Reducing heat loss with "counter-current exchangers".

Due 1/14/04

Please respond to these questions in concise, clear prose of 1 1/2 to 2 pages total length.

Baleen whales (such as the minke whale we talked about in class) have large mouths and, as you might guess, large TONGUES. If you think about your own tongue (or bite it by accident) you will realize that it has a heavy blood supply and not much insulation. Those traits are necessary for the tongue to do its job, both in you and in the whale. Unlike you, however, many whales live in very cold water. That raises the following question:

How does an animal with a large, poorly insulated tongue in very cold water avoid losing so much heat that it suffers hypothermia each time it opens its mouth?

It was recently discovered that in gray whales (and probably others too), the veins and arteries that deliver blood are arranged similarly to a man-made device called a **counter-current exchanger**. These "devices" also appear in many other animals (including you!) to transport one conserved quantity (e.g. oxygen) while minimizing loss of another (e.g. heat). Here's what they look like in a gray whale[•]:

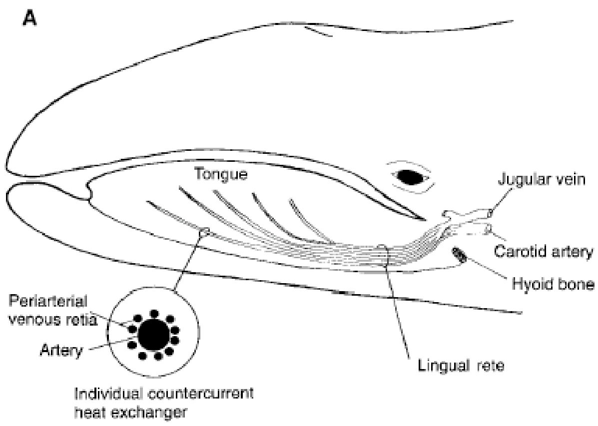
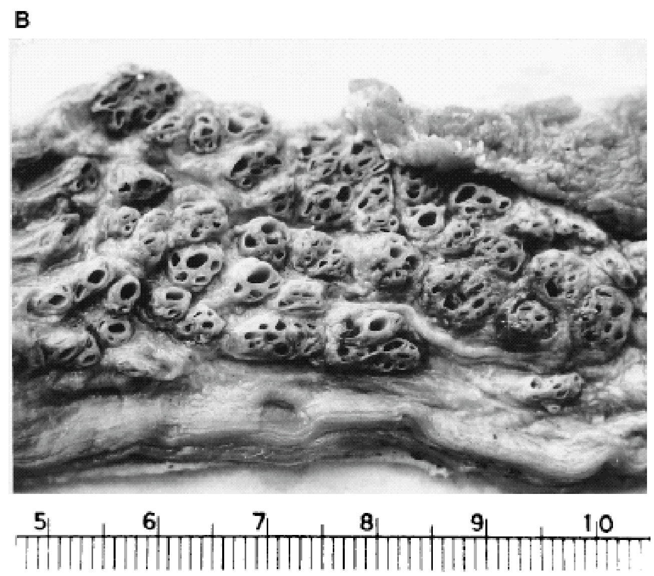


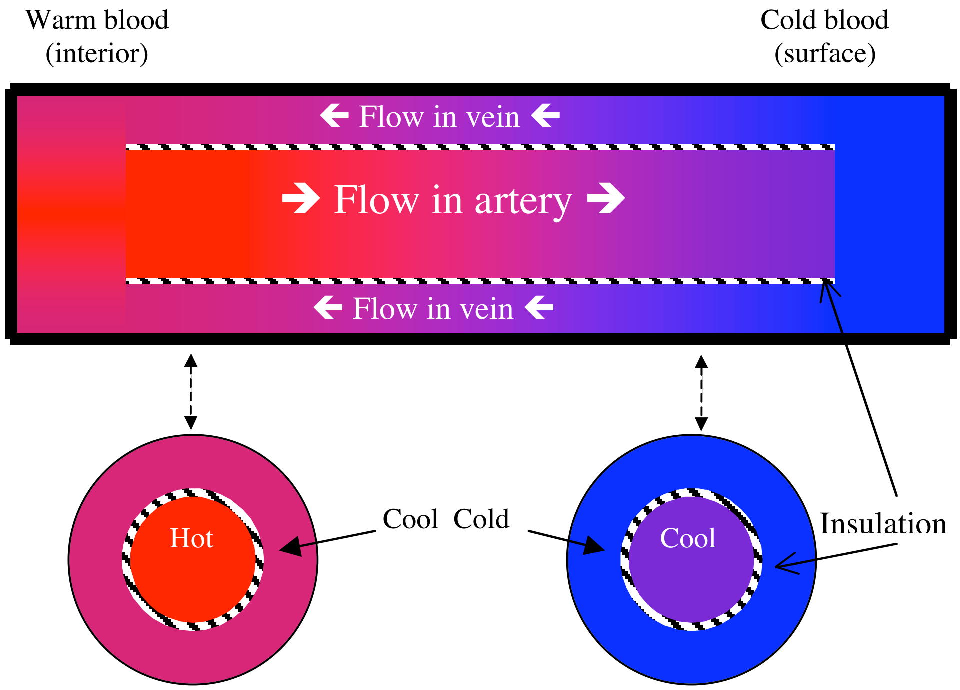
Fig. 1. (A) Schematic diagram of the vascular heat exchanger in a gray whale calf (LACM 92044). Head length, 120 cm. (B) Cross section through the left lingual rete, composed of numerous individual countercurrent heat exchangers (scale is in centimeters).



The geometry of the whale's counter-current exchanger is that each artery (blood flowing outwards) is surrounded by a group of veins (blood flowing inwards). In this study question, we're going to figure out: **Is this an effective geometry to minimize heat loss**?

[•] If you want, check out the source article for these pictures: Heyning J. E., and J.G. Mead (1997) Thermoregulation in the mouths of feeding gray whales. Science 278 (5340): 1138-1139

Figure 2



Start by examining the schematic diagram above. It shows a lengthwise section through an artery and a surrounding set of veins (top) and two cross sections at different ends (bottom). To make things simpler I've drawn the veins as a single big tube enclosing the artery. In reality it is several little tubes (Figure 1) but the effect is much the same. The left end represents the interior of the animal, where the blood from the veins eventually is oxygenated and flows into the artery. The right end is the tongue surface, where the blood is giving up its oxygen to sustain the tissues. The artery and vein are separated by some tissue, which I've labeled "insulation" because heat must be conducted through it to move between the two vessels.

<u>Discussion Item A</u>: Describe the direction of heat flux in the two cross sections drawn in Figure 2. Is heat flowing from the artery to the vein or the other way? Make a similar sketch for yourself representing a cross section right in the middle. Which way is heat flowing there? Justify your answer using Fourier's Law of heat conduction,

$$\text{Heat flux} = Q = k\,A\,(T_1 - T_0)\,/\,L$$

You don't need to put actual numbers in the formula, just interpret the terms! Assume that the temperature is constant in the radial direction within the artery and within the vein (as sketched in Figure 2).

<u>Discussion Item B</u>: Imagine yourself as a blood cell flowing in this artery/vein array. Starting at the left end (the animal's interior) describe what happens to your temperature as you travel a complete circuit to the surface and back. If there is a change in the cell's temperature, explain where the heat comes from and why. Use what you have determined about the flow of

heat. Did you (the cell) transport any heat as a result of your complete journey, and if so, how much and in which direction?

Discussion Item C: We can investigate the effects on heat loss of different counter-current exchanger morphologies by devising a computer model that uses Fourier's Law. An example is in the Excel spreadsheet for this exercise. Download this document from the website and open it from within Excel. You can get it at this link:http://courses.washington.edu/ocean350/StudyQuestions/StudyQuestion1.xsl.zip

In the center of the spreadsheet is a plot of temperatures in one artery-vein complex in a whale's tongue. Above and to the left of that are the parameters that determine how the system works:

i. *morphological traits*: radii of the vein and artery, thickness of the insulation between them, overall length of the vessels, etc.;
ii. *physical properties*: heat capacity and conductivity of the tissues (generally similar to those of water); and
iii. *physiological conditions*: flow rate of blood through the vessel, rate of heat loss.

Note that this model has some simplifications and approximations, so the results are just estimates. Nonetheless, even a simple model enables us to ask questions such as:

- How much heat is lost for various levels of blood flow?
- Is the system effective at conserving heat?
- Would the system function better, worse or the same if the morphology were altered?

For the exercise, use the model to do the following:

1. Make a copy of the spreadsheet, and work with that rather than the original (in case something goes wrong!). Note the rate of heat loss.
2. Investigate the effect of changing the total length of the vessels, by changing the appropriate entry in the spreadsheet and hitting "enter". The spreadsheet will automatically calculate the new temperature distribution in the vessels. Does the heat loss increase or decrease with increases in vessel length?
3. Investigate the effect of changing the flow rate in the vessels. Does the heat loss increase or decrease with increases in flow rate? Speculate on whether it is better to have a small number of vessels with high flow rate or a large number of vessels with low flow rate to produce a required total flow of blood.
4. Investigate the effect of increasing the insulation between the vein and artery. Does increasing insulation save or lose heat overall?

Discuss your findings and speculations in one or two paragraphs.