Sternomastoid muscle function and fatigue in man

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(Received 25 February/30 June 1980; accepted 28 July 1980)

Summary

1. A technique has been devised to measure the effect of stimulation frequency on the contraction force in an accessory muscle of respiration, the sternomastoid, in man. The frequency/force curve was found to be very similar to that of the quadriceps and adductor pollicis muscles.

2. Fatigue of the sternomastoid due to inspiratory loading or sustained maximum voluntary ventilation resulted in reduced force generation at low stimulation frequencies compared with maximum force. This type of fatigue frequently persisted for several hours.

3. If low frequency fatigue were to develop in patients with pulmonary disease it could have important consequences for the development of respiratory failure.

Key words: maximum ventilation, respiratory muscle fatigue, sternomastoid muscle function.

Introduction

The function of muscle is to generate force. Failure to generate force (i.e. fatigue) can occur for a variety of reasons ranging from failure of neural drive to impaired actomyosin cross-bridge function (Edwards, 1978). Techniques have been developed to measure the contractile properties of a large proximal muscle (quadriceps) and a small distal muscle (adductor pollicis) in man (Edwards, Young, Hosking & Jones, 1977b). The force response to increasing stimulation frequency (i.e. frequency/force curve) is shifted to the right as a consequence of fatiguing muscular activity and the forces produced at low frequencies of stimulation are thus reduced relative to the forces attained with high stimulation frequencies (Edwards, Hill, Jones & Merton, 1977a). Since respiratory muscles in patients with obstructive lung disease are required to generate the increased forces necessary for ventilation over long periods of time without rest, it is possible that they could develop 'low frequency fatigue'.

The intercostal muscles and diaphragm are relatively inaccessible but the sternomastoid is a suitable muscle for study because it is superficial and can easily be electrically stimulated. In patients with obstructive lung disease and hyperinflation the sternomastoid is an important muscle of respiration (Campbell, Agostoni & Newsom-Davis, 1970). The principal aim of this study was to investigate sternomastoid function and the factors involved in fatigue.

Methods

The subjects were healthy volunteers with normal respiratory function and all studies were approved by the Committee on the Ethics of Clinical Investigation of University College Hospital Medical School.

Measurement of sternomastoid contraction force

Unilateral contraction of the sternomastoid produces lateral flexion of the head and neck to the ipsilateral side and rotation to the contralateral side. During stimulated contractions of the left sternomastoid a horizontal component of
face pad A, pad applied to mastoid region

FIG. 1. Scheme of equipment for recording the forces of isometric contractions of the sternomastoid during electrical stimulation.

Force in the coronal plane was measured at the left mastoid process through a 4 cm² firm pad, which was connected to a strain gauge and rapid-response oscillograph. A second firm pad was closely applied to the right face and chin to prevent rotation and lateral flexion (Fig. 1). The subject was seated in a dental chair which supported the head and neck posteriorly in the anatomical position. Breathing was suspended at mid-tidal volume during stimulation. The chair and both pads were easily adjustable, ensuring maximal stabilization in all subjects and reduction of movement during stimulation to a minimum. Small differences in muscle length about the anatomical position did not affect the results.

**Electrical stimulation of sternomastoid**

The sternomastoid is flat, thin and superficial. It is easily stimulated with a surface electrode (cathode) placed over its mid-point, where it receives its innervation from the spinal accessory nerve, a second electrode (anode) being applied to the sternal head. The electrodes were made of aluminium foil (2 cm²) covered with absorbent paper soaked in sodium chloride solution (150 mmol/l saline). The muscle was made to contract as a result of stimulation of the intramuscular nerves by unidirectional square-wave impulses of 50 μs duration and 50–80 V. To generate a frequency/force curve the sternomastoid was stimulated at 1, 3, 5, 8, 10, 15, 20, 30, 50, 80 and 100 Hz. This sequence was performed at least twice on each subject. Stimulation at each of the lower frequencies was for 5–10 s and at high frequencies for 2 s, sufficient to allow plateau forces to be reached. The isolated tetanic stimulation of the left sternomastoid, with the head immobilized, produced slight muscle shortening, amounting to 3–4% of its length, when measured by calipers.

The effect of an increased workload on the contractile properties of the sternomastoid muscle was investigated in the following ways.

**Inspiratory resistance**

Four subjects undertook a period of inspiratory loading, with a resistance provided by corks with central apertures of different diameters, that enabled the subject to generate 70% of maximum inspiratory mouth pressure with each breath, expiration being unloaded. Mouth pressure was displayed on an oscilloscope and the subject attempted to sustain the target pressure throughout every inspiration for 200 breaths. Tidal volume, respiratory frequency and the pattern of breathing were selected by the subject; the mean respiratory frequency was 15 breaths/min. Analysis on one subject (no. 1) confirmed that there was no alteration of arterial-blood gas tensions during the period of inspiratory loading.

**Sustained maximum voluntary ventilation**

Baseline values of forced expiratory volume in 1 s (FEV₁) and 15 s maximum voluntary ventilation were established by using a bellows spirometer (Oldelft Floop I). Three normal subjects then performed 10 min of maximum ventilation using a partial rebreathing technique to keep endtidal Pco₂ steady. Oxygen was added to the system to maintain the inspired oxygen concentration at 30% (Eger, Kellogg, Mines, Lima-Ostos, Morrill & Kent, 1968). The flow signal from a pneumotachograph (Fleisch) was integrated and tidal volume displayed by a paper recorder (Hewlett Packard). The subject was informed of his progress and encouraged to make maximum efforts. Each of the three subjects was studied on two separate occasions. In each test the frequency/force curve of the sternomastoid was recorded before the period of maximum respiratory effort and about 10 min afterwards.

**Portable equipment for assessing sternomastoid function**

The fixed equipment was unsuitable for the study of subjects elsewhere than the laboratory and we therefore designed portable apparatus for testing muscle function. This equipment measured a component of the contractile force through a pressure-transducer probe (Elcomatic)
applied to the tendon of the sternal head of the sternomastoid. The probe displaced the tendon posteriorly and consequently measured an anterior force vector as the muscle contracted and sought to straighten. The probe was kept firmly applied to the muscle tendon by a clamp, which was itself fixed to a solid circular plate held against the upper chest. Subjects were tested with the head and neck in the anatomical position and movement was reduced to a minimum by a second operator firmly holding the head. The relation between the forces when measured simultaneously by the tendon transducer and the mastoid strain gauge were linear and the two techniques produced very similar results. With the portable equipment the force at 20 Hz, as a percentage of maximum force, was $81.7 \pm 5.0\%$ (mean $\pm$ SD, $n = 6$) compared with $80.5 \pm 9.2\%$ ($n = 10$) when sternomastoid forces were measured in the laboratory. In this study the fixed equipment was used during the investigation of muscle function before and after breathing through an inspiratory resistance and the portable equipment before and after sustained maximum voluntary ventilation.

Electromyography

For two subjects the electromyogram (EMG) of the sternomastoid was recorded for standard tensions before and after inspiratory loading. The EMG was recorded by using surface electrodes (Disa type 13 K 60 tin-plate) one placed over the centre of the muscle and one at the sternal insertion. In order to quantify EMG activity the raw signal was full-waved rectified and smoothed with a time constant of 0.2 s and displayed on the oscillograph record. During experiments the site of the electrodes was not changed.

Results

Frequency/force curve

Frequency/force curves were recorded for 10 subjects, force being expressed as a percentage of maximum force for each subject. A useful numerical index of the frequency/force relationship was given by the force generated at 20 Hz as a percentage of maximum force. For the 10 subjects this was $80.5 \pm 9.2\%$. The coefficient of variation for this value between two successive tests on the 10 subjects was 10%. The frequency/force curve of the sternomastoid was very similar to that of the quadriceps and adductor pollicis muscles (Fig. 2). For the quadriceps the force at 20 Hz, as percentage of maximum force, was $74.2 \pm 7.7\%$ ($n = 40$) and for adductor pollicis $73.1 \pm 7.8\%$ ($n = 10$).

Low frequency fatigue

Inspiratory resistance. After inspiratory loading the frequency/force curve was recorded after the subjects had rested quietly for 10 min. For each stimulation sequence the force at different

![Fig. 2. Frequency/force curve of the sternomastoid, quadriceps and adductor pollicis in normal subjects. O, Sternomastoid (mean $= \pm$ SD, $n = 10$); O, adductor pollicis (mean $= \pm$ SD, $n = 10$); X, quadriceps (mean only for clarity, $n = 40$). (In different subjects maximum force was achieved at 50, 80 or 100 Hz. The mean values at these frequencies are therefore less than 100%).]
frequencies was expressed as a percentage of the maximum force achieved. The curves were substantially shifted to the right so that the forces generated at low frequencies of stimulation were reduced whilst those at high frequencies were almost normal (Fig. 3a). The shift occurred after inspiratory loading in each of seven studies done on four subjects. The shift in the frequency/force curve was reflected in the fall of the force at 20 Hz as a percentage of maximum force; this was reduced to $38.0 \pm 8.0\%$ ($P < 0.001$). The recovery of the muscle was slow; the fatigue was demonstrated at 20, 30 and 60 min after the test, and the muscle only returned to a normal contractile state after several hours (see Fig. 4).

Sustained maximum voluntary ventilation. On two occasions three normal subjects had sternomastoid muscle function assessed before and 10 min after a 10 min period of isocapneic maximum voluntary ventilation. During the tests similar levels of ventilation were achieved, the mean sustained minute ventilation was 58.5% of the 15 s maximum voluntary ventilation (range 54.5–64.1). The subjects experienced respiratory muscle pain, particularly affecting the accessory muscles, and a cramp-like pain in the right hypochondrium. In all six tests the sternomastoid developed substantial low frequency fatigue (Fig. 3b), the force at 20 Hz as a percentage of maximum force falling from $82.5 \pm 8.0$ to $55.6 \pm 8.5\%$ ($P < 0.001$).

**EMG studies**

A linear relationship between the amplitude of the smoothed rectified EMG and force during isometric voluntary contractions was demonstrated for the sternomastoid and confirmed for the adductor pollicis and quadriceps. After inspiratory loading and the development of low frequency fatigue in the sternomastoid the relationship between the smoothed rectified EMG and force was again examined (Fig. 5). With fatigue a given amplitude of the EMG was associated with less force than in fresh muscle; conversely, a given level of force was associated with an increase in the EMG and therefore increased motor unit activity. This finding was confirmed in the quadriceps and adductor pollicis muscles.

**Discussion**

**The frequency/force curve**

This study has shown that the contractile properties of an accessory muscle of respiration,
Respiratory muscle fatigue

the sternomastoid, are the same as in other skeletal muscles. For force generation the shape of the frequency/force curve is of considerable physiological importance. The firing frequency of motor neurons during everyday activities is low, between 5 and 30 Hz, and therefore on the steep part of the curve. If force generation at low stimulation frequencies is reduced it thus becomes necessary to increase stimulation frequency or recruit additional motor units to maintain force production.

The determination of the frequency/force curve of the sternomastoid by using a strain gauge applied to the mastoid region to record a lateral vector of contraction force is effective and reproducible, but difficult. The technique is time consuming and is uncomfortable for the subject. The finding that recording an alternative vector of the contractile force, by using a transducer firmly applied to and displacing the muscle tendon, produced the same frequency/force curve was important. This technique is rapid, easy and much more acceptable to the subject. The apparatus is also portable.

Low frequency fatigue

It is clear from this study that after the respiratory stress of both inspiratory loading and sustained maximum voluntary ventilation normal subjects develop substantial low frequency fatigue in the sternomastoid muscles. The respiratory muscles of patients with pulmonary disease work against a greatly increased inspiratory load, to which they are exposed with each breath, for long periods and with no opportunity to rest the muscles for more than a few seconds. It is therefore possible that the respiratory muscles eventually develop low frequency fatigue.

Muscle fatigue and respiratory failure

If the respiratory muscles were to develop low frequency fatigue the implications for force generation and ventilation would be important. It has previously been demonstrated that the slope of the linear relationship between the smoothed rectified EMG and force is increased after fatiguing contractions (Edwards & Lippold, 1956) and our work illustrates that this shift is associated with low frequency fatigue. Because the frequency/force curve is shifted to the right it becomes necessary to increase the excitation of the muscle if force is to be maintained and, in respiratory terms, the central respiratory drive must be increased if ventilation is not to fall. For a maximum voluntary contraction the motor neuron firing frequency is only greater than 30 Hz for a few seconds (Jones, Bigland-Ritchie & Edwards, 1979). Similarly there may well be a limit to the respiratory drive that can be sustained for long periods. With the development of low frequency fatigue it is therefore implicit that the maximum sustained level of ventilation must fall, and for many patients with severe pulmonary disease it is the maximum sustained level of ventilation that limits activity (Clark, Freedman, Campbell & Winn, 1969). A further consequence of low frequency fatigue could be that maximal respiratory drive (i.e. maximal firing frequency) becomes necessary to maintain ventilation and thus any depression of drive (i.e. sedatives, carbon dioxide, narcosis or excess oxygen therapy) would cause a fall in ventilation.

The cause of low frequency fatigue is not known but an important factor may be reduced activation of the myofibrillar apparatus. An essential feature of this type of fatigue is that it is long-lasting, frequently persisting for many hours, and during this time the muscle EMG is entirely normal. This fatigue will therefore not be detected by techniques of recognizing fatigue that rely on alterations of the power spectrum of the EMG (Moxham, De Troyer, Farkas, Macklem, Edwards & Roussos, 1979). The long duration of low frequency fatigue suggests that in some patients one of the benefits of assisted ventilation may be that the respiratory muscles are rested and their contractile properties can return to normal.
Acknowledgments

Dr S. G. Spiro and Dr S. Freedman were closely involved with this project and we greatly appreciate their advice and support. Mr A. Cobley helped with the experimental work throughout the study. Support from the Wellcome Trust and Muscular Dystrophy Group of Great Britain is gratefully acknowledged.

References


