarctation or interruption type VSD (case 5).
 - Double outlet left ventricle (case 6).
3. Malalignment between the atrial and ventricular septal planes.
 - Overriding/straddling tricuspid valve: double inlet left ventricle spectrum (cases 7 and 8).
 - Overriding/straddling mitral valve: double inlet right ventricle spectrum (case 9).
 - Overriding/straddling tricuspid valve in association with juxtaposition of the atrial appendages.
4. Twisted or crisscross heart (case 10).

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Nonstandard Abbreviation and Acronym

TSM trabecula septomarginalis

Although ventricular septal malalignment in these conditions has been well recognized, the way it has been described in the literature is often difficult or confusing and sometimes incorrect. For instance, the difference between the anterior and posterior malalignments of the outlet septum is not only the direction but also the mechanism of malalignment that will be discussed later. Another example is the malalignment type VSD in a straddling/overriding mitral valve that has inaccurately been described to involve the anterior part of the ventricular septum or wrongfully described to involve the region of the infundibular septum.⁶ To avoid such inaccuracy or incorrectness, we propose a systematic approach to the various forms of malalignment type VSD. Although we highlight general rules or strong tendencies in the morphological presentations of most of the described conditions, rare cases can present with any unusual morphological features as there is no rule without exception. In this article, we strictly focus on the morphological features without any embryological explanation or hypothesis. In our article, we use the following definitions for terms commonly used in the description of malalignment type VSDs.

DEFINITION OF TERMS

Ventriculoinfundibular Fold

The ventriculoinfundibular fold is a muscular fold or inner heart curvature that separates an arterial from an atrioventricular valve at the base of the ventricles.^{14,15} When it is present, as in a normal right ventricle, it completes the muscular infundibulum, supporting the arterial valve. Its absence implies that the arterial valve is not supported by the muscular infundibulum, with fibrous continuity between the arterial and atrioventricular valves.

Outlet Septum

The outlet septum is the dividing wall between the subaortic and subpulmonary outflow tracts underneath the semilunar valves. The outlet septum is also called the infundibular or conal septum. In normal hearts, the outlet septum occupies a small area between the anterior and posterior limbs of the trabecula septomarginalis (TSM) (septomarginal trabeculation) or septal band. As it merges imperceptibly with the ventriculoinfundibular fold, the outlet septum is not clearly definable in normal hearts.^{14,15} When the outlet septum is malaligned and loses its interventricular position, the

outlet septum is recognizable as a distinct structure within the right or left ventricle. Infrequently, the outlet septum is severely hypoplastic, and the arterial valves are divided by a fibrous outlet septum or raphe.¹⁶

Crux Cordis

The crux cordis is an external landmark of the heart where the atrioventricular sulcus is crossed by the continuation of the posterior interatrial and interventricular groove.^{5,6} In abnormal hearts with malalignment between the atrial and ventricular septal planes, the crux cordis is defined as the point where the posterior interatrial groove meets the atrioventricular sulcus.⁶

Overriding Versus Straddling

Overriding describes the commitment of the valvar annulus to both ventricles across the ventricular septum.^{5,6,17} Straddling refers to the attachment of the supporting tension apparatuses (ie, the chords and papillary muscles) in both ventricles. Therefore, both atrioventricular and arterial valves may override the ventricular septum, whereas only the atrioventricular valves may straddle across the ventricular septum. Overriding of a valvar annulus implies that a part of the septum underneath the overriding valve is malaligned from its normal or usual position.¹⁷ Although straddling of an atrioventricular valve occurs with overriding in most cases, straddling may occur without overriding and overriding may occur without straddling. Straddling without overriding occurs without ventricular septal malalignment.

Double Outlet Right Ventricle

Double outlet right ventricle is a type of ventriculoarterial connection in which >50% of both arterial trunks arise from the right ventricle.^{16,18,19} Although both arterial trunks are usually supported by bilateral muscular infundibulum or conus, double outlet right ventricle is not defined by the presence or absence of the infundibulum or conus.¹⁶

SYSTEMATIC APPROACH TO VENTRICULAR SEPTAL MALALIGNMENT

When there is ventricular septal malalignment, it can be characterized objectively and with clarity by defining the following 5 essential features:

1. The malaligned part of the ventricular septum.
2. The reference structure (ie, in relation to which structure the septum is malaligned?).
3. The mechanism of malalignment.
4. The direction of malalignment.
5. The severity of malalignment.

Ventricular septal malalignment most commonly involves the outlet component of the ventricular septum. The malalignment of the outlet septum occurs in relation to the rest of the ventricular septum. When it is malaligned, the outlet septum is no longer an interventricular structure but belongs to either the right or the left ventricle, depending on the direction of its malalignment. Rarely, the plane of the whole or a major part of the ventricular septum is malaligned in relation to the atrial septal plane so that the tricuspid or mitral valve overrides the defective ventricular septal crest with or without straddling.⁴⁻⁹

There are 2 general mechanisms: flap-door and en-bloc displacement (Figure 1). Flap-door mechanism refers to the situation where the involved part of the septum swings open like a door that is hinged to a door frame. In this mechanism, the malaligned part of the septum remains inserted to a margin of the VSD, forming a certain angle in relation to the reference structure. Frequently, the malaligned outlet septum inserts to the margin of the VSD perpendicular to the plane of the ventricular septum. En-bloc displacement refers to the situation where a part of the septum is displaced as a unit, leaving the rest of the septum so that the malaligned part of the septum does not insert to any part of the VSD margin but is more or less parallel to the plane of the reference structure.

When the outlet septum is involved, the direction and extent of malalignment determine the degree of aortic or pulmonary valve overriding and, therefore,

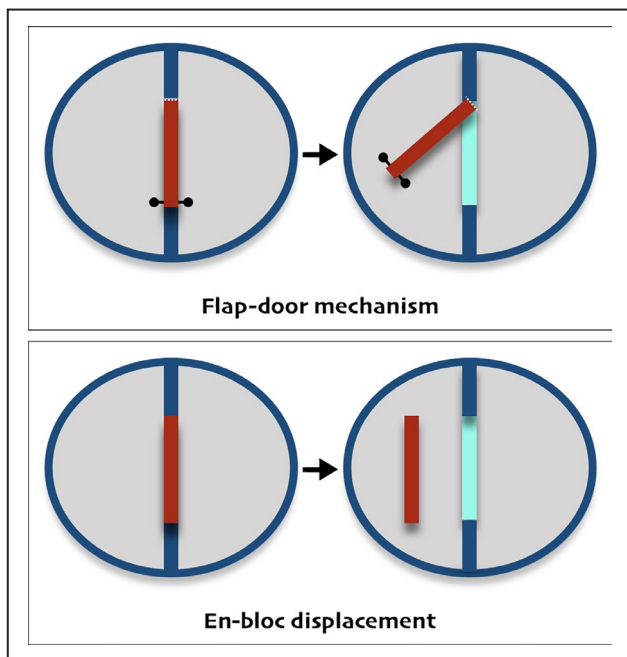


Figure 1. Flap-door vs en-bloc displacement mechanisms of ventricular septal malalignment.

In flap-door mechanism, the malaligned part of the septum remains inserted to a margin of the ventricular septal defect. In en-bloc displacement mechanism, the malaligned part of the septum is parallel with the rest of the septum.

the type of ventriculoarterial connection. When the ventricular septum is malaligned in relation to the atrial septal plane, the direction and extent of malalignment determines the severity of tricuspid or mitral valve overriding and, therefore, the type of atrioventricular connection. On the contrary, the atrial septum may appear malaligned from the normally positioned ventricular septum when the appendage of one atrium is displaced to the other side and juxtaposed on top of the appendage of the other atrium.

Rarely, the atrial and ventricular septa are malaligned in a complex manner, resulting in twisted or crisscross hearts (Figure 2).¹⁰⁻¹³ As the VSD involves a grossly twisted ventricular septum, the atrioventricular valves frequently appear to override the ventricular septal crest with or without straddling of their tension apparatuses. By the same token, an arterial valve or valves may appear to arise from the right or left ventricle, depending

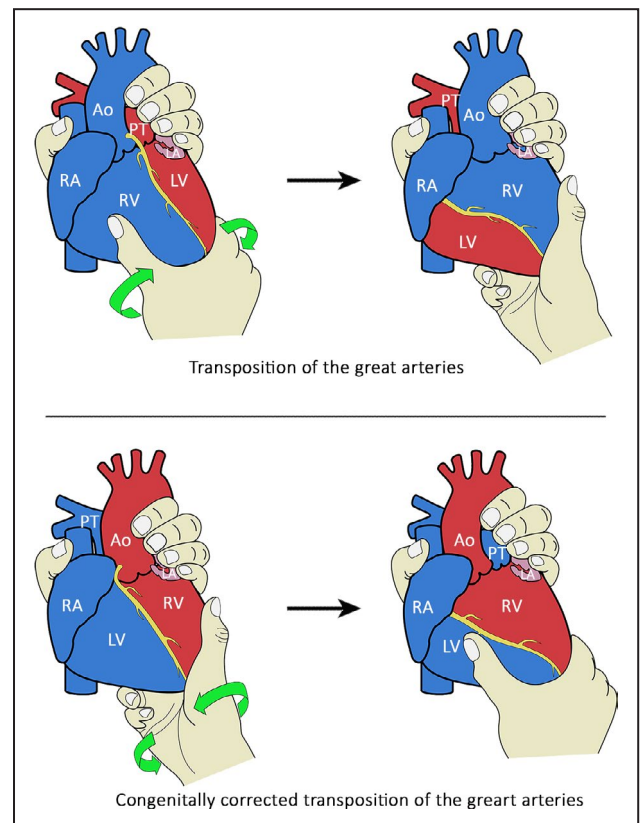


Figure 2. Twisting.

The cardiac chambers and arterial trunks show unusual spatial relationship as if the heart is twisted around the long axis of the heart. The hearts with D-loop ventricles typically appear twisted clockwise by the observer's right hand on the apex while the back of the heart is held by the observer's left hand. The hearts with L-loop ventricles typically appear twisted counterclockwise. The atrial and ventricular septa are twisted and malaligned, with one or both atrioventricular valves frequently overriding/straddling the ventricular septum. Data derived from Yoo, et al.¹³ Ao indicates aorta; LA, left atrium; LV, left ventricle; PT, pulmonary arterial trunk; RA, right atrium; and RV, right ventricle.

on which part of the curved ventricular septal plane is referenced to define the ventriculoarterial connection.

In evaluating the ventricular septal malalignment, there are 2 constant features. First, the outlet septum is simply a downward extension of the truncal septum and divides the arterial outflow tracts. Therefore, the outlet septum has a constant unbreakable relationship to the arterial valves when they are present. This rule does not apply in hearts with only one arterial valve, such as a truncal valve. Second, the lower part of the atrial septum is always interposed between the 2 atrioventricular valves regardless of any pathological feature in the underlying ventricles. This rule does not apply in hearts with an atrioventricular septal defect in which the lower part of the atrial septum is deficient.

CASE 1: ANTERIOR MALALIGNMENT OF OUTLET SEPTUM IN TETRALOGY OF FALLOT

The VSD in tetralogy of Fallot typically involves the outlet part of the ventricular septum that is cradled between the anterior and posterior limbs of the TSM (Figure S1).^{20,21} The outlet septum is malaligned into the right ventricle like a flap door with its hinges on the anterior limb of the TSM that forms the left margin of the VSD (Figure 3). The pulmonary valve and subpulmonary outflow tract are encroached on by the displaced outlet septum. Being a structure attached to the outlet septum, the aortic valve is also displaced into the right ventricle to override the ventricular septal crest or to arise entirely from the right ventricle. The VSD is typically crescentic in shape, with a large transverse diameter and a smaller vertical diameter. Most commonly, the VSD reaches the membranous septum to be a perimembranous VSD. Less commonly, the posterior margin of the VSD does

not reach the membranous septum. The outlet septum can be vestigial or absent, with the large aortic and small pulmonary valves divided by the malaligned raphe between the 2 valves. The VSD may also extend toward the inlet and trabecular parts of the ventricular septum, forming a large confluent defect.

CASE 2: ANTERIOR MALALIGNMENT OF OUTLET SEPTUM IN EISENMENGER VSD WITH DOUBLE OUTLET RIGHT VENTRICLE

The Eisenmenger VSD involves the same anatomical location as the VSD in tetralogy of Fallot (Figure S2).²² However, the subpulmonary outflow tract and pulmonary valve are not significantly encroached on by the malaligned outlet septum. Both tetralogy and Eisenmenger VSD can be associated with double outlet right ventricle when >50% of the aortic valve overrides the ventricular septal crest, as shown in this case. If untreated, further hypertrophy of the outlet septum and aberrant muscle bundles may cause secondary subpulmonary stenosis, mimicking the morphologic features of tetralogy of Fallot.²³ However, the pulmonary valve is larger than the aortic valve in Eisenmenger VSD, whereas the pulmonary valve is always smaller than the aortic valve in tetralogy of Fallot.

CASE 3: ANTERIOR MALALIGNMENT OF OUTLET SEPTUM IN DOUBLE OUTLET RIGHT VENTRICLE WITH SUBPULMONARY VSD, VARIANT 1

Double outlet right ventricle with subpulmonary VSD or Taussig-Bing malformation has also been called

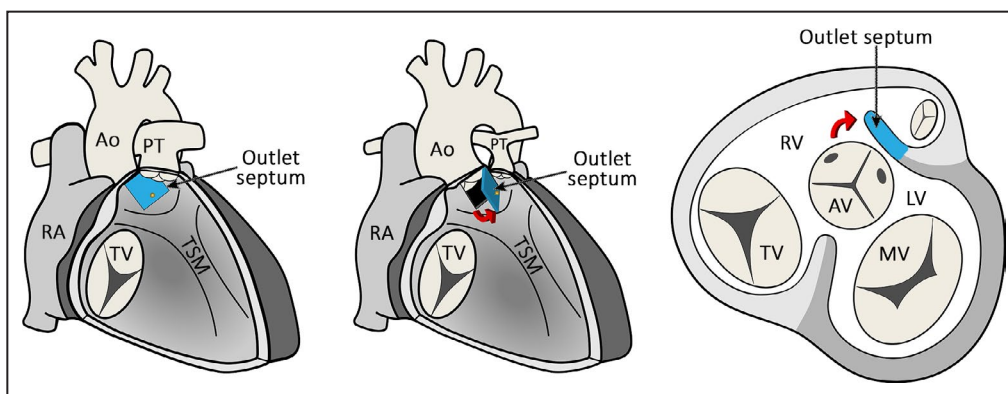


Figure 3. Cartoons showing the flap-door mechanism of malalignment of the outlet septum in tetralogy of Fallot.

The door of the outlet septum opens into the right ventricle (RV) with the hinges on the left side, resulting in subpulmonary outflow tract narrowing, small size of the pulmonary valve, and overriding of the large aortic valve (AV). Ao indicates aorta; LV, left ventricle; MV, mitral valve; PT, pulmonary arterial trunk; RA, right atrium; RV, right ventricle; TSM, trabecula septomarginalis; and TV, tricuspid valve.

the transposition of the great arteries–type double outlet right ventricle as it appears to have originated from the family of transposition of the great arteries (Figure S3).^{18,19,24,25} The outlet part of the ventricular septum in the setting of transposition is considered malaligned into the right ventricle, like a flap door with its hinges along the right margin. As a consequence, the VSD is cradled between the limbs of the TSM, with the outlet septum inserted to the right margin of the VSD, and the pulmonary valve overrides the ventricular septal crest or arises entirely from the right ventricle.^{19,26} The great arteries tend to be related side by side with the aorta on the right in this variant. The dimensions of the subaortic outflow tract and aortic valve are encroached on, and an obstructive lesion of the aortic arch in a form of tubular hypoplasia, coarctation of the aorta, or interruption of the aortic arch is commonly associated. The case presented herein was associated with interruption of the aortic arch between the origins of the left common carotid and left subclavian arteries.

CASE 4: ANTERIOR MALALIGNMENT OF OUTLET SEPTUM IN DOUBLE OUTLET RIGHT VENTRICLE WITH SUBPULMONARY VSD, VARIANT 2

This variant of double outlet right ventricle with subpulmonary VSD or Taussig-Bing malformation also appears to have originated from the family of transposition of the great arteries (Figure S4). The outlet septum and the arterial valves are displaced as a unit into the right ventricle, leaving the posteriorly located pulmonary valve closely related to the VSD. As a consequence, the VSD is cradled between the limbs of the TSM and the pulmonary valve is displaced into the right ventricle. In contrast to case 3 (variant 1), the

outlet septum inserts to neither side of the VSD but is parallel with the rest of the ventricular septum within the right ventricle.²⁰ In this variant, the great arterial relationship is usually similar to that seen in classic transposition, with the aorta on the right and anterior aspect of the pulmonary trunk. As in the variant 1, the dimensions of the subaortic outflow tract and aortic valve are encroached on, and an obstructive lesion of the aortic arch is commonly associated.

CASE 5: POSTERIOR MALALIGNMENT OF OUTLET SEPTUM IN INTERRUPTION OF THE AORTIC ARCH

The VSD seen in patients with interruption of the aortic arch or coarctation of the aorta is frequently associated with posterior malalignment of the outlet septum, causing narrowing of the subaortic outflow tract above the VSD (Figure S5).²⁷⁻³¹ It was logically hypothesized that reduced blood flow through the aorta during fetal development results in underdevelopment of the aortic arch. In this case with interruption of the aortic arch distal to the origin of the left subclavian artery, the VSD appears to be formed by a flap door mechanism with the outlet septum hinged to the ventriculofundibular fold (marked with white dots in Figure S5, upper panels), where the aortic valve is attached in its left ventricular aspect, as explained with cartoons in Figure 4. The outlet septum is tipped backward into the left ventricle and causes subaortic stenosis above the VSD. Therefore, the tip of the outlet septum protrudes into the left ventricular outflow tract, whereas displacement of the aortic valve appears less conspicuous. Usually, the large pulmonary arterial trunk remains to arise from the right ventricle through the muscular infundibulum. It is in contrast to the anterior malalignment type VSDs in which

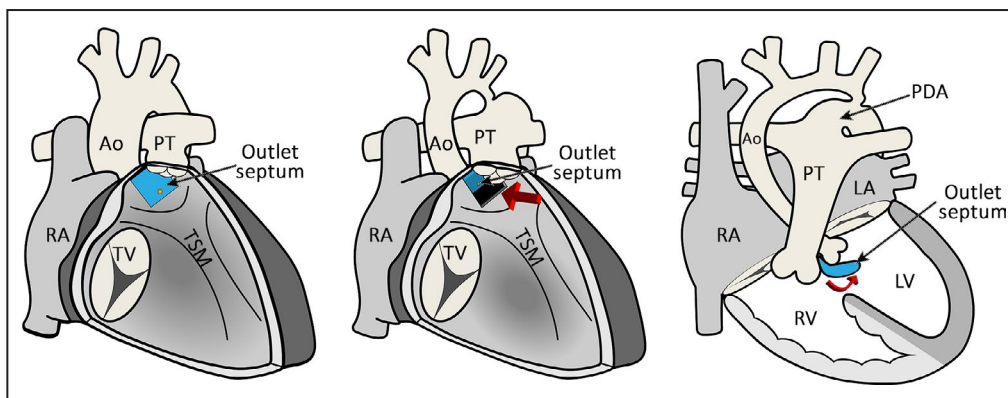


Figure 4. Cartoons showing the flap-door mechanism of malalignment of the outlet septum in so-called interruption or coarctation type of ventricular septal defect.

The door of the outlet septum opens into the left ventricle (LV) (red arrow) with the hinges on the top along the ventriculofundibular fold/aortic valve attachment, resulting in narrowing of the subaortic outflow tract and small aortic valve. Ao indicates aorta; LA, left atrium; PDA, patent ductus arteriosus; PT, pulmonary arterial trunk; RA, right atrium; RV, right ventricle; TSM, trabecula septomarginalis; and TV, tricuspid valve.

the outlet septum with the aortic or pulmonary valves is displaced partly or entirely into the right ventricle (Figure 3 and cases 1–3). The VSD formed by a similar mechanism may be either a perimembranous or a muscular defect. In contrast to the other forms of VSD involving the outlet septum, the aortic valve does not form a direct border of the VSD. The aortic valve may form a border of the VSD when the VSD is a doubly committed and juxta-arterial type in which the outlet septum is absent. Although the outlet septum is absent in such cases, the fibrous raphe separating the aortic and pulmonary valves is aligned with the ventricular septal plane or displaced into the left ventricle.²⁸ This is in contrast to the large VSDs involving the subaortic region in which the aortic valve appears to override the ventricular septum. As the ventricular septum normally curves rightward and forward, approaching the aortic valve, a large hole in the subaortic part of the ventricular septum leaves the aortic valve mildly overriding the ventricular septal crest if the outlet septum is not malaligned. Paradoxically, the posteriorly displaced outlet septum may align with the rest of the ventricular septum or be placed above the left ventricle (Figure S5, Case 5, left lower panel).

CASE 6: POSTERIOR MALALIGNMENT OF OUTLET SEPTUM WITH DOUBLE OUTLET LEFT VENTRICLE

Double outlet left ventricle is rare (Figure S6). The illustrated case demonstrates that the pulmonary arterial trunk arises entirely from the left ventricle through a short and stenotic infundibulum and that the aorta arises from both ventricles with 60% of the aortic valve committed to the left ventricle. The anatomical features appear to be attributable to backward displacement of the outlet septum and the arterial valves into the left ventricle.^{32,33} There also seems to be a mild degree of clockwise rotation, as seen from the apex. The posteriorly located subpulmonary outflow tract is severely encroached on, and the pulmonary valve is small. The VSD primarily involves the outlet part of the ventricular septum but extends also to the inlet of the right ventricle. The extreme forms of double outlet left ventricle may show further posterior displacement of the outlet septum and the arterial valves with complete absence of both subaortic and subpulmonary infundibulum.

CASE 7: OVERRIDING AND STRADDLING TRICUSPID VALVE IN SITUS SOLITUS WITH D-LOOP VENTRICLES

It has been known that overriding and straddling of the tricuspid valve occurs through the VSD involving the

inlet part of the septum that does not extend to the crux cordis (Figure S7).^{5,6} In most cases, the junction between the 2 atrioventricular valves at the crux cordis is demarcated internally by a muscular ridge called posteromedian muscle ridge (also known as posteromedial muscle or posterior ridge).^{5,6,34} Note in this case that the posterior interventricular groove is displaced toward the right ventricle away from the crux cordis (marked with green dotted arrow in Figure S7, case 7, right panel). The VSD appears to be formed by a flap-door mechanism with the hinges at the anterior interventricular groove and free edge at the posterior interventricular groove. The malalignment is in relation to atrial septal plane.⁵ As a consequence, the VSD is more conspicuous posteriorly at the ventricular inlets, whereas it becomes less conspicuous anteriorly. The VSD is not limited to the inlet component of the septum. The spectrum of tricuspid valve overriding and straddling encompasses from a minor form to complete double inlet left ventricle (Figure 5). In this spectrum of the hearts including double inlet left ventricle, the small right ventricle is characteristically found superiorly away from the crux cordis. Overriding/straddling tricuspid valve in situs solitus and D-looped ventricles is associated most commonly with normally related and connected great arteries. As the ventricular septum is malaligned rightward and forward, the right ventricular outflow tract tends to be encroached on. However, any other type of ventriculoarterial connection may be associated.

CASE 8: OVERRIDING AND STRADDLING TRICUSPID VALVE IN SITUS SOLITUS WITH L-LOOP VENTRICLES

Overriding and straddling of the tricuspid valve are also seen in hearts with discordant atrioventricular connection (Figure S8).^{5,6} As in cases with concordant atrioventricular connection described above, the tricuspid valve overrides and straddles through a malalignment type VSD formed by a flap-door mechanism, with the hinges at the anterior interventricular groove and the free edge at the posterior interventricular groove. The ventricular septum is displaced leftward, upward, and forward in relation to the atrial septal plane (marked with red dotted arrow in Figure S8, middle right panel). As a result, the ventricular septal insertion to the posterior wall is displaced toward the morphologically right ventricle, and the right ventricle is positioned superiorly away from the crux cordis, leaving a posteromedian muscle ridge along the posterior inferior wall of the left ventricle. As a consequence, the VSD appears conspicuous posteriorly below the overriding and straddling left-sided tricuspid valve. It becomes inconspicuous

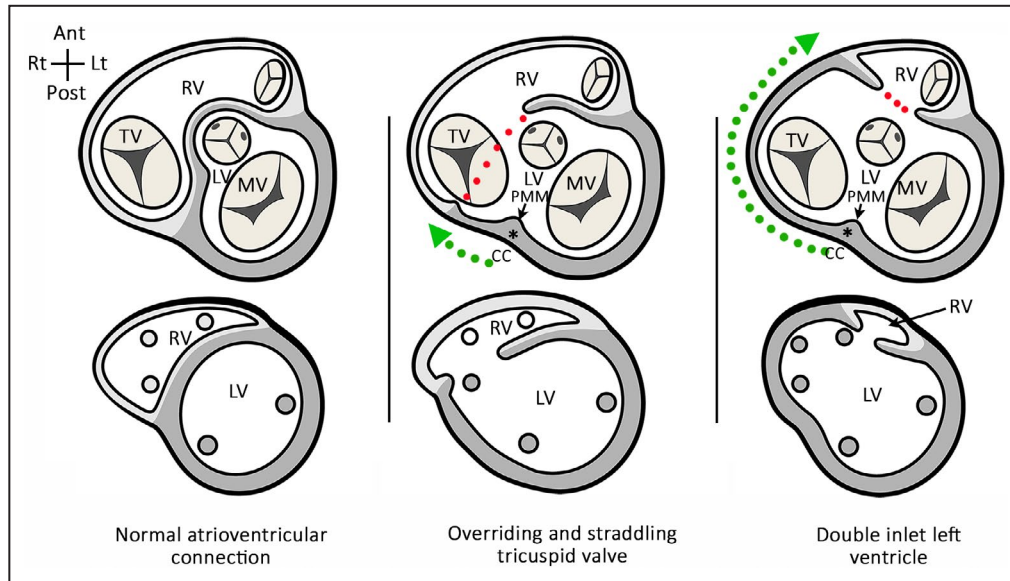


Figure 5. Short axis cuts of the ventricles seen from the apex, showing the spectrum of tricuspid valve (TV) overriding/straddling and double inlet left ventricle (LV) in the setting of situs solitus, D-loop ventricles, and normally related and connected great arteries.

The ventricular septum is malaligned like a flap door, with the hinges at the anterior interventricular groove and the posterior insertion offset from the crux cordis (CC) posteriorly. The green dotted arrows indicate the direction and severity of malalignment. The ventricular septal defect is marked with red dotted lines. An elevated muscular ridge, called the posteromedian muscle ridge (PMM), is usually seen along the posterior wall of the LV inlet between the 2 atrioventricular valves. The classic positions of the papillary muscles are marked with circles in the lower panel diagrams. Ant indicates anterior; Lt, left; MV, mitral valve; Post, posterior; Rt, right; and RV, right ventricle.

anteriorly, especially when malalignment is minimal. With further overriding, the atrioventricular connection moves into the spectrum of double inlet left ventricle (Figure 6). The ventriculoarterial connection is discordant in most cases in this spectrum of situs solitus and L-loop ventricles. Reflecting the direction of septal malalignment, the subaortic outflow tract tends to be encroached on. However, any other type of ventriculoarterial connections can be associated.

CASE 9: OVERRIDING AND STRADDLING MITRAL VALVE WITH DOUBLE OUTLET RIGHT VENTRICLE

Mitral valve overriding and straddling occurs most frequently in hearts with transposition of the great arteries or double outlet right ventricle, and infrequently in hearts with concordant ventriculoarterial connection (Figure S9).^{3,35} It has been described that mitral valve straddling occurs through an anteriorly located VSD. The case described herein shows that the ventricular septum is malaligned like a flap door with the hinges attached to the crux cordis and posterior interventricular groove (Figure 7). The ventricular septum is malaligned leftward and backward in relation to the atrial septal plane so that the VSD

appears large anteriorly and becomes less conspicuous posteriorly toward the crux cordis. Wenink and Gittenberger-de Groot described that the infundibular part of the septum is malaligned relative to the TSM.⁶ However, the case described herein clearly demonstrates that the malalignment involves the major part of the ventricular septum (marked with a blue line in Figure S9, case 9, right upper panel), except the outlet septum. The malalignment is in relation to the atrial septal plane (marked with a green line). The primary overriding and straddling part of the mitral valve is the anatomically anterior leaflet that may be divided into 2 and inserts to the papillary muscle in the right ventricle. As the anterolateral and posteromedial papillary muscles are usually normally formed and positioned, the mitral valve is supported by 3 papillary muscles or equivalents. When it occurs in the context of transposition of the great arteries, leftward and posterior malalignment of the ventricular septum may result in commitment of the pulmonary valve to the right ventricle, with the VSD being located closer to the pulmonary valve than to the aortic valve. Because of the subpulmonary location of the VSD, similar cases were often named as Taussig-Bing malformation with mitral valve straddling.^{6,7,36,37} However, there is a fundamental difference in the location of the VSD. In Taussig-Bing

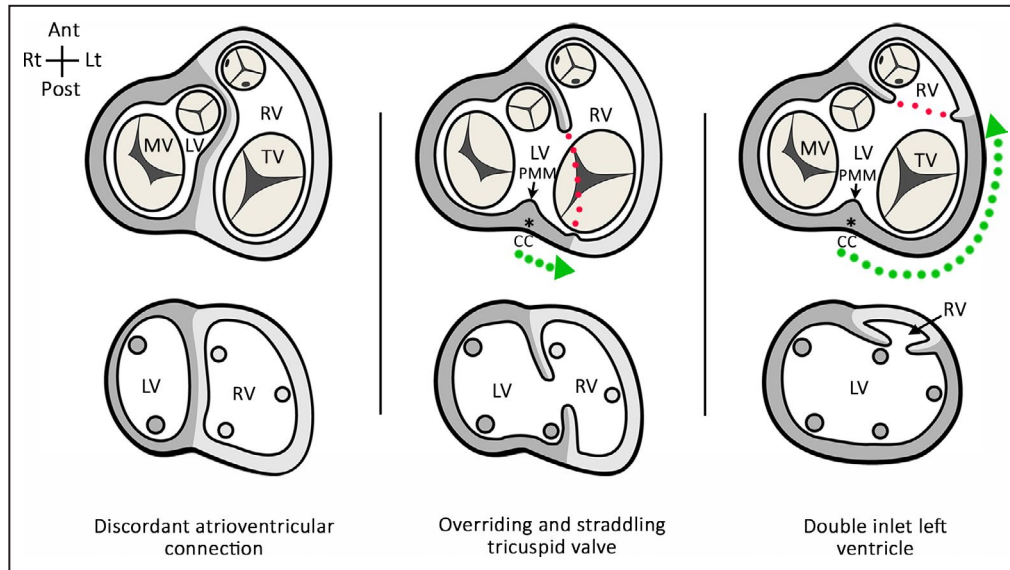


Figure 6. Short axis cuts of the ventricles seen from the apex, showing the spectrum of tricuspid valve (TV) overriding/straddling and double inlet left ventricle (LV) in the setting of situs solitus, L-loop ventricles, and transposed/malposed great arteries.

The ventricular septum is malaligned like a flap door with the hinges at the anterior interventricular groove and the posterior insertion offset from the crux cordis (CC) posteriorly. The green dotted arrows indicate the direction and severity of malalignment. The ventricular septal defect is marked with red dotted lines. An elevated muscular ridge, called the posteromedian muscle ridge (PMM), is usually seen along the posterior wall of the LV inlet between the 2 atrioventricular valves. The classic positions of the papillary muscles are marked with circles in the lower panel diagrams. Ant indicates anterior; Lt, left; MV, mitral valve; Post, posterior; Rt, right; and RV, right ventricle.

malformation, the VSD is cradled between the limbs of the TSM. In hearts with mitral valve straddling, the VSD is conspicuous anteriorly but extends to the inlet toward the crux cordis. There is an unusual recess (marked with an asterisk in Figure S9, right panels) at the left superior corner of the right ventricle along the markedly deviated ventricular septum. In addition, the subpulmonary outflow tract instead of the subaortic outflow tract is severely encroached on. With a greater degree of overriding and straddling, the posterior leaflet and one or both papillary muscles may be committed to the right ventricle. The spectrum of mitral valve overriding and straddling encompasses from a minor form to complete double inlet right ventricle⁵ (Figure 7). Therefore, the small left ventricle in double inlet right ventricle is found posteriorly at the right or left side of the crux cordis in hearts with double inlet right ventricle. The hearts with situs solitus and L-loop ventricles may also be associated with overriding and straddling of the right-sided mitral valve, although overriding and straddling of the left-sided tricuspid valve is more common.³⁸ Similar to the case with situs solitus and D-loop ventricles described herein, the VSD in cases with situs solitus and L-loop ventricles involves predominantly the anterior part of the septum but extends posteriorly toward the crux cordis.³⁸

CASE 10: TWISTED HEART WITH DOUBLE OUTLET RIGHT VENTRICLE

The essential feature of the heart described herein is the unexpected spatial relationship of the cardiac chambers and the arterial trunks for the given segmental connections (Figure S10).¹⁰⁻¹³ In the presence of concordant atrioventricular connection as in this case, the heart appears to be twisted clockwise, as shown in the upper panel in Figure 2. As the consequence, the right ventricular inlet is placed above the left ventricular inlet with the atrioventricular connection axis crossing each other, as shown by the probes through the tricuspid and mitral valves in this 3-dimensional printed case. The atrial septum is oriented in a more vertical plane, whereas the ventricular septal plane is oriented in a more horizontal plane. A VSD typically, but not always, occupies the inlet part of the septum through which the tricuspid valve may override and straddle.³⁵ When it occurs in the setting of situs solitus and L-loop ventricles, twisting is usually in a counterclockwise direction (Figure 2, lower panel). Although malalignment with twisting most frequently occurs in the setting of situs solitus with D- or L-loop ventricles and transposition or double outlet right ventricle, hearts with any segmental connection, including double inlet connection, may show twisted arrangement.^{10-13,39}

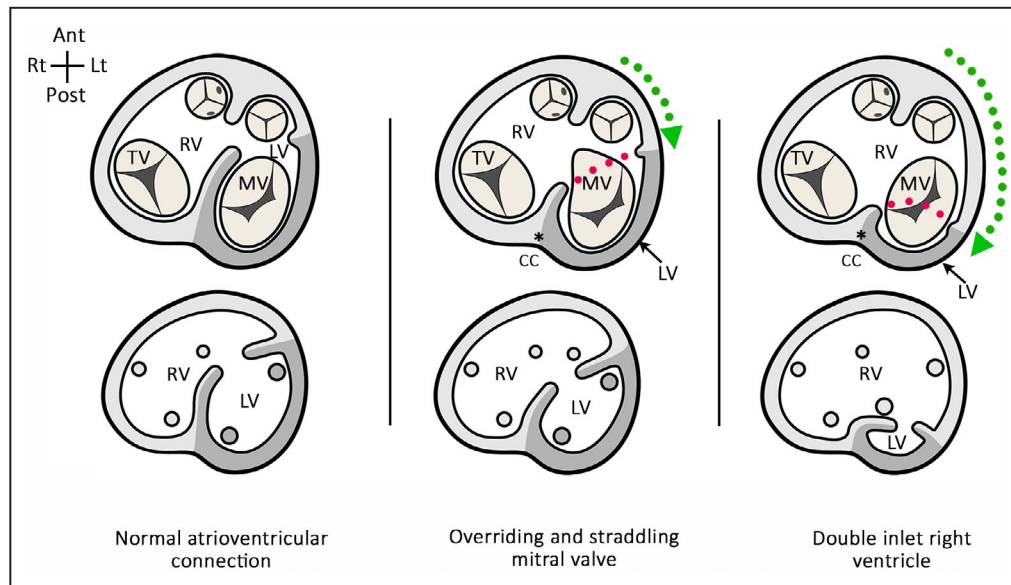


Figure 7. Short axis cuts of the ventricles seen from the apex, showing the spectrum of mitral valve (MV) overriding/straddling and double inlet right ventricle (RV) in the setting of situs solitus, D-loop ventricles, and transposed/malposed great arteries.

The ventricular septum is malaligned like a flap door with the hinges at the crux cordis (CC) and posterior interventricular groove and the anterior interventricular groove deviated toward the side of the left ventricle (LV). The green dotted arrows indicate the direction and severity of malalignment. The ventricular septal defect is marked with red dotted lines. The classic positions of the papillary muscles are marked with circles in the lower panel diagrams. Ant indicates anterior; Lt, left; Post, posterior; Rt, right; and TV, tricuspid valve.

SUMMARY

Malalignment of the ventricular septum results in various forms of congenital heart disease, such as tetralogy of Fallot, double outlet right or left ventricle, overriding and straddling mitral or tricuspid valve, and double inlet left or right ventricle. Ventricular septal malalignment can be characterized objectively and with clarity by defining the 5 essential features that include the malaligned part of the ventricular septum, the reference structure, the mechanism of malalignment, the direction of malalignment, and the severity of malalignment. Although we highlight general rules or strong tendencies in the morphological presentations of most of the described conditions with a malalignment type VSD, rare cases can present with any unusual morphological features as there is no rule without exception.

ARTICLE INFORMATION

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Disclosures

None.

Supplementary Material

Figures S1–S10

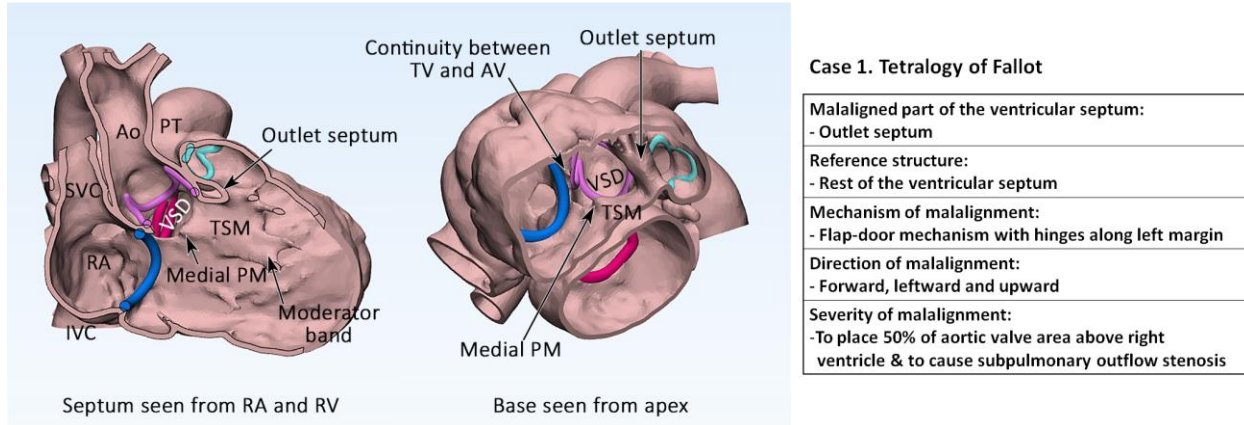
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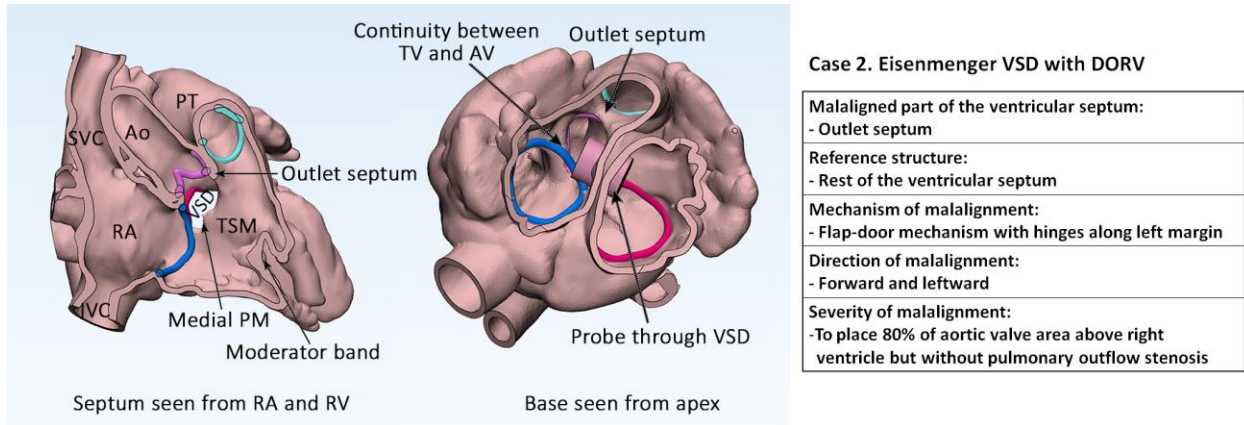
SUPPLEMENTAL MATERIAL

Figure S1. Case 1.



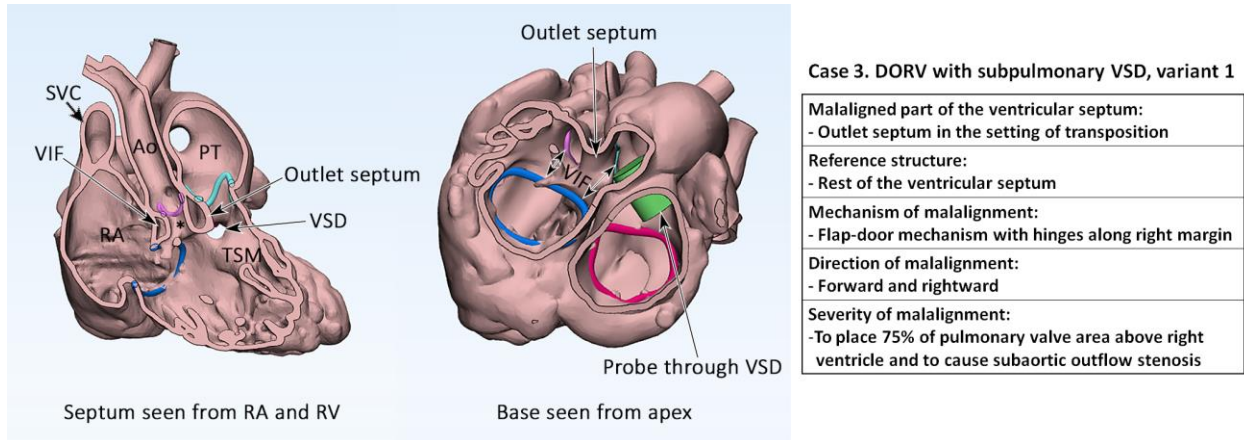
Anterior malalignment of outlet septum in tetralogy of Fallot. Ao, aorta; AV, aortic valve; IVC, inferior vena cava; PM, papillary muscle; PT, pulmonary arterial trunk; RA, right atrium; RV, right ventricle; SVC, superior vena cava; TSM, trabecula septomarginalis; TV, tricuspid valve; VSD, ventricular septal defect. The annuli of the tricuspid, mitral, aortic and pulmonary valves are colored in blue, red, pink and green, respectively.

Figure S2. Case 2.



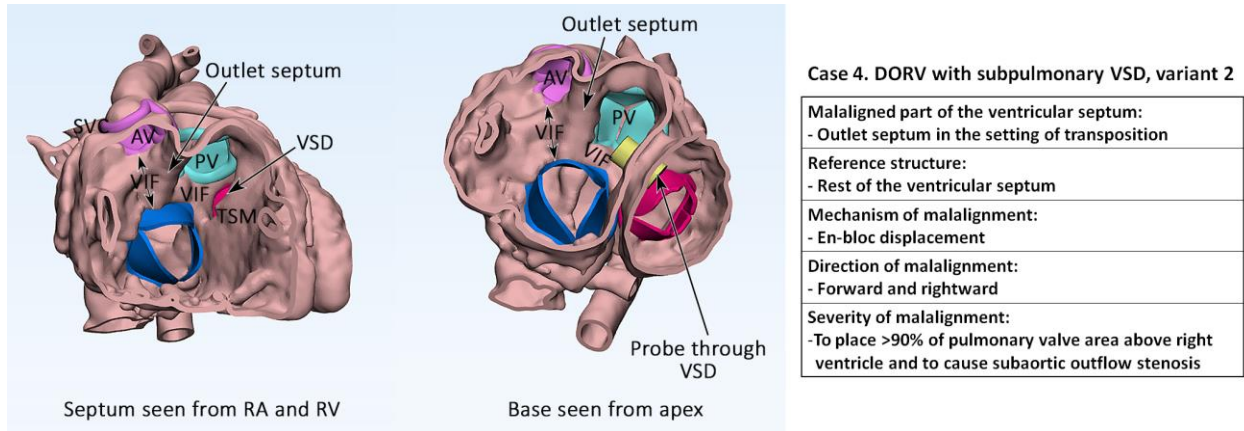
Anterior malalignment of outlet septum in Eisenmenger ventricular septal defect (VSD) with double outlet right ventricle (DORV). Ao, aorta; AV, aortic valve; IVC, inferior vena cava; PM, papillary muscle; PT, pulmonary arterial trunk; RA, right atrium; RV, right ventricle; SVC, superior vena cava; TSM, trabecula septomarginalis; TV, tricuspid valve. The annuli of the tricuspid, mitral, aortic and pulmonary valves are colored in blue, red, pink and green, respectively.

Figure S3. Case 3.



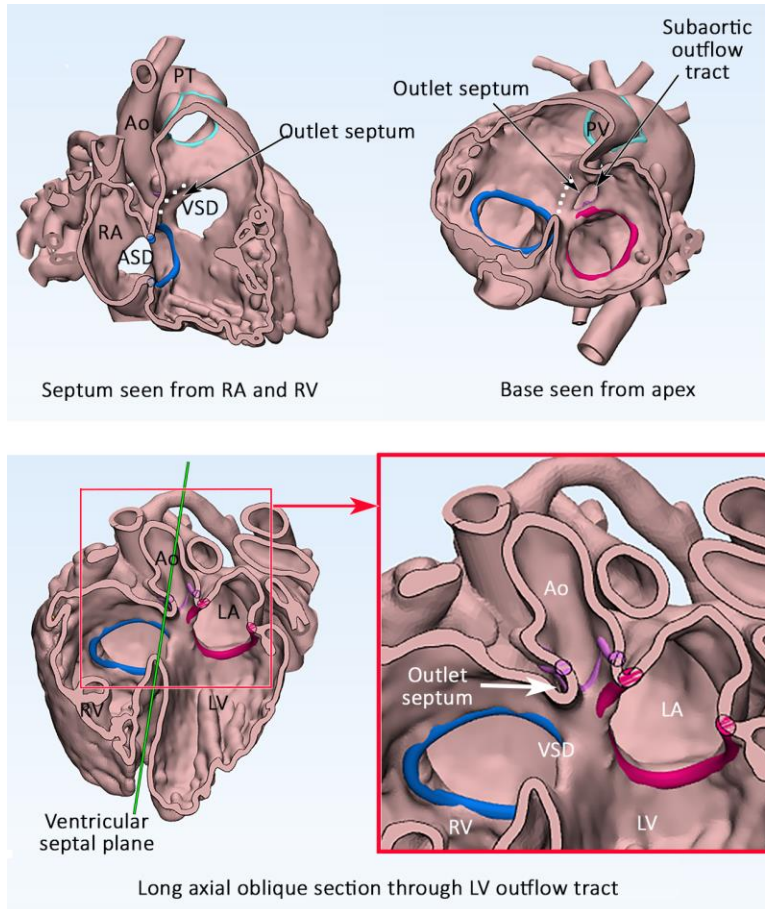
Anterior malalignment of outlet septum in double outlet right ventricle (DORV) with subpulmonary VSD, Variant 1. Ao, aorta; PT, pulmonary arterial trunk; RA, right atrium; RV, right ventricle; SVC, superior vena cava; TSM, trabecula septomarginalis; VIF, ventriculoinfundibular fold; VSD, ventricular septal defect. The annuli of the tricuspid, mitral, aortic and pulmonary valves are colored in blue, red, pink and green, respectively.

Figure S4. Case 4.



Anterior malalignment of outlet septum in double outlet right ventricle (DORV) with subpulmonary VSD, Variant 2. AV, aortic valve; PV, pulmonary valve; RA, right atrium; RV, right ventricle; SVC, superior vena cava; TSM, trabecula septomarginalis; VIF, ventriculoinfundibular fold; VSD, ventricular septal defect. The tricuspid and mitral valves are colored in blue and red, respectively.

Figure S5. Case 5.

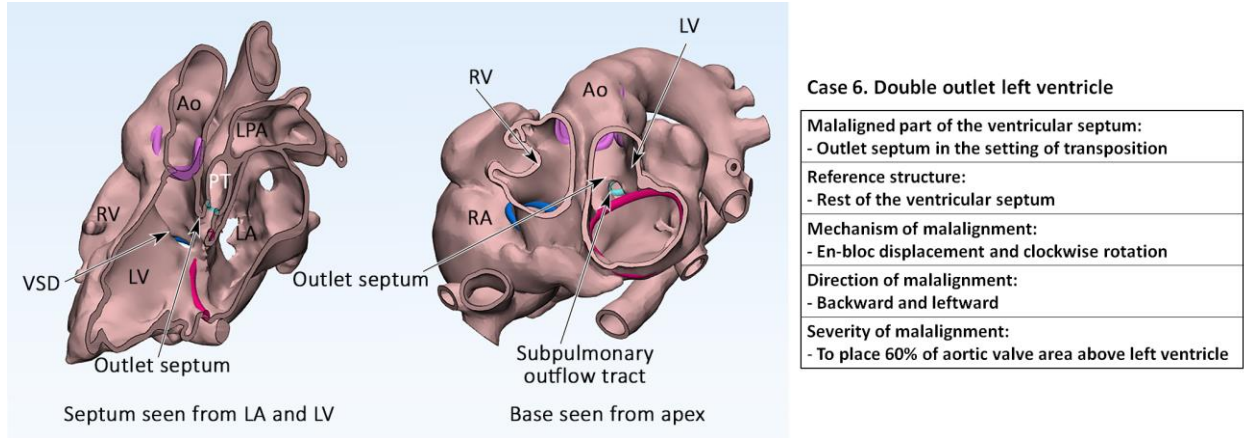


Case 5. VSD with interrupted aortic arch

Malaligned part of the ventricular septum:
- Outlet septum
Reference structure:
- Rest of the ventricular septum
Mechanism of malalignment:
- Flap-door mechanism with hinges along VIF
Direction of malalignment:
- Backward
Severity of malalignment:
- To cause subaortic outflow stenosis. Note that the aortic valve does not override the ventricular septum.

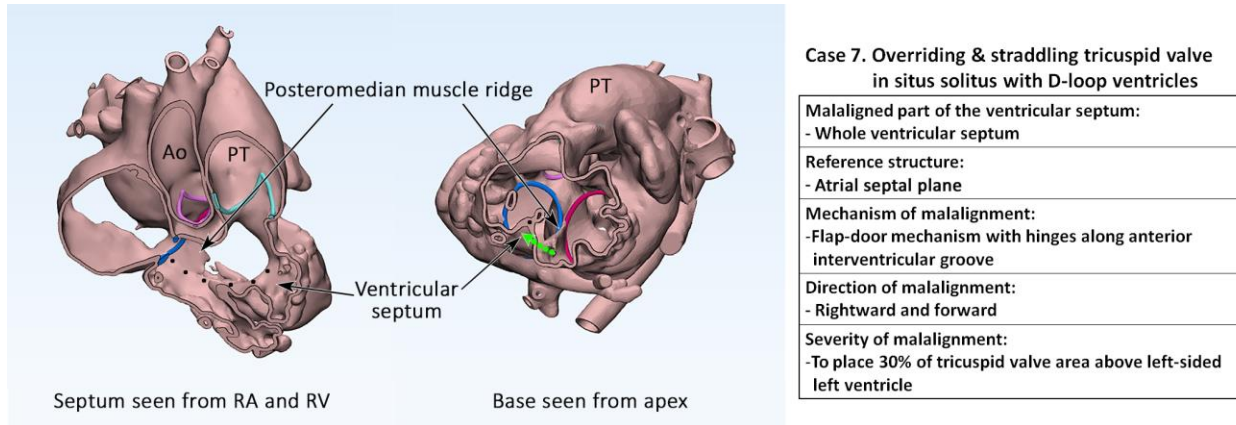
Posterior malalignment of outlet septum in interruption of the aortic arch. Ao, aorta; ASD, atrial septal defect; LA, left atrium; LV, left ventricle; PT, pulmonary arterial trunk; RA, right atrium; RV, right ventricle; VIF, ventriculoinfundibular fold (marked with white dotted line in upper panels); VSD, ventricular septal defect. The annuli of the tricuspid, mitral, aortic and pulmonary valves are colored in blue, red, pink and green, respectively.

Figure S6. Case 6.



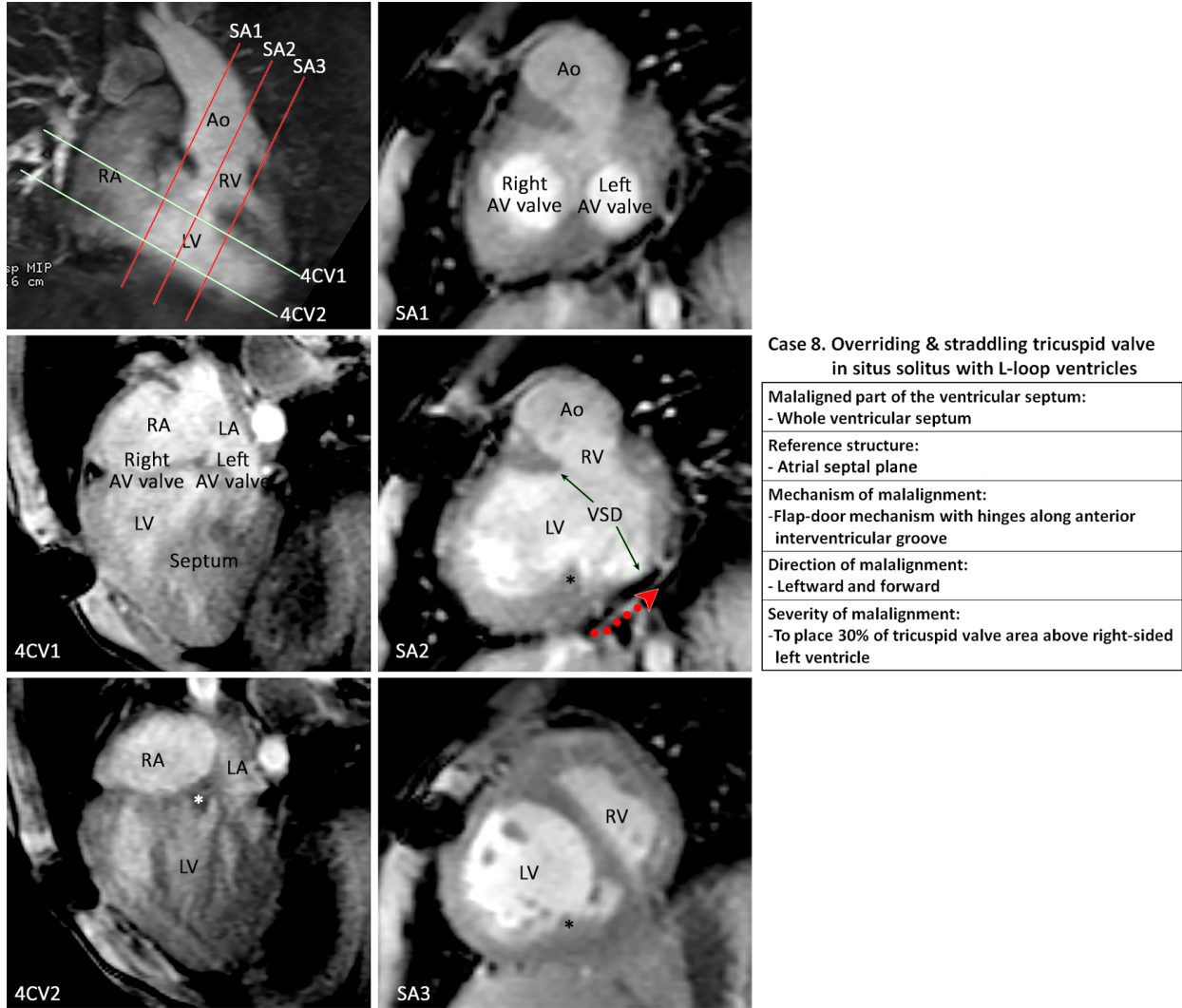
Posterior malalignment of outlet septum with double outlet left ventricle. Ao, aorta; LPA, left pulmonary artery; LA, left atrium; LV, left ventricle; PT, pulmonary arterial trunk; RA, right atrium; RV, right ventricle; VSD, ventricular septal defect. The annuli of the tricuspid, mitral, aortic and pulmonary valves are colored in blue, red, pink and green, respectively.

Figure S7. Case 7.



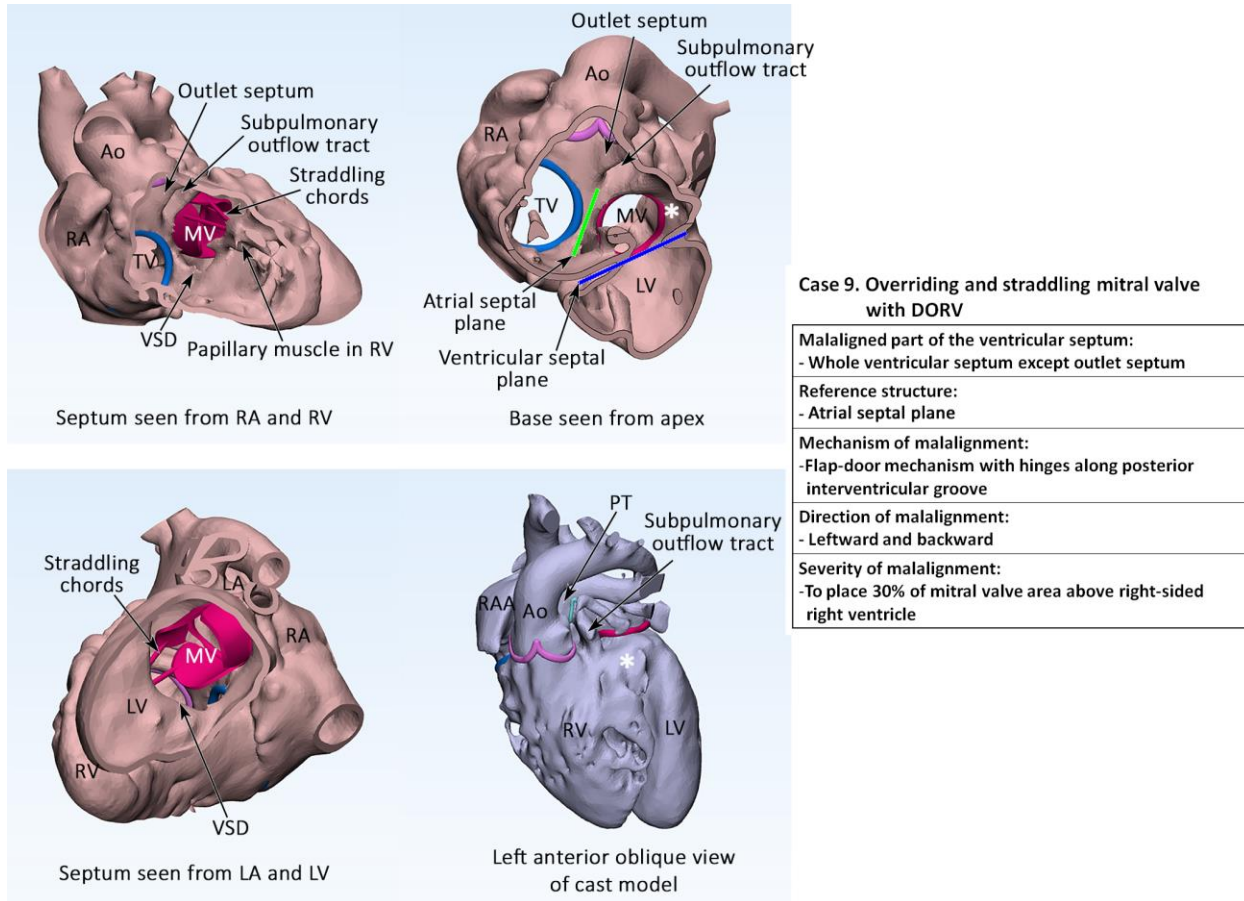
Overriding and straddling tricuspid valve in situs solitus with D-loop ventricles. Ao, aorta; PT, pulmonary arterial trunk; RA, right atrium; RV, right ventricle. The margin of the ventricular septal defect is marked with black dotted line in left panel. The annuli of the tricuspid, mitral, aortic and pulmonary valves are colored in blue, red, pink and green, respectively.

Figure 8. Case 8.



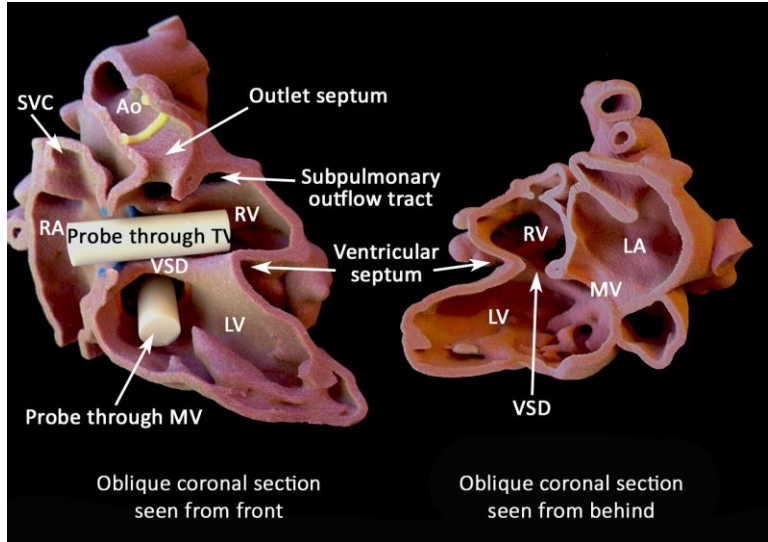
Overriding and straddling tricuspid valve in situs solitus with L-loop ventricles. The imaging planes for 4-chamber (4CV) and short-axis (SA) views are indicated in left-upper panel by green and red lines, respectively. Posteromedian muscle ridge is marked with white or black asterisk. Ao, aorta; AV, atrioventricular; LA, left atrium; LV, left ventricle; PT, pulmonary arterial trunk; RA, right atrium; RV, right ventricle; VSD, ventricular septal defect.

Figure S9. Case 9.



Overriding and straddling mitral valve with double outlet right ventricle. Ao, aorta; LA, left atrium; LV, left ventricle; MV, mitral valve; PT, pulmonary arterial trunk; RA, right atrium; RAA, right atrial appendage; RV, right ventricle; SVC, superior vena cava; TSM, trabecula septomarginalis; TV, tricuspid valve; VSD, ventricular septal defect. The tricuspid and mitral valves are colored in blue and red, respectively.

Figure S10. Case 10.



Case 10. Twisted heart with atrioventricular concordant connection and DORV

Malaligned part of the ventricular septum:	- Atrial and ventricular septum
Reference structure:	- Long axis of the heart
Mechanism of malalignment:	- Twisting
Direction of malalignment:	- Clockwise as seen from ventricular apex
Severity of malalignment:	- Approximately 120 degree twisting with right ventricle above and left ventricle below

Twisted heart with double outlet right ventricle. The atrial and ventricular septal planes are marked with green and blue lines, respectively. Asterisk indicates unusual recess in right ventricle along the deviated ventricular septum. Ao, aorta; DORV, double outlet right ventricle; LA, left atrium; LV, left ventricle; MV, mitral valve; RA, right atrium; RV, right ventricle; SVC, superior vena cava; TV, tricuspid valve; VSD, ventricular septal defect.