SESSION I

Principles of vascular control

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Summary

The distribution of nutrient materials to, and the uptake of waste products from, the tissues occurs only in the capillary bed. Arteriolar resistance ensures that blood enters the capillaries at a pressure only slightly higher than that of the colloid osmotic pressure of the blood. Arteriolar resistance is normally under the influence of a sparse sympathetic vasoconstrictor discharge superintended by the activity of 'vasomotor centres' in the brain stem. The activity of these 'vasomotor centres' is itself modified appropriately by afferent impulses from the sino-aortic baroreceptors.

Veins subserve mainly a capacity role but are also involved in veno-constrictor reflexes.

OHM in 1928 formulated his law relating to the factors which governed the flow of electricity in an electrical circuit.

$$I = E/R,$$

where I is the current flow, E is the potential difference across the circuit and R is the resistance.

Cardiac output

The same law determines the flow of blood pumped out by the heart from aorta, through its arterial branches thence via arterioles, capillaries, venules and veins to arrive finally back to the right side of the heart

$$\text{Flow (cardiac output)} = \frac{\text{Potential difference}}{\text{Vascular resistance}}.$$

Potential difference is given by $P_1 - P_2$ where P_1 is the mean aortic pressure (circa 100 mmHg) and P_2 is the right atrial pressure (circa 0-3 mmHg).

Vascular resistance is mainly resident in the arterioles, for it is in traversing this section of the vessel bed that the pressure mainly falls. Poiseuille, in 1846, was the first to show this and to show that the resistance offered by a vessel to blood flow was inversely proportional to its radius and proportional to its length. A further factor—the viscosity of the blood—also contributed to the resistance offered to

blood flow. The full Poiseuille formula may be written

$$\text{Flow} = \frac{\pi (P_1 - P_2) r^4}{8 L \eta}$$

where r is the radius and L the length of the vessel, $P_1 - P_2$ the pressure drop across the vessel and η the viscosity. It will be seen that as the radius factor is to the fourth power, halving the radius will increase the resistance it offers sixteen times.

Regional circuits

The heart in resting man ejects some 5.5 l/min. The different regional circuits possess a different resistance to blood flow. Thus of this 5.5 l/min, the brain receives 750 ml/min, the heart 250 ml/min, the gastro intestinal tract and liver 1300 ml/min, the kidneys 1200 ml/min, the skin, in equable temperatures, 200 ml/min and the muscles about 1000 ml/min. The remainder (bone, fat, connective tissue) thus receive about 800 ml/min.

Resistance

Clearly this tells us very little about the resistance offered by these circuits for the weights of the organs are so dissimilar. Thus the muscles weigh some 35 kg in an adult athletic male which shows that their blood flow/100 g weight is only $1000/350 = 3$ ml/100 g/min at rest. The kidneys weigh only 300 g, so then flow per 100 g/min is 400 ml/100 g/min. Hence it has become customary to express resistance offered by a regional circuit in terms of PRU_{100} —that is the resistance to flow which the blood vessels of 100 g of the tissue concerned exerts.

$$\text{PRU}_{100} \text{ value} = \frac{\text{mean pressure head}}{\text{flow per 100 g/min}}.$$

Thus for muscle at rest:

$$\begin{aligned} \text{PRU}_{100} \text{ value} &= \frac{\text{mean pressure head}}{\text{flow per 100 g/min}} \\ &= \frac{100 \text{ mmHg}}{3 \text{ ml/100 g/min}} = 3.33. \end{aligned}$$

However, in exercise, muscle blood flow may reach 60 ml/100 g/min and the corresponding PRU₁₀₀ value is

$$\frac{120 \text{ mmHg}}{60 \text{ ml/100 g/min}} = 2 \text{ PRU}_{100}.$$

The kidneys have a PRU₁₀₀ value of $\frac{100}{400} = 0.25$.

The brain has a PRU₁₀₀ value of $\frac{100 \text{ mm}}{55 \text{ ml/100 g/min}} = 1.9$.

The skin at rest weighing 2 kg receives a flow of 200 ml/min at an equable temperature but this may increase to 4 l/min (a flow of 200 ml/100 g/min) in heat stress.

Obviously the muscle vessels offer the greatest resistance to flow at rest but this resistance can be greatly lowered in exercise. This muscle hyperaemia is due to the vasodilator action of metabolites released by the muscle cells and is not due to nervous factors.

Nervous factors

The resistance of the arterioles of most circuits is partly due to a basal myogenic tone of the smooth muscles of the arterioles themselves and partly due to the influence of sympathetic vasoconstrictor noradrenergic nerves which supply the arterioles. This sympathetic nervous discharge which reduces arteriolar radius is under the influence of the discharge rate of the vasomotor centres in the medulla and brain stem. Spinal anaesthesia to a level sufficient to obtund the thoracolumbar sympathetic outflow thus lowers the blood pressure.

Vasomotor centre activity itself is influenced by higher corticohypothalamic centres. Emotion raises the blood pressure. However, much of the activity of the vasomotor centre is tonically controlled by the discharge of stretch receptors (baroreceptors) situated mainly in the carotid sinuses, the aortic arch and the root of the right subclavian artery. Stretch of these regions of the vascular circuit caused by systolic output of the heart causes a burst of impulse activity which ascends afferent fibres of the sinus and aortic nerves to exert an inhibitory action on the vasomotor centre and hence on sympathetic vasoconstrictor discharge. If the mean blood pressure tends to rise, increased baroreceptor discharge thereby aroused causes negative feed-back on the vasomotor discharge which minimizes the pressure rise. Conversely, a fall of systemic blood pressure lessens baroreceptor activity and the resulting vasoconstriction affecting skin, muscles and abdominal viscera, hoists the peripheral resistance and hence reduces the degree of hypotension which would otherwise have occurred.

It should be clearly understood that the range of sympathetic impulse frequency seen in the mammalia (including man) in life is only that from, perhaps, 1 imp/sec in a single sympathetic fibre in resting conditions to some 16 imp/sec in maximal sympathetic activity which occurs in severe haemorrhagic systemic hypotension. This has been excellently shown by Mellander (1960) using his 'hind limbs' preparation. Both hind limbs are vascularly isolated from the rest of the animal by dissection and ligation, leaving only their arterial supply (via the aorta) and their venous return (via the inferior vena cava) intact. The hind limbs are enclosed in a plethysmograph which allows measurement of their volume. The arterial pressure is measured continuously and the blood flow through the limbs is measured by cannulation of the vena cava.

On stimulating the sympathetic nerves to the hind limbs, there is a sharp reduction of flow (due to arteriolar vasoconstriction) and a prompt reduction of limb volume (due to venoconstriction—for the venules represent the capacity part of the system). Both these effects are induced even when the rate of stimulation of the sympathetic vasoconstrictors is raised only from 1 shock/2 sec to 2 shocks/sec. Each effect is maximal at 16 shocks/sec.

Arterioles

The arteriolar vasoconstriction of course reduces the hydrostatic pressure reaching the capillaries. This, normally 30–35 mmHg at the arteriolar end of the capillary and some 10–15 mmHg at the venular end of the capillary, offsets the osmotic pressure of the plasma proteins (25 mmHg). Thus sympathetic vasoconstriction by lowering hydrostatic pressure induces an osmotic uptake of tissue fluid into the blood across the capillary wall and vice versa, and arteriolar vasodilatation favours transudation of fluid from the plasma into the tissues. Both these changes can be studied quantitatively using the Mellander technique.

Capillaries

The capillaries are the key point of the vascular system, for it is across the huge surface area of their walls that the diffusion of oxygen and nutrient material occurs from blood to tissues and the diffusion of CO₂ and metabolites takes place in the reverse direction.

The capillaries are not an important site of resistance for their length is so short (750 μm). They are not innervated and changes in the area of the capillary bed are due to variations in tone of the precapillary sphincters which lie at the end of the arterioles.

Venules and veins

Finally, we reach the venules and veins. As the pressure in the peripheral venules of a man lying

horizontally is only some 10 mmHg and as the pressure in the right atrium is itself 3 mmHg or so, it follows that the pressure head available for venous return is only 7 mmHg. Yet venous return equals cardiac output so it is obvious that the veins provide a low resistance part of the circuit. Their great importance resides in the changes of capacity which they can display. At normal low transmural pressures such as seen in man lying horizontally, the thin walled veins are semi-collapsed and present an elliptical profile. When the transmural pressure rises, however, the veins assume a circular profile and even with the same perimeter, the cross sectional area of a circle exceeds that of an ellipse. Hence their capacity increases. A further increase of transmural pressure distends the elastic veins even more and venous return to the heart is temporarily reduced on assuming the upright posture because of the hydrostatic rise of pressure in the leg veins. This reduction of venous return, however, causes a lowering of cardiac output which in turn reduces baroreceptor

inhibition of vasomotor discharge. Venoconstriction occurs reflexly which stabilizes the situation. After sympathetic blockade, tilting a man upright causes him to faint owing to venous pooling. His blood pressure and consciousness can be restored by pumping up the pressure in the trousers of a g-suit applied to the lower half of his body. The g-suit pressure reduces the transmural pressure in his dependent veins and hence offsets the increase in capacity which the postural gravitational factor has induced.

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