World Journal for Pediatric and Congenital Heart Surgery
2019, Vol. 10(1) 90-97

DOI: 10.1177/2150135118811115
journals.sagepub.com/home/pch
SAGE

The Arterial Switch Operation in 2019: How to Do It and How to Teach It

Richard A. Jonas, MD[1]

Abstract

This article presents technical aspects of the arterial switch procedure. The arterial switch procedure is a technically reproducible operation that involves less three-dimensional judgment and fewer difficult sequencing decisions than many other complex cardiac procedures. Hemostasis is the most important principal that must be adhered to mainly through meticulous surgical technique. Meticulous technique will also lead to successful transfer of the coronary arteries. Teaching a surgical trainee how to manage a child who requires an arterial switch procedure requires instruction in the technical aspects of the procedure. However, this is just one component of the overall management of babies requiring this procedure. Attention and training should be directed at all areas of competence that have been emphasized by bodies such as the American College of Surgeons. Simulation is playing an increasingly important role in the instruction of surgical trainees within the domain of congenital heart disease.

Keywords

arterial switch operation, congenital heart surgery, education, all levels, congenital heart disease (CHD)

Submitted August 31, 2018; Accepted October 10, 2018.

Introduction

The arterial switch procedure was first successfully performed by Dr Adib Jatene in the mid-1970s in Brazil.[1] The child was an older infant with a ventricular septal defect, so that left ventricular pressure was maintained allowing a one-stage arterial switch. Professor Magdi Yacoub in the late 1970s developed the concept of a two-stage arterial switch procedure for patients with transposition and an intact ventricular septum.[2] He placed a preliminary pulmonary artery band and approximately one year later performed an arterial switch. The two-stage technique usually required placement of a right ventricular to pulmonary artery conduit. In 1983, Dr William Norwood and Dr Aldo Castaneda at Children's Hospital Boston were the first to successfully report performance of a one-stage arterial switch in newborns.[3] They took advantage of the natural preparedness of the left ventricle that is a consequence of the fetal circulation with the patent ductus arteriosus equalizing pressures in both ventricles. In addition, they applied the newly described Lecompte maneuver to allow direct anastomosis of the pulmonary arteries.[4] Initially, the early mortality of the arterial switch was higher than the alternative atrial switch procedures including the Mustard and Senning operations. However, as experience with the operation increased, the early mortality decreased as various technical maneuvers were learned. Most importantly, experience was gained in transferring some of the more challenging and unusual coronary artery patterns.

Technical Aspects of the Arterial Switch Operation

Setup

We strenuously avoid placement of internal jugular lines in newborns and rely on intracardiac right atrial and left atrial lines for postoperative medication administration and monitoring. It is important that the neck should be extended by a shoulder roll as this helps to draw the great vessels out of the neck.[5]

The Key to a Successful Arterial Switch: Hemostasis

By using very small needles such as the BV1 needle for the aortic and pulmonary artery anastomoses and BV175 7/0 Prolene for the coronary buttons, it is possible to reduce needlehole bleeding even when tissue is very delicate. It is critically important to prophylactically reinforce even the most miniscule imperfections in suture lines that would be difficult to access after the Lecompte maneuver. For example, under the

[1] Department of Cardiovascular Surgery, Children's National Health System, Washington, DC, USA

Corresponding Author:
Richard A. Jonas, Department of Cardiovascular Surgery, Children's National Health System, 111 Michigan Avenue NW, Washington, DC 20010, USA.
Email: rjonas@cnmc.org

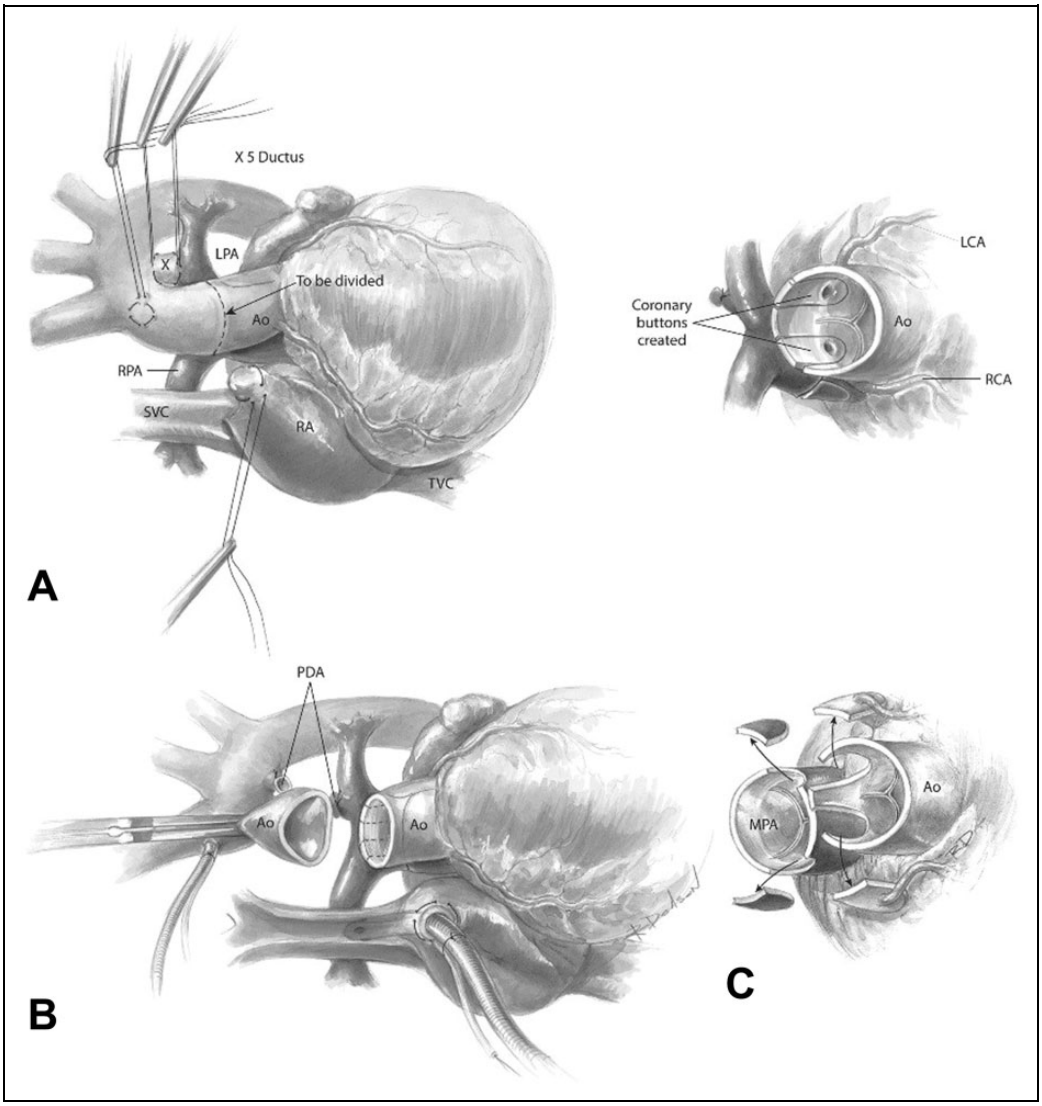

Figure 1. Preliminary steps for the arterial switch procedure. A, The aortic cannulation suture is placed distally in the ascending aorta. A single venous cannula is placed through the right atrial appendage. The ductus will be suture ligated as indicated. The ascending aorta will be divided at approximately its midpoint as indicated by the dashed line. B, The ductus has been suture ligated and divided. The ascending aorta has been cross-clamped and has been divided at its midpoint. The coronary arteries will be excised as indicated. Inset: Details of excision of the coronary buttons. C, The first 2 to 4 mm of the coronary arteries have been mobilized. Appropriate U-shaped areas of tissue are excised from the proximal neoaorta guided by marking sutures that were placed before bypass was commenced.

left coronary artery at the lower most point of the button is a particularly difficult site to access. Areas and suture lines that are at greater risk of bleeding such as three-way junctions also warrant reinforcement with an additional suture. Tension should be avoided on suture lines. The cardiac anesthesia team should be highly experienced in optimizing neonatal hemostasis. This includes maintenance of the hematocrit above 25 in order to avoid dilution of platelets and coagulation factors and to minimize edema through maintenance of osmolarity.[6]

Technical Aspects of Usual Coronary Transfer

It is critically important to mark the transfer sites on the main pulmonary artery before cardiopulmonary bypass and before separating the aorta and pulmonary artery. Transfer is a simple rotation and it is not necessary to place the button either higher or lower than its original location. The button suture line must pull the ostium open and avoid creating a slit. Care should be taken to avoid rotation of the aortic anastomosis. Coronary compression must be noted if the overlying main pulmonary artery is tending to compress the coronaries. A simple tuck with a mattress suture can usually alleviate localized compression. Even usual coronaries have variability in the location of the ostia and this should be carefully noted before the buttons are harvested.

Steps in the Arterial Switch Procedure

The arterial cannula is placed distally in the ascending aorta. There is no advantage in placing it more distally in the arch. We use a single venous cannula as this will decompress both the

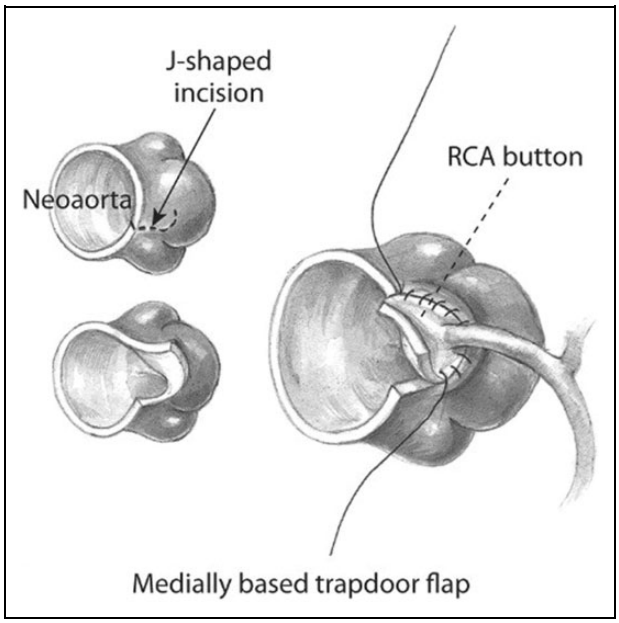

Figure 2. The medially based trapdoor flap is an alternative to excision of an U-shaped area of tissue. The flap is achieved by creation of a J-shaped incision. The trapdoor flap requires less rotation of the coronary buttons but adds to the circumference of the proximal neoaorta.

right and left atrium because of the presence of an atrial septal defect (ASD). Cooling to deep hypothermia is begun. After application of the aortic cross-clamp, a single dose of preferred cardioplegia is given as for all neonatal procedures. Division of the aorta is usually at approximately the midpoint opposite the pulmonary bifurcation (Figure 1A-C). We harvest U-shaped coronary buttons because we find that the top of the "U" is helpful for handling and orientation (Figure 1C). The main pulmonary artery is divided sufficiently distally to allow U-shaped areas to be excised above the neoaortic valve. A key point to remember about transposition is that the subaortic conus will usually raise the sinuses of the original aortic valve above the level of the neoaortic valve. Thus, the new level of implantation should not be in the sinuses of Valsalva but should be above the sinotubular junction. We rarely use medially based trapdoor flaps as these increase the mismatch between the proximal and distal neoaorta. However, on occasion where the location of the coronary implant site can result in excessive rotation of the button, it may be helpful to use a medially based trapdoor flap (Figure 2).

The Lecompte maneuver brings the pulmonary bifurcation anterior to the ascending aorta (Figure 3). Double suture ligation and division of the ductus should be completed immediately after going on bypass and should be done with great care as the tissue can be fragile. (If there is bleeding, it is generally advisable to control the aortic end of the ductus gently with forceps while cooling and then to reduce flow to a very low rate for a minute or two while an accurate suture is placed that will not injure the recurrent laryngeal nerve.) Ductal division and mobilization of the branch pulmonary arteries into the first generation hilar branches on both the right and left are essential maneuvers to minimize tension on the pulmonary artery anastomosis. The coronary donor areas are filled with a bifurcated autologous pericardial patch that is quite a bit larger than the buttons that were excised. This patch should be thought of as enlarging the neopulmonary anastomosis and helping to achieve a better match of the proximal neopulmonary artery and distal pulmonary artery. As noted above, the redundancy of the pericardial patch may result in compression of an anteriorly placed coronary artery. However, a tuck that lifts the pericardial patch off the coronary artery is usually adequate to avoid ongoing coronary compression.

The ASD is closed during a brief period of circulatory arrest of six to seven minutes. The aortic cross-clamp is released and perfusion of the myocardium is carefully observed. The pulmonary anastomosis is undertaken as warming is begun. A left atrial monitoring line is routine.

Difficult Coronary Arteries

Intramural coronary arteries. Intramural coronary arteries can usually be managed by splitting between the ostia and raising a large button (Figure 4). This frequently necessitates release of the commissure of the neopulmonary valve that may overlie the intramural segment of the coronary artery. We have generally avoided unroofing the intramural segment, though some believe that this is important.

Difficult single coronary arteries. Any situation where much of the left ventricle is supplied by a coronary artery that passes behind the main pulmonary artery can present a challenge. This is particularly true when there is a single right-sided coronary artery where the left main coronary artery itself passes behind the pulmonary artery. We experienced a feedback loop early in our experience where ischemia of the left ventricle led to left ventricular dilation and further tension on the left main coronary artery. However, this is generally easily dealt with by mobilizing the longer segment of the left coronary artery. Modern bypass techniques also minimize the edema that frequently contributed to this feedback loop in the early years of the arterial switch procedure. Use of a very low hematocrit was a particularly important factor that resulted in excessive ventricular edema.

One other form of single coronary artery that can be challenging is the anteriorly placed single coronary artery with the right main coronary branch runs directly away from the line of transfer (Figure 5). In general, mobilization of a longer segment than usual of the coronary artery will facilitate direct transfer. However, on occasion we have constructed a very short (3-4 mm) autologous pericardial tube that is 3 to 4 mm in diameter as an extension to relieve tension on the coronary arteries.

Surgical Mentoring With Specific Reference to Teaching the Arterial Switch Operation

Teaching the technical skills and judgment required to successfully undertake the arterial switch or any other

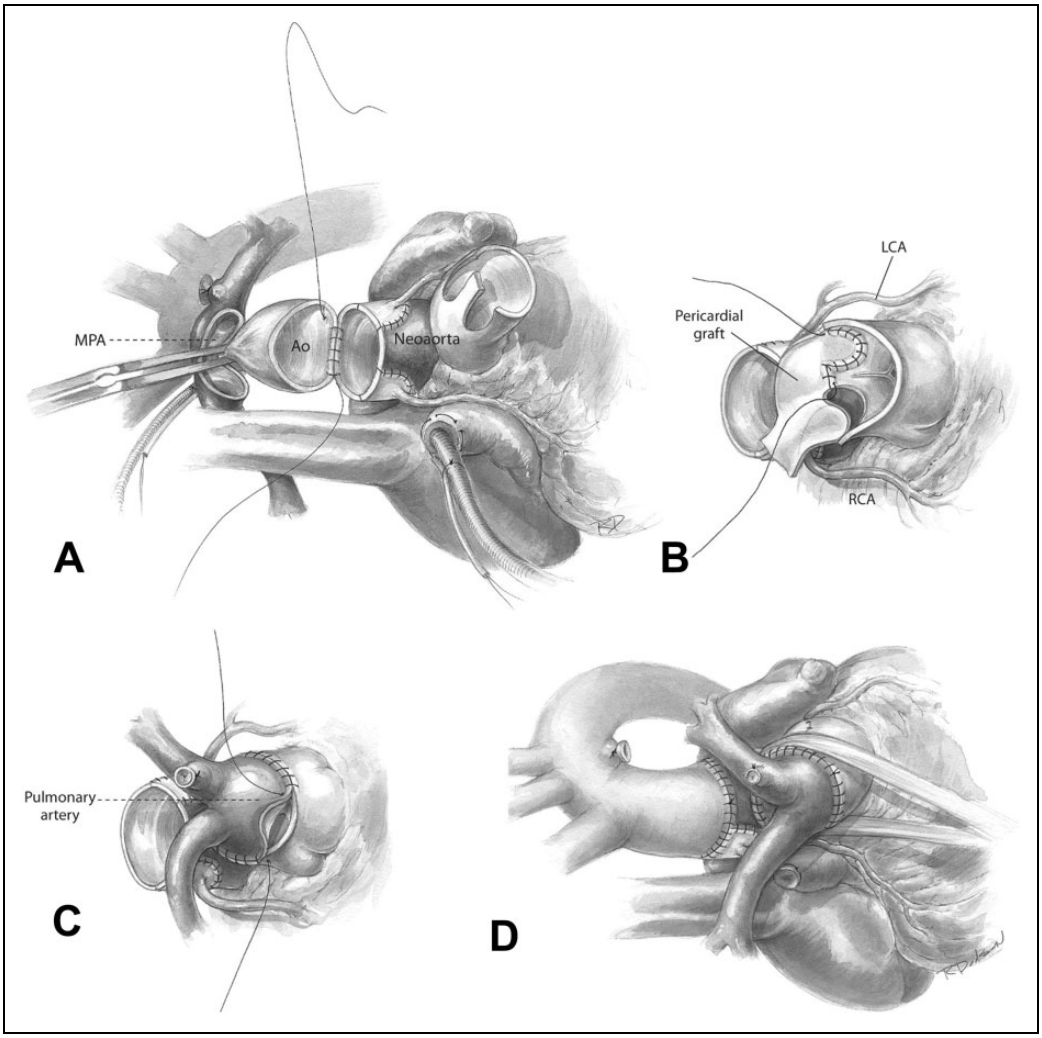

Figure 3. A, After completion of the coronary suture line, the aortic anastomosis is fashioned using continuous 6/0 Prolene. The points of junction with the coronary suture lines are reinforced with mattress sutures. B, The coronary donor areas are filled with a single bifurcated patch of autologous pericardium lightly treated with glutaraldehyde. C, The pulmonary anastomosis is fashioned following release of the aortic cross-clamp. A continuous suture technique is employed. D, The completed arterial switch procedure.

procedure is just one small component of surgical training. The American College of Surgeons and other training organizations such as the Australasian College of Surgeons have emphasized the importance of the trainee achieving competence in many different professional areas. The nine areas of competence emphasized for trainees by the Australasian College are laid out in Table 1.

Textbook Learning

The surgical mentor should assist the trainee in identifying a surgical textbook that comes closest to describing the points that the mentor considers important in learning a specific surgical procedure. This was the most important rationale for this author in writing his own surgical textbook "*Comprehensive Surgical Management of Congenital Heart Disease*."[7] As noted above, the second edition has the additional advantage of surgical videos. The audio commentary that accompanies each edited video states the same points that will be emphasized in the Operating Room (OR) during the procedure itself.

Internet Accessible and Recordable Comprehensive OR Video Monitoring

Having an Internet accessible video monitoring system is a great advantage in supervising trainees in the current era. The system at Children's National Medical Center in Washington, DC includes four different screens that can be viewed online within the hospital. It is heavily utilized by not only the supervising surgeon who can follow the preparation of the patient before a procedure including the patient's hemodynamic stability, but in addition, the system is used frequently by the cardiology team responsible for routine intraoperative transesophageal echocardiography as well as the anesthesia

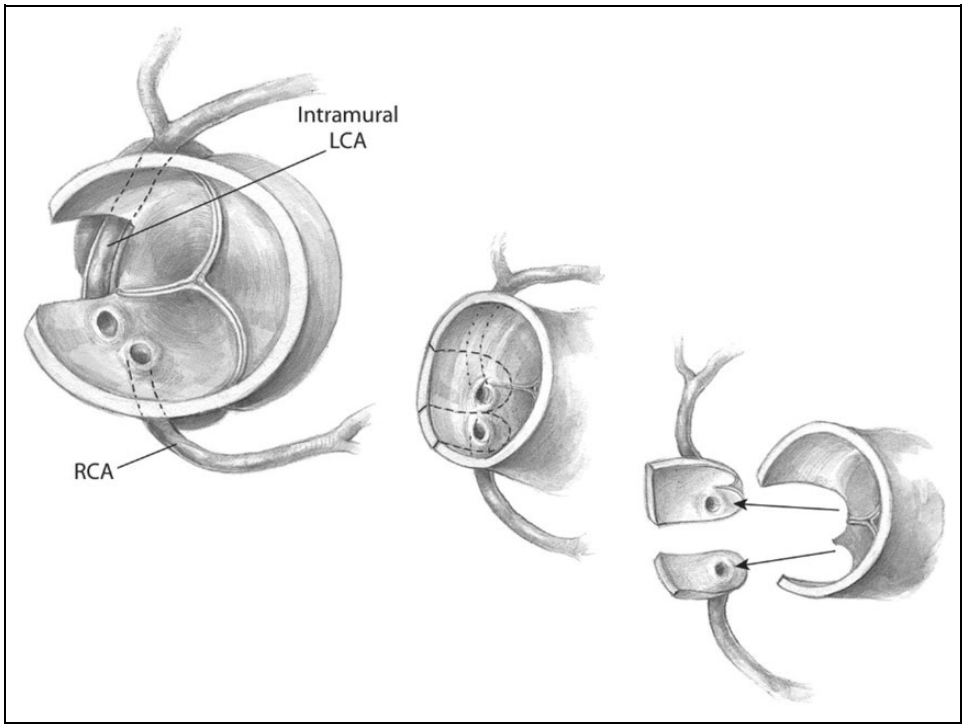

Figure 4. The most common form of intramural coronary artery is a left main coronary artery which has its ostium in the right posterior facing sinus with the coronary vessel itself emerging externally from the left posterior facing sinus. The intramural segment of the artery frequently passes behind the top of the posterior commissure of the coronary aortic valve. The inset demonstrates that the intramural coronary artery is usually best dealt with by separating the two closely spaced coronary ostia and excising a larger than usual left coronary button often with detachment of the posterior commissure of the neopulmonary valve.

attending and fellow who are able to follow the progress of the procedure. The system includes a steerable operating room camera that enables members of the nursing, perfusion, anesthesia, and surgical team to be recognized, a hemodynamic monitoring screen that contains all of the same information as the principal monitor within the operating room, and an overhead camera within the OR surgical light as well as a headlight camera that is routinely worn by the fellow who will be instructed in the procedure. The system has recording capability enabling the fellow to view his or her performance after the procedure.

The End of the Halstead Tradition

The Halstead tradition of "see one, do one, teach one" was widely applied in the 1970s and 1980s when current senior-level surgeons were undertaking their training. This "method" was in many ways a reflection of the inadequate manpower of the time as the extremely rapid expansion of cardiac surgery following the introduction of coronary artery surgery had significantly outstripped the number of individuals available to undertake procedures. The extremely high volume of cases undertaken by trainees in that era combined with unrestricted work hours led to very rapid learning of necessary skills. It was truly a case of sink or swim so that trainees who had difficulty coping with the Halsted method simply did not remain within the field.

In the new era, not only restricted duty hours but in addition a reduced number of straightforward cases of acquired heart disease following the introduction of percutaneous catheter methods as well as increased scrutiny of outcomes at many levels have all contributed to ending the Halstead tradition. In its place is a more rational learning system that allows trainees to progress at a personal pace that is appropriate for their own rate of surgical development. Some individuals have labeled this method the "Zwisch model" following its description by Dr Zwischenberger, Chairman of the Department of Surgery and Surgeon-in-Chief at the University of Kentucky.[8] Table 2 shows the four main stages of the Zwisch model including the attending surgeon role and the resident learner role at progressive levels of training.

Feedback for Fellows

It is helpful for surgical trainees to have regular feedback from the attending staff regarding their personal performance. In Washington, DC, we find that a good time for these two-way discussions is on Saturday mornings when the fellow on duty presents cases to the attending staff. These meetings also include a review of the Society of Thoracic Surgery (STS) database entries for the cases performed during the previous week. It is an opportunity for the fellow to ask questions without the pressure of peers being present. In addition, honest feedback can be provided to the fellows regarding their

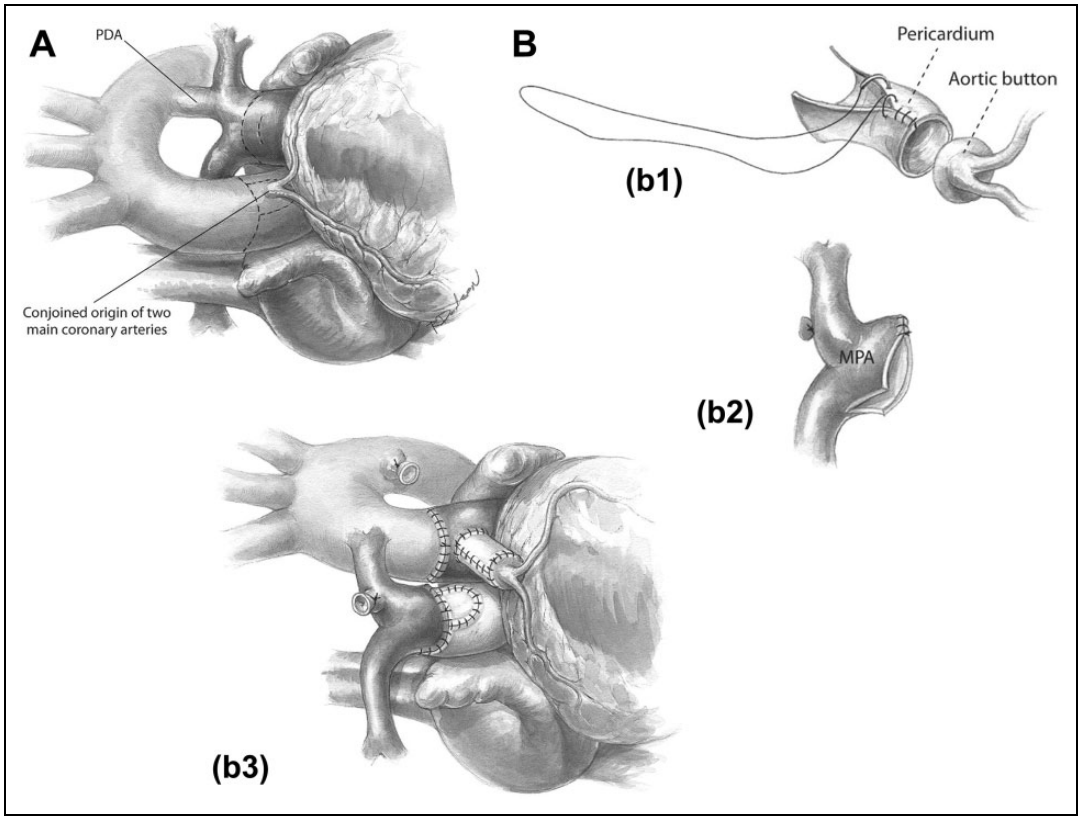

Figure 5. Single coronary artery from the left anterior facing sinus. A, The single coronary pattern is usually found with side-by-side great arteries. The dashed lines indicate incisions for division of the main pulmonary artery and aorta as well as excision of the single coronary button. B, If direct coronary implantation results in excessive tension on the right coronary artery despite extensive mobilization, a tube of autologous pericardium should be created and used for extension of the single coronary artery. The inset above (b1) demonstrates creation of an autologous pericardial tube. The inset below (b2) demonstrates that it is often helpful to shift the pulmonary anastomosis rightward in order to prevent compression of the transferred single coronary artery by the main pulmonary artery. (b3) illustrates the completed procedure including the pericardial tube extension.

Table 1. The Nine Areas of Competence Emphasized for Trainees by the Royal Australasian College of Surgeons.

The Goal of Surgical Training: Competence in All Nine Areas
Medical expertise
Technical expertise
Judgment—clinical decision-making
Professionalism and ethics
Health advocacy
Communication
Collaboration and teamwork
Management and leadership
Scholarship and teaching

performance in the operating room as well as outside of the operating room. It is also an opportunity to review the fellow's progress with clinical research activities. In keeping with the nine areas of competence, mentoring advice can be provided regarding interpersonal issues that may have arisen with intensive care or OR staff and nurses. On occasion, there can be discussion at this time regarding longer term career planning goals. Similar advice can be helpful for junior attending staff who need to be mentored in their early years of independent operating after the brief exposure to congenital surgery that is afforded by a one-year Accreditation Council for Graduate Medical Education (ACGME) fellowship. A graduate of an ACGME program should ideally seek a position in a program where such support is going to be available from a senior mentor for at least three to four years.

Simulation for Surgical Training

Three-dimensional (3-D) printing is emerging as a useful method for surgical simulation. Early 3-D printers used polymers that were not suitable for direct surgical simulation. However, newer polymers are being developed that allow the trainee to be guided realistically through complex operations such as the arterial switch, interrupted aortic arch, and truncus arteriosus.[9,10] Currently, these models are most suited for extracardiac procedures such as those described, but with further refinement, it is likely that intracardiac procedures such as baffling and muscle bundle resection will be feasible.

Three-dimensional models have proven to be helpful in educating nursing and paramedical staff about surgical procedures. Simulation in the intensive care unit is also an excellent method for guiding trainees in emergency procedures such as

Table 2. The Four Main Stages of the Zwisch Model Including the Attending Surgeon Role and the Resident Learner Role at Progressive Levels of Training Surgery.

Zwisch Stage	Attending Surgeon Behaviors	Resident Learner Behaviors
Show and tell	Performs key portions of procedure	Performs opening and closing of procedure
	Narrates the case ("thinks out loud")	Acts as first assistant and observes procedure
	Demonstrates key steps and anatomy	
Smart help	Shifts roles between surgeon and first assistant	Shifts roles between surgeon and first assistant
	When first assisting, leads resident in surgeon role	Demonstrates increasing ability to perform key steps of procedure with attending assistance
	Optimizes the field and exposure	
	Coaches on next step of procedure	Is knowledgeable of all component technical skills
Dumb help	Follows lead of resident	Accomplishes the next step of the procedure with increasing efficiency
	Coaches regarding refinement of technical skills	Recognizes critical transition point issues
No help	Provides no unsolicited advice	Performs the procedure with an experienced first assistant
	Monitors progress	Safely completes the procedure without faculty
	Ensures patient safety (as during all steps)	Recovers from most errors
		Recognizes when to ask for help or advice

extracorporeal membrane oxygenation cannulation or even cardiopulmonary resuscitation and emergency reopening of a sternotomy in the setting of tamponade.[11] A comprehensive video monitoring system within the intensive care unit that is coordinated with hemodynamic monitoring is extremely helpful.

Training Advanced Fellows in Complex Neonatal Procedures

The contraction of coronary artery surgery and more recently aortic valve surgery following the introduction of catheter methods has been associated with reduced interest in training in the United States in general cardiothoracic surgery. Many training programs have closed throughout the United States over the last 10 years including all three programs that were active in the greater Washington area 20 years ago. However, the demographics of the "baby boom" population are resulting in a rapid expansion of the population of patients who are likely to require cardiac surgery. This fact combined with a reduced number of US cardiothoracic graduates is likely to lead to a shortage of both general cardiothoracic surgeons and ultimately congenital cardiac surgeons.[12] Many programs have adapted to the reduced number of trainees through hiring of surgical support staff including physician assistants, nurse practitioners, and a larger number of recent graduates as junior attendings. At Children's National in Washington, DC, we have found that training international fellows is a win-win for both the trainees and our program. Cardiac surgery is rapidly expanding in India and China in particular. Many trainees in these countries have limited opportunities to participate in the ultracomplex neonatal surgery that is a large component of practice in the United States. These trainees on arrival in the United States are generally already accomplished microvascular surgeons who have overcome the numerous visa and licensing hurdles in order to be able to practice as an international medical graduate in the United States. These many hurdles and how to navigate them are laid out in Chapter 2 of the second edition of the author's textbook.[13]

Conclusion

The arterial switch procedure is a technically reproducible operation that involves less 3-D judgment and fewer difficult sequencing decisions than many other complex cardiac procedures. Hemostasis is the most important principle that must be adhered to mainly through meticulous surgical technique. Meticulous technique will also lead to successful transfer of the coronary arteries.

The arterial switch procedure is not a difficult operation to teach to a technically competent trainee who should already have acquired comprehensive microvascular skills before undertaking this procedure as the operating surgeon.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

References

1. Jatene AD, Fontes VF, Paulista PP, et al. Anatomic correction of transposition of the great vessels. *J Thorac Cardiovasc Surg*. 1976;72(3): 364-370.
2. Yacoub MH, Radley-Smith R, Maclaurin R. Two stage operation for anatomical correction of transposition of the great arteries with intact ventricular septum. *Lancet*. 1977;1(8025): 1275-1278.
3. Castaneda AR, Norwood WI, Jonas RA, et al. Transposition of the great arteries and intact ventricular septum: anatomical repair in the neonate. *Ann Thorac Surg*. 1984;38(5): 438-443.
4. Lecompte Y, Neveux JY, Leca F, et al. Reconstruction of the pulmonary outflow tract without prosthetic conduit. *J Thorac Cardiovasc Surg*. 1982;84(5): 727-733.
5. Jonas RA. *Transposition of the Great Arteries in Comprehensive Surgical Management of Congenital Heart Disease*. 2nd ed. London, England: Taylor & Francis; 2014:371-394.

6. Jonas RA. *Surgical Technique and Hemostasis in Comprehensive Surgical Management of Congenital Heart Disease*. 2nd ed. London, England: Taylor & Francis; 2014:243-244.
7. Jonas RA. *Comprehensive Surgical Management of Congenital Heart Disease*. 2nd ed. London, England: Taylor & Francis; 2014.
8. DaRosa DA, Zwischenberger JB, Meyerson SL, et al. A theory-based model for teaching and assessing residents in the operating room. *J Surg Educ*. 2013;70(1): 24-30.
9. Yoo SJ, Spray T, Austin EH III, Yun TJ, van Arsdell GS. Hands-on surgical training of congenital heart surgery using 3-dimensional print models. *J Thorac Cardiovasc Surg*. 2017; 153(6): 1530-1540.
10. Costello JP, Olivieri LJ, Krieger A, et al. Utilizing three-dimensional printing technology to assess the feasibility of high-fidelity synthetic ventricular septal defect models for simulation in medical education. *World J Pediatr Congenit Heart Surg*. 2014;5(3): 421-426.
11. Su L, Spaeder MC, Jones MB, et al. Implementation of an extracorporeal cardiopulmonary resuscitation simulation program reduces extracorporeal cardiopulmonary resuscitation times in real patients. *Pediatr Crit Care Med*. 2014;15(9): 856-860.
12. Grover A, Gorman K, Dall TM, et al. Shortage of cardiothoracic surgeons is likely by 2020. *Circulation*. 2009;120(6): 488-494.
13. Jonas RA. Becoming a congenital heart surgeon: training and certification, and visa issues for foreign medical graduates. In: *Comprehensive Surgical Management of Congenital Heart Disease*. 2nd ed. London, England: Taylor & Francis; 2014:9-18.