

## Original Articles

# In Vitro Evaluation of Flow Distribution in All-Region Perfusion during the Norwood Operation

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Presented at the AmSECT 58th International Conference, St. Louis, MO, March 6–8, 2020.

**Abstract:** Continuous all-region perfusion has the potential to reduce total body ischemia during the Norwood procedure. This technique involves placing cannulas in the innominate artery, descending aorta, and native aortic root, thus providing continuous flow to the whole body at mild hypothermia (32–34°C) during the entire operation. However, the cannulation strategy in this approach must be optimized to achieve adequate flow rates to all vascular beds. To ensure appropriate blood flow rates to three cannulas of different caliber supplied by two inflow pumps, a benchtop evaluation of comparative flow rates through branched cannulas with variable independent perfusion pressures was conducted. Two isolated vertical columns with outlets at 10 mmHg intervals to allow for adjustable perfusion pressures were filled with expired banked packed red blood cells and fresh frozen plasma. The main arterial line was bifurcated with an 8-Fr arterial cannula inserted at the base of one column and a 4-mm (outside diameter [OD]) olive tip cannula inserted at the base of

the other column. Flow rates were measured on each branch of the ¼" arterial lines. Under experimental cardiopulmonary bypass (CPB) perfusion pressures of 30–50 mmHg on the 8-Fr arterial cannula column, the branched olive tip cannula accommodated less than 25% of total flow at total flow rates of 50–700 mL/min. This fraction is insufficient to sustain adequate lower body perfusion. However, the olive tip flow fraction was found to be sufficient for coronary blood flow (5–20 mL/kg/min) when olive tip perfusion pressures close to average neonatal diastolic blood pressures (20–60 mmHg) were tested. For all-region perfusion during the Norwood operation, primary CPB arterial flow should be divided to the head and coronary circulation with an independent pump delivering flow to the descending aorta. This should avoid cerebral over-circulation and insufficient flow to the lower body. **Keywords:** all-region perfusion, Norwood operation, in vitro, olive tip cannula, three region perfusion. *J Extra Corpor Technol.* 2020;52:261–5

The Norwood procedure is the principal operation for the palliation of neonates born with hypoplastic left heart syndrome and other forms of single ventricle heart disease. Recent advances now allow the Norwood procedure, originally conducted under deep hypothermic circulatory arrest, to be conducted at mild hypothermia with continuous perfusion to the head, beating heart, and lower body (1–5). This technique, termed all-region perfusion, could in

theory enhance post-operative recovery and reduce the risk of ischemic complications such as acute kidney injury and low cardiac output syndrome (6). However, the practicality of operating three independent blood pumps in addition to three blood suction and venting pumps on most of today's cardiopulmonary bypass (CPB) consoles is limited by the console platform size and orientation. Consequently, a means of safely providing two of the three regions of circulation off the same blood pump was evaluated. Initially, our CPB configuration involved the main arterial pump providing flow to both the head and descending aortas via Y-connector bifurcation, although the accessory (i.e., cardioplegia) pump provided coronary flow. However, this configuration was observed to provide suboptimal flow to the lower body as measured by lower

Received for publication May 12, 2020; accepted September 3, 2020.  
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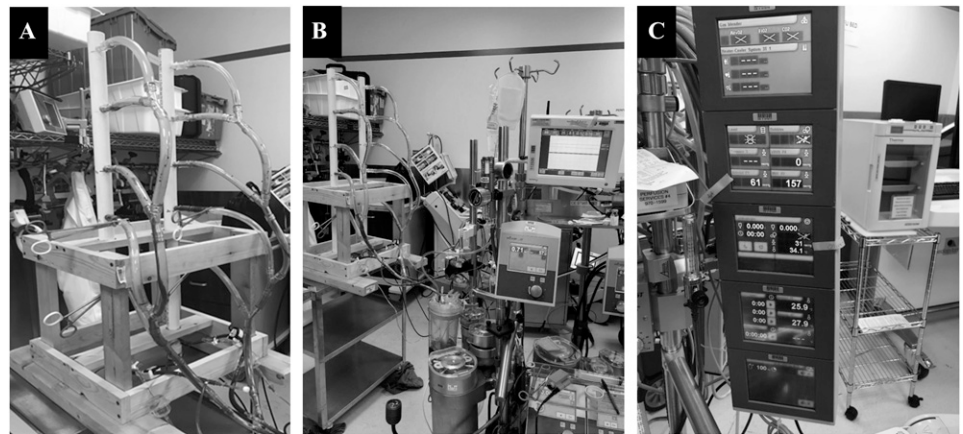
The senior author has stated that the authors have reported no material, financial, or other relationship with any healthcare-related business or other entity whose products or services are discussed in this paper.

extremity arterial line pressure when providing appropriate flow to the head. We hypothesized that a different configuration—using the Y-connector to provide flow to the head and coronary circulation—would provide sufficient flow to both regions.

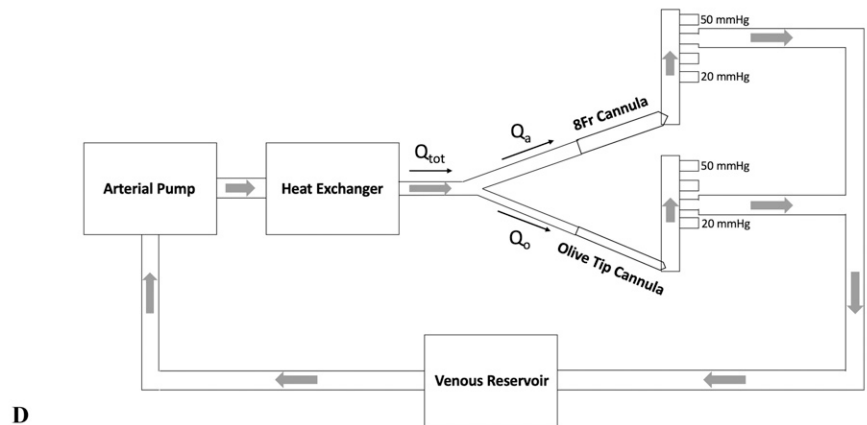
## MATERIALS AND METHODS

To test our hypothesis, we built an in vitro system to evaluate comparative flow rates through cannulas in a branched configuration (Figure 1A–D). The circuit consisted of an S5 heart–lung machine (HLM) (LivaNova, London, United Kingdom), cardiomy reservoir (Terumo Medical, Somerset, NJ), Vanguard CSC14 cardioplegia heat exchanger (LivaNova), and tubing attached to our uniquely crafted 1½"-diameter vertical columns. The circuit was primed with expired banked packed red blood cells and fresh frozen plasma to a final hematocrit of 31% and maintained at a temperature of 34°C. Line pressure was measured with the S5 HLM at three points: 1) at the outflow of the roller pump, 2) at the base of vertical column 1, and 3) at the base of vertical column 2. The main CPB

arterial inflow was bifurcated with a Y-connector to an 8-Fr arterial cannula (DLP® Straight Tip Arterial Cannula, Medtronic, Minneapolis, MN) and a 4-mm (OD) olive tip cannula (DLP arteriotomy cannula, Medtronic), each supplying an isolated vertical column filled with blood. These columns represented artificial “vascular beds” with independent perfusion pressures varied via outlets at 10 mmHg intervals. To achieve a perfusion pressure of 30 mmHg, for instance, the outlets at 10 mmHg and 20 mmHg were clamped allowing outflow to spill into ½" diameter tubing at the 30 mmHg outlet and return to the reservoir. Pressures at the base of the columns were measured using disposable transducers (ICU Medical, San Clemente, CA) attached to the S5 HLM pressure module. Oversizing the vertical columns and drainage tubing greatly reduced the possibility of flow resistance influencing the perfusion pressure. The perfusion pressures of each column and the total arterial inflow rate were varied systematically (8-Fr perfusion pressure 30–60 mmHg; olive tip perfusion pressure 20–60 mmHg; total flow rate 50–700 mL/min), and flows through each cannula were measured via multiple ultrasonic flow meters (M4, Spectrum Medical, Gloucester, United Kingdom). Data analysis was performed in



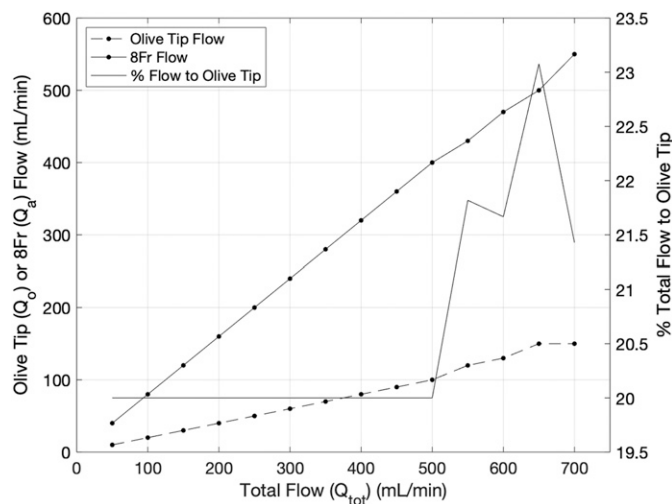
**Figure 1.** In vitro system for assessing comparative flow rates through branched cannulas. (A) Custom two-column flow system. (B) CPB console and M4 monitor for flow measurements along with the in vitro system. (C) Console monitor showing readouts of branch perfusion pressures on an experimental trial with 30 mmHg perfusion pressure on the olive tip cannula and 60 mmHg perfusion pressure on the 8-Fr arterial cannula. (D) Arterial pump, Y-connector bifurcation, independent columns with variable perfusion pressures (20–50 mmHg), and common venous drainage.



MATLAB (MathWorks, Natick, MA) using built-in tools for natural interpolation.

## RESULTS

Measurement of flows through the branched cannula in vitro system shown in Figure 1 was performed for all experimental values of perfusion pressure and total flow. To confirm that clamping column outlets resulted in accurate perfusion pressures, an image was taken of the CPB console during an experimental trial with olive tip column pressure set at 30 mmHg and 8-Fr column pressure set at 60 mmHg. As shown in Figure 1C, the measured pressures were 31 mmHg and 61 mmHg, respectively. During testing, it was found that at total flow rates of 50–700 mL/min, the olive tip cannula created significant resistance, limiting flow to less than 25% of total flow, as shown in Figure 2. This result held for all tested perfusion pressures on the columns supplied by the 8-Fr arterial and olive tip cannulas. Next, to evaluate whether the olive tip flow portion would be sufficient for coronary perfusion during a typical Norwood operation, total flow was held at 200 mL/min, which is approximately half of ideal total CPB flow to a 3-kg neonate (i.e., 450 mL/min and 150 mL/kg/min). Perfusion pressures on the 8-Fr arterial cannula and olive tip cannula branches were varied, and flow through the olive tip was measured. A natural interpolation was performed between the olive tip flow data, as shown in Figures 3A and B, which resulted in a roughly planar three-dimensional surface plot showing flow through the olive tip cannula on the vertical axis and perfusion pressures to the two independent columns on the horizontal axes. The surface plot indicated that



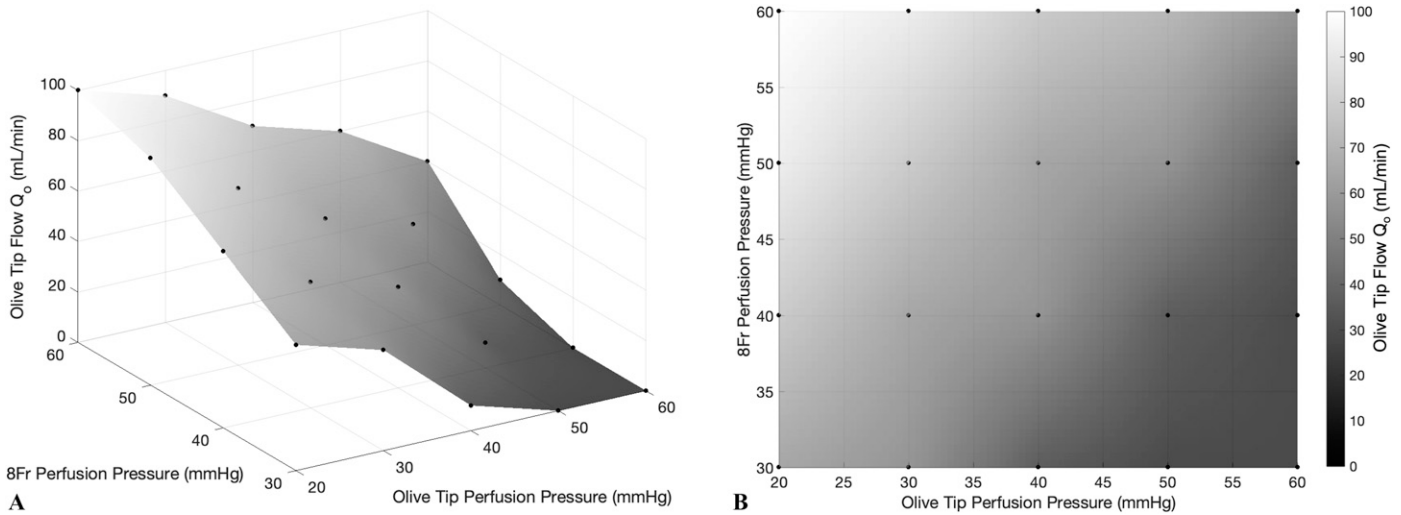
**Figure 2.** Flow distributions to 8-Fr arterial and olive tip cannulas. Total inflow was varied while keeping both column perfusion pressures at 50 mmHg. The olive tip cannula flow rate as a fraction of total inflow is plotted as the solid line with respective axis on the right.

olive tip cannula flow values tended to be higher when pressures in the olive tip cannula column were low and pressures in the 8-Fr cannula column were high. A colored contour plot was created using the natural interpolation data to determine which sets of perfusion pressure values would result in adequate coronary perfusion (Figure 4). The results showed that olive tip flows between 15 and 60 mL/min, or 5–20 mL/kg/min in the case of a 3-kg infant, could be achieved at a wide range of 8-Fr arterial cannula and olive tip cannula perfusion pressures as indicated by the area color coded in green. The contour plot also indicates that olive tip cannula flows could potentially be excessive (i.e., >60 mL/min, red) or insufficient (i.e., <15 mL/min, black) at various perfusion pressures tested.

## DISCUSSION

The in vitro system in this study enabled measurement of flows through branched cannulas with a wide range of total inflows and perfusion pressure values. Furthermore, the clamping method used to manipulate perfusion pressures in the two parallel flow branches resulted in accurate measured pressure values during experimental trials as shown in Figure 1C. Significant resistance to flow was observed in the olive tip cannula, as demonstrated in Figure 2, with 8-Fr perfusion pressure values of 30–60 mmHg, which is a representative range for normal neonatal CPB cerebral perfusion pressures. This was consistent with our anecdotal experience during initial operations where this cannula, Y-connected to the 8-Fr cannula, was used to perfuse the lower body. In these cases, lower body arterial blood pressure measurements and near-infrared spectroscopy indicated insufficient flow, but increasing total arterial flow would have risked cerebral over-circulation.

To determine whether flows through the olive tip cannula are appropriate for coronary perfusion, an assumption was made that physiological peak coronary circulation pressure in single ventricle neonates is approximately equal to average diastolic blood pressure in this age-group, which is 20–60 mmHg (7, p. 208). Another assumption was made that single ventricle coronary blood flow is approximately equal to 3% of total cardiac output, which in this age-group is 800–1,000 mL/min (7, p. 17). In summarizing these assumptions, adequate coronary blood flow for the Norwood operation can be established as 16–30 mL/min, or 5.3–10.0 mL/kg/min for a 3-kg neonate, at a perfusion pressure within the range of 20–60 mmHg. Results from the next experiment, shown in Figure 3, suggest that flows through the olive tip cannula are indeed appropriate for coronary circulation. At a total flow rate close to what is used in the operating room for the head and heart circuit (50–75 mL/kg/min), a coronary flow rate of 15–60 mL/min was achieved at a wide range of 8-Fr arterial and olive tip



**Figure 3.** Flow through olive tip cannula as a function of branch perfusion pressures with  $Q_{tot}$  200 mL/min. (A) 3D perspective view with natural interpolation between data points, shown in red. (B) Bird-eye projection with associated color bar for reference.

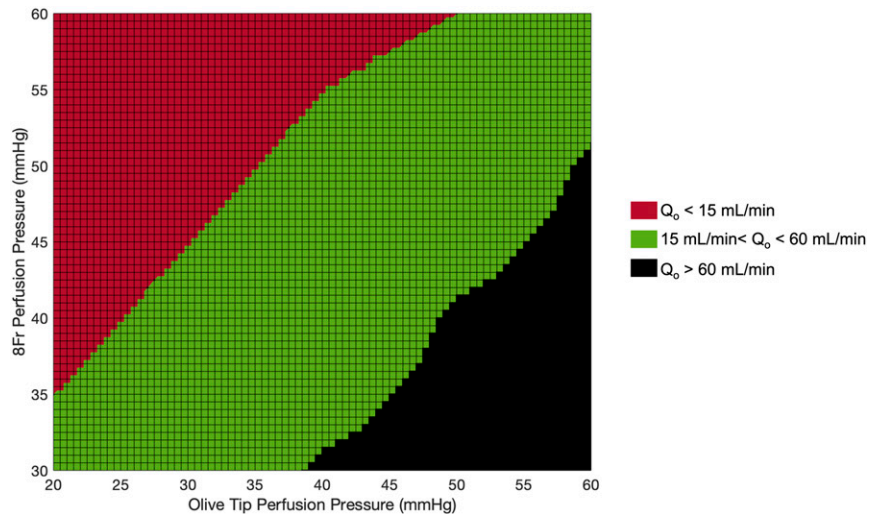
perfusion pressures as shown in Figure 4. For instance, at a total inflow rate of 200 mL/min with an 8-Fr perfusion pressure of 50 mmHg—the target cerebral blood pressure on bypass, ideal coronary flows were achieved at experimental coronary perfusion pressures of approximately 35–60 mmHg.

**CONCLUSION**

Our results indicate that a 4-mm olive tip cannula, when bifurcated off of an arterial line supplying a primary 8-Fr cannula, accommodates less than 25% of total flow over a large range of total CPB flow and perfusion pressures. This

percentage of flow is likely insufficient to provide adequate perfusion to the lower body should this cannula be placed into the descending aorta during a Norwood operation. However, when the olive tip cannula supplied a column with perfusion pressure values over the physiological range for neonatal coronary circulation, the cannula accommodated flows that are likely sufficient to provide adequate perfusion to the coronary arteries. Thus, for all-region perfusion during the Norwood operation, primary CPB arterial flow should be divided to the head and coronary circulation with an independent pump delivering flow to the descending aorta. This should theoretically avoid insufficient flow to the lower body and the risk of cerebral over-circulation.

**Figure 4.** Colored contour plot of interpolated olive tip cannula flow data from Figure 3B. Black indicates insufficient olive tip flow ( $Q_o$ ) to sustain coronary circulation (i.e., <15 mL/min; <5 mL/kg/min). Green indicates sufficient olive tip flow to sustain coronary circulation (i.e., 15–60 mL/min; 5–20 mL/kg/min). Red indicates excessive olive tip flow for coronary circulation (i.e., >60 mL/min; >20 mL/kg/min).



**ACKNOWLEDGMENTS**

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. This research did not require approval from the institutional review board.

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