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

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Similowski, Thomas, Christian Straus, Valérie Attali, Alexandre Duguet, and Jean-Philippe Derenne. 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,twCMS 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.

respiratory muscles; phrenic nerve stimulation

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 volunteers to breathe against the load while voluntarily uncoupling the diaphragm and RCM (8). This voluntary 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 pulmonary function.

**Methods**

**Pressures.** Esophageal pressure (Pes) and gastric pressure (Pga) 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 transducers (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 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. A similar pair of electrodes was placed over the muscle mass of the right and left 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 (bandwidth 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 together with Pes and Pdi on the Hewlett-Packard oscillograph placed 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-Industry, Outeau, France). Both phrenic nerves were stimulated simultaneously at the posterior border of the sternocleidomastoid muscle at the level of the cricoide 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 milliamperes were plotted to establish supramaximal stimulation. The ELS intensity required to meet the criteria for supramaximal 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 (S/N S40113 B, maximal output 2.5 T; Magstim, Whitland, Dyfed, UK) following the previously reported technique (23, 24). Throughout the experiments, extreme care was taken to minimize variations in the relative positions of the subject and stimulating coil (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 endexpiration 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 intervening, 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 significantly 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 Pga; 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 determination 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). Inspiration was kept unloaded to avoid progressive hyperinflation and therefore the interference of increasing lung volume with the fatigue process (32). During the diaphragm fatigue protocol, the subjects were asked to produce Pdi swings without activating EMGsm, with both signals being continuously displayed on the oscilloscope. One investigator monitored the adequacy of this maneuver and helped the subject maintain it throughout the fatiguing run. The inspiratory resistance was adjusted to enable the subjects to attain easily, with each breath, 60% of the 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 activating 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
contraction of the scalenes (respiratory pulse). A similar target (60% P_{es,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
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, tw \(_{CMS} \) was 32.83 ± 2.92 cmH\(_2\)O, whereas Pdi, tw \(_{ELS} \) was 28.57 ± 1.68 cmH\(_2\)O (\( P = 0.030 \)). This difference was entirely accounted for by a larger Pes, tw \(_{CMS} \) (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, tw \(_{ELS} \) was reduced, on average, by 39% and Pdi, tw \(_{CMS} \) 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, tw \(_{ELS} \) immediately after fatigue 57% at baseline vs. 75% for Pdi, tw \(_{CMS} \), \( P = 0.07 \); Fig. 4).

Therefore Pes, tw/Pga, tw was much lower when CMS was employed than when ELS was used (average Pes, tw \(_{ELS} \) at baseline vs. 2.12 ± 0.16 and 2.17 ± 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, tw \(_{ELS} \) and Pes, tw \(_{CMS} \) after fatigue was slightly more pronounced than at baseline (Fig. 4, middle), but this variation was not statistically significant (3.64 ± 1.02 cmH\(_2\)O after fatigue vs. 5.52 ± 0.87 cmH\(_2\)O 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,tw\textsubscript{CMS} and Pdi,tw\textsubscript{ELS}**

At baseline, Pdi,tw\textsubscript{CMS} was larger than Pdi,tw\textsubscript{ELS} (mean difference 4.3 cmH₂O, \(P = 0.030\)), with the difference being due to a larger Pes,tw CMS (Fig. 3) as
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and its time course is slower (22). Also, the $P_{di,tw ELS}$- $P_{di,tw CMS}$ into negative pleural pressure. As a result, the amplitude cage and improves the transformation of diaphragm force 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 the CMS-related RC deflation is smaller than with ELS, and its time course is slower (22). Also, the $P_{di,tw ELS}$-$P_{di,tw CMS}$ difference is decreased at high lung volumes (13), in line with increased impedance to RC expansion (6) or decreased efficiency of the CMS-stimulated RCM (4). The decreased difference between $P_{es,tw ELS}$ and $P_{es,tw CMS}$ at the end of the RC fatigue protocol in this study provides strong support for the above hypothesis.

The fact that this difference was completely abolished and not merely reduced is somewhat surprising, but it has to be kept in mind that, contrary to the diaphragm, CMS may not provide supramaximal RCM stimulation. Inframaximal RCM stimulation could very well be sufficient to explain a $P_{es,tw CMS}$-$P_{es,tw ELS}$ difference when RCM are fresh but not when they are fatigued. Given the number of muscles activated, it would be very difficult (if at all possible) to demonstrate that all of them are or are not supramaximally activated. This is probably not a major issue regarding our reasoning, to the extent that CMS-related diaphragm contractions were supramaximal both before and after the diaphragm and the RCM fatigue protocols (Fig. 1).

A change in CMS twitch pressure must then be due to a factor influencing the $P_{di}$ output independent of its degree of electrical activation, in the present case the action of RCM on the rib cage. Because we took very strict precautions to avoid any change in the relationship of the magnetic field with the stimulated structures (24) and because the gap between $P_{es,tw ELS}$ and $P_{es,tw CMS}$ 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.

$P_{di,tw CMS}$ Reduction After RCM Fatigue Protocol

Impaired contractility of the diaphragm is not likely to be the cause of the reduction in $P_{di,tw CMS}$ with RCM fatigue, since there are no changes in $P_{di,tw ELS}$ or $P_{ga,tw CMS}$ (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 $P_{es}$ 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 RCM in the $P_{di,tw ELS}$-$P_{di,tw CMS}$ difference, we strongly believe that the decrease in $P_{es,tw CMS}$ after the RCM fatigue 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, $P_{di,tw ELS}$ and $P_{ga,tw ELS}$ were both reduced, leading to a 40% reduction in $P_{di,tw CMS}$ and indicating fatigue of the diaphragm. This is supported by the close similarity between the changes in $P_{ga,tw CMS}$ and $P_{ga,tw ELS}$ with fatigue. It therefore follows that diaphragm fatigue can affect the results of CMS, with the pattern of changes in the $P_{es}$ and $P_{ga}$ 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 $P_{es,tw CMS}$ than in $P_{es,tw ELS}$, with the reduction in $P_{ga,tw}$ being similar with the two techniques; and 2) RCM fatigue is associated with a dramatic decrease in $P_{es,tw CMS}$ without significant change in $P_{ga,tw CMS}$. 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 $P_{ga,tw CMS}$ is indicative of the diaphragmatic contribution to task failure; 2) a reduction in $P_{di,tw CMS}$ without
a major change in $\text{P}_{\text{es}, \text{twCMS}}/\text{P}_{\text{ga}, \text{twCMS}}$ is suggestive of predominant diaphragm fatigue; 3) a reduction in $\text{P}_{\text{di}, \text{twCMS}}$ with a decrease in $\text{P}_{\text{es}, \text{twCMS}}/\text{P}_{\text{ga}, \text{twCMS}}$ is associated with predominant RCM fatigue, of which maintenance of $\text{P}_{\text{ga}, \text{twCMS}}$ is highly characteristic; and 4) global inspiratory muscle fatigue should reduce $\text{P}_{\text{di}, \text{twCMS}}$ in association with decreases in both $\text{P}_{\text{ga}, \text{twCMS}}$ and $\text{P}_{\text{es}, \text{twCMS}}/\text{P}_{\text{ga}, \text{twCMS}}$.

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 ($\text{P}_{\text{di}, \text{twELS}}$ reduced by 8%), Mador et al. (16) observed a reduction in $\text{P}_{\text{di}, \text{twCMS}}$ largely resulting from a reduction in $\text{P}_{\text{es}, \text{twCMS}}$, 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 $\text{P}_{\text{di}, \text{tw}}$ reduction with a good correlation between the pattern of $\text{P}_{\text{di}, \text{tw}}$ 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 $\text{P}_{\text{di}, \text{twCMS}}$ than in $\text{P}_{\text{di}, \text{twELS}}$. Those subjects who mostly recruited the diaphragm tended to have a greater fall in $\text{P}_{\text{di}, \text{twELS}}$ than in $\text{P}_{\text{di}, \text{twCMS}}$. In a study by Hamneggard et al. (9), isocapnic maximal ventilation decreased $\text{P}_{\text{di}, \text{twCMS}}$ while preserving $\text{P}_{\text{es}, \text{tw}}/\text{P}_{\text{ga}, \text{tw}}$, 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 $\text{P}_{\text{di}, \text{twELS}}$ more decreased than $\text{P}_{\text{di}, \text{twCMS}}$. $\text{P}_{\text{es}, \text{twELS}}/\text{P}_{\text{ga}, \text{twELS}}$ was reduced, and small changes in $\text{P}_{\text{es}, \text{twCMS}}/\text{P}_{\text{ga}, \text{twCMS}}$ 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 $\text{P}_{\text{di}, \text{twCMS}}$ (presence or absence of a reduction in $\text{P}_{\text{ga}, \text{twCMS}}$, $\text{P}_{\text{es}}/\text{P}_{\text{ga}}$) 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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