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Original Article

Complexity stratification of the arterial switch operation: a second learning curve*

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Abstract The arterial switch operation has become a safe operation in many centres. The complexity of the procedure has evolved over the last two decades. Several anatomical features can hardly be considered complex today, namely, normal coronary anatomy, circumflex coming off the right coronary artery, eccentric ostium, and early take-off of an infundibular artery. In addition, as peri-operative mortality becomes very low, the outcomes need to be evaluated on the peri-operative morbidity, late reoperations, and late deaths. The arterial switch operation remains complex in around 20% of the cases, where one or several complexity factors are associated. The complexity of the coronary arteries is a major factor. According to a classification essentially based on the course of the coronary arteries, complex coronaries include: double-looping coronaries, anterior-looping coronaries, intramural coronaries, and single coronary ostium. The most challenging coronary pattern remains the association of a single ostium with intramural course. Other features are equally complex: severe malalignment of the commissures, aortic arch obstruction, multiple ventricular septal defect, Taussig–Bing with subaortic obstruction, double-outlet right ventricle non-committed ventricular septal defect, transposition of the great arteries-intact ventricular septum >3 weeks, transposition of the great arteries-ventricular septal defect with high lung resistances and weight <2.5 kg. Owing to the fact that the risks of arterial switch operation vary according to the experience of the centres, we defined the arterial switch operation complexity based on a subjective approach as proposed by the Aristotle comprehensive score. The recent introduction of a morbidity score will allow to stratify more accurately the outcomes when the peri-operative mortality is very low or nil. The complexity of the coronary patterns tends to be well controlled today. It remains that rare coronary failures and aortic root dilation will occur in the long term, requiring a close follow-up of the most complex patients. Successfully achieving complex arterial switch operation implies a second learning curve.

SINCE THE FIRST PUBLICATION BY JATENE ET AL[1] IN 1976, the arterial switch operation has become a safe and reproducible technique,[2–5] allowing anatomical repair of transposition of the great arteries and selected forms of double-outlet right ventricle. The hospital mortality of the arterial switch operation given by the Society of Thoracic Surgeons Congenital Database[6] is 2.4% for arterial switch operation in transposition of the great arteries with intact ventricular septum and 6.4% for arterial switch operation with transposition of the great arteries-ventricular septal defect, with several centres reporting 0% mortality on overall series of arterial switch operation.[2]

The evaluation of quality of care is becoming more accurate[7] and also different in our congenital heart surgery speciality. The traditional evaluation based on the risk for hospital mortality becomes obsolete for procedures with very low mortality and the assessment of quality requires measuring objectively morbidity as we started with the morbidity score.[8] Nevertheless, none of our two modern STAT Mortality and Morbidity Scores[7,8] can predict the risk of mortality or morbidity of individual patients undergoing an arterial switch operation. Moreover, the risk

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for mortality is variable depending on the performance of the surgeon and his team.

In comparison, the comprehensive Aristotle complexity score[9,10] is designed to be a constant value. It includes detailed benchmarks of mortality and morbidity through the analysis of procedure-dependent and -independent factors, which provide a case-mix to evaluate the risk of the arterial switch operation.

Definition of the complex arterial switch operation

To circumvent the variability of risk, we will refer essentially to complexity factors in using the recently updated procedure-dependent factors of the arterial switch operation. It is noticeable that this approach is subjective, based on expert surgeons' opinion and on the literature and personal experience.[2]

Arterial switch operations are complex when undertaken in the presence of one or several of the following features:

- Complex coronary anatomy
- Malaligned commissures
- Aortic arch obstruction
- Multiple ventricular septal defect
- Double-outlet right ventricle
- Late referral
- Weight <2.5 kg.

Complex coronary anatomy

There are individual preferences for classification and surgical techniques of arterial switch operation. We have followed for two decades a similar coronary classification based on the course of the vessels, as well as a standardised surgical technique that was described elsewhere.[11,12] Following a recent study,[2] we believe that today arterial switch operation cannot be considered complex when associated with one or several of these anatomical features: normal coronary anatomy, circumflex coming off the right coronary artery, eccentric ostium, and early take-off of an infundibular artery from the left or right coronary artery.

The complex coronary patterns represent around 20% of the coronary anatomy.

Double-looping coronaries (with two ostia; Fig 1)

These are the most frequent complex coronary arteries (15%).

The right coronary artery crosses in front and either the circumflex (Fig 1a) or the entire left trunk (Fig 1b) crosses behind. This later pattern is frequent in Taussig–Bing and sometimes called inverted coronary artery.

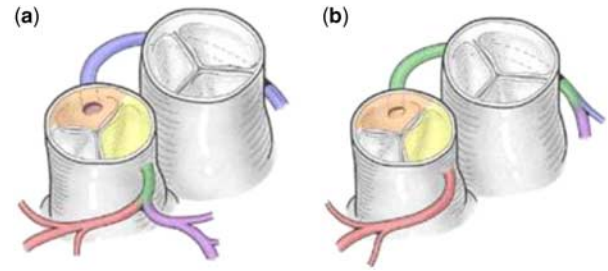

Figure 1.
*Double-looping coronaries (with two ostia; 15%). (**a**) Right coronary artery looping anteriorly and Cx looping posteriorly and (**b**) right coronary artery looping anteriorly and the entire left trunk looping posteriorly.*

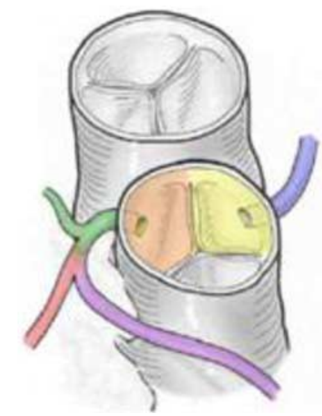

Figure 2.
Anterior-looping coronaries (with two ostia; 0.1%). Left anterior descending coming off the right coronary artery.

Anterior-looping coronaries (with two ostia; Fig 2)

These are very rare (0.1%). Left anterior descending coming from the right coronary artery and looping in front, with Cx coming from the left ostium.

Intramural coronaries (Fig 3)

These represent 5% and are very challenging. They can be repaired with very low mortality[2] following the technique described by Mee et al.[13] The most challenging form is when the intramural coronary arteries are coming from a single ostium.

Single coronary ostium (Fig 4)

This represents 5%. The forms with single right ostium are the most frequent.[14] The transfer is theoretically simpler as only one button is to be moved. In fact, the transfer is made difficult by the risk of kinking and stretching and implies to largely mobilise the coronary trunks on a long distance.

Single ostium associated with intramural coronary, described initially by Yacoub and Radley Smith[15] as type B, is the most challenging coronary

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patterns. Different techniques are proposed. The technique of coronary relocation, described by Planche et al,[16] implies to rotate the common coronary button on 180°C. This technique is at risk for compression of the transferred coronary button by the pulmonary bifurcation standing in front following the Lecompte manoeuvre. The most appropriate technique is to create a fistula between the great vessels to re-route the single coronary ostium into the neoaortic root. This technique, first described by Aubert et al,[17] was refined by Takeuchi and Katogi[18] and Moat et al.[19]

Malaligned commissures

Malaligned commissures are not an absolute risk when minor. It makes the coronary transfer more difficult. The incidence of malaligned commissures varies from 50% in the Kim et al[20] series to 15% in our recent experience[2] and was associated with early or late mortality.[2,20] Several techniques are used depending on the severity of the malalignment: trap-door, implantation above a commissure, tube reconstruction of a coronary artery,[20] and rotation of the neoaortic root (Fig 7). The transfer of the right coronary button is solved in placing the button in high position[11,12] above the commissure. The transfer is more challenging for the left button. Performing a rotation of the neoaortic root to the right or to the left, when doing the end-to-end distal aortic anastomosis, allows to realign the commissures in placing the anterior commissure of the neoaortic valve close to the middle line.

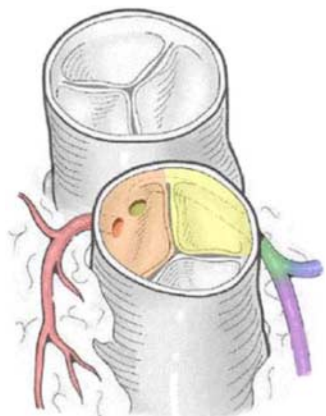

Figure 3.
Intramural coronary (5%).

Aortic arch obstruction

Frequently associated with Taussig–Bing, the anatomical repair is more complex because of the aortopulmonary size mismatch (Fig 5). It is necessary to enlarge (Fig 5) the ascending aorta in using a homograft patch. The small diameter of the neo-pulmonary annulus can create a right ventricular outflow tract obstruction, which is difficult to handle, as many times the right coronary artery is crossing in front the infundibulum. Side-by-side vessels are frequent in transposition of the great arteries-ventricular septal defect-coarctation. It could be necessary to move the pulmonary artery trunk to the right pulmonary artery branch (Fig 6) to avoid a compression of the right coronary artery that is frequently looping in front of the aorta.

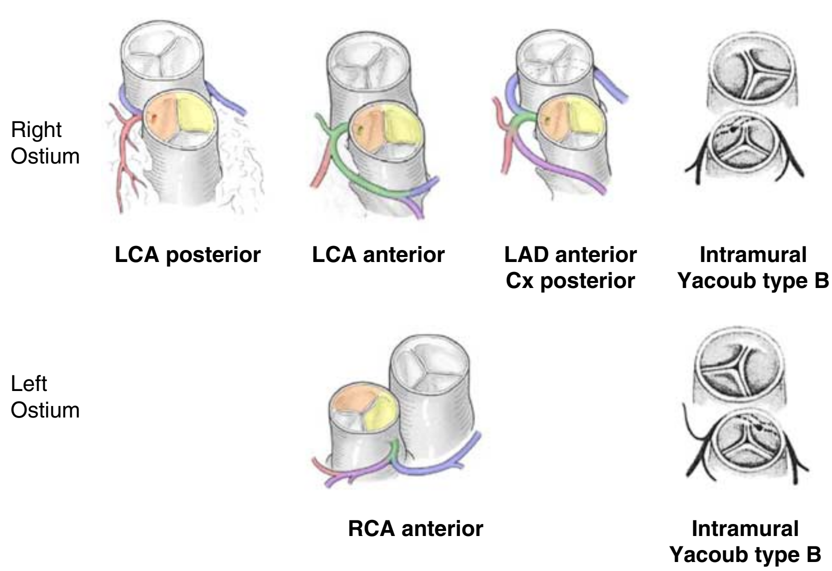

Figure 4.
Single ostium (5%). LAD = left anterior descending; LCA = left coronary artery; RCA = right coronary artery.

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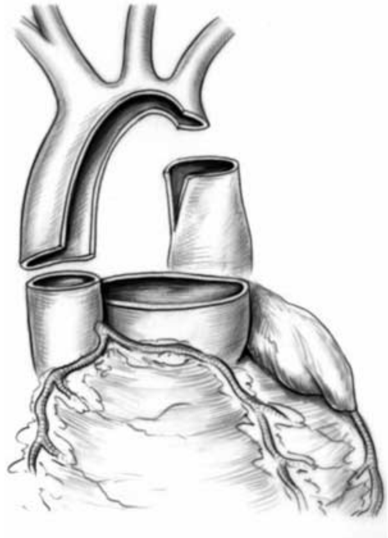

Figure 5.
Aortopulmonary mismatch.

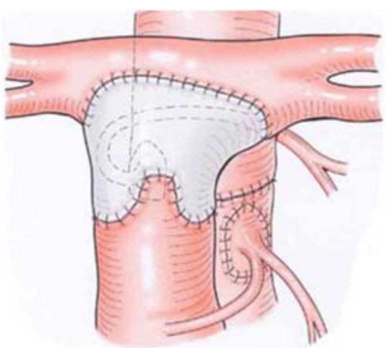

Figure 6.
Side-by-side vessels. Translation of the pulmonary trunk towards the right pulmonary artery.

Multiple ventricular septal defect

The presence of two ventricular septal defects does not contraindicate one stage repair. Over two ventricular septal defects, a pulmonary artery banding is a reasonable approach, but the repair should be performed before 6 months of age to avoid long-term impairment of the neoaortic valve.

Double-outlet right ventricle

Taussig–Bing

Double-outlet right ventricle associated with subpulmonary ventricular septal defect is complex because of multiple challenging associations: complex coronary anatomy with frequently double-looping coronaries, arch obstruction and side-by-side vessels, as already mentioned, and the presence of a subaortic obstruction by posterior malalignment of the conal septum (Fig 8).

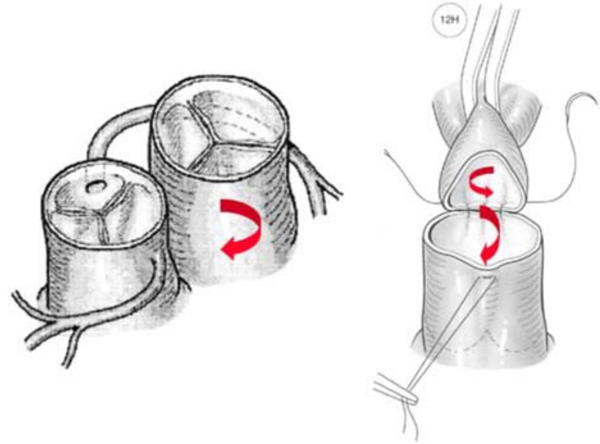

Figure 7.
Malaligned commissures.

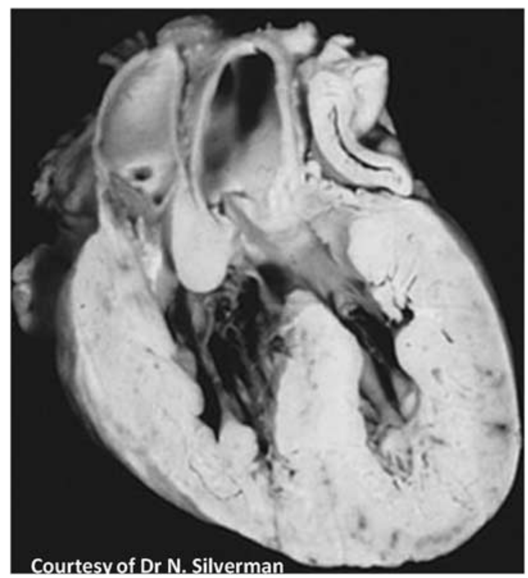

Figure 8.
Taussig–Bing with subaortic obstruction.

Double-outlet right ventricle non-committed ventricular septal defect

This complex form of double-outlet right ventricle is sometimes treated like a Taussig–Bing anomaly by rerouting of the ventricular septal defect to the pulmonary artery followed by arterial switch.[2,21,22]

Late referral

Transposition of the great arteries-intact ventricular septum >3 weeks of age

In western countries, the delay in performing an arterial switch operation >1 month is most often due to an associated extra-cardiac lesion contraindicating the arterial switch operation, typically a

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Table 1. Procedure-dependent complexity factors for the four ASO procedures.

ASO procedures	Procedure-dependent complexity factors
ASO	Double loops (2 ostia) Anterior loop (2 ostia) Single ostium Intramural coronary Malaligned commissures Age >3 weeks
ASO and VSD repair	Double loops (2 ostia) Anterior loop (2 ostia) Single ostium Intramural coronary Malaligned commissures VSD, multiple, repair Aortopulmonary diameter mismatch Side-by-side vessels DORV non-committed VSD
ASO and VSD repair + aortic arch repair	Double Loops (2 ostia) Anterior loop (2 ostia) Single ostium Intramural coronary Malaligned commissures VSD, multiple, repair Aortopulmonary diameter mismatch Side-by-side vessels Taussig–Bing with subaortic obstruction
ASO + aortic arch repair	Double loops (2 ostia) Anterior loop (2 ostia) Single ostium Intramural coronary Malaligned commissures Age >3 weeks

ASO = arterial switch operation; DORV = double-outlet right ventricle; VSD = ventricular septal defect

necrotising enterocolitis, a brain haemorrhage, a severe infection, or a very low birth weight.[23] The delayed arterial switch operation is undertaken after left ventricle retraining using a moderate pulmonary artery banding and a Blalock–Taussig shunt. The left ventricle reconditioning is obtained in 1–4 weeks, but is associated with significant morbidity.[2]

Transposition of the great arteries-ventricular septal defect with high lung resistances

This population of patients is seen in countries with suboptimal paediatric cardiac surgery resources. When the pulmonary hypertension is severe, with lung resistances over six Woods units, there is an ongoing controversy between: doing a palliative arterial switch operation and leaving the ventricular septal defect open,[24] using a fenestrated patch,[25] using a unidirectional patch technique,[26] or abstaining.

Table 2. Procedure-independent complexity factors.

ASO procedures	Procedure-independent complexity factors
ASO	Weight <2.5 kg Others (STS pre-operative factors list)
ASO and VSD repair	Weight <2.5 kg Lung resistances >6 Woods unit Others
ASO and VSD repair + aortic arch repair	Weight <2.5 kg Others
ASO + aortic arch repair	Weight <2.5 kg Others

ASO = arterial switch operation; STS = Society of Thoracic Surgeons; VSD = ventricular septal defect

Weight <2.5 kg

Extreme low birth weight, <1.5 kg, is clearly a risk factor. Between 1.5 and 2.5 kg, the arterial switch operation has been attempted with quite good success. The multi-centric Congenital Heart Surgeons' Society study including 507 infants with weight between 1 and 2.5 kg reports that weight at <2.5 kg is an incremental risk factor for arterial switch.[27]

Listing of complexity factors

Tables 1 and 2 provide the list of procedure-dependent and -independent factors according to the four types of arterial switch operation. This listing will be discussed at the Society of Thoracic Surgeons and European Association for Cardio-Thoracic Surgery Database meeting along with other procedures.

Discussion

Coronary transfer in complex coronary arteries can be achieved with minimal risk and even with 0% peri-operative mortality in our series of 101 consecutive arterial switch operations with 45% of complex forms.[2] There is nevertheless a late risk of around 2% of coronary failure following arterial switch with complex coronaries. Coronary artery stenosis or occlusion could be silent because of the denervation of the great vessels. It is our practice to check the patency of the complex coronary arteries using computed tomography scan or magnetic resonance imaging, completed by coronarography when needed.

So far, the pulmonary valve seems to perform well under systemic pressures, with a long-term risk of aortic regurgitation around 2%. Nevertheless, the long-term dilation of the neoaortic root is a potential risk in forms with native large pulmonary roots.

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Following more than a decade of work, the Society of Thoracic Surgeons and European Association for Cardio-Thoracic Surgery Databases have acquired now reliable benchmarks to measure the mortality and the morbidity associated with a given procedure. With the newly developed STAT Mortality and Morbidity Scores,[7,8] it is possible to compare objectively the complexity of the procedures and the institutions. Nevertheless, it is not yet possible today to predict the risk of mortality and morbidity for a given patient. This requires a more comprehensive analysis, which is provided by the comprehensive Aristotle Score.[9] The introduction of procedure-dependent complexity factors in the congenital databases should, in the future, allow to refine the exactness of the evaluation. Looking at the accuracy of the risk for mortality stratification models available today, the STAT Mortality Score obtained a C-index of 0.78 with data from the Society of Thoracic Surgeons and European Association for Cardio-Thoracic Surgery Databases,[7] whereas the Comprehensive Aristotle Score reached a C-index of 0.860[10] with data from a single centre.

The introduction of a morbidity score[8] is a decisive step to evaluate procedures with low mortality. Placing in perspective the outcomes of the arterial switch, it is anticipated that families and referral paediatric cardiologists, as well as payers, will favour centres with low morbidity. Decreasing morbidity[2] in the arterial switch operation requires not only an excellent surgical technique, but also an optimal performance from the other participants of the team.

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