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Minimal Incision Congenital Cardiac Surgery

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Abstract

Minimally invasive techniques have had limited application in congenital cardiac surgery, primarily due to the complexity of the defects, small working area, and the fact that most defects require exposure to intracardiac structures. Advances in cannula design and instrumentation have allowed application of minimal incision techniques but in most cases, cardiopulmonary bypass is still required. Image guided surgery, which uses non-invasive imaging to guide intracardiac procedures, holds the promise of permitting performance of reconstructive surgery in the beating heart in children.

Surgical techniques to reduce post-operative recovery time and improve the cosmetic results have had selective application in pediatric cardiac surgery when compared to that in adults. Application of reduced incision approaches for open heart procedures have been largely confined to operations where much of the intracardiac repair is carried out through the right atrium, such as closure of atrial or ventricular septal defects, AV canal defects, AV valve repair/replacement. With the availability of flexible pediatric size cannulas for cardiopulmonary bypass, the length of the midline incision has been limited to the lower portion of the sternum or a small inframammary incision. The technique for intracardiac repair, however, has not changed and usually follows the same principles as for the conventional full sternotomy approach. For extracardiac procedures, where usually a thoracotomy incision has been used for open repair, thoroscopic techniques with conventional or robotic instruments have been applied to a wide range of pediatric procedures.

Thoroscopic Approach for Non-Cardiac Procedures

To date, application of thoroscopic procedures in children has been mostly confined to repairs of non-cardiac defects or to provide access to the pericardium or epicardium, usually for pacer lead implantation. Examples include ligation of patent ductus ¹, division of vascular rings ², creation of a pericardial window, innominate artery or aortic suspension for tracheal compression, and more recently, pacer lead insertion for biventricular pacing. The main limitation to further application of endoscopic techniques has been the difficulty in performing true reconstructive operations that require suturing and tying knots.

Instruments

Imaging the surgical field in thoracoscopy as in most forms of port access to internal structures is almost always optical imaging with a rigid glass rod scope equipped with a high resolution digital video camera at the back end for projection of the image on to a screen visible by the

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surgeon. Scopes are available in a variety of sizes and lengths that can fit any size child from a 2.7mm scope for a very premature infant ³ to 10mm scope used in adults. Similarly, thoroscopic instruments are available in all sizes. The main limitation of the instruments is however, the lack of dexterity, that is they are single action instruments where only one motion is achieved with a jaw-like action at the tip, which limits the range of motion at the surgical site. Suturing tissue is possible but difficult and tying knots very time consuming. Other forms of tissue fixation such as stapling or the use of tissue anchors has not been used very often in pediatric applications. Most automatic stapling devices made for laparoscopic procedures are designed for adults and require a larger port than used in children and a larger working area inside the thorax. This has been partly overcome by the new flexible stapling devices, but the working area is still too large for use in young children.

Surgical Approach

In thoroscopic procedures, ports which are introduced across the chest wall to facilitate insertion of instruments are simple hollow tubes since the chest cavity is not pressurized like the abdominal cavity is. Port position in children is critical due to the small working space and the relatively short distance between the chest wall and the surgical site. For procedures on the aortic arch such as ligation of a patent arterial duct or division of vascular ring, typically four ports are used in the left chest, two lateral ports for instruments, the central port for the scope, and one additional port for a lung retractor. In some procedures on the great vessels, such as innominate artery suspension for tracheal compression, the right chest is entered to access the arch vessels with port position similar to that used on the right side.

Results

Thoroscopic procedures in children have been used mainly for extracardiac defects or for access to the epicardium for pacer lead placement ⁴. There has not been however, widespread acceptance of thoroscopic techniques in large part due to the lack of familiarity with the procedures by most pediatric cardiac surgeons. The fact that the majority of patients with a patent duct have it closed by device occlusion in the catheterization laboratory, and that other lesions such as vascular rings are rare, has contributed to the limited application of thoroscopic techniques in children. The operative risks involved in these procedures are low with injury to a large vessel and hemorrhage being extremely rare. Conversion to an open procedure in most reports has been limited to the early experience by the reporting surgical team. Injury to other adjacent structures such as the left recurrent nerve, or thoracic duct does not seem to be different then with open procedures ⁵. The incidence of most of these complications is 1% or less, except for recurrent nerve injury which occurs in 1-3% of patients, with most of these being transient injury ⁵. Late recurrence of a patent duct has been reported following thoroscopic closure with an incidence varying from 0.6% to 3% ⁶.

Mini-sternotomy Open-Heart Procedures

Small incisions to access the heart have been described for over two decades with various approaches being preferred by some groups. Small anterior thoracotomy or limited midline sternotomy are the two most common approaches. Since almost all repairs in children are intracardiac, cardiopulmonary bypass is currently required with the exception of recent reports of "hybrid" procedures where the intracardiac defect is repaired with a device delivered by direct trans-cardiac approach (see Hybrid Procedures – below). The majority of reports however, still utilize conventional open heart techniques with cardiopulmonary bypass and cardiac arrest ⁷. Cannulation for bypass in children is usually done through the thorax to avoid injury to femoral or neck vessels that could result in long term disability. This technique has been applied to more complex congenital defects in infants and children ^{8,9}.

Surgical Approaches

The approaches reported for minimally incision repair of intracardiac defects in children vary from an anterior, infra-mammary thoracotomy, posterior thoracotomy, or a limited inferior sternotomy. Phrenic nerve damage has been reported in as many as 16% of children having ASD closure through an anterior right thoracotomy¹⁰. Breast and pectoral muscle maldevelopment has also been reported along with paresthesia around the breast and even the right arm¹¹. The proposed advantages of a limited sternotomy are avoidance of pericardial incisions near the phrenic nerve, or the need to create myocutaneous flaps as often done with the infra-mammary incision, which may result in hematomas and skin denervation. The other potential advantage is the ability to rapidly enlarge the incision if needed, to gain access to other cardiac structures.

Since many of the intracardiac repairs in infants and children are accomplished through the right atrium, inferior partial sternotomy incisions can provide sufficient exposure for cannulation for cardiopulmonary bypass while giving direct access to the right atrium. Examples include repair of ASD, VSD, complete AV canal defect, trans-atrial repair of tetralogy of Fallot (TOF), and mitral valve repair. This approach offers several advantages in that exposure to the great vessels can be accomplished in children of all ages with sufficient ease to permit safe cannulation for bypass. Retraction of the sternum superiorly, usually with a table mounted retractor, provides access to the upper thorax for aortic and superior caval cannulation (Figure 1).

Results

Our experience with the partial sternotomy approach for repair of simple and complex congenital heart defects indicates that the procedure can be done safely, with similar bypass and cross-clamp times compared to a full sternotomy approach. Late follow up also indicates this approach is equally effective in achieving repair of the intracardiac defects equivalent to those achieved with full sternotomy⁸. Working in such a small working area can be difficult and is facilitated by specialized instruments that keep the surgeons hands out of the line of sight of the operative field. Achieving complex repairs with much suturing can be time consuming, but, with experience the ischemic times reported are similar to those in open procedures. Dexterous instruments with greater degrees of freedom may be helpful in these procedures, but other than telerobotic instruments, such dexterous instruments are not available for clinical use yet. The main drawback of the mini-sternotomy approach, however, remains the fact that the procedure still uses cardiopulmonary bypass and cardioplegic arrest of the heart to permit direct visual inspection of the intracardiac defect and repair.

Robotically Assisted Surgery

Conventional thoracoscopic instruments have limited degrees of freedom, which hampers performance of complex maneuvers that involve tissue reconstruction such as suturing and tying knots, particularly under tension. Robotic surgical instruments have the dexterity required for these complex maneuvers and therefore hold the promise of facilitating truly thoracoscopic repair of cardiac defects even in children^{12,13}. Currently there is only one approved robotic systems available in North America. The system is tele-operated, which means that the controller is separate from the robotic instruments and actuator motors. The DaVinci system (Intuitive Surgical Inc. Sunnyvale, CA) has three or four robotic arms that are mounted on the surgical arm cart, which can be moved over the surgical field. One arm holds a dual channel scope and cameras that provide a stereoscopic view of the surgical field. The surgeon sits at the master controller viewing the operative field through two separate displays, one for each eye, which provide an image from each scope channel and camera. Magnification can be added

and the motion of the instruments with respect to the hand held controllers can be varied to adjust for fine control.

Although experience with robotic systems in cardiac surgery on adults is now widespread, application of these for congenital heart defects has been limited to adults or older teenagers with ASDs and/or non-cardiac thoracic procedures in children¹³. The main limitation to application of robotic systems in children has been the size of the available instruments (8mm diameter) and endoscope (10mm diameter) as well as the required working area for instrument task performance: 5mm diameter instruments and scopes are now available and hold the promise of permitting application of robotic systems to smaller infants and children, however their working area is still large (Figure 2). Future advances in robotics will likely include the ability to integrate images of the operative field with previously obtained images of the relevant anatomic structures by CT, MRI or ultrasound. Smaller or hand-held actuated surgical instruments have been developed in Japan but have not been introduced into the U.S. Other forms of instrument or catheter navigation tools that have dexterity have been developed and used mainly to guide catheter based interventions (Hansen Medical, Mountain View, CA). The concept however, could be applied to surgical procedures if the steerable instrument were coupled with conventional surgical tools such as scissors, graspers, or needle holders.

Image Guided Intracardiac Surgery (IGIS)

The term “image guided” intervention describes the process of using non-invasive imaging to plan an intervention, navigate instruments or catheters to the desired area, perform a repair, and evaluate the results of the intervention. The term has been applied to catheter or needle based procedures such as image guided needle biopsy or delivery of radioactive therapy for local control of tumors, and to image guided surgery where the procedure is planned by pre- or intraoperative imaging, and surgical tools are guided to the target area using the images obtained. The type of imaging used can vary from fluoroscopy to CT, MRI, or ultrasound in the case of non-optical imaging, to near-infrared for optical imaging through material that is opaque to visible light such as blood or at times amniotic fluid.

In cardiac surgery the term image guided surgery is reserved for procedures where intracardiac structures are the surgical target and are accessed either via vessels using catheter based instruments, or direct trans-cardiac interventions. The major challenge to IGIS is the rapid motion of the heart requiring real-time imaging to permit instrument navigation and tissue manipulation. Two-dimensional projection imaging, such as fluoroscopy, while providing real time imaging with high spatial resolution, is used mostly for general orientation and gross navigation through great vessels and cardiac chambers. To obtain three-dimension (3D) information, bi-plane imaging is required. The major disadvantages of fluoroscopy however, are that irradiating energy is required and it is not suitable for soft tissue imaging, such as identification of atrial or ventricular septal defects, AV valves, or intracardiac structures. Contrast agents provide “snap shot” images of the blood tissue interface but this technique is quite limited for guiding interventional procedures other than simple device deployment or balloon dilatation, all of which travel in the vessel lumen or inside the cardiac chambers.

Ultrasound on the other hand, is suitable for guiding intracardiac interventions since it can provide real-time imaging with frame rates far beyond what humans can process (60 to 200Hz or frames per second). 3D echocardiography at frame rates that provide real-time or live images (25Hz) is available now and is being applied to diagnose complex cardiac defects as well as to guide interventions. With the recent availability of trans-esophageal probes for 3D echo, the possibilities for 3D echo guided intracardiac procedures have become evident to cardiac surgeons as well as interventional cardiologists. The main drawback of ultrasound is the lack of spatial resolution for imaging very small or very fine structures such as single valve chords

or leaflets. However, as the technology advances, resolution and frame rate will be improved to the point where ultrasound will likely be the preferred mode of imaging for guiding intracardiac procedures such as device closure of atrial septal defects, and catheter ablation therapy for atrial flutter or atrial fibrillation. The latter will likely be combined with currently used navigation tools such as electromagnetic trackers (CARTO System, Biosense Webster, Diamond Bar, CA).

Hybrid Procedures

The term “hybrid procedures” refers to the combined use of direct surgical access to cardiac structures, and catheter based techniques to treat a variety of cardiac defects. Early reports of the intra-operative use of angioplasty balloons to treat pulmonary artery branch stenosis were an exciting innovation to treat a difficult problem, but were later criticized as being somewhat blind in that the full extent of the balloon and relationship to pulmonary artery branches was not known at the time of angioplasty. This resulted in limited application of these techniques intra-operatively. Surgeons then began to use fluoroscopy and contrast agents to overcome these limitations, resulting in safer procedures and more effective interventions. In congenital cardiac surgery, surgeons have explored the use of catheter based devices to repair a number of defects in order to avoid or limit the use of cardiopulmonary bypass or to treat defects that would require a ventriculotomy to access. Examples include device closure of muscular ventricular septal defects (VSDs)¹⁴, balloon pulmonary valvotomy as part of the repair of Tetralogy of Fallot or patients with pulmonary atresia and intact ventricular septum¹⁵, and even closure of prosthetic para-valvular leaks¹⁶. For per-ventricular closure of muscular VSDs, the device is introduced via a sheath inserted directly into the right ventricle and navigation and positioning of the device guided by epicardial or trans-esophageal echocardiography¹⁴. (Figure 3)

Ductal Stenting for Lesions with Duct Dependent Systemic Perfusion

For congenital cardiac defects that depend on a patent arterial duct to maintain systemic circulation, stenting of the arterial duct along with restricting pulmonary blood flow has been utilized in many centers to avoid cardiopulmonary bypass in the neonatal period¹⁷, Reviewed in¹⁸. In almost all cases however, fluoroscopy has been the main method of imaging the arterial duct and aortic arch to guide positioning of the stent.

Future Advances

The technology developments that will likely have the greatest impact on image guided intracardiac surgery are advances in non-invasive imaging, displays, and aids to instrument navigation as well as specialized instruments. Improvements in spatial and temporal resolution will allow visualization of the rapidly moving structures in the heart such as valve leaflets, chordae, and ventricular muscle bundles. Displays will provide true depth perception (stereoscopic) so that the surgeon can easily understand the relationships between various cardiac structures and surgical instruments. The advantage of this type of high resolution 3D visualization will also be the ability to simultaneously assess the effect of the tissue manipulation and cardiac reconstruction is having on cardiac function and blood flow. To accomplish beating heart repair of intracardiac defects there will also be a need for specialized instruments such as ports for insertion of instruments and for tissue manipulation and reconstruction. In addition, the instruments will need to be compatible with the imaging modality to avoid artifacts and for visualization within the operative field (Figure 4). Currently there is a great deal of work being done at Universities and in corporate research laboratories to address all these needs. The National Institutes of Health has already recognized this need as reflected in a recent Workshop organized in Bethesda, MD¹⁹. It is safe to say that within

a few years, surgeons will be repairing a number of intracardiac defects in children using image guided surgical techniques.

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Figure 1.

Mini-sternotomy approach for open heart repair of intracardiac defects in children. A table mounted retractor facilitates cannulation, which is done through the thorax in most children. (From “Minimally Invasive and Robotically Assisted Cardiac Surgery, and Extracorporeal Membrane Oxygenation”, in *Nadas’ Pediatric Cardiology*, Saunders-Elsevier, Philadelphia, PA, 2006., page 871)

Figure 2. Tele-robotic surgical instruments for the DaVinci Surgical System showing 8mm (below) and 5mm (two at top) instruments flexing to 90°. Note that the working area, that is the distance from the bend to the tip of the instrument is similar for both size instruments.

Figure 3.

(A) Four-chamber view of a mid- to posterior muscular ventricular septal defect (VSD) via intraoperative transesophageal echocardiography (TEE). LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle. (B) Color Doppler flow across the VSD. (C) Using a forceps tip, the right ventricular free wall is probed to determine the shortest distance from the free wall to the VSD, staying away from the anterior papillary muscle of the tricuspid valve. (D) A needle is introduced into the right ventricular cavity and a guide-wire manipulated into the left ventricle. (E) An introducer sheath is passed over a dilator and positioned into the left ventricular cavity. (F) The device is pushed into the sheath and the LV disc deployed by gently retracting the sheath. (G) The RV disc is similarly deployed, but the device is still attached to the delivery cable. This allows for TEE confirmation of valve function and VSD closures, as well as recapture of the device into the sheath (by advancing the sheath), necessary. (H) Final confirmation of lack of shunting. (From Bacha EA, Cao QL, Galantowicz ME, Cheatham JP, Fleishman CE, Weinstein SW, Becker PA, Hill SL, Koenig P, Alboliras E, Abdulla R, Starr JP, Hijazi ZM. Multicenter experience with perventricular device closure of muscular ventricular septal defects. *Pediatr Cardiol.* 2005 Mar-Apr;26(2):169-75)

Figure 4.

Artifact created by a metallic instrument in the ultrasound image (top row). The effect of polyurethane foam coating on the suture device imaging is shown in the bottom row. A, Uncoated; B, Coated with polyurethane foam. (2D- two-dimensional ultrasound imaging; 3D- Three-dimensional ultrasound imaging).