Operative Techniques in Thoracic and Cardiovascular Surgery

Construction of the Right Ventricle-to-Pulmonary Artery Conduit in the Norwood: The "Dunk" Technique

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Neonatal palliation of hypoplastic left heart syndrome requires relief of systemic outflow obstruction, provision of unobstructed coronary blood flow, creation of a nonrestrictive atrial septal communication, and limitation of excessive pulmonary blood flow using a Gore-Tex (WL Gore Co., Newark, DE) tube graft. Until Sano and coworkers reintroduced the right ventricle (RV) to pulmonary artery (PA) conduit modification of the Norwood procedure in 2003, pulmonary blood flow had been provided by a modified Blalock–Taussig shunt.[1] The RV-PA conduit results in a higher diastolic pressure than the Blalock–Taussig shunt and therefore more favorable coronary perfusion. The Single Ventricle Reconstruction Trial, a multicenter, randomized controlled trial comparing the RV-PA conduit with the modified Blalock–Taussig shunt, showed that at 12 months transplant-free survival was better with the RV-PA conduit.[2] Despite better survival, subjects who received the RV-PA conduit had a high rate of intervention on the RV-PA conduit. As initially described, the proximal anastomosis was constructed between a Gore-Tex graft and the epicardium layer of the RV outflow tract ventriculotomy. Obstruction could develop due to muscular hypertrophy in the area of the ventriculotomy, resulting in worsening cyanosis. In an effort to prevent this complication, extensive undermining of the ventriculotomy site was performed with the potential to impact RV function. The technique illustrated in this article uses a ringed Gore-Tex graft for the RV-PA conduit and the proximal graft is inserted full thickness, or dunked, through the RV free wall. The end of the conduit is within the RV chamber and the potential for obstruction is minimal. (This approach was described to the first author by J.A.Q. and further refined based on suggestions from T.L.S., another early adopter of the technique.) The procedure perfusion strategies described below are those used at the Children's Hospital of Wisconsin.

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Description of Procedure

A successful Norwood operation requires both optimal technique and extracorporeal support strategies to permit safe and precise reconstruction. Preoperative stabilization is essential. Hypoplastic left heart syndrome is routinely diagnosed in the antenatal period and supportive measures are undertaken immediately following delivery. For patients presenting in the newborn period with either impending ductal closure or heart failure, a period of resuscitation will be necessary. Except in the rare patient unresponsive to prostaglandin E_1 or with a critically restrictive atrial septal defect, surgery should not take place until the circulation has been stabilized and low output/acidosis resolved. Surgery is typically scheduled electively at 2-5 days of life. Initial arterial cannulation is via a Gore-Tex graft anastomosed end to side to the innominate artery. α-Blockade is used routinely during cardiopulmonary bypass and today this is accomplished with phentolamine. A 250 μg/kg bolus of phentolamine is given after initiation of cardiopulmonary bypass; if additional afterload reduction is indicated, an infusion can be started at 1-2 μg/kg/min. The patient is cooled to a bladder temperature of 18°C over at least 30 minutes using a pH stat perfusion strategy for cooling. The hematocrit is maintained above 25%. A single dose of blood cardioplegia is injected via the arterial cannula. Continuous cerebral perfusion is used routinely to minimize the period of deep hypothermic circulatory arrest. Typically, flow is maintained to the innominate artery at a rate of 40-60 mL/kg/min. During the period of continuous cerebral perfusion, near infrared spectroscopy is used to manage flow and P_{CO_2}. Modified ultrafiltration is used routinely following separation from cardiopulmonary bypass. Postoperative management is facilitated by the routine use of an oximetric catheter (Abbott Laboratories, North Chicago, IL) and 2-site near infrared spectroscopy (Covidien, Corp, Mansfield, MA) that has been described previously.[3-6]

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Operative Technique

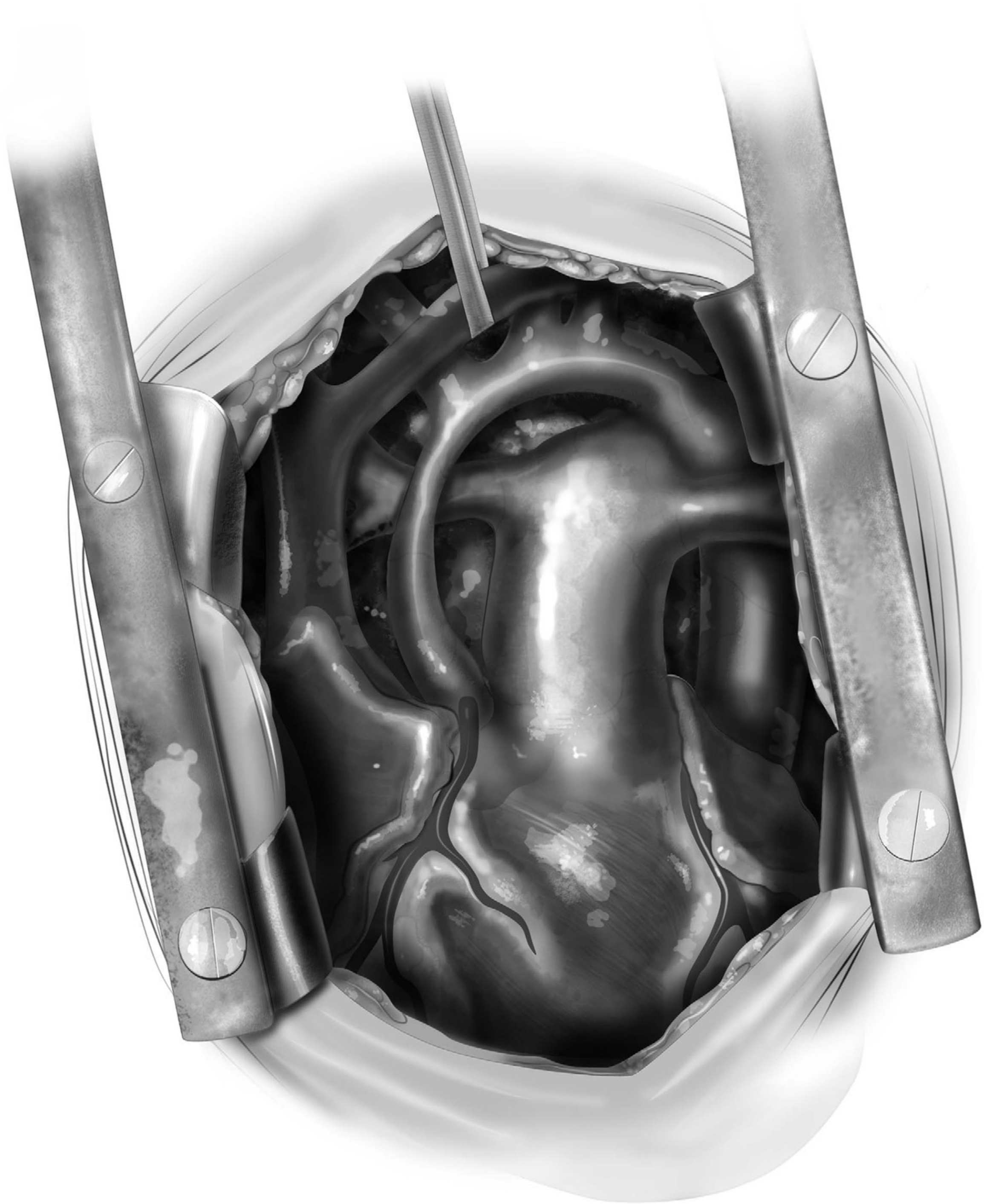

Figure 1 After a median sternotomy, the pericardium is opened and the vascular structures are mobilized. The innominate vein is mobilized and looped with a tape; this allows for atraumatic retraction and facilitates exposure of the brachiocephalic vessels.

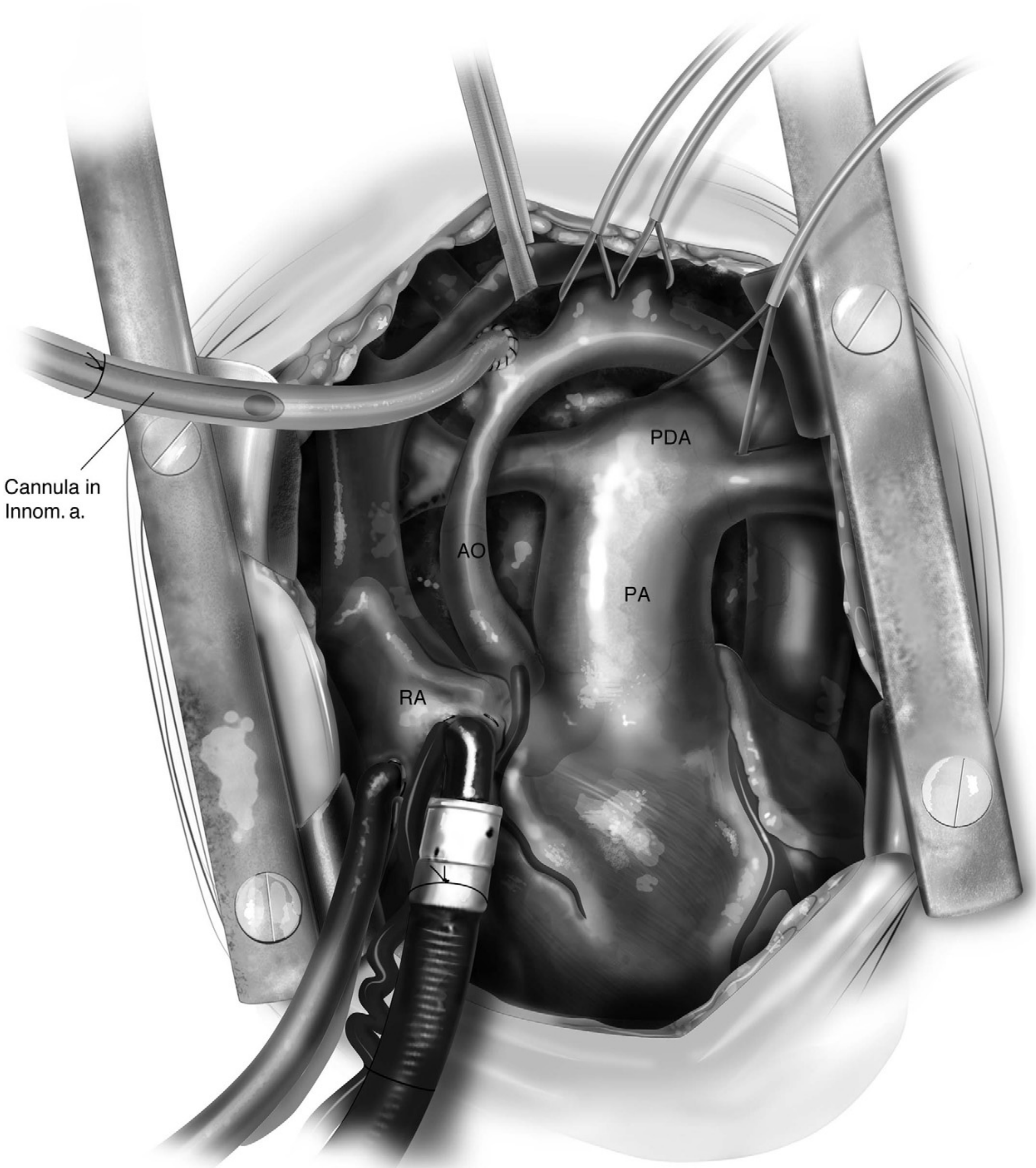

Figure 2 Cannulation for cardiopulmonary bypass. A Gore-Tex graft (3.0 mm for patients less than 3.0 kg and 3.5 mm for patients greater than 3.0 kg) is anastomosed to the innominate artery and used for arterial cannulation; an 8-Fr arterial cannula (Medtronic, Minneapolis, MN) is used. The right atrial appendage is cannulated with a 16-Fr venous cannula (Medtronic). Cardiopulmonary bypass is instituted and the patient is cooled over 30 minutes to a bladder temperature of <20°C. With initiation of cardiopulmonary bypass, the branch pulmonary arteries are snared and a 13-Fr ventricular vent (Medtronic) is placed through a separate purse-string in the right atrial free wall and directed across the tricuspid valve into the RV. The vent is useful to prevent ventricular distension as contractions become less effective with hypothermia. Ao = aorta; Innom. a. = innominate artery; PA = pulmonary artery; PDA = patent ductus arteriosus; RA = right atrium.

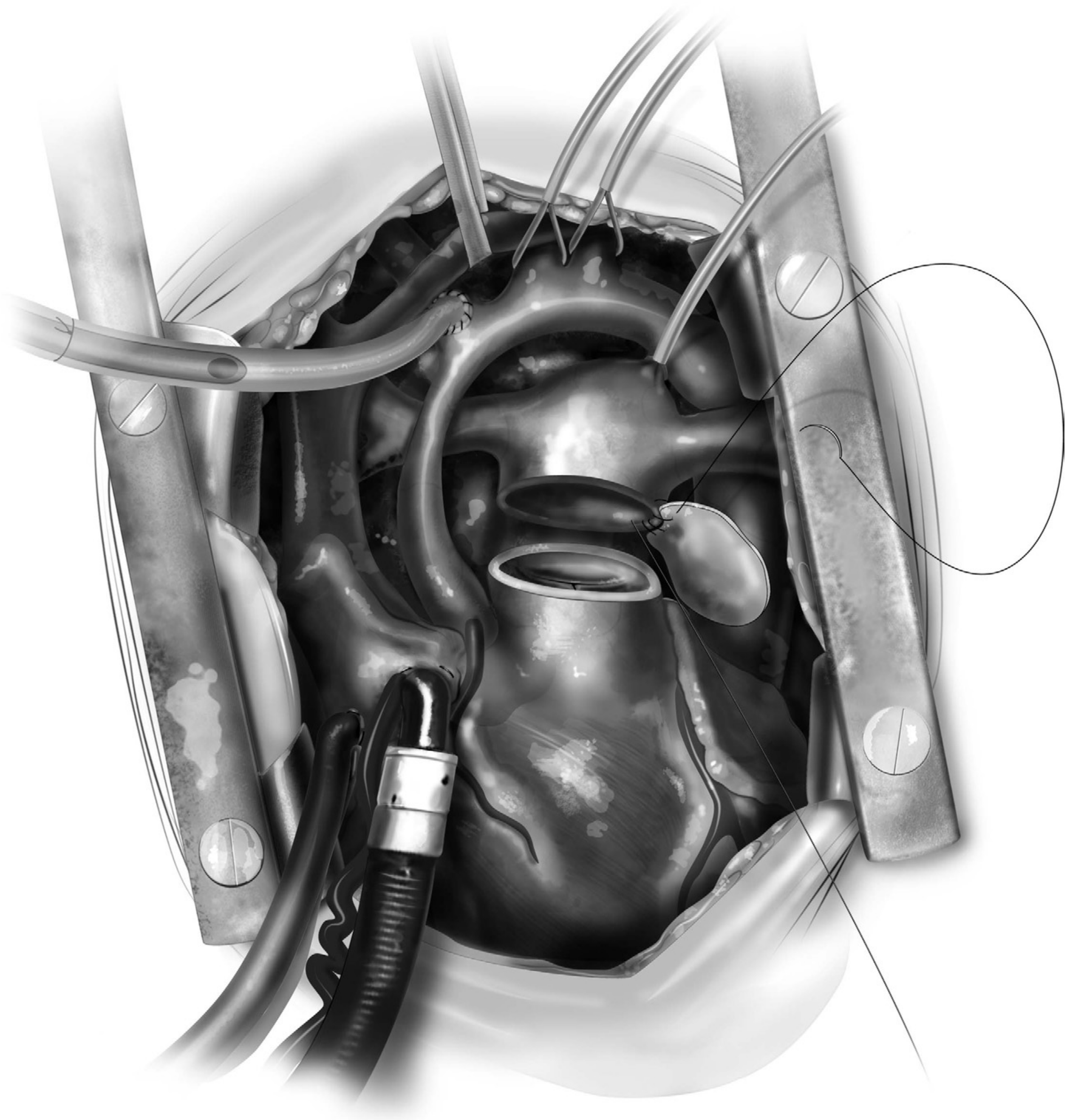

Figure 3 Division and patching the main pulmonary artery. After cooling for approximately 10 minutes, the main pulmonary is divided just proximal to the takeoff of the branch pulmonary arteries and the distal pulmonary artery confluence is patched. Although the heart is beating, there is no risk of air embolism among patients with aortic atresia. For patients with a patent aortic valve, the risk of air embolism can be minimized by ensuring correct vent placement and waiting until hypothermia renders cardiac contractions ineffective. This is confirmed by a nonpulsatile arterial waveform trace. Alternatively a small vascular clamp can be placed across the pulmonary root to prevent entrainment of air.

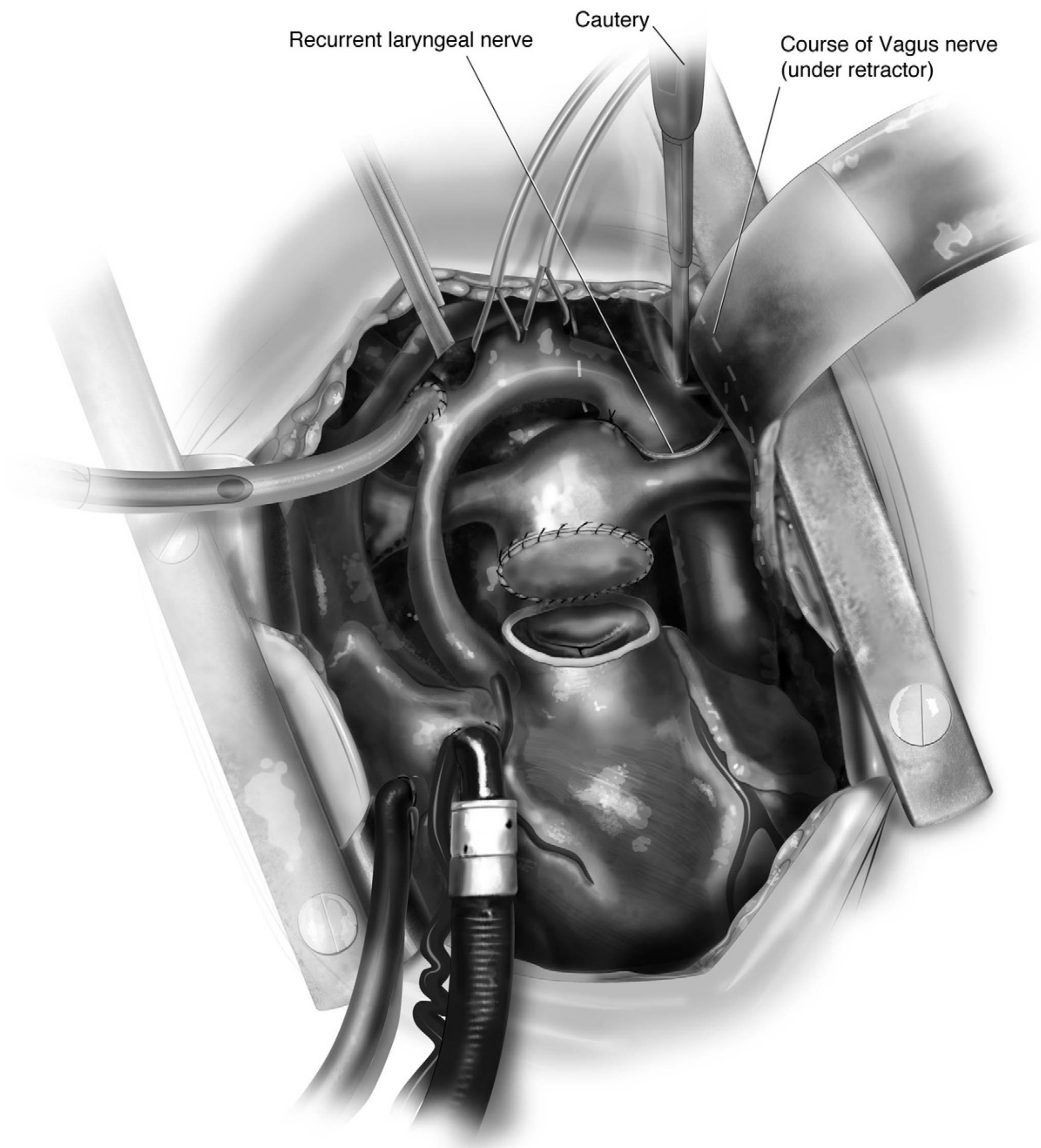

Figure 4 Mobilization of the proximal descending aorta. After the pulmonary artery confluence is patched, the ductus arteriosus is ligated and the proximal descending aorta is mobilized during the final 10 minutes of cooling. An insulated malleable retractor is used to retract the pericardium and pleura. An insulated cautery is used at low settings to divide the first 2 or 3 sets of intercostal branches. The use of an insulated retractor and cautery tip minimizes the risk of recurrent nerve injury.

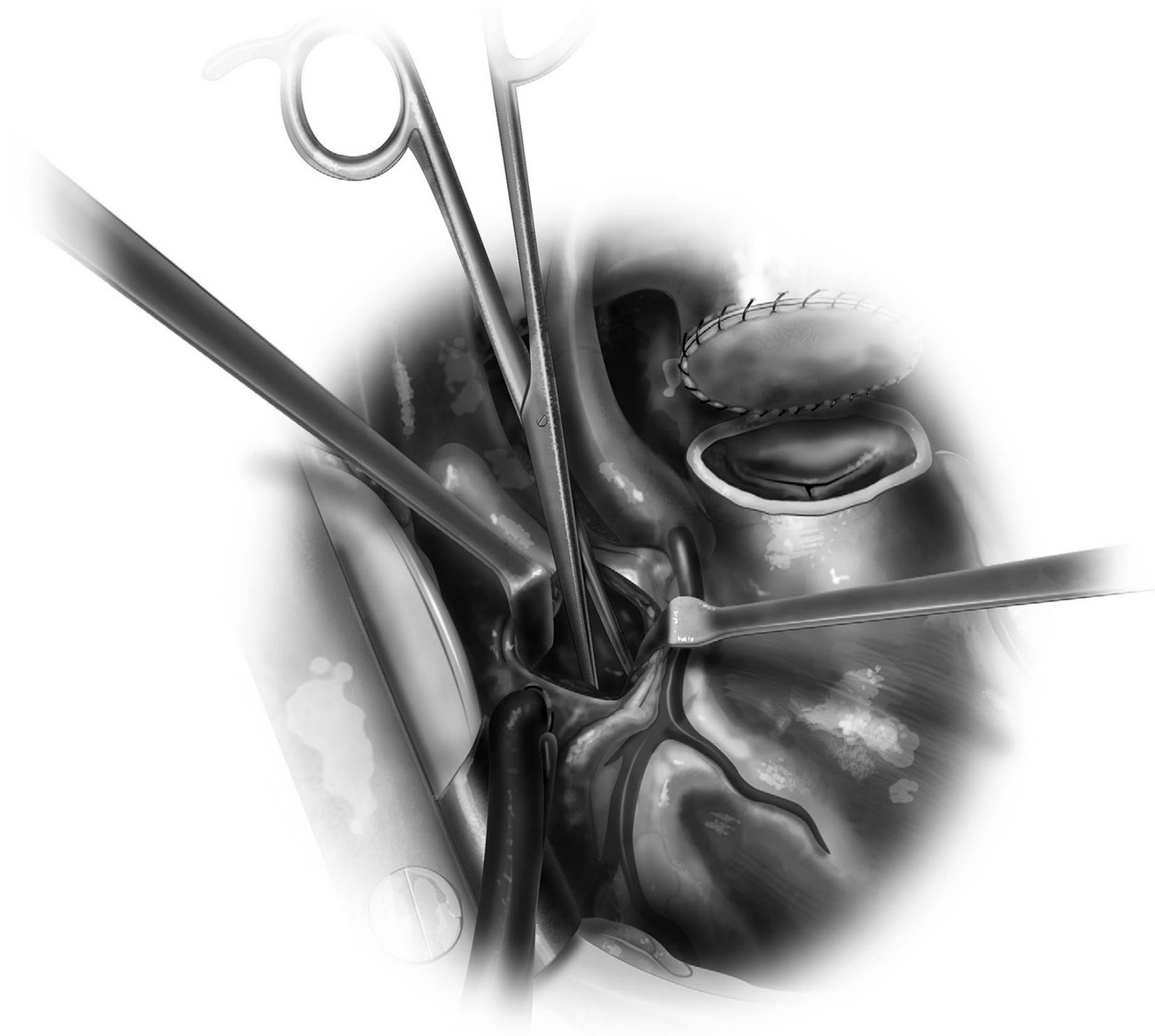

Figure 5 Atrial septectomy. After cooling for at least 30 minutes and reaching a bladder temperature between 18 and 20°C, circulatory arrest is established. The arterial line is clamped; the brachiocephalic vessels are snared, and the descending thoracic aorta is clamped. Cardioplegia is delivered via a side arm on the arterial cannula. After cardioplegia is being delivered, the venous cannula is removed and an atrial septectomy is performed.

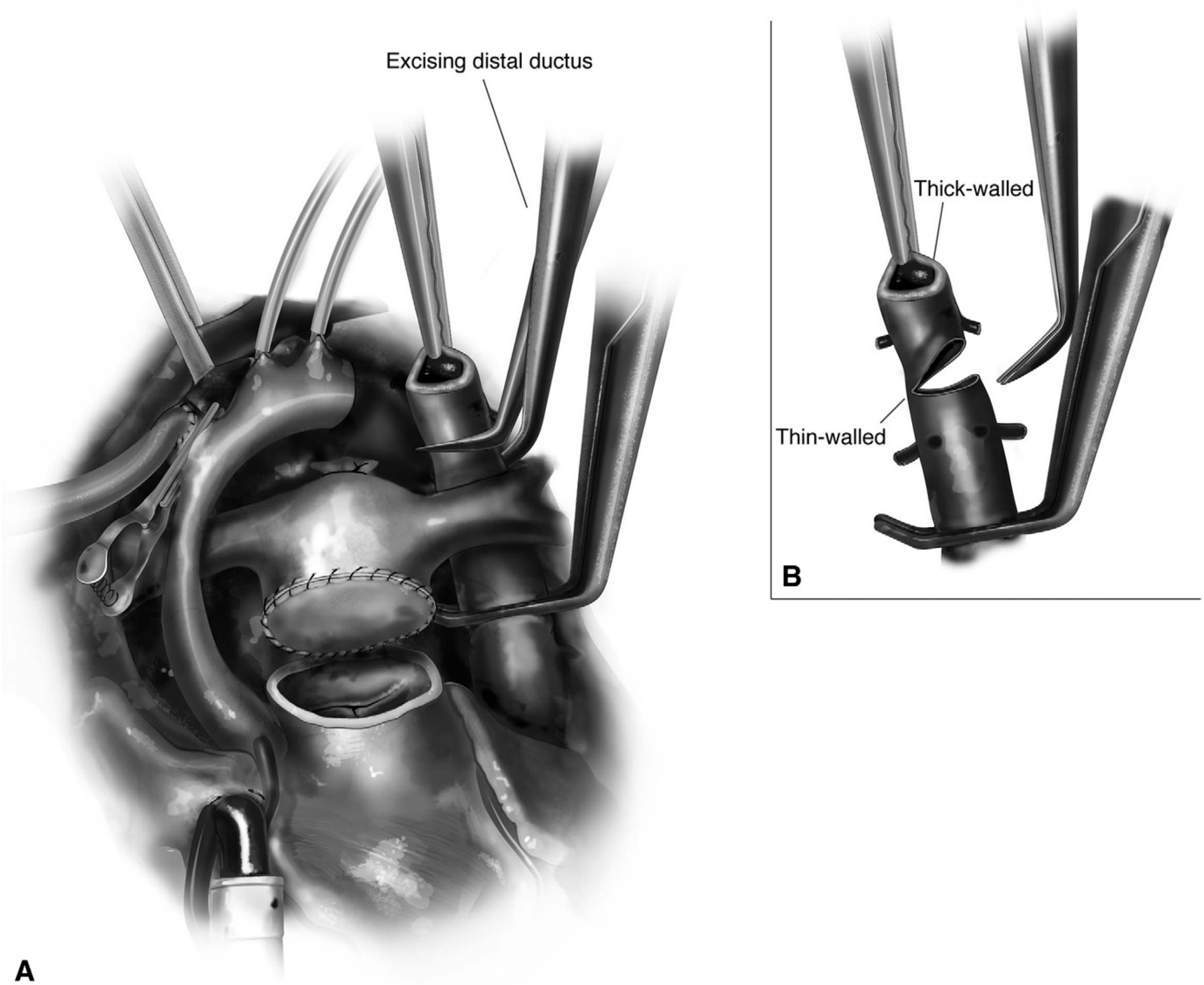

Figure 6 Initiation of continuous cerebral perfusion (A) and excision of the ductus arteriosus (B). (A) After delivering cardioplegia and completing the atrial septectomy, cerebral perfusion is initiated. A fine vascular clamp is placed across the origin of the innominate artery; the snares on the right subclavian artery and right common carotid artery are loosened and antegrade flow is established. Because of the extensive collateral flow in a neonate, the snares on the left common carotid artery and left subclavian artery as well as the descending thoracic aortic clamp must remain on throughout the period of cerebral perfusion. (B) The aortic isthmus is divided and the ductus arteriosus is divided just distal to the ligature on the pulmonary artery side of the ductus. All residual ductal tissue is excised from the descending thoracic aorta. Two indicators are used to ensure that the ductal tissue is completely excised. First, the arterial duct is thicker walled and the texture more friable than the true descending aorta. Excision is continued until thin-walled normal textured artery is encountered. Second, the excision is continued to within 2-3 mm of the first set of intercostal branches. Because the intercostal arteries arise from the descending thoracic aorta and not the ductus arteriosus, this will further ensure complete excision of the ductal tissue.

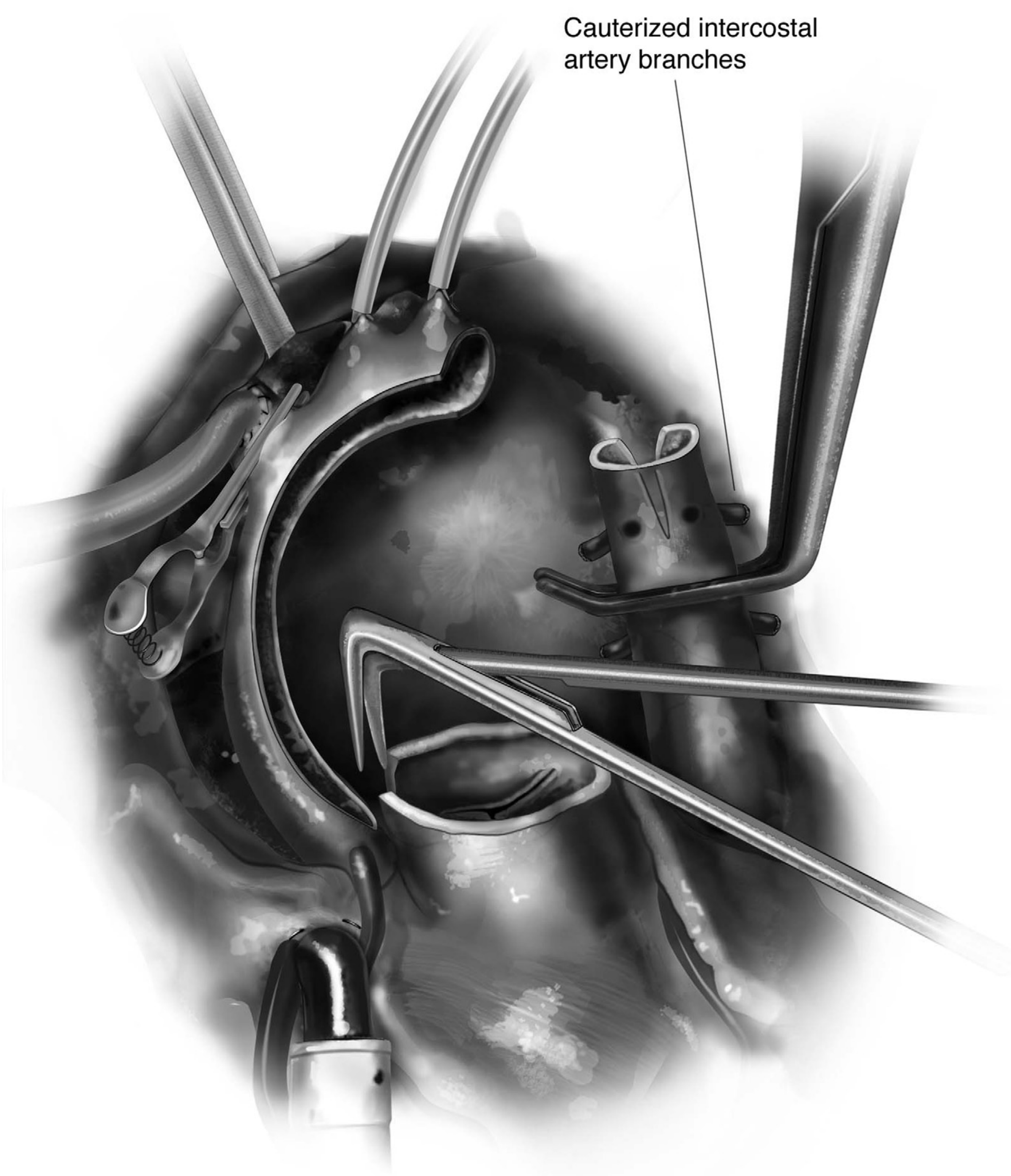

Figure 7 Arch reconstruction. The undersurface of the aortic arch is incised beginning at the open aortic isthmus and extending proximally down the ascending aorta. Great care must be taken with the diminutive ascending aorta to avoid spiraling down the ascending aorta. The incision must end precisely at the kissing point between the ascending aorta and the pulmonary root. A cutback is made in the pulmonary root at the site of implantation of the ascending aorta. The posterior commissure of the pulmonary valve is adjacent to the ascending aorta and the cutback extends about 2 mm below the sinotubular junction just left of this commissure. It is also important to end the aortic incision 2-3 mm cephalad to the level of the pulmonary root cutback. This results in a small degree of redundancy in the proximal ascending aorta and ensures a patulous nonstenotic connection between the aortic root and the pulmonary root. A cutback is also made into the posterior left lateral descending thoracic aorta. After excision of the ductal tissue, the first set of intercostal vessels should be close to the proximal end of the descending thoracic aorta. Mobilization of proximal descending aorta is necessary to permit the reconstruction of the distal aortic arch.

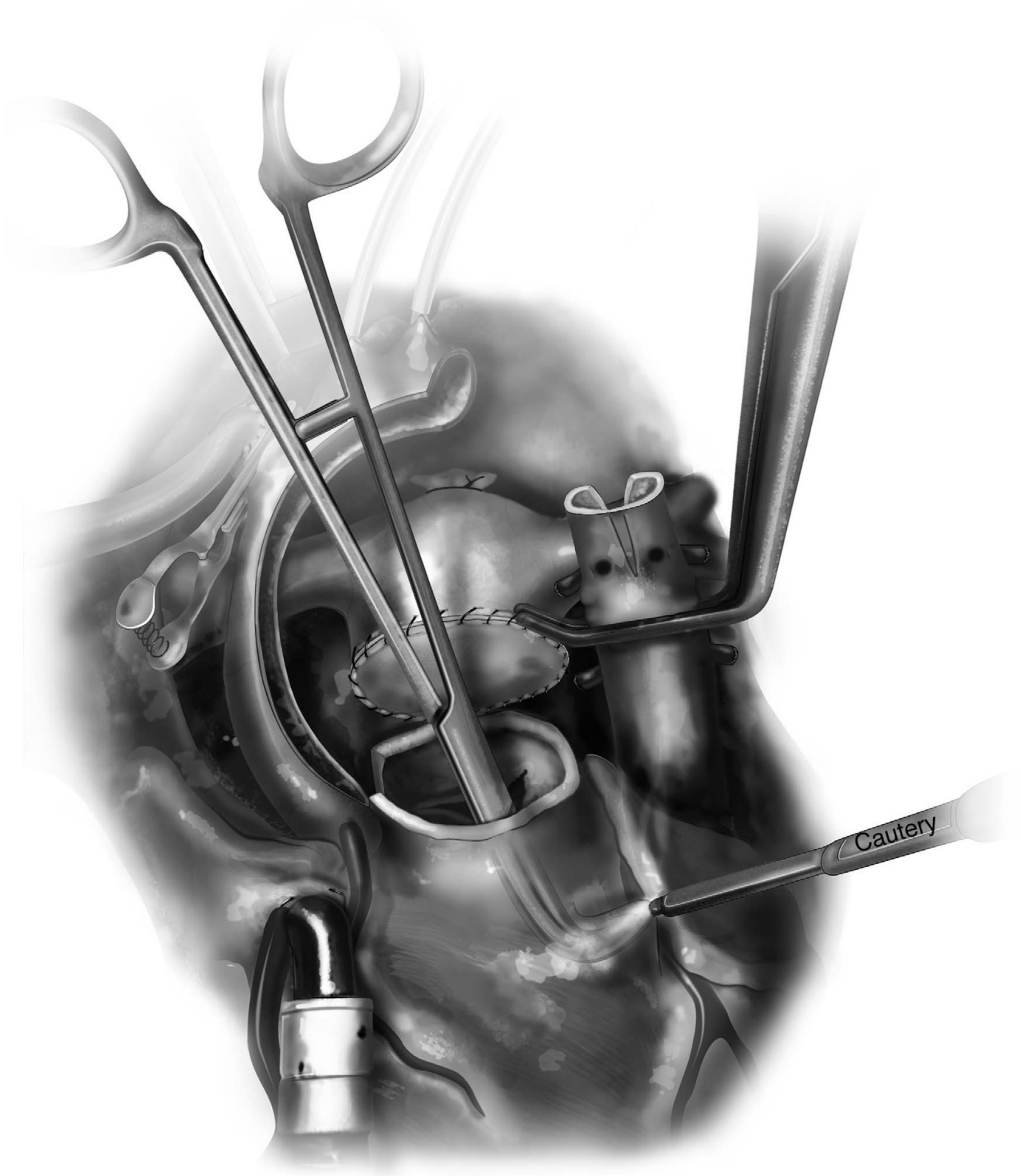

Figure 8 Identifying the site for the proximal RV-PA conduit connection. While the pulmonary root is open, a small right-angle clamp is directed across the valve. A site for the proximal RV-PA conduit is identified at least 1 cm below the nadir of the pulmonary valve cusp and well away from any large epicardial coronary arteries. This site is marked with the electrocautery.

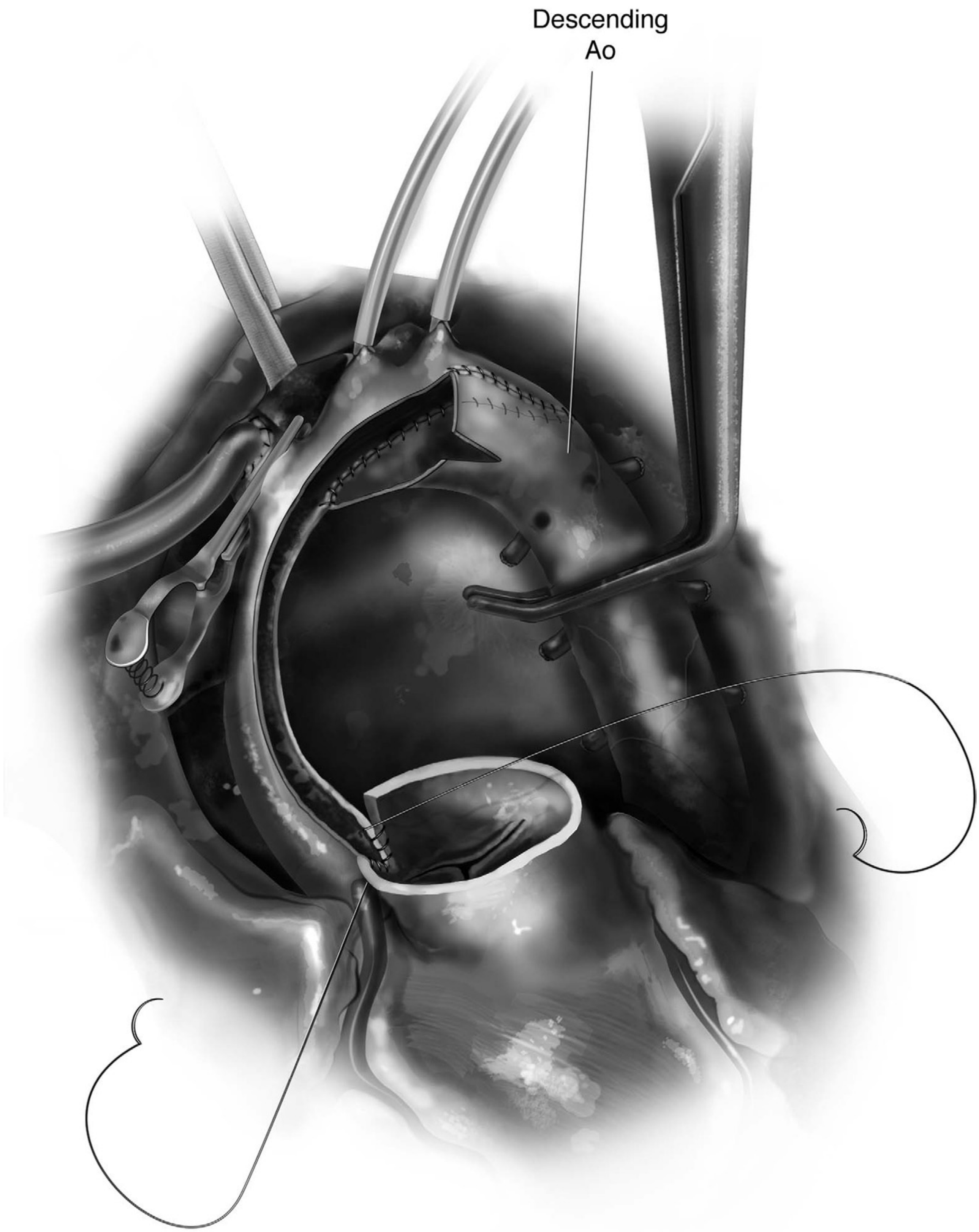

Figure 9 Arch reconstruction, continued. The opened distal arch is interdigitated into the cutback in the proximal descending aorta and the posterior walls sutured together with 7-0 prolene suture. The clamp on the descending thoracic aorta assists with pulling it up and approximating it to the distal arch. A second small, 2- to 3-mm cutback is made in the anterior portion of the descending aorta. The connection between the adjacent sites on the ascending aorta and the cutback in the pulmonary root are accomplished with 7-0 prolene or 8-0 prolene in the case of a very small (≤2 mm) ascending aorta. Ao = aorta.

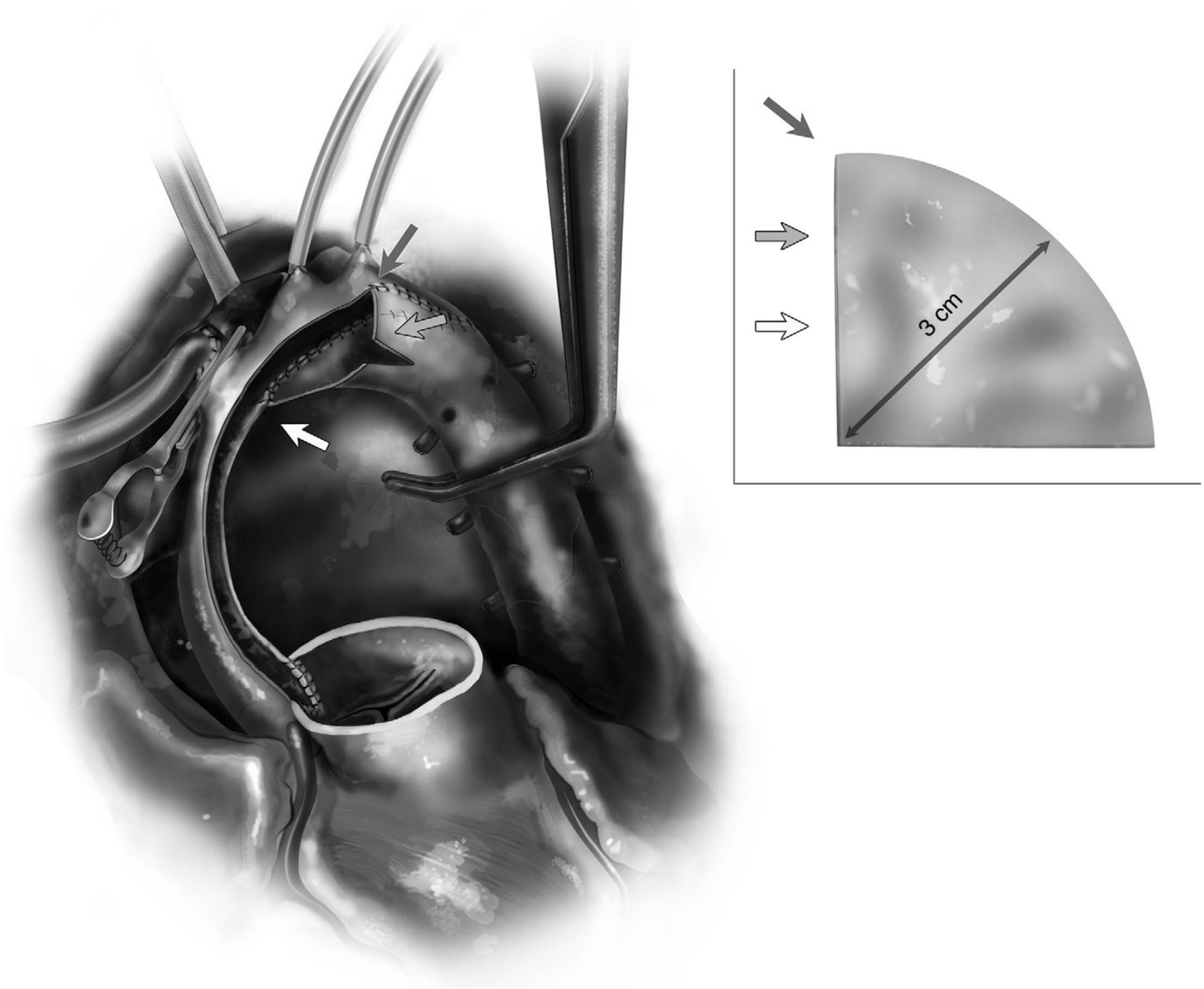

Figure 10 Arch reconstruction, continued. A patch is used for completion of the arch reconstruction and creation of the neoascending aorta. This patch is a quarter circle with a radius of 3 cm and can be pulmonary homograft, pericardium, or porcine small intestinal submucosa (CorMatrix, Alpharetta, GA). The straight edge will be sewn down the left edge of the ascending aorta; the arrows in the figure indicate the alignment.

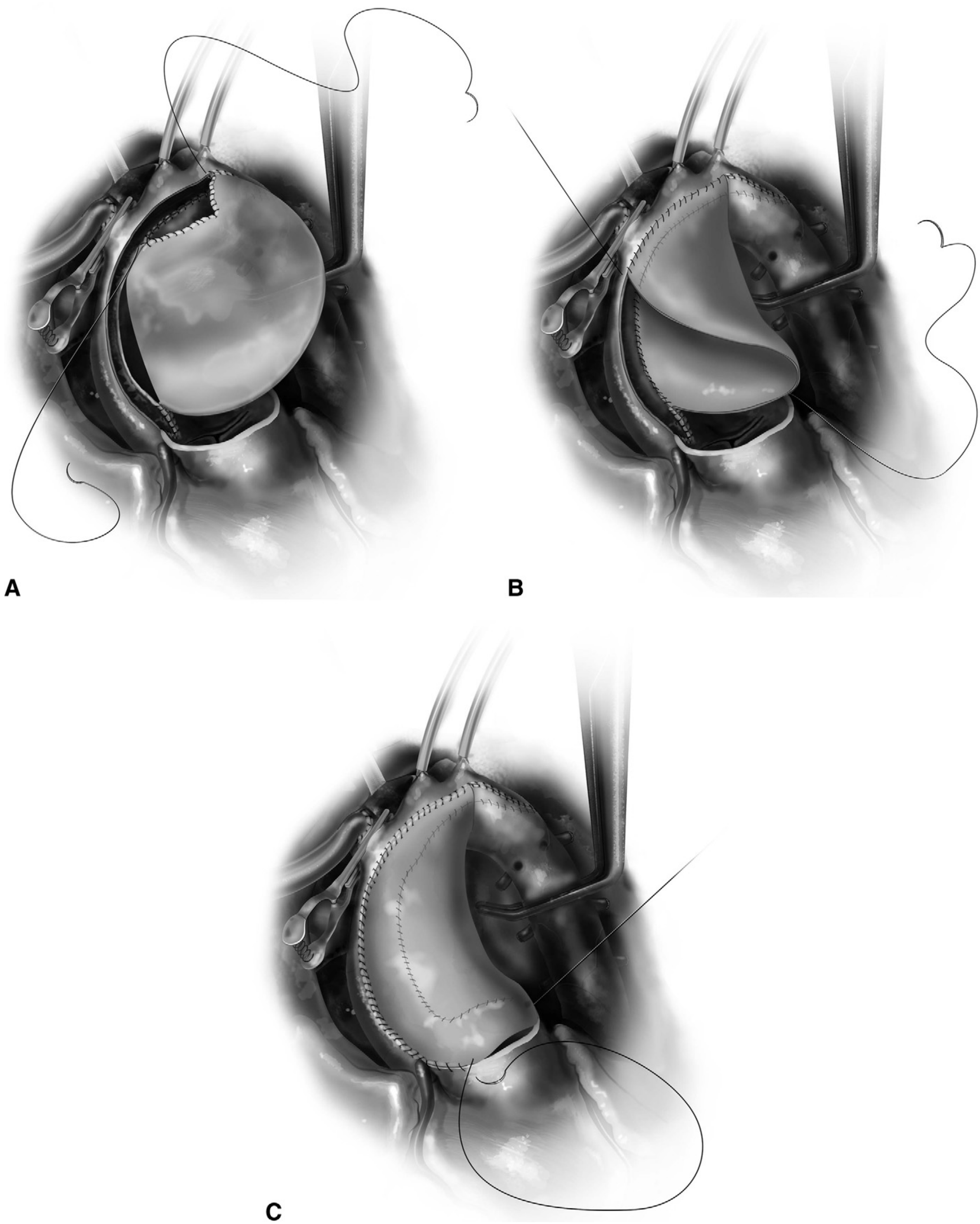

Figure 11 Arch reconstruction, continued. (A) The straight edge of the patch is sutured along the anterior cutback in the descending aorta and down the left side of the ascending aorta. (B) The curved edge is sewn to the right edge of the ascending aorta. When the junction of the ascending aorta and pulmonary root is reached, the excess patch is trimmed and the proximal connection between the patch and the pulmonary root is completed. (C) After the proximal patch is trimmed, the neoaorta is completed.

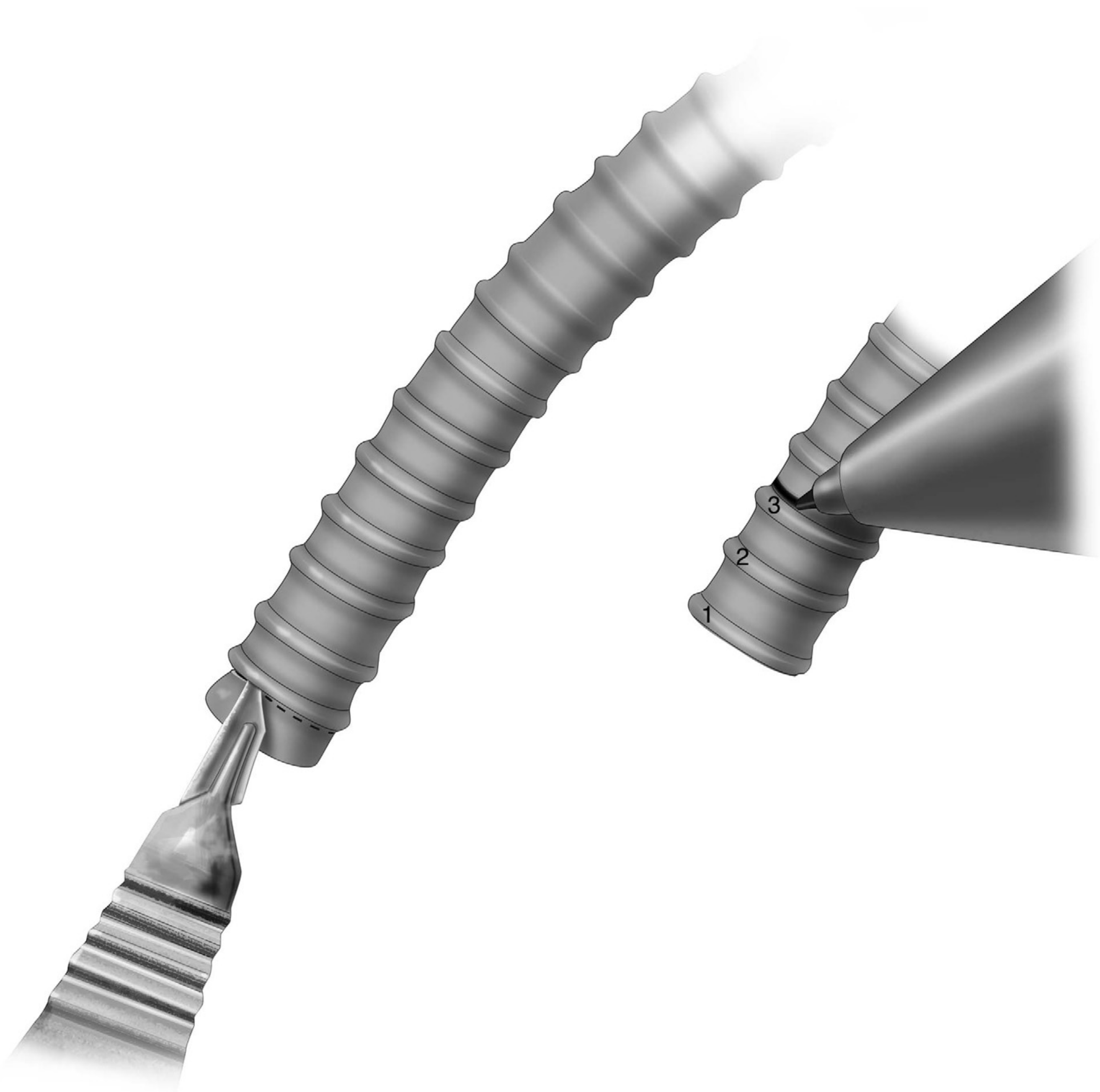

Figure 12 Construction of the RV-PA conduit. A ringed Gore-Tex tube graft is brought up and one end is cut flush with the external ring. A marking pen is used to mark the third ring from the end. This corresponds to the thickness of the RV free wall and ensures that only a millimeter or two of the graft protrudes into the RV cavity. If too long a portion of the graft is placed within the RV cavity, the conduit can contact the opposite wall of the ventricle, resulting in obstruction.

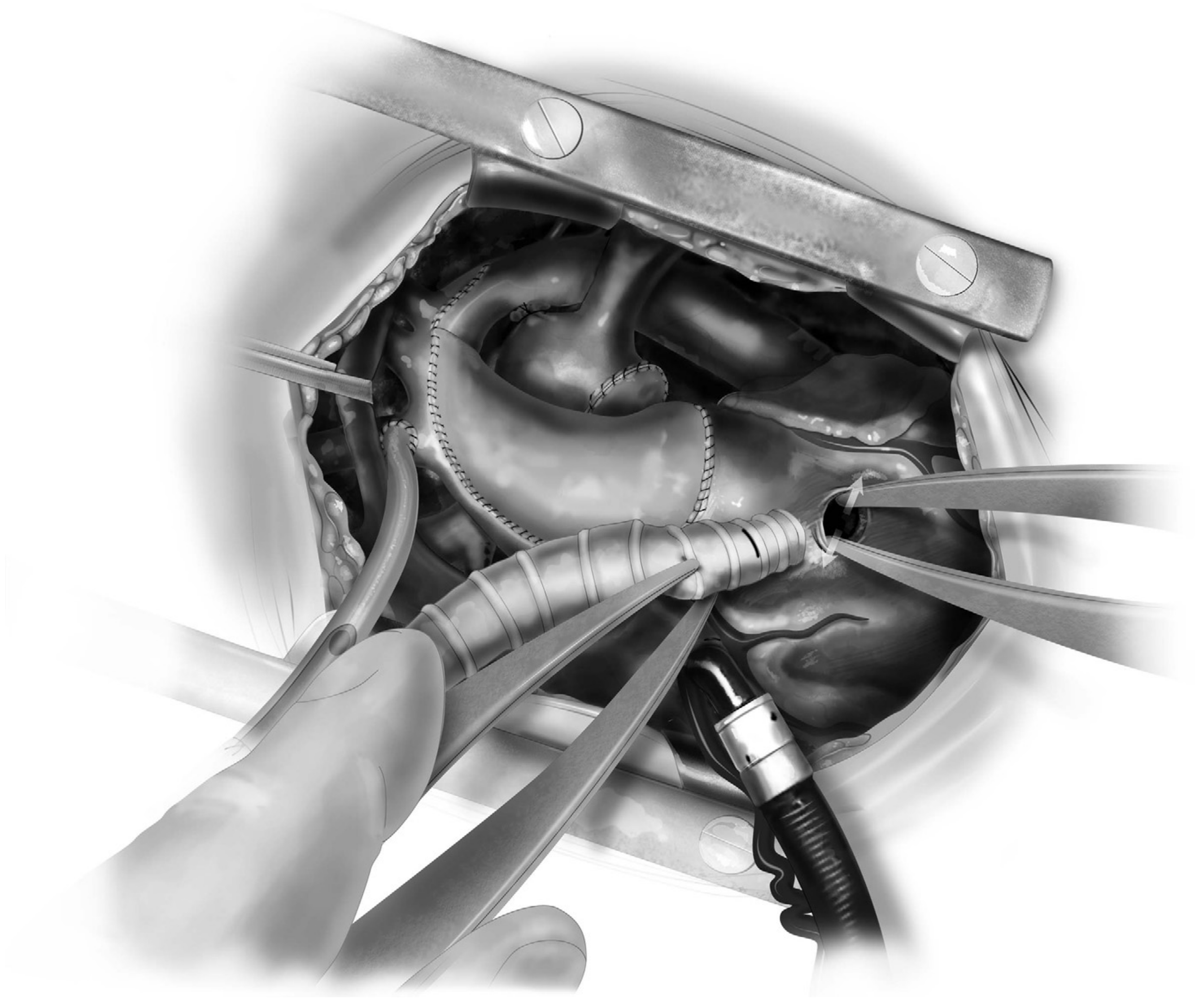

Figure 13 Construction of the RV-PA conduit, continued. A stab incision is made in the RV free wall at the previously identified site for the proximal RV-PA conduit connection. No muscle resection is necessary. The graft is then inserted across the RV free wall into the RV cavity.

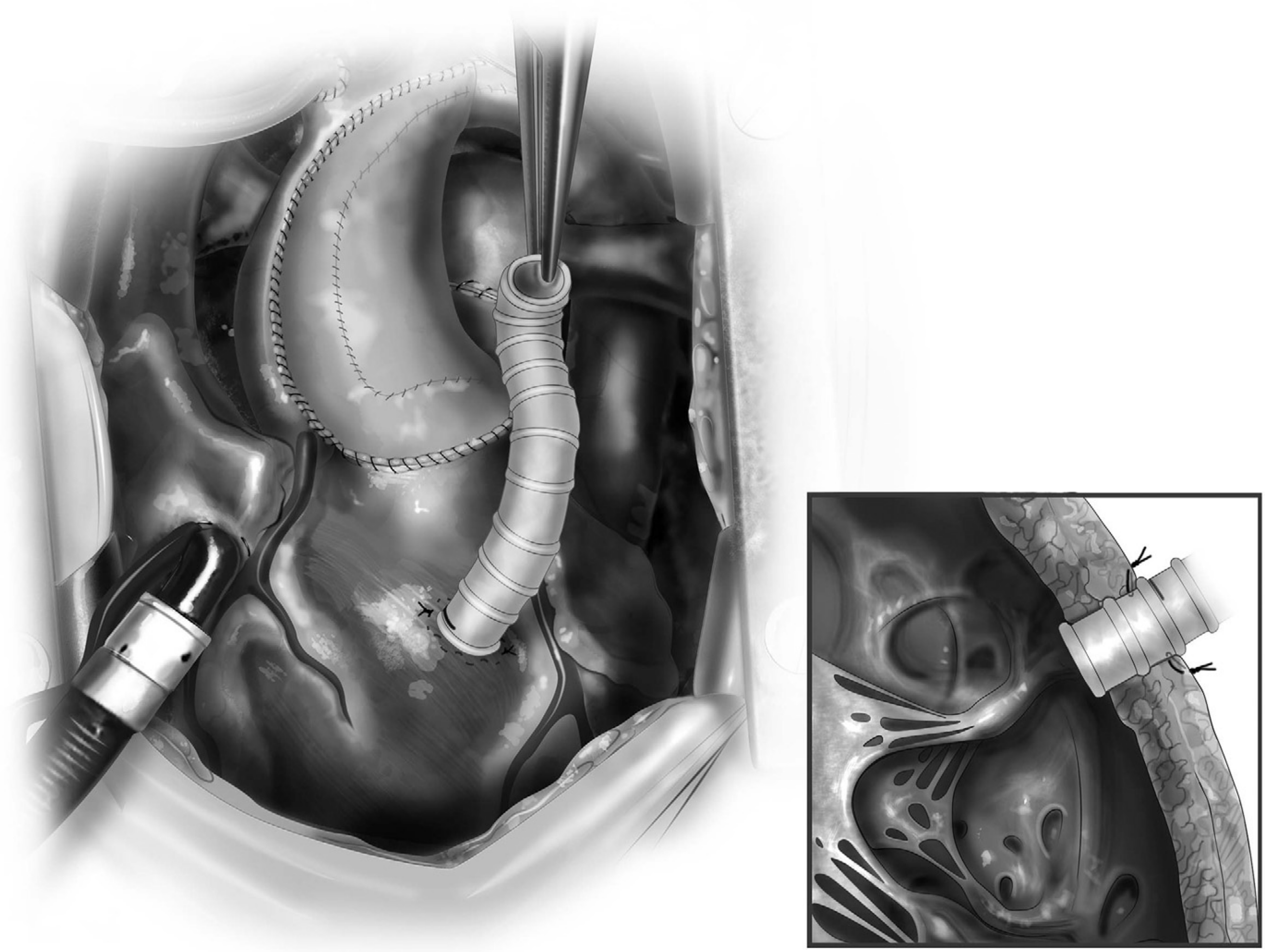

Figure 14 Construction of the RV-PA conduit, continued. The ringed Gore-Tex tube graft is positioned so that the third ring from the end is flush with the epicardium. This ensures that only a millimeter or two of the graft protrudes into the RV cavity. Two 6-0 prolene purse-strings are used to tighten the epicardium around the proximal conduit. No additional fixation sutures are used.

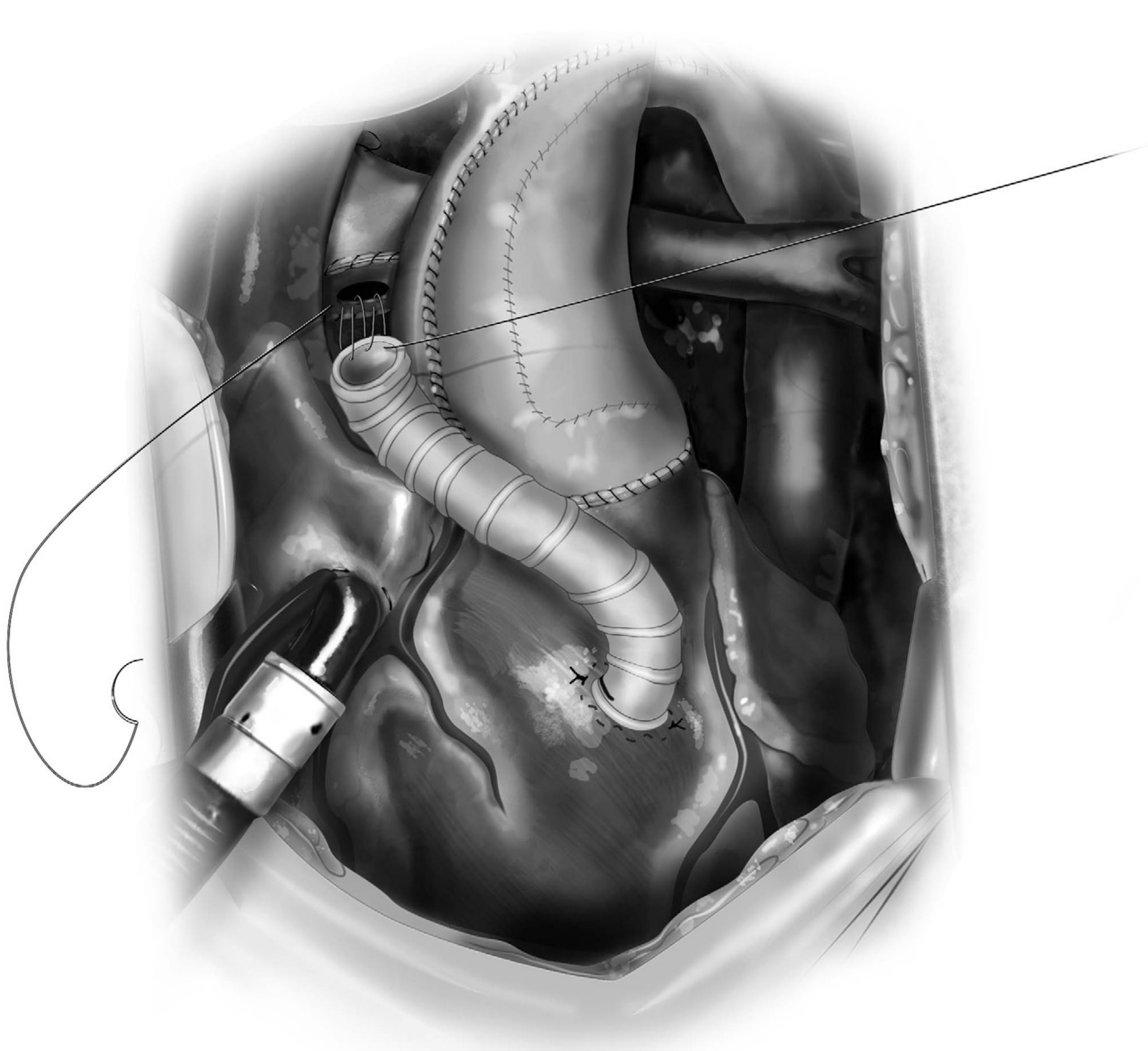

Figure 15 Construction of the RV-PA conduit, continued. The conduit is positioned to the right of the neoascending aorta. The branch pulmonary arteries are fully mobilized and this allows the central pulmonary artery to be positioned to the right of the neoascending aorta. An arteriotomy is made in the pulmonary artery patch and the distal RV-PA connection is completed with 8-0 prolene.

Discussion

Since February 2008, 85 patients with hypoplastic left heart syndrome underwent a Norwood procedure at the Children's Hospital of Wisconsin and 40 had the RV-PA modification illustrated in this article. These 40 patients included 15 high-risk patients representing 37.5% of the cohort. Risk factors included 7 patients with prematurity or low birth weight (<2.5 kg), 3 patients with genetic syndrome (1 patient each with DiGeorge, chromosome 1 deletion, and undefined genetic syndrome), 4 patients with intact or highly restrictive atrial septal communications, 4 patients with other anomalies of pulmonary venous drainage including partial anomalous pulmonary venous connection (n = 1) and Scimitar syndrome (n = 3), and 1 patient with anomalous origin of the coronary artery from the pulmonary artery. There were 3 patients with heterotaxy syndrome. Four patients had more than 1 risk factor. Despite a substantial number of high-risk patients, there were only 4 hospital deaths for a stage 1 survival rate of 90%. There were 3 additional late deaths at 8, 9, and 13 months of age and 3 patients have been successfully transplanted. Only 1 patient required revision of the RV-PA conduit. In this case the intracavitary portion of the conduit was too long and obstructed when it came too close to the posterior wall of the ventricular cavity. This was revised and the patient is a long-term survivor. One additional patient developed excessive neointimal buildup in the proximal conduit and underwent an early bidirectional Glenn shunt.

The RV-PA conduit has been shown to result in improved survival in a subset of patients undergoing the Norwood procedure.[7] This survival benefit occurred despite an increased incidence of reintervention directed at the RV-PA conduit.[2] The benefit of the technique outlined here is the decreased risk of proximal obstruction. In addition, with this technique only a stab incision in the RV free wall is required and there is no need to resect additional RV muscle. Less RV muscle re-

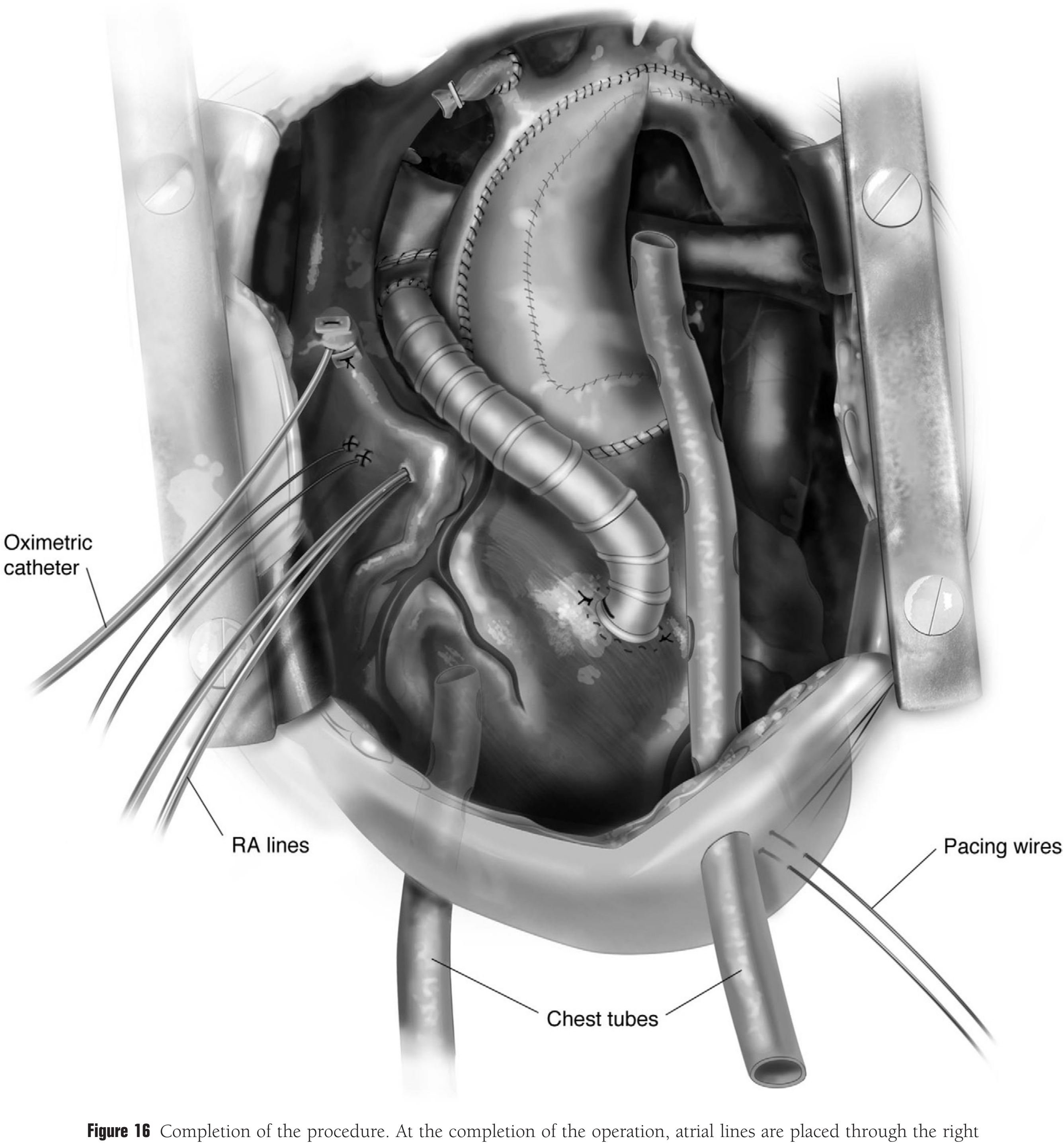

Figure 16 Completion of the procedure. At the completion of the operation, atrial lines are placed through the right atrial appendage cannulation site for additional central venous access. An oximetric catheter (Abbott Laboratories) is placed in the superior vena cava through a small felted purse-string suture. Although conduction problems are rare, arrhythmias are common and therefore both atrial and ventricular pacing wires are placed. We routinely leave the chest open. The sternotomy is closed once the patient begins to diurese and when vasoactive drug support has been weaned to low levels. Typically chest closure is performed on postoperative day 2 or 3. RA = right atrium.

section could result in better long-term single ventricle function.

The goal for the Norwood procedure is to create a stable anatomy that optimizes the potential for subsequent single ventricle palliation. Successful reintervention on residual or recurrent lesions is possible and may in some cases ameliorate the impact of residual or recurrent lesions.[8,9] There are, however, data that show that residual or recurrent lesions will contribute to interstage deaths and that the cumulative hemodynamic burden will impact long-term survival and potentially impact neurodevelopmental outcome.[10,11] Although the technique illustrated above has resulted in a low rate of reintervention on both the arch and the proximal RV-PA conduit, this strategy does use continuous cerebral perfusion. The summed risk–benefit ratio of continuous cerebral perfusion with longer total support time and exposure to the cardiopulmonary bypass circuit vs the diminished risk of recurrent or residual lesions are of course difficult to define and will require additional study. Current neurodevelopmental outcomes using these strategies are at least consistent with other contemporary outcomes and perhaps provide some reason to be optimistic concerning this perfusion strategy.[12]

Conclusions

The "dunk" technique of proximal RV-PA conduit construction in which a ringed Gore-Tex conduit is placed through the entire thickness of the RV free wall is simple to perform and results in a low incidence of reintervention directed at the conduit and excellent survival.

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