# Pulmonary hepatic flow distribution in total cavopulmonary connections: Extracardiac versus intracardiac

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**Objective:** Pulmonary arteriovenous malformations can occur after the Fontan procedure and are believed to be associated with disproportionate pulmonary distribution of hepatic venous effluent. We studied the effect of total cavopulmonary connection geometry and the effect of increased cardiac output on distribution of inferior vena caval return to the lungs.

**Methods:** Ten patients undergoing the Fontan procedure, 5 with extracardiac and 5 with intracardiac configurations of the total cavopulmonary connection, previously analyzed for power loss were processed for calculating the distribution of inferior vena caval return to the lungs (second-order accuracy). One idealized total cavopulmonary connection was similarly analyzed under parametric variation of inferior vena caval offset and cardiac output flow split.

**Results:** Streaming of the inferior vena caval return in the idealized total cavopulmonary connection model was dependent on both inferior vena caval offset magnitude and cardiac output flow-split ratio. For patient-specific total cavopulmonary connections, preferential streaming of the inferior vena caval return was directly proportional to the cardiac output flow-split ratio in the intracardiac total cavopulmonary connections ($P < .0001$). Preferential streaming in extracardiac total cavopulmonary connections correlated to the inferior vena caval offset ($P < .05$) and did not correlate to cardiac output flow split. Enhanced mixing in intracardiac total cavopulmonary connections is speculated to explain the contrasting results. Exercising tends to reduce streaming toward the left pulmonary artery in intracardiac total cavopulmonary connections, whereas for extracardiac total cavopulmonary connections, exercising tends to equalize the streaming.

**Conclusions:** Extracardiac and intracardiac total cavopulmonary connections have inherently different streaming characteristics because of contrasting mixing characteristics caused by their geometric differences. Pulmonary artery diameters and inferior vena caval offsets might together determine hepatic flow streaming. (J Thorac Cardiovasc Surg 2011;141:207-14)

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Pulmonary arteriovenous malformations (PAVMs), also referred to as pulmonary arteriovenous fistulas, can occur after the Fontan procedure, resulting in decreased systemic oxygenation. PAVMs are intrapulmonary arterial to venous shunts in which the systemic venous blood reaches the pulmonary venous system through abnormal vascular connections proximal to the gas exchange units. The primary consequence of PAVMs is decreased systemic oxygen saturation. The prognosis for patients with PAVMs undergoing the Fontan procedure is often poor without reoperation to reconstruct the Fontan baffle. PAVMs have been postulated in the past to be secondary to disproportionate distribution of hepatic factors between the 2 lungs.[1-5] More recent studies confirmed that geometric configuration of the total cavopulmonary connection (TCPC) to preferentially stream hepatic venous flow to a single lung leads to PAVMs.[6] Thus it is important to determine TCPC geometric characteristics necessary to avoid preferential hepatic venous flow streaming. A recent study underscores the importance of geometric characteristics in a particularly complex case of PAVMs.[7]

The TCPC is a double-inlet, double-outlet connection that routes the venous return from the superior vena cava (SVC) and inferior vena cava (IVC) to the left pulmonary artery (LPA) and the right pulmonary artery (RPA). Although most previous hemodynamic studies of the TCPC have focused on the power loss characteristics,[8-12] flow streaming might be an equally important characteristic, specifically during the early growing period of the lung after conversion from Glenn stage to a Fontan connection. Thus one can postulate that an ideal TCPC needs to impose the least hemodynamic

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**Abbreviations and Acronyms**

CO = cardiac output
IVC = inferior vena cava
LPA = left pulmonary artery
PAVM = pulmonary arteriovenous malformation
RPA = right pulmonary artery
SVC = superior vena cava

resistance (for minimal power losses), as well as facilitate balanced left and right streaming of inferior venous return for sufficient hepatic factor transport to both lungs.

In this study we quantify the flow branching of inferior blood returning through the Fontan baffle to the pulmonary arteries in the 2 major types of TCPCs, namely extracardiac and intracardiac TCPCs. Of particular interest is the following question: What are the geometric parameters of TCPCs (eg, pulmonary artery diameters and vessel offset) that can be controlled during the construction of a Fontan TCPC to avoid preferential streaming of hepatic venous flow? The answer to this question has strong clinical implications from the standpoint of choosing a particular TCPC type along with an understanding of the desired geometric characteristics for reducing the risk of PAVM formation. Also, it provides another perspective given the substantial literature on power loss characteristics of the TCPC and its correlation with the geometry of the connection.



## MATERIALS AND METHODS

The blood-flow fields through 10 patient-specific TCPC geometries, as well as an idealized TCPC geometry, were computed by using computational fluid dynamics tools and then analyzed to calculate the distribution of the IVC flow between the left and right lungs. The results were then examined to correlate TCPC geometry type (extracardiac or intracardiac) and influence of exercise on the distribution/streaming characteristics.

### Patients' Data

Ten patients, 5 each with extracardiac and intracardiac TCPCs, were selected from the Georgia Tech MRI database of patients undergoing the Fontan procedure (http://fontan.bme.gatech.edu). The database is part of a National Institutes of Health–funded ongoing study for understanding Fontan hemodynamics. The demographics of the 10 patients are shown in Table 1. All patients were imaged at Children's Hospital of Philadelphia. Informed consent was obtained from all patients, and all study protocols complied with the Institutional Review Boards of the Children's Hospital of Philadelphia and the Georgia Institute of Technology. The inclusion criteria for this study were as follows: (1) availability of axial magnetic resonance images to reconstruct the TCPC and aortic arch, (2) availability of clinical information necessary to categorize each study group, and (3) availability of computational results under resting and simulated exercise conditions at equal pulmonary lung resistance conditions. For all these criteria, 10 was the maximum of more than 200 patients in the database. For all 10 patients, the anatomy of the TCPC was reconstructed by using previously described segmentation and reconstruction techniques.[13,14] Geometric offsets of the IVC relative to the SVC were calculated for each of the patient-specific TCPCs from previously described methods.[15] There was no significant difference in cardiac output (CO) between the 2 groups of patients, and the mean age of both groups was above the threshold[16] for any variation in SVC/IVC flow ratio.

### Computational Model

Computational fluid dynamics simulations were conducted with FIDAP (ANSYS, Inc, Canonsburg, Pa) for each TCPC. Some of the data, along with the detailed description of the simulation parameters, have been published previously in the context of energy loss characteristics of the TCPC.[17] The flow conditions for each of the models correspond to the resting conditions and 2 simulated levels of exercise, namely the 2x and 3x resting flow conditions.[17] The CO flow split is defined as the fraction of the net inflow streaming to the LPA. In these simulations the CO flow split for each patient corresponds to imposed equal pulmonary lung resistance condition. Imposing this condition ensures that the difference in the split of CO between the 2 lungs is purely governed by the resistance of the TCPC and not from differences in left and right pulmonary vascular bed resistances. This is an important condition to ensure that hepatic venous flow streaming characteristics are not biased by patient-to-patient variation in the difference between left and right lung resistance. Results on the idealized TCPC model are also presented for varying flow split and offset of the IVC from the SVC to help develop insight into the flow-split physics.

### Flow-Split Computation

Figure 1 shows a schematic that explains the methodology for flow-split computation on an idealized 1-dimensional offset TCPC. Ten thousand particles were uniformly seeded in a cross-section of the IVC. These particles have zero mass, and their trajectories were computed by integrating the following equation of motion for each particle, using a second-order Runge–Kutta numeric method:

$$\dot{x} = u(x, y, z)$$
$$\dot{y} = v(x, y, z)$$
$$\dot{z} = w(x, y, z),$$

where $u$, $v$, and $w$ are the 3-dimensional velocity components obtained from the computational model for each particle. Note that only the steady-state computational fluid dynamics solutions were considered for this analysis. Therefore the velocity is not a function of time. $\dot{x}$, $\dot{y}$, and $\dot{z}$ are the time derivatives of the actual 3-dimensional particle position at time $t$ given by x($t$), y($t$), and z($t$).

Figure 2, *A*, shows a plot of all the trajectories calculated for the seeded particles in Figure 1. Each trajectory is sorted based on whether the particle is bound to the left lung or the right lung, respectively. Based on the fate of the particle trajectory, the cross-section shown in Figure 1 is then partitioned into left-bound or right-bound areas. Examples of partitioning are shown in Figure 2, *B*. The corresponding flow distribution is then calculated by integrating the velocity over the partitioned domains. Equations are shown at the 2 outlets of the LPA and RPA in Figure 1. The end result is the estimation of the exact split of the blood returning from the IVC to the 2 lungs. We note here that we assume the hepatic factor or factors to be uniformly mixed with the IVC blood. This calculation is denoted as hepatic venous flow split and is different from CO flow split in the sense that it is the split of IVC flow alone to the LPA.

### Normalization

The CO flow split to the LPA is normalized by CO, and the estimated hepatic venous flow split to the LPA is normalized to the total IVC flow. Therefore a 50% value indicates equal streaming.

### Statistical Analysis

Because the data were nonnormally distributed and corresponded to a 2-sample population (extracardiac vs intracardiac), the nonparametric Mann–Whitney test was used to examine statistical significance among