The ventilatory cost of activity*

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Cotes, J. E. (1975). *British Journal of Industrial Medicine*, 32, 220-223. **The ventilatory cost of activity.** The energy cost of activity, depending on its intensity, varies between 6 and 50 kJ min⁻¹ with average values for essential daily tasks and for hard work respectively of 12 and 28 kJ min⁻¹. The levels of ventilation required to sustain these activities are, on average, 15 and 33 l min⁻¹ with an overall range of $\pm 30\%$. Additional ventilation is needed for speech. The requirements for individual activities are reviewed.

Changing from rest to a state of physical activity entails the additional expenditure of energy and transport of oxygen, for which purpose the cardiac output and the ventilation minute volume are increased. For the majority of subjects the level of energy expenditure which can be sustained during work is determined mainly by the ability of the circulation to deliver blood to the muscles, but for patients with impaired lung function the limiting factor is usually the ventilatory capacity. For such subjects the ventilatory cost of work is particularly important.

Unfortunately, whilst the energy cost of activities is reliably documented, for example, by Passmore and Durnin (1955), and Spitzer and Hettinger (1958), the data for the ventilatory cost are less satisfactory. This is because the measurements were made using mainly the dry gas meter of Kofranyi and Michaelis (1940) which has a high resistance to airflow. However, there is now evidence from studies where equipment was used which had a low resistance to airflow, and that the ventilatory cost is on average the same under survey conditions as it is in the laboratory (Adam, 1966; Cotes, 1969; Miller, 1974). The relationship is approximately:

$$\dot{V}_E = 0.5 \dot{n}O_2 \text{ (or } 22\dot{V}_{O_2}) + 2(\text{SD } 5.4) \text{ l min}^{-1}$$

where $\dot{V}_E$ is ventilation minute volume in l BTPS

min⁻¹ and $\dot{n}O_2$ and $\dot{V}_{O_2}$ are uptake of oxygen respectively in the units mmol min⁻¹ and l STPD min⁻¹ (Cotes, 1975). The use of this relationship permits the allocation of levels of ventilation to the data for energy expenditure cited above.

Units for energy expenditure

Under the SI system the unit of energy expenditure is the joule and there are 4.18 J to the calorie (not 4.19 as reported recently (British National Committee for Nutritional Sciences, 1972)). The energy equivalent of oxygen at a respiratory exchange ratio of 0.86 is 0.457 kJ per mmol which is approximately 20 kJ per 45 mmol (11) of oxygen.

Ventilatory cost of activity

The ventilatory costs are summarized in the Figure where the activities are classified into seven overlapping grades of energy expenditure given on the abscissa. The lightest grade, 6 to 10 kJ min⁻¹, is light sedentary work. 8 to 16 kJ min⁻¹ embraces dressing and undressing, walking at a slow pace, and factory jobs entailing machine minding and light assembly work in an upright posture. 12 to 20 kJ min⁻¹ include moderate work with the arms: for example, polishing, washing clothes, and bricklaying, and also walking at a medium pace. 16 to 24 kJ min⁻¹ includes hard work using the arms: for example, scrubbing, machine fitting, and milking cows by hand, and also walking at a fast pace on level

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FIGURE. Human energy expenditure and ventilation during selected tasks. The marked point is the average for young men performing sustained hard work reported by Hughes and Goldman (1970). In general people who are physically fit and are of below average body weight have values at the bottom of each category whilst those who are unfamiliar with the task, are overweight, or have parenchymal lung disease lie towards the top, but there is big individual variation for which some additional causes are discussed in the text.

ground. 20 to 40 kJ min⁻¹ is what might be regarded as heavy work, including cycling and swimming, many activities in horticulture, coal mining, etc. 30 to 50 kJ min⁻¹ is very heavy work, including hand sawing and planing, stoking a furnace, and climbing stairs carrying a load. Above 40 kJ min⁻¹ is exceptionally heavy work such as athletics, using an axe, ski-ing, or playing squash.

The ordinate of the figure gives the corresponding ventilatory costs of which those for heavy work and for essential daily tasks, including dressing and undressing, are of outstanding importance. For the activities defined as heavy work the mean ventilation is about 33 l min⁻¹ and the range from 20 to 50 l min⁻¹. For the activities which might be considered

to be essential for a tolerable life lived on level ground, the range of ventilation is 10 to 25 l min⁻¹.

Discussion

For any defined task the range of ventilation is considerable. This is due to variation in energy expenditure and the relationship of the ventilation to the uptake of oxygen. The energy expenditure is influenced by the body weight of the person (Cotes, 1969) and by his or her physical dimensions, skill, and familiarity with the task (Cotes and Meade, 1959; 1960). It is not much influenced by lung disease (Colin *et al.*, 1972).

After standardizing to a constant level of energy expenditure the ventilatory cost is affected by a number of factors. These include diurnal variation, the state of physical training of the subjects, the extent of isometric contraction, and the size of the muscle groups which are employed. Diurnal variation of the order of 25% has been reported between measurements which are made in the early hours of the morning and in the middle of the day (Crockford and Davies, 1969) but the finding has not been confirmed (Wahlberg and Åstrand, 1973). No material difference is observed between measurements which are made in mid-morning and in the afternoon after a light lunch. Physical training affects mainly the rate of energy expenditure which can be sustained by aerobic metabolic pathways without recourse to anaerobic metabolism. Below this level (Owles point, Cotes, 1975) the ventilation is not much affected by the state of training of the subject, but it is sometimes increased if the subject is not familiar with the test procedure. The role of the size of the muscle is illustrated by the higher ventilation relative to energy expenditure of arm work compared with leg work. The difference is on average about 15% (Cotes, Allsopp, and Sardi, 1969). The effect of superimposed isometric muscular contraction is variable but may exceed 100% (Wiley and Lind, 1971). The ventilation is also affected by large changes in barometric pressure such as occur at high altitude or in a caisson; it is increased in old age and in a number of medical conditions, including lung disease.

The increase in ventilation with age is inconspicuous for aerobic work with the legs (Cotes *et al.*, 1973) and for work with the arms it occurs mainly after the age of 65 years (Norris, Shock, and Yiengst, 1955). The increase with cardiac or respiratory disease reflects mainly the extent of uneven lung function and of hypoxaemia but also the responsiveness of the respiratory control system. In patients with mild airways obstruction due to bronchitis the exercise ventilation is within normal limits, but as the disease progresses some increase occurs. This is usually only of the order of 15% because an increased deadspace ventilation is often offset by a smaller

rise in alveolar ventilation during exercise compared with healthy subjects. In the absence of alveolar hypoventilation the ventilation may be further increased: for example, in some patients with panacinar emphysema and proliferative disease of the lung parenchyma. Hyperventilation also occurs in cyanotic congenital heart disease and mitral stenosis where in a recent study, the exercise ventilation exceeded that in the control group by approximately 50% (Cotes and Reed, 1973). Thus the present data for healthy subjects also apply to the majority of patients with chronic bronchitis and airways obstruction, but may underestimate the ventilation in the presence of material abnormality of the lung parenchyma or of haemodynamic disorders secondary to heart disease.

Breathlessness on exertion in patients with lung disease is due mainly to a reduction in ventilatory capacity. The level of exercise ventilation usually becomes important only when it is encroached upon by the ventilatory impairment. In these circumstances people who lead physically active lives or perform heavy work might be conscious of their disability at an earlier stage in the disease than those whose lives were mainly sedentary. They then might seek treatment sooner and so have a better prognosis. However, the energy expenditure for heavy work is matched by that for the everyday activities of walking up hill or upstairs so the apparent advantage in this respect for the manual worker or sportsman is relatively small.

Normal living includes climbing stairs, walking up hills, and undertaking hard work. These activities usually require the ability to sustain a ventilation of on average 33 l min^{-1} (range 20 to 50 l min^{-1}). An additional 20 l min^{-1} may be required if the subject is carrying a load or if speech is undertaken concurrently. A sheltered life entailing minimal expenditure of energy may be supported by ventilation levels of half these amounts. However, the ventilation needed for different tasks varies materially between individuals in the manner indicated in the Figure.

In patients with lung disease breathlessness on exertion may be reduced by remedies directed towards increasing the ventilatory capacity including the use of bronchodilator or steroid drugs, treatment of infection, and abandonment of smoking. It may also be alleviated by reducing the energy cost, by working at a slower rate or using power-assisted tools or mechanical aids such as a walking frame. For a given rate of energy expenditure the ventilatory cost may sometimes also be reduced by portable oxygen therapy.

There is need for both closer scrutiny of the energy and ventilatory costs of activities which give rise to breathlessness in individual subjects and consideration of the ways in which these costs can be reduced.

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