special communication

Application of a cervical stimulating apparatus for bilateral transcutaneous phrenic nerve stimulation

PETER R. EASTWOOD, JANINE A. PANIZZA, DAVID R. HILLMAN, AND KEVIN E. FINUCANE
Department of Pulmonary Physiology, Sir Charles Gairdner Hospital, and Department of Human Movement, and University of Western Australia, Nedlands, Western Australia, 6009 Australia

Eastwood, Peter R., Janine A. Panizza, David R. Hillman, and Kevin E. Finucane. Application of a cervical stimulating apparatus for bilateral transcutaneous phrenic nerve stimulation. *J. Appl. Physiol.* 79(2): 632–637, 1995.—Transcutaneous bilateral phrenic nerve stimulation (tPNS) is frequently used to assess diaphragmatic function in humans. Commonly, stimulation is performed with hand-held electrodes; however, these are unsuitable for studies requiring repeated PNS and where recruitment of rib cage and neck muscles may shift the probes in relation to the nerves. In this study we describe the design of a cervical neck brace and electrode probes that maintain stimulating electrodes in constant position relative to the phrenic nerves and facilitates studies requiring repeated maximal PNS. The effectiveness of the apparatus was examined by *1)* reviewing the reproducibility of the transdiaphragmatic pressure response to 0.1 ms tPNS (PdiT) at relaxed functional residual capacity in four subjects studied on 25 ± 8 (SD) occasions (≥24 h apart) over a 4-yr period, and *2)* measuring peak-to-peak amplitude of the left and right diaphragmatic compound muscle action potentials (surface electrodes) during two prolonged studies (38 ± 9 min) in each subject, when tPNS was performed during repeated submaximal and maximal inspiratory efforts. PdiT was reproducible in each subject when measured repeatedly within a single study [coefficient of variation (CV) of 3.8 ± 0.8%] and over separate days (CV of 11.5 ± 3.5%). The peak-to-peak amplitudes of the left and right compound muscle action potentials were also reproducible (CV of 8.4 ± 4.3 and 8.4 ± 2.9%, respectively) and independent of the degree of effort. The apparatus appears effective for the maintenance of maximal stimulation under varied conditions for long periods and provides reproducible measurements of PdiT both within and between studies.

diaphragm; twitch; respiratory muscles; potentiation

SUPRAMAXIMAL phrenic nerve stimulation (PNS) has been used widely to assess the degree of activation of the human diaphragm during maximal and submaximal inspiratory efforts (3, 4, 9, 14, 20, 21, 29). Electrical stimulation using surface or subcutaneous (wire or needle) electrodes positioned close to the phrenic nerve is the most common method of stimulation, although in recent years cervical and cortical magnetic field stimulation has been extensively explored as an alternative (11, 12, 28).

Difficulties common to all of these methods include: optimal siting of the electrode or coil to maximize activation of the diaphragm and minimize stimulation of extra-diaphragmatic muscles, maintenance of a constant and maximal stimulus over a period of time, and minimizing discomfort to the subject. Potential hazards associated with the use of needle or fine wire electrodes include pneumothorax, soft tissue damage, and phrenic nerve injury (6, 30).

The most simple and widely available of these techniques is transcutaneous bilateral PNS (tPNS) with hand-held electrodes (3, 17, 19, 23, 24, 29); however, it is difficult to maintain stimulus maximality for other than short periods of time and repeated repositioning of the electrodes is required. For prolonged studies requiring repeated tPNS it is a substantial advantage to use a device that maintains the position of the stimulating electrodes constant relative to the phrenic nerves regardless of the type of inspiratory maneuvers involved. Gandevia and McKenzie (9) used a modified cervical collar for this purpose; however, this apparatus was cumbersome and access to the antero-lateral aspects of the neck was limited. Subsequently, we developed a cervical stimulating apparatus using a lightweight neck brace that allowed free access to the site of stimulation and easy readjustment between individuals. This apparatus has been used by us for over 4 yr to help determine the response of the diaphragm to supramaximal tPNS under a variety of experimental conditions including loaded breathing (7), hyperventilation (8), and submaximal and maximal inspiratory efforts (25, 26).

Although PNS has been in use for 10 yr since first introduced by Bellemare and Bigland-Ritchie (3), there has been no report of the reproducibility of data obtained during prolonged studies or of data in individual subjects during repeated studies over several years. In this paper we describe our cervical stimulating apparatus and evaluate its effectiveness by examining the reproducibility of data obtained with its use in four subjects studied repeatedly over 4 yr and, more specifically, by examining the reproducibility of diaphragm compound muscle action potentials (cMAPs) measured during relaxation and repeated submaximal and maximal inspiratory efforts in the same four subjects.

METHODS

Apparatus

Cervical brace. Two basic requirements for a brace suitable for tPNS are that the head and neck be comfortably but ade-

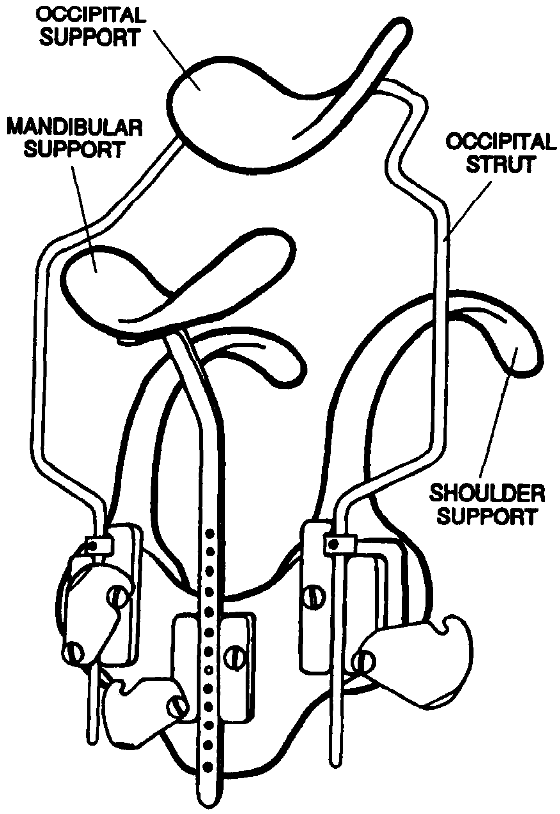

FIG. 1. Schematic diaphragm of modified cervical brace for bilateral transcutaneous phrenic nerve stimulation studies in humans.

quately immobilized and that either side of the neck be accessible for precise placement of the stimulating probes. A sterno-occipital mandibular immobilizing brace (model 8005, Camp International, Jackson, MI) was ideally suited to meet these demands (Fig. 1). The orthosis is comfortable and lightweight, being designed for long-term immobilization of the head and neck. Adjustable occipital and mandibular supports allow the head to be positioned in varying degrees of flexion or extension. Small diameter (6.4 mm) stabilizing struts allow free access to the neck at the site of the phrenic nerve (27). The struts to the occipital support provide a convenient anchor point for the electrode probes. The absence of fittings on the back of the brace allows studies to be performed with the subject standing, sitting, or supine while the head and neck remain fixed. The brace is easily readjusted for use in different individuals. Minor modifications were made to the brace: the struts to the occipital support were lengthened and widened to permit easier manipulation of the stimulating probe, and a 13-cm piece was removed from the inferior aspect of the sternal section to minimize any potential effect of this part of the brace on movement of the anterior rib cage. This had little effect on the stability of the entire brace.

3-Dimensional adjustment clamps. Purpose-designed clamps that held each stimulating probe in position were attached to the occipital struts of the brace (Department of Biophysics, Sir Charles Gairdner Hospital, Perth, Western Australia) (Fig. 2). These clamps allowed a wide range of movement of the stimulating probes in three planes.

Stimulating probes. The phrenic nerves are most accessible for transcutaneous stimulation at the posterior border of the sternomastoid muscle at the level of the cricoid cartilage (27). Optimal position of the electrodes is achieved by pushing and securing the probes sufficiently deeply into the skin to displace the posterior border of the sternomastoid anteriorly and to prevent the sternomastoid from moving dorsally beneath the probe during maximal inspiratory efforts.

Previous studies have used both unipolar (3, 9) and bipolar (17, 19, 23, 24) electrodes to transcutaneously stimulate the phrenic nerves. We tested both types of electrodes during a variety of inspiratory maneuvers and found that unipolar electrode probes (tip diameter 4.2 mm, cathode placed over the sternum) were uncomfortable, particularly when excessive pressure was developed over this small area of contact during strong inspiratory efforts, and that electrical stimulation was also felt at the cathode, which, although not painful, was irritating. These problems were eliminated by use of bipolar electrodes that were used throughout. The larger area of contact of the bipolar electrodes (2 felt pads 6.0-mm diameter and 2.3 cm apart) eliminated discomfort experienced with the unipolar probe. The bipolar electrodes eliminated independent cathode irritation and were made to fit the adjustment clamps and brace (Dept. of Biophysics, Sir Charles Gairdner Hospital). To avoid anode block the cathode was always closer to the clavicle than the anode (18). The bipolar stimulating probes were 13.5 cm long, the electrode end was curved to help displace the left and right sternomastoid muscles anteromedially and bring the electrodes into close approximation with the phrenic nerves where they travel over the anterior scalene muscles. The electrodes were mounted on a swivel to permit adjustment of the electrode head independently of the 3-dimensional adjustment clamp (Fig. 2).

Measurements, protocol, and analysis. During each study in which tPNS was used, continuous measurements were made of respired volumes with a pneumotachograph (Fleisch No. 2), rib cage, and abdominal motion by respiratory inductive plethysmography (Respitrace, Ardsley, NY), and esophageal (Pes) and gastric (Pg) pressure using 10-cm balloon catheters, placed in the middle one-third of the esophagus and stomach, respectively, coupled to differential pressure transducers (model PM131, Statham Instruments, Oxnard, CA). Transdiaphragmatic pressure (Pdi) was obtained by electrical subtraction (Pdi = Pg − Pes). The magnitude of change in Pdi with each momentary phrenic nerve stimulus (PdiT) was examined at high gain by using a sample-and-hold unit

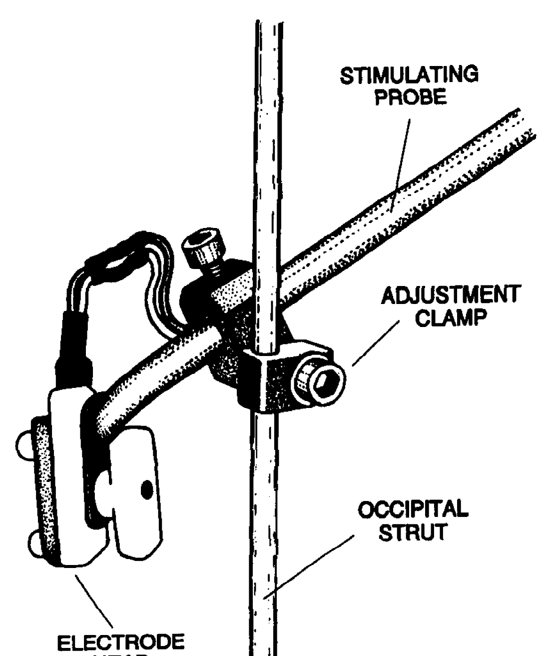

FIG. 2. Schematic diaphragm of 3-dimensional adjustment clamp and bipolar stimulating probe for bilateral transcutaneous phrenic nerve stimulation (setup is shown for stimulation of left phrenic nerve only).

(Dept. of Biophysics, Sir Charles Gairdner Hospital) similar to that designed by Hales and Gandevia (13). All signals were recorded continuously on a 12-channel direct writing polygraph (Grass Instruments, Quincy, MA).

The bipolar electrodes were attached to a dual output isolated stimulator (model S88, Grass Instruments) so that the phrenic nerves could be stimulated simultaneously. The stimulator was set to deliver a 0.1-ms square-wave pulse at a fixed time interval (e.g., 1 Hz) or was triggered manually. The left and right diaphragm electromyograms were recorded with two pairs of surface electrodes placed over the left and right 7th and 8th intercostal spaces. The diaphragm cMAPs produced with each stimulus were simultaneously displayed (10 ms/division) on a digital oscilloscope (model 5110, Tektronix, Beaverton, OR) using the impulse from the stimulator to trigger the oscilloscope.

At the beginning of each experiment the probes were positioned using 1-Hz stimulation with submaximal current and with the clamps loose; when the nerve was located, electrode position was adjusted to maximize both PdiT and cMAPs, optimize subject comfort, and minimize stimulation of the brachial plexus. The clamps were then tightened. Maximal stimulation was achieved by increasing the stimulus current through each electrode until there was no further increase in the amplitude of the cMAPs during relaxation at relaxed functional residual capacity (FRC) with the glottis closed. The current used was then increased by a further 10–20% to ensure supramaximal stimulation (in general, >10 mamps). The maximal cMAP for each hemidiaphragm was stored on the oscilloscope as a baseline for judging adequacy of each subsequent stimulus, the cMAPs of which were momentarily displayed on the oscilloscope, superimposed on the stored signals. During the course of a study, when a decrease in either the left or right cMAP was observed, indicating submaximal tPNS, the probe was immediately repositioned and maximal cMAP rapidly restored. While monitored on an oscilloscope during all studies, the left and right cMAPs were also continuously recorded in latter studies (see below) on a 486DX personal computer using a data-acquisition package (LabVIEW, National Instruments, Austin, TX) at a collection frequency of 6,000 Hz.

To evaluate the effectiveness and reproducibility of this method of tPNS in maintaining maximal stimulation before, during, and after maneuvers requiring submaximal and maximal inspiratory efforts, we examined two groups of data.

1) tPNS at relaxed FRC: reproducibility of repeated measurements of PdiT over 4 yr. The effectiveness of the cervical stimulating apparatus in providing reproducible measurements of PdiT at relaxed FRC was assessed by examining data from repeated measurements in four individuals obtained over a 4-yr period. All measurements were made after a minimum of 5 min of quiet breathing. On each occasion subjects were instructed to relax at FRC and close the glottis. The phrenic nerves were then stimulated three times, ~1 s apart. After a few breaths, tPNS was repeated.

The data from the four subjects, who were studied on 25 ± 8 separate occasions (≥24 h apart), were examined. PdiT was measured at relaxed FRC, under each of three conditions: *1*) seated, *2*) standing, or *3*) standing with a rigid abdominal cast moulded at relaxed FRC to minimize shortening of the diaphragm. Measurements under each condition were made on separate days with the exception of 4 ± 2 occasions in each subject when, on the same day, measurements were made standing both with and without an abdominal cast. On these occasions, sufficient time for recovery was allowed between the two conditions (>10 min). Measurements of PdiT while seated were unavailable in one subject as that subject was not in the related experiments (Table 1).

Five measurements were selected for analysis on each occasion. Selection was based on constancy of end-expiratory abdominal and rib cage configuration and end-expiratory Pes and Pg. The mean value of these measurements was calculated to represent the PdiT for a single day. The percent coefficient of variation (CV; 100 × SD/mean) was calculated for each set of measurements within a single day. The daily mean values of PdiT were used to calculate the between-day CV for all tests performed on each subject under the three conditions. The mean PdiT of each subject under each condition were compared using analysis of variance with sidak post hoc test, or unpaired *t*-tests.

2) tPNS before, during, and after graded inspiratory efforts: reproducibility of left and right cMAPs and effects on magnitude of PdiT. The effectiveness of the cervical stimulating apparatus in maintaining maximal tPNS during inspiratory efforts of varying intensity was determined prospectively in a separate study in which the reproducibility of left and right cMAPs was measured.

The same four subjects who had participated in the other studies were studied on two separate occasions ≥24 h apart. Subjects performed graded inspiratory efforts against a closed glottis (submaximal and maximal Mueller maneuvers) at usual FRC. During each effort subjects were instructed to achieve a target Pdi by activating the diaphragm and intercostal/accessory muscles while minimizing activity of the abdominal muscles. Pdi was displayed on a storage oscilloscope to the subject. The abdomen was enclosed in a rigid cast moulded at relaxed FRC.

At the beginning of each study several maximal Mueller maneuvers at relaxed FRC were performed to determine maximum Pdi (Pdi_{max}). Each maneuver was repeated until three reproducible efforts were obtained (within 5% of each other). Pdi_{max} was determined from the highest pressure recorded during these three efforts.

After ≥5 min of quiet breathing, baseline measurements of PdiT were obtained by performing tPNS between six and nine times at relaxed FRC. The subjects then performed sequences of Mueller maneuvers at each of 25, 50, 75, or 100% of Pdi_{max}. Each sequence involved between 10 and 14 successive efforts. Each effort was maintained for 2–5 s and was separated from the next effort by 30 s. In each subject the initial sequence required performance of maximal Mueller maneuvers (100% Pdi_{max}). The subsequent order of performance of the sequences of submaximal Mueller maneuvers was randomized. Two to 5 min of quiet breathing separated each sequence of efforts.

Throughout the study tPNS was performed at usual FRC immediately before each effort, during each effort at a time when Pdi was stable, and at usual FRC one breath after each effort. Immediately before commencement of each sequence of maximal or submaximal Mueller maneuvers, tPNS was performed between 6 and 9 times at relaxed FRC.

The amplitudes of the left and right cMAPs (peak-to-peak amplitude) and magnitude of PdiT were calculated from *1*) all artefact-free measurements obtained at relaxed FRC before each sequence of maneuvers and *2*) all artefact-free measurements obtained when tPNS was performed before, during, and after each individual inspiratory effort.

Individual measurements were rejected for analysis only if there was evidence of esophageal contraction just before or during initiation of the twitch, or if the cMAPs were affected by the electrocardiogram. CV was calculated for each set of measurements within a single day, and the means of each set of measurements were used to calculate the between-day CV for measurements at FRC and during graded inspiratory efforts. Results were compared using analysis of variance with sidak post hoc test or unpaired *t*-tests as appropriate.

TABLE 1. *Magnitude and variability of PdiT at Relaxed FRC*

Subject	Gender	Sitting, No Cast N	Sitting, No Cast Between days PdiT	Sitting, No Cast Between days CV	Sitting, No Cast Within-day CV	Standing, No Cast N	Standing, No Cast Between days PdiT	Standing, No Cast Between days CV	Standing, No Cast Within-day CV	Standing, With Cast N	Standing, With Cast Between days PdiT	Standing, With Cast Between days CV	Standing, With Cast Within-day CV
JP	F	19	22.4±3.6	16.1	3.5±1.5	7	21.0±2.0*	9.5	4.5±1.7	14	27.4±3.6	13.1	2.7±0.8
PE	M	15	28.1±3.1	11.0	3.5±1.6	4	27.8±2.9*	10.4	2.9±2.7	11	34.2±1.9	5.6	3.8±2.9
DH	M	13	21.1±2.2	10.4	3.3±1.5	6	20.4±3.1	15.2	4.3±1.3	9	22.3±1.9	8.5	4.7±2.9
KEF	M					5	20.5±1.9*	9.3	5.4±2.5	12	25.3±4.3	17.0	3.6±1.2
Mean			23.8±3.7	12.5±3.1	3.4±0.1		22.4±3.6	11.1±2.8	4.3±1.0		27.3±5.0	11.0±5.0	3.7±0.8

Magnitude (in cmH_2O) and percent coefficient of variation (CV) (100 × SD/mean) of 5 representative measurements of transdiaphragmatic twitch pressure (PdiT) from different testing days (N) over a 4-yr period (between days) and mean of CV values of the 5 measurements of PdiT from each day (within day). Values are means ± SD. Measurements were done with or without a rigid abdominal cast applied at relaxed functional residual capacity. * Significantly different compared with values from standing, with cast, $P < 0.05$.

RESULTS

1) tPNS at relaxed FRC: reproducibility of repeated measurements of PdiT over 4 yr. From January 1990 to March 1994, measurements of PdiT at relaxed FRC were obtained in four subjects on 25 ± 8 (SD) separate occasions (≥24 h apart) using the protocol outlined above. The magnitude and variability of PdiT developed under each condition of measurement is shown for each subject in Table 1. When abdominal displacement was unrestricted by a cast, PdiT was similar when sitting or standing. When standing, PdiT increased in three of the four subjects (22.4 ± 3.6 vs. 27.3 ± 5.0 cmH_2O, $P < 0.05$) with application of an abdominal cast. Regardless of the condition of measurement, PdiT obtained within a single day was highly reproducible in each individual (CV = 3.8 ± 0.8%). Measurements obtained on separate days were more variable (CV = 11.5 ± 3.5%).

2) tPNS before, during, and after graded inspiratory efforts: reproducibility of left and right cMAPs and effects on magnitude of PdiT. Throughout the course of each study (38 ± 9 min duration), the variability of left and right cMAP amplitudes were small when tPNS was performed at relaxed FRC before (CV = 6.4 ± 3.8 and 5.3 ± 3.3% for left and right cMAP amplitudes, respectively) or after each maneuver (6.6 ± 4.3 and 5.8 ± 3.6%, respectively). There were no systematic changes in left or right cMAP relative to baseline after each successive inspiratory effort. During inspiratory efforts, the variability of the amplitude of the left and right cMAPs with tPNS was small (CV = 8.4 ± 4.3 and 8.4 ± 2.9%, respectively) and independent of the intensity of inspiratory effort (Table 2). Generally, amplitudes of both the left and right cMAPs tended to be greater during inspiratory efforts than at relaxed FRC before each level of effort (mean increase of 7.0 ± 13.3 and 3.2 ± 20.7%, respectively), although these differences were not statistically significant.

In contrast to cMAP amplitudes, in each subject PdiT measured one breath after each effort of a sequence progressively increased and reached a plateau between one and four efforts after the initial effort. The degree to which PdiT increased was dependent on the intensity of inspiratory effort: little change in PdiT was observed after efforts requiring generation of 25 and 50% Pdi_{max} (2.4 ± 9.4% decrease and 7.5 ± 6.4% increase, respectively), but significant increases were observed after efforts of 75 and 100% Pdi_{max} (12.6 ± 4.0 and 20.5 ± 8.2%, respectively, $P < 0.05$). PdiT measured during efforts was also dependent on the degree of activation of the diaphragm, decreasing linearly with increasing Pdi in all subjects ($r = -0.91 \pm 0.03$, $P < 0.05$).

DISCUSSION

The cervical stimulating apparatus described in this study permits maximal tPNS to be maintained during prolonged studies involving submaximal and maximal inspiratory efforts, obviating the need for repeated relocation of the phrenic nerves. Results obtained with this apparatus are comparable to those from earlier studies using other techniques to stimulate the phrenic nerves. The magnitude of PdiT was similar to previously reported values during transcutaneous stimulation at relaxed FRC both with (3, 17) and without an abdominal cast (3, 17, 24, 29). Reproducibility of PdiT obtained at

TABLE 2. *Percent coefficient of variation of left and right cMAP amplitudes at relaxed FRC and during graded inspiratory efforts*

Subject	FRC	Degree of effort (% Pdimax) 25	50	75	100
		Left cMAP amplitudes			
JP	2.2±1.4	4.3±1.4	5.4±1.7	7.0±2.4	9.9±1.2
PE	5.6±4.6	18.4±5.7	9.7±2.1	13.3±1.9	14.5±4.3
DH	1.6±0.8	3.3±0.1	5.6±2.3	3.8±1.1	9.0±2.6
KEF	3.0±1.5	5.7±1.5	4.6±0.8	8.6±1.3	11.6±0.2
Mean	3.1±1.8	7.9±7.0	6.3±2.3	8.2±4.0	11.2±2.4
		Right cMAP amplitudes			
JP	1.5±1.1	8.8±3.2	12.1±3.4	9.5±2.9	11.5±4.5
PE	3.2±1.5	10.6±4.1	10.4±0.3	12.1±6.5	7.7±3.1
DH	1.8±0.8	2.3±0.7	6.5±2.8	4.7±0.5	5.2±0.6
KEF	1.9±1.1	7.9±1.0	8.3±1.6	6.2±2.9	11.5±4.9
Mean	2.1±0.8	7.4±3.6	9.3±2.4	8.1±3.3	9.0±3.1

Percent CV of left and right compound muscle action potential (cMAP) amplitudes during inspiratory efforts requiring generation of target proportion of maximum transdiaphragmatic pressure. Values are means ± SD from 2 separate studies on 4 subjects. Measurements were done with a rigid abdominal cast applied at relaxed functional residual capacity.

relaxed FRC in four subjects over 4 yr was similar to previously reported values in studies by using tPNS (17, 23, 24, 29) and fine wire (16), needle (2), and cervical magnetic (28) phrenic nerve stimulation, both within a single day (CV = 3.8 ± 0.8%) and between days (CV = 11.5 ± 3.5%).

tPNS is a simple benign technique that has several potential advantages over alternate methods. Inserting needle or fine wire electrodes subcutaneously (2, 14, 16, 20, 22) can be painful during both insertion and stimulation (22) and is associated with the potential dangers of soft tissue damage, sepsis, and nerve trauma (6, 30). Adequate positioning of needle electrodes relative to the phrenic nerves has been reported to require ≥1 h (14), although experience is said to reduce this considerably (D. K. McKenzie, personal communication). Cervical (28) and cortical magnetic stimulation (11, 12) of the phrenic nerves are relatively painless techniques. However, the magnetic pulse tends to produce a wide field of stimulation with coexistent contraction of the deltoid, trapezius, rhomboid, and sternomastoid muscles (28), and hence is a less specific stimulus to the phrenic nerves. Furthermore, contraction of other respiratory muscles can significantly influence the measurement of Pdi (5), complicating interpretation of PdiT obtained by this method.

The magnitude of PdiT elicited in response to momentary bilateral supramaximal PNS during diaphragmatic relaxation allows the presence or absence of fatigue to be determined (2, 4). Applied during diaphragmatic contraction, the magnitude of PdiT in response to this stimulus reflects the degree of diaphragmatic activation (3, 9). Over the past 4 yr, we have used our cervical stimulating apparatus to measure PdiT both at rest and during loaded inspiration for these purposes. Measurements have been made during progressive inspiratory threshold loading (7), progressive hyperventilation (8), and submaximal and maximal Mueller maneuvers (25, 26). For the results to be interpretable, it is essential that stimulus maximality be maintained (2, 4). As with these earlier studies, we used cMAP amplitude to monitor the intensity of nerve stimulation. A decrease in amplitude below the maximum established at the start of the experiment (see METHODS) was regarded as evidence of movement of the stimulating electrodes relative to the phrenic nerves with loss of maximal stimulation. In general, once the electrodes were adequately positioned at the start of each experiment, maximal stimulation was well maintained throughout studies both at FRC and during inspiratory efforts. Occasionally, during inspiratory efforts of greater than moderate degree, recruitment of neck muscles (principally the sternomastoid muscles) displaced the electrodes relative to the nerves, causing a decrease in cMAP. When this occurred, stimulus maximality was rapidly restored by repositioning the probe, suggesting that the decreased cMAP amplitude was not attributable to transmission fatigue (1). Careful positioning of the probes to minimize the leverage that the sternomastoids were able to exert on them largely obviated the problem, except in one well-muscled subject where threshold loads requiring repeated generation of inspiratory pressure in excess of 65% of maximum consistently displaced the electrode (7).

The effectiveness of the cervical stimulating apparatus in maintaining maximal stimulation of the phrenic nerves during repeated submaximal and maximal inspiratory efforts was specifically addressed in this study. The variability of cMAP amplitudes was small and independent of the inspiratory effort demonstrating the effectiveness of the apparatus in maintaining maximal stimulation during graded inspiratory efforts. In general, rather than decreasing, both left and right cMAP amplitudes obtained during inspiratory efforts tended to be greater than values obtained at relaxed FRC before each level of effort (mean increase of 7.0 ± 13.3 and 3.2 ± 20.7%, respectively). Possible explanations include an enlargement of the muscle fiber action potentials due to a transient increase in their resting membrane potential, a phenomenon that has been previously observed to occur during and after muscle activation (15), or that the diaphragm shortened during inspiratory efforts (even though the abdomen was enclosed in a rigid cast) with resultant artefactual augmentation of cMAP amplitude (10), or that stimulation of the phrenic nerves at rest was submaximal and contraction of the neck muscles during inspiratory efforts improved the position of the probes relative to the nerve. Of these possibilities, the latter is the least likely because the increase in cMAP amplitude was similar regardless of the Pdi achieved and degree of recruitment of neck muscles, and a similar increase in amplitude was observed during inspiratory efforts with the diaphragm alone, where contraction of neck muscles was negligible.

The cervical stimulating apparatus reported in this study provides an effective method for reproducibly stimulating the phrenic nerves under many conditions for long periods of time, it avoids the need for an investigator to hold the electrodes in place and obviates the necessity to constantly relocate the nerves. The technique is noninvasive, is associated with minimal subject discomfort, and is easy to apply. These properties make it a satisfactory method for both scientific and clinical investigation of diaphragmatic function in experienced or naive subjects.

Address for reprint requests: D. R. Hillman, Dept. of Pulmonary Physiology, Sir Charles Gairdner Hospital, Verdun St., Nedlands, Western Australia 6009, Australia.

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REFERENCES

1. **Aldrich, T. K.** Transmission fatigue of the rabbit diaphragm. *Respir. Physiol.* 69: 307–319, 1987.
2. **Aubier, M., D. Murciano, Y. Lecocguic, N. Viires, and R. Pariente.** Bilateral phrenic nerve stimulation: a simple technique to assess diaphragmatic fatigue in humans. *J. Appl. Physiol.* 58: 58–64, 1985.
3. **Bellemare, F., and B. Bigland-Ritchie.** Assessment of human diaphragm strength and activation using phrenic nerve stimulation. *Respir. Physiol.* 58: 263–277, 1984.
4. **Bellemare, F., and B. Bigland-Ritchie.** Central components of diaphragmatic fatigue assessed by phrenic nerve stimulation. *J. Appl. Physiol.* 62: 1307–1316, 1987.
5. **De Troyer, A., and M. Estenne.** Limitations of measurement of

transdiaphragmatic pressure in detecting diaphragm weakness. *Thorax* 36: 169–174, 1981.
6. **Drachler, D. H., G. H. Koepke, and J. G. Weg.** Phrenic nerve injury from subclavian vein catheterization: diagnosis by electromyography. *J. Am. Med. Assoc.* 236: 2880–2881, 1976.
7. **Eastwood, P. R., D. R. Hillman, and K. E. Finucane.** Ventilatory responses to inspiratory threshold loading and role of muscle fatigue in task failure. *J. Appl. Physiol.* 76: 185–195, 1994.
8. **Eastwood, P. R., D. R. Hillman, J. A. Panizza, and K. E. Finucane.** Hyperventilation: respiratory muscle recruitment under isocapnic and hypercapnic conditions. *Eur. Respir. J.* 6 *Suppl.*: 377S, 1993.
9. **Gandevia, S. C., and D. K. McKenzie.** Activation of the human diaphragm during maximal static efforts. *J. Physiol. Lond.* 367: 45–56, 1985.
10. **Gandevia, S. C., and D. K. McKenzie.** Human diaphragmatic EMG: changes with lung volume and posture during supramaximal phrenic stimulation. *J. Appl. Physiol.* 60: 1420–1428, 1986.
11. **Gandevia, S. C., and J. C. Rothwell.** Activation of the human diaphragm from the motor cortex. *J. Physiol. Lond.* 384: 109–118, 1987.
12. **Gea, J., J. M. Espadaler, R. Guiu, X. Aran, L. Seoane, and J. M. Broquetas.** Diaphragmatic activity induced by cortical stimulation: surface versus esophageal electrodes. *J. Appl. Physiol.* 74: 655–658, 1993.
13. **Hales, J. P., and S. C. Gandevia.** Assessment of maximal voluntary contraction with twitch interpolation: an instrument to measure twitch responses. *J. Neurosci. Methods* 25: 97–102, 1988.
14. **Hershenson, M. B., Y. Kikuchi, and S. H. Loring.** Relative strengths of the chest wall muscles. *J. Appl. Physiol.* 65: 852–862, 1988.
15. **Hicks, A., J. Fenton, S. Garner, and A. J. McComas.** M wave potentiation during and after muscle activity. *J. Appl. Physiol.* 66: 2606–2610, 1989.
16. **Hubmayr, R. D., W. J. Litchy, P. C. Gay, and S. B. Nelson.** Transdiaphragmatic twitch pressure: effects of lung volume and chest wall shape. *Am. Rev. Respir. Dis.* 139: 647–652, 1989.
17. **Koulouris, N., D. A. Mulvey, C. M. Laroche, J. Goldstone, J. Moxham, and M. Green.** The effect of posture and abdominal binding on respiratory pressures. *Eur. Respir. J.* 2: 961–965, 1989.
18. **Mannheimer, J. S., and G. N. Lampe.** *Clinical Transcutaneous Electrical Nerve Stimulation.* Philadelphia, PA: Davis, 1984.
19. **Markand, O. N., J. C. Kincaid, R. A. Pourmand, S. S. Moorthy, R. D. King, Y. Mahomed, and J. W. Brown.** Electrophysiologic evaluation of diaphragm by transcutaneous phrenic nerve stimulation. *Neurology* 34: 604–614, 1984.
20. **McKenzie, D. K., B. Bigland-Ritchie, R. B. Gorman, and S. C. Gandevia.** Central and peripheral fatigue of human diaphragm and limb muscles assessed by twitch interpolation. *J. Physiol. Lond.* 454: 643–656, 1992.
21. **McKenzie, D. K., B. L. Plassman, and S. C. Gandevia.** Maximal activation of the human diaphragm but not inspiratory intercostal muscles during static inspiratory efforts. *Neurosci. Lett.* 89: 63–68, 1988.
22. **Mier, A., and C. Brophy.** Measurement of twitch transdiaphragmatic pressure: surface versus needle electrode stimulation. *Thorax* 46: 669–670, 1991.
23. **Mier, A., C. Brophy, J. Moxham, and M. Green.** Twitch pressures in the assessment of diaphragm weakness. *Thorax* 44: 990–996, 1989.
24. **Mier, A., C. Brophy, J. Moxham, and M. Green.** Influence of lung volume and rib cage configuration on transdiaphragmatic pressure during phrenic nerve stimulation in man. *Respir. Physiol.* 80: 193–202, 1990.
25. **Panizza, J. A., K. E. Finucane, P. R. Eastwood, and D. R. Hillman.** Diaphragm lengthening effects transdiaphragmatic pressure and estimates of diaphragm strength using phrenic nerve stimulation. *Eur. Respir. J.* 6, *Suppl.*: 194S, 1993.
26. **Panizza, J. A., K. E. Finucane, P. R. Eastwood, D. R. Hillman, and R. A. O'Sullivan.** Estimating diaphragm strength from submaximal inspiratory efforts. *Proc. Ann. Sci. Meet. Thorac. Soc. Aust. N. Z.*, 1992.
27. **Sarnoff, S. J., L. C. Sarnoff, and J. L. Whittenberger.** Electrophrenic respiration VII. The motor point of the phrenic nerve in relation to external stimulation. *Surg. Gynecol. Obstet.* 93: 190–196, 1951.
28. **Similowski, T., B. Fleury, S. Launois, H. P. Cathala, P. Bouche, and J. P. Derenne.** Cervical magnetic stimulation: a new painless method for bilateral phrenic nerve stimulation in conscious humans. *J. Appl. Physiol.* 67: 1311–1318, 1989.
29. **Similowski, T., S. Yan, A. P. Gauthier, P. T. Macklem, and F. Bellemare.** Contractile properties of the human diaphragm during chronic hyperinflation. *New Eng. J. Med.* 325: 917–923, 1991.
30. **Vest, J. V., M. Pereira, and R. M. Senior.** Phrenic nerve injury associated with venipuncture of the internal jugular vein. *Chest* 78: 777–779, 1980.