Eur Respir J, 1994, 7, 1788–1792
DOI: 10.1183/09031936.94.07101788
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European Respiratory Journal
ISSN 0903 - 1936

# Comparison of cervical magnetic stimulation and bilateral percutaneous electrical stimulation of the phrenic nerves in normal subjects

S. Wragg*, R. Aquilina**, J. Moran+, M. Ridding*, C. Hamnegard*, T. Fearn++, M. Green** , J. Moxham*

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**ABSTRACT: Cervical magnetic stimulation is a new technique for stimulating the phrenic nerves, and may offer an alternative to percutaneous electrical stimulation for assessing diaphragmatic strength in normal subjects and patients in whom electrical stimulation is technically difficult or poorly tolerated.**

**We compared cervical magnetic stimulation with conventional supramaximal bilateral percutaneous electrical stimulation in nine normal subjects. We measured oesophageal pressure (Poes), gastric pressure (Pgas) and transdiaphragmatic pressure (Pdi). The maximal relaxation rate (MRR) was also measured.**

**The mean magnetic twitch Pdi was 36.5 cm$H_2O$ (range 27–48 cm$H_2O$), significantly larger than electrical twitch Pdi, mean 29.7 cm$H_2O$ (range 22–40 cm$H_2O$). The difference in twitch Pdi was explained entirely by twitch Poes, and it is possible that the magnetic technique stimulates some of the nerves to the upper chest wall muscles as well as the phrenic nerves. We compared bilateral, rectified, integrated, diaphragm surface electromyographic (EMG) responses in three subjects and found results within 10% in each subject, indicating similar diaphragmatic activation. The within occasion coefficient of variation, *i.e.* same subject/same session, was 6.7% both for magnetic and electrical twitch Pdi. The between occasion coefficient of variation, *i.e.* same subject/different days, was 6.6% for magnetic stimulation and 8.8% for electrical. There was no difference between relaxation rates measured with either technique.**

**We conclude that magnetic stimulation is a reproducible and acceptable technique for stimulating the phrenic nerves, and that it provides a potentially useful alternative to conventional electrical stimulation as a nonvolitional test of diaphragm strength.**

*Eur Respir J., 1994, 7, 1788–1792.*

*Kings College Hospital, London, UK. ** The Royal Brompton Hospital, London, UK. +Queen Elizabeth Hospital, Adelaide, Australia. ++Dept of Statistical Science, University College London, London, UK.

Correspondence: S. Wragg
Dept of Thoracic Medicine
Kings College Hospital
Bessemar Road
London SE5 9PJ
UK

Keywords: Diaphragm
magnetic stimulation
phrenic nerve

Received: November 19 1993
Accepted after revision June 18 1994

Cervical magnetic stimulation has been reported by SimILOWSKI *et al.* [1] as a technique for stimulating the phrenic nerves. Magnetic stimulation is used routinely by neurologists in clinical practice to assess nerve and muscle function.

The technique is reported to be safe [2] and relatively simple, and provides a nonvolitional test of diaphragmatic strength [3]. Such a test could be of considerable clinical value, especially in the situation when there is doubt concerning the patients ability to fully co-operate and perform volitional manoeuvres, and where electrical stimulation is difficult to perform. We hypothesized that if magnetic stimulation fully activated the diaphragm the transdiaphragmatic pressures would be similar to those achieved by conventional supramaximal bilateral electrical stimulation of the phrenic nerves [4], and we therefore compared the two techniques.

## Methods

We undertook cervical magnetic phrenic stimulation and bilateral percutaneous electrical stimulation in nine normal subjects, three females and six males, age range 30–50 yrs. Subjects gave informed consent and the protocol was approved by the Hospital Ethics Committee.

Twitch transdiaphragmatic pressure (Pdi) was measured in the semirecumbent position with a noseclip on and the mouth closed. The semirecumbent position was chosen as one in which both normal subjects and patients are comfortable, and in which the phrenic nerves are most easily stimulated electrically [5]. The abdomen was not bound [6]. Oesophageal pressure (Poes) and gastric pressure (Pgas) were recorded from latex balloon catheters (PK Morgan 71510) positioned and tested in the standard

Fig. 1. – Magnetic stimulation of phrenic nerve roots. Note neck flexion and midline position of coil.

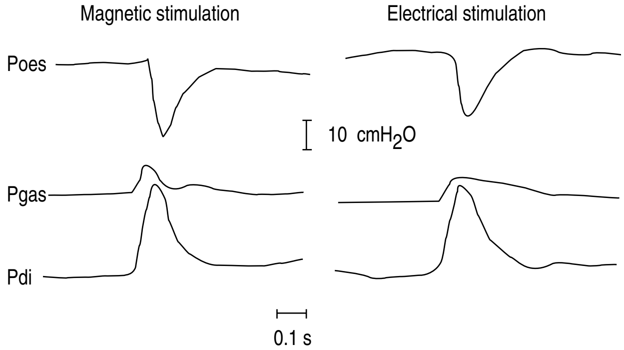


Fig. 2. – Recording of magnetic and electrical twitch pressures from the same subject. Poes: oesophageal pressure; Pgas: gastric pressure; Pdi: transdiaphragmatic pressure.

manner [6, 7]. Pressures were measured by means of Validyne MP45-1 differential pressure transducers (range ±150 $cmH_2O$, Validyne Co, Northridge, CA, USA). Pdi was obtained by electrical subtraction of Poes from Pgas, using Pdi at resting end-expiration as the reference point [8].

All signals were displayed on an eight channel strip chart recorder (Mingograph 800, Siemens). Twitch responses were rejected from analysis when baseline oesophageal pressure immediately before stimulation, at zero flow, was more than 1 $cmH_2O$ different from that at functional residual capacity (FRC) [9]. Since monitoring of FRC and thoracoabdominal configuration with either linearized magnetometers or inductive plethysmography is not possible during magnetic stimulation, due to stimulation artifact, we relied on Poes as a measure of the FRC position [10, 11].

Bilateral surface diaphragm electromyographic (EMG) responses were recorded during electrical stimulation using silver/silver chloride disk electrodes placed over the seventh intercostal space at the anterior axillary line and was displayed on an oscilloscope.

Percutaneous phrenic nerve stimulation was performed with bipolar electrodes (Medelec Ltd, Old Woking, Surrey, UK) with felt tips soaked in saline. The electrodes were connected to a constant voltage stimulator (Digitimer, Welwyn, Herts, UK) which produced square wave impulses of 100 µs duration. The phrenic nerves were stimulated at the posterior border of the sternomastoid muscle at the level of the cricoid cartilage [12]. On each occasion the stimulus intensity was increased in 10 v increments, until there was no further increase in twitch Pdi or diaphragm EMG amplitude. For each formal study, the electrical stimulus intensity was increased a further 20%. Magnetic stimulation was performed using a Magstim 200 (Magstim Co. Ltd, Whitland, Dyfed, Wales, UK) with a circular 90 mm coil (P/N 9784-00; maximum output 2.5 Tesla). This stimulates nervous tissue by induced electric currents resultant from a time varying magnetic field of brief duration [2]. To stimulate the phrenic nerve roots, the neck was flexed and the coil was placed over the spinous process of C7, moving up or down the midline between C5–C7 until the maximum response was obtained; thereafter, all stimulations were performed at the same position (fig. 1).

On each occasion, having located the optimal site for stimulation, the subject received 20 electrical stimulations followed by 20 magnetic stimulations or *vice versa*, depending on randomization. For the comparative study, magnetic stimulations were at 100% stimulator output. The shortest interval between stimulations was 15 s. An example of electrical and magnetic diaphragmatic twitch responses is illustrated in figure 2.

In five subjects, twitch Pdi were studied at various magnetic stimulus intensities to determine the response curve. Each subject received five stimulations at each stimulus intensity. On a separate occasion, bilateral surface EMGs were recorded in three of the five subjects. To record EMGs reliably, the recording amplifiers (Digitimer D150, Welwyn, UK) were electronically switched-off for 2 ms after the stimulus.

To investigate the reproducibility of magnetic and electrical responses, two subjects were studied on four separate occasions, and one other subject on three occasions.

In addition to the amplitude of the twitch transdiaphragmatic pressure, the maximum relaxation rate (MRR) was measured from both twitch oesophageal and twitch transdiaphragmatic pressures. To be acceptable for analysis of MRR the twitch pressure wave-forms had to display a smooth upstroke and decay [13]. MRR was calculated as the maximal rate of decay of pressure/peak pressure and had the units of % pressure loss·10 $ms^{-1}$ [14]. All results were analysed by analysis of variance.

## Results

All subjects completed both the percutaneous and magnetic stimulation studies, and all found magnetic stimulation to be the more tolerable, for two reasons. Firstly, electrical stimulation at high stimulus intensities elicits cutaneous pain that is not present with magnetic stimulation. Secondly, the electrical technique often requires repeated stimulation to ensure that stimulation is optimal; small movements of the electrode produce submaximal excitation. With magnetic stimulation, having once determined the position of the coil that gives a maximal response, it is usually possible to obtain satisfactory responses for each stimulation.

The results at various magnetic stimulus intensities are shown in figures 3 and 4; in all subjects there was a plateau of twitch Pdi and peak-to-peak amplitude of EMG, indicating supramaximality of stimulus. The results of magnetic and percutaneous electrical stimulation for the nine subjects are shown in figure 5. The mean electrical twitch Pdi ($Pdi_e$) was 29.7 (range 22–40) $cmH_2O$, compared with 36.5 (range 27–48) $cmH_2O$ for magnetic twitch Pdi ($Pdi_m$), with a mean difference of 6.8 $cmH_2O$. This difference was statistically significant (95%confidence interval (CI) 2.2–11.4). Analysis of the components of Pdi revealed mean magnetic twitch Poes of 26.1 *versus* mean electrical Poes of 19.7, a mean difference of 6.4 (95% CI 1.1–11.7). Mean magnetic Pgas was 10.4 *versus* mean electrical Pgas of 10.0, a mean difference of 0.4 (95% CI -2.0–2.8). Pdi and Poes were significantly larger ($p<0.05$) with the magnetic technique. There was no significant difference for Pgas.

Analysis of variance of the replicate measurements within subject revealed the within occasion coefficient of variation (CV) to be 6.7% for $Pdi_m$ and 6.7% for $Pdi_e$.

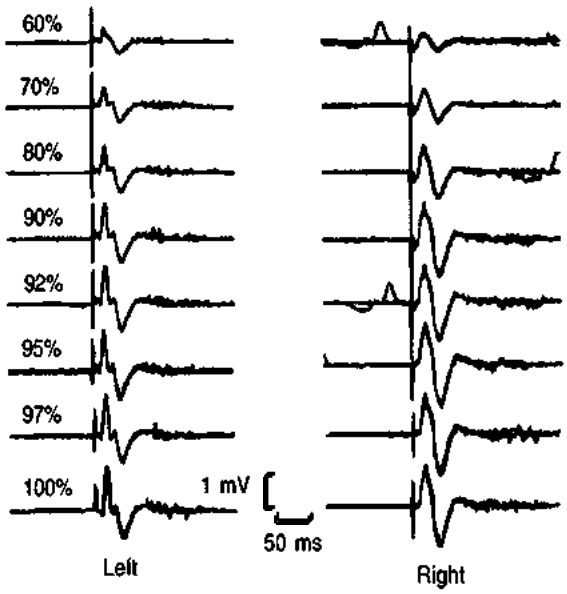


Fig. 3. – Bilateral surface diaphragm electromyographic responses (EMGs) from subject No. 3; each response consists of three superimposed EMGs at the magnetic stimulator output indicated.

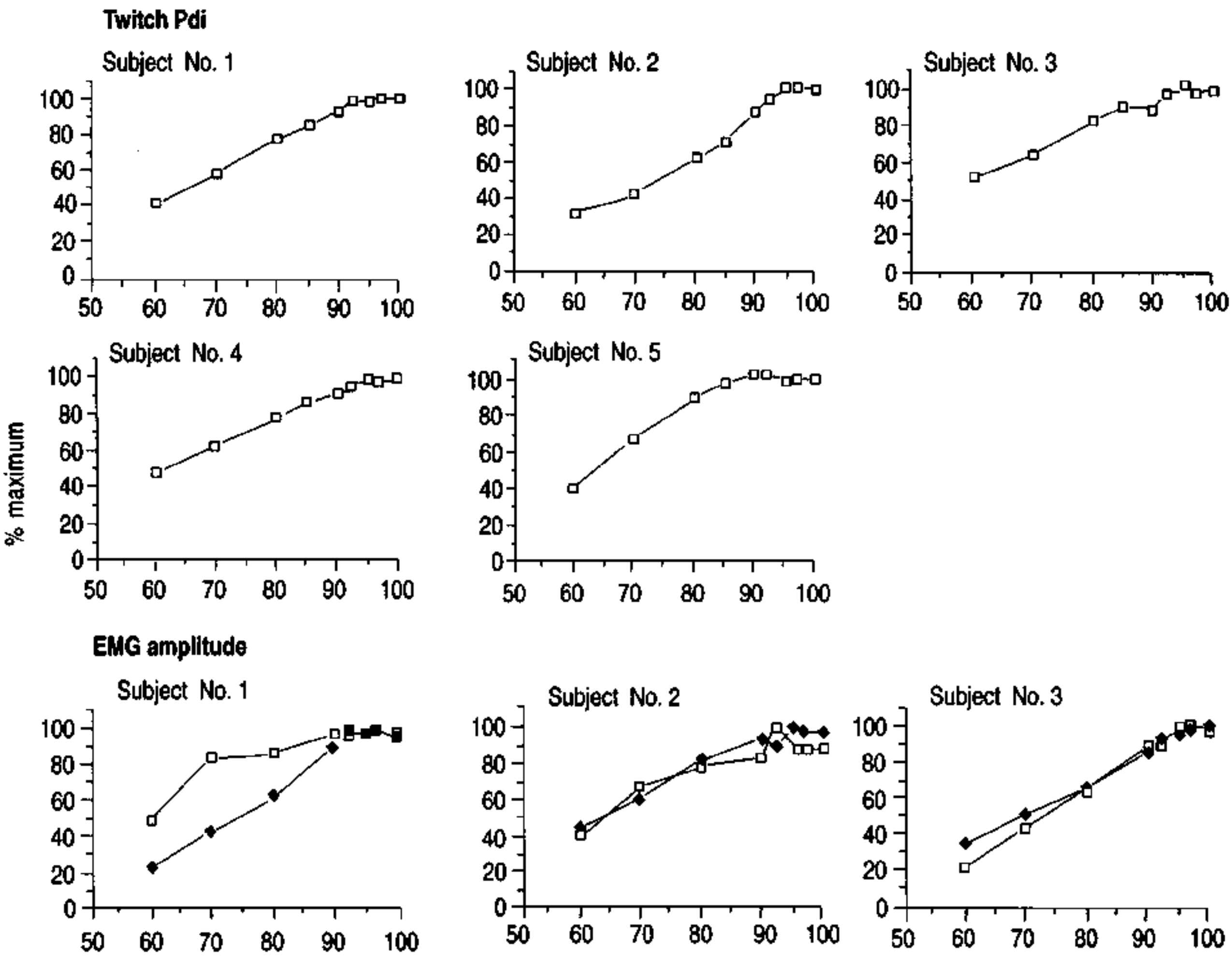


Fig. 4. – Response of twitch Pdi (five subjects) and electromyographic (EMG) amplitude (three subjects) to magnetic stimulation. —❑—: EMG; left; —◆— : EMG right.

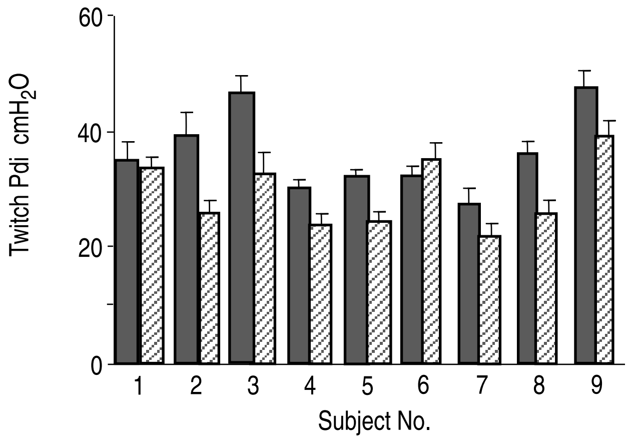


Fig. 5. – Mean twitch Pdi (+SD), electrical *versus* magnetic stimulation for nine subjects. ■: magnetic Pdi; ▨: electrical Pdi. Pdi: transdiaphragmatic pressure.

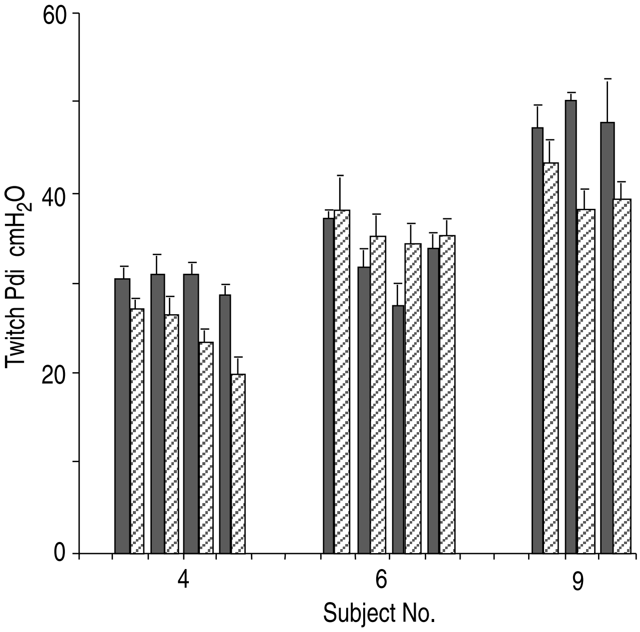


Fig. 6. – Reproducibility data for subjects Nos 4, 6 and 9. Each paired column represents mean Pdi (+SD) for electrical and magnetic stimulations on same day. ■: magnetic Pdi; ▨: electrical Pdi. Pdi: transdiaphragmatic pressure.

Table 1. – Comparison of maximal relaxation rate (MRR) from oesophageal (Poes) and transdiaphragmatic (Pdi) pressures using cervical magnetic stimulation and bilateral percutaneous electrical stimulation, in nine subjects

| | MRR % pressure loss·10 $ms^{-1}$ | | | |
|---|---|---|---|---|
| | Magnetic | | Electrical | |
| | Poes | Pdi | Poes | Pdi |
| Mean<br>range | 8.42<br>(6.5–9.5) | 7.04<br>(5.7–8.1) | 8.69<br>(6.6–10) | 7.94<br>(6.3–10.1) |
| Within occasion CV % | 10 | 9.5 | 12.3 | 12.4 |
| Between occasion CV % | 11 | 6.2 | 13.3 | 11.7 |

CV: coefficient of variation.

Between occasion CV was 6.6% for $Pdi_m$ and 8.8% for $Pdi_e$. The between occasion reproducibility of $Pdi_m$ and $Pdi_e$ is illustrated in figure 6.

MRR results, both from oesophageal and transdiaphragmatic pressures, are given in table 1. MRR could be measured satisfactorily from 84% of magnetic stimulations and 60% of electrical. There was no difference between techniques for Poes MRR or Pdi MRR.

## Discussion

In this study, the phrenic nerves were readily stimulated by electrical and magnetic stimulation, with magnetic stimulation producing a higher twitch Pdi. The magnetic technique was simple to perform and well-tolerated. The within occasion CV for twitch Pdi was the same for both techniques, and in agreement with other studies [1, 4, 6, 15]. Our results suggest the magnetic technique is less variable between occasions; CV 6.6% for $Pdi_m$ and 8.8% for $Pdi_e$; however, this difference was not statistically significant. To ensure that electrical stimulations were supramaximal, stimulus intensity was 20% above that producing both maximum Pdi and diaphragm EMG "M" wave amplitude.

There are several possible explanations why the Pdi response from magnetic stimulation was greater than that from supramaximal electrical stimulation. Firstly, neck flexion, required for the magnetic technique may have altered thoracoabdominal configuration [10, 11]. Whilst we were able to see a small increase in the anteroposterior (A-P) diameters of both the abdomen and chest, using linearized magnetometers, we were unable to demonstrate a change in lung volume at FRC, determined in separate studies using whole body plethysmography, with neck flexion. It is, therefore, unlikely that the altered configuration resulting from neck flexion accounted for the difference in Pdi between the two techniques [16].

A second, and perhaps more likely, explanation is that the magnetic technique is less specific and recruits other muscles that stabilize the upper rib cage during diaphragm contraction. In order to look for a gross difference in upper rib cage and abdominal movement between the techniques, we used a light source projected on to the subject, recording the shadow during contraction with a videorecorder. We were able to play back the recordings in slow motion. In four subjects studied in this way, the initial movement of the A-P abdominal diameter was to increase, whilst the A-P diameter of the upper rib cage decreased. There were no obvious differences between the two stimulation techniques. Similar configurational changes have been reported when pacing the diaphragm in C1 quadriplegics [17], whereas isolated contraction of the trapezius and sternocleidomastoid muscles results in an increase of the A-P diameter of the rib cage.

Although the sternomastoid muscle is stimulated with the electrical technique, it is evident that both arm and shoulder muscles are activated during magnetic stimulation. Analysis of the components of Pdi demonstrates that the oesophageal component is greater for magnetic stimulation, whilst there is no significant difference in gastric pressure between the two techniques. These findings support the view that magnetic stimulation is less specific and may splint the upper rib cage, reducing chest wall compliance and facilitating larger oesophageal and hence transdiaphragmatic pressures [18].

A third, but unlikely, possibility could be that magnetic and electrical stimulation produced different levels of excitation of the diaphragm. To investigate this, we analysed diaphragm EMGs during stimulation. In three subjects, bilateral surface diaphragm EMGs were recorded with a Digitimer D200 analyser during stimulation by both techniques. In each subject, results of rectified integrated EMGs were within 10%, and support the view that stimulation with 100% magnetic stimulator output achieves similar diaphragmatic excitation to that of supramaximal electrical stimulation.

The electrical twitch Pdi MRR in this study, (7.94) was similar to that (7.4) found by WILCOX *et al.* [13]. No significant difference was found between the magnetic and electrical MRR for twitch Poes and Pdi.

## Conclusion

Magnetic stimulation of the phrenic nerves appears safe, and is simple, effective and reproducible. It is well-tolerated by normal subjects. The conventional technique of electrical stimulation is frequently time-consuming, can be technically difficult, and at the high stimulus intensity necessary for supramaximal stimulation is sometimes poorly tolerated by patients. The magnetic technique may be less specific than its electrical counterpart, and this characteristic could make it a less sensitive index of the function of the diaphragm.

In the clinical situation, when diaphragm strength needs assessment, magnetic stimulation may allow diaphragmatic dysfunction to be distinguished from a poor response due to difficulty with electrical stimulation of the phrenic nerves. We achieved supramaximal stimulation in the subjects studied at 100% magnetic stimulator output. It is possible, that in some subjects the limited output of the stimulator may preclude supramaximal stimulation. However, technical progress with magnetic stimulators will undoubtedly result in more powerful machines. The ease with which reproducible responses can be achieved by magnetic stimulation may allow hitherto technically difficult sequential studies of diaphragm contractility to be undertaken both in the physiological and clinical arena. Whereas electrical stimulation, because it is more specific, may be well-suited to physiological studies, particularly in normal subjects, magnetic stimulation is better suited for clinical investigation and follow-up.

## References


1. Similowski T, Fleury B, Launois S, Cathala HP, Bouche P, Derenne JP. Cervical magnetic stimulation: a new painless method for bilateral phrenic nerve stimulation in conscious humans. *J Appl Physiol* 1989; 67: 1311–1318.
2. Barker AT, Freeston IL, Jalinous R, Jaratt JA. Magnetic stimulation of the human brain and peripheral nervous system: an introduction and the results of all initial clinical evaluation. *Neurosurgery* 1987; 20: 100–109.
3. Diehl JL, Lofaso F, Deleuze P, Similowski T, Lemaire F, Brochard L. Clinically relevant diaphragmatic dysfunction after open-heart surgery. *J Thorac Cardiovasc Surg* 1994; 107(2): 487–498.
4. Bellemare F, Bigland-Ritchie B. Assessment of human diaphragm strength and activation using phrenic nerve stimulation. *Respir Physiol* 1984; 58: 263–277.
5. Mier A, Brophy C, Moxham J, Green M. Twitch pressures in the assessment of diaphragm weakness. *Thorax* 1989; 44: 990–996.
6. Koulouris N, Mulvey DA, Laroche CM, Goldstone J, Moxham J, Green M. The effect of posture and abdominal binding on respiratory pressures. *Eur Respir J* 1989; 2: 961–965.
7. Baydur A, Pangiotis K, Behrakis K, Zin WA, Jaeger M, Milic-Emili J. A simple method of assessing the validity of the esophageal balloon technique. *Am Rev Respir Dis* 1982; 126: 788–791.
8. Agostoni E, Rahn H. Abdominal and thoracic pressures at different lung volumes. *J Appl Physiol* 1960; 15: 1087–1092.
9. Roussos C, Fixley M, Gross D, Macklem PT. Fatigue of inspiratory muscles and their synergistic behaviour. *J Appl Physiol: Respirat Environ Exercise Physiol* 1979; 46: 879–904.
10. Loring SH, Mead J, Griscom NT. Dependence of diaphragmatic length on lung volume and thoracoabdominal configuration. *J Appl Physiol* 1985; 59: 1961–1970.
11. Mead J, Milic-Emili J, Turner JM. Factors limiting depth of a maximal inspiration in human subjects. *J Appl Physiol* 1963; 18: 295–296.
12. Sarnoff SJ, Sarnoff LC, Whittenberger J. Electrophrenic respiration. VII. The motor point of the phrenic nerve in relation to external stimulation. *Surg Gynaecol Obstet* 1951; 93: 190–196.
13. Wilcox PG, Eisen A, Wiggs BJ, Pardy RL. Diaphragmatic relaxation rate after voluntary contractions and uni- and bilateral phrenic stimulation. *J Appl Physiol* 1988; 65: 675–682.
14. Wiles CM, Young A, Jones DA, Edwards RHT. Relaxation rate of constituent muscle-fibre types in human quadriceps. *Clin Sci* 1979; 56: 47–52.
15. Hubmayr RD, Litchy WJ, Gay PC, Nelson SB. Transdiaphragmatic twitch pressure: effects of lung volume and chest wall shape. *Am Rev Respir Dis* 1989; 139: 647–652.
16. Mier A, Brophy C, Moxham J, Green M. Influence of lung volume and rib cage configuration on transdiaphragmatic pressure during phrenic nerve stimulation in man. *Respir Physiol* 1990; 80: 193–202.
17. Danon J, Druz WS, Goldberg NB, Sharp JT. Function of the isolated paced diaphragm and the cervical accessory muscles in C1 quadriplegics. *Am Rev Respir Dis* 1979; 119: 909–919.
18. Nava S, Levy RD, Gibbons L, Bellemare F. Determinants of diaphragmatic response to bilateral phrenic nerve stimulation in man. *Am Rev Respir Dis* 1987; 135: A332.