Caval Contribution to Flow in the Branch Pulmonary Arteries of Fontan Patients With a Novel Application of Magnetic Resonance Presaturation Pulse

Mark A. Fogel, MD; Paul M. Weinberg, MD; Jack Rychik, MD; Anne Hubbard, MD; Marshall Jacobs, MD; Thomas L. Spray, MD; John Haselgrove, PhD

Background—A complete understanding of fluid mechanics in Fontan physiology includes knowledge of the caval contributions to right (RPA) and left (LPA) pulmonary arterial blood flow, total systemic venous return, and relative blood flow to each lung.

Methods and Results—Ten Fontan patients underwent cine MRI. Three cine scans of the pulmonary arteries were performed: (1) no presaturation pulse, (2) a presaturation pulse labeling inferior vena cava (IVC) blood (signal void), and (3) a presaturation pulse labeling superior vena cava (SVC) blood. The relative signal decrease is proportional to the amount of blood originating from the labeled vena cava. This method was validated in a phantom. Whereas 60±6% of SVC blood flowed into the RPA, 67±12% of IVC blood flowed toward the LPA. Of the blood in the LPA and RPA, 48±14% and 31±17%, respectively, came from the IVC. IVC blood contributed 40±16% to total systemic venous return. The distributions of blood to each lung were nearly equal (RPA/LPA blood = 0.94±11).

Conclusions—In Fontan patients with total cavopulmonary connection, SVC blood is directed toward the RPA and IVC blood is directed toward the LPA. Although the right lung volume is larger than the left, an equal amount of blood flow went to both lungs. LPA blood is composed of equal amounts of IVC and SVC blood because IVC contribution to total systemic venous return is smaller than that of the SVC. This technique and these findings can help to evaluate design changes of the systemic venous pathway to improve Fontan hemodynamics. (Circulation. 1999;99:1215-1221.)

Key Words: Fontan procedure ■ blood flow ■ lung ■ magnetic resonance imaging ■ heart defects, congenital
contained 0.9% sodium chloride as a marker. Both reservoirs contained aqueous cupric sulfate to approximate the T1 relaxation properties of blood.

Measurement of the chloride concentration in both input and output reservoirs and measurement of flow rate in each output allowed calculation of the percentage of flow to each output reservoir. Chloride concentration was measured by a Ciba chloride analyzer.

The flow rate in the output limbs was measured with the graduated cylinder and stopwatch by determining the volume of fluid entering the graduated cylinder in 1 minute.

Patients
We prospectively studied 10 patients with functional single ventricles who underwent Fontan reconstruction at The Children’s Hospital of Philadelphia between June 1, 1995, and March 31, 1996. Patients were 1.8 ± 0.3 years old and were studied 1.6 ± 0.4 weeks after Fontan completion. Nine patients had hypoplastic left heart syndrome, and 1 had critical subaortic stenosis with multiple ventricular septal defects and aortic hypoplasia. All patients underwent a lateral wall tunnel total cavopulmonary connection with side-to-side anastomosis of the right SVC to the RPA with patch augmentation of that junction. Patients with insignificant flow across the fenestrations in their baffle were chosen, with average aortic saturation of 91.4 ± 2.9%.

For them to enter the study, they could have no discrete pulmonary artery stenosis (as delineated by MRI); the diameters of the LPA and RPA were within 20% of each other and >50% of that of the descending aortic diameter. Patients with bilateral SVC–to–pulmonary artery connections were excluded. Patients were stable enough to undergo a 1-hour MRI scan under sedation. Informed consent was obtained from all participants. No patient had arrhythmias that precluded imaging in the scanner.

Magnetic Resonance Imaging
All patients were sedated and tolerated this without incident.

Studies were performed on a 1.5-T Siemens Vision system. The scanning protocol was as follows (Figure 2A and 2B).

1. Parameters we use to obtain spin-echo images of the heart have been described previously. We initially obtained spin-echo transverse images of the heart (Figure 2A, top left) to identify the site of the branch pulmonary artery connection to the SVC and the lateral wall tunnel baffle.

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The sodium chloride (NaCl) input reservoir had a chloride concentration ([Cl\(^{-}\)]) that measured 228 mmol/L, and the plain water input reservoir measured the chloride concentration at 2 mmol/L. NaCl Input Sat indicates presaturation pulse applied to NaCl input limb; No Sat, no presaturation pulse applied.
2. With the transverse images used to precisely localize the center of the systemic venous pathway (by multiplanar reconstruction), sagittal spin-echo images were acquired spanning the region of the heart (Figure 2A, right, and 2B, left) to localize the long axis of the systemic venous pathway. This was used to evaluate the superior-inferior dimension of the branch pulmonary arteries for subsequent cine imaging and to determine placement of the presaturation band.

3. Gradient echo imaging (cine): Prospective ECG-gated, gradient-echo axial images were obtained at the level of the branch pulmonary artery anastomosis to the SVC (Figure 2A, bottom left, and Figure 2B, right). The position of the plane of the cine series is shown in Figure 2B, (left). Eight to 10 images were obtained, spanning the entire cardiac cycle. The saturation pulse takes 1.0 ms to apply and is applied 4.7 ms before the center of the excitation pulse used in the acquisition sequence. The TR ranged from 40 to 60 ms (depending on the R-R interval), the TE was 7.3 ms, field of view was 180 to 280 mm, matrix was 128×256 pixels (which was interpolated to 256×256), and number of excitations was 3. Slice thickness was determined by the superior-inferior width of the branch pulmonary artery and ranged from 6 to 10 mm.

Three sets of gradient-echo images of the branch pulmonary arteries at the same level were obtained (Figure 2B, right): (1) no presaturation pulse (Figure 2B, top); (2) a presaturation band placed inferior to the image plane (Figure 2B, middle) to destroy spins from IVC blood and produce a signal void. The band thickness extended from the IVC–right atrial junction to just below the imaging plane and ranged from 3 to 8 cm (Figure 2B, middle left); (3) and a presaturation band placed superior to the image plane (Figure 2B, bottom) to destroy the spins from SVC blood. The band thickness was equal to the previous presaturation band.

The leading edge of the saturation band was ∼3 mm from the imaging plane.

The entire study was obtained in 1 hour. Respiratory gating was not performed, because respiration plays a minor role.6

Data Analysis
Images were downloaded onto a Sun SPARC station 10 (Sun Microsystems) and VIDA (volumetric image and display analysis)8 was used to manipulate the images.

Calculation of the contribution of fluid from the sodium chloride input reservoir to each output limb of the phantom used the formula (left limb is used as an example)

\[(\text{Cl}_L)(Q_L)\]

(1) Contribution of flow to left limb = \[\frac{\text{Cl}_L(Q_L)}{\text{Cl}_L(Q_L)+\text{Cl}_R(Q_R)}\],

where [Cl], and [Cl], are the chloride concentrations in the left and right output reservoirs and Q, and Q, are the flow rates to the left and right output reservoirs, respectively.

The mean blood signal intensity in each pulmonary artery just distal to the anastomosis site was measured in a rectangle 3 mm in length and the width of the branch pulmonary artery (Figure 2A, bottom left). This was performed with the same rectangular shape and position used for all 3 cine image sets. The width of the branch pulmonary artery was also measured at that point. The data for each individual patient represent the integrated flow over the entire cardiac cycle.

The derivation of flow calculations to follow and exact formulas are given in the Appendix.

The IVC contribution to branch pulmonary artery flow is a function of both the decrease of total signal intensity in the branch pulmonary artery from the first to the second cine set (saturation of IVC blood producing a signal void) and the cube of the radius of the branch pulmonary artery. The SVC contribution to flow in each branch pulmonary artery is calculated similarly.

The percentage of blood in the LPA and RPA originating from the IVC is a function of the decrease in total signal intensity from the first to the second cine set (saturation of IVC blood producing a signal void) and the first to the third cine set (saturation of SVC blood producing a signal void) in the individual pulmonary artery. The percentages of blood in the LPA and RPA originating from the SVC were similar to that from the IVC, except that the numerators were different.

The amount of caval contribution to the total systemic venous return is a function of the sum of the decrease in total signal intensity from the first to the second cine set and the first to the third cine set in both branch pulmonary arteries.

The distribution of blood flow to each lung was the weighted average of percent caval contribution to the systemic venous return and the caval contribution to each pulmonary artery.

Statistics
Comparisons between 2 means were made by the paired 2-way Student’s t test and the Wilcoxon rank sum test. All measurements are mean±SD. Intraobserver variability was determined by replicate measures using the coefficient of variation. A single trained observer performed all image analysis steps. Significance was taken at P<0.05. This analysis was performed on a PC using Excel 5.0 and JMP version 3.1.4 (SAS Institute Inc).

Results
Validation in a Phantom
The left output limb mean velocity was 32 cm/s, and that of the right output limb was 40 cm/s. Sodium chloride measurement of percent contribution of the sodium chloride input to flow in each output limb was within 10% of MRI measurements (Figure 1 and Table).

Caval Contribution to Pulmonary Arterial Flow
Figure 2B displays the raw image data. Note how similar and uniform the signal is in both RPA and LPA in the top right panel without a presaturation pulse. Compare this with the decreased signal intensity in the LPA in the middle panel when the IVC blood is saturated. Also compare this with the decreased signal intensity in the RPA in the bottom panel when the SVC blood is saturated.

The first and second sets of bars in Figure 3 display the percent IVC and SVC contributions, respectively, to LPA and RPA flow. The IVC contributed significantly more blood to the LPA than the RPA, with an LPA/RPA flow ratio of 2.5±1.5 (Figure 2B, middle right). Significantly more blood in the SVC, however, was directed toward the RPA than the LPA, with an LPA/RPA flow ratio of 0.68±0.19 (Figure 2B,
The fluid mechanics of Fontan physiology has received much attention, and ways to optimize this physiology have been explored. This included work into the basic driving forces of blood flow into the pulmonary arteries in the absence of a "pulmonary" pumping chamber, optimization of the velocity profiles, and computational fluid dynamics using finite-element analysis. This body of literature is predicated to various degrees on the knowledge of caval contributions to the branch pulmonary arteries, caval contributions to total systemic venous return, and relative blood flow to each lung. This underlies the need to obtain these values in vivo.

It has classically been thought that IVC blood carries a majority of systemic venous return. Recent suggested modifications to systemic venous pathway geometry take advantage of this by attempting to direct more IVC flow to the larger right lung and SVC flow to the smaller left lung. Salim et al' recently demonstrated in normal children that caval contributions to systemic venous return vary with age, from a low in the IVC of 45% at 2.2 years old (at 1.8 years old in our study, the IVC contribution was 40%) to a high of 65%, the adult value, at 6.6 years old. In the face of changing caval flow and a fixed systemic venous pathway geometry, the dynamics of systemic venous flow is likely to change with age. Indeed, IVC flow directed toward the LPA makes sense for a 2-year-old, but this same patient at almost 7 years old will wind up with a vast majority of total systemic venous return directed toward the smaller lung.

The purpose of this study was to delineate the components of pulmonary blood flow in vivo by use of MRI and a novel application of the presaturation pulse.

The presaturation pulse acts as a marker of blood from the vessel it is applied to by producing a signal void. By placing a presaturation "band" on a vessel and imaging "downstream," one can observe where the blood from that vessel goes by the "negative washout." This study used the concept of quantifying this flow by measuring the decrease in signal intensity, validated it in a phantom, and measured the various flow components in vivo. We used images triggered to the ECG because we have demonstrated that the vast majority of flow in the systemic venous pathway is due to cardiac effects.

Our observation that a substantial amount of SVC blood preferentially streams to the RPA and a substantial amount of IVC blood preferentially streams to the LPA is consistent with anecdotal evidence by angiocardiology.

The way blood preferentially streams from the vena cava is a function of the geometry of the systemic venous pathway, the amount of flow each vena cava carries, and the amount of flow each lung can accommodate. The geometry of the systemic venous pathway in our study group differs from the geometry studied by others in vitro. The systemic venous pathways in our study patients were created in 2 stages by use of the "hemi-Fontan" procedure: a side-to-side anastomosis of the SVC to the RPA, with patch augmentation anterior to the SVC-RPA connection.

The distance between the axial centers of the SVC and the intra-atrial baffle is called the "offset." Although in our patients, there is no lateral offset of the SVC and IVC to each other, there is an offset anteroposterior to the RPA and LPA from the SVC and IVC. Sharma et al noted that a zero offset of the SVC and IVC carries a 100% power loss; however, they did not study a side-to-side anastomosis or an anteroposterior offset.

LPA blood originated from both vena cavae equally. This is because the IVC (lower flow) contributes a majority of its blood to the LPA (40% of systemic venous return × 66% of IVC blood is directed to the LPA = 0.26), whereas the SVC (larger flow) contributes a small amount of blood to the LPA (60% of systemic venous return × 40% of the blood is directed to the LPA = 0.24).

A majority of RPA blood originated from the SVC. This is because the SVC (higher flow) contributes a majority of its blood to the RPA (60% of systemic venous return × 60% of...
the blood is directed to the RPA (0.36), whereas the IVC (lower flow) contributes a small amount of blood to the RPA (40% of systemic venous return × 33% of the blood is directed to the RPA = 0.12).

As mentioned, the IVC has classically been thought to carry a majority of systemic venous return. Some groups have modified the systemic venous pathway geometry to take advantage of this by channeling IVC blood into the RPA (larger lung) and SVC blood into the LPA (smaller lung). Our data demonstrated that without this modification, the reverse (larger lung) and SVC blood into the LPA (smaller lung). Our studies had patients with lateral wall tunnel total cavopulmonary connection may direct blood preferentially to the LPA, “filling up” the smaller left lung and leaving the right lung “underfilled”; this may be the reason why both lungs receive equal perfusion. If true, altering the geometry of the systemic venous pathway may optimize perfusion to both lungs and thereby optimize systemic oxygenation. Other causes for equal perfusion to both lungs are the patient’s age (affects caval contribution to the systemic venous return), thromboembolic phenomenon, or autonomic nervous system alterations.

Our studies were performed early after Fontan reconstruction, before hospital discharge. It is unknown how the flow components would change later in the patient’s course.

Limitations
Because MRI measures fixed planes in space, through-plane motion may cause “partial volume” of some of the signal intensity. Because the pulmonary arteries are minimally pulsatile in this physiology, this would not change our results significantly.

Similarly, “partial-volume effects” can occur when blood vessels are imaged because the signal intensity at the edges averages the signal of the blood and the surrounding soft tissue. This problem was avoided by measuring the decrease in signal intensity from images with a presaturation pulse and those without a presaturation pulse. The difference between the signal intensities is solely from blood.

The saturation pulse takes 1.0 ms to apply and is applied 4.7 ms before the center of the excitation pulse used in the acquisition sequence. During that period, some recovery of spins would have occurred. This effect is not appreciable because of the small amount of time available for the spins to recover. It would also not change the relative percentages because spin recovery would occur in both pulmonary arteries.

The right-to-left flow from systemic to pulmonary venous pathways across the baffle fenestration would, in theory, alter the exact numbers for relative caval contribution to systemic venous return only. To minimize this, we studied patients with insignificant flow across this (aortic saturation, 91.4 ± 2.9%).

It should be noted that this study was performed in sedated, supine patients. The findings may be altered with increased patient activity.

Finally, this technique is not applicable to patients with turbulent flow in the pulmonary arteries because turbulence would create a signal void and alter the calculations. This would probably apply only to patients with moderate to severe bilateral pulmonary artery obstruction.

Conclusions
This study has validated the use of a presaturation pulse to quantify the relative contributions of caval flow to pulmonary artery flow and total systemic venous return. It may be used to evaluate flow components in the various systemic venous pathways created surgically.

In Fontan patients, SVC blood is directed more toward the RPA and IVC blood is directed more toward the LPA. Nevertheless, LPA blood is composed of equal amounts of IVC and SVC blood, and the majority of RPA blood is from the SVC. In addition, the IVC accounts for only 40% of the total systemic venous return, and equal amounts of blood flow to each lung. These findings may help in designing a better Fontan procedure and change the way the systemic venous pathway geometry is created.

Appendix
Derivation of Blood Flow Calculations
The assumptions (where k, k′, etc., are constants) are that (1) the imaging slice thickness equals the pulmonary artery diameter; (2) flow in the systemic venous pathway is laminar; (3) the signal intensity is proportional to the volume of tissue; and (4) after caval blood saturation, the decrease in signal intensity, \( \delta t \), is proportional to the blood volume (\( \delta V \)) from the cava:

\[
\delta V = (k)(\delta t).
\]

The remaining signal is not equal to the signal from the unsaturated vena cava because nonblood tissue may be present in each pixel. \( \delta V \) enters an artery in time \( \delta t \) and fills the vessel for a distance \( (v_r)(\delta t) \), where \( v_r \) is mean velocity. Saturated blood is the sum of all \( \delta V \) in that artery, which is the integral of \( \delta V \) in each pixel over area \( A \). Extending the pulmonary artery width and the length of \( (v_r)(\delta t) \), Area \( A \) is...
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\[ A = 2R(v_n)(\delta t), \]

where \( R \) is the arterial radius. Thus,

\[ \text{Total saturated caval blood in } \delta t \]
\[ = \sum \text{area} \frac{\delta \text{Vol}}{\text{area}} = \sum (k)(\delta t). \]

Substituting the product of the average signal drop \((k)(\delta t))\) in area A by area A (Figure 1, Equation 3) over time \( \delta t \) into Equation 4, we obtain

\[ \text{Total saturated caval blood in } \delta t \]
\[ = \sum (k)(\delta t) = (k')(\delta t)/(R)(v_n)(\delta t). \]

Because of periodic flow, we integrate Equation 6 over the cycle (heartbeat) to obtain

\[ \text{Total saturated caval blood over cardiac cycle} \]
\[ = \sum \sum \delta \text{Vol} = (k') \sum (\delta t)/(R^3). \]

where \( k' = (k)(\delta t) \). Writing D for \( \sum (\delta t) \) (the sum of all average signal intensity drops over the cardiac cycle), we obtain

\[ \text{Total saturated caval blood over cardiac cycle} = (k')D/(R^3). \]

Use the notation \( R_L, R_S = \text{LPA and RPA radii, respectively; } D_L, D_S = \text{average intensity drop (D) in the LPA when the IVC and SVC are saturated, respectively; } D_{IV}, D_{SR} = D \text{ in the RPA when the IVC and SVC are saturated, respectively; } V_{IL}, V_{SL} = \text{volume of blood (V)} \) entering the LPA when the IVC and SVC are saturated, respectively; and \( V_{IR}, V_{SR} = V \) entering the RPA when the IVC and SVC are saturated, respectively.

1. Cava1 contribution to each pulmonary artery: Using the IVC and LPA as an example, the fraction of blood from the IVC that enters the LPA is

\[ \frac{V_{IL}}{V_{IL} + V_{IR}} = \frac{(k' D_{IH})(R_L^3)}{D_L(R_L^3) + D_{IH}(R_L^3)}. \]

Other ratios of caval blood entering the pulmonary arteries are written similarly.

2. The percentage of blood in each pulmonary artery from each vena cava: Using the IVC and LPA as an example, the fraction of blood in the LPA that originated from the IVC is

\[ \frac{V_{IL}}{V_{IL} + V_{SL}} = \frac{(k' D_{IH})(R_L^3)}{D_L(R_L^3) + (k' D_{SL})(R_L^3)}. \]

Other ratios of pulmonary artery blood that originated from each vena cava are written similarly.

3. Cava1 contribution to total systemic venous return: Using the IVC as an example, the fraction of total systemic venous return that that is contributed from the IVC is

\[ \frac{V_{IL} + V_{IR}}{V_{IL} + V_{IR} + V_{SL} + V_{SR}} = \frac{(k' D_{IH})(R_L^3) + (k' D_{SR})(R_R^3)}{(D_L(R_L^3) + (D_{IH})(R_L^3) + (D_{SR})(R_R^3))}. \]

The SVC contribution to total systemic venous return is written similarly.

4. Relative blood flow to each lung: Using the following notation: \( I_{IL}, S_{IL} = \% \text{ IVC and } \% \text{ SVC contribution to total systemic venous return, respectively; } I_{IR}, S_{IR} = \% \text{ IVC and } \% \text{ SVC contribution to LPA flow, respectively; and } I_{SR}, S_{SR} = \% \text{ IVC and } \% \text{ SVC contribution to RPA flow, respectively (all values calculated from the previous equations). Using the LPA as an example, the fraction of total systemic venous return that enters the LPA is } I_{IL}(I_L) + S_{SR}(S_L). \)

The % for RPA flow is written similarly, with \( I_R \) and \( S_R \) instead of \( I_L \) and \( S_L \).

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References


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