Physiology of Blood Flow and Oxygen Utilization by Peripheral Tissue in Circulatory Shock

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The primary defect that characterizes circulatory shock is acute perfusion failure, in which oxygen metabolism is critically impaired by decreased delivery of oxygen to tissues. Four categories of hemodynamic deficits are described as the basic mechanisms of circulatory shock: hypovolemia, cardiac failure, distributive deficits, and vascular obstruction. Perfusion failure can be identified by the development of lactic acidosis, because anerobic metabolism is the consequence of the oxygen deficit during circulatory failure. Lactic acidosis at present represents the best single objective measure of the severity of shock.

The pathophysiological defect that characterizes circulatory shock is perfusion failure, in which blood flow to maintain the function of vital organ systems is critically reduced. With reduction in tissue perfusion and decreased delivery of oxygen to the capillary exchange beds, oxidative metabolism is critically impaired. There is decreased formation of high-energy phosphate bonds and an increase in the permeability of cellular membranes. The cellular sodium pump fails, sodium enters, and potassium escapes from the cells; the cells swell; and ultimately there is rupture of lysosomal membranes, with release of lytic enzymes and autodigestion.

In the absence of metabolic oxygen, the anerobic pyruvate–lactate shunt is activated, which accounts for production of excesses of lactic acid. The magnitude of lactic acidosis corresponds to the severity of the oxygen deficit. The concentration of lactate in arterial blood therefore provides a quantitative measure of the oxygen deficit and, in turn, of the severity of perfusion failure. In patients who present with acute perfusion failure, the concentration of lactate in arterial blood characteristically exceeds 2 mmol/L (180 mg/L). When lactate concentrations increase from 2 to 8 mmol/L, the survival rate progressively decreases, from about 90% to 10%. Lactic acidosis, therefore, is a sine qua non of oxygen deficit and at present represents the best single objective measure of the presence and severity of shock.

Because of the ease with which it can be measured, blood pressure has been the traditional marker for the diagnosis of shock. With more complete understanding of the role of perfusion failure as the fundamental defect in shock, the capability for routinely measuring cardiac output by the thermodilution technique in conjunction with cardiac filling pressures by using the pulmonary artery catheter has added an important dimension to clinical assessment of the patient in shock. This is especially true for the patient in whom shock is due to a reduction in intravascular volume, myocardial infarction, or obstruction of the main stream of blood flow, e.g., caused by pulmonary embolism. However, in patients with septic shock states, cardiac output may be normal or even increased: it is the distribution of the cardiac output rather than the volume of blood flow that is the critical issue. For these reasons, measurement of an index of oxygen utilization is important to provide a measure of "effective" blood flow, in the sense of indicating adequate or inadequate oxygen delivery.

Four categories of hemodynamic deficits are recognized in the current classification of circulatory shock: hypovolemia, cardiac failure, distributive defects, and vascular obstruction.

Hypovolemia accounts for the vast majority of instances of acute circulatory failure in general hospital practice. The volume of blood within the intravascular compartment is depleted to the extent that effective tissue perfusion cannot be maintained. When the plasma volume is reduced to less than two-thirds of normal, immediate survival is threatened. Hypovolemia follows the endogenous or exogenous loss of blood, plasma, and (or) electrolyte fluids. Accordingly, the routine of fluid challenge guided by the measurement of central venous or pulmonary artery pressure represents the highest priority of intervention other than control of fluid loss, especially hemorrhage.

Cardiogenic shock represents primary pump failure. Cardiac rhythm, cardiac contractility, or myocardial work capability is compromised to the extent that the cardiac output is critically reduced.

Distributive defects represent impairment in the distribution of blood flow or blood volume. Two major subsets of distributive defects are recognized: high-output defects, in which there is typically a high cardiac output and a low peripheral resistance, and low-output defects, in which the cardiac output is reduced and the peripheral resistance is usually increased. In the high-output defect, the blood is shunted from the arterial to the venous circulation or traverses capillaries without effective exchange of oxygen at the cellular level. The low-output defect is characterized by intravascular sequestration of blood, particularly in the venous capacitance circuit, and represents a selective form of relative hypovolemia. In such patients, the total intravascular volume may be normal or near normal, but the capacity of the intravascular space is expanded.

Finally, an impedance or obstruction to the mainstream of blood flow represents an obstructive defect. This is the case in pulmonary embolism or pericardial tamponade. In these pathological conditions, it is the obstruction to blood flow that precludes effective tissue perfusion, and therefore accounts for the shock state.

The development of circulatory shock can be assessed by the use of either systemic or local indices of tissue perfusion. The concentration of lactate in blood, mixed venous oxygen tension and saturation, oxygen delivery, and oxygen consumption are commonly used to assess perfusion of tissues. Transcutaneous oxygen tension, toe temperature, subcutaneous oxygen tension, and muscle oxygen histograms are measures of local conditions that have clinical application.

Mixed venous oxygen tension and saturation are used to
approximate the concentrations of oxygen in tissue. Presumably these values represent weighted means of the venous oxygen tension and saturation from the different capillary beds. Mathematical analysis has been presented to support the use of venous oxygen tension and saturation as indicative of the concentrations in tissue. Because increased extraction of oxygen by the tissues is the primary compensatory adaptation to decreased perfusion, changes in mixed venous oxygen tension and saturation can be used to monitor circulatory performance. Clinically, these quantities have been correlated with the presence of lactic acidosis, changes in oxygen delivery, and survival. However, patients with adult respiratory distress syndrome of septic shock and patients undergoing general anesthesia may evidence tissue hypoxia despite normal values for mixed venous oxygen tension and saturation. The lack of correlation between mixed venous and tissue oxygen described in these settings can be explained by abnormalities in capillary tissue diffusion, arterio-venous shunts, or distributive abnormalities in systemic flow.

Arterial lactate concentration has been proposed as an indicator of tissue anerobiosis. As tissues become hypoxic, glucose is increasingly utilized as an energy source and metabolized to lactate. In experimental studies, lactate concentration has been found to correlate with oxygen deficit. Clinical studies have demonstrated the usefulness of lactate concentration in predicting survival in all forms of shock. The rate of clearance of lactate is also extremely useful in monitoring a patient's response to therapy. The major limitation of arterial lactate concentration stems from the fact that its increase occurs only after circulatory compensatory mechanisms have been exhausted.

Systemic oxygen consumption and oxygen delivery are also used as indices of perfusion. Systemic oxygen consumption can be calculated from cardiac index and arterial and mixed venous oxygen content or can be directly measured from expired gases. Clinical studies have demonstrated an excellent correlation between the two methods. Oxygen debt (the decrease in oxygen consumption from baseline) was one of the earliest indices found to correlate with survival from experimental shock. In subsequent clinical reports, the amount of oxygen consumption has been correlated with survival in critically ill patients. The use of oxygen consumption as an index of perfusion is hampered by the influence of metabolic rate. For example, a low value for systemic oxygen consumption may not be due to hypoperfusion but rather may reflect hypometabolism due to sedation, hypothermia, or underlying malnutrition. Conversely, an increased oxygen consumption may not be adequate in a hypermetabolic setting and thus may not reflect underlying hypoperfusion. In addition, systemic oxygen consumption decreases only after compensatory mechanisms of increased oxygen extraction have been exhausted and thus is a relatively late finding of tissue hypoperfusion.

Oxygen delivery is calculated from cardiac output and arterial oxygen content. Clinical and experimental studies have attempted to identify the critical amount of oxygen delivery associated with either a decrease in oxygen consumption or an increase in the lactate concentration in blood. However, in critically ill patients oxygen consumption appears to be dependent on oxygen delivery. Variations in metabolic rate and distributive abnormalities of systemic and microcirculatory flow have been implicated as contributing to this phenomenon. Under the circumstances, the identification of a critical value for oxygen delivery is difficult.

Peripheral measurements of tissue perfusion have been advocated by several investigators. These measurements not only reflect regional perfusion; but in addition, because flow is redistributed away from muscle, skin, and subcutaneous tissue as circulatory failure ensues, they also serve as indicators of systemic circulatory compromise. Transcutaneous oxygen sensors have been used as a noninvasive measurement of tissue oxygenation. Under normal flow conditions, transcutaneous oxygen tension approximates systemic arterial values. In low-flow states, because the flow to the skin is reduced, the transcutaneous oxygen tension falls, leading to a decrease in the ratio of transcutaneous to arterial oxygen tension. This characteristic can be used to assess the severity of low-flow shock. Measurement of toe temperature is another noninvasive tool that can be adapted to monitor circulatory failure. With tissue hypoperfusion, the temperature gradient between the central surface of the first toe and the ambient temperature decreases. In hypovolemic, septic, and cardiogenic shock, the changes in this gradient have been correlated with lactate concentration and survival.

In recent years, therefore, we have increasingly recognized the importance of the pathophysiological diagnosis and assessment of tissue perfusion as a basis for more specific therapeutic interventions. The management of hypovolemic shock is contingent on control of fluid loss and aggressive volume repletion guided by hemodynamic measurements. The treatment of cardiogenic shock focuses on the appropriate management of cardiac arrhythmias and reduction of workload on the heart by pharmacological or mechanical interventions. In instances of distributive effects, and especially for treatment of bacterial shock, the control of infection by both medical and surgical interventions is the issue to survival. In patients with obstructive shock, the removal of the physical impediment by either surgical or pharmacological (thrombolytic) interventions constitutes the mainstay of management.

References
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