

Robotic-Assisted Endoscopic Thoracic Aortic Anastomosis in Juvenile Lambs

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ABSTRACT

Background: Advances in robotic technology have enabled a wider range of applications for minimally invasive techniques in cardiac surgery, including mitral valve repair and coronary artery bypass grafting. With increased technical sophistication, robotic-assisted techniques can be developed for the endoscopic repair of certain congenital cardiac lesions.

Objective: The purpose of this study was to assess the feasibility of closed chest thoracic aortic anastomosis in a juvenile ovine model.

Methods: Lambs, aged 45 to 55 days, underwent surgery that was performed using the da Vinci robotic surgical system. Using 3 ports, the surgeon dissected the descending thoracic aorta and mobilized it free from attachments, using single-lung ventilation and CO₂ insufflation. Snares were introduced through 2 stab wounds for aortic occlusion proximally and distally. In 4 lambs, the aorta was completely transected and reanastomosed using interrupted nitinol sutures. One lamb underwent longitudinal aortotomy, and patch aortoplasty was performed with the placement of a Gore-Tex patch. Snares were released and the animals were recovered once hemodynamically stable. Animals were sacrificed at 6 to 12 hours after surgery and the descending aorta was harvested. Burst-pressure testing was performed on the anastomoses.

Results: All 5 lambs survived the procedure with stabilization of hemodynamic parameters following surgery. The mean aortic clamp time was 47 ± 17 minutes, and the anastomosis was completed in 26 ± 5 minutes. The mean burst pressure was 163 ± 9 mm Hg.

Conclusions: Endoscopic thoracic aortic anastomosis can be performed safely and with adequate exposure in a juvenile large-animal model using computer-assisted surgical techniques. With further refinements, these approaches could be applied to the repair of congenital anomalies of the aorta, including interrupted aortic arch and aortic coarctation.

INTRODUCTION

The advent of robotic surgical technology holds promise for endoscopic repairs of congenital cardiovascular lesions that currently require open-chest techniques. Obvious benefits of minimally invasive surgery include faster recovery, improved cosmetic results, and reduced wound complications. Video-assisted thoracoscopic approaches for patent ductus ligation and congenital subaortic resection have been reported with encouraging results [Burke 1995, Miyaji 2000]. However, because of technical limitations, the development of less invasive surgical techniques to treat congenital cardiac disease has not progressed as rapidly as the development of surgical techniques for acquired heart disease.

With wrist-enhanced instrumentation, 3-dimensional visualization, and computer-enabled motion scaling, robotic-assisted surgery allows more precise manipulation and handling of tissues than do conventional endoscopic instruments. As a result, this technology is ideally suited for cardiovascular procedures on subjects with limited thoracic dimensions. In this study, we assess the feasibility of closed-chest aortic anastomosis in a juvenile large-animal model using the da Vinci robotic system.

MATERIALS AND METHODS

Surgical Preparation

Mixed Western lambs (45-55 days old, 16.2 ± 1.3 kg) were anesthetized with inhaled isoflurane and mechanically ventilated. Lambs were positioned with the right chest down, and three 10-mm incisions for the port sites were made in the left chest (Figure 1). The surgeon's left instrument was inserted in the fourth intercostal space (ICS) in the midaxillary line. The camera was inserted in the sixth ICS in the posterior axillary line. The surgeon's right instrument was introduced through the ninth ICS in the midaxillary line. An additional

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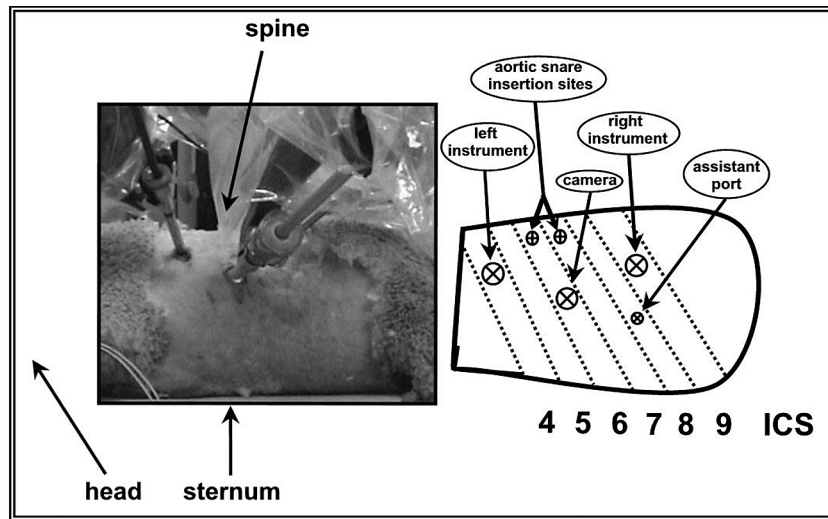


Figure 1. Photograph of operative setup with optimal animal positioning and placement of the 2 instrument ports and the camera port. The accompanying diagram indicates placement of all ports, including stab incisions for the introduction of the aortic snares. ICS indicates intercostal space.

5-mm assistant port was placed in the eighth ICS in the anterior axillary line. The da Vinci surgical robotic system (Intuitive Surgical, Mountain View, CA, USA) was used as previously described [Shennib 1998, Mohr 1999]. All procedures were performed by a single surgeon (V.M.R.).

Once surgery began, right lung ventilation was instituted, and CO₂ insufflation was used at pressures between 3 and 8 mm Hg. The descending thoracic aorta was dissected and mobilized free from its attachments. Intercostal arteries were ligated with an endoscopic clip applier. The aorta was encir-

led with no. 1 monofilament polypropylene sutures proximally and distally. Rubber catheters (18 Fr) were introduced through separate stab incisions. The sutures were advanced through the catheters to gain proximal and distal control of the aorta. Once snared proximally and distally, the aortas were transected in 4 lambs. The anastomosis was constructed in an interrupted fashion with anastomotic clips (Coalescent Surgical, Sunnyvale, CA, USA) (Figure 2). The clip device, the U-Clip, is a penetrating, self-closing nitinol clip attached to a standard surgical needle. In a fifth lamb, a 10-mm longitudinal

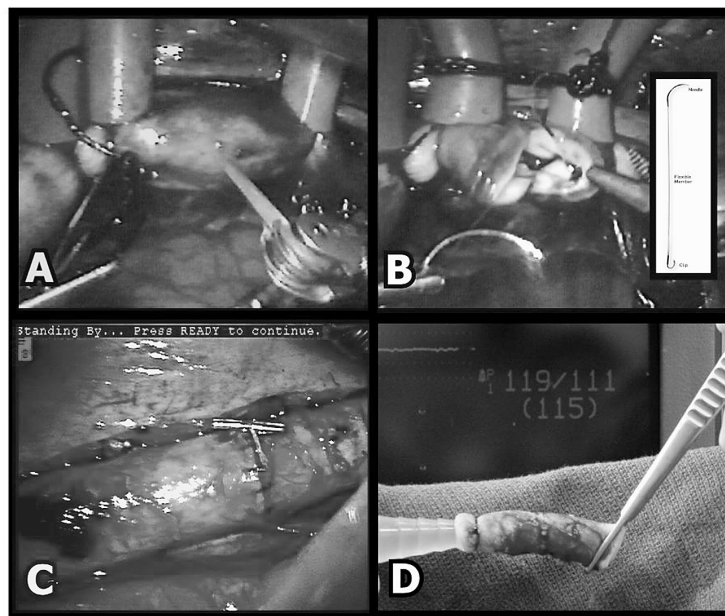


Figure 2. End-to-end anastomosis. A, Descending aorta with snares for proximal and distal occlusion. B, Photograph of anastomosis being performed following complete transection. Structure of nitinol clips used for anastomosis shown. C, Completed anastomosis in situ. D, Explanted aortic segment undergoing burst-pressure testing.

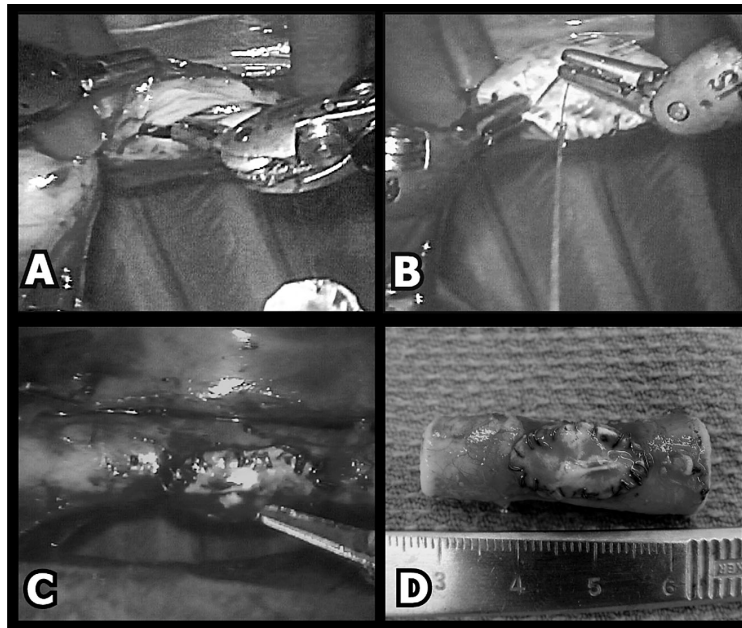


Figure 3. Patch aortoplasty. A, Linear aortotomy. B, Patch closure being performed. C, Completed aortoplasty in situ. D, Explanted aortic segment with patch in place.

aortotomy was performed, and a Gore-Tex patch was placed using the same nitinol clips (Figure 3). The snares were removed sequentially to check for bleeding. Any bleeding points were sutured closed with the clips. The lambs were then stabilized hemodynamically with fluid administration, and acidosis was corrected with sodium bicarbonate, if necessary. Animals were recovered from anesthesia and extubated once breathing spontaneously.

All animals received humane care in compliance with the *Principles of Laboratory Animal Care* formulated by the National Society of Medical Research and the *Guide for the Care and Use of Laboratory Animals* prepared by the Institute of Laboratory Animal Resources and published by the National Institutes of Health. The protocol was approved by the Committee on Animal Research at the University of California, San Francisco, USA.

Tissue Harvest

Lambs were sacrificed at 6 to 12 hours after surgery. A left thoracotomy was performed and the aortic segment with the anastomotic site was harvested with at least 2 cm of aorta on either side of the anastomosis for burst testing.

Burst Testing

A Masterflex roller pump circulated saline through ¼-inch Tygon tubing. One end of the aortic segment was attached to the end of the tubing. Once pump flow was instituted, the distal end of the vessel segment was occluded. The pressure generated was measured with an in-line catheter attached to a pressure transducer. The flow was increased gradually to increase the pressure in the circuit. The burst pressure was recorded as the pressure at which a leak developed at the anastomotic site.

RESULTS

All animals survived the procedure, with a mean heart rate of 89.6 ± 9.5 beats per minute and a mean arterial pressure of 65 ± 5.4 mm Hg. All 5 lambs were breathing spontaneously following extubation, with a mean O₂ saturation of 98.4 ± 1.1 . For the 4 anastomoses, the mean clamp time was 44.2 ± 13.4 minutes (Table). The anastomosis was completed in 26.3 ± 5.2 minutes. Cross-clamp and anastomosis times decreased with each successive preparation. The patch aortoplasty required 34 minutes of aortic occlusion and took 23 minutes to complete.

TISSUE ANALYSIS

At harvest, the anastomotic site was intact and had evidence of good hemostasis in all lambs. There was no evidence of major bleeding from the anastomotic site in any of the specimens. On closer inspection, we observed that all aortic

Technical Details of the Operative Experience

	Aortic Occlusion Time, min	Anastomosis Time, min	Vessel Diameter, mm	Burst pressure, mm Hg
Anastomosis #1	58	30	9.2	161
Anastomosis #2	52	24	8.3	168
Anastomosis #3	39	31	8.3	151
Anastomosis #4	28	20	9	172
Aortoplasty	34	23	9.5	103

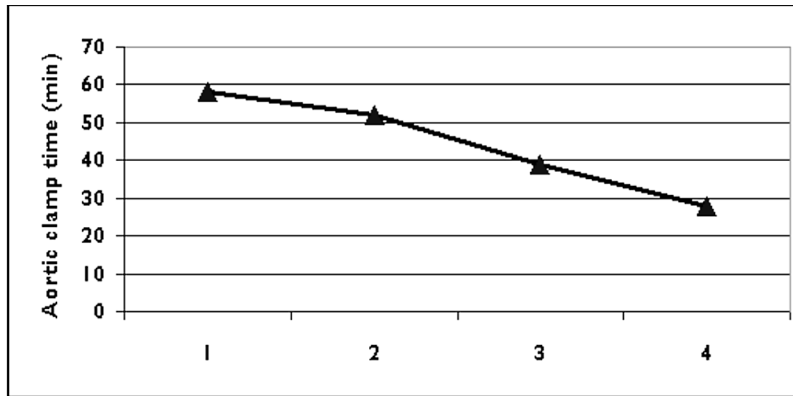


Figure 4. Learning curve associated with the robotic-assisted thoracic aortic anastomosis. A greater than 50% reduction in the aortic cross-clamp time was found over the course of these studies.

segments were widely patent. For the 4 aortic anastomoses, the mean vessel diameter was 8.7 ± 0.5 mm and mean burst pressure was 163 ± 9.2 mm Hg. The aortoplasty vessel had a diameter of 9.5 mm with a burst pressure of 103 mm Hg.

IMPACT OF LEARNING CURVE

Figure 4 illustrates the dramatic learning curve associated with robotic-assisted thoracic aortic anastomosis. As we gained experience with the robotic system and operative setup, the cross-clamp and anastomosis times decreased dramatically. Even during the short period of this study, the aortic cross-clamp time decreased 52%, with the final anastomosis requiring 28 minutes of occlusion.

DISCUSSION

Advances in minimally invasive surgery have been responsible for dramatic reductions in hospital stay and patient morbidity. Over the last 5 years, less invasive approaches have been developed for the surgical treatment of acquired heart disease. However, application of these minimally invasive techniques in pediatric cardiac surgery has been limited by the constraints of size, available instrumentation, and technical complexity. Robotic-enhanced technology is well suited to meet the challenges of endoscopic pediatric cardiac surgery. Computer-assisted tremor reduction and motion scaling, along with 3-dimensional visualization, serve to enable the surgeon to perform more technically challenging procedures with minimal access. Wrist-enhanced instrumentation provides the surgeon with additional degrees of freedom for movement, further reducing operative space requirements.

Although robotics has numerous potential applications in pediatric cardiac surgery, there are several technical limitations that must be addressed before these techniques can be used clinically. The lack of tactile feedback impairs surgeon dexterity when performing precise maneuvers with fine (6-0 and 7-0) monofilament suture, as required during knot tying and tightening a running anastomosis. As a result, we used

interrupted nitinol suture clips to perform the anastomosis. The clips were easy to handle with the endoscopic instruments and held the tissue together well. Adequate exposure can be compromised at times by bleeding in the operative field. This problem can be overcome by engineering improved suction devices. Furthermore, the specimens used in this study had a mean weight of more than 16 kg, placing them at the higher end of the pediatric size spectrum. Spacing requirements of the endoscopic instrumentation restrict the minimum patient size. Using wrist-enhanced instruments at extreme angles results in the loss of a degree of freedom of motion, a phenomenon known as singularity [Falk 2000]. However, with advances in miniaturization, robotic-assisted surgery can be used in increasingly smaller patients.

This study demonstrates the feasibility of safely performing an end-to-end anastomosis of a subcentimeter thoracic aorta with a robotic-assisted closed-chest approach. All animals recovered, with an intact anastomosis in all cases. Although the mean burst pressure of 162 mm Hg indicates the initial integrity of an anastomosis performed endoscopically with nitinol clips, it fails to account for the additional stability afforded by the processes of coagulation and collagen deposition and maturation, occurring days to weeks after the anastomosis. The patch aortoplasty was performed to demonstrate the ease of handling prosthetic graft material with the robotic surgical system.

With further refinements, these techniques could be applied to minimally invasive approaches to congenital aortic anomalies such as coarctation or interrupted aortic arch. The potential applications of robotics in the treatment of congenital heart disease include other off-pump cases such as palliative shunts (ie, Blalock-Taussig shunt), assistance with percutaneous procedures, and selected cases requiring cardiopulmonary bypass, including the repair of certain atrial septal defects.

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