Cervical magnetic stimulation as a method to discriminate between diaphragm and rib cage muscle fatigue

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Cervical magnetic stimulation as a method to discriminate between diaphragm and rib cage muscle fatigue. J. Appl. Physiol. 84(5): 1692-1700, 1998.—Inspiratory muscle fatigue can probably determine hypercapnic respiratory failure. Diaphragm fatigue is detected by electrical phrenic stimulation (ELS), but there is no simple tool to assess rib cage muscle (RCM) fatigue. Cervical magnetic stimulation (CMS) costimulates the phrenic nerves and RCM. We reasoned that changes in transdiaphragmatic pressure twitch (Pdi,tw) with CMS and ELS should be different after selective diaphragm vs. RCM fatigue. Five volunteers performed inspiratory resistive tasks while voluntarily uncoupling diaphragm and RCM. Baseline Pdi,twELS and Pdi,twSMS were 28.57 ± 1.68 and 32.83 ± 2.92 cmH2O. After selective diaphragm loading, Pdi,twELS and Pdi,twCMS were reduced by 39 and 26%, with comparable decreases in gastric pressure twitch (Pga,tw). Esophageal pressure twitch (Pes,tw) was better preserved with CMS. Therefore Pes,tw/Pga,tw was lower with ELS than CMS (−1.24 ± 0.16 vs. −1.73 ± 0.11, P = 0.05). After selective RCM loading, there was no diaphragm fatigue, but Pes,twCMS was significantly reduced (−30%). These findings support the role of rib cage stiffening by CMS-related RCM contraction in the ELS-CMS differences and suggest that CMS can be used to assess RCM fatigue.

EITHER INCREASED LOAD to the inspiratory muscles or their decreased performance is relevant to the pathophysiology of various respiratory disorders. When faced with an obligatory load that exceeds their capabilities, inspiratory muscles are susceptible to development of fatigue, resulting in structural damage that requires inspiratory muscle rest for recovery (20). This process is commonly accepted as one mechanism of hypercapnic respiratory failure and forms the basis of many therapeutic strategies aimed at resting or unloading the inspiratory muscles. The 1989 National Heart, Lung, and Blood Institute workshop on respiratory muscle fatigue (20) emphasized the relevance of studying inspiratory muscle fatigue. It stressed the value of using transdiaphragmatic pressure (Pdi) in response to bilateral supramaximal transcutaneous electrical stimulation of the phrenic nerve in the neck (ELS) to detect diaphragmatic fatigue in an objective nonvolitional manner. Although the diaphragm is the main agonist of inspiration, extradiaphragmatic inspiratory muscles acting on the rib cage (RC) (e.g., scalenes or sternomastoid muscles, henceforth termed rib cage muscles, RCM) can also be faced with increased loads and suffer fatigue (10, 17, 26). The clinical relevance of RCM fatigue has not been established, and yet the importance of RCM function is rapidly emerging from recently gathered data. In normal subjects during exercise, RCM and abdominal muscles seem to play a key role in generating pressures that displace the RC and abdomen, respectively, allowing the diaphragm to contract quasi-isotonically and act as a flow generator rather than as a pressure generator (1). In normal individuals faced with dynamic hyperinflation, the diaphragm is mainly used to overcome the corresponding intrinsic positive end-expiratory pressure (PEEP), whereas RCM provide a large part of the subsequent pressure needed to produce tidal volume (30). In chronic obstructive pulmonary disease (COPD) patients during incremental exercise, there is a progressive increase in the contribution of RCM to total inspiratory pressure, and again the diaphragm essentially serves to overcome PEEP (29). Hence it is highly likely that RCM fatigue can become a significant component of diseases in which diaphragm function is chronically impaired and the contribution of RCM to ventilation is increased. COPD (7, 11) and slowly progressing neuromuscular diseases associated with predominant diaphragm dysfunction, such as amyotrophic lateral sclerosis (2, 21), are examples of such disorders. Nevertheless, in contrast to the diaphragm, in which ELS can detect fatigue (3, 20), there is no easy-to-use, objective, nonvolitional test for RCM fatigue.

In the present investigation, we sought to take advantage of some of the characteristics of cervical magnetic stimulation (CMS) to devise such a tool. CMS was introduced a few years ago as a method for phrenic nerve stimulation (23). It provokes bilateral diaphragm contractions, probably through depolarization of both phrenic nerve trunks at the upper part of their mediastinal path (24). In contrast to ELS, CMS does not activate the diaphragm alone. It induces contractions in several muscle groups that act to stiffen the RC and increase esophageal pressure Twitches (Pes,tw), resulting in higher Pdi twitch (Pdi,tw) values (13, 22). We based our reasoning on these characteristics of CMS on the one hand and on a set of facts and predictions on the other hand as follows. With diaphragm fatigue, one expects Pdi,tw elicited by a stimulation specifically of the diaphragm (namely, ELS) to decrease with a proportionate reduction in gastric pressure Twitch (Pga,tw) and Pes,tw, whereas no changes are expected with RCM fatigue. If a stimulation technique involving the diaphragm and RCM (namely, CMS) is used, diaphragm fatigue should be associated with a disproportionately greater decrease in Pga,tw than in Pes,tw, because the action of RCM on the RC should be maintained. Con-
versely, RCM fatigue should not decrease Pga,tw, but it
should reduce Pes,tw, with a tendency for the gap
between Pes,tw,ELS and Pes,tw,CMS to close. We therefore
tried to isolate diaphragm and RCM fatigue induced by
an inspiratory resistive load by asking trained volun-
tees to breathe against the load while voluntarily
uncoupling the diaphragm and RCM (8). This volun-
tary uncoupling made it possible to load one set of
muscles alone.

MATERIALS AND METHODS

Subjects

Five healthy male volunteers (age 25–33 yr, height 172–
187 cm, and weight 68–85 kg) participated in the study after
ethical approval. All subjects were studied sitting in a chair
equipped with head rests and with their abdomens unbound.
They had been informed of the purpose of the study and the
methods used. Three subjects had previous experience with
respiratory muscle studies. All subjects had normal pulmo-

Methods

Pressures. Esophageal pressure (Pes) and gastric pressure
(Pgα) were measured with two balloon-tipped catheters
(thin-walled balloon sealed over a polyethylene catheter with distal
side holes, 60 cm length, 1.7 mm ID). The catheters were
connected to two Validyne MP45 differential pressure trans-
ducers (Validyne, Northridge, CA). Pdi was obtained on-line
by connecting the Pes and Pga catheters to a third transducer of
the same type. Pes and Pdi were continuously displayed to
the subjects on a Hewlett-Packard oscillograph.

Electromyograms (EMGs). Surface recordings of the right
and left costal diaphragmatic EMG (EMGdi) activity were
obtained using disposable silver cup electrodes taped to the
skin on the anterior axillary line in the sixth to eighth right
and left intercostal spaces. The position of the electrodes was
optimized for the raw EMG signal during quiet breathing as
well as for the response to ELS (see below). A similar pair of
electrodes was placed over the muscle mass of the right
sternomastoid muscle (EMGsm) at the level of the upper part
of the thyroid cartilage. It is likely that the electrodes detected
activity in both the sternomastoid and scalenes. It is also possible
that the electrodes picked up activity from the platysma.

EMG signals were amplified and band-pass filtered (band-
width 20 Hz–5 kHz; DISA amplifiers, Dantec, Copenhagen,
Denmark). EMGsm was rectified and integrated using a
leaky integrator with a 50-ms time constant. It was displayed
with Pes and Pdi on the Hewlett-Packard oscillograph
plotted in front of the subjects.

Stimulations. ELS was performed according to well-
established techniques (19). Square-wave shocks of 0.1-ms
duration and adjustable amplitude were delivered using a
pair of synchronized stimulators (Curamètre, Bio-Industrie,
Outreau, France). Both phrenic nerves were stimulated simul-
taneously at the posterior border of the sternocleidomastoid
muscle at the level of the cricoïd cartilage, using bipolar
electrodes with saline-soaked felt tips 5 mm in diameter and
having a 2-cm distance between electrodes. The right and left
phrenic nerves were first located using low current ELS, and
recruitment curves showing the amplitude of EMGdi
response (M wave) vs. stimulation intensity expressed in milli-
amperes were plotted to establish supramaximal stimulation.
The ELS intensity required to meet the criteria for suprama-
aximal stimulation ranged from 25 to 50 mA. To facilitate the
recovery of adequate stimulation throughout the study, the spots
were carefully marked on the skin using a permanent marker.

CMS was performed using a Magstim 200 stimulator
equipped with a doughnut-shaped 90-mm coil (SN 540113 B,
maximal output 2.5 T; Magstim, Whitland, Dyfed, UK) follow-
ing the previously reported technique (23, 24). Throughout
the experiments, extreme care was taken to minimize varia-
tions in the relative positions of the subject and stimulating
cal (see Ref. 24 for details). All stimulations were performed
with the output of the stimulator set at 100% of its maximal
possible intensity. To verify that this produced supramaximal
diaphragm activation, simplified recruitment curves were
built by comparing the amplitudes of bilateral M waves
obtained with 60, 90, 95, and 100% of the maximal output of
the stimulator (24) (Fig. 1). Supramaximal activation was
judged to be obtained in all subjects (Fig. 1).

All stimuli were delivered at end expiration with the glottis
closed to minimize the influence of lung volume on surface
EMGdi.

Procedures. Two fatiguing protocols (diaphragm protocol
and RCM protocol, see below) were used. All subjects were
studied on two separate occasions with several days interven-
ing, and with one of the two fatiguing protocols being
performed on each occasion.

TRAINING. Before each experiment, the subjects were given
enough time to learn how to generate Pdi without signifi-
cantly contracting inspiratory neck muscles (namely, while
keeping EMGsm silent as assessed by visual feedback on Pdi
and EMGsm; pattern 1, Fig. 2) and how to generate Pes
without contracting the diaphragm (namely, to produce Pes
swings without Pdi swings as assessed by visual feedback of
Pdi and Pgs; pattern 2, Fig. 2). Maximal static Pdi (Pdi,max)
and maximal static Pes (Pes,max) were determined using
patterns 1 and 2, respectively. Maximal contractions were
performed from functional residual capacity (FRC), against
an occluded airway, using standard criteria for the determina-
tion of maximal static pressures (static effort sustained at
least 1 s, 3 reproducible measurements).

STIMULATIONS IN RELAXED CONDITIONS. To preclude twitch
potentiation, the subjects were asked to breathe quietly and
to remain relaxed for 20 min (28). ELS and CMS were then
performed at relaxed FRC, with the glottis closed.

FATIGUE PROTOCOLS. The subjects were asked to breathe
through an inspiratory resistance placed on the inspiratory
line of a Hans Rudolph one-way valve (Hans Rudolph, Kansas
City, MO). Expiration was kept unloaded to avoid progressive
hyperinflation and therefore the interference of increasing
lung volume with the fatigue process (32). During the dia-
phragm fatigue protocol, the subjects were asked to produce
Pdi swings without activating EMGsm, with both signals
being continuously displayed on the oscilloscope. One investi-
gator monitored the adequacy of this maneuver and helped
the subject maintain it throughout the fatigue run. The inspira-
tory resistance was adjusted to enable the subjects to
attain a target Pdi,max previously determined using the same
maneuver. The subjects were instructed to maintain a constant Pdi
throughout inspiration (square-wave breathing pattern). No particular instruction
was given regarding the duration of inspiration or breathing
frequency. Task failure was defined as the inability of the
subject to maintain the 60% Pdi,max target without activat-
ing EMGsm for five consecutive breaths. For the RCM fatigue
protocol, the subjects were asked to produce Pes swings while
keeping the Pdi trace flat. This maneuver was also carefully
monitored to ensure adequate performance by the subject,
and palpation of the neck muscles was performed to detect

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contraction of the scalenes (respiratory pulse). A similar target (60% Pes,max) and similar criteria for task failure were used.

When the breathing pattern became suggestive of approaching task failure, one operator prepared the electrodes for ELS and superimposed a few stimuli on voluntary respiration to check the adequacy of stimulation by measuring M-wave amplitude. A second operator prepared the coil for CMS. Immediately after task failure, ELS and CMS were performed in rapid succession. This sequence was repeated five times, with systematic permutation of the order of application of the stimulation techniques. With this method, it took ~3 min to collect the corresponding information. This procedure was repeated after 30 and 60 min.

Data analysis. Pressure signals digitized at 500 Hz and EMG signals digitized at 2,000 Hz using a Data Translation DT 2801-A analog-to-digital board were stored in a personal computer. For each twitch, the amplitude of the corresponding M wave was first checked. Data were rejected if M-wave amplitude was below 90% of the amplitude measured at baseline before the fatiguing run or if there was evidence of

Fig. 1. Simplified 4-point recruitment curves built to verify supramaximal nature of diaphragm responses to cervical magnetic stimulation (CMS) before diaphragm fatigue protocol (A) and rib cage muscle (RCM) protocol (B). To harmonize scales between subjects, amplitudes of diaphragm M waves are expressed as percentages of amplitude measured after CMS using maximal output of stimulator. ○, Right hemidiaphragm; □, left hemidiaphragm. Amplitude of M waves recorded immediately after task failure is also shown on right.
contamination by an electrocardiogram complex. Data were also rejected if the Pes value immediately preceding the twitch suggested departure from relaxed FRC or if there was esophageal contraction. Three valid twitches were averaged for each stimulation technique at each analysis point (baseline, immediately after task failure, and subsequent points). The amplitudes of Pdi,tw, Pes,tw, and Pga,tw were measured from peak to baseline.

**Statistics**

Statistical analysis was performed using the software packages Statview and SuperAnova (Abacus Concept, Berkeley, CA) and an Apple Macintosh computer. All differences were assessed with a Fisher’s protected least square difference test after ANOVA for repeated measures. ANOVA was performed to compare the two stimulation techniques, the two fatigue protocols, and the pressure changes over time. The day-to-day reproducibility of each technique was assessed by comparing baseline values using cross-correlation analysis. Data in the results section are reported as means ± SE. Differences are considered significant at P < 0.05. NS indicates not significantly different.

**RESULTS**

**Baseline**

Under relaxed conditions at FRC, Pdi,twCMS was 32.83 ± 2.92 cmH2O, whereas Pdi,twELS was 28.57 ± 1.68 cmH2O (P = 0.030). This difference was entirely accounted for by a larger Pes,twCMS (Fig. 3). Pes,tw/Pdi,tw, an indicator of the inspiratory action of the stimulation-related diaphragm contraction, was 0.62 ± 0.01 and 0.59 ± 0.04 with CMS and ELS, respectively (NS, P = 0.089). Pes,tw/Pga,tw was −1.65 ± 0.04 vs. −1.44 ± 0.13 with CMS and ELS, respectively (NS, P = 0.115). There was no significant difference between the values observed on days 1 and 2.

**Diaphragm Fatigue Protocol**

All the subjects were able to perform the requested maneuver and to maintain it with a reasonably consistent pattern of inspiratory muscle activation until task failure. The time elapsed between the start of the run and the point at which the subject was no longer able to achieve the target pressure adequately (diaphragm endurance time) ranged from 18 to 43 min. Immediately after disconnection from the mouthpiece, Pdi,twELS was reduced, on average, by 39% and Pdi,twCMS was reduced by 26% (Fig. 4, top). Probably because of the limited number of observations, the magnitude of the reduction in Pdi,tw was not significantly different between the two techniques, but it was close to being so (P = 0.067). The reduction in Pga,tw was exactly the same with the two techniques (Fig. 4, bottom), but the reduction in Pes,tw was less marked with CMS than with ELS (average Pes,twELS immediately after fatigue 57% at baseline vs. 75% for Pdi,twCMS, P = 0.07; Fig. 4). Therefore Pes,tw/Pga,tw was much lower after the diaphragm fatigue protocol with ELS than with CMS (2 ± 0.16 and 2 ± 0.11, respectively, P = 0.05, vs. −1.44 ± 0.13 and −1.65 ± 0.04 at baseline, P = 0.115). The difference between Pes,twELS and Pes,twCMS after fatigue was slightly more pronounced than at baseline (Fig. 4, middle), but this variation was not statistically significant (3.64 ± 1.02 cmH2O before fatigue vs. 5.52 ± 0.87 cmH2O after, P = 0.282). The pattern of recovery over the 60 min after fatigue was similar with both techniques (Fig. 4) and consistent with the partial recovery data reported previously by Laghi et al. (12).

**RCM Fatigue Protocol**

One subject was unable to adequately coordinate his diaphragm and RCM and therefore to decrease Pes...
without increasing Pdi. The following results thus pertain to four subjects only. The RCM endurance time ranged from 11 to 22 min, ~50% shorter than the diaphragm endurance time. All subjects spontaneously mentioned that the RCM maneuver was much more difficult to achieve and much more uncomfortable than the diaphragm maneuver, as previously noted by Ward et al. (25). Immediately after the RCM fatigue protocol, Pes,twELS and Pga,twELS, and hence Pdi,twELS, were basically unchanged (Fig. 5), indicating the absence of diaphragm fatigue. This was also the case for Pga,twCMS. However, Pes,twCMS was significantly reduced compared with baseline values (−30 ± 4%, P = 0.032; Fig. 5, middle), resulting in a significant fall in Pdi,twCMS (33.60 ± 3.81 cmH₂O at baseline vs. 26.22 ± 2.59 cmH₂O immediately after task failure, P = 0.017; Fig. 5, top). Because of this selective decrease in Pes,twCMS, the characteristic ELS-CMS difference in Pes,tw was abolished immediately after task failure, and there was a dramatic decrease in Pes,twCMS/Pga,twCMS. With recovery, this difference reappeared and returned to the baseline value after a 60-min rest (Fig. 5, middle).

**DISCUSSION**

CMS is gaining popularity as a tool for clinical investigation. It is therefore important to fully evaluate how various factors can affect its results. With regard to inspiratory muscle fatigue, some investigators suggest that a fall in Pdi,twCMS after loading largely represents a change in diaphragmatic contractility (9, 13). Others suggest that both diaphragm and RCM fatigue may contribute to the observed changes (15, 16). In an attempt to resolve the issue, the present study specifically compares ELS and CMS after loading protocols that should clearly dissociate diaphragm and RCM fatigue (8). Our results confirm that CMS is able to detect diaphragm contractile fatigue in healthy human volunteers and suggest that task failure resulting from a load to RCM alone can also be associated with important changes in the pattern of pressure responses to CMS, even in the absence of diaphragm fatigue.

**Critique of Methods**

For our conclusions to be valid, we must be certain of the selectivity of the fatigue protocols employed. We therefore used a procedure very similar to that employed by Fitting et al. (8) to demonstrate dissociation between diaphragmatic and RCM fatigue. In their study, the imposed breathing pattern was tightly linked to EMG indexes of fatigue. When the subjects principally used their diaphragms to overcome the load, a decrease in the high-to-low frequency ratio (H/L) of EMGdi was noted in the absence of changes in the EMGsm H/L. When the subjects used RCM to overcome the load, the changes in H/L were reversed. Because we took particular care to monitor the pattern of muscle recruitment during the fatiguing tasks, we are confident that we achieved a satisfactory degree of selectivity. In addition, the fact that Pga,twELS decreased after the diaphragm fatigue protocol and did not change after the RCM fatigue protocol is indicative of selectivity. Nevertheless, we are aware that some degree of “cross-recruitment” may have been present but undetected in our protocols. This is particularly true for the diaphragm fatigue protocol in which the scalenes may have been slightly active despite a silent recording from the surface electrodes, or tonic contractions of neck muscles might have been overlooked because we used integrated rather than raw EMG signals for feedback. It is not likely, however, that such recruitment could have been sufficient to induce fatigue. During the RCM fatigue protocol, a passive Pdi could also have developed as a result of diaphragm stretching in response to the fall in abdominal pressure. We did not find evidence for such a phenomenon, and as before, it is not likely
that its magnitude, if present, could have been sufficient to induce fatigue.

Two additional methodological issues warrant a brief mention. First, it could be argued that potentiation influenced our measurements of Pdi,tw immediately after task failure (14, 28). To the best of our knowledge, potentiation of diaphragm twitches has been evidenced after nonfatiguing brief inspiratory maneuvers, and how it interferes with measurements performed after a fatiguing task remains unknown. The pattern of twitch potentiation is similar with ELS and CMS (14, 28), and there does not seem to be any particular reason to think that potentiation should affect the nature of the partitioning of Pdi,tw into Pes,tw and Pga,tw, thus forming the basis of our reasoning. Although twitch potentiation cannot be excluded in our study, we therefore feel that, if present, it would have little influence on our discussion. Second, Pes,tw and Pga,tw can be out of phase when measured with balloon-catheter systems, leading peak Pdi,tw measured from Pes-Pga subtraction to be lower than peak Pes,tw plus Pga,tw. In our study, the time lag between Pes,tw and Pga,tw was minimal, as can be the case in normal subjects and when pressure measuring devices with high-frequency responses are used. Nevertheless, we express and discuss our results in terms of Pes,tw/Pga,tw and avoid relating Pes,tw or Pga,tw to Pdi,tw.

Mechanism for Differences Between Pdi,twCMS and Pdi,twELS

At baseline, Pdi,twCMS was larger than Pdi,twELS (mean difference 4.3 cmH\textsubscript{2}O, \(P = 0.030\)), with the difference being due to a larger Pes,tw CMS (Fig. 3) as
previously reported (13, 16, 22, 27). The mechanism for the difference between Pdi,tw_CM and Pdi,tw_ELS is presently believed to be the consequence of rib cage stiffening by prior RCM contraction during CMS. With ELS, the diaphragm is theoretically the only muscle contracting. It therefore interacts with a relaxed, highly distensible RC cage, resulting in a “paradoxical” inward motion of the upper rib cage. By contrast, in addition to the diaphragm, the sternomastoid, scalenes, parasternal, trapezius, and pectoralis muscles are also activated by CMS (13, 23). The CMS-induced contraction of these muscles modifies the characteristics of the rib cage and improves the transformation of diaphragm force into negative pleural pressure. As a result, the amplitude of electrical activation. The absence of control of the strength of RCM contractions and not their degree of electrical activation. The absence of control of the strategy of inspiratory muscle fatigue during which there is no change in the relationship of the magnetic field with the stimulated structures (24) and because the gap between Pes,tw_ELS and Pes,tw_CM closed only after the RCM fatigue protocol, we are confident that what changed was actually the strength of RCM contractions and not their degree of electrical activation. The absence of control of the supramaximal nature of RCM activation is currently a limit to a precise and reproducible quantification of RCM fatigue, but it does not affect the ability of the technique to detect it.

Pdi,tw_CM Reduction After RCM Fatigue Protocol

Impaired contractility of the diaphragm is not likely to be the cause of the reduction in Pdi,tw_CM with RCM fatigue, since there are no changes in Pdi,tw_ELS or Pga,tw_CM (Fig. 5). Increased lung volume, which would have reduced RCM efficiency (4), was probably also not an important factor, since we took care to keep expiration unloaded and thus to limit the risk of dynamic hyperinflation in these healthy subjects. In addition, twitches were retained for analysis only if the immediately preceding Pes value corresponded to the FRC value. Finally, there is no particular reason to think that the degree of electrical activation of RCM by CMS should have been different after the RCM fatigue protocol than after the diaphragm fatigue protocol. Therefore, given the key role of CMS in the Pdi,tw_ELS-Pdi,tw_CM difference, we strongly believe that the decrease in Pes,tw_CM after the RCM fatiguing protocol was due to impairment of RCM action on the rib cage, namely, RCM fatigue.

Detection of Diaphragm Fatigue with CMS

After the diaphragm fatigue protocol, Pdi,tw_ELS and Pga,tw_ELS were both reduced, leading to a 40% reduction in Pdi,tw_CM and indicating fatigue of the diaphragm. This is supported by the close similarity between the changes in Pga,tw_CM and Pga,tw_ELS with fatigue. It therefore follows that diaphragm fatigue can affect the results of CMS, with the pattern of changes in the Pes and Pga component being different from the case of RCM fatigue.

Relevance and Perspectives

As stated in the introduction, RCM are probably of major importance in various situations. During exercise, they predominantly generate pressures to take charge of RC expansion, whereas the diaphragm predominantly generates flow (1). During hyperinflation, they predominantly produce inspiratory tidal volume, whereas the diaphragm predominantly overcomes the elastic load (29, 30). In the presence of diaphragm fatigue, they are capable of spelling the diaphragm to maintain the ventilatory adaptation to CO2 (31). When there is chronic diaphragm dysfunction, their activity and strength can be increased probably as a compensatory mechanism (2, 7). It logically follows that RCM fatigue or weakness can theoretically be responsible for failure to maintain ventilation or to adapt ventilation to an increased demand. In this view, the ability of CMS to identify RCM fatigue appears relevant and could find many pathophysiological applications.

In the clinical setting, however, selective loading of inspiratory muscle groups is not the rule, and the problem is more partitioning global inspiratory muscle fatigue into its diaphragm and RCM components than diagnosing RCM fatigue per se. We submit, speculatively, that this could be made possible using CMS. Indeed, the results presented in Figs. 4 and 5 can be summarized as follows: 1) diaphragm fatigue is associated with a smaller decrease in Pes,tw_CM than in Pes,tw_ELS, with the reduction in Pga,tw being similar with the two techniques; and 2) RCM fatigue is associated with a dramatic decrease in Pes,tw_CM without significant change in Pga,tw_CM. In the context of global inspiratory muscle fatigue during which there is no particular control of the strategy of inspiratory muscle use, these results would suggest that 1) a reduction in Pga,tw_CM is indicative of the diaphragmatic contribution to task failure; 2) a reduction in Pdi,tw_CM without
a major change in Pes,twCMS/Pga,twCMS is suggestive of predominant diaphragm fatigue; 3) a reduction in Pdi,twCMS with a decrease in Pes,twCMS/Pga,twCMS is associated with predominant RCM fatigue, of which maintenance of Pga,twCMS is highly characteristic; and 4) global inspiratory muscle fatigue should reduce Pdi,twCMS in association with decreases in both Pga,twCMS and Pes,twCMS/Pga,twCMS.

This set of propositions is consistent with results of several studies of CMS in inspiratory loading protocols in which no particular attempt was made to dissociate the diaphragm and RCM. After inspiratory threshold loading resulting in little, if any, diaphragm fatigue (Pdi,twELS reduced by 8%), Mador et al. (16) observed a reduction in Pdi,twCMS largely resulting from a reduction in Pes,twCMS, a pattern very close to the one observed in this study after RCM fatigue. After voluntary hyperpnea (15), the same group observed various patterns of Pdi,tw reduction with a good correlation between the pattern of Pdi,tw reduction and the pattern of breathing adopted during the fatiguing task. Those subjects who had a predominant RCM recruitment tended to have a greater fall in Pdi,twCMS than in Pdi,twELS. Those subjects who mostly recruited the diaphragm tended to have a greater fall in Pdi,twELS than in Pdi,twCMS. In a study by Hamnegard et al. (9), isocapnic maximal ventilation decreased Pdi,twCMS while preserving Pes,tw/Pgaw, suggesting diaphragm fatigue in these subjects. Finally, in an inspiratory resistive breathing study by Laghi et al. (13), in which the subjects were asked to produce a negative mouth pressure until they became unable to do so no matter what inspiratory muscles they used, task failure was associated with a Pdi,twELS more decreased than Pdi,twCMS. Pes,twELS/Pga,twELS was reduced, and small changes in Pes,twCMS/Pga,twCMS were observed. Although from the protocol design it is not possible to deny that global fatigue could have occurred, we submit from the analysis of our own study that the subjects of Laghi et al. (13) experienced predominant diaphragm fatigue, despite the fact that they did recruit their RCM during the fatiguing task.

In conclusion, we feel that this study validates two hypotheses previously made by other investigators: namely, that CMS is valuable to detect diaphragm fatigue despite its lack of specificity for diaphragm activation (13) and that CMS can provide information regarding the relative roles of diaphragm and RCM fatigue in inspiratory task failure (16). The comparison of ELS and CMS before and after an inspiratory muscle fatiguing task (or, in reverse, after a period of inspiratory muscle unloading) could be a useful tool to diagnose RCM fatigue and perhaps to partition global inspiratory muscle fatigue into its diaphragm and RCM components. Although more data collection is warranted, we propose that, if only CMS is used to investigate the mechanisms of inspiratory task failure, careful analysis of the pattern of reduction in Pdi,twCMS (presence or absence of a reduction in Pga,twCMS, Pes/Pga) should allow the investigator to make reasonable assumptions regarding the respective contributions of diaphragm and RCM fatigue to task failure. CMS might then provide a simple means to investigate and follow up global inspiratory muscle fatigue.

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