continuing education

Pressure-Flow-Resistance

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Fluid flowing through a tube exerts a force vector outward against the walls of the tube perpendicular to the direction of flow. This force is called *pressure. Resistance* is that force which opposes pressure. The direction of its vector is therefore opposite that of pressure; that is, the force vector of resistance is perpendicular to the direction of fluid flow, but pushing inward on the walls of the tube.

Flow between any two points in a tube is from the area of greater pressure to the area of lesser pressure and is proportional to the pressure difference or gradient between those two points. This pressure gradient is referred to as ΔP, and the relationship between flow, pressure, and resistance may be expressed as:

(1) $$\text{Flow} = \frac{\Delta P}{\text{Resistance}}$$

It can be seen from this equation that in order for flow to exist between two points in a tube, the pressure gradient must exceed the resistance. The amount of resistance depends upon the viscosity of the fluid, the length of the tube, and the diameter of the tube. It may be thought of as the frictional power which acts to impede flow. All fluid does not flow through a tube at the same speed, but rather flows in a laminar fashion. That is, the fluid flows in layers: the fluid in the center of a tube flows fastest and, as the outer layer of the tube diameter is approached, the fluid flows more slowly. The diameter of the tube is therefore the most significant factor in determining the resistance to flow presented by the tube. The quantity of resistance is represented by the equation:

(2) $$\text{Resistance} = \frac{\text{viscosity x length}}{\text{diameter}^4}$$

Substituting these factors for the term resistance in equation (1), we have Poisueille's law:

(3) $$\text{Flow} = \frac{\text{pressure x diameter}^4}{\text{viscosity x length}}$$

Although Poisueille's law is a law of physics, it can be correctly applied to blood flow in the circulatory system if one takes into account the difference between the circulatory system and a rigid tube system. When blood enters the aorta from the left ventricle its flow is pulsatile. However, the arteries, particularly the aorta and large arteries, are extremely elastic. These vessels, called the *Windkessel vessels,* are capable of expanding and contracting to accept the intermittent output of the heart. This damps the pulsatile nature of the blood flow so that it is changed into smooth (laminar) flow by the time the blood reaches the arterioles. The changing of pulsatile flow to laminar flow by the Windkessel vessels is known as the *Borelli principle.*

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During total cardiopulmonary bypass, the length of the blood vessels in the body remains relatively stable, excluding of course A-V shunting, so the length is not a significant factor in altering resistance, pressure, or flow. Also during cardiopulmonary bypass, once maximum hemodilution has been reached with the mixing of the priming volume with the patient's blood volume, the viscosity of blood is proportional to the hematocrit and since there is usually no further drastic change in hematocrit, it also is not a significant factor in altering resistance, pressure, or flow.

Resistance to blood flow in the body is presented mainly by the arterioles. Since this resistance is downstream from the heart and at the outer limit or periphery of the arterial system at the arterioles, it is termed peripheral resistance. Arterioles are small vessels which are capable of altering their diameter in response to nervous stimuli or by autoregulation mechanisms. In addition, numerous pharmacological agents mimic or activate nervous stimuli to change the arteriolar diameter. Therefore, assuming a stable flow rate, be it produced by a cardiopulmonary bypass circuit or by the cardiac output, a small change in the diameter of the arterioles would produce a significant change in arterial pressure [diameter^4, from equation (3)].

It is at this point that the confusion arises in attempting to evaluate tissue perfusion on the basis of arterial pressure. Tissue perfusion is accomplished only by blood flow through the capillary beds. When flow meets a point of resistance, such as in the arterioles, the pressure upstream is increased. However, the pressure downstream from the point of resistance is reduced in proportion to the amount of resistance. Therefore, arteriolar constriction (decreassed diameter of the arterioles) increases arterial pressure, but decreases capillary blood flow by decreasing the pressure at the arterial end of the capillaries. The pressure gradient along the capillaries is decreased, which is followed by a decrease in capillary blood flow. Although the arterial blood pressure is increased, at the same flow rate, tissue perfusion becomes decreased.

Arteriolar constriction (increased peripheral resistance) is often seen during cardiopulmonary bypass, usually as the bypass time increases. Many factors have been implicated as the cause of this increased resistance such as: metabolic acidosis due to inadequate tissue perfusion, insufficient depth of anesthesia, hypovolemia, hyper-response to sympathetic stimuli, non-pulsatile flow, etc., though these causal factors have not been documented.

In order to put pressure in its proper perspective, let us rearrange equation (3), eliminating viscosity and length, since these factors are relatively insignificant or stable during bypass:

$$(4) \quad \text{Pressure} = \frac{\text{Flow}}{\text{diameter}^4}$$

The quantitive value of pressure is important only to assure that there is enough driving force to overcome the resistance presented to flow, and thereby maintain blood flow. Assuming a stable cardiac output or perfusion flow rate, sudden increases in pressure represent increased peripheral resistance, not increased tissue perfusion. Should this occur during cardiopulmonary bypass, the anesthesiologist has the necessary drugs at hand to control arteriolar tone. It is at this point that the perfusionist must elicit his help in achieving satisfactory tissue perfusion within acceptable arterial pressure limits. The perfusionist may reduce the arterial pressure to a certain extent by manipulating the extracorporeal circuit, *but not with impunity.*

To reduce the arterial pressure any significant amount, the perfusion flow rate must be reduced more than 20% thus defeating the object, tissue perfusion. Holding up volume in the arterial reservoir may have the same affect to a lesser extent but the volume in question is a significant amount and again the tissue perfusion is sacrificed.

The perfusionist is equally at a disadvantage when trying to increase the arterial pressure by manipulation of the bypass circuit. Increasing arterial blood flow rate may transiently to a small extent increase the arterial pressure.. However, this is a temporary achievement at best and is limited by a rapid concomitant reduction in arterial reservoir level due to a non-increasing venous return which in turn is a result of the extreme distensibility of the venous (capacitance) system. Only by completely filling this venous system by the means of drastic, and usually absurd, fluid therapy (up to 5 liters of colloid and 3 liters of crystalloid solution) can the perfusionist expect to see a direct relationship between blood flow rate and arterial pressure. Only one drug, Dopamine hydrochloride (INTROPIN), has been found that has any vasoconstricting effect on the venous system and this effect is unpredictable and frequently absent.

The purpose of blood flow during cardiopulmonary bypass is to provide the minimum metabolic needs of the tissues of the patient. Although flow rate influences pressure, during extracorporeal circulation, it **should not** serve pressure. A perfusionist is just that; one who, with the aid of extracorporeal equipment and advanced technology, perfuses the tissues in the absence of cardiac output. Since tissue perfusion is accomplished by adequate blood flow, then this must be his chief concern. Regardless of the popular misinterpretation of the concept of pressure, a perfusionist cannot and does not exist to achieve an arbitrary arterial blood pressure during cardiopulmonary bypass.