Cold feet

Why do Antarctic penguins' feet not freeze in winter when they are in constant contact with the ice and snow? Years ago I heard on the radio that scientists had discovered that penguins had collateral circulation in their feet that prevented them from freezing but I have seen no further information or explanation of this. Despite asking scientists studying penguins about this, none could give an answer.

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Penguins, like other birds that live in a cold climate, have adaptations to avoid losing too much heat and to preserve a central body temperature of about 40 °C. The feet pose particular problems since they cannot be covered with insulation in the form of feathers or blubber, yet have a big surface area (similar considerations apply to cold-climate mammals such as polar bears).

Two mechanisms are at work. First, the penguin can control the rate of blood flow to the feet by varying the diameter of arterial vessels supplying the blood. In cold conditions the flow is reduced, when it is warm the flow increases. Humans can do this too, which is why our hands and feet become white when we are cold and pink when warm. Control is very sophisticated and involves the hypothalamus and various nervous and hormonal systems.

However, penguins also have 'counter-current heat exchangers' at the top of the legs. Arteries supplying warm blood to the feet break up into many small vessels that are closely allied to similar numbers of venous vessels bringing cold blood back from the feet. Heat flows from the warm blood to the cold blood, so little of it is carried down the feet.

In the winter, penguin feet are held a degree or two above freezing – to minimise heat loss, whilst avoiding frostbite. Ducks and geese have similar arrangements in their feet, but if they are held indoors for weeks in warm conditions, and then released onto snow and ice, their feet may freeze to the ground, because their physiology has adapted to the warmth and this causes the blood flow to feet to be virtually cut off and their foot temperature falls below freezing.

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I cannot comment on the presence or absence of collateral circulation, but part of the answer to the penguin's cold feet problem has an intriguing biochemical explanation.

The binding of oxygen to haemoglobin is normally a strongly exothermic reaction: an amount of heat (DH) is released when a haeomoglobin molecule attaches itself to oxygen. Usually the same amount of heat is absorbed in the reverse reaction, when the oxygen is released by the haemoglobin. However, as oxygenation and deoxygenation occur in different parts of the organism, changes in the molecular environment (acidity, for example) can result in overall heat loss or gain in this process.

The actual value of DH varies from species to species. In Antarctic penguins things are arranged so that in the cold peripheral tissues, including the feet, DH is much smaller than in humans. This has two beneficial effects. Firstly, less heat is absorbed by the birds' haemoglobin when it is deoxygenated, so the feet have less chance of freezing.

The second advantage is a consequence of the laws of thermodynamics. In any reversible reaction, including the absorption and release of oxygen by haemoglobin, a low temperature encourages the reaction in the exothermic direction, and discourages it in the opposite direction. So at low temperatures, oxygen is absorbed more strongly by most species' haemoglobin, and released less easily. Having a relatively modest DH means that in cold tissue the oxygen affinity of haemoglobin does not become so high that the oxygen cannot dissociate from it.

This variation in DH between species has other intriguing consequences. In some Antarctic fish, heat is actually released when oxygen is removed. This is taken to an extreme in the tuna, which releases so much heat when oxygen separates from haemoglobin that it can keep its body temperature up to 17 °C above that of its environment. Not so cold-blooded after all!

The reverse happens in animals that need to reduce heat due to an overactive metabolism. The migratory water-hen has a much larger DH of haemoglobin oxygenation than the humble pigeon. Thus the water-hen can fly for longer distances without overheating.

Finally, foetuses need to lose heat somehow, and their only connection with the outside world is the mother's blood supply. A decreased DH of oxygenation by the foetal haemoglobin when compared to maternal haemoglobin results in more heat being absorbed when oxygen leaves the mother's blood than is released when oxygen binds to foetal haemoglobin. Thus heat is transferred into the maternal blood supply and is carried away from the foetus.

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