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Activation of human inspiratory muscles in an upside-down posture

Anna L. Hudson[a,b], Fabrice Joulia[c,d], Annie A. Butler[a,b], Richard C. Fitzpatrick[a,b], Simon C. Gandevia[a,b], Jane E. Butler[a,b,*]

[a] Neuroscience Research Australia, Australia
[b] University of New South Wales, Australia
[c] UMR MD2, Aix Marseille University & IRBA, Marseille, France
[d] University of Toulon, La Garde, France

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ABSTRACT

During quiet breathing, activation of obligatory inspiratory muscles differs in timing and magnitude. To test the hypothesis that this coordinated activation can be modified, we determined the effect of the upside-down posture compared with standing and lying supine. Subjects ($n = 14$) breathed through a pneumotachometer with calibrated inductance bands around the chest wall and abdomen. Surface electromyographic activity (EMG) was recorded from the scalene muscles. Crural diaphragmatic EMG and oesophageal and gastric pressures were measured in a subset of six subjects. Quiet breathing and standard lung function manoeuvres were performed. The upside-down posture reduced end-expiratory lung volume. During quiet breathing, for the same inspiratory airflow and tidal volume, ribcage contribution decreased, abdominal contribution increased and transdiaphragmatic pressure swing doubled in the upside-down posture compared to standing ($p < 0.05$). Despite this, crural diaphragm EMG was unchanged, whereas scalene muscle EMG was reduced by ~half ($p < 0.05$). Thus, the mechanical effect of an upside-down posture differentially affects inspiratory muscle activation.

1. Introduction

Respiratory muscle contraction to ventilate the lungs is a continual requirement. It is usually under automatic control by respiratory centres in the pontomedullary region of the brainstem and in mammals, inspiration is the crucial phase of the respiratory cycle (Feldman, 2011; Feldman and Del Negro, 2006). During quiet breathing in human subjects in the seated posture, there is coordinated contraction of the obligatory inspiratory muscles with differences in the timing and degree of activation of intramuscular EMG recordings (for review see Butler, 2007; Butler and Gandevia, 2008; Butler et al., 2014; Hudson et al., 2011).

The mechanical action of the respiratory muscles is determined, like all skeletal muscles, by the bony structure(s) to which they attach and the displacement of these structures when the muscles contract. In the upright posture, the mechanical actions of the inspiratory muscles expand the abdominal wall and expand and elevate the ribcage against gravity. Body posture changes often and in diverse ways that can acutely alter respiratory mechanics. As first described by Konno and Mead (1967), for the same change in lung volume there is greater ribcage expansion when upright, but abdominal expansion dominates in the supine posture. A change to the supine posture also affects pleural and abdominal pressures developed during tidal breathing and inspiratory muscle activity can, in some cases, be altered (e.g. Butler et al., 2001; Druz and Sharp, 1981; Segizbaeva et al., 2011; Steier et al., 2009). When present, changes in inspiratory muscle EMG are concerted, with a decrease in phasic EMG activity in all muscles (diaphragm, scalenes and parasternal intercostals) with a change from upright to supine posture (Druz and Sharp, 1981).

It is not known if the activation of inspiratory muscles can be differentially affected by the unusual posture of upside-down suspension. This is important as it establishes if the activation of respiratory muscles is adaptable to a wide range of postures that humans can adopt and if the coordinated (i.e. concerted) pattern of inspiratory muscle activation can be altered. If so, this suggests that neural drive from the pontomedullary respiratory centres to different inspiratory muscles can be differentially distributed in an adaptive manner. The rationale for an upside-down posture was that in addition to a decrease in functional residual capacity as known to occur in the supine posture compared to upright (e.g. Lim and Luft, 1959), an upside-down posture would

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* Corresponding author at: Neuroscience Research Australia, Margarete Ainsworth Building, Barker Street, Randwick, NSW 2031, Australia.
Tel.: +61 2 9399 1608; fax: +61 2 9399 1027.
E-mail address: j.butler@neura.edu.au (J.E. Butler).

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elicit further mechanical changes and differentially affect inspiratory muscles. We hypothesised that in the upside-down posture, the reversed effects of gravity on chest wall, lung and respiratory muscle mechanics would alter thoracoabdominal movement and intrathoracic pressures generated by the muscles and that we would observe a concurrent differential adaptation of inspiratory muscle activity. Specifically, we expected: (i) an increase in inspiratory diaphragmatic activity to counteract the effect of gravity on the abdominal contents to generate comparable caudal movement of the muscle and transdiaphragmatic pressure and (ii) a decrease in scalene activity due a decreased requirement of the mechanical action of the scalenes to elevate the upper ribcage while upside down. We tested these hypotheses by determining the effect of the upside-down posture on ventilation, thoracoabdominal expansion, inspiratory pressures and inspiratory muscle activity during quiet breathing, compared to standing and lying supine.

2. Material and methods

The studies were carried out in 14 healthy subjects (5 females) aged 24–56 years. They gave informed written consent to the procedures, which conformed with the Declaration of Helsinki and were approved by the Human Research Ethics Committee of the University of New South Wales. Respiratory parameters and inspiratory scalene electromyographic activity (EMG) were recorded during quiet breathing in three postures: standing, lying supine and upside down (Fig. 1A). In a subset of six subjects, diaphragm EMG and oesophageal and gastric pressures were also measured.

Respiratory displacements of the chest wall and abdomen were monitored with inductance bands around the ribcage at the level of the nipples and abdomen at the level of the umbilicus. These were calibrated in each body posture by the conventional isovolume calibration manoeuvre. During ventilatory recordings, subjects wore a nose clip and breathed through a mouthpiece connected to a pneumotach (model 3700, Hans Ruldoph Inc., MO, USA) and the signal of airflow was integrated to give changes in lung volume.

Surface EMG recordings from the right scalene muscles were made with self-adhesive electrodes (Ag–AgCl; 10 mm diameter; Cleartrace, ConMed Corporation, Utica, NY, USA). One electrode was placed in the posterior triangle of the neck, posterior to the border of the sternocleidomastoid muscle at the level of the cricoid cartilage, and the second electrode was placed ~2 cm caudally over the muscle. This close interelectrode distance minimised any movement of the electrodes relative to the underlying muscle with changes in posture. In 6 subjects (all male), a nasogastric multi-pair electrode catheter (5 EMG channels) with two balloons was inserted to record diaphragmatic EMG, oesophageal (P_{oes}) and gastric (P_{ga}) pressures. The position of the EMG electrodes and balloons in the thoracic and abdominal compartments were verified (see Luo et al., 2008) and adjusted in different postures prior to recordings as required. Abdominal muscle activity (external oblique) was monitored with electrodes placed ~2 cm apart at the level of the anterior superior iliac spine, midway between the umbilicus and the anterior superior iliac spine. A ground electrode was placed over the right shoulder.

All signals were stored on computer via a Cambridge Electronic Design 1401 interface (Cambridge, UK) for subsequent analysis. EMG was amplified, band-pass filtered (100–1000 Hz) and sampled at 5 kHz. All other parameters were sampled at 1 kHz.

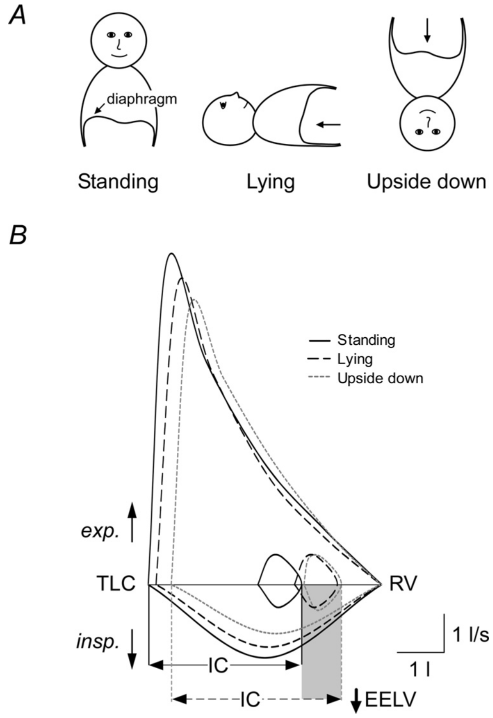

Fig. 1. Schematic showing the three postures tested and representative flow-volume loops recordings. (A) A change in posture and gravitational vector will alter chest wall, lung and respiratory muscle mechanics, such as the effect of the abdominal contents on diaphragm length and zone of apposition (denoted by the arrow). (B) Flow-volume loops for a single subject during a forced vital capacity manoeuvre performed while standing, lying and upside down. The thin horizontal line represents zero airflow with changes in inspiratory (insp.) and expiratory (exp.) flow shown below and above this line, respectively. Changes in lung volume between residual volume (RV) and total lung capacity (TLC) are shown as well as typical traces from a quiet breath in each posture (by the smaller circular curves). Inspiratory capacity (IC) during standing is indicated from end-expiratory lung volume (EELV) by the continuous vertical lines. While upside down (dashed vertical lines), there was an increase in IC which suggests EELV decreased (grey shaded area). The inspiratory flow is relatively slow compared to typical flow-volume loops, as subjects did not perform a fast inhalation following the expiratory manoeuvre. The curves have been smoothed for all postures for presentation and aligned to RV.

Subjects were tested in three postures: (i) standing upright, (ii) lying supine on a firm mattress and (iii) upside down while suspended from the ceiling by an ankle harness (Gear Sports, USA) attached to an electric hoist (HSG Mini Electric Hoist, Zhejiang Kaixun Mechanical and Electrical Co. Ltd., Zhejiang, China). To maintain anatomical posture of the arms and allow subjects to relax their shoulders and arms while upside down, they were strapped (by Velcro) to the side of the body or held there by an experimenter.

In each posture, 30 s of quiet breathing was performed without explicit instructions other than to breathe ‘normally’ or ‘quietly’. Subjects then repeated the isovolume calibration manoeuvre to verify the calibration of the ribcage and abdominal bands. Finally, inspiratory capacity, slow vital capacity and forced expiratory volume manoeuvres were repeated twice, in the same or a separate session.

A control study was performed in a subset of five subjects (three females) to determine if the surface electrodes used to measure scalene muscle activity in the main study moved relative to the underlying muscle in the different postures. A multi-pair electrode, normally used to measure intraoesophageal diaphragm EMG (Luo et al., 2008), was placed along the length of the right scalene muscle from its cranial limit at the hairline to its caudal limit at the clavicle. Tape was placed on the skin between each of the nine electrodes to avoid cross talk, conductive gel was then applied to each electrode, and then the whole catheter was taped to the skin along its entire length. This allowed us to monitor inspiratory scalene EMG over five pairs of electrodes across the length of the muscle. EMG was amplified, band-pass filtered (53–1000 Hz) and sampled at 2 kHz. All other parameters were sampled at 1 kHz.