Bio Factsheet
www.curriculum-press.co.uk Number 160

Countercurrent Flow in Biology

Countercurrent flow is a mechanism which maintains diffusion gradients across membranes. In turn, this means that transport or exchange of substances across the membrane can be fast and efficient. This Factsheet summarises the process and describes the type of exam questions which have appeared in recent years.

Countercurrent flow is a simple concept; it is just two substances flowing through a part of the body in opposite directions. The aim of this opposite flow is to maintain a **gradient** of some sort (eg temperature gradient or concentration gradient of oxygen), which will then ensure that heat or oxygen etc is transferred efficiently from one to the other.

To understand this, imagine two parallel but separate water pipes, arranged next to each other and in contact along their length. Water entering one pipe is hot, and water entering the other is cold. Heat will pass from one to the other.

Now consider two situations; water flow in the same direction and water flow in opposite directions

Water flow in the same direction

If water flow is in the same direction, initially, the temperature difference will be at its maximum. But the difference will be reduced as heat is transferred from the hotter to the colder pipe. The cold stream of water will warm, the hot stream will cool: so at the end of the pipes (provided they are long enough], both streams of water will be the same temperature (the average of their two initial temperatures).

Water flow in the opposite direction

If we take the same tubes and the same starting temperatures but run the currents in opposite directions, the temperature of water in the pipes never equalizes. A temperature gradient is always maintained. This makes heat transfer from the hot water to the cold water much more efficient.

Living organisms use countercurrent flow to:

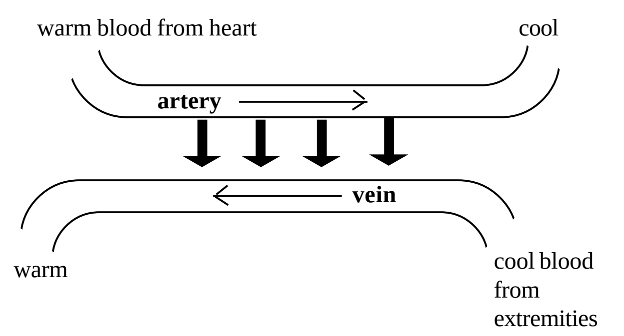
- transfer heat from one part of the body to another
- reduce heat loss to the environment
- transfer nutrients from one part of the body to another
- transfer oxygen from one part of the body to another and from mother to foetus
- transfer waste products from one part of the body to another

Countercurrent exchange of heat

Mammals and birds

The arteries of our arms and legs run parallel to a set of deep veins (Fig 1). If we need to conserve heat, blood flow in these deep veins can be increased. As warm blood from the heart passes down the arteries, the blood gives up some of its heat to the colder blood which is returning in the veins from our extremities.

Fig 1. Countercurrent heat exchange



When heat loss is no problem, most of the venous blood from the extremities returns through veins located near the surface.

Countercurrent heat exchangers operate in the legs of many birds. Penguins, vultures, ducks and sea gulls all have them. A sea gull, for example can maintain a normal temperature in its torso while standing with its unprotected feet in freezing water.

When it is cold, the lack of insulation in birds' legs means a lot of heat could be lost. Remember, in endotherms (birds and mammals), the single biggest use of energy is to keep warm and wading birds or birds living on the water cannot afford to lose heat this way.
To minimize such loss, the arteries and veins in the legs of many birds lie in contact with each other. Arterial blood leaves the bird's core (trunk) at body temperature, while venous blood in the bird's foot is quite cool. As the cool blood returns toward the core, heat is transferred from the warm arteries into the cool veins. Thus, arterial blood reaching the feet is already cool and venous blood reaching the core has already been warmed. In addition, by constricting the blood vessels in its feet a bird may further decrease heat loss by reducing the amount of blood flow to its feet at low temperatures.

Fig 2 shows the arrangement of veins around an artery in the leg of a turkey vulture. A countercurrent blood flow is maintained through the artery and veins. The arterial blood warms the cool blood in the veins, so reducing loss of heat from the artery to the outside air.

Fig 2. Countercurrent flow in the leg of a turkey vulture

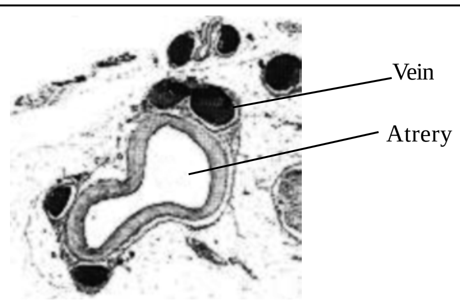


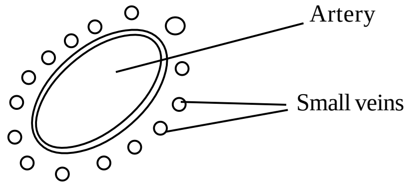
Table 1 shows how successful the turkey vulture is at maintaining internal temperatures.

Table 1. Endothermy in a turkey vulture

Temperature °C			
External air	Core body	Skin beneath crown	Skin beneath nape
10	39.5	13.8	36.8
30	38.7	31.6	37.5
40	40.3	39.8	39.5

The flippers of seals have a similar arrangement of veins surrounding a central artery (Fig 3).

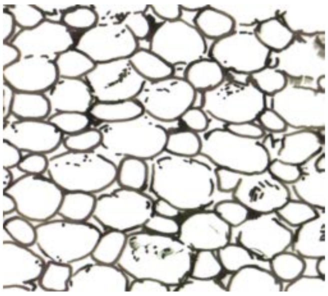
Fig3



Tuna keep their most active swimming muscles 14°C warmer than the sea by using a countercurrent heat exchanger.

Cold, oxygen-rich blood passes into a series of fine arteries that take the blood into the active muscles. These fine arteries lie side by side with veins draining those muscles. So, as the cold blood passes into the muscles, it picks up the heat that had been generated by these muscles and keeps it from being lost to the surroundings. Fig4 shows a cross section through the heat exchanger. Note the close, parallel packing of the arteries (thick walls) and veins (thin walls).

Fig 4. Heat exchanger in tuna



Countercurrent exchange of gases

Fish

Some fish gills have an efficient countercurrent system to ensure rapid uptake of oxygen from the water; blood in the gill filaments flows in the opposite direction to water passing over the gill. Along with efficient ventilation, this ensures that a diffusion gradient for oxygen is maintained at the gas exchange surfaces.

Exam Hint:- *This topic comes up a lot in AQA B papers and occasionally on all the other Boards.*

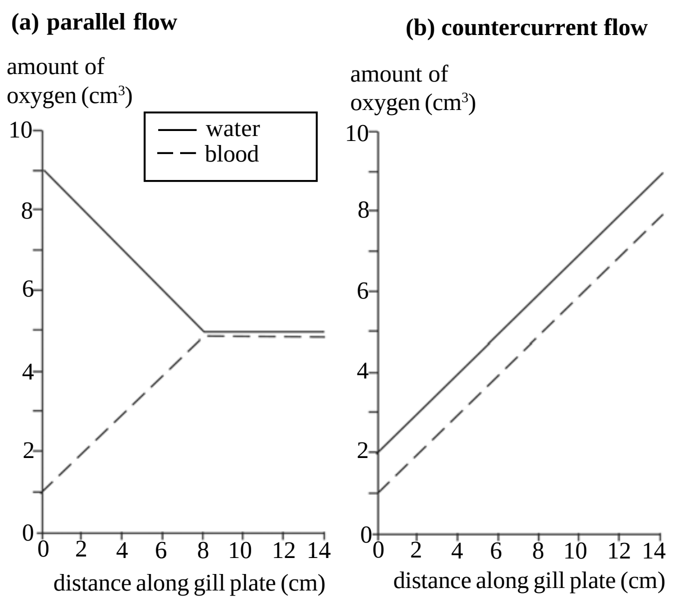
Typical Question:
Describe how a diffusion gradient for oxygen is maintained at the gas exchange surface of a fish.
(2 marks)

Markscheme
Swimming /buccal/opercular cavities ensure ventilation;
Oxygen removal by blood;
Countercurrent flow of blood and water at gills

Note: This question did not ask for adaptations which merely increase the surface area –it wanted detail about how the gradient was maintained. Many students confuse these or, think they are in the kidney and start writing reams about 'multipliers'.

But not all fish have countercurrent flow - some have parallel flow. Fig 5 shows the relative volumes of oxygen in seawater and blood as the water moves across the gill plates in parallel and countercurrent flow.

Fig 5. Parallel and countercurrent flow



Now it is easy to see the advantages of coutercurrent flow:
- In parallel flow, gas exchange can occur over 8 cm
- In countercurrent flow, gas exchange can over 14cm

- In parallel flow, max volume of oxygen in the blood is $4.9cm^3$
- In countercurrent flow, max volume of oxygen in the blood is $8cm^3$

Exam Hint:- *Here is an extract from a recent Chief Examiner's report about a question on countercurrent flow in fish gills*

In general, countercurrent flow is well understood in terms of the maintenance of diffusion and concentration gradients. However, some candidates drew diagrams which clearly showed they did not understand the concept. Only the most able made the crucial point; because of the countercurrent flow equilibration of concentrations is not reached, hence the diffusion gradient is constantly maintained over the entire length of the gills.

The placenta

The structure of the placenta is extremely well adapted to its functions. Fetal capillary blood flow and maternal capillary blood flow is in opposite directions, (countercurrent) which enables greater exchange of substances. Table 2 summarises the substances that need to be exchanged.

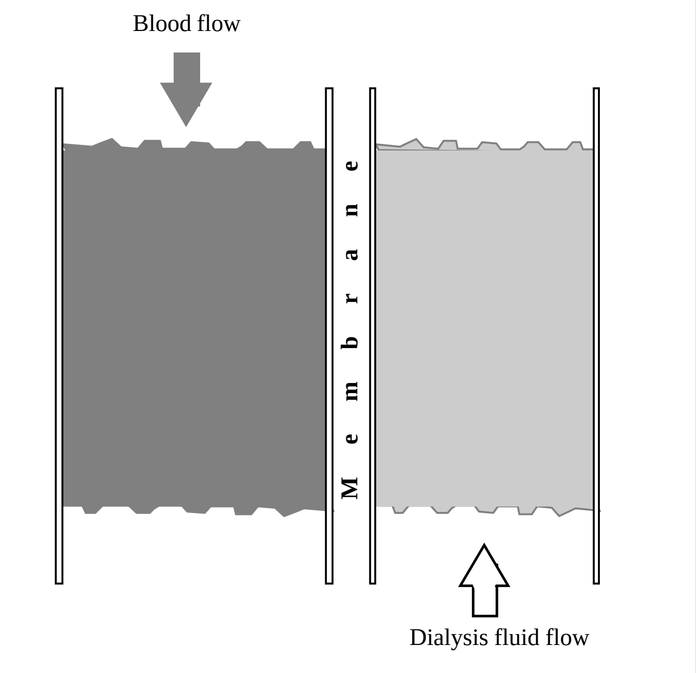
Table 2. Comparison of maternal and fetal blood

	Concentration of substances			
Substance	**Umbilical arteries**	**Umbilical vein**	**Uterine arteries**	**Uterine veins**
Oxygen	Low O_2 tension	High O_2 tension	High O_2 tension	Low O_2 tension
Carbon dioxide (HCO_3^-)	High CO_2/HCO_3^- tension	Low CO_2/HCO_3^- tension	LowCO_2/HCO_3^- tension	High CO_2/HCO_3^- tension
Glucose + other sugars	Low	High	High	Low
Amino acids, lipids	Low	High	High	Low
Urea + other nitrogenous waste	High	Low	Low	High

Countercurrent exchange of solutes

Fluid in the ascending and descending limbs of the loop of Henle of the kidney flow in a countercurrent fashion.

Fig 5. Counterflow



The key points to make here are:
- Sodium chloride is actively pumped out of the ascending limb into the surrounding tissue fluid
- the water potential of this tissue fluid is therefore lowered
- water therefore moves out of the descending limb by osmosis
- the net effect is that the concentration of solute at any particular level of the loop is slightly lower in the ascending limb than in the descending limb
- A water potential gradient is set up between filtrate in collecting duct and the surrounding tissue
- this occurs along the length of collecting duct
- water is withdrawn from the collecting duct

Once again, the countercurrent flow serves to maintain a gradient – in this case a water potential gradient.

Artificial kidneys also make use of countercurrent flow. Fig 5 shows that blood and bath fluid flow in opposite directions across the dialysis membrane. Once again, this maintains a diffusion gradient through the entire length of the system.

Conclusion

- Countercurrent flow is an efficient way of maintaining a gradient
- This gradient may be heat, oxygen, carbon dioxide, solutes or nutrients
- This topic has been examined very frequently in short answer questions and occasionally, as an essay.

Acknowledgements:
This Factsheet was researched and written by Kevin Byrne.
Curriculum Press, Bank House, 105 King Street, Wellington, Shropshire, TF1 1NU.

ISSN 1351-5136