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Relationship between transdiaphragmatic and mouth twitch pressures at functional residual capacity

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ABSTRACT: The clinical application of transdiaphragmatic twitch pressure ($P_{di,tw}$) response to phrenic nerve stimulation has been hindered by the requirement for placement of oesophageal and gastric balloons. Investigators have reported that mouth twitch pressure ($P_{mo,tw}$) estimates $P_{di,tw}$ accurately at lung volumes above and below functional residual capacity (FRC). However, it is not known whether $P_{mo,tw}$ estimates $P_{di,tw}$ accurately when stimulation is performed at FRC during relaxed conditions. The aim of this study was to develop a simple method whereby measurements of P_{mo} could be used to predict oesophageal twitch pressure ($P_{oes,tw}$) and possibly $P_{di,tw}$ at FRC.

The study was performed in 11 healthy volunteers during phrenic nerve stimulation.

At FRC, 9 of the 11 subjects showed a poor correlation between $P_{mo,tw}$ and $P_{oes,tw}$, and between $P_{mo,tw}$ and $P_{di,tw}$, probably due to varying degrees of glottic closure. Stimulations performed while subjects maintained an inspiratory flow of ~50 mL·s^{-1}, or at the point of reattaining FRC during an inspiration preceded by a limited exhalation, produced good correlations between $P_{mo,tw}$ and $P_{oes,tw}$ (r=0.97 in both instances) and $P_{mo,tw}$ and $P_{di,tw}$ (r=0.96 and r=0.95, respectively), with a steep slope. The respective slopes for the $P_{mo,tw}$ $P_{oes,tw}$ relationship were 0.88 and 0.94, and for the $P_{mo,tw}$ $P_{di,tw}$ relationship, 0.59 and 0.54. Unfortunately, these manoeuvres produced a significant increase in transpulmonary pressure (3.6±0.6 (SE) and 5.6±1.4 cmH$_2$O, respectively), suggesting change in diaphragmatic length. Stimulations delivered while subjects performed an inspiratory effort or during exhalation against a high resistance preceded by a limited inhalation could not be used to predict $P_{oes,tw}$ and $P_{di,tw}$ from $P_{mo,tw}$.

In conclusion, although transdiaphragmatic and oesophageal twitch pressure could be predicted from mouth twitch pressure during some inspiratory manoeuvres mouth twitch pressure was not reliable for the prediction of the oesophageal and transdiaphragmatic twitch pressure at functional residual capacity during relaxed conditions in healthy volunteers.

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Measurement of maximal inspiratory pressure ($P_{I,max}$) is the standard means of assessing global inspiratory muscle strength. However, $P_{I,max}$ is dependent on a subject's comprehension of the manoeuvre, good co-ordination, and maximal muscle recruitment. Not surprisingly, some healthy subjects have values of $P_{I,max}$ below the normal range [1]. If a low $P_{I,max}$ value is found, additional investigation of respiratory muscle function is necessary. This normally necessitates the insertion of gastric and oesophageal balloon catheters to measure transdiaphragmatic pressure (P_{di}) following maximal inspiratory efforts, a sniff manoeuvre, and/or phrenic nerve stimulation [1].

By being independent of subject co-operation and motivation, phrenic nerve twitch stimulation is a potentially use-ful means of evaluating diaphragmatic muscle contractility [2]. However, recordings of transdiaphragmatic twitch pressure ($P_{di,tw}$) require placement of oesophageal and gastric balloon catheters, which has limited the clinical application of this approach. In healthy subjects [3, 4] and in patients with respiratory muscle weakness [4], measurement of mouth twitch pressure ($P_{mo,tw}$) appears to be a useful noninvasive method of estimating $P_{oes,tw}$ and $P_{di,tw}$ at lung volumes above [3] and below functional residual capacity (FRC) [4]. Similowski *et al.* [5] have reported a good correlation between $P_{mo,tw}$ and $P_{oes,tw}$ and between $P_{mo,tw}$ and $P_{di,tw}$ in patients with chronic obstructive pulmonary disease (COPD) when performing inspiratory efforts from FRC (nonisometric manoeuvres). A potential source of error with techniques that involve stimulation at volumes above or below FRC is the need to monitor and standardize lung volume and degree of diaphragmatic activation accurately during phrenic nerve stimulation and to account for alterations in these variables when interpreting the measurements of $P_{mo,tw}$.

When electrical stimulation of the phrenic nerves is performed at FRC under relaxed conditions, the correlation between $P_{mo,tw}$ and $P_{di,tw}$ has ranged from marginal [3] to unacceptable [5]. Being able to achieve an accurate prediction of $P_{di,tw}$ from recordings of $P_{mo,tw}$ obtained at FRC would be advantageous, since diaphragmatic length is a major determinant of $P_{di,tw}$ amplitude, and stimulation performed at lung volumes above and below FRC can, respectively, underestimate or overestimate diaphragmatic contractility.

The aim of this study was to determine whether it is possible to design a simple method whereby measurements of P_{mo} could be used to predict measurement of $P_{oes,tw}$ and $P_{di,tw}$ at FRC. After commencing the study, it became clear that many subjects developed varying degrees of glottic closure during phrenic nerve stimulation, which interfered with the ability to predict $P_{oes,tw}$ and $P_{di,tw}$ from the P_{mo} signal. Accordingly, additional experiments were undertaken employing a number of manoeuvres to produce glottic patency during phrenic nerve stimulation.

Methods

Subjects

Eleven normal subjects, aged 25–43 yrs (mean 33 yrs) volunteered for this study. The study was approved by the Human Studies Subcommittee of Edwards Hines Jr Veterans Administration Hospital, and informed consent was obtained from all subjects.

Pressure, lung volume and airflow recordings

Oesophageal (P_{oes}) and gastric (P_{ga}) pressures were measured separately with two thin-walled latex balloon-tipped catheters (Physio-Dyne Instruments Corp, Massapequa, NY, USA), coupled to pressure transducers (MP-45; Validyne, Northridge, CA, USA) as described previously [6, 7]. The oesophageal balloon containing 0.5 mL of air [6] was positioned in the mid-oesophagus using the occlusion technique [8]. A gastric balloon containing 1.0 mL of air [6] was advanced 65 cm from the nares. P_{di} was obtained by electronic subtraction of P_{oes} from P_{ga}. A third transducer (MP-45; Validyne, Northridge, CA, USA) was employed to measure P_{mo}, sensed at the mouthpiece. Lung volume was monitored with a spirometer (Spiroflow; P.K. Morgan Ltd, Gillingham, Kent, UK). Flow was measured *via* a pneumotachograph (Model 3813; Hans Rudolf Inc., Kansas City, MO, USA). A noseclip was in place during the experiments and subjects were studied in the seated position.

Phrenic nerve stimulation

Bilateral phrenic nerve stimulation was performed using a magnetic stimulator (Magstim 200; Magstim Co. Ltd, Wales) with a circular 90 mm coil (P/N 9784-00). This device stimulates neuromuscular structures by inducing electrical currents in the tissue secondary to a time varying magnetic field (<1 ms total pulse duration) of electromagnetic energy [9]. At maximal output of the stimulator, the magnetic field is 2.0 Tesla. To achieve stimulation of the phrenic nerve roots, the subject's neck was flexed and the coil was placed over the cervical spine. While the subject relaxed at FRC, the site of optimal stimulation was determined by moving the coil between C5 and C7, until the maximum response was obtained [10, 11]. This position was marked with a felt pen, and, thereafter, all stimulations were performed at this position.

Experiment 1

The purpose of this experiment, which was conducted in 11 subjects, was to study the relationship between $P_{mo,tw}$ and $P_{di,tw}$ with subjects relaxed at FRC. Phrenic nerve stimulations were initially delivered at 100% of the output of the magnetic stimulator (*i.e.* 2.0 Tesla), and were then delivered in progressive decrements of 10%, until 40–50% of maximal output was produced. At each level of output, the subject received 4–10 stimulations, with a minimum interval of 4 s between each. By varying the intensity of stimulation, it was possible to achieve a wide range of $P_{di,tw}$ values at a constant lung volume and a constant degree of diaphragmatic activation. This facilitated the detection of any significant correlation between $P_{mo,tw}$ and $P_{oes,tw}$ and between $P_{mo,tw}$ and $P_{di,tw}$.

Experiment 2

The purpose of this experiment, which was conducted in four subjects, was to examine the relationship between $P_{mo,tw}$ and $P_{oes,tw}$ and between $P_{mo,tw}$ and $P_{di,tw}$ at the point of reaching FRC (as indicated by a spirometric signal), during a gentle exhalation after first inhaling ~300 mL above resting volume (fig. 1). A two-way valve, inserted between the mouthpiece and spirometer (fig. 2a), was constructed in such a manner that there was minimal resistance during inspiration (fig. 2b), but

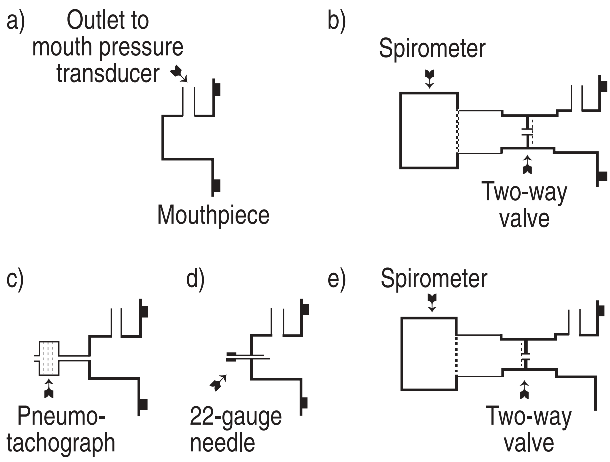

Fig. 1. – Schematic representation of the set-up used in each experiment. In each case, an outlet from the mouthpiece was connected to a pressure transducer for measurement of mouth pressure. a) In Experiment 1, the mouthpiece was occluded. b) In Experiment 2, a two-way valve was interposed between the mouthpiece and spirometer; the valve was designed such that resistance to exhalation was greater than resistance to inhalation (see text and figure 2 for details). c) In Experiment 3A, the mouthpiece was connected to a pneumotachograph; d) In Experiment 3B a 22-gauge needle was inserted in the mouthpiece; and e) in Experiment 3C a two-way valve was interposed between the mouthpiece and a spirometer, so that resistance to inhalation was greater than resistance to exhalation.

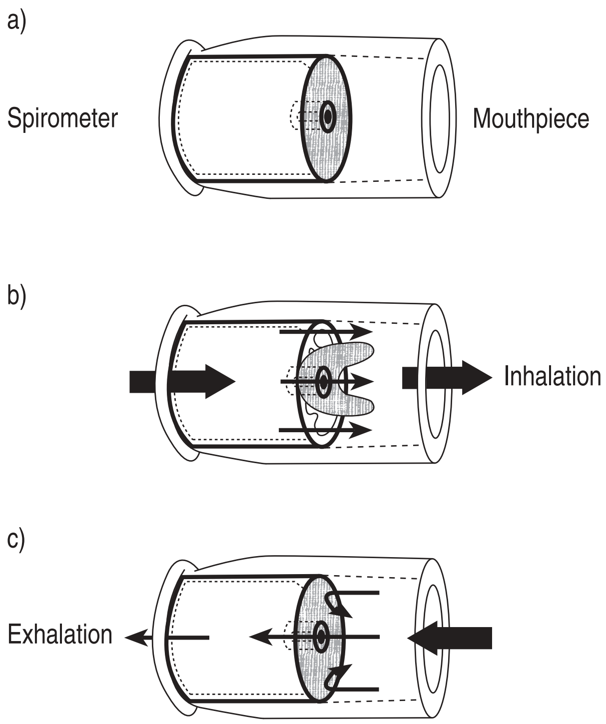

Fig. 2. – Two-way valve used in Experiments 2 and 3C. a) This valve was placed between the mouthpiece and the spirometer. b) A thin rubber diaphragm is easily displaced by airflow, allowing inhalation against minimal resistance. c) During exhalation, the rubber diaphragm is pushed against a plastic ring forcing expiratory flow through a high resistance conduit. By turning the valve in the opposite direction it is possible to generate high resistance during inhalation, as employed in Experiment 3C.

resistance was high during exhalation (fig. 2c). This valve was used in an attempt to reduce the external dissipation of P_{mo} changes during phrenic nerve stimulation by avoiding a direct communication between the mouthpiece and the large tubing connected to the spirometer.

While subjects rested at FRC, the operator connected the spirometer to the mouthpiece, and then asked the subject to inhale slowly. After inhaling ~300 mL, the subject was asked to exhale gently against a high resistance, whilst maintaining a P_{mo} of <6 cmH_2O. At the point that the subject reached FRC, as indicated by a spirometric signal, the operator stimulated the phrenic nerves. Magnetic stimulations were initiated at 100% of the output of the stimulator, and were then progressively decreased in decrements of 10%, until 40–50% of maximal output was produced. The manoeuvre was repeated 4–6 times at each output.

Experiment 3

The purpose of these experiments was to examine the relationship between $P_{mo,tw}$ and $P_{oes,tw}$ and between $P_{mo,tw}$ and $P_{di,tw}$, whilst subjects performed different inspiratory efforts.

Experiment 3A. The purpose of this experiment, conducted in six subjects, was to examine the relationship between $P_{mo,tw}$ and $P_{oes,tw}$ and between $P_{mo,tw}$ and $P_{di,tw}$, whilst subjects maintained an inspiratory flow rate of ~50 $mL \cdot s^{-1}$. A mouthpiece was connected to the pneumotachograph through nondistensible tubing (fig. 1). Inspiration was initiated from FRC, and a digital display of the subject's flow rate (Fluke 12 multimeter; J Fluke Mfg. Co. Inc, Everett, WA, USA) was displayed to help him/her achieve the target. A single stimulation was delivered while the subject maintained the target flow, and then exhaled and rested for 30–60 s. The procedure was repeated 4–9 times. The output of the magnetic stimulator was set initially at 100%, and then progressively decreased in decrements of 10% until an output of 40% was achieved.

Experiment 3B. The purpose of this experiment, conducted in seven subjects, was to examine the relationship between $P_{mo,tw}$ and $P_{oes,tw}$ and between $P_{mo,tw}$ and $P_{di,tw}$, whilst subjects maintained a P_{mo} of approximately -2 cmH_2O starting from FRC. A digital display of P_{mo} helped the subject achieve the target. To prevent buccal muscle use and glottic closure, a 22-gauge needle was inserted in the mouthpiece [12] (fig. 1). Whilst maintaining the target pressure, the subject received 4–7 stimulations from the magnetic stimulator. The output was set initially at 100%, and then progressively decreased in decrements of 10% until an output of 40% was achieved.

Experiment 3C. The purpose of this experiment, conducted in four subjects, was to examine the relationship between $P_{mo,tw}$ and $P_{oes,tw}$ and between $P_{mo,tw}$ and $P_{di,tw}$ at the point of reaching FRC (as indicated by the spirometric signal), during a gentle inspiratory effort after first exhaling ~300 mL below resting volume (fig. 1). In this experiment a two-way valve (also used in Experiment 2) was inserted between the mouthpiece and spirometer (fig. 2a) and turned so that the subject had to inhale against a high resistance. The subject was asked to keep the mouthpiece in position. While the subject was resting at FRC, the operator connected the spirometer to the mouthpiece, and then asked the subject to exhale slowly. When the subject had exhaled ~300 mL, he/she was asked to inhale gently against a high resistance, while maintaining a P_{mo} of approximately -6 cmH_2O. At the point that the subject reached FRC (as indicated by a spirometric signal), the operator stimulated the phrenic nerves. Magnetic stimulations were initiated at 100% of the output of the stimulator, and were then progressively decreased in decrements of 10% until 40% of maximal output was produced. The manoeuvre was repeated 4–7 times at each output.

Data analysis

Data were recorded and digitized at 250 Hz using a 12-bit analogue-to-digital converter (CODAS; DATAQ Instruments Inc., Akron, OH, USA) connected to a computer (EMPAC Int. Corp., Fremont, CA, USA). The amplitudes of $P_{mo,tw}$, $P_{oes,tw}$ and $P_{di,tw}$ were measured as the difference between the maximum pressure displacement secondary to phrenic nerve stimulation and the baseline of each pressure signal immediately preceding stimulation. Transpulmonary pressure (P_L) was obtained as the difference between P_{mo} and P_{oes}. Paired t-tests were used to compare P_L and $P_{di,tw}$ recorded with different protocols. Linear regression analysis was employed to calculate the correlation between different variables. A p-value of less than 0.05 was considered significant.

Results

Experiment 1

As a result of the change in stimulator output, $P_{di,tw}$ ranged 1.4–46.8 cmH_2O. The relationship between $P_{mo,tw}$ and $P_{oes,tw}$ and between $P_{mo,tw}$ and $P_{di,tw}$ elicited by phrenic nerve stimulation in 11 subjects relaxing at FRC are shown in figures 3 and 4. Overall, the correlations

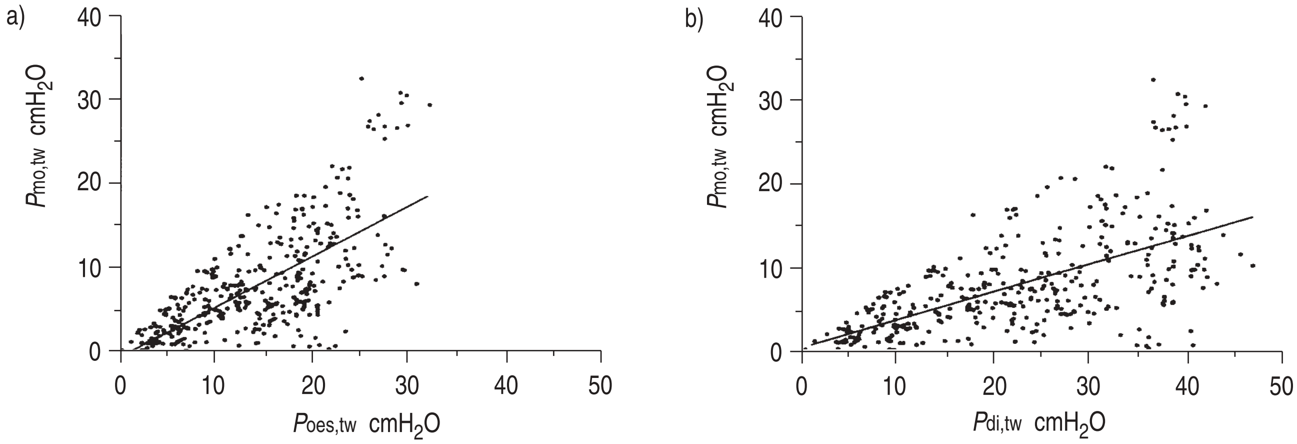

Fig. 3. – Relationship between: a) mouth twitch pressure ($P_{mo,tw}$) and oesophageal pressure ($P_{oes,tw}$); and b) between $P_{mo,tw}$ and transdiaphragmatic twitch pressure ($P_{di,tw}$) during phrenic nerve stimulation in 11 subjects relaxing at functional residual capacity. The overall correlations were weak (r=0.68 for the correlation between $P_{mo,tw}$ and $P_{oes,tw}$; and r=0.61 for the correlation between $P_{mo,tw}$ and $P_{di,tw}$), probably because many subjects developed varying degrees of glottic closure during phrenic nerve stimulation.

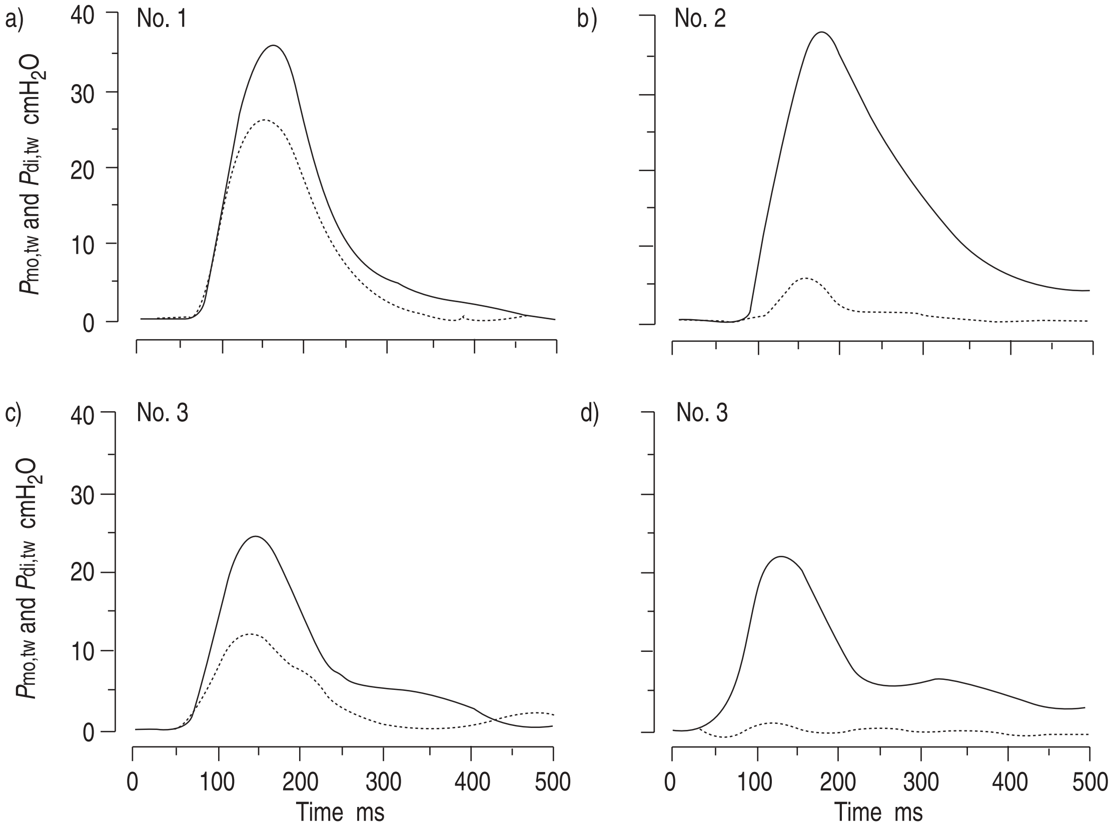

Fig. 4. – Mouth twitch pressure ($P_{mo,tw}$) and transdiaphragmatic twitch pressure ($P_{di,tw}$) during phrenic nerve stimulation in three representative subjects relaxing at functional residual capacity. To facilitate comparison between the two pressure tracings, the polarity of the mouth pressure (P_{mo}) signal has been inverted. a) In subject No. 1, an increase in $P_{di,tw}$ was accompanied by an increase in the P_{mo} signal; in this subject the $P_{mo,tw}$-$P_{di,tw}$ relationship remained constant over wide range of stimulation outputs. b) In subject No. 2, an increase in $P_{di,tw}$ was accompanied by only a small rise in the P_{mo} signal, which was not altered by increasing the output from the stimulator; this implies that the degree of glottic closure increased in proportion to the output of the stimulator. c) and d) In subject No. 3, an increase in $P_{di,tw}$ was accompanied by variable increase in the P_{mo} signal, suggesting varying degrees of glottic patency. ····· : mouth pressure; ———: transdiaphragmatic pressure.

between $P_{\mathrm{mo,tw}}$ and $P_{\mathrm{oes,tw}}$ and $P_{\mathrm{mo,tw}}$ and $P_{\mathrm{di,tw}}$ were relatively weak (r=0.68 and r=0.61, respectively; p<0.001 in both instances), and the respective slopes were 0.6 and 0.3. Two subjects, however, showed close relationships between $P_{\mathrm{mo,tw}}$ and $P_{\mathrm{di,tw}}$ (r values 0.99 and 0.87, and slopes 0.71 and 0.56, respectively).

Experiment 2

The correlations between $P_{\mathrm{mo,tw}}$ and $P_{\mathrm{oes,tw}}$ and between $P_{\mathrm{mo,tw}}$ and $P_{\mathrm{di,tw}}$ in four subjects stimulated at the point of reattaining FRC during an exhalation preceded by a limited inhalation were relatively weak (r=0.46 and r=0.50, respectively; p<0.001 in both instances), and the slopes were very low (0.16 and 0.09, respectively).

Experiment 3A

The correlations between $P_{\mathrm{mo,tw}}$ and $P_{\mathrm{oes,tw}}$ and between $P_{\mathrm{mo,tw}}$ and $P_{\mathrm{di,tw}}$ elicited by phrenic nerve stimulation in six subjects whilst maintaining a constant inspiratory flow started at FRC were significant (r=0.97 and r=0.96, respectively; p<0.001 in both instances), and the slopes were relatively steep (0.88 and 0.59, respectively) (fig. 5). However, with this manoeuvre, P_{L} increased from 4.0±0.9 (mean±SE) to 7.6±0.9 cmH_2O (p<0.005), signifying, at least in part, that a change in diaphragmatic length had occurred.

Experiment 3B

The correlations between $P_{\mathrm{mo,tw}}$ and $P_{\mathrm{oes,tw}}$ and between $P_{\mathrm{mo,tw}}$ and $P_{\mathrm{di,tw}}$ elicited by phrenic nerve stimulation in seven subjects whilst maintaining a P_{mo} of ~ -2 cmH_2O starting from FRC were relatively weak (r=0.72 and r=0.66, respectively; p<0.001 in both instances).

Experiment 3C

The correlations between $P_{\mathrm{mo,tw}}$ and $P_{\mathrm{oes,tw}}$ and between $P_{\mathrm{mo,tw}}$ and $P_{\mathrm{di,tw}}$ in four subjects stimulated at the point of reattaining FRC during an inhalation preceded by a limited exhalation were strong (r=0.97 and r=0.95, respectively; p<0.001 in both instances) and the slopes were 0.94 and 0.54, respectively (fig. 5). However,

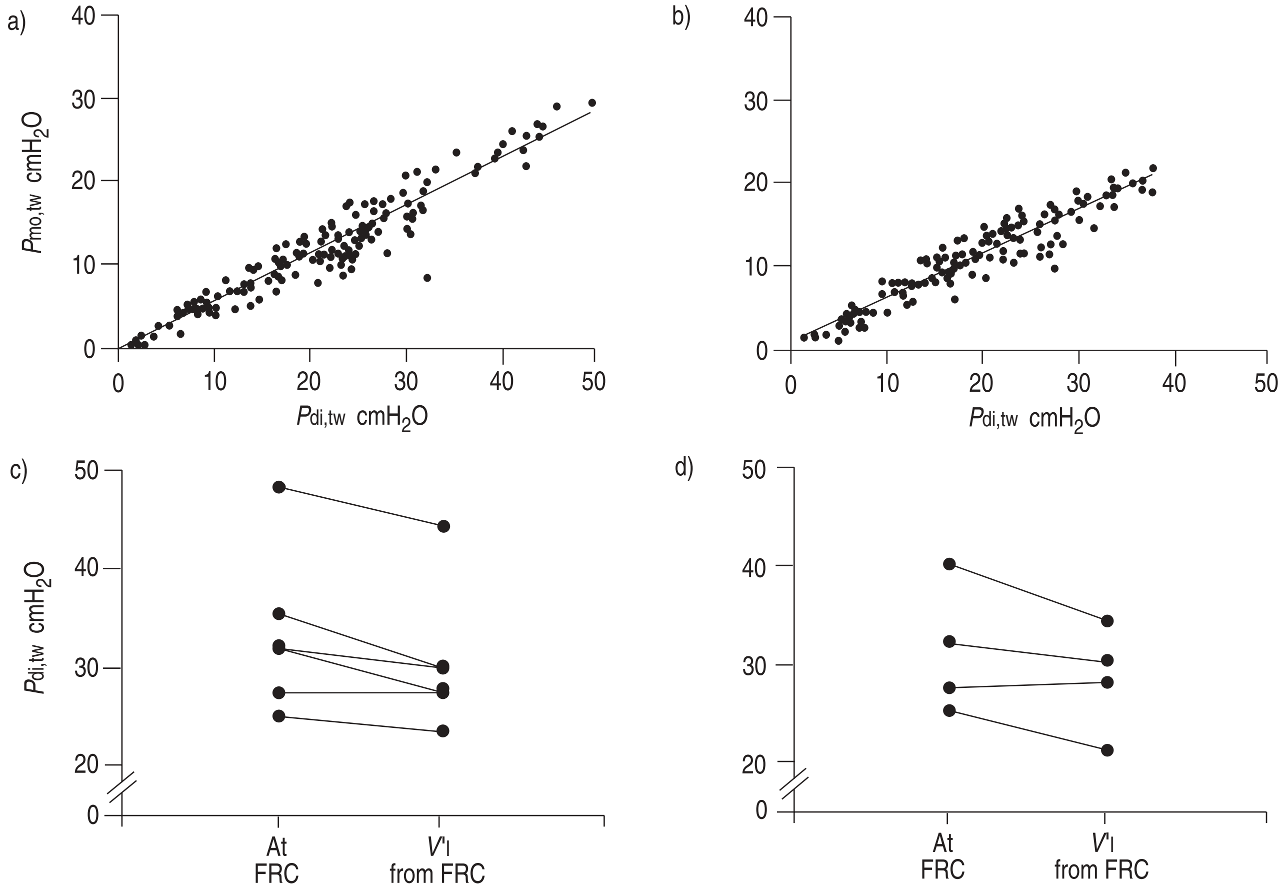

Fig. 5. – a) Experiment 3A: correlation between mouth twitch pressure ($P_{\mathrm{mo,tw}}$) and transdiaphragmatic twitch pressure ($P_{\mathrm{di,tw}}$) during phrenic nerve stimulation in six subjects, whilst maintaining an inspiratory flow (V'_{I}) rate of ~50 $mL \cdot s^{-1}$ (r=0.96; p<0.001), with a relatively steep slope, 0.59. b) Experiment 3C: correlation between $P_{\mathrm{mo,tw}}$ and $P_{\mathrm{di,tw}}$ in four subjects stimulated at the point of reaching functional residual capacity (FRC) (as indicated by spirometry), during a gentle inspiratory effort after first exhaling to ~300 mL below FRC (r=0.95; p<0.001), with a slope of 0.54. Both manoeuvres increased transpulmonary pressure (panels c and d, which correspond to panels a and b, respectively), in most subjects, resulting in a fall in $P_{\mathrm{di,tw}}$ (see text for details).

with this manoeuvre, P_L increased from 4.0±1.8 to 9.5±1.6 cmH_2O ($p<0.05$), signifying, at least in part, that a change in diaphragmatic length had occurred.

Discussion

We observed a good correlation between $P_{mo,tw}$ and $P_{oes,tw}$ and between $P_{mo,tw}$ and $P_{di,tw}$ when the subjects maintained a constant inspiratory flow (Experiment 3A), and when subjects performed a limited exhalation and then gently inhaled to the point of reattaining FRC, as indicated by spirometry (Experiment 3C). In these two experiments, the correlations between $P_{mo,tw}$ and $P_{oes,tw}$ had slopes close to unity and intercepts close to zero, indicating that $P_{mo,tw}$ was closely related to $P_{oes,tw}$ and also similar in magnitude. Agreement between $P_{mo,tw}$ and $P_{di,tw}$ was also very good, but not as tight as that between $P_{mo,tw}$ and $P_{oes,tw}$. This finding is not surprising, since there is no physiological reason that the gastric component of $P_{di,tw}$ should be directly transmitted to P_{mo}.

Unfortunately, both with Experiment 3A and Experiment 3C, P_L at the point of stimulation was greater than at resting FRC. This increase in P_L was, at least in part, due to an increase in lung volume, with consequent decrease in diaphragmatic length of sufficient extent to be physiologically important). Indeed, in most subjects (fig. 5), $P_{di,tw}$ at resting FRC was greater than that obtained whilst subjects maintained an inspiratory flow of ~50 mL·s^{-1} (Experiment 3A), or at the point of reattaining FRC (as indicated by the spirometry signal), during inspiration preceded by a limited exhalation (Experiment 3C). In an additional subject, Experiment 3C was repeated whilst rib cage and abdominal cross-sectional areas were recorded with a respiratory inductive plethysmograph (RIP). The high resistance conduit used in this protocol (figs. 1 and 2) requires generation of some P_L to initiate airflow, and the resulting intrathoracic gas rarefaction is not detected by the spirometer but is measured by RIP. When spirometry signalled that the subject had reached FRC, the RIP signal indicated that thoracic volume had actually increased by 140 mL above relaxed FRC (fig. 6). During the inspiratory manoeuvres described in Experiments 3A and 3C, it is also possible that some degree of glottic narrowing might have occurred. Any resulting increase in airway resistance could contribute to the increase in P_L.

Changes in $P_{di,tw}$ show a linear relationship to changes in lung volume [11, 13–15], thus recordings of $P_{mo,tw}$ during phrenic nerve stimulation at lung volumes above FRC (Experiments 3A and 3C) or below FRC (the expiratory manoeuvre described by HAMNEGARD *et al.* [4]) may still be a potentially useful screening tool in evaluating patients suspected of impaired diaphragmatic contractility. For this purpose, it is necessary to identify the threshold value of $P_{mo,tw}$ above which significant diaphragmatic weakness can be excluded. In healthy volunteers, HAMNEGARD *et al.* [4] and HUGHES *et al.* [16] reported the lowest value of $P_{mo,tw}$ during gentle expiratory efforts to be 10 and 12 cmH_2O, respectively. Thus, $P_{mo,tw}$ values less than 10 cmH_2O during a gentle expiratory manoeuvre indicate impaired diaphragmatic contractility.

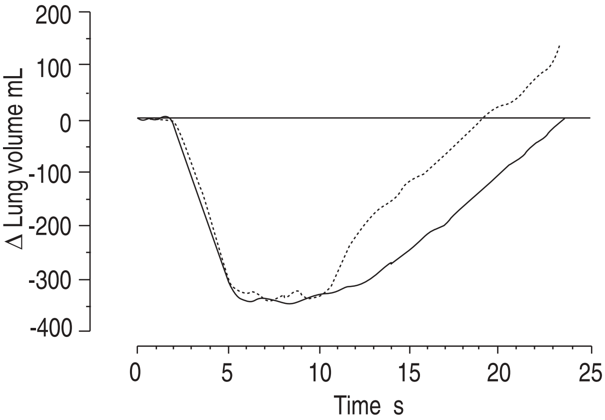

Fig. 6. – Changes (Δ) in lung volume, as recorded by spirometry and respiratory inductive plethysmography (RIP) in a representative subject, during a gentle inspiratory effort after first exhaling 350 mL below functional residual capacity (FRC) (Experiment 3C, see text for details). When spirometry signalled that the subject had reached FRC, the RIP signal indicated that thoracic volume had actually increased to 140 mL above relaxed FRC. Such a discrepancy is due to thoracic gas rarefaction secondary to the high inspiratory resistance conduit (see text for details). ·····: RIP; ———: spirometer.

We found that the lowest $P_{mo,tw}$ value whilst subjects maintained an inspiratory flow of ~50 mL·s^{-1} was 11 cmH_2O (Experiment 3A), and the lowest $P_{mo,tw}$ at the point of reattaining FRC (as indicated by the spirometric signal), during an inspiration preceded by a limited exhalation was 12 cmH_2O (Experiment 3C). Therefore, if during a gentle inspiratory effort a patient has a $P_{mo,tw}$ less than 11 cmH_2O, diaphragmatic dysfunction should be suspected. In such a circumstance, further evaluation with the use of oesophageal and gastric balloons is recommended to exclude the possibility that the low $P_{mo,tw}$ value was due to phrenic nerve stimulation performed at an unduly high lung volume and/or because the voluntary diaphragmatic contraction had decreased the number of myofibrils available for depolarization by stimulation, *i.e.* twitch occlusion [5]. The inspiratory technique described in Experiment 3A is simple and serves as an adjunct to the exhalation technique described by HAMNEGARD *et al.* [4], especially in patients who are unable to coordinate their expiratory effort as required with the latter technique [4].

Following magnetic stimulation, $P_{oes,tw}$ is generated by the co-ordinated action of diaphragmatic and rib cage muscle contraction [11]. Thus, $P_{mo,tw}$ induced by cervical magnetic stimulation, as described in the current experiments and by HAMNEGARD *et al.* [4], may be an index of global inspiratory muscle performance rather than one of selective diaphragmatic contractility. For clarification, this issue requires further experimentation.

In summary, during phrenic nerve stimulation performed while subjects relaxed at functional residual capacity, the correlations between mouth and oesophageal twitch pressure and between mouth and diaphragmatic twitch pressure were poor. This phenomenon was probably due to varying degrees of glottic closure, consistent with the findings of SIMILOWSKI *et al.* [5]. Certain manoeuvres successfully avoided glottic closure, but they produced a significant increase in transpulmonary pressure, indicating, at least in part, change in diaphragmatic length.

In conclusion, use of mouth twitch pressure and a variety of respiratory manoeuvres did not allow reliable prediction of the value of transdiaphragmatic twitch pressure at functional residual capacity during relaxed conditions in healthy volunteers.

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