Minimally invasive paediatric cardiac surgery

Emile Bacha and David Kalfa

Abstract | The concept of minimally invasive surgery for congenital heart disease in paediatric patients is broad, and has the aim of reducing the trauma of the operation at each stage of management. Firstly, in the operating room using minimally invasive incisions, video-assisted thoracoscopic and robotically assisted surgery, hybrid procedures, image-guided intracardiac surgery, and minimally invasive cardiopulmonary bypass strategies. Secondly, in the intensive-care unit with neuroprotection and 'fast-tracking' strategies that involve early extubation, early hospital discharge, and less exposure to transfused blood products. Thirdly, during postoperative mid-term and long-term follow-up by providing the children and their families with adequate support after hospital discharge. Improvement of these strategies relies on the development of new devices, real-time multimodality imaging, aids to instrument navigation, miniaturized and specialized instrumentation, robotic technology, and computer-assisted modelling of flow dynamics and tissue mechanics. In addition, dedicated multidisciplinary co-ordinated teams involving congenital cardiac surgeons, perfusionists, intensivists, anaesthesiologists, cardiologists, nurses, psychologists, and counsellors are needed before, during, and after surgery to go beyond apparent technological and medical limitations with the goal to 'treat more while hurting less'.

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Introduction

Minimally invasive surgery for congenital heart disease in paediatric patients, in a traditional sense, refers to therapeutic approaches designed specifically to minimize physical trauma associated with surgery and thereby maximize the likelihood of rapid recovery with minimal morbidity. Many such approaches are possible owing to technological innovation. Importantly, however, the trauma associated with surgery is not only physical but can also cause both emotional stress and altered neurodevelopmental outcomes. Therefore, strategies designed to prevent or minimize such phenomena can be considered to be within the broad concept of minimally invasive surgery.

The median sternotomy has long been considered to be the only surgical approach to the heart, offering complete visualization of all cardiac structures, ease of cannulation, and fast diagnosis and treatment of procedural complications. From the 1990s onwards, innovation in medical devices, multimodality imaging, and operative instruments, as well as the strong desire of patients and their parents for less-invasive surgical procedures led to the development of minimally invasive surgery for congenital heart disease. These procedures, which involve smaller incisions, were designed to produce better cosmetic results, and to reduce rehabilitation time and pain when compared with traditional open heart surgery. The primary aim of minimally invasive paediatric cardiac surgery is to reduce the trauma of an operation at each stage of congenital heart disease management. This broad concept decreases the overall use and duration of cardiopulmonary bypass and the impact of its adverse effects; improves perioperative neuroprotection; and has led to the development of new image-guided cardiac surgical procedures; optimizing fast-tracking strategies with early extubation, mobilization, and hospital discharge; and provision of adequate cardiac and extracardiac support after surgery.

The objective of this Review is to introduce the concept of the minimally invasive approach towards surgery for children with congenital heart disease, and provide a broad overview of multiple techniques, including minimally invasive sternal-sparing incisions, video-assisted thoracoscopic surgery (VATS), robotically assisted surgery (RAS), hybrid procedures, minimization of the effects of cardiopulmonary bypass, and other specific 'trauma-sparing' strategies in the operating room, intensive-care unit, and after hospital discharge.

Minimally invasive incisions

Midline sternal-sparing approaches

In the 1990s, concomitant with the advent of improvements in sternal retractors and cannulae, as well as competition from catheterization-based percutaneous procedures, several authors proposed repairing simple congenital heart defects (typically atrial septal defects) via a 'mini sternotomy' or partial sternotomy (Figure 1). This approach is the most-commonly used incision for a minimally-invasive approach in paediatric cardiac surgery.[1,2] As surgeons became increasingly comfortable with 'key-hole' surgery for atrial septal defects, the partial lower or upper sternotomy began to be used for closure

Department of Paediatric and Congenital Cardiac Surgery, Morgan Stanley Children's Hospital of New York-Presbyterian, Columbia University Medical Centre, 3959 Broadway, New York, NY 10032, USA (**E. Bacha, D. Kalfa**).

Correspondence to: E. Bacha eb2709@columbia.edu

Competing interests
The authors declare no competing interests.

Key points

- Minimally invasive surgery for congenital heart disease in paediatric patients is a broad concept; the aim is to reduce the trauma of the operation at each stage of management
- Minimally invasive incisions produce better cosmetic results, and reduce rehabilitation time and pain when compared with traditional open heart surgery
- Minimally invasive incisions and cardiopulmonary bypass strategies, video-assisted thoracoscopic surgery, robotically assisted surgery, hybrid procedures, and image-guided intracardiac surgery have been developed
- Improvement of these minimally invasive strategies relies on the development of new devices, real-time multimodality imaging, and aids to instrument navigation
- Reducing global trauma and morbidity related to surgery requires a multidisciplinary co-ordinated approach involving congenital cardiac surgeons, perfusionists, anaesthesiologists, intensivists, cardiologists, and nurses
- The goal of the team dedicated to minimally invasive paediatric cardiac surgery is to go beyond technological and medical limitations to 'treat more while hurting less'

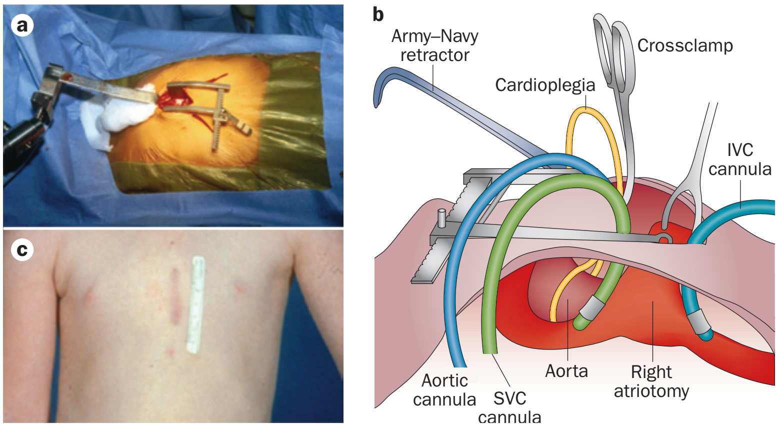

Figure 1 | The lower partial (or 'mini') sternotomy. **a** | The procedure starts with a 2–3 cm midline incision over the xyphoid process and lower sternum. Only the lower third to half of the sternum is opened. The fact that the manubrium and upper sternum is left undisturbed provides an added level of robustness to the sternal closure, beyond the cosmetic benefit of a small incision. **b** | Parasagittal cutaway view of subxiphoid incision showing cephalad retraction of the sternum, bicaval and aortic cannulas, cardioplegia, and aortic cross-clamp through the incision. **c** | The healed partial lower sternotomy scar in a patient after tetralogy of Fallot repair. Part b reprinted from *Ann. Thorac. Surg.* **70**(1), Bichell, D. P. *et al.*, Minimal access approach for the repair of atrial septal defect: the initial 135 patients, 115–118, © (2000), with permission from Elsevier. Abbreviations: IVC, inferior vena cava; SVC, superior vena cava.

of ventricular septal defects,[3] tetralogy of Fallot (ToF) correction, mitral valve repair, and even arterial switch operations.[4] In addition to the cosmetic advantage of a smaller incision, the partial sternotomy was also found to promote a substantially earlier return to normal life, including physical activities such as gymnastics.[5] These improvements in recovery reflect the fact that the upper sternum (manubrium) is not divided during minimally invasive surgery, thus allowing the entire upper thoracic clavicular–sternal joint area to remain undisturbed, as opposed to being stretched during a full sternotomy. We now use a partial lower sternotomy in the majority of our patients, irrespective of age, attempting to leave at least a few millimetres of sternum intact at the cranial top to improve alignment of the sternal halves and promote sternal healing (D. Kalfa & E. Bacha, unpublished work).

Some surgeons have criticized the partial sternotomy approach,[6,7] citing reduced exposure of essential structures, such as the ascending aorta, as the primary disadvantage. Indeed, this issue is the Achilles' heel of the partial sternotomy, and some surgeons have resorted to femoral cannulation, which is not indicated in young children, owing to the high likelihood of femoral vessel injury.[8] However, the majority of surgeons have now become comfortable cannulating the ascending aorta centrally, using strategically placed pericardial stay sutures to improve visualization.

Importantly, the partial lower sternotomy is best performed in young children, owing to their rib cages being less bony and more cartilaginous than those of older children and, therefore, easier to retract and the cardiovascular structures easier to expose with shorter incisions. Furthermore, the heart is closer to the sternum in young children, thus facilitating manipulations. The younger the child, the better the exposure—the partial lower sternotomy is almost impossible to perform in adults. We, therefore, now recommend closure of atrial septal defects before the age of 2 years as opposed to before the traditionally recommended age of 5 years in asymptomatic children.

Mini thoracotomy and axillary approach

The right anterolateral thoracotomy or right submammary incision (Figure 2) was initially used in adolescent and adult women for cosmetic reasons, and has steadily gained popularity to treat congenital heart disease thanks to the combination of good cosmetic and functional results.[9–12] Lesions repaired using this approach are typically right-sided defects such as atrial septal and ventricular septal defects of all types and tricuspid valve anomalies. A right vertical infra-axillary thoracotomy (Figure 3) or a right posterolateral thoracotomy is also used for some of these defects.[13–15] The disadvantage of this incision includes less control of cardiovascular structures as the heart is further away from the incision.

Paediatric cardiac surgeons benefited from the experience gained by their adult surgery colleagues in performing 'mini mitral surgery',[16] and the operative set-up for right anterolateral thoracotomy is typically the same. Owing to the risk of damage to the mammary gland in prepubescent females, this approach is typically reserved for postpubescent females where the location of the mammary gland is known, and a submammary incision can be made. A study of this approach in prepubescent girls demonstrated significant asymmetrical breast development in only 5% of patients, and a 98% satisfaction rate for the cosmetic result.[17] However, we believe that a 5% rate of asymmetrical breast development is unacceptable, when a small incision could have been made over the xyphoid process with no damage to the breast tissue. We generally prefer central cannulation over peripheral cannulation if possible.

Video-assisted thoracoscopic surgery

The incisions discussed above represented the first steps in the development of minimally invasive cardiac surgery in children. These incisions reduced the duration

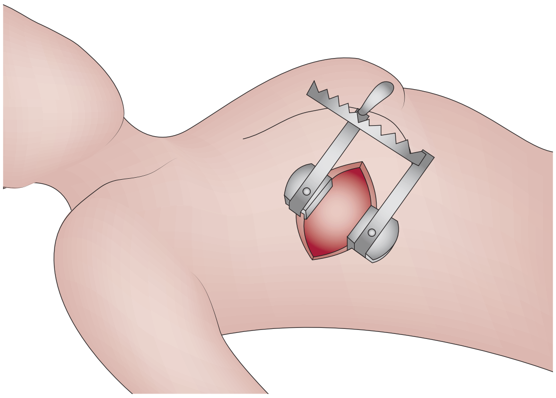

Figure 2 | A right submammary incision (also called right anterolateral thoracotomy). This cosmetic incision is mostly applied in women with developed breasts.

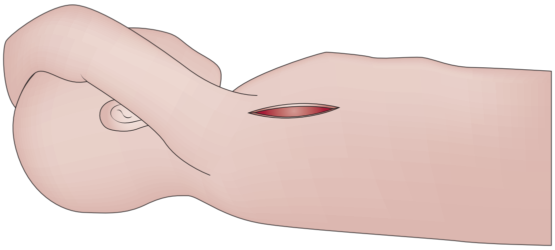

Figure 3 | The position of the incision in the right vertical infra-axillary thoracotomy.

of hospital stay, promote earlier recovery of school and physical activities, reduce postoperative pain, and improve cosmetic outcomes.[18] Nevertheless, in young children, thoracotomy-based approaches have been associated with long-term morbidities such as scoliosis, shoulder girdle abnormalities, chest wall asymmetry, winged scapula, chronic pain syndromes, and breast deformities.[19,20] To address these issues, VATS (Figure 4) has been used in children with congenital extracardiac or intracardiac lesions.

Extracardiac VATS procedures

Extracardiac procedures are performed through multiple, 2–4 mm intercostal incisions known as thoracostomies, which avoids the division of large muscle groups.

Patent ductus arteriosus ligation

In 1991, Laborde *et al.* successfully ligated a patent ductus arteriosus (PDA) with a titanium clip during a VATS procedure.[21] During this procedure, three or four intercostal muscle-splitting thoracostomies are used to introduce the videoscope, a lung retractor, operating instruments, and electrocautery. PDAs >1 cm are first ligated with endoscopic knot-tying techniques before application of the titanium clip. Laborde's group have now reported the technique in >700 children with a mean operative time of 20 min and no deaths.[22] Other groups have reported excellent results for this procedure, sometimes in premature infants with a body weight as low as 575 g, with no residual shunt documented at 5 years of follow-up, very rare or no complications (transient recurrent laryngeal nerve palsy, chylothorax), and a short duration of hospital stay (generally 1 day for elective procedures).[23–28]

Division of vascular ring

Vascular ring describes the abnormal formation of the aorta or adjacent vessels, which encircle and compress the trachea and oesophagus. The VATS technique to treat vascular ring is the same as for PDA ligation. Division of vascular ring can be safely performed by VATS when at least one element of the ring is not patent. Typically, this would be a double aortic arch with an atretic left segment or a right aortic arch, aberrant left subclavian artery, and left-sided ligamentum arteriosum.[29,30] We do not recommend a VATS division when the segment of the ring to be divided is patent, as vascular control of the aorta is required, which is difficult to perform safely with thoracoscopic techniques. Burke *et al.* reported successful VATS division of vascular ring in eight children (aged 40 days to 5.5 years) with excellent results, no deaths, and one case of chylothorax.[29]

Other extracardiac VATS procedures

VATS principles have been applied to many other simple extracardiac procedures in children with congenital heart disease,[18] such as ligation of systemic-to-pulmonary artery collaterals, venous collaterals,[31] azygous vein, thoracic duct, creation of pericardial window, aortopexy, diaphragm plication,[32] or placement of permanent epicardial pacemaker leads. These examples represent rare cases, however, and no reliable outcome data for these procedures are available.

Intracardiac VATS procedures

VATS principles have also been applied to procedures for intracardiac congenital defects in paediatric patients. Only children older than 2 years of age with atrial or ventricular septal defects have benefited from these techniques so far.[33] VATS repair of these anomalies requires modification of cardiopulmonary bypass and myocardial protection strategies, in that femoral cannulation is typically necessary to initiate bypass and myocardial protection can be performed using either ventricular fibrillation or aortic clamping and cardioplegic arrest. The aorta can be clamped with a standard instrument through a thoracostomy or a limited thoracotomy. Adolescents can also benefit from an endovascular aortic occluder, placed under TEE guidance.[34] Totally thoracoscopic repair of atrial and ventricular septal defects, without the use of robotics, in children avoids the complexity and the high financial burden related to robotically associated surgical procedures, particularly in developing countries.[33]

Closure of atrial septal defects

Several groups in China have demonstrated the feasibility of totally thoracoscopic repair of atrial septal defects, without the use of robotics, in a series that included children and adults.[35–37] The youngest child was aged 6 years. Cardiopulmonary bypass was achieved peripherally and closure of the defect was performed through three ports. Although the technique was demonstrated

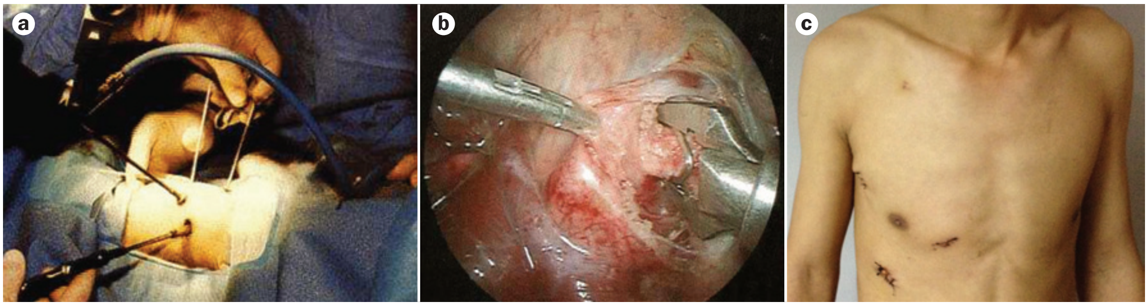

Figure 4 | Video-assisted thoracoscopic surgery. **a** | Operative set-up of video-assisted thoracoscopic surgical closure of a patent ductus arteriosus. **b** | Intraoperative view: a clip is applied to the patent ductus arteriosus. **c** | Postoperative photograph showing minimal scarring. Part c reproduced from Liu, G. *et al.* Totally thoracoscopic surgery for the treatment of atrial septal defect without of the robotic Da Vinci surgical system. *J. Cardiothorac. Surg.* doi:10.1186/1749-8090-8-119 © 2013.

to be safe, it remains essentially unused in Western countries, where most patients would undergo closure of an atrial septal defect at a much earlier age, typically before starting school. A study by Wang *et al.* published in 2011 showed that this technique can be extended to a younger population, with a mean age of 5.8 years.[38]

In 2012, another group from China showed the feasibility and safety of nonrobotically assisted VATS closure of atrial septal defects on perfused beating hearts in a series of 24 patients (mean age 14.4 ± 18.7; range: 8–45 years).[39] A large perfusion needle was inserted into the root of the aorta through one of the three ports and allowed deairing of the left ventricle. The aorta, which was not cross-clamped, was perfused through femoral cannulation with normothermic oxygenated blood throughout the procedure. After right atriotomy on the beating heart, a suction tube was positioned in the coronary sinus ostium through a port to keep the operation field bloodless.[39] The major concern with this procedure is the risk of air embolization into the brain, with resultant stroke. Given the extremely high safety profile of surgery for atrial septal defects performed with cardiopulmonary bypass and cardioplegic arrest or induced ventricular fibrillation, we do not recommend that this beating heart approach should be performed widely.

Closure of ventricular septal defects

In 2011, Ma *et al.* demonstrated the feasibility and safety of totally thoracoscopic repair of ventricular septal defects in a series of 36 children[40,41] There were no deaths or major complications, and no clinically relevant residual ventricular septal defect with the thoracoscopic approach.[40,41] However, procedures performed under peripherally established cardiopulmonary bypass were associated with lactate elevation in the local (lower limb) and systemic circulation.[42] Because both atrial and ventricular septal defects can be closed via a very limited chest incision in small children using direct cannulation and suturing (as opposed to thoracoscopic suturing, which is slower), thoracoscopic approaches are less attractive, and, in our view, less safe than direct cannulation.

Cardioscopy

Cardioscopy is another video-based innovative surgical tool that allows surgeons to observe remote intracardiac structures by introducing flexible cameras in the arrested and empty heart chambers. This avoids the need to use excessive retraction, extend the chest wall incision, or add a ventricular incision, all of which can be harmful. This technique can, therefore, contribute to minimally invasive management in children undergoing cardiac surgery. Cardioscopy has been reported to simplify difficult-to-expose mitral valve repair, allow closure of remote muscular ventricular septal defects, assist in the initial placement and replacement of septal occlusion devices, and facilitate removal of left ventricular thrombi.[18,43]

Robotically assisted surgery

The VATS techniques discussed above represented the second step in the development of minimally invasive cardiac surgery in children. These procedures are technically demanding, and can potentially present safety issues if complications arise as a result of the limited (not open) access to the heart. In the early 2000s, robotic paediatric cardiac surgery was developed with the aim of increasing the precision of thoracoscopic surgery and facilitate VATS procedures.[44] The presence of instrumentation that replicates the actions of the human wrist, tremor abolition, and motion scaling in robotic systems was shown to enhance dexterity by nearly 50% compared with laparoscopic surgery.[45] The evolution of robotics for cardiac surgery in children was slower than in the adult patient population, particularly for intracardiac procedures for several reasons. First, the smaller thoracic cavity and narrower intercostal space in children increases the risk of contact between instruments during surgery. Second, cardiopulmonary bypass in paediatric patients is challenging. Third, the ischaemic time is prolonged as a result of the increased time required for suturing in children. Moreover, the large size of current robotic systems have limited the extent to which this technology can be used in small children.[46] This issue has been partly addressed by the new generation of the Da Vinci® (Intuitive Surgical, Inc., Sunnyvale, CA, USA) surgical system, which uses portholes of 5–8 mm as compared with earlier versions for which the portholes were 10 mm. Despite these technical difficulties, however, some groups have performed RAS in children for both extracardiac and intracardiac lesions.

Extracardiac RAS procedures

In 2002, Le Bret *et al.* were the first to demonstrate the feasibility, safety, and efficiency of RAS closure of PDA in children ($n=28$).[47] Compared with the standard VATS technique ($n=28$), the RAS procedure required a longer operative time, which was probably related to a learning curve. The researchers concluded that a robotic approach for PDA closure in children has no particular advantage over the VATS technique.[47]

In 2003, a group from Boston (MA, USA) showed that robotic surgical systems could offer substantial advantages in terms of safety.[48] Mihaljevic *et al.* reported successful RAS division of a vascular ring in two children—one aged 8 years and one aged 10 years. No complications occurred and the duration of hospital stay was shorter compared with conventional open-heart surgery. The investigators maintained that the robotic system had advantages over standard surgical techniques in terms of enhanced intracorporeal dexterity, optimized hand-eye alignment, and tremor filtering that facilitated tissue handling and dissection.[48]

Intracardiac RAS procedures

Until the mid-2000s, intracardiac RAS procedures were limited to adult patients. Between 2006 and 2008, several groups reported robotically assisted totally endoscopic repair of atrial septal defects in various series that included adolescent patients (age range 12–61 years).[49,50] Typically, the procedure is performed using peripheral cardiopulmonary bypass, transthoracic aortic occlusion, anterograde cardioplegia, four port incisions, and a 2.0–2.5 cm working port. The conclusion in all three of these studies was that the RAS procedure had reproducible value and excellent cosmetic results.[49,50] Others have published case reports or small series of other procedures involving RAS, such as mitral or tricuspid valve repair and sinus venosus atrial septal defect repair.[51,52]

Research on RAS-enabled intracardiac repairs on the beating heart in children is ongoing. Theoretically, instruments could be used on the beating heart to repair a structure with no cardiopulmonary bypass support. A variety of beating-heart approaches have been assessed for the repair of intracardiac pathologies, including atrial[53,54] and ventricular[55] septal defects, and mitral valve regurgitation.[56] Del Nido and colleagues used animal models to investigate a real-time, 3D echocardiography system to visualize the heart noninvasively and to facilitate beating-heart atrial septal defect repair and mitral valve plasty.[57,58] In another study, Smeets *et al.* investigated an electromagnetic tool tracking and navigation system for beating-heart intracardiac surgical procedures in 15 patients (age range 15–78 years).[59] This group expect that new intracardiac imaging technology associated with tool-tracking systems, together with the dexterity and stability of robotic instruments, could make off-pump intracardiac repair safe and effective.[44]

At the present time, however, the future of intracardiac RAS repairs for congenital lesions is unclear. Robotic technology has not been widely accepted by paediatric cardiac surgeons, primarily owing to the high cost of this technology, the lack of paediatric size instruments, and the small chest volumes of children that limit the operative space. Robotic technology has definite advantages, however, such as superior intrathoracic range of motion, improved visualization at angles, and the cosmetic advantages of limited skin incisions. Ultimately, the field of RAS is in its infancy, and technological modifications are required before its use can become widespread. Areas for future research include reductions in instrument size, the development of sophisticated robotic wrists and small 3D endoscopes, determination of optimal port placement, improving tactile feedback, novel devices for joining tissues or anchoring surgical prostheses, visual and motion stabilization systems, and intracardiac imaging.[44]

Hybrid procedures

Hybrid procedures combine elements from both percutaneous catheterization and surgery, and are often characterized by the use of intraoperative imaging techniques on the beating heart. A close collaboration between surgeons and interventional cardiologists is, therefore, mandatory for the development of such a concept in paediatric cardiac surgery for congenital defects. Hybrid procedures are appropriate in clinical situations where neither surgery nor catheterization alone offer optimal treatment, or when the combination of both techniques reduces invasiveness.[60] An estimated 5% of procedures for congenital heart defects currently have a hybrid component.

Hybrid single-ventricle palliation

Hybrid single-ventricle palliation is intended to replace maximally invasive, Norwood stage I palliation surgery for hypoplastic left heart syndrome and other single-ventricle related anomalies. The hybrid procedure does not require cardiopulmonary bypass, and involves bilateral branch pulmonary artery bandings, ductal stenting via the main pulmonary artery purse-string, and dilatation with or without stenting of a restrictive atrial septal defect (Figure 5). All of these interventions are performed through a median sternotomy, typically in a hybrid operating room or a catheterization laboratory.[61–63] Hybrid single-ventricle palliation decreases the number of times cardiopulmonary bypass is needed before achieving complete palliation, and avoids the trauma related to a prolonged hospitalization during the neonatal period. Evidence exists that myocardial damage after heart surgery is greater in neonates than in infants.[62,64,65] In patients with anatomy suitable for biventricular repair, such as patients with borderline hypoplastic left heart syndrome, hybrid single-ventricle palliation can also enable the observation period before and after the operation to be extended to allow for left ventricular growth.[66] Caldarone *et al.* showed that a newly established hybrid programme for single-ventricle palliation provides initial results that are comparable with those obtained with a well-established Norwood programme.[67]

Potential complications with the hybrid stage I procedure are the risks of the patient developing retrograde

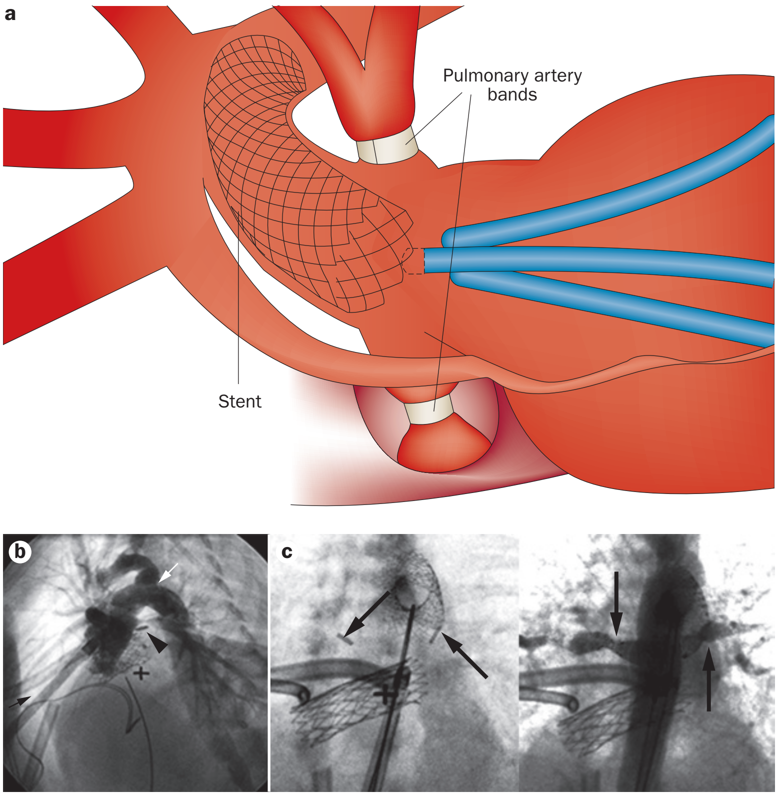

Figure 5 | The hybrid stage I procedure for hypoplastic left heart syndrome. **a** | An approach based on an off-pump median sternotomy is used, whereby bilateral pulmonary artery bands are placed first (to control the pulmonary overcirculation), and then a ductal stent is placed via a sheath inserted in the main pulmonary artery. **b** | Intraoperative angiogram showing the anatomy of a patient undergoing the hybrid stage I procedure. The black arrow indicates the sheath being introduced into the main pulmonary artery, the arrowhead shows a clip that marks the left pulmonary artery band, and the white arrow shows the isthmus, which in this case is wide open, indicating a low risk of development of retrograde coarctation. An atrial stent is already present. **c** | Imaging after placement of the ductal stent. The atrial stent is also seen. Left panel: fluoroscopy. The clips (arrows) mark the band sites. Right panel: angiography via the main pulmonary artery sheath. The banded sites (arrows) are clearly visible on each left and right branch of the pulmonary artery. Part b reprinted from *J. Thorac. Cardiovasc. Surg.*, **131**(1), Bacha, E. A. *et al.*, Single-ventricle palliation for high-risk neonates: The emergence of an alternative hybrid stage I strategy, 163–171.e2, © (2006), with permission from Elsevier. Part c reprinted from *Semin. Thorac. Cardiovasc. Surg. Paediatr. Card. Surg. Annu.*, **8**(1), Bacha, E. A. *et al.*, Hybrid procedures in paediatric cardiac surgery, 78–85, © (2005), with permission from Elsevier.

aortic coarctation[68] (Figure 6), or pulmonary artery branch stenosis,[69] the lack of antegrade blood flow to the brain only until the second stage operation,[70] and the additional surgical complexity that is introduced to the second stage of the procedure.[67] The precise indications for hybrid single-ventricle palliation compared with the conventional Norwood procedure remain unclear,[71] although the technique has been widely accepted for the treatment of neonates with high-risk morbidities, such as advanced shock, sepsis, or other contraindications to cardiopulmonary bypass (for example, head bleeding).

Hybrid procedures on the RVOT

Several procedures on the right ventricular outflow tract (RVOT), including intraoperative balloon dilatation and stenting of the pulmonary arteries, perventricular pulmonary valve implantation, and intraoperative balloon dilatation of the pulmonary valves during repair of ToF, are currently performed by paediatric cardiac surgeons using hybrid techniques.

Intraoperative balloon dilatation and stenting of the pulmonary arteries can be used to treat distal branch pulmonary artery stenosis, or to redilate a previously implanted stent. This procedure can be safely performed without cardiopulmonary bypass, via a puncture of the RVOT.[72] Intraoperative fluoroscopy, together with active suture fixation of the proximal stent, reduces the need for late reintervention.[73] One of the most technically challenging aspects of this technique is the distal positioning of the device to avoid injury to the branch pulmonary artery carina.[74–76] Butera *et al.* reported the hybrid use of cutting-balloon angioplasty in a 2-year-old girl with ToF that allowed the salvage of the left pulmonary artery.[77] Holzer *et al.* showed that using a well-equipped hybrid operating suite facilitated safe intraoperative delivery of pulmonary artery stents in patients with a wide variety of conditions and of various ages, and that close co-operation between the surgical and interventional teams was essential.[78]

Perventricular pulmonary valve implantation via direct puncture of the right ventricular apex or free wall during a surgical procedure has major advantages compared with conventional catheter-based implantation. This hybrid procedure provides direct access to the RVOT, thus avoiding potential femoral vessel injury and the complex, catheter-related intravascular manoeuvres required to cross the tricuspid valve to reach the RVOT. This hybrid technique also extends the indication for pulmonary valve implantation to patients with ToF who have undergone initial repair with a transannular patch rather than a conduit between the right ventricle and pulmonary artery. During the procedure, the previously enlarged RVOT can be downsized to the desired diameter with external sutures. This technique has been reported by a few groups, using the Shelhigh® (Millburn, NJ, USA) injectable pulmonic valve system.[60,73,79,80] In 2008, Dittrich *et al.* reported successful hybrid pulmonary valve implantation through a transverse mini thoracotomy, and injection of a self-expanding tissue valve through the main pulmonary artery, in an 8-year-old boy with ToF.[81]

During minimally invasive surgery for ToF, intraoperative balloon dilatation of the pulmonary valves can be used to relieve RVOT obstruction, while preserving some valve competency.[82] The basis for this technique is that a balloon can be introduced across the valve at a diameter smaller than the valve annulus, and expanded to a greater diameter to split the fused commissures and stretch the annulus without exposing the leaflets to axial shear forces (Figure 7).[82,83] In 2009, Burke *et al.* reported hybrid ventricular decompression in three patients with pulmonary atresia with intact septum.[84] Direct access to the right ventricle through a subxiphoid incision with transventricular sheath placement was used to provide optimum catheter position for radiofrequency perforation of membranous pulmonary atresia, followed by balloon dilation.

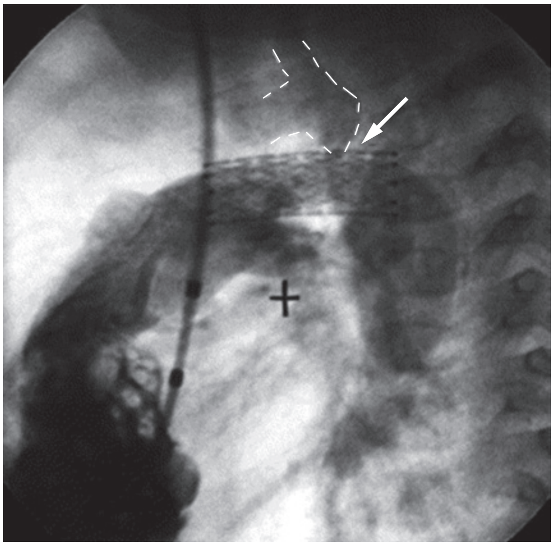

Figure 6 | Development of retrograde coarctation (white arrow) in a 3-month-old patient after a hybrid stage I procedure. The dashed line indicates the aortic arch. Reprinted from *J. Thorac. Cardiovasc. Surg.*, **131**(1), Bacha, E. A. *et al.*, Single-ventricle palliation for high-risk neonates: The emergence of an alternative hybrid stage I strategy, 163–171.e2, © (2006), with permission from Elsevier.

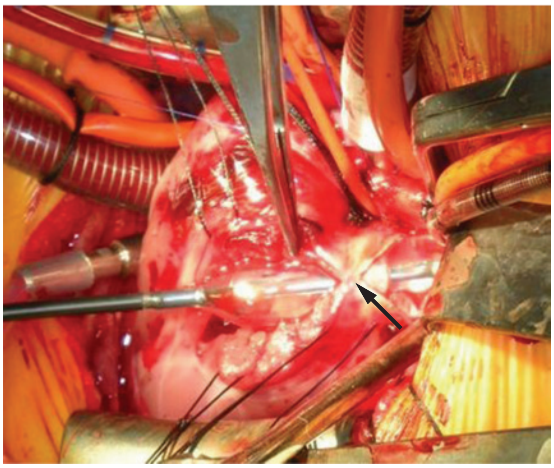

Figure 7 | Intraoperative view of a dilated balloon (arrow) placed across an intact pulmonary annulus during valve-sparing tetralogy of Fallot repair.

Hybrid closures of septal defects

Perventricular closure of ventricular septal defects is a hybrid approach using real-time transoesophageal echocardiography on a beating euvolemic heart (Figure 8).[80,85] This technique can be considered in patients with muscular ventricular septal defects that cannot be addressed using percutaneous closure, including children who have an additional cardiac defect requiring conventional surgical repair and infants weighing <5 kg.[60]

Under continuous transoesophageal echocardiographic guidance and via a median sternotomy, the right ventricle is punctured, a guide wire is passed through the ventricular septal defect to allow the progressive deployment of both disks of the closure device on the beating heart.[55,86] The main advantages of this technique over standard surgery is the real-time feedback provided by continuous transoesophageal echocardiography and the lack of cardiopulmonary bypass.[87] Complications can be related to right ventricular disk expansion in patients with right ventricular hypertrophy, entanglement of the subvalvar apparatus, and perforation of the left ventricular free wall.

Peratrial closure of atrial septal defects can also be performed using a hybrid technique. Patients suitable for this procedure are usually those with a haemodynamically relevant atrial septal defect who are not candidates for percutaneous device closure (such as low-weight premature neonates with large defects) or cardiopulmonary bypass (such as children with severe bronchopulmonary dysplasia or intraventricular haemorrhage).[85,88,89]

Other hybrid procedures

Other hybrid procedures in paediatric cardiac surgery include the use of intraoperative diagnostic angiography to diagnose potential residual haemodynamic defects after surgical repair.[60] This strategy is particularly useful in patients who need pulmonary arterioplasty, as these individuals are particularly difficult to assess with intraoperative TEE.[90]

In 2008, Schmitz *et al.* reported the hybrid implantation of isthmus stents via the ascending aorta, hybrid redilatation of an isthmus stent, and the hybrid occlusion of an intrahepatic portocaval shunt in patients aged 14 days to 45 years.[89] In addition, intraoperative balloon dilatation of the pulmonary veins, to 'crack' the hypertrophic intimal layer in pulmonary vein obstructive disease and guide the surgeon down the correct layer to excise, has been described.[60,91] Improvement of hybrid techniques will rely on the development of new devices, such as absorbable stents and low-profile septal closure devices; intraoperative imaging;[92,93] energy sources, such as ultrasound for controlled tissue erosion;[94] and robotic technology.[95]

Reducing surgical trauma

The concept of minimally invasive paediatric cardiac surgery is broader than simply limiting the length of the surgical incision. The aim should also be to reduce the trauma of an operation at each stage of management of the congenital heart defect—in the operating room, in the intensive-care unit, in the hospital ward, and even after discharge. The concept of reducing global trauma and morbidity related to the surgical procedure requires a multidisciplinary co-ordinated approach involving congenital cardiac surgeons, perfusionists, anaesthesiologists, intensivists, cardiologists, and nurses.

In the operating room

Numerous efforts have been made to reduce the trauma related to cardiopulmonary bypass in infants and children. Strategies to reduce inflammation include the use of steroids, aprotinin to reduce bleeding, ultrafiltration and leucocyte reduction, and biocompatible coated circuits. The only widely accepted approach is the use of a miniaturized circuit to help minimize fluid

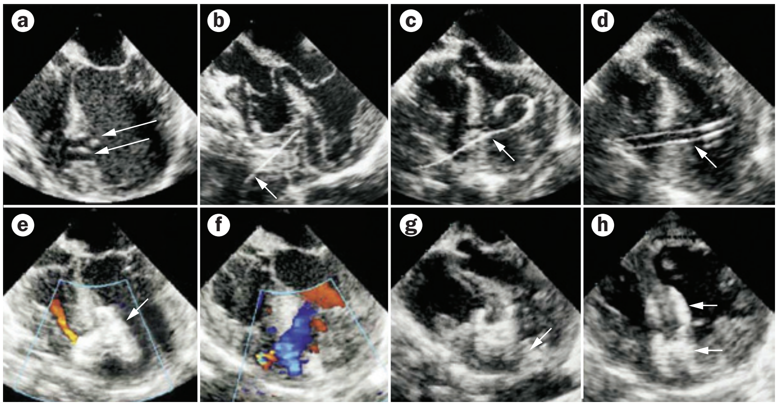

Figure 8 | Perventricular closure of a complex mid-muscular ventricular septal defect. The procedure is performed off-pump on the beating heart under transoesophageal echocardiography guidance. **a** | Identification of the defect (arrows). **b** | A needle (arrow) is introduced through the right ventricular free wall. **c** | A wire (arrow) is passed through the needle into the left ventricle via the ventricular septal defect. **d** | A sheath (arrow) is introduced with the tip positioned into left ventricular cavity. **e** | The first umbrella device (arrow) is positioned. **f** | A residual shunt (blue area) is noted. **g** | A second device (arrow) is positioned using the same technique. **h** | Complete eradication of the shunt. The two arrows indicate two separate devices. Reprinted from *Semin. Thorac. Cardiovasc. Surg. Paediatr. Card. Surg. Annu.*, **8**(1), Bacha, E. A. *et al.*, Hybrid procedures in paediatric cardiac surgery, 78–85, © (2005), with permission from Elsevier.

load and modulate the inflammatory response after cardiopulmonary bypass.[96]

Strategies for neuroprotection in paediatric cardiac surgery were proposed with the aim of minimizing cerebral trauma related to the disease and to cardiopulmonary bypass in infants and children.[97] These techniques include anterograde cerebral perfusion;[98] near-infrared spectroscopic monitoring associated with the treatment of low regional cerebral oxygen saturation;[99] the use of anaesthetics such as dexmedetomidine, which does not cause respiratory depression;[100] therapeutic hypothermia; remote ischaemic preconditioning;[101] the use of erythropoietin[102] and brain-derived neurotrophic factor;[103] and treatment with umbilical cord blood stem cells.[104] Again, no consensus exists among surgeons as to the best method of reducing surgical trauma. The debate about the choice between deep hypothermic arrest versus selective antegrade perfusion, in particular, continues unabated. The only prospective study on this subject did not show a benefit for antegrade cerebral perfusion over deep hypothermic circulatory arrest.[98]

Breakthroughs in real-time multimodality imaging, specialized instrumentation, miniaturization, and computer-assisted modelling of flow dynamics and tissue mechanics are key to the development of advanced image-guided intracardiac surgery. This concept involves the use of noninvasive imaging to plan a cardiac surgical procedure, navigate instruments into the heart, and perform the intracardiac repair.[105] High-resolution 3D transoesophageal intracardiac echocardiography[106] and MRI[107] have been investigated for real-time imaging guidance in surgical repair of cardiac defects: in addition to the anatomic detail, MRI can provide intraoperative assessment of organ and device function. Near-infrared spectroscopy can also provide real-time intravascular imaging of intracardiac structures in a normally perfused and beating heart.[108] These new and minimally invasive technologies should address the rapid motion of the heart in children requiring real-time imaging to make instrument navigation and tissue manipulation feasible, safe, and effective. Laser surgery has also been applied to the field of paediatric cardiac surgery to avoid the use of cardiopulmonary bypass in very young children, and has been reported to be safe and feasible for valvular angioplasty in a 4-month-old female with pulmonary atresia and intact ventricular septum.[109]

In the intensive-care unit

A 'fast-tracking' approach, involving early extubation, mobilization, and hospital discharge, can be adopted for many patients undergoing surgery for congenital heart disease.[110,111] The use of low-dose opioids, perioperative strategies to decrease the inflammatory response[112,113] and the need for transfusion allow safe, early extubation either at the end of the procedure in the operating room, or within a few hours in the intensive-care unit.[110] Preisman *et al.* demonstrated in a prospective randomized study that anaesthetic management with early cessation of mechanical ventilation in the operating room seems to be safe and decreases the duration of intensive-care unit and overall hospital stay in children undergoing cardiac surgery.[114] In a meta-analysis, Alghamdi *et al.* showed that early extubation (in the operating room or ≤6 h after surgery) was associated with a reduction in early mortality, defined as occurring before hospital discharge or in the first 30 days after the surgical procedure.[115] The investigators also reported a trend toward less respiratory morbidity and lower hospital costs with early extubation.[115] A high-dose fentanyl anaesthetic strategy was associated with a lower stress response, less coagulopathy, and a lower transfusion requirement when compared with low-dose fentanyl in children aged between 30 days and 3 years who were undergoing repair of a septal defect or ToF.[116] This finding is clinically relevant, as the number of units of blood required for transfusion in the intraoperative and early postoperative periods has emerged as important risk factors for longer duration of mechanical ventilation after paediatric cardiac surgery.[117]

On the hospital ward and after discharge

Evidence exists of high levels of anxiety and depression in children with congenital heart disease and among members of their families. Ozbaran *et al.* reported psychiatric disorders and adjustment disorders, with symptoms of depression and anxiety, in children and adolescents with left ventricular assist devices.[118] In a study by Rossi and colleagues, a post-traumatic stress disorder was diagnosed in 52% of mothers and 40% of fathers of children who underwent a heart or lung transplantation.[119] These data emphasize the theory that minimally invasive perioperative surgical management in children with congenital heart disease should provide psychological support to both children and parents. In addition, two-way communication between parents and providers should be encouraged through a multidisciplinary consultation–liaison team including psychiatrists, psychologists, nurses, and counsellors, to prevent the development of psychological and psychiatric disorders.

The trauma related to the diagnosis and surgical management of congenital heart disease, along with centralization of paediatric cardiology services into geographically remote tertiary centres, make psychological support for families and clinical monitoring of patients after hospital discharge increasingly pertinent. Home video-conferencing for patients with severe congenital heart disease was demonstrated to provide more-effective follow-up in terms of clinical observation and reduced levels of parental anxiety when compared with telephone follow-up.[120] The development of point-of-care self-monitoring of oral anticoagulation at home is another innovative tool that could be used to reduce the daily negative impact of paediatric cardiac surgery after hospital discharge.[121]

Conclusions

Minimally invasive surgery for congenital heart disease in paediatric patients was initially developed as a means of performing cardiac repairs via smaller, cosmetically more-appealing incisions. The field has evolved, however, and the aim is now to reduce the psychological and physical trauma of an operation using various technical advances. This philosophy is the guiding principle at each step of a child's journey in the hospital. Strategies include shorter or more-hidden incisions, heavy reliance on intra-operative image-guidance, video-assistance and robotic assistance (as opposed to a surgeon's direct inspection), hybrid procedures where interventional cardiologists and cardiac surgeons work in concert, meticulous attention to haemostasis and neuroprotection, as well as fast-tracking approaches that involve early extubation, less blood transfusions, and local and regional anaesthesia. Finally, adequate emotional and family support needs to be provided after hospital discharge. New technological advances, such as better surgical instruments, smaller cannulae, and lower profile retractors, as well as improvements in the fields of cardiopulmonary bypass and anaesthesia will undoubtedly continue to propel the field forward with the goal of 'treating more while hurting less'.

Review criteria

The PubMed database was searched for papers published between 1995 and 2013 using the key terms "minimally-invasive pediatric cardiac surgery", "minimally invasive incisions", and "minimally invasive congenital heart surgery". All papers selected for inclusion in the Review were published in the English language and obtained in full text and where appropriate. The references of selected papers were also searched for additional resources.

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Author contributions

Both authors researched data for the article, contributed to the discussion of content, wrote the manuscript, and reviewed/edited the article before submission.