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Surgical Management of Pulmonary Atresia With Ventricular Septal Defect and Major Aortopulmonary Collaterals: A Protocol-Based Approach

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Historically, outcomes of pulmonary atresia with ventricular septal defect and major aortopulmonary collaterals have been quite poor. Over the past 15 years, our group has strived to apply a consistent surgical strategy for this lesion based on two guiding principles: early unifocalization of all important collaterals; and the early establishment of a low-pressure pulmonary arterial bed, preferably using simultaneous intracardiac repair. We describe a management protocol that has been developed to handle the highly variable nature of pulmonary blood flow observed with this lesion.
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Pulmonary atresia with ventricular septal defect (PA.VSD) and major aortopulmonary collateral arteries (MAPCAs) is a complex lesion characterized by atresia of the pulmonary valve, a tetralogy type VSD, and pulmonary blood flow derived from systemic arterial collateral vessels. The natural history of this lesion is dismal, with less than 50% survival past 2 years and steadily increasing rates of patient attrition over time.[1] To improve these outcomes, earlier surgical approaches included an initial palliative procedure to increase pulmonary blood flow and stimulate growth of the true pulmonary arteries, followed by staged unifocalization.[2-5] The staged approach, however, has yielded disappointing results, as the majority of patients do not ultimately achieve complete repair with an acceptable pulmonary artery pressure.

The highly variable nature of the pulmonary blood flow with MAPCAs leaves the entire pulmonary vascular bed in a precarious state. Certain lung segments may be at risk for the development of pulmonary vascular occlusive disease, while other segments are simultaneously hypoperfused. These varying pulmonary "microclimates" contribute to a time-dependent risk of attrition of lung segments. For this reason, our surgical approach has been aimed at constructing a single compartment, unobstructed, low-pressure pulmonary circulation, preferably with a separated, two-ventricle circulation at an early age. This is most effectively achieved with a one-stage bilateral unifocalization early in life, before attrition of collaterals occurs or microvascular disease occurs. The technical approach relies on maximal use of native tissue, whether that tissue is of true pulmonary artery origin or of collateral origin.

Naturally, a successful regimen must be tailored to account for the complexity and variability of this lesion. While simultaneous intracardiac repair is the optimal goal, it must be recognized that for a certain proportion of patients, a staged approach may be necessary anatomic or physiologic limitations. Indeed, the intracardiac repair can, and should, only be performed once a low pulmonary vascular resistance can be assured. Only a broadly applicable surgical management protocol that is morphologically and physiologically driven, and adheres to the principles outlined above, can provide favorable results for the greatest numbers of patients with this lesion.

Management Strategy

Diagnosis

Owing to the inherent variability of the lesion, the clinical presentation can be marked by profound cyanosis or congestive heart failure, but typically is that of a relatively well-balanced, completely mixed circulation. The diagnosis is typically established by echocardiography in the newborn period, but higher-resolution delineation of the anatomy is mandatory prior to surgical intervention. Echocardiography

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is particularly useful to characterize the intracardiac anatomy, the presence of additional lesions, and coronary anomalies. The size of the proximal pulmonary artery and status of the pulmonary arterial confluence can be reliably determined as well.

Cardiac catheterization is an essential element of the surgical management, and should be performed in the neonatal period at the time of diagnosis. A detailed roadmap of all sources of pulmonary blood flow can be generated with angiography. To develop an effective surgical strategy, it is necessary to characterize the presence of, and arborization of, the true pulmonary arteries, and identify the origins and contributions of all aortopulmonary (AP) collaterals. Additionally, all communications between collaterals and the true pulmonary artery system must be clearly identified, in order to define lung segments that are "isolated supply" segments, perfused by collaterals only or by true pulmonary arteries only, and "dual supply" segments that are perfused by both collaterals and true pulmonary arteries simultaneously. Finally, all points of stenosis must be characterized in every collateral.

Of equal importance is the acquisition of hemodynamic data. Distal pressure measurements reveal important information about the health of the affected lung segments and the likelihood of a one-stage complete repair.

Timing of Repair

Our preference is to perform a midline complete bilateral unifocalization at between 3 and 6 months of age. This is appropriate in the large majority of patients. The rationale for this timing is that most patients will remain with stable cardiopulmonary physiology during these first few months, and that the intervention is early enough to avoid both the development of pulmonary vascular disease in high flow collaterals, and occlusion and loss of highly stenotic collaterals. The most important goal of this first operation is to create a one-compartment pulmonary artery system with normalized flow and pressure, such that normal vessel development can occur. Ideally, simultaneous intracardiac repair should also be performed, but only if low pulmonary artery pressure can be assured. If high pulmonary artery pressure is predicted with intracardiac repair, then the intracardiac repair is not performed at the time of the initial unifocalization, and an appropriately sized systemic to pulmonary artery shunt is performed that will ensure appropriate pressure in the pulmonary artery system.

Occasionally, intervention cannot wait until the ideal 3- to 6-month period, and may be necessary in neonates. There are three unusual circumstances when this earlier approach is necessary: 1) cardiopulmonary instability (profound cyanosis or overcirculation); 2) the presence of a unilateral ductus arteriosus providing flow to one lung; and 3) the presence of centrally confluent but very hypoplastic true pulmonary arteries that arborize completely to all lung segments, and are supplied by multiple "dual supply" collaterals.

Goals of Surgical Management

Complete Unifocalization

Unifocalization refers to the surgical reconstruction of the pulmonary arterial tree, incorporating as many lung segments as possible by maximal recruitment of the true PA and MAPCA systems. The most reliable predictor of favorable outcome for this lesion is post-repair right ventricular (RV) pressure, which is ultimately dependent on the proportion of pulmonary segments included, as well as the status of the pulmonary microvasculature.

Intracardiac Repair

The VSD can be closed and right ventricular to pulmonary artery continuity established using a cryopreserved allograft valved conduit, at the time of unifocalization, if the pulmonary arterial resistance is judged to be sufficiently low. Ideally, the post-repair RV systolic pressure should be less than 60% of the left ventricular (LV) systolic pressure. This assessment can be made empirically if the unifocalization is relatively uncomplicated and the pulmonary arteries and collaterals are of adequate size. Alternatively, our group has described the utility of objective intraoperative assessment of the pulmonary arterial resistance for purposes of intracardiac repair at the time of unifocalization, using the intraoperative flow study.[6] During the operation, following completion of the unifocalization, while still on cardiopulmonary bypass (CPB), the pulmonary arterial pressure is continuously measured while pulmonary blood flow through a separate perfusion circuit is incrementally increased up to a full cardiac output. If the mean pulmonary artery pressure remains below 25 mm Hg at a full flow, an RV/LV pressure ratio less than 0.5 can be expected following VSD closure.

Delaying Intracardiac Repair and Creating a Central Source of Pulmonary Blood Flow

If VSD closure is deferred at the time of the unifocalization because of a predicted RV/LV pressure ratio above 0.5, an appropriately sized central shunt between the aorta and the newly constructed pulmonary artery is created, aiming for a mean pulmonary artery pressure less than 30 mm Hg. Follow-up catheterization is then performed after a 6-month period to re-evaluate the pulmonary vascular bed for VSD closure.

We believe that using a right ventricular to pulmonary artery conduit as the source of pulmonary blood flow, in the setting of an open VSD, is contraindicated for several reasons. First, the incidence of aneurysms and pseudoaneurysms in these hypertensive conduits is unacceptable. Second, pulmonary flow and pressure is completely uncontrolled.

Morphology-Based Surgical Algorithm

Patients with PA.VSD and MAPCAs can be grouped into four commonly encountered subsets with important surgical im-

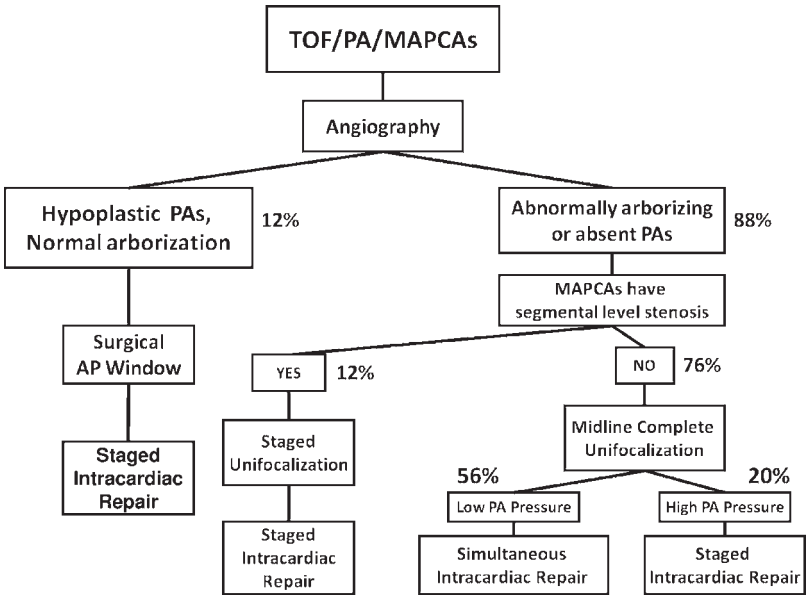

Figure 1 Morphology-based surgical algorithm for PA.VSD and MAPCAs. Pulmonary angiography dictates the surgical strategy employed. Percentages shown are the proportion of total patients in the authors' experience.

plications. While patients fall along a spectrum of disease, this perspective aids the implementation of a prospective management strategy that can be widely applied to patients with PA.VSD and AP collaterals (Fig. 1). The percentages indicated for each subset are derived from the authors' experience.

Large Caliber MAPCAs Without Significant Segmental Level Stenoses (56%)

This group has the most favorable anatomy for one-stage bilateral unifocalization, intracardiac repair, and right ventricular outflow tract reconstruction (Fig.2). The intrapericardial true pulmonary arteries may be present or absent. If present, they are usually confluent and moderately or severely hypoplastic with relatively unobstructed, albeit incomplete, arborization. The collaterals can vary in number from two to eight, are of large caliber, and supply variable but significant portions of the lungs ranging from 30% to 100%. These collaterals may be unobstructed or have significant stenoses, but the stenoses are generally more proximal, and do not predominantly involve the vessels at the segmental level of the lungs. The large caliber of the collaterals, along with the true pulmonary arteries, provide adequate raw material for the unifocalization, such that low pulmonary artery pressure is highly likely following simultaneous intracardiac repair.

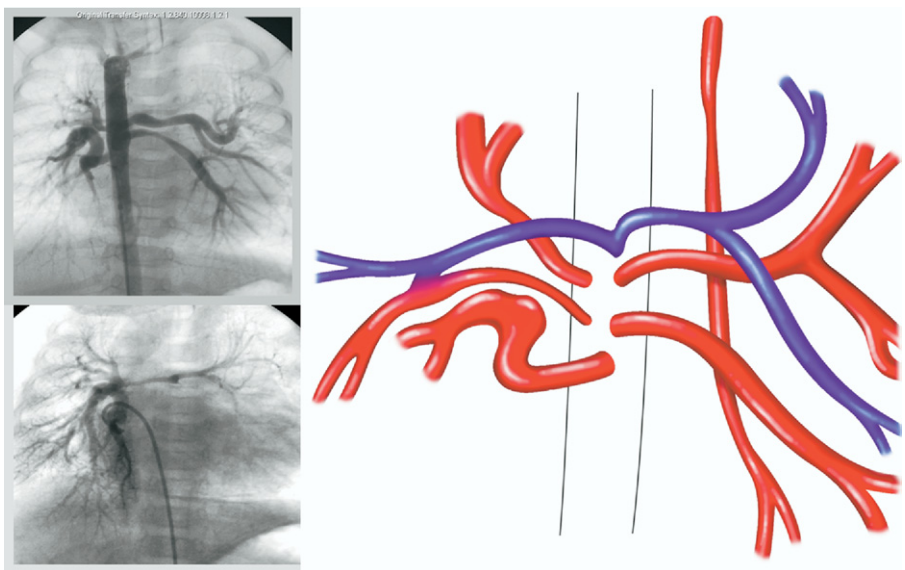

Figure 2 Angiographic and schematic representation of the anatomy conducive to a one-stage unifocalization and complete repair. These patients have well-developed MAPCAs without significant distal stenoses and represent slightly more than half of all patients in the authors' series.

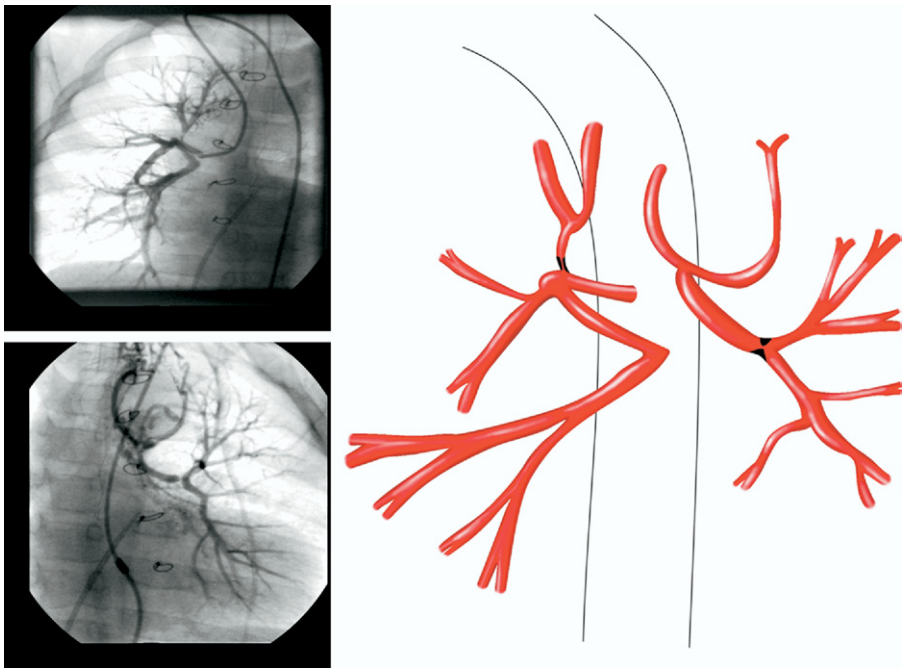

Figure 3 The pulmonary angiograms and diagram depict small- to moderate-sized collaterals with proximal stenoses. This patient subgroup is amenable to one-stage complete unifocalization. However, intracardiac repair must be deferred due to elevated pulmonary arterial resistance.

Small-To-Moderate Caliber MAPCAs Without Segmental Level Stenoses (20%)

All of the morphologic variations in this subset are similar to those in the group just described above, except the caliber of the collaterals is smaller (Fig. 3). Thus, there is less raw material for unifocalization. This subset is amenable to one-stage bilateral unifocalization; however, the likelihood of high pulmonary vascular resistance and elevated pulmonary artery pressure is great, such that simultaneous intracardiac repair should not be performed. Instead, an appropriately sized central aorta to neopulmonary artery shunt is created.

Centrally Confluent Fully Arborizing Hypoplastic True Pulmonary Arteries With "Dual Supply" MAPCAs (12%)

In these cases, the true pulmonary arteries are present, confluent, of small caliber, and arborize to all lung segments (Fig. 4). The collaterals are usually multiple, small, and connected peripherally into the normally arborizing true pulmonary arteries (ie, the collaterals are all of the "dual supply" type). Everything is small caliber; thus, there is a dearth of raw material available for unifocalization. Furthermore, unifocalization is actually not necessary because the small true pul-

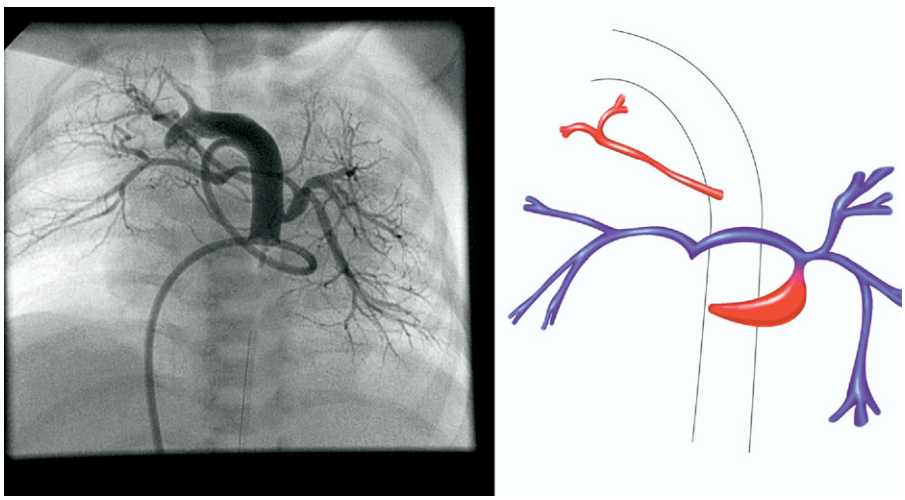

Figure 4 The morphology depicted is that of a well-arborizing, but hypoplastic true pulmonary arterial tree and poorly developed collaterals. This subgroup requires an initial AP window to induce PA growth prior to completing the repair.

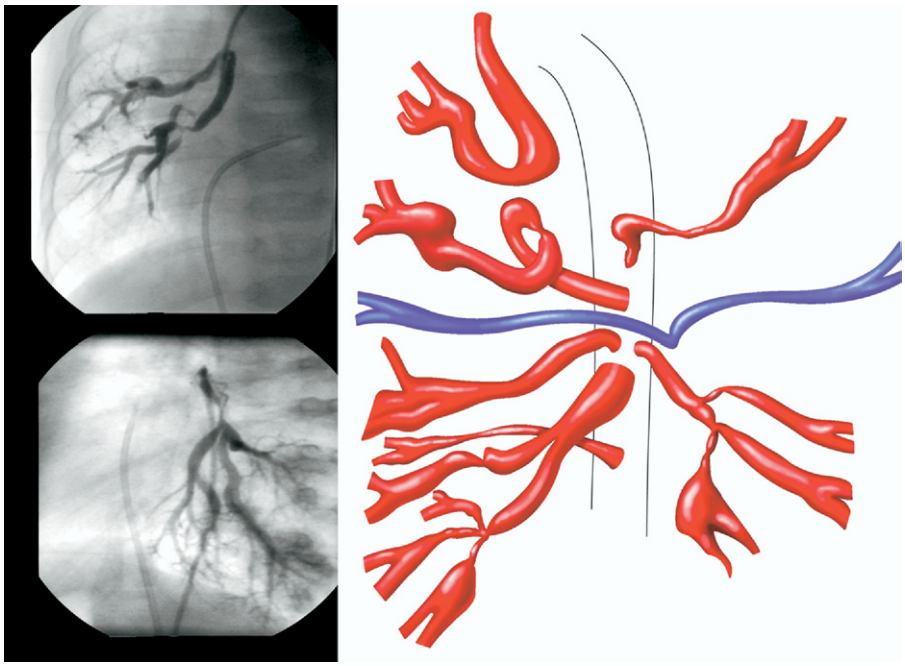

Figure 5 The dominant collateral system depicted has multiple stenoses at the segmental level. Present in 13% of the authors' experience, sequential unilateral unifocalizations are required due to the distal extent of the obstructive lesions.

monary arteries supply all lung segments. The authors' preference in these cases is to perform a central AP window by direct end-to-side anastomosis of the small main pulmonary trunk to the ascending aorta in the neonatal period to promote growth of the pulmonary arteries. Our group has previously described the stringent criteria that would necessitate creation of an AP window.[7]

Repeat angiography is performed 3 to 6 months after the AP window to assess pulmonary arterial growth. We have aggressively pursued early subsequent repair. Over 70% of patients with initial AP window in our series have successfully undergone definitive repair.

MAPCAs With Extensive Segmental Level Stenoses (12%)

In a small minority of patients, the AP collaterals have multiple peripheral stenoses that extend to the segmental level vessels, creating as many as 15 to 20 stenotic points (Fig. 5). To achieve a technically acceptable unifocalization result in this small subset of patients, staged sequential thoracotomies are preferred. At the time of each single lung unifocalization, a modified Blalock-Taussig shunt is fashioned from a major systemic artery to the newly unifocalized pulmonary arterial tree.

Once bilateral unifocalization is completed, suitability for complete repair is guided by repeat cardiac catheterization. If intracardiac repair is deemed feasible, the intraoperative flow study described above can serve as a valuable assessment of the health of the pulmonary vascular bed.

Surgical Technique

Single-Stage Unifocalization

Our group has previously described the authors' preferred surgical approach to one-stage unifocalization.[8,9] Optimal exposure is obtained through a median sternotomy with a generous midline incision to permit wide retraction. Following a subtotal thymectomy, the anterior pericardium is harvested and preserved in 0.6% glutaraldehyde. If present, the intrapericardial pulmonary arteries are completely mobilized to the lobar and segmental branches in each hilum. The dissection of the MAPCAs is aided by exposing the subcarinal space superior to the roof of the left atrium. The transverse sinus is opened widely to reveal the collaterals in the central mediastinum. The descending aorta in the posterior mediastinum is dissected to expose the origins of the MAPCAs. The pleura are opened anterior and posterior to the phrenic nerve to further delineate the course of the MAPCAs. The SVC is circumferentially mobilized to isolate collaterals as they enter the lung parenchyma. This dissection results in the exposure of the MAPCAs over their entire course, from their systemic origin to their segmental level branching points within the lung parenchyma, thereby facilitating appropriate direct rerouting of the collaterals during unifocalization.

Every effort is made to remain off bypass for the bulk of the collateral dissection and even for initial parts of the unifocalization reconstruction. However, eventually progressive cyanosis and/or the technically driven need for a decompressed heart and lungs requires the institution of CPB. Once bypass is initiated, all MAPCAs must be rapidly controlled at their

aortic origin to allow controlled perfusion. With the heart decompressed and beating, a calcium-supplemented blood prime is utilized at moderate hypothermia for the remainder of the unifocalization.

The underlying goal of unifocalization is to restore unobstructed pulmonary blood flow to the greatest number of lung segments. This is accomplished by utilizing the maximal amount of native tissue for anastomoses and pulmonary arterial reconstruction. Extensive distal dissection and mobilization into the segmental level branches of all available AP collaterals maximizes vessel length, insuring a tension-free reconstruction. Whenever patch augmentation of newly unifocalized branch vessels is required, care is taken to avoid circumferential use of non-viable conduits to preserve the growth potential of native tissue. We have found that cryopreserved pulmonary arterial homograft provides durable long-term results for these reconstructions in children. Collateral to collateral anastomoses and collateral to true pulmonary artery anastomoses are performed with long side-to-side connections rather than end-to-side connections whenever possible. Essentially, all anastomoses are performed in the dissected central mediastinum, and rarely if ever are collaterals routed over the hilar structures. 8-0 monofilament suture is used almost exclusively for the unifocalization.

Assessment of Suitability for Intracardiac Repair: The Intraoperative Flow Study

The decision to close the VSD should be made judiciously. Inappropriately closing the VSD will result in pulmonary hypertension and early right ventricular failure. Inappropriately leaving the VSD open will result in pulmonary overcirculation if a right ventricular to pulmonary artery conduit is placed. We have developed an objective intraoperative assessment of the post-unifocalization pulmonary arterial resistance using controlled pulmonary perfusion and pressure measurement.[6] With the patient still on CPB following the unifocalization, the left atrium is fully vented, and the main pulmonary artery is cannulated and perfused using an independent calibrated roller pump head. A pressure-monitoring catheter is secured directly in the main PA. The lungs are gently inflated to normal volume. Flow into the pulmonary artery system is progressively increased to the equivalent of at least one indexed cardiac output. If the mean PA pressure consistently stays below 25 mm Hg, the VSD can be safely closed. This threshold of 25 mm Hg, under these conditions, reliably predicts a systolic RV/LV pressure ratio at or below 0.5. If the flow study pressure measurement exceeds 25 mm Hg, then the VSD is left open. Importantly, we do not then place a right ventricular to pulmonary artery conduit, but prefer to use controlled central shunt between the neopulmonary artery and the ascending aorta, as explained earlier, aiming for a mean pulmonary artery pressure below 30 mm Hg.

Intracardiac Repair

Intracardiac repair is performed following aortic cross-clamping and cardioplegia-induced cardiac arrest. A longitudinal ventriculotomy is performed and the right ventricular cavity is inspected. Obstructive muscle bundles are resected and the VSD is identified. The VSD is closed with an autologous pericardial patch, previously harvested and fixed in 0.6% glutaraldehyde. The atrial septum is inspected for a patent foramen ovale or atrial septal defect. If present, it is closed. RV to PA continuity is created with the use of an appropriately-sized homograft valved conduit. The distal connection between the conduit and the newly reconstructed pulmonary arterial confluence is performed with 6-0 or 7-0 monofilament non-absorbable suture. The proximal anastomosis between the right ventricle and the conduit is performed by directly anastomosing the posterior aspect of the circumference of the conduit to the RV and augmenting the anterior aspect with a hood of homograft tissue. To minimize myocardial ischemia, the proximal anastomosis can be performed following removal of the aortic cross clamp during the rewarming phase.

Close attention is paid to hemodynamic parameters while weaning from CPB. Intracardiac pressure monitoring catheters are placed to monitor the right atrial, left atrial, and right ventricular pressures. After separation from bypass, transesophageal echocardiography is performed to rule out any significant residual lesions. The sternum is left open if there are bleeding or ventilation concerns. In these patients, delayed sternal closure is usually possible by the second postoperative day.

Results

Our group has followed this approach for PA.VSD with MAPCAs since 1992. Over the past 15 years, data are available for 462 patients who were managed in this fashion. Median age at operation was 7.7 months, ranging from 10 days to 39 years. The morphologic spectrum is described above. The median diameter of true PAs was 2.0 mm. Complete absence of intrapericardial pulmonary arteries occurred in 23.5% of patients.

Operative mortality was 2.3% over the past 9 years. Mortality was higher in earlier years, yielding an overall mortality for the entire series of 5.9%. Actuarial survival at 5 years was 85.5%. There were no definable risk factors for early death other than "earlier year of operation." Importantly, "complete absence of true pulmonary arteries" had no adverse influence on early outcome. The combination of DiGeorge syndrome and gastroesophageal reflux was found to be an important risk factor for late mortality. Surgical reintervention for PA reconstruction was required in 22.6% of patients.

Complete single-stage unifocalization via median sternotomy was achieved in 76% of patients. Intracardiac repair was possible at initial operation in 56%. At 5 years, 90% of patients were completely repaired, indicating that most patients who did not achieve initial intracardiac repair eventually did. The RV/LV pressure ratio was 0.41 ± 0.12 immediately postoperatively and 0.36 ± 0.11 at 7-year follow-up, and showed no difference in patients who had completely absent true pulmonary arteries originally. This would implying that,

when managed appropriately, both small true pulmonary arteries and MAPCAs grow and develop.

Discussion

The primary objective of a programmatic approach to PA.VSD and major AP collaterals is to demonstrate meaningful improvement over the otherwise bleak natural history of this lesion, and to do this in an unbiased cohort of patients followed from birth, not in a cohort of older selected patients. Less favorable long-term outcomes from staged approaches can be largely attributed to the significant loss of lung segments, and development of pulmonary vascular disease, as a result of prolonged uncontrolled flow through collaterals because of delayed or deferred completion unifocalization.[10-14] The most important factor in improving the long-term prognosis of these patients is not the achievement of intracardiac repair alone, but the achievement of intracardiac repair with a low RV/LV pressure ratio. Our strategy to avoid irreversible pulmonary vascular damage and loss has been to aggressively pursue single-stage complete unifocalization whenever possible. To that end, we have been able to achieve the goal of intracardiac repair with an RV/LV pressure ratio of 0.5 or less in approximately three-quarters of patients with PA.VSD and MAPCAs. Especially promising is the sustained low right ventricular pressure at midterm follow-up, which reflects growth of native tissue used in unifocalization.

While nearly 90% of patients in our experience have achieved complete repair, there exists a small subset of patients that are especially problematic. These patients typically present with significant cyanosis in the neonatal period and have small, unobstructed MAPCAs. In our experience, these patients require repeated peripheral PA reconstructions and may never undergo intracardiac repair. Despite the challenges posed by this subgroup, there have been some notable successes in this subgroup, and even in those who have never achieved intracardiac repair, a stable and reliable source of pulmonary blood flow has been the rule.

As we continually strive to improve outcomes in PA.VSD with MAPCAs, our 15-year experience has demonstrated that a dedicated, prospectively applied approach can yield favorable results over time. The operative mortality was 11% for the first 6 years and subsequently declined to 2.3% for the last 9 years of the series. Implementation and refinement of the intraoperative flow study has aided surgical decision-making and partially accounts for the improvement in early operative outcomes. However, the relatively favorable long-term results are likely due to the development of a systematic approach that requires detailed preoperative imaging and planning, commitment to surgical principles of early intervention before damage occurs, maximal native tissue utilization, and advances in postoperative cardiac critical care. While patients with PA.VSD and MAPCAs certainly present formidable challenges for the surgeon, single-stage unifocalization, whenever possible, provides these patients the best chance for meaningful long-term survival.

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