Aortopulmonary Collaterals in Single-Ventricle Congenital Heart Disease
How Much Do They Count?
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Broadly defined, aortopulmonary collateral blood vessels (APCs) arise from the systemic arteries and supply blood to the pulmonary circulation. In the setting of acquired and congenital pulmonary and cardiac disease, the number and caliber of these vessels can increase and lead to a significant systemic-to-pulmonary shunt. APCs typically arise from the descending aorta, subclavian artery branches, and bronchial and intercostal arteries. Unlike normal bronchial arteries, they often supply flow to the terminal respiratory unit and do not necessarily travel in close proximity to the bronchial tree. Prominent APCs are associated with a variety of congenital heart diseases but are more prevalent with cyanotic lesions, particularly tetralogy of Fallot with pulmonary valve atresia. APCs are also commonly found in patients with single-ventricle heart disease, and their extent may fluctuate with successive surgical procedures.1–3 The impact and assessment of APCs in patients with a functionally single ventricle is the focus of the discussion that follows.

From a physiological standpoint, APCs may have both beneficial and adverse consequences. The principal advantageous effect of APCs is to improve systemic arterial oxygen saturation by increasing pulmonary blood flow leading to a higher “mixed” saturation in the ventricle. In addition, APCs may potentially inhibit the development of pulmonary arteriovenous malformations in patients with a bidirectional Glenn shunt by providing a route for hepatic venous blood to reach the lungs. Among the negative effects of APC flow is that it can compete with and limit the more effective, lower saturated blood flow to the lungs from the pulmonary arteries. Also of concern is that all APC flow returns to the single ventricle and thereby results in an additional volume load. Because these patients are at risk for the development of systolic and diastolic heart failure and atrioventricular valve regurgitation, any increased work or dilation can justifiably be viewed as undesirable. APCs, by adding to pulmonary artery blood flow, may also increase pulmonary artery pressure. Because the Fontan circulation depends on passive venous flow into the pulmonary arteries, increases in pressure may be poorly tolerated and lead to decreased cardiac output, pleural effusions, hepatic congestion, peripheral edema, and protein-losing enteropathy. Flow energy dissipation effects from APC flow may incur significant energy losses and contribute further to the morbidity of Fontan patients.5 Finally, APCs that are in close association with the bronchial tree may dilate, erode into the airway, and rupture, leading to life-threatening hemoptysis.

Despite the numerous mechanisms by which APCs may affect single-ventricle patients, there are only a few studies that directly address this issue, and most of these have focused on the outcomes of Fontan surgery. Several centers have reported that higher APC flow was associated with an increased incidence of pleural effusions, elevated pulmonary artery pressure, and mortality.2–4 In contrast, other groups have found that APC flow was not significantly related to postoperative venous pressures, duration of pleural effusions, or resource utilization.6–7 McElhinney et al8 found that those patients with significant APCs were, in fact, less likely to have prolonged pleural effusions.

Given the limited and conflicting results regarding the importance of APCs in determining outcomes, it is not surprising that there are no well-established guidelines for the treatment of APCs in single-ventricle patients. Elimination of APCs is usually accomplished by transcatheter occlusion, typically with vascular coils or embolization foam. There is general agreement that large, discrete APCs should be occluded and that smaller vessels should be treated if patients are symptomatic; however, there is no consensus as to whether APCs should routinely and aggressively be identified and eliminated.9,10

An important factor contributing to the uncertainty regarding the clinical impact of APCs and efficacy of treating them is the lack of a broadly accepted and accurate means to quantify APC flow. In current clinical practice, the most common method is a qualitative assessment of x-ray angiograms during catheterization. This approach is suboptimal because the identification of collaterals during catheterization is dependent on angiographic technique, including the site, and rate and amount of contrast injection. For example, in a comprehensive review of 268 catheterizations in patients after bidirectional Glenn or Fontan procedures, Friedman et al11 found that 56% of APCs originated from the internal mammary arteries and the thyrocervical trunks. Only 9% of these vessels were visualized on aortography; the remainder required selective angiography in the subclavian or more
distal arteries. The investigators estimated the cross-sectional area for those APCs that were discrete by comparison with the known diameter of the angiographic catheter, but this is difficult to achieve with accuracy in many vessels and does not include small APCs, which may be numerous and carry a significant amount of flow. Another method of quantifying APC flow is to measure the pulmonary venous effluent during cardiopulmonary bypass (with the pulmonary arteries snared) at the time of Fontan surgery and relate this to the flow delivered through the aortic cannula.\(^2\)\(^6\) The requirement for cardiopulmonary bypass obviously limits the applicability of this approach. Moreover, the measurements are made under nonphysiological conditions including nonpulsatile low-pressure arterial flow, general anesthesia, lack of pulmonary blood flow, and hypothermia. Lim et al.\(^7\) reported the use of the thermal indicator dilution technique to quantify APC flow in patients with a bidirectional superior cavo pulmonary shunt. Iced saline was injected into the systemic ventricle while a thermistor catheter in the ascending aorta recorded the temperature. Greater APC flow was evidenced by lower temperature during the recirculation phase. An important limitation of this approach is that actual flow rates cannot be measured. In addition, the technique is invasive, cannot be applied in patients with significant valve regurgitation, and may be confounded by streaming effects in patients with an aortopulmonary anastomosis. More recently, Inuzuka et al.\(^11\) quantified APC flow in patients with bidirectional superior cavo pulmonary shunts with the use of lung perfusion nuclear scintigraphy (99m-Tc–labeled macroaggregated albumin) and oxygen saturation data from cardiac catheterization. The tracer was administered intravenously in the leg and went directly to the systemic circulation via the inferior vena cava. The lung count on the scintigam thus reflected the relative amount of APC flow, whereas the total body count minus the lung count reflected the amount of systemic flow. This relative flow information was then converted to absolute flow rates by incorporating oxygen saturation data and applying the Fick principle. This technique is applicable only to patients with superior cavo pulmonary shunts and not with a Fontan circulation. Moreover, it is invasive and exposes the patient to additional ionizing radiation from the perfusion scintigraphy.

In this issue of Circulation: Cardiovascular Imaging, Grosse-Wortmann et al.\(^12\) report for the first time on the systematic use of cardiac MRI to measure APC flow in patients after the bidirectional cavo pulmonary connection (BCPC) and Fontan surgeries. The investigators measured blood flow in multiple vessels using the standard cardiac MRI flow measurement technique called “phase contrast cine MRI,” which has been extensively validated in vitro and in vivo.\(^13\)\(^14\) In brief, this method is based on the principle that the signal from hydrogen nuclei (such as those in blood) flowing through specially designed magnetic field gradients accumulates a predictable phase shift that is proportional to its velocity. Multiple phase images are constructed across the cardiac cycle in which the signal amplitude (brightness) of each voxel is proportional to mean flow velocity within that voxel. Using commercially available software, regions of interest around a vessel are defined, and the flow rate is calculated as the product of the mean velocity and the cross-sectional area.

Grosse-Wortmann et al calculated APC flow using 2 methods. The more straight-forward one, method A, was to sum the individual pulmonary vein flows and then subtract from this the flow measured in the left and right pulmonary arteries. With method B, APC flow was calculated by subtracting the total systemic venous return from the ascending aorta flow. Total systemic venous return ideally would be calculated as the sum of all superior vena cava (SVC) flow and inferior vena cava (IVC) flow; however, it is technically difficult to make a flow measurement in the IVC close to the heart because of the short distance between the hepatic veins and right atrium. Therefore, the authors calculated IVC flow as the sum of descending aorta flow at the diaphragm plus any systemic venous collateral flow from the SVC to the IVC. Both of these methods include bronchial artery flow as part of APC flow and would overestimate APC flow in the setting of systemic venous to pulmonary venous collateral vessels.

Among 36 cardiac MRI studies in patients who had undergone BCPC or Fontan surgery, APC flow was quantifiable in 24 studies (67%). Measurements were unsuccessful in the others because of artifact related to implanted metallic devices or the inability to measure flow in the pulmonary veins because of their complex anatomy. Agreement between the two APC flow calculation methods was modest (intraclass correlation coefficient of 0.73) with several instances in which method A was significantly larger than method B. The authors attribute these discrepancies to erroneously low ascending aorta flow measurements caused by complex flow patterns in patients with an aortopulmonary anastomosis and a dilated reconstructed ascending aorta. Based on method A, the contribution of APC flow to total pulmonary flow (pulmonary venous flow) was 46% (range, 32% to 90%) in the BCPC group (n = 16) and 20% (range, 18% to 61%) in the Fontan group (n = 8). Stated differently, the percent of proximal aortic flow that was diverted to APCs was 36 ± 14% (mean ± SD) in the BCPC group and 26 ± 9% in the Fontan group. Comparison with angiographic assessment of APCs was not performed.

These data indicate that APC flow can cause a substantial volume load to the functionally single ventricle and contribute significantly to pulmonary flow. Because the indications for cardiac MRI in this study often included conditions that might be associated with promotion of APC development (eg, suspected pulmonary venous obstruction), it is unclear how representative these results are for the more general population of surgically palliated single-ventricle patients. Although APC flow was relatively high, in this small series it did not significantly correlate with ventricular end-diastolic pressure, atrial pressure, pulmonary vascular resistance, or pulmonary artery pressure at catheterization.

A principal challenge in the evaluation of this MRI technique to measure APC flow, as well as those discussed earlier, is that there is no in vivo gold standard by which to validate accuracy. Recognizing this, the authors checked for internal consistency by assessing the equivalency of flow leaving the heart (ascending aorta) versus total venous return to the heart in each patient. The reported discrepancy was a
mean of 7.9 ± 14.5% (range, 0% to 44%) of ascending aorta flow in the BCPC group (n = 16) and 7.1 ± 11.3% (range, 0% to 25%) of ascending aorta flow in the Fontan group (n = 7). These suboptimal results are probably related to some of the known technical limitations and pitfalls of phase contrast cine MRI measurements,15–17 which are then compounded in the setting of multiple measurements. In this case, the measurement most vulnerable to inaccuracies probably is the individual pulmonary veins because of their small caliber, proximity to the lung, and varied anatomy. In particular, it is unclear from the information provided in the study whether there was sufficient spatial resolution to minimize partial volume errors.18 The authors reported better internal consistency when measuring pulmonary vein flow by MRI in a previous study,19 in which the subjects were adults with normal anatomy. Additional validation work tailored to this clinical application is therefore warranted. Studies might include comparisons of flow measurements to ventricular stroke volumes quantified by cine MRI tomography and in vitro measurements using flow circuits and pediatric-sized vessels and flow rates.

Despite these limitations, Grosse-Wortmann et al are to be congratulated for pioneering this approach to measuring APC flow. Their method is noninvasive, free of ionizing radiation, and can be combined with other cardiac MRI techniques to provide a wealth of clinically relevant information. As such, it is an attractive tool for resolving the uncertainty regarding the clinical impact of APCs and efficacy of treating them. For example, one might envision a multicenter longitudinal study in which single-ventricle patients have serial APC flow measurements by MRI, and these data are correlated with a variety of clinically important outcomes. Furthermore, APC flow measurement should add to the utility of cardiac MRI as an alternative to routine cardiac catheterization for the preoperative assessment of patients with single-ventricle heart disease.20 One concern with this approach has been that MRI is less sensitive than selective x-ray angiography for the detection of multiple small APCs that may warrant coil occlusion. APC flow measurements could identify this scenario, localize the lung segments that are most involved, and set objective criteria for transcatheter intervention.

In summary, APCs are commonly found in patients with surgically palliated single-ventricle heart disease. Their clinical significance and the indications for occluding them are not well established. An important step toward improving our knowledge would be the development of a robust technique to quantify APC flow. MRI flow measurements as described by Grosse-Wortmann et al have the potential to meet this need but require additional validation and refinement before widespread use can be recommended.

Disclosures

None.

References


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