In failing Ross procedures, preserving the autograft in the aortic position is ideal if there is autograft root dilation with symmetrical cusps resulting in central regurgitation and if the pulmonary allograft is functional. However, this may not be possible if the autograft has more extensive dysfunction, asymmetric dilation, and eccentric regurgitation. Therein, the idea of the Ross reversal was conceived and first published in 2007 due to our increasing experience with autograft reoperations, allograft reoperations, and valve-sparing root reimplantations. Despite the Ross reversal being a relatively long and technically demanding operation, we believe that aortic root surgeons experienced with the various aspects of Bentall, allograft, Ross, David, and other advanced aortic root procedures should have the necessary skills to reliably and reproducibly achieve success. The core tenets of the Ross reversal are as follows:

1. An autograft valve in the aortic position that functions adequately to keep the patient alive and with reasonable quality of life should be acceptable in the pulmonic position. This is because the stress and pressure on a valve are lower in the pulmonic position than on the systemic side of the circulation, and patients tolerate residual pulmonic valve regurgitation much better than aortic valve regurgitation.

2. A live autograft should have better longevity back in the pulmonary position than another pulmonary allograft or xenograft valve.

In this review, we provide a step-by-step illustrated technique as well as detail our experience with the Ross reversal. Although more experience and long-term follow-up is needed, we believe that salvaging a failing pulmonary autograft in the aortic position by reimplanting it back in its native position will provide patients with durable benefit.

**PREOPERATIVE EVALUATION AND PLANNING**

Routine preoperative imaging for patients being considered for a Ross reversal includes a transthoracic echocardiogram with evaluation of the autograft valve function, severity of pulmonary valve dysfunction, both right and left ventricular size and function, and any other associated abnormalities that may require intervention. A gated computed tomography scan with contrast is performed for evaluation of the aortic/autograft root size, symmetry, and calcification as well as the size and calcium burden in the ascending aorta and aortic arch. Based on the computed tomography scan, the strategy and safety of re-entry is also decided (magnetic resonance imaging is not precise enough). If peripheral cannulation is needed, our preference is right axillary artery and right femoral vein.

The primary indication for Ross reversal has been autograft regurgitation, with most cases caused by autograft root dilation. Backup options should the autograft not be good enough or if the autograft is damaged during the dissection are discussed with the patients. Arguments can be made for whether severe pulmonary allograft dysfunction is required to justify replacement with a less-than-perfect recycled autograft; however, we have become increasingly comfortable with having a lower threshold
for doing so, since no patients in our series have required a repeat intervention on the right side during follow-up.

**SURGICAL TECHNIQUE**

After anesthetic induction, patients receive a central line with pulmonary artery catheter, arterial line, Foley catheter, and transesophageal echocardiogram probe for the procedure. After re sternotomy, the right side of the heart and the aorta are fully dissected out, with careful attention to staying in the correct plane to minimize bleeding. Intravenous heparin bolus is given for anticoagulation for a target activated clotting time of >480 seconds with additional heparin given throughout the procedure per institutional protocol. Arterial cannulation is performed in either the distal ascending or proximal aortic arch depending on coexistent ascending and arch pathology, and venous cannulas are inserted in the superior vena cava and inferior vena cava. The space between the aorta and pulmonary artery is carefully and widely opened, as this plain is typically obliterated up to the previous allograft to pulmonary artery anastomosis. After applying the crossclamp, myocardial protection is provided with induction antegrade and retrograde cold blood cardioplegia (Buckberg). Caval tapes are placed, and the right atrium is routinely opened for direct cannulation of the coronary sinus with a purse-string suture for secure retrograde cardioplegia delivery. Repeated doses of retrograde cardioplegia are delivered for 2 minutes every 15-minute interval. At this point, if the left side of the heart has not yet been dissected free from adhesions, we do this following cardiopulmonary arrest. This dissection is performed by first defining the pericardial border and then extending the dissection only as far as is needed for the pulmonary root replacement. If required, a left atrial vent is placed through an incision of the fossa ovalis of the interatrial septum.

Next, the aorta is transected immediately above the distal autograft anastomosis and the autograft root is carefully dissected out down to the level of the aortic annulus, exactly as we would do for a David reimplantation procedure, with care taken not to injure the coronaries in the process. The aortopulmonary window is dissected free, with care taken to not injure the right branch of the pulmonary artery, starting the dissection from right under the aorta progressing towards the allograft anastomosis where the plane usually is obliterated. The coronary buttons are excised and mobilized from the autograft root early while maintaining a good rim of healthy tissue around each ostium. The autograft and the pulmonary allograft are usually plastered together, making the identification of the plane difficult, and therefore, we err on the side of leaving allograft tissue on the autograft rather than vice versa.

Careful intraoperative assessment of the autograft valve is performed with attention paid to the overall calcium burden, presence of fenestrations, symmetry, and cusp height. Calcium is often present around the annulus, particularly if the annular anastomosis was previously buttressed with bovine pericardium or felt. The Ross reversal is possible, even if there is significant amount of calcium as most of this can be trimmed carefully. As mentioned previously, if the valve cusps are symmetrical and of good shape and quality, our preference is to forego the Ross reversal and perform a David reimplantation; however, this decision has usually been made ahead of time based on the pre-bypass echocardiogram. Of note, significant annular calcium would prevent reimplantation, so its presence should factor into the decision-making. If the autograft valve or conduit is too far damaged and not able to be repaired, we proceed with aortic root replacement with either a valved-conduit or aortic allograft plus another pulmonary allograft or valved-conduit replacement on the right side, in accordance with our preoperative discussion with the patient. In our experience, we have found most commonly that the autograft valve quality is concerning for durability in the aortic position but good enough to be acceptable for Ross reversal.

Once the decision is made to proceed with the Ross reversal, the fibrous connection between the autograft and the left ventricular outflow tract muscle is cut in the middle (Figure 1). This fibrous skirt is typically 5-10 mm wide. By cutting the middle of the skirt, this allows for a 3- to 4-mm rim of healthy tissue on the proximal portion of the autograft that can then be reimplanted on the right side of the heart while simultaneously leaving enough tissue on the aortic annulus for safe implantation of a new aortic valve. This rim allows for maintaining the native geometry and helps avoid infringing on the conduction system. If felt was previously used for support of the proximal suture line this may present with calcification, although in our experience we have usually been able to debride all the calcium without injuring the autograft valve.

Once the autograft has been procured, back-table preparation is performed. The autograft is inspected and refashioned to recreate the native pulmonary root geometry as best as possible (Figure 2). This is done through direct suture of defects or augmentation of these defects with excised excess aortic or autograft tissue or autologous pericardium. Most often we are able to suture close with a running 5-0 PROLENE the defects made from excising the coronary ostium from the autograft root; however, a patch can be used. During the initial steps of mediastinal dissection, we look for and identify areas where we can harvest autologous pericardium if needed for autograft repair. Cusp manipulations and repairs have been performed as needed without overdoing it.

We then turn our attention to the right ventricular outflow tract, where there is usually a pulmonary allograft present. We excise the conduit completely, leaving as little allograft, foreign material, and scar tissue behind as possible but without risking damage to the left coronary (Figure 3).
The left main and first septal artery are close; therefore, it is imperative to stay on the allograft during dissection. The underside of the excised pulmonary conduit is an area that is prone to bleeding, so meticulous attention is paid at this step to achieve perfect hemostasis. Retrograde cardioplegia is given to help identify any points of bleeding, and we use a combination of Bovie and suture ligations with 6-0 PROLENE to proactively secure hemostasis.

Next, an aortic root replacement is performed with either a composite graft (mechanical or bioprosthetic depending on patient preference) or an aortic allograft. The proximal anastomosis is first performed to the new aortic annulus (Figure 4). Depending on the conduit chosen, we prefer to do interrupted pledgeted ETHIBOND sutures for valved conduits and a running 4-0 PROLENE suture for aortic allografts using a parachute technique. Once completed, the coronary buttons are then reimplanted into the new aortic root (Figure 4, illustrated insert).

Once both coronary button anastomoses are completed, the reconstituted pulmonary autograft is reimplanted on the right side using a continuous 4-0 PROLENE suture. Access to the pulmonary artery and right ventricular outflow tract is easier before completion of the distal aortic anastomosis. The distal autograft to pulmonary artery anastomosis is performed first, followed by the proximal autograft to the right ventricular outflow tract anastomosis (Figure 5). We orient the pulmonary autograft according to the best size and shape as dictated by the unique anatomy present. We have found that for most cases the original orientation (which is easy to identify) has been the best orientation. Lastly, the aortic valved-conduit is anastomosed to the distal native aorta (Figure 5, illustrated insert). Following a warm dose of terminal cardioplegia, the crossclamp is removed and the heart is allowed to reperfuse.

Post-bypass transesophageal echocardiogram is performed to evaluate the function of the pulmonary autograft.

FIGURE 1. Following dissection of the autograft root and subsequent transection of the aorta, the coronary buttons are mobilized in standard fashion. The autograft root is then excised from the aortic annulus leaving a 3- to 4-mm rim of tissue on the native aortic annulus and a 3- to 4-mm rim of tissue on the pulmonary autograft.

FIGURE 2. Reconstitution of the pulmonary autograft.
in its native position and competency of the new aortic root valved-conduit as well as routine assessment of biventricular function. After appropriate deairing has been performed, the patient is weaned off cardiopulmonary bypass, decannulated, and protamine administered to reverse the effects of heparin. The mediastinum is policed for hemostasis, chest drains are placed, and the chest is closed in standard fashion. Before discharge, patients receive a transthoracic echocardiogram and a computed tomography scan.

**OUR EXPERIENCE**

In 2017, we published our series of Ross reversals and their short and mid-term outcomes. In 39 patients undergoing reoperation for failing autografts, 30 of 39 underwent Ross reversal, 4 of 39 had a David reimplantation procedure, 1 of 39 had an autograft repair, and 4 of 39 patients were unable to have their autograft salvaged. Of the 30 patients undergoing Ross reversal, the median time interval from the original Ross procedure to Ross reversal was 12 years (range, 5-19 years). There were no operative mortalities, and 1 patient required reoperation for bleeding. The average crossclamp and cardiopulmonary bypass times were 143 minutes and 174 minutes, respectively. One patient developed renal failure requiring dialysis as well as prolonged ventilation, and 5 patients developed postoperative atrial fibrillation, with no other occurrences of major postoperative morbidity for the remaining patient cohort. The median hospital length of stay was 7.2 days (range, 4-41 days). During a median follow-up of 4.1 years (range, 7 months to 11 years), no patients required reoperation, 24 patients were free of pulmonary valve dysfunction, and 6 patients had clinically tolerated moderate or greater pulmonary valve regurgitation.

After publishing our series, we have performed 11 more reoperations in patients with a failing Ross procedure. Of

**FIGURE 3.** Excision of the dysfunctional pulmonary homograft.

**FIGURE 4.** Proximal aortic root anastomosis for a valved-conduit. Alternatively, an aortic allograft is also used depending on the case specifics. Coronary buttons are anastomosed in standard fashion (illustrated insert).
these 11 additional operations, there were 6 Ross reversals, 2 David reimplantations, and 3 Bentall procedures. Our follow-up of these patients continues to demonstrate similar good results, with no patients requiring reoperation although admittedly longer-term follow-up is still needed. A commentary accompanying our published series expressed skepticism but the author admitted that “Perhaps there is a place for this procedure in treating some patients, such as the 8 in this series, with absolute indications for allograft valve replacement.” In addition, it remains to be seen if our results can be replicated by others outside our institution, with recent published case reports demonstrating acceptance of the procedure. In the transcatheter era, percutaneous interventions are becoming increasingly used as first-line treatment for either left-sided or right-sided (or both) valve dysfunction in patients with a failing Ross. We would be remiss to not provide a word of caution about transcatheter “toxicity” when a reoperation at an expert referral center can provide a more durable result as well as provide the opportunity to salvage the autograft (Figure 6). In our hands, the procedure has been predictable and reproducible, with only one planned Ross reversal not being performed at the time of surgery.

CONCLUSIONS
To rescue the native pulmonary valve in patients with a previous Ross procedure, the Ross reversal is a viable option to consider in patients who have autograft root dilation, eccentric autograft regurgitation (not immediately inviting to a reimplantation), and a dysfunctional pulmonary allograft. Although experience is still limited, we believe that more widespread adoption of this procedure is possible in the hands of expert aortic root surgeons to afford patients the benefit of their own living valve. The availability of this option should also lower the anxiety about the Ross operation transforming a 1-valve disease into a 2-valve disease.

Conflict of Interest Statement
The authors reported no conflicts of interest.

The Journal policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict
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