The science and art of aortic and/or pulmonary root translocation

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ABSTRACT

This review aims to present and compare different surgical techniques of root translocation of the great arteries except the Ross procedure. The historical aspects, technical considerations, and results are briefly elucidated.

Keywords: Aortic root, congenital heart disease, double-root translocation, half-turned truncal switch operation, Nikaidoh procedure, pulmonary root, pulmonary root translocation, root translocation

INTRODUCTION

The term "translocation" literally means "the movement of something from one place to another," while "root" refers to the "embedded part of a bodily organ or structure."[1,2] The ability to physically move great vessels with their "roots" and implant them onto the appropriate ventricular chamber has allowed us to radically expand the boundaries of anatomical biventricular repairs of complex congenital lesions. This review aims to present and compare different surgical techniques of root translocation of the great arteries except the Ross procedure. The historical aspects, technical considerations, and results are briefly elucidated.

Embryological basis of root translocation

During embryonic development, the cardiac outflow tract is initially a single tubular structure connecting the primitive right ventricle (RV) to the aortic sac. This common lumen is divided into its aortic and pulmonary components by a combination of an aortopulmonary septum and outflow tract cushions.[3] Neural crest cells play an important role in the process of aortopulmonary septation.[4] In addition, the outflow tract also needs to establish continuity with the primitive left ventricle (LV) which occurs by a process called "wedging" where the myocardial wall of the outflow tract undergoes a counterclockwise rotation (as viewed from the ventricular side) so that the aortic valve rotates behind the pulmonary trunk, going down and to the left to settle between the two atrio–ventricular (AV) valves, therefore establishing mitral–aortic continuity that is typical of a normal heart.[5]

The conus arteriosus, more commonly known as the "conus," is a muscular cuff that supports the aortic and/or pulmonary valve.[6] Appreciation of the "differential conal development theory" is fundamental to the embryologic understanding of the various methods of root translocation.[7] During normal embryonic development, the subpulmonary conus grows, whereas the subaortic conus undergoes resorption. Van Praagh describes this as an "embryonic arterial switch."[6] In transposition of the great arteries (TGA), the exact opposite occurs – the subaortic conus enlarges, whereas the subpulmonary conus is resorbed.[8,9] Double-outlet RV (DORV) falls in the middle of this spectrum with variable amounts of both subaortic and subpulmonary conii.[10] It should be mentioned here that the definition of DORV on the basis of the presence of double conii is highly controversial and depends on where the anomaly lies along the spectrum.[11]

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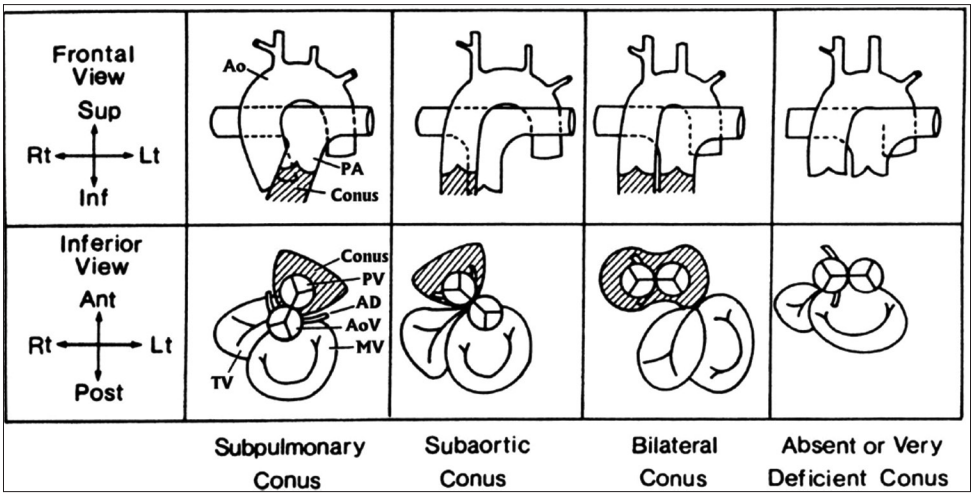

Figure 1: The four main anatomical types of sub-semi-lunar infundibulum or conus arteriosus: subpulmonary, subaortic, bilateral (subaortic and subpulmonary), and absent or very deficient. The upper row of diagrams shows the infundibulum (crosshatched) and great arteries as seen from the front (frontal view). The lower row of diagrams shows the infundibulum (crosshatched), the semilunar valves – the aortic valve, indicated by the coronary arteries, and the pulmonary valve, indicated by the absence of coronary arteries – and the atrioventricular valves – the mitral valve, being a two-leaflet valve, and the tricuspid valve, being a three-leaflet valve – as seen from below (inferior view), similar to a subxiphoid two-dimensional echocardiogram. In all diagrams, a ventricular D-loop is assumed to be present. The subpulmonary conus is normal. Resorption of the subaortic conal-free wall permits aortic–mitral fibrous continuity. The presence of a subpulmonary infundibulum prevents pulmonary valve–atrioventricular valve fibrous continuity. A subpulmonary conus is associated with solitus normally related great arteries (diagrammed here), inversus normally related great arteries, and in tetralogy of Fallot, both with solitus normally related great arteries and with inversus normally related great arteries. A subpulmonary conus can also be associated with double outlet right ventricle with hypoplastic left heart syndrome (e.g., with mitral atresia) and with aortic–tricuspid fibrous continuity. The subaortic conus is characterized by resorption of the subpulmonary conal-free wall, permitting pulmonary–mitral direct fibrous continuity. The presence of a complete muscular subaortic conus prevents aortic–atrioventricular fibrous continuity. The subaortic conus and great arteries shown here are associated with typical D-transposition of the great arteries , that is, transposition of the great arteries (S, D, D). A subaortic conus also occurs with L-transposition of the great arteries, that is, transposition of the great arteries (S, L, L), and with transposition of the great arteries (I, L, L). A bilateral conus, being both subaortic and subpulmonary, prevents semilunar–atrioventricular fibrous continuity. A bilateral conus is associated with typical double-outlet right ventricle, both with D-loop ventricles and with L-loop ventricles. A bilateral conus can also be associated with transposition of the great arteries when there is a muscular subpulmonary outflow tract obstruction (stenosis or atresia). Rarely, it is possible for solitus normally great arteries to be associated with a bilateral conus if the subpulmonary part of the conus is well developed and if the subaortic conal-free wall is present but poorly developed, just 1 or 2 mm in height between the aortic valve above and the mitral valve below; I have seen only one such case in my life, in a patient with the incomplete form of common atrioventricular valve canal with an ostium primum defect at the atrial level, no ventricular septal defect, and a cleft mitral valve. Hence, what matters most morphogenetically is not just the anatomical type of conus that is present but rather how much the sub-semi-lunar conal-free wall is present or has been resorbed. In the rare case that I am referring to, a small amount of the subaortic conal-free wall had not been resorbed, but not enough to disrupt the normal type of aortic valve-to-left ventricular approximation. The bilaterally absent or very deficient conus can be associated with double-outlet left ventricle with aortic–mitral and pulmonary–mitral fibrous continuity, even with an intact ventricular septum. However, double-outlet left ventricle does not always have a bilaterally absent or very deficient conus. AD: Anterior descending (coronary artery), Ant: Anterior (ventral), Inf: Inferior (caudad), Lt: Left, Post: Posterior (dorsal), Rt: Right, Sup: Superior (cephalad) (reproduced with permission from Praagh[6])

Table 1: Historical aspects of root translocation techniques

Technique	Investigator	Years	Country
Aortic root translocation/ posterior root translocation/ Nikaidoh	Bex *et al*.[12] Nikaidoh[13]	1980 1984	France USA
Aortic root translocation with arterial switch	Bautista-Hernandez *et al*.[14]	2007	USA
Aortic root translocation with atrial switch	Jacobs *et al*.[15]	2006	USA
Pulmonary root translocation	da Silva *et al*.[16]	2000	Brazil
En bloc rotation of both outflow tracts	Yamagishi *et al*.[17]	2003	Japan
Double-root translocation	Hu *et al*.[18]	2007	China

Figure 1 depicts the presence/absence of conii in different conotruncal anomalies.

Historical aspects of root translocation techniques

These are listed in Table 1.

Significance of the Ross procedure

The Ross procedure was introduced in 1967.[19] Although devised for a completely different indication (aortic valve replacement), the Ross procedure will have to be acknowledged as "the mother of all root translocations". The Ross procedure provided "proof of concept" as, for the first time, it was shown that a great vessel and its valve can be disconnected from one ventricle and reconnected to another. The entire concept of the Ross operation is based on the presence of a free standing subvalvar muscle cuff (conus).[20] This same principle has been extended to other root translocations and is

discussed further. In order to concentrate on all the other "root translocations," further discussion on the Ross procedure is being deliberately avoided.

Clinical scope of root translocations

Root translocation can be considered for all conotruncal anomalies and pulmonary stenosis (PS) where routing left ventricular blood through a ventricular septal defect (VSD) to the aorta is either not possible or is not desirable. This would include TGA/congenitally corrected TGA (ccTGA)/DORV with/without VSD and PS.

Routing is not possible: Noncommitted/remote/restrictive (nonroutable) or nonexistent ventricular septal defect
Anatomical correction of the above lesions would entail redirection of LV blood through the VSD to the aorta. However, if the VSD is not routable for any reason, root translocation can be considered. In patients with TGA and subpulmonic VSD nonroutable to the aorta and left ventricular outflow tract obstruction (LVOTO), the aim is to close the VSD and to route the LV via the VSD to the aorta along with relief of LVOTO. Aortic root translocation is best considered in this subset as an alternative to the traditional Réparation à l'ètage Ventriculaire or Rastelli operation.

Routing is not desirable
Sometimes, routing of the VSD to the LV is feasible, but may entail creation of a long intraventricular tunnel. This tunnel is adynamic and compromises native ventricular volume. Moreover, the blood flow is not "straight," there is energy loss due to tunneled flow from the LV to the aorta,[21] and there is a risk of development of subaortic stenosis at follow-up. In such conditions, root translocation can be considered.

TRANSLOCATION OF THE AORTIC ROOT

Aortic root translocation/posterior root translocation/ Bex–Nikaidoh procedure

The aortic root translocation/posterior root translocation/ Bex–Nikaidoh procedure was introduced by Bex in 1980.[12] Interestingly, the procedure was advertised as an option to the arterial switch operation (ASO) at a time when the atrial switch operation was the most popular and accepted palliative procedure for TGA, and the ASO had just entered the clinical arena.[22] As stated in the original paper, "The three distinct advantages of this procedure allowing its application in newborns are as follows: its technical simplicity; the avoidance of any tubes of a foreign material, which permits a normal growth; and above all, the absence of an anastomosis involving the coronary arteries."[12] At the time of publication, the procedure was primarily performed in only anatomical specimens, with its successful clinical use being reported in a 3-month-old girl with TGA and subpulmonary stenosis.[12] This procedure (which now bears his name) was truly popularized by Hisashi Nikaidoh in 1984.[13] It was offered as a surgical option for the currently popular indication of TGA/VSD/LVOTO (PS). Surgical ingenuity and improved skills have expanded the application of the Nikaidoh procedure to patients with DORV and ccTGA.

Technique
Figure 2 depicts the Nikaidoh procedure. Cardiopulmonary bypass (CPB) is initiated with high aortic and bicaval cannulation. Maximum possible dissection should be performed without cross clamp to minimize the myocardial ischemia time. The aorta is completely separated from the pulmonary artery (PA) down to the base of the heart. Proximal coronary arteries and branch PAs are mobilized as well. After aortic cross clamp and administration of cardioplegia, the aortic root is harvested along with free anterior RV wall. Like the Ross procedure, care must be taken to avoid injury to septal branches of the left anterior descending coronary artery. Distally, the aorta is divided at the sinotubular junction.[23] Sometimes, aortic root detachment can be incomplete. When it is incomplete, the aorta remains attached under the left coronary artery and is rotated clockwise to be implanted onto the LVOT.[24] Then, the main PA is transected, and the Lecompte maneuver is performed. The narrow LVOT is opened across the conal septum into the VSD. The aortic root is then implanted onto the LVOT using the free anterior RV wall to close the VSD. The coronaries are re-implanted if necessary.

Although the original description only used a pericardial baffle for right ventricular outflow tract (RVOT) reconstruction, currently, several options are used including nonvalved transannular patch, homografts,

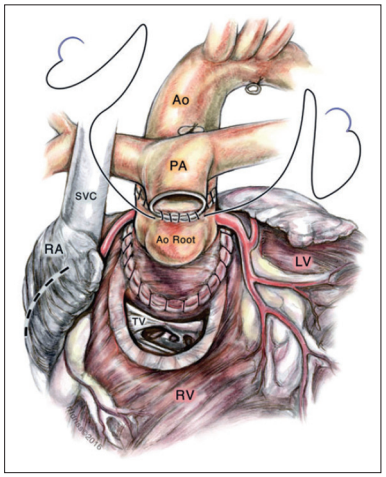

Figure 2: Aortic root translocation (Nikaidoh procedure). Completed aortic root translocation (ventricular septal defect closed with right ventricle free wall, anteriorly positioned pulmonary artery confluence, right atrial incision for ASD closure). Ao: Ascending aorta, LV: Left ventricle, PA: Main pulmonary artery, RA: Right atrium, RV: right ventricle, SVC: Superior vena cava, ASD: Atrial septal defect, TV: Tricuspid valve (reproduced with permission from Nikaidoh[18])

monocusp valves, or bovine jugular vein conduits.[25,26] The procedure is technically demanding and can potentially destabilize the aortic valve.[26] As with all procedures involving coronary artery translocation, in this procedure also, there is a potential risk of kinking or distorting the coronary arteries.[24,26]

Outcomes

Morell *et al.* reported their experience with 12 patients using the Nikaidoh procedure.[27] The median age of the patients was 2 years (range, 5 months to 9 years), and the median follow-up was 33 months (range, 21–57 months). They used homografts for RVOT reconstruction. There were no early or late deaths. There were three early reoperations, one pacemaker implantation, and four late reoperations. Three patients experienced moderate aortic insufficiency (AI).

Yeh *et al.* reported their experience with 19 patients with a median age of 3.3 years (range, 0.9–9.3 years) in 2007.[25] The median follow-up was 11.4 years (range, 0.1–23 years). There were no early or late deaths. Five patients needed reoperation for the RVOT, whereas none of the patients needed reintervention for the LVOT or aortic valve. No patient had more than mild AI.

In 2014, Kramer *et al.* reported the mid-term outcomes in 21 patients undergoing a modified Nikaidoh procedure between 2006 and 2012.[28] Seventeen patients underwent root translocation, whereas four patients had *en bloc* rotation of the outflow tracts (described below). The median age at operation was 9.9 months (range, 1.7 months to 21.5 years). The median follow-up was 2.3 years (range, 0.3–6.4 years). There were two early and one mid-term deaths. There were no re-interventions for LVOTO. Four patients developed conduit failure, out of which two needed conduit replacements. Five patients had no AI. Nine patients had trivial, whereas four patients had mild AI.

In 2015, Raju *et al.* reported their experience with 32 patients with a mean age of 7.5 months (range, 16 days to 42 years) and a mean weight of 7.7 kg.[26] They also evaluated the performance of different RVOT conduits. Five patients had a concomitant Mustard procedure for ccTGA. There was no early death. After a median follow-up of 20.8 months (range, 1 month to 16.5 years), there were no late deaths. No patients needed re-intervention for the left side. Fourteen patients needed transcatheter re-intervention (mostly for RVOT), whereas six patients needed reoperations – all for RVOT. One patient had moderate AI. Hazekamp *et al.* have comprehensively summarized recent large series reporting outcomes of the Nikaidoh procedure.[24]

Aortic root translocation and arterial switch

In 2007, Bautista-Hernandez *et al.* from Boston introduced the concept of Ross-switch-Konno [Figure 3].[14] This approach combines the concepts of the Nikaidoh procedure, the Ross–Konno operation, and the ASO.

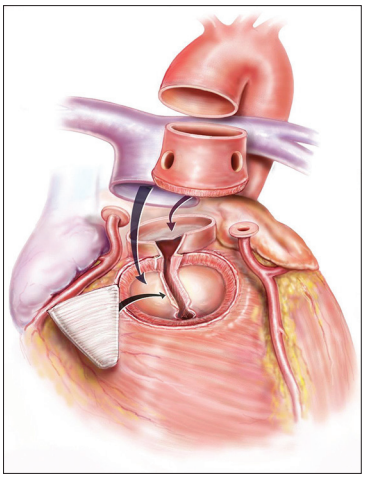

Figure 3: Ross-switch-Konno procedure. The aortic autograft is excised, and the coronaries are mobilized; the main pulmonary artery is transected and an incision is extended across the pulmonary valve annulus and outlet septum connecting to the ventricular septal defect accomplished by insertion of a triangular-shaped VSD patch. The aortic autograft is re-inserted into the left ventricular outflow. The aortic root autograft is then rotated 180° so that the defects from the coronary buttons face anteriorly. The coronaries are then reimplanted. Before reestablishing ascending aortic continuity, the branch pulmonary arteries are mobilized and brought anterior to the aorta (Lecompte maneuver) in preparation for right ventricular outflow reconstruction (reproduced with permission from Bautista-Hernandez *et al.*[24])

Technique

Aortic cannulation is high, moderate-deep hypothermia is employed. After aortic cross clamp and administration of cardioplegia, the aorta is transected just above the commissures. Right ventriculotomy is performed, and the aortic root is harvested. Next, unlike the arterial switch, the coronaries are excised as circular buttons. During excision of the coronaries, great care needs to be taken to keep the sinotubular junction intact and thereby prevent distorting the aortic root (which might risk future dilation of the aortic root). The main PA is transected, and a longitudinal incision is made to enlarge the LVOT. The VSD and the enlarged LVOT are closed with a triangular Dacron patch. The aortic root is rotated through 180° (so that coronary openings face anteriorly) and is sutured to the LVOT and to the VSD patch anteriorly. The ascending aorta is sutured to the aortic root after a Lecompte maneuver. The coronaries are re-implanted, and the RVOT is reconstructed using a homograft.[14]

The addition of an arterial switch and aortic root rotation differentiates this operation from the Nikaidoh procedure.[14] The authors suggest that the advantages of this approach are that it can be used in infants as well as in older children. Second, because the presence of a VSD is not essential to accomplish this procedure in these patients, it can be applied to different anatomical

variants. Next, there is ample room for insertion of an oversized homograft without the risk of sternal compression as the conduit is in an orthotopic position. Extensive experience with coronary translocation for the ASO allows using this approach even in patients with a nonfavorable coronary anatomy. However, there is a concern for late development of neo-aortic root dilation with associated aortic valve regurgitation.[14]

Outcomes

The same group (Bautista-Hernandez *et al.* from Boston) reported their experience with 11 patients.[14] The median age was 7 months (range, 1 month to 11 years), and eight patients were <1 year of age. There were no early deaths. After a median follow-up of 59 months (range, 2–137 months), there were no late deaths. Five patients needed the expected RV-PA conduit replacement. None of the patients developed LVOTO.

Lee *et al.* from Korea reported their experience with two patients using this approach.[29] Both patients had re-intervention-free mid-term survival over the 5-year follow-up period.

Aortic root translocation and atrial switch for double discordance

Anatomical correction of double discordance necessitates an atrial switch along with an ASO (double switch). The presence of LVOTO precludes the ASO component of the operation. The options in such a situation are, firstly, an atrial switch-Rastelli with the inherent complications of a nonorthotopic RV-PA conduit. Due to the atypical anatomy of the conduction bundle in ccTGA, creation of an intraventricular baffle with or without VSD enlargement might carry a high risk of conduction disturbances.[30] The other option is to perform an atrial switch with aortic root translocation (Nikaidoh). This concept was introduced by Jacobs *et al.* in 2006.[15] This additional option allows expanding the indications of anatomical repair of ccTGA.

Technique

This technique involves a combination of the Nikaidoh procedure (described above) with an atrial switch operation. Unlike the routine Nikaidoh procedure, in patients with ccTGA anatomy, the aortic root needs to be sutured to the right ventricular aspect of the interventricular septum to avoid injury to the conduction tissue. Harvest of the aortic root allows excellent visualization of the VSD margins, which might help mitigate the risks of conduction disturbances.[15] Addition of an atrial switch to an already complex operation makes this procedure challenging.

Outcomes

Jacobs *et al.* described their experience with three patients undergoing the Senning-aortic root translocation.[15] One patient had straddling and overriding of the morphologic tricuspid valve. One patient died of a cerebrovascular accident. Davies *et al.* described the procedure in detail in a 7-year-old boy in 2008.[30] Hraska used this concept for anatomical repair of a patient with ccTGA, atrial situs inversus, and an inlet VSD.[31] This patient had an uneventful recovery and was well at 6-month follow-up. Hu *et al.* reported using the modified Nikaidoh (double-root translocation – described below) procedure along with Senning in four patients with no deaths at early follow-up (mean, 7 months and range, 2–26 months).[32] In 2017, Brizard *et al.* used the Senning–Bex/Nikaidoh procedure in six patients to achieve anatomical repair of ccTGA.[33] Two of these needed a permanent pacemaker, and two required revision of the atrial switch. There was no death at a median follow-up of 2.1 years (range, 0.1–8.5 years).

TRANSLOCATION OF PULMONARY ROOT

Conceptually, translocation of the pulmonary root is opposite of the Nikaidoh procedure. The pulmonary root is harvested and translocated "anteriorly" as opposed to posterior translocation of the aortic root in the Nikaidoh procedure. Pulmonary root translocation for TGA/VSD/PS has been introduced and popularized by da Silva *et al.* from Brazil.[16]

Technique

The steps of the procedure are demonstrated in Figure 4. The PA is dissected and mobilized as much as possible before the initiation of CPB. CPB is initiated, and the heart is arrested. A right ventriculotomy is performed, and the pulmonary root is harvested using careful visualization from outside and inside. Care should be taken to avoid injury to the pulmonary, aortic, or mitral valve. Entering the interventricular septum is also avoided. The opening in the LV is checked for injury to the mitral valve and is closed using a glutaraldehyde-treated autologous pericardial patch. The VSD is inspected – it often needs enlargement which is achieved by resection of the conal septum. Then, a Dacron baffle is constructed to route the LV to the aorta. Enlargement of the pulmonary valve is performed if necessary using a monocusp valve. The intact PA is brought anteriorly to the left of the aorta without a Lecompte maneuver and is sutured to the right ventriculotomy complemented with an autologous pericardial patch. Pulmonary root translocation keeps the aorta and coronary arteries untouched in contrast to the Nikaidoh procedure.[34] da Silva *et al.* reported adequate growth of the implanted pulmonary root.[35] They, however, do not recommend this procedure for a small or remote VSD or small/heavily trabeculated RV. As in the Rastelli procedure, it is mandatory for the VSD to be routable to the aorta with or without enlarging it. Pulmonary atresia or extremely small/dysplastic pulmonary valves are contraindications for this procedure.[35]

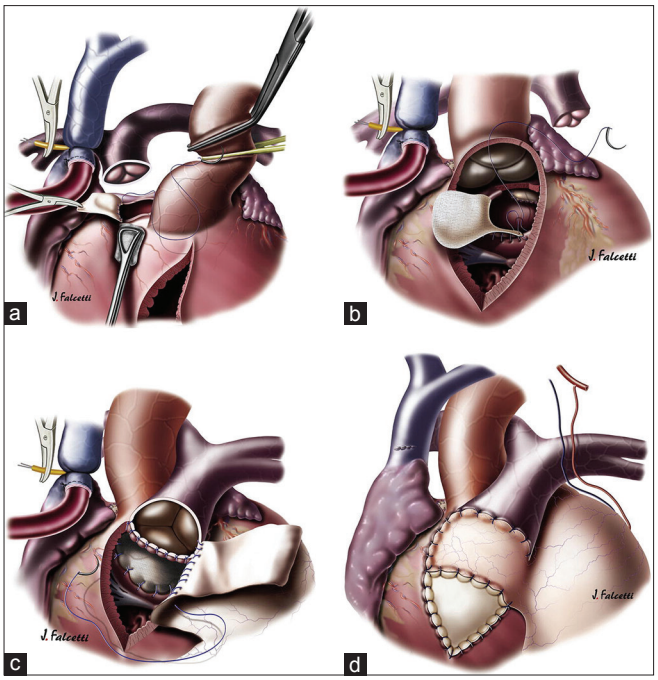

Figure 4: Pulmonary root translocation. (a) The pulmonary root is dissected out, and its origin is closed using a glutaraldehyde-treated autologous pericardial patch. (b) After partial resection of the conal septum, a Dacron patch is used to create a tunnel from the left ventricle to the aorta. (c) The pulmonary root is sutured to the right ventriculotomy with a running 6-0 polydioxanone suture, and the right ventricular outflow tract is completed using an *in situ* pericardial patch combined with a glutaraldehyde-treated autologous pericardial patch. (d) The final appearance after the procedure. (Reproduced with permission from da Silva *et al.*[33])

Interestingly, pulmonary root translocation was first described as a technique for anatomic correction of double-outlet LV (DOLV).[36,37] In 1992, Chiavarelli *et al.* reported the surgical correction of DOLV in a 4-month-old female infant.[36] The authors presented pulmonary root translocation as an alternative to intraventricular tunnel repair. Similarly, in 1995, DeLeon *et al.* reported pulmonary root translocation as a useful option to achieve biventricular repair in patients with DOLV.[37]

Outcomes

Da Silva *et al.* described their most updated outcomes with translocation of the pulmonary root in 2012.[35] Forty-four patients with a mean age of 24 months (median, 11 months; range, 1 month to 11 years) who had pulmonary root translocation were followed up for a mean period of 72 ± 52.1 months. Nearly one-third (n = 15) of the 44 patients needed enlargement of the pulmonary annulus. There were three early deaths and one late death. The 10-year re-intervention-free survival was 82.9%. Seven patients needed eight re-interventions. Tateishi *et al.* have reported the use of this technique in combination with an atrial switch (Senning) in a 6-year-old boy with ccTGA/VSD/PS.[38]

TRANSLOCATION OF BOTH ROOTS/VENTRICULAR OUTFLOW TRACTS

This could be an *en bloc* rotation of outflow tracts or double-root translocation.

En bloc rotation of outflow tracts (half-turned truncal switch/*en bloc* rotation of truncus arteriosus)

En bloc rotation of both outflow tracts was first described by Yamagishi *et al.* in 2003.[17] They described the use of this technique in a 7-kg girl where the aortic and pulmonary roots were harvested together as one block (called as truncal block in the publication), rotated through 180° and re-implanted onto the appropriate ventricles.

Technique

Details of the procedure are demonstrated in Figure 5. After institution of moderately hypothermic CPB and cardioplegic arrest, the aorta is transected above the coronaries. The proposed line of incision around the truncal root goes around both the great arterial valves. The PA is incised obliquely to retain the anterior wall with the proximal PA. Both coronaries are harvested. The RV is incised along the aortic annulus. The infundibular septum is incised along the right and left sides, and the incision is continued around the pulmonary valve. After carefully visualizing the mitral valve, pulmonary–mitral continuity is incised, and a truncal block which includes the aortic and pulmonary valves is harvested. The truncal block is rotated through 180°. Now, the posterior aortic annulus is anastomosed to the LVOT. Coronaries are re-implanted, and the VSD is closed with a patch. Lecompte maneuver is performed to translocate the PA bifurcation anteriorly, and the aortic anastomosis is completed. The posterior pulmonary wall is anastomosed directly, whereas the anterior RVOT is augmented with a monocusp patch.[17]

Coronary harvest and transfer is a mandatory and an inevitable accompaniment of this procedure. Nonfavorable coronary anatomy was initially thought to be a contraindication for this procedure. However, a recent report from the same group in Japan shows that this repair can be pursued even in patients with nonfavorable anatomy (single coronary).[39] They believe that a margin of 3 mm between the left coronary and posterior pulmonary annulus allows for the safe performance of this procedure. In patients where this distance is <3 mm, aortic root translocation should be preferred. Caution must still be exercised in coronary anatomies where important branches run in front of the aorta or between the great arteries.[39] This procedure can be performed even in patients with a small/remote VSD or small RVs.[40]

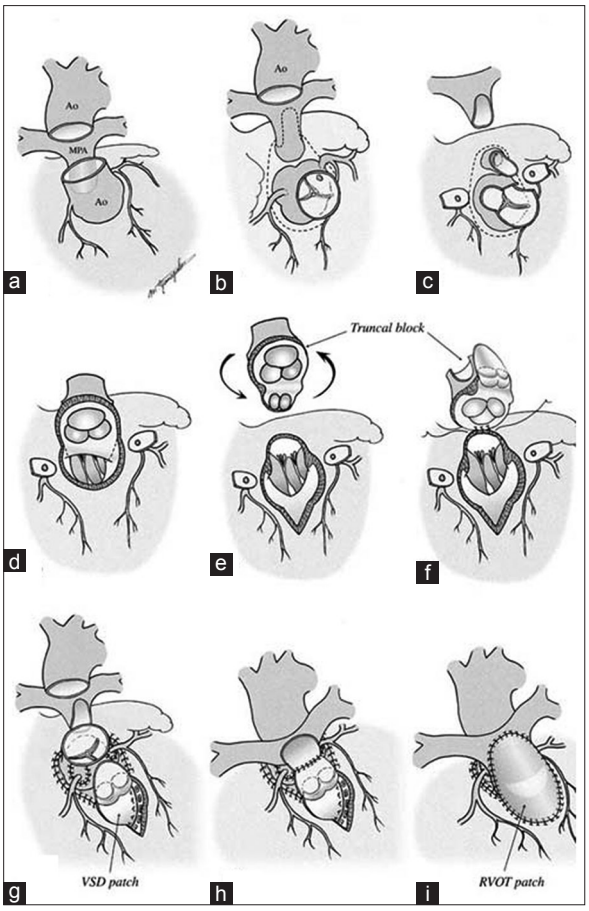

Figure 5: *En bloc* rotation of outflow tracts (half-turned truncal switch). (a) The aorta was located anteriorly, and the main pulmonary artery was located posteriorly. The aorta was transected 10 mm above the coronary orifices. (b) Antero–superior view of the truncal root. The dotted line indicates the incised line. The supposed incised line on the main pulmonary artery runs obliquely from the posterior wall of the pulmonary annulus to the anterior wall of the pulmonary bifurcation. (c) The main pulmonary artery was incised obliquely so as to keep the anterior wall to the proximal side. Both coronary arterial buttons were resected. (d) Along the aortic annulus, the anterior wall of the right ventricle was incised. The dotted line indicates the incised line on the infundibular septum. (e) The midline of the fibrous continuity between the pulmonary valve and the mitral valve was incised. The truncal block involving both semilunar valves was separated from the ventricular outflow tract. The resected truncal block was half turned. (f) The half-turned truncal block was anastomosed to the ventricular outflow tract. First, the posteriorly translocated aortic annulus was anastomosed to the left ventricular outflow orifice. The up-front pulmonary commissure was cut through. (g) After anastomosis of the aortic annulus, both coronary buttons were anastomosed to the corresponding defects of the aortic wall. The ventricular septal defect was closed with an expanded polytetrafluoroethylene patch (ventricular septal defect patch). The superior margin of the patch was anastomosed to the prominence of the infundibular septum. (h) After the pulmonary bifurcation was translocated anteriorly, the ascending aorta was reconstructed by means of end-to-end anastomosis. Continuity of the posterior pulmonary wall was reconstructed by means of direct anastomosis with each remnant wall. (i) The right ventricular outflow tract was covered with an autologous pericardial patch (right ventricular outflow tract patch) equipped with a monocusp expanded polytetrafluoroethylene valve (reproduced with permission from Yamagishi *et al*.[37])

Mair *et al*. reported their initial experience with three patients using this technique in 2006.[41] They called this procedure "*en bloc* rotation of the truncus arteriosus." However, in a letter to the editor by Dr. Robert Anderson in 2016, it was suggested that the use of the term "truncal" in a surgical context would be inappropriate.[42] He advised the use of the term "rotation of outflow tracts." Hence, the most appropriate surgical term might be "*en bloc* rotation of outflow tracts."

Outcomes

In 2018, Hongu *et al*. from Kyoto, Japan, reported outcomes of 14 patients with a median age of 1.2 years (range, 0.2–5.1 years).[40] The median follow-up was 5.2 years (range, 0.4–15.7 years). There was no early death, and one late death occurred due to arrhythmia, 11 months after the operation. None of the patients had outflow tract obstruction or coronary insufficiency. Three patients needed subsequent mitral valve repair in the form of annuloplasty. The mechanism of mitral regurgitation was valve tethering rather than distortion of the annulus.

The same group also reported the use of this technique in a 10-month-old patient with TGA/remote VSD/PS and a single coronary artery.[39] This shows that the procedure can be performed even in patients with an unfavorable coronary anatomy.[43]

Mair *et al*. reported the follow-up of the original cohort of patients undergoing *en bloc* rotation of the outflow tracts in 2016.[44] In their experience, 16 patients underwent this operation over a period of 13 years. Their median age was 0.39 years (range, 0.1–2.25 years). There was one early and one late death. The median follow-up was 3.95 years (range, 153 days to 9.96 years). Both the aortic and pulmonary valves showed evidence of growth on the basis of follow-up echocardiographic measurements. There were three reoperations – one patient needed aortic valve repair, one needed VSD closure, and one patient needed pacemaker implantation. They recommend that an oversized VSD patch should not be used in patients with an oversized aortic root, as it can lead to central AI.

Double-root translocation

Translocation of both great vessel roots as a modification of the Nikaidoh procedure was reported by Hu *et al*. in 2007.[18] They described the technique in detail and introduced the term "double-root translocation" in 2009.[45] They also reported their initial experience with forty patients in the same article.

Technique

After institution of CPB and cardioplegic arrest, coronaries are mobilized, and the aorta is transected above the sinotubular junction. The aortic root is harvested off the RV. In patients with antero–posterior relation, the aortic root and coronaries are harvested *en bloc*; otherwise, they need re-implantation. The pulmonary root is

Table 2: Root translocation techniques

Technique	Aortic root	Pulmonary root	Coronaries	Lecompte maneuver	VSD	RVOT reconstruction	Advantages	Disadvantages
Nikaidoh[13]	Translocated posteriorly	Valve excised	Mobilized +/− translocated	Yes	Essential	Large RVOT patch/conduit	- Straight LVOT - RV volume not reduced - RVOT in orthotopic position - VSD size/position less relevant	- Coronary anatomy limiting factor - Very small pulmonary annulus limiting factor (limits posterior displacement) - Needs coronary handling - Pulmonary valve sacrificed - Coronary stretch/ distortion in small pulmonary annulus - Risk of AR - Technically complex
Aortic root 0translocation with arterial switch[14]	Translocated posteriorly	Valve excised	Translocated	Yes	Not essential	Conduit	Same as Nikaidoh	- Needs aortic autograft rotation and complete coronary translocation - Technically complex
Pulmonary root translocation[16]	Untouched	Translocated anteriorly	Untouched	No	Essential (part of intracardiac baffle)	Not required±valve augmentation	- No handling of aorta/coronaries - Pulmonary root has growth potential - Useful when obstruction (LVOTO) is sub-valvar	- Still needs LV to aorta intracardiac baffle - VSD routability limiting factor - Not possible in small/atretic pulmonary valve - Risk of mitral valve injury - Technically complex
En bloc rotation of outflow tracts[17]	Translocated 180° rotation	*en bloc* after	Translocated	Yes	Not essential	Not required±valve augmentation	- Same as Nikaidoh - RVOT conduit avoided - Growth potential in both roots	- Needs coronary handling - Coronary anatomy limiting factor (crossing RVOT) - Risk of mitral valve injury/ regurgitation - Technically complex
Double root translocation[45]	Translocated posteriorly	Translocated anteriorly	Translocated	Yes	Not essential	Not required±valve augmentation	Same as *en bloc* rotation of outflow tracts	- Needs coronary handling - Technically complex - Unnecessary separation of both roots

Contd...

Table 2: Contd...

Technique	Aortic root	Pulmonary root	Coronaries	Lecompte maneuver	VSD	RVOT reconstruction	Advantages	Disadvantages
Rastelli[47]	Untouched	Untouched	Untouched	No	Essential (part of intracardiac baffle)	Nonanatomic conduit	Native roots and coronaries untouched	- VSD size/location limiting factor - Adynamic intracardiac baffle - Baffle reduces RV volume - Baffle can interfere with TV - RV-PA conduit nonanatomic - Long-term risk of LVOTO+RVOT re-interventions - Unsatisfactory long-term outcomes

AR: Aortic regurgitation, LVOT: Left ventricular outflow tract, LVOTO: Left ventricular outflow tract obstruction, PA: Pulmonary artery, LV: Left ventricle, RV: Right ventricle, RVOT: Right ventricular outflow tract, RVOTO: Right ventricular outflow tract obstruction, VSD: Ventricular septal defect, TV: Tricuspid valve

harvested (incision 5 mm below the annulus) without sacrificing its valve unlike the Nikaidoh procedure. While harvesting the pulmonary root, care must be taken to avoid injury to the conduction and mitral valve apparatus (distortion of pulmonary–mitral continuity).[5,45] In patients with AV discordance, the anterior portion of the pulmonary annulus must be kept intact to avoid injury to the conduction tissue.[45] In cases of minimum/no subpulmonary infundibulum (TGA), the pulmonary root needs to be harvested very carefully. LVOT is enlarged as necessary. VSD is closed with a Dacron patch. The aortic root is implanted onto the LVOT with or without coronary re-implantation. The Lecompte maneuver is performed, and aortic anastomosis is completed. RVOT to PA connection is established. Smaller pulmonary valves may need augmentation using a monocusp bovine jugular vein patch or a homograft pulmonary patch.

It has been suggested that double-root translocation is a modification of the *en bloc* rotation technique,[40] and that separation of the two roots and valves might be unnecessary and troublesome.

Outcomes

Hu *et al.* reported double-root translocation in forty patients over a 4-year period and reported their results in 2009.[45] The median age at operation was 3.8 years (range, 0.3–18 years). The maximum follow-up was 19 months. Thirty patients had a diagnosis of TGA/VSD/PS, whereas ten patients had a diagnosis of DORV/VSD/PS. Four patients needed extracorporeal membrane oxygenation support; of these, two died. The same group reported their extended experience for patients with DORV/noncommitted VSD/PS in 2010.[46] The median age at surgery was 48 months (range, 1–16 years). They reported no early or late deaths and no reoperations at a mean follow-up of 21.9 months (range, 2–36 months). Table 2 summarizes all the root translocation techniques and compares them with the Rastelli procedure.

Theoretically, complex conotruncal anomalies can be treated with either the single-ventricle pathway or complex anatomic biventricular repair. The Fontan pathway is technically straightforward, outcomes are predictable, and the risk of reoperation is low. However, long-term Fontan complications are inevitable, and having two good sized ventricles is of no advantage in the Fontan circuit.[48] On the other hand, complex biventricular repairs come with their own set of problems such as risk of heart block, outflow tract obstructions, and high probability of reoperations. Despite the known long-term complications, the Rastelli operation remains one of the more popular options to deal with these complex conotruncal anomalies with LVOTO.[49] Most of these problems can be attributed to intraventricular tunneling to route blood from the LV to the aorta through the VSD. Intraventricular tunnels are adynamic, which cause flow turbulence and decrease effective RV volume. Moreover, the RV-PA conduit is in a nonorthotopic position. This results in energy loss and might also cause accelerated endothelial thickening with subsequent narrowing of the tunnel.[21,40] Moreover, tunneling often needs VSD enlargement which increases the risk of heart block, and the enlargement might not always be effective.[50,51] Herein lies the importance of root translocations. By placing the great vessel onto the appropriate ventricle, the need for an intraventricular tunnel is completely ameliorated. The outflows are more "in-line" and are likely to be more energy efficient. The outcomes discussed above show that the only reoperative risk that remains is that for the RVOT patch or RV-PA conduit which remains the holy grail of pediatric cardiac surgery.[52] However, root translocations are complex operations, dealing with anatomical areas not normally

encountered, have a long learning curve - and might not necessarily be reproducible in everyone's hands. Extensive experience with coronary translocation in the ASO might be extrapolated to root translocations.

CONCLUSION

Root translocation techniques include a variety of options with several modifications. Acceptable outcomes with a biventricular repair can be achieved with appropriate modifications of the surgical technique. Coronary artery patterns no longer limit the use of these techniques. These procedures continue to evolve, and long-term results are awaited.

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Conflicts of interest

There are no conflicts of interest.

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