Theoretical Treatise: Arterial Pressure during Aortic Surgery

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Abstract: The optimum arterial perfusion pressure during cardiopulmonary bypass (CPB) remains uncertain. A correlation in some form with the patients’ resting pressure almost certainly exists. Temperature and hematocrit affect blood viscosity. The optimum perfusion pressure during aortic surgery will vary after the initiation of CPB resulting cooling, heating, and hematocrit changes. Poiseuille’s Law was used in conjunction with the previously published effects of temperature and hematocrit on blood viscosity to determine the perfusion pressure that would result in the same organ blood flow. Two different scenarios were modeled, constant flow and flow as predicted by Q10 to reflect required oxygen delivery. Temperature, hematocrit, and flow all have a large effect on blood viscosity and, thus, through Poiseuille’s Law, blood pressure. As patients are cooled, their blood viscosity goes up through the inherent viscoelastic properties of blood. As temperature drops from 37°C to 17°C, viscosity doubles. This increased viscosity is offset by a reduction in hematocrit, which is invariably associated with CPB. As the hematocrit drops from 30% to 10%, viscosity of blood halves. These two factors clinically can cancel each other out. The figure demonstrates the effect on blood pressure of a constant flow for various temperature and hematocrits. Reduced need for oxygen delivery, secondary to the principles of Q10, can result in a lower than expected theoretical perfusion pressure. As temperature drops from 37°C to 17°C, based on Q10, oxygen delivery reduces by 75%. This indicates that flow can be reduced by over 60% if the hematocrit falls from 30% to 20%. This theoretical treatise predicts that blood pressure management should be temperature- and hematocrit-dependent. The target optimal blood pressure will vary during the course of surgery as a result of heating, cooling, and hemodilution. Clinical correlation is needed.

Keywords: cardiopulmonary bypass, aortic, blood pressure, temperature, hematocrit.

METHODS

Poiseuille’s Law, equation (1), was used in conjunction with the previously published effects of temperature and hematocrit on blood viscosity to determine the perfusion pressure that would result in the same organ blood flow. Two different scenarios were modeled, constant flow, and flow as predicted by Q10 to reflect required oxygen delivery (4).

Pressure depends on flow, viscosity, and impedance into which the flow is occurring. These variables are related by Poiseuille’s Law (1). Aortic surgery is frequently associated with extreme temperatures and excessive hemodilution (2). As blood cools, its viscosity rises, and as hemodilution occurs, its viscosity falls (3). Because the pressure on bypass is determined by viscosity, the pressure required to achieve a desired flow will depend on the blood viscosity, which in turn depends on the blood temperature and hematocrit.

This theoretical analysis based on previously published data by other research groups is aimed to demonstrate the potential effects of temperature and hematocrit on blood pressure needed to create a given tissue flow.

METHODOLOGY

Poiseuille’s Law, equation (1), was used in conjunction with the previously published effects of temperature and hematocrit on blood viscosity to determine the perfusion pressure that would result in the same organ blood flow. Two different scenarios were modeled, constant flow, and flow as predicted by Q10 to reflect required oxygen delivery (4).

Theory

The following previously published and validated mathematical formula was used:

\[ \Delta P = \frac{8\mu LQ}{\pi r^4} \text{ or } \Delta P = \frac{128\mu LQ}{\pi d^4} \]  

\[(1)\]

where \(\Delta P\) is the pressure drop, \(L\) is the length of pipe, \(\mu\) is the dynamic viscosity, \(Q\) is the volumetric flow rate,
r is the radius, d is the diameter, and \( \pi \) is the mathematical constant.

Einstein’s equation for spheres in suspension has been shown to be a reasonable estimate of the effect of hematocrit and temperature on blood viscosity \((5,6)\).

\[
\mu = \mu_p \left( \frac{1}{1 - \alpha \phi} \right) \tag{2}
\]

where \( \mu \) is whole blood viscosity, \( \mu_p \) is plasma viscosity, \( \phi \) is the hematocrit, and \( \alpha \) is defined by equation 3

\[
\alpha = 0.076 \exp \left[ 2.49\phi + \frac{1107}{T} \exp (-1.69\phi) \right] \tag{3}
\]

where \( \phi \) is hematocrit and \( T \) is the absolute temperature if the blood in degrees Kelvin.

**Normalization**

The technique of normalization (usually used in frequency domain analysis) was used \((7)\). In this treatise, the blood pressure was referenced to the pressure at 37°C. This means that values vary around the number 1.0. The actual value for clinical practice is obtained by multiplying the pressure at 37°C by the normalized pressure value in our data. This technique was used because the optimum pressure at 37°C still remains to be defined.

**Constant Flow Analysis**

**Blood Pressure:** The effect of viscosity on blood pressure for a constant flow is shown in Figure 1. The viscosity of blood at 37°C is normally \(3 \times 10^{-3}\) to \(4 \times 10^{-3}\) pascal-seconds (Pa-s).

**Temperature:** The effect of temperature on blood viscosity is shown in Figure 2.

**Hematocrit:** The effect of hematocrit on viscosity is shown in Figure 3.

**Flow as Predicted by Q₁₀**

**Blood Pressure:** The metabolic requirements of the body predicted by \(Q_{10}\) do not alter the validity of Poiseuille’s Law, so Figure 1 still holds true.

**Temperature:** As temperature falls by 10°C, the metabolic rate halves \((Q_{10})\) \((8,9)\). This means at 27°C and 17°C, the metabolic rate is 50% and 25%, respectively, of that at 37°C. As oxygen delivery is directly related to flow for a given perfusion pressure, this means the flow can be reduced by 50% and 75%, respectively, at 27°C and 17°C. The effect of temperature on blood viscosity in combination with the reduction in flow needed resulting from \(Q_{10}\) prediction is shown in Figure 4.

**Hematocrit:** As hematocrit falls, the oxygen delivery falls. If it is assumed that a hematocrit of 21% is adequate to deliver enough oxygen at 37°C, then as the hematocrit falls to 15%, the oxygen delivery falls by 29% \((21–15)/100/21\).
This means that the flow must increase by 29% to counteract this hemodilution. The effect of hematocrit on viscosity in combination with reduced oxygen delivery is shown in Figure 5.

RESULTS

Constant Flow Analysis

Blood Pressure: It can be seen (Figure 1) that the blood viscosity is a direct linear relationship with required perfusion pressure for a given flow (10).

Temperature: The effect of temperature on blood viscosity is shown in Figure 2 (5,6). Temperature on cooling to $17^\circ C$ from $37^\circ C$ results in an increased viscosity of 16%, which as a result of the relationship shown in Figure 1 means blood pressure will rise by 16%.

Hematocrit: The effect of hematocrit on viscosity shown in Figure 3 (11). Hematocrit on falling from 40% to 15% results in a decreased viscosity of 33%, which as a result of the relationship shown in Figure 1 means blood pressure will fall by 33%.

Flow as Predicted by $Q_{10}$

Temperature: The effect of temperature on blood pressure is shown in Figure 4. Cooling from $37^\circ C$ to $15^\circ C$ results in a decrease in required perfusion pressure. The reduction in required perfusion pressure falls by 77% with a hematocrit of 40% and 66% with a hematocrit of 15%. In clinical practice patients, the solid line superimposed on the graph predicts that blood pressure on bypass to achieve adequate oxygen delivery at $17^\circ C$ can be 50% lower than that at $37^\circ C$.

Hematocrit: The effect of hematocrit at $37^\circ C$ and $17^\circ C$ on blood pressure is shown in Figure 5. This is an alternative graphical representation of Figure 4.

DISCUSSION

The optimum arterial perfusion pressure during cardiopulmonary bypass (CPB) remains uncertain (12,13). A correlation in some form with the patient’s resting pressure almost certainly exists. This is the basis for the theoretical concept of root mean square-directed perfusion pressure (14). This, however, does not take into account the effect of cooling and hematocrit changes, which is an integral part of the majority of aortic operations. The optimum perfusion pressure during aortic surgery will vary after the initiation of CPB resulting from temperature, hematocrit, and flow.

Hemodilution and cooling through their effects on blood viscosity have significant opposing effects on the required perfusion pressure as patients are cooled and diluted. The optimum pressure for perfusion at temperatures commonly associated with aortic procedures depends on the exact temperature and the concomitant hematocrit–patient-directed perfusion. Because the hematocrit and temperature of the patients change during the course of surgery, the optimum blood pressure will change depending on the exact temperature and hematocrit. This is conceptually shown in Figure 6.

A conundrum exists when the flow is reduced secondary to a reduced need for oxygen delivery with cooling ($Q_{10}$). Should the perfusion pressure be maintained? Further work is needed with regard to this concept.

The relationships among temperature, hematocrit, flow rate, and viscosity are nonlinear, i.e., blood pressure = function (temperature, hematocrit, flow). This means that studies on blood pressure management at cold temperatures and extreme hemodilutions may have confounding factors that are currently not controlled for.

This theoretical treatise predicts that blood pressure management should be temperature- and hematocrit-dependent. The target optimal blood pressure will vary during the course of surgery as a result of heating, cooling, and hemodilution. Clinical correlation is needed.

Limitations

Any theoretical work has many limitations. However, the laws of physics still apply and this analysis demonstrates potential issues and conundrums in current perfusion practice. The effects of age and associated lesions
such as atherosclerotic and coronary artery disease have not been included in this analysis.

Low flow (low shear rate) results in viscosity increases (the Fahraeus-Lindqvist effect) that our modeling does not account for as a result of the complexity and number of unknown variables (15).

REFERENCES