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A3_5 The Shivers

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Abstract

This report investigates the amount of heat energy given out from shivering, and whether the amount of heat it produces is sufficient enough to make it worthwhile. The report finds that it would require approximately 9 minutes of constant shivering to raise the temperature of an adult human by 1K, thus making the biological phenomenon useful to some extent.

Muscle

Shivering is defined as the involuntary tremor of skeletal muscle; and is used as a thermoregulatory mechanism for the production of heat [1]. The heat produced is a by-product of the muscle activity. The energy source of muscle contraction is derived from the reaction

$$\mathrm{Mg.ATP^{2-}} + \mathrm{H_2O} \rightleftharpoons \mathrm{Mg.ADP^{1-}} + \mathrm{Pi^{2-}} + \mathrm{H^+}\,, \tag{1}$$

where ATP is Adenosine Triphosphate, ADP is Adenosine Diphosphate and Pi is orthophosphate. The reaction is activated by actin filament and takes place at sites on myosin filament in individual sarcomere inside muscle tissue [2]. The process of muscle contraction is complex and involves many chemical reactions. However in physical terms, the position of the equilibrium of a chemical reaction is determined both by the change in internal energy (or enthalpy) H, and the entropy S:

$$\Delta G = \Delta H - T\Delta S\,, \tag{2}$$

where ΔG is the change in Gibbs free energy. For muscle, ΔG and ΔH are -60kJmol^{-1} and -48kJmol^{-1} respectively [3]. A hypothetical muscle working at 100% thermodynamic efficiency would therefore absorb 12kJ of energy per mole. In practice muscles do not exceed 50% efficiency [4]. Hence approximately 6kJ of energy is lost as heat per mole. Considering muscle undergoing isometric contraction, i.e. constant length, this heat production can be expressed as $13\mathrm{mWg^{-1}}$ muscle [5].

Heat transfer

Taking the average mass of a human to be 70kg, and that skeletal muscle makes up about 40% of total body mass, if all skeletal muscle contracted,

$$\text{Total heat production} = 13 \times 10^{-3}\mathrm{Wg^{-1}} \times 70 \times 10^{3}\mathrm{g} \times 0.4 = 364\mathrm{W}\,. \tag{3}$$

The amount of heat Q needed to increase the temperature of a substance of mass m is given by

$$Q = mc\Delta T\,, \tag{4}$$

where c is the specific heat capacity and ΔT is the change in temperature. Since approximately 57% of body mass is water, and assuming the remainder is just fat and bone in equal proportions, the change in temperature ΔT in one second is given by

$$\Delta T = \frac{P \times t}{mc_{body}}\,. \tag{5}$$

Therefore,

$$\Delta T = \frac{364\mathrm{W}\times 1\mathrm{s}}{70\mathrm{kg}\times\left[0.57 c_{water} + 0.43\left(\frac{c_{fat} + c_{bone}}{2}\right)\right]}\,. \qquad (6)$$

Given that the specific heat capacity c_{water} is 4180$\mathrm{Jkg}^{-1}\mathrm{K}^{-1}$ [6], c_{fat} is 1930 $\mathrm{Jkg}^{-1}\mathrm{K}^{-1}$ and c_{bone} is 440 $\mathrm{Jkg}^{-1}\mathrm{K}^{-1}$ [7], the change in temperature ΔT in one second is found to be $1.8 \times 10^{-3}\mathrm{K}$. Therefore to increase the temperature of the human body by 1K would take

$$\frac{1}{1.8\times 10^{-3}} = 555.5\ \mathrm{s}\,. \qquad (7)$$

Or, approximately 9 minutes.

Conclusion

The calculations above show that shivering can produce a small but significant amount of energy. Thermoregulation is vitally important to warm-blooded mammals, since enzymes essential for biological reactions are optimal in a narrow temperature range [8]. Therefore a variation of 1-2K can be the difference between life and death. However, shivering is often considered to have a rather low efficiency, since the movement of limbs is supposed to disturb the insulating air layer and increase convective heat loss [9]. Furthermore, there are many assumptions made in these calculations that vary from reality. Firstly, the assumption is made that all skeletal muscle will be active in shivering, which will not be the case in practice. Secondly, the assumption of isometric tetanic contraction is not accurate. In addition, shivering could only be at best a temporary measure, since it can only be sustained for a maximum of 2 hours [10].

References

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