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Perfusion Methods and Modifications to the Cardiopulmonary Bypass Circuit for Midline Unifocalization Procedures

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Abstract: Pulmonary atresia with ventricular septal defect and major aortopulmonary collateral arteries (PA/VSD/MAPCAs) is a rare form of congenital heart disease. The midline unifocalization procedure has been developed for the treatment of PA/VSD/MAPCAs. These are complex and very lengthy procedures that require an entirely different method of perfusion. The purpose of this study was to review our perfusion modifications to support these unifocalization procedures. Sixty-four unifocalization procedures have been performed at our institution during the past 3 years. The median age was 4.1 months (range 1 month–3.5 years) and the median weight at surgery was 4.5 kg (range 3.5–19 kg). The median duration of cardiopulmonary bypass was 352 minutes (range 128–629 minutes), and the median duration of cross-clamp was 24 minutes (range 14–72 minutes). The conduct of surgery included cooling to a rectal perfusion temperature of 25° and a flow rate of 100 mL/kg/min. A pH-stat strategy and del Nido cardioplegia were used. Modifications to the cardiopulmonary bypass circuit include upsizing the oxygenator, reservoir, cannulae, vent catheter, and tubing. All circuits were modified to include the capability of performing an intraoperative flow study. This study is used to determine whether the VSD can be closed during surgery. A collateral flow study circuit is also set up for first-time operations to measure the residual collateral flow after all of the MAPCAs have been harvested. Patients who require midline unifocalization will invariably require very lengthy periods of support on cardiopulmonary bypass. We have adapted our perfusion circuitry to prepare for the demands on the bypass circuit to meet the requirements of this patient population. Our institution has developed a systematic approach for the conduct of perfusion to best serve our patients presenting with PA/VSD/MAPCAs. **Keywords:** congenital heart disease, pulmonary arteries, veins, pulmonary valve. *J Extra Corpor Technol. 2019;51:147–52*

Pulmonary atresia with ventricular septal defect and major aortopulmonary collateral arteries (PA/VSD/MAPCAs) is a complex and relatively rare form of congenital heart disease (1). This defect is characterized by the entirety of pulmonary blood flow originating from systemic blood vessels called MAPCAs. This is a recapitulation of the very earliest phase of embryologic pulmonary circulation (2,3).

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Our center has pioneered the surgical treatment called midline unifocalization for the treatment of PA/VSD/MAPCAs (4–6). Just as the underlying congenital heart defect is extremely complex, so too are the procedures for the treatment of this condition. As a consequence, the surgical procedures are very lengthy and require an entirely different method of perfusion. The purpose of the study was to review our perfusion modifications to support the midline unifocalization procedures.

MATERIALS AND METHODS

The study summarizes our experience with 64 patients who underwent a unifocalization procedure over a 3-year

time period. This study had been previously approved by the Institutional Review Board at Stanford University. The median age at surgery was 4.1 months (range 1–42 months), and the median weight was 4.5 kg (range 3.5–19 kg). These patients had a mean of 4.2 ± .4 MAPCAs.

The unifocalization procedures require harvesting of the MAPCAs and bringing these vessels together in combination with the branch pulmonary arteries. The MAPCAs are carefully identified and dissected out to their origin off the descending aorta or other sources (7–13). This portion of the surgery can usually be performed off bypass with the perfusionist on standby in the event of significant bleeding or desaturation.

Because MAPCAs are the source of pulmonary blood flow in these patients, cardiopulmonary bypass is going to be required throughout the unifocalization procedure. It is imperative to proximally ligate all of the MAPCAs immediately after going on bypass to eliminate this source of runoff. The perfusion pressure will initially be quite low but will rise commensurately with the size of the MAPCAs as they are ligated. The decrease in pressure can be compensated with a transient increase in cardiopulmonary bypass flow. The unifocalization process will typically last between 4 and 6 hours, as the vessels are small and require precise surgical attention.

We perform unifocalization procedures at 25°C with a flow rate of 100 cc/kg/min and pH-stat strategy. The initiation of bypass and cooling is performed at 200 cc/kg/min until the target rectal temperature is reached. We use an 8°C cooling gradient between rectal and esophageal temperatures as our protocol. The hematocrit is maintained between 30 and 40% throughout the duration of cardiopulmonary bypass, and the goal is to achieve a hematocrit of 45 to 55% at the conclusion of bypass.

We strictly avoid the use of volatile gasses (such as isoflurane) as we have noted a higher than expected incidence of multisystem organ failure (specifically liver and kidney failure) when these gasses are used. These observations are anecdotal in nature and have not been verified in a scientific study. However, we believe strongly in our observations regarding this matter and, thus, would state "et cavete a user" (let the user beware).

To support the prolonged lengths of cardiopulmonary bypass, we modify the circuit to include upsizing of the oxygenator, reservoir, cannulae, vent catheter, and tubing (Figure 1).

We feel that it is necessary to upsize the components of the cardiopulmonary bypass circuit for two main reasons. First, we have found that there is an increased need for surface area for these excessively lengthy bypass runs. When using standard equipment, we would be on maximum gas flow settings with suboptimal arterial and venous gases. On three occasions, we had to change the oxygenator to a larger size to complete the case. This necessitated the change to our practice. Second, we have noted that this subset of patients required more flow than our traditional patients. For this reason, we upsized our cannula by a factor of 1 to provide the additional needed flow; for example, if we would use a 14-F cannula vs. a 12-F cannula to achieve desired flows. One impact of this change in practice was an increased dilutional factor for the patients. Upsizing our circuits means an increase in the prime volume. Although not ideal, it is necessary for the safety of the patient. The conversion from a conventional bypass circuit to one for a unifocalization procedure is summarized in Table 1.

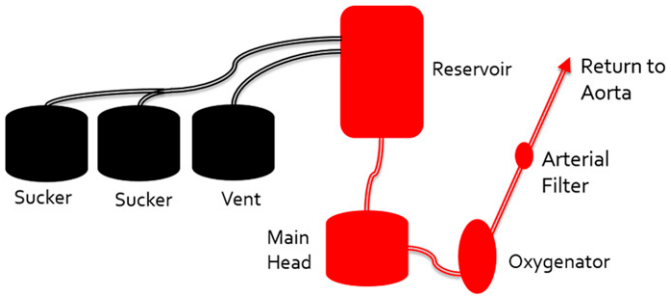

Figure 1. Diagram of the cardiopulmonary circuit for support of a unifocalization procedure. The portions shown in red have been upsized because of the prolonged period of bypass.

A critical crossroads in these procedures comes after the unifocalization is completed and in the assessment of whether the VSD can be closed or not. This decision is fundamentally based on the adequacy of the unifocalized bed. The goal is to close the VSD if the resultant right ventricular pressure is going to be less than half systemic (14). The advantages of closing the VSD include complete normalization of the circulation and fully saturated oxygen levels (Figure 2).

Twenty years ago, we developed the intraoperative flow study to help in making this determination regarding VSD closure (15). All of our cardiopulmonary bypass circuits are modified for unifocalization procedures to include the capability of performing an intraoperative flow study (Figure 3). A separate arterial line is primed and the reconstructed pulmonary artery cannulated. The systemic perfusion is then decreased to half flow, and flow to the pulmonary arteries is gradually increased to a goal of 3 L/min/m^2 (16). We accept a maximal mean pulmonary artery pressure of 25 mmHg (Table 2). Some groups have continued to use the original criteria of 2.5 L/min/m^2 and a pressure of 30 mmHg (17). Patients who pass this test proceed to VSD closure using del Nido cardioplegia solution and then with subsequent placement of a right ventricle to pulmonary artery conduit, whereas those who do not pass this physiologic test undergo placement of a systemic-to-pulmonary artery shunt.

Table 1. Upsizing of tubing and oxygenators—conversion standard vs. modifications.

Weight Range (kg)	Oxygenator	Boot	Venous Line × Arterial Line
Standard circuit			
0–15	RX-05	¼"	¼" × ¼"
15–40	RX-15RE30	3/8	3/8" × ¼"
>40	RX-25	½"	3/8" × 3/8"
Modified circuit for unifocalizations			
0–8	RX-05	¼"	¼" × ¼"
8–30	RX-15RE30	3/8	3/8" × ¼"
>30	RX-25	½"	3/8" × 3/8"

Over many years and many hundreds of unifocalization procedures, we have realized that some patients are "ideal" candidates and de facto will pass the flow study. The best preoperative indicators that a patient will pass the flow study include the oxygen saturations (>84%) and the cardiac catheterization data (Qp:Qs > 1.5). If a patient meets these criteria, then it is good evidence of an adequate pulmonary vascular bed, and we no longer would perform an intraoperative flow study. We also make an assessment of the quality of the MAPCAs while they are being harvested and unifocalized, and this may influence our decision regarding the flow study. As a consequence of this change in philosophy, we now perform flow studies in only about 20% of the patients. By inference, this also means that the failure rate for the flow study is now much higher than it was when we studied all patients.

One additional study that we have performed over the past several years is an assessment of the residual collateral flow in patients with MAPCAs (18). Patients who met the eligibility criteria (i.e., primary midline unifocalization and candidates for two ventricle repair) had a diversion loop added to the left ventricular vent system before surgery (see Figure 4). After the initiation of cardiopulmonary bypass, a left ventricular vent catheter was placed through the right superior pulmonary veins into the left ventricle. This left ventricular vent return would represent a sum of the pulmonary collateral flow, coronary collateral flow, and potentially any flow entrained through the atrial or VSD. It is only when the aorta is cross-clamped that the latter two sources of flow are fully eliminated, and thus, the study was only conducted in the 30 patients who underwent cross-clamping for complete repair (i.e., VSD closure). During the cross-clamp period, the left ventricular diversion loop was opened for one-minute intervals and the amount of residual collateral flow measured during this interval in an RX-05RE reservoir. The percentage of residual collateral flow is the amount of left ventricular vent return collected during a minute interval divided by the total pump flow (ie 100 mL/Kg/min × body weight).

RESULTS

The 64 patients underwent midline unifocalization with a median duration of cardiopulmonary bypass of 352 minutes (range 128–629 minutes). Fifty-six of the 64 patients (87%) had a single-stage complete repair, whereas eight patients (13%) had a unifocalization shunt. For the 56 patients who had a single-stage complete repair, the median duration of cross-clamp was 24 minutes (range 14–72 minutes). None of the patients required extracorporeal membrane

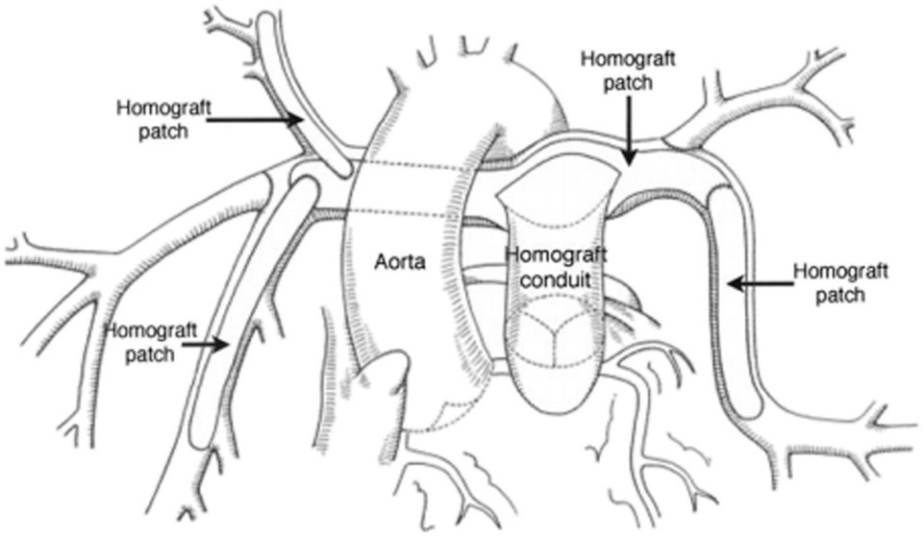

Figure 2. Illustration demonstrating a unifocalization of MAPCAs with complete repair, including placement of a conduit from the right ventricle to the reconstructed pulmonary arteries. (Used with permission from Mainwaring RD, et al. Eur J Cardiothorac Surg. 2012;42(2): 235–41)

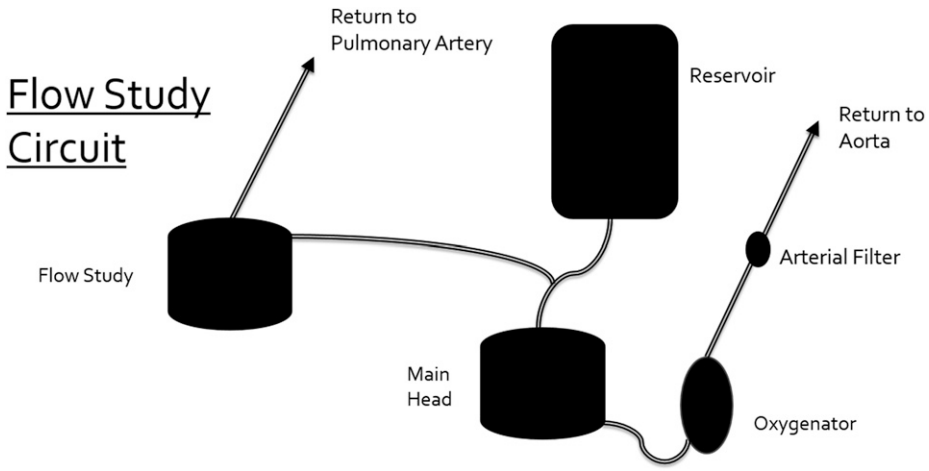

Figure 3. Diagram of the flow study circuitry. An extra pump head is dedicated to perfusing the reconstructed pulmonary arterial bed.

oxygenation. There was one in-hospital mortality (1.3%) and no late mortality to date in this cohort.

DISCUSSION

This article was written in an effort to summarize the perfusion methods and modifications that we have implemented to the cardiopulmonary bypass circuit for midline unifocalization procedures. Many of the basic modifications on upsizing the circuit are made necessary because of the very lengthy procedures that are required. However, there are also two modifications that are specific to this circuitry, namely, the intraoperative flow study and the residual collateral flow study. We have adapted our perfusion circuitry to prepare for the demands on the bypass circuit to meet the requirements of this patient population.

One of the major modifications to the cardiopulmonary bypass circuit is for the intraoperative flow study. This requires setting up in advance and commits one roller head to the pulmonary artery perfusion line. We have obtained much valuable information over the years with the flow study. It should be recognized that the flow study can provide spurious information. Specifically, if during the study the left ventricular vent cannot keep up with the pulmonary venous return, the arterial trace will begin to show signs of override. However, this also means that the left atrium is full and will falsely elevate the flow study numbers. It is also possible to falsely elevate the flow study numbers if the lungs are not ventilated but at low mean airway pressures and if there are pleural collections of fluid. Conversely, the pulmonary artery flow study numbers can also be falsely low, primarily because of either major bleeding from the reconstructed bed or if the side-hole in the pressure catheter is partially out of the vessel. Thus, the flow study is a valuable tool in determining the feasibility of VSD closure but must be carried out with exacting attention to detail to avoid some of these common pitfalls.

Table 2. Flow study chart demonstrating flow by absolute amount and percentage of the total goal.

Flow %	Flow at an Index of 3.0
25	180 cc/min
50	360 cc/min
75	450 cc/min
100	730 cc/min

This example is for a patient with a body surface area of .24.

A recent study that we have added is the residual collateral flow study (18). This was originally designed to evaluate the amount of collateral flow that would be conducted by systemic-to-pulmonary vessels that are not MAPCAs. In theory, if the signal for involution of MAPCAs was never triggered, then there might also be a myriad of other smaller vessels that might persist as well. It is also known that patients who are hypoxemic for prolonged periods of time (several years) will increase the size and number of collaterals to a significant degree (19–22).

The data from our study conducted in 32 patients demonstrated that following ligation of the MAPCAs, the mean residual collateral flow was 5.5 ± 1.0 mL/kg/min or 5.5% of the pump flow. The range of residual collateral flow was .8 to 15.2%, as shown in Figure 5. Although most patients had relatively modest amounts of residual collateral flow, averaging just 5.5% of the pump flow (normal values would be 1%), there were 6 patients of 32 who had residual collateral flow of 8% or greater. These patients certainly fall outside the normal range and, at the upper end, have a significant amount of blood flow redirected away from the systemic circulation.

The relationship between residual collateral flow and preoperative saturation is shown in Figure 6. The best fit

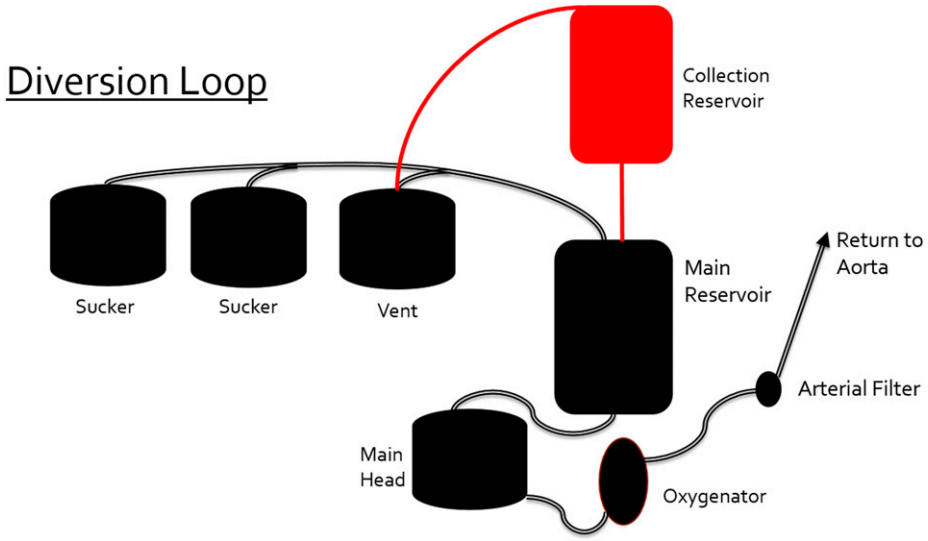

Figure 4. Diagram of the left ventricular vent diversion loop used for measuring residual collateral flow during repair of PA/VSD/MAPCAs.

line has the equation: $y = -.5x + 46$, with $R^2 = .53$ ($p < .001$). This line has a negative slope, indicating that the higher the preoperative oxygen saturations, the lower the residual collateral flow.

There are two potential clinical benefits to performing an assessment of residual collateral flow following harvesting of MAPCAs. As mentioned, some patients at the upper end of the spectrum of residual flow may have a significant amount of blood flow siphoned away from the systemic circulation while on cardiopulmonary bypass. It is possible that this amount of diverted flow would manifest as a lower perfusion pressure and be compensated for by increasing pump flow. However, it is also possible that this amount of "stolen" pump flow might not manifest in a lower perfusion or be treated inappropriately with a vasoconstrictor. If the true cause of the low perfusion pressure is not ascertained, it is a matter of conjecture whether 5 or 6 hours of systemic perfusion at 15% less than expected would have an adverse clinical effect. The other potential benefit of performing the residual collateral flow study is the potential that a high value might alert the surgical team that there is an undiscovered MAPCA that is still contributing to collateral flow. By establishing the norms for residual collateral flow, the finding of a value well out of that range might prompt a search for a residual MAPCA.

In summary, patients who require midline unifocalization will require very lengthy periods of support on cardiopulmonary bypass. We have adapted our perfusion circuitry to prepare for the demands on the bypass circuit to meet the requirements of the patient population. Our institution has developed a systematic approach for the conduct of perfusion to best serve our patients presenting with PA/VSD/MAPCAs.

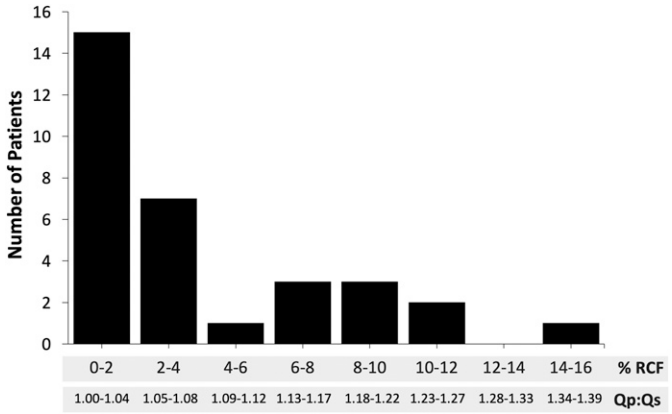

Figure 5. Histogram demonstrating the residual collateral flow following harvesting of the MAPCAs in the 32 patients undergoing repair of PA/VSD/MAPCAs. (Used with permission from Mainwaring RD et al. Ann Thorac Surg 2019;108:154–9)

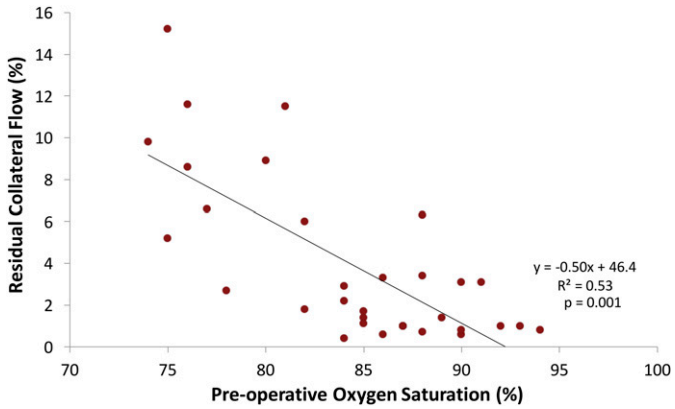

Figure 6. Relationship between residual collateral flow and preoperative oxygen saturation. This relationship is described by the equation: $y = -.5x + 46$, $R^2 = .53$ ($p < .001$). (Used with permission from Mainwaring RD et al. Ann Thorac Surg 2019;108:154–9)

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