

# What Is Optimal Flow and How to Validate This

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**Abstract:** Since the introduction of cardiopulmonary bypass, clinicians have tried to define the optimal blood flow for a given patient. The difficulty in determining a correct blood flow lies in the fact that cardiac surgery is done in a very inhomogeneous population, from neonates to the octogenarian, and often under non-physiologic conditions (hypothermia, hemodilution, low flow, etc.). Although clinicians acknowledge that maintaining a minimum oxygen delivery is more meaningful than using a fixed flow rate based on the metabolic needs of awake resting volunteers, the latter is most used in clinical practice. This is explained by the fact that no values are available on critical oxygen delivery for adequate tissue oxygenation under a given clinical condition. This was an overview of the relevant literature. In most centers, perfusionists use in-line monitoring, such as venous saturation or venous blood gases, for estimation of adequacy of tissue perfusion. Unfortunately, these oxygen-derived parameters have a poor correlation with anaerobic energy supply. Measurement of intermittent whole blood lactate concentration is used to com-

pensate for this poor relationship, but as it monitors the concentration at given time points, it precludes optimally timely intervention by the perfusionist. The physiologic buffering by bicarbonate of the acid generated by converting pyruvate into lactate will produce carbon dioxide. As a consequence, carbon dioxide-derived parameters do have a good correlation with inadequate tissue perfusion. In-line monitoring of carbon dioxide production gives real-time information on tissue perfusion. Use of a standard reference flow for each patient is a poor option, because it does not reflect the metabolic need of the patient. Oxygen-derived parameters, such as venous saturation or partial venous oxygen tension, are poor predictors of anaerobic metabolism. A combination of intermittent whole blood lactate measurement with carbon dioxide-derived parameters predicts anaerobic energy production and allows proactive intervention by the perfusionist. **Keywords:** cardiopulmonary bypass, tissue perfusion, blood flow. *JECT. 2007;39:278–280*

## INTRODUCTION

In humans, cardiac output is regulated based on metabolic needs. The basal cardiac output is between 2.8 and 3 L/m<sup>2</sup>/min but can increase up to 15 L/m<sup>2</sup>/min during exercise. However, when a patient is placed on cardiopulmonary bypass (CPB), this delicate metabolic balance is disturbed. Instead of being controlled by a metabolic feedback system, cardiac output will now be determined by the perfusionist, who has to decide the ideal cardiac output for a given condition. Determination of the correct blood flow is difficult because judgment needs to be made on derived and calculated parameters because very little direct information regarding the adequacy of tissue perfusion can be obtained during CPB. Also, during CPB, non-physiologic conditions that occur such as hemodilution and hypothermia further impact flow requirements. Because of these difficulties, many perfusionists use standard blood flows. Most perfusionists will use flows of 2.2–2.8 L/m<sup>2</sup>/min (1). These reference values were obtained by measuring blood

flows in resting non-anesthetized, healthy volunteers. We will study whether these standard flows really cover the metabolic needs of patients during the different phases of CPB.

## DETERMINANTS OF CARDIAC OUTPUT

Cardiac output is defined as the volume the heart (or during CPB, a pumping system) can deliver per minute, but this value does not mean anything in isolation. What is of real interest is the amount of oxygen that can be delivered to the tissues. Oxygen delivery depends on the cardiac output and the oxygen content per liter of blood. Thus, it would make much more sense to try to determine the optimal oxygen delivery for a given condition. Doing so would also put hematocrit and thus hemodilution into the equation.

Recently, several large randomized studies showed a correlation between the lowest hematocrit on bypass and the incidence of postoperative renal failure (2–7). The reason of this correlation is most likely because of the fact that the medullar portion of the kidney is at particular risk for low oxygen status. Ranucci et al. (7) clearly showed

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that augmenting blood flow could markedly ameliorate the negative relationship between hematocrit and the occurrence of renal failure. Their conclusion was that it was not the hematocrit value in itself that was the main cause of the renal failure but that it was more dependent on a critical oxygen delivery. They found the critical oxygen delivery to be 272 mL/min/m<sup>2</sup>. This finding makes it possible to abandon reference blood flows and to replace them with critical oxygen delivery values. This approach makes it also possible to actively modulate the incidence of CPB-associated morbidity.

### PARAMETERS OF ANAEROBIC METABOLISM

Under normal resting conditions, oxygen delivery matches the overall metabolic demands of the organs; oxygen consumption by the body is ~25% of the oxygen delivery. Under these conditions, energy production is almost completely aerobic. However, this situation will change drastically whenever oxygen delivery is jeopardized by low cardiac output or reduced arterial oxygen content. Because of the high reserve oxygen content of normal oxygen delivery, small reductions in oxygen delivery will not affect oxygen consumption, but once a critical oxygen delivery is reached, oxygen consumption starts to decrease as it becomes dependent on oxygen delivery. To produce sufficient energy, the failing aerobic energy supply will now be expanded with anaerobic energy production through pyruvate conversion to lactate.

As a direct consequence of anaerobic metabolism, blood lactate concentration starts to rise. Lactate concentration can be considered a good marker of non-optimal tissue perfusion (8). Once the anaerobic metabolism comes into play, increased proton production will lead to tissue acidosis. The physiologic buffering of these protons with bicarbonate will lead to anaerobic carbon dioxide production (9). In a situation where oxygen supply is no longer sufficient for aerobic energy supply, there will be a linear decrease in oxygen consumption and thus also in carbon dioxide production, but at the same time, there will be carbon dioxide production from the anaerobic energy production. As a result, the net carbon dioxide production will rise, and the respiratory quotient will increase (10). In a state of cardiogenic shock, the increased carbon dioxide produced can no longer be removed by the natural lung because pulmonary blood flow will also be reduced in shock. Because of this, there will be widening of the partial carbon dioxide tension gap between arterial and venous blood.

### ESTIMATE OF ORGAN PERFUSION DURING CPB

To validate the quality of perfusion and to estimate tissue oxygenation, perfusionists use several approaches

including commonly used in-line measurements of venous saturation and blood gases. Unfortunately, venous saturation and venous partial oxygen tension are an indirect reflection of tissue oxygenation, and a high venous saturation/venous partial oxygen tension does not preclude that one or more organs are not optimally perfused. Indeed, several studies have shown that oxygen-derived parameters are poor in predicting lactate accumulation during CPB (11).

Therefore, the question remains of how one could or should effectively monitor tissue perfusion and oxygenation during CPB. In small children, the introduction of near infrared spectroscopy (NIRS) of both the cerebral circulation and the kidney has been shown to be very helpful for the rapid detection of perfusion maldistribution in complex congenital corrections such as the Norwood procedure (12). In an adult population, less conclusive evidence is available to support the routine use of NIRS. This can be explained in part by the fact that an adult population will not only have a cardiac pathology, but in the majority of cases, also a pronounced atherosclerosis of the complete vascular tree. Also, associated morbidity can severely jeopardize perfusion adequacy of a given organ(s). However, a recent prospective randomized study in a patient cohort of 200 patients showed a significant benefit in patient outcome in the group where NIRS was used to evaluate cerebral desaturation (13).

Another approach is to measure at given time intervals the lactate concentrations in whole blood. This technique is used more and more as a standard approach in European hospitals because lactate electrodes are now standard on most blood gas analyzers. Over the years, many authors have studied the evolution of lactate during CPB (14–18). In the literature, anaerobic energy production, validated by an increased lactate concentration, is found in up to 20% of all patients during CPB (19). Most authors could find a positive correlation between increased lactate concentration and duration of aortic cross-clamp, duration of CPB, and hemodilution (8,10,15). However, a major disadvantage of this approach is that it monitors the evolution of lactate accumulation but does not permit timely intervention.

Recently, Ranucci proposed continuous monitoring of carbon dioxide-derived parameters for rapid detection of anaerobic energy supply (10). Today's microporous hollow fiber oxygenators are extremely efficient in removing carbon dioxide. Indeed, perfusionists who routinely measure gas exhaust carbon dioxide tension observe an almost immediate increase in capnographic values when they administer bicarbonate ions or packed red cell concentrates. Because of this high efficiency, the oxygenator is, in contrast to the natural lungs, better at removing excess carbon dioxide produced by the anaerobic metabolism. As a consequence, widening of the arterio-venous partial carbon

dioxide tension gap reflects anaerobic carbon dioxide production with a critical oxygen delivery will be reflected during CPB by an increase in capnographic values. Carbon dioxide-derived parameters were more efficacious compared with oxygen-derived parameters in predicting lactate accumulation during CPB (11). The best indicator was the ratio between oxygen delivery and carbon dioxide, followed by carbon dioxide production, and then by the ratio between carbon dioxide production and oxygen consumption (10). All indicators were normalized for body surface area.

## CONCLUSIONS

A reference flow, as used in many centers, is no guarantee of an adequate tissue perfusion. A minimum oxygen delivery is a better reflection for satisfying a given metabolic need. However, validation of critical oxygen delivery is necessary. Oxygen-derived parameters such as venous oxygen saturation and venous partial pressure are poor predictors of tissue perfusion. Measurement of local oxygen consumption by NIRS in children or continuous measurement of carbon dioxide production in adults is a more sensitive indicator of inadequate tissue perfusion. Carbon dioxide-derived parameters in combination with intermittent whole blood lactate levels provide inline information regarding tissue perfusion, allowing the perfusionist to proactively intervene to optimize tissue perfusion during CPB.

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