Assessment of Abdominal Muscle Contractility, Strength, and Fatigue

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We evaluated abdominal muscle contractility and fatigue by measuring twitch gastric pressure (Pga_t) after percutaneous supramaximal electrical stimulation of the abdominal wall before and after sit-ups to task failure. Mouth pressures during maximal voluntary expulsive maneuvers (Pmax) at TLC and FRC with superimposed twitches, and maximum voluntary ventilation (MVV) were also assessed. Mean fresh Pga, was 36.1 ± 3.0 cm H₂O with a coefficient of variation that ranged between 3.0 to 4.8%. Pga decreased by 25% (p < 0.001) and 37% (p < 0.001) at 1 and 30 min after sit-ups. During maximal voluntary contraction twitch occlusion never occurred. Pmax at TLC and FRC decreased by 15% (p < 0.001) and 11% (p < 0.017) at 1 min, and 8% (p < 0.036) and 9% (p < 0.030) at 30 min after sit-ups, respectively. Despite the abdominal muscle fatigue, MVV values at 1 and 30 min after sit-ups were not significantly different from the value obtained before the sit-ups. We conclude that (1) Pga is a useful objective indicator of abdominal muscle contractility and fatigue; (2) during maximal voluntary expulsive maneuvers the abdominal muscles are never fully activated; (3) sit-ups lead to substantial low-frequency fatigue but little high-frequency fatigue of the abdominal muscles, which has little effect on maximal breathing capacity. Suzuki J, Tanaka R, Yan S, Chen R, Macklem PT, Kayser B. Assessment of abdominal muscle contractility, strength, and fatigue.

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The abdominal muscles are the principal expiratory muscles. Whereas at rest they are silent or nearly so, they immediately start contributing to ventilation when ventilatory requirements increase during exercise (1), CO₂ rebreathing (2, 3), and during inspiratory (3, 4) or expiratory (5) loading. Patients with chronic obstructive pulmonary disease often contract the abdominal muscles during expiration even at rest (6). But, in contrast to a vast literature concerning the inspiratory muscles, very little is known about the physiology of the expiratory muscles. Like the diaphragm (7) the expiratory muscles may fatigue under load, causing the capacity for developing force to decrease with potentially an impact on performance. Expiratory muscle fatigue has been produced in healthy subjects breathing through an expiratory resistance (8). However, the loss of force was quantified by maximal voluntary expiratory mouth pressure (Pmax) in which central fatigue may have contributed an unknown amount. To overcome this problem one should override volition by stimulating the abdominal wall directly with surface electrodes. Magnetic stimulation of the efferent spinal nerves was recently reported to be a potentially useful technique (9), and although submaximal surface stimulation is possible (10) no data exist on direct supramaximal electrical stimulation of the abdominal wall.

We therefore decided to develop a technique of percutaneous electrical stimulation of the abdominal wall. A abdominal muscle strength was evaluated by twitch gastric pressure with supramaximal stimulation (Pga_t). To assess the effect of fatiguing exercise on abdominal muscle contractility, muscle fatigue was induced by sit-ups until task failure. A s a functional assessment of the effect of decreased abdominal muscle contractility we measured maximum voluntary ventilation (MVV).

METHODS

Subjects

The experiments were performed in six healthy male subjects (35 ± 2 yr of age, 1.75 ± 0.04 m, 66 ± 4 kg). The study was approved by the Ethics Committee of the Montreal Chest Institute, and written informed consent was obtained from all subjects.

Pressures and Chest Wall Configuration

The measurements were done with the subjects in a fixed seated position. Esophageal (Pes) and gastric (Pga) pressures were measured using two conventional balloon catheters connected to pressure transducers (Fujikura FPM-02PG; Servoflo, Lexington, MA). Transdiaphragmatic pressure (Pdi) was obtained as Pga – Pes.

A direct current-coupled respiratory inductive plethysmograph (Resitrace; Resitrace Corp., A.dsley, N Y) was used to monitor changes in chest wall configuration. Because we wished to document
the changes in configuration of the abdomen relative to the lower rib cage, the upper band was placed on the lower rib cage below the nipple, and the abdominal band was placed at the level of umbilicus.

**Stimulation**

Two pairs of large (4.6 × 8.9 cm) autoadhesive surface stimulation electrodes (VERSA-STIM 651-1842; Conmed Corp., Utica, NY) were applied to the abdominal wall, each pair between the lateral edge of the sheath of the rectus abdominis muscle and the midaxillary line on each side of the abdominal wall (see Figure 1). Because the rectus abdominis is less important for expiration than the other abdominal muscles (3, 11) and since in pilot experiments we found that additional electrodes over the recti did not increase Pga, we chose not to place electrodes over these muscles. The electrodes were connected in series to a constant current stimulator (D 57-H; Digitimer Ltd., Welwyn Garden City, U.K.) to make stimulus intensity independent of changes of electrode impedance during the experiment. The stimulating pulse was a single square wave of 0.05 ms in duration and the stimulus intensity ranged from 0.1 to 1 A in steps of 0.1 A. In order to quantify possible effects of an inadvertent detachment of electrodes during an experiment we gradually reduced electrode surface by cutting away increasingly larger parts during a pilot experiment. Because of the constant current, 20 to 40% of the total electrode surface could be taken away before any significant reduction in Pga, occurred. Moreover, since the electrodes are very adhesive, we never found any significant detachment excluding this as a confounding variable during the actual experimental protocols.

**Twitch Gastric Pressure**

When the abdominal wall was stimulated during relaxation against an expiratory resistance from TCL to FRC, the first several Pgas had the same amplitude, after which Pga decreased gradually (see Figure 2). This indicates that the optimal length of the stimulated muscles in the relaxation configuration is close to TLC. We therefore chose to monitor changes in Pga, by stimulating at TLC while the subjects relaxed with the glottis closed in all experiments. The subjects trained to relax at TLC before the actual experiment. Consistency of Pga, Pes, and R espirator tracings and zero Pdi confirmed relaxation. In addition, the point of relaxation at TLC on a Konno-Mead diagram (relating abdominal circumference [A B] to lower rib cage circumference [R C]) (12) was on or close to the relaxation line (see Figure 4).

While the subject relaxed at TLC the stimulus current required to elicit a maximal Pga, was established by progressively increasing stimulus current (Figure 3). To measure twitch characteristics we chose a final stimulus intensity at least one level higher than necessary to elicit maximal Pga. Subsequently, seven to eight stimulations were done for one relaxation at TLC. Two successful tests per subject were performed for the control measurement prior to the fatigue protocol and one for all other sessions. The average Pga amplitude of each test was used for the data analysis.

**Twitch Potentiation and Pressure-Frequency Relationship**

On a different occasion, in order to quantify a possible confounding effect of twitch potentiation (13), Pga was measured before and at 1, 2, 5, 10, and 15 min after three Pmax maneuvers (see below) in five subjects. The order of measurements and the interval among the measurements after sit-ups in the experimental protocol were based on the results from the twitch potentiation protocol.

In addition, short trains of supramaximal stimulations at 10, 20, 50, and 100 Hz were applied in an attempt to compare the proportion of muscle activation during maximal voluntary expulsive maneuvers and supramaximal tetanic abdominal wall stimulation. Because these tetanic stimulations were painful and therefore very difficult to endure we could obtain results in only two subjects by keeping the duration of the stimulation trains short (~0.2 s).

**Maximal Voluntary Expiratory and Inspiratory Mouth Pressures**

Maximal voluntary expiratory and inspiratory mouth pressures (Pmax and Pmax) were measured with a pressure transducer (Fujikura FPM-02PG) using a mouthpiece with a small leak to prevent glottic closure (14). Pmax was measured at TLC and FRC, and Pmax was measured during a maximal inspiratory effort against a closed airway (Mueller maneuver) at FRC. The subjects supported their cheeks with their hands during both maneuvers, and they were given strong verbal encouragement to give maximal effort. The measurements were repeated until three similar values sustained for longer than 1 s were obtained, and the highest value thus obtained is reported. During all voluntary expulsive maneuvers superimposed twitches were applied to the abdominal wall in order to assess the activation level of the muscles.

**Maximum Voluntary Ventilation**

A airflow at the mouth was measured with a heated pneumotachograph (Fleisch No. 3; Fleisch, Lausanne, Switzerland) and a differential pressure transducer (Fujikura FPM-02PG). Volume was measured by integration of flow. A written instruction on how to perform MVV (frequency > 60 min⁻¹ with a large tidal volume), the subjects did a maximal ventilatory effort for 15 s manually supporting the mouth.

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**Figure 1.** The attachment of the surface stimulation electrodes on the anterolateral abdominal wall. Note that the middle part of the abdominal wall was not stimulated directly.

**Figure 2.** Changes in Pga and lung volume with the supramaximal twitch abdominal wall stimulation during relaxation from TLC by the quasi-static method. The subject held a mouthpiece connected to a two-way valve, which had a small hole on the expiratory port, and relaxed with the glottis open after deep inspiration. The stimulus intensity was 0.9 A and the duration was 0.05 ms.
To A. (0.1) usles current intensity, which was progressively increased from 0.1 to 1 A. (0.3) artifacts. The ordinates are in arbitrary units.

Because the EMG needles were positioned very near the stimulation electrodes a big stimulation artifact was observed on top of which the M-waves appeared 2 to 10 ms after the onset of the artifacts. The ordinates are in arbitrary units.

**Figure 3.** (Top panel) The relationship between Pga and the stimulus current intensity, which was progressively increased from 0.1 to 1 A. (Bottom panel) The relationship between the stimulus current intensity and the M-waves (the evoked muscle compound action potentials) of the four abdominal muscles (rectus abdominis muscle [Rectus], external oblique [External] and internal oblique [Internal] muscles, and transversus abdominis muscle [Transv]). Because the EMG needles were positioned very near the stimulation electrodes a big stimulation artifact was observed on top of which the M-waves appeared 2 to 10 ms after the onset of the artifacts. The ordinates are in arbitrary units.

**Twitch Transdiaphragmatic Pressure**

In order to document any fatiguing effect of the sit-ups (see below) on the diaphragm, percutaneous bilateral phrenic nerve stimulation was performed with two handheld cathodes applied to the skin over the phrenic nerves on the neck (16). Two electrode pads were placed on the clavicles The stimulating site and orientation of the cathodes were adjusted by maximizing the M-waves and minimizing stimulation of the brachial plexus. The stimulus current was subsequently progressively increased until no further increase in M-wave amplitude occurred Thereafter, a 20 to 30% greater current was used to stimulate throughout all tests while monitoring the constancy of the M-waves. In the event of decrease in M-waves the measurement was discarded and repeated. Ten stimulations were performed during each relaxation at FRC and the average Pdi of each run is reported. Five of the six subjects were studied because it was technically impossible to obtain Pdi in one subject.

**Sit-ups**

Sit-ups were selected to induce abdominal muscle fatigue. The subjects lay on their backs on mattresses with their hips flexed and legs bent as much as possible at the knees and their hands folded behind their heads. The position of the legs minimized the use of muscles attaching to the femurs, particularly the iliopsoas muscles, putting more load on the abdominal muscles. The subject’s feet were held down on the floor during the sit-ups. The sit-ups had to be performed touching the lateral side of the knee with lateral side of the contralateral elbow in a crossover fashion. This rolling action was chosen to increase the activation of all abdominal muscles, particularly the obliques, other than the rectus abdominis. The subjects performed 20 sit-ups during a 2-min period. If they finished before the 2 min were up, they rested for the time remaining in the period. These 2-min periods were repeated until task failure despite strong verbal encouragement. A 15-min period was attempted to confirm it. Two subjects could not perform two full periods i.e. 40 sit-ups. They were subsequently assisted by a helper slightly pushing on their backs in order to attain a minimum of four repetitions sufficient to induce overt abdominal muscle fatigue.

**Experimental Protocol**

Control Pdi, Pga, Pmax (at TLC and FRC), Pmax (at FRC), and MVV were measured in this order. The subjects then rested for 10 min. Subsequently the sit-ups were performed. After the sit-ups Pdi was measured at 10 and 30 min, and Pga, Pmax, and Pmax were measured at 1, 10, and 30 min after the end of the sit-ups. MVV was measured at 1 and 30 min after the end of the sit-ups. The measurements after sit-ups were done in the same order as the control measurement. On a different day, Pga was measured in three subjects before and at 10 min after sham lying down for the same duration as sitting up but without exercise) to confirm the reproducibility of Pga.

**Electromyogram Study**

In order to document muscle activity pattern during the stimulation as compared with sit-ups we acquired the abdominal electromyogram (EMG) in two subjects. Four pairs of fine-wire electrodes coated by polyurethane with a diameter of 0.1 mm were inserted into each of the four abdominal muscles (the rectus abdominis, the external and internal obliques, and the transversus abdominis on the right side) by using the method described by Abe and colleagues (11). They were implanted about 10 mm apart along the axis of the fiber bundles of the
four muscles through a 23-gauge needle using high-resolution ultrasound echography (DRF-400; Diasonics Inc., M Iipitas, CA), which allowed easy insertion under direct vision. The sites of insertion for the rectus, the external and internal obliques, and the transversus were 2 cm to the right of umbilicus, 2 cm above the level of umbilicus in the right midclavicular line, the level of umbilicus in the right midclavicular line, and 1 cm below the right costal margin in the anterior axillary line, respectively. A bout 1 mm of the wire was bent backwards from the needle tip allowing firm fixation in the muscle tissue after the guide needle was removed and the wires were then firmly taped to the abdominal wall. The EMG signals were amplified, passed through a band-pass filter of 16 to 800 Hz, and monitored on a screen (Model TE42; TECA). Because the EMG activity of each muscle was different during different maneuvers correct electrode placement was confirmed by supine head flexion, isometric trunk rotation, and gradual hyperpnea. Particularly during gradual hyperpnea, EMG activity of the transversus was observed first and that of the rectus last. Furthermore, a gradual decrease of expiratory EMG activity of the expiratory muscles during the early phase of inspiration (postexpiratory expiratory activity) was clearly recognized for the internal oblique and for the transversus during this maneuver (11, 17). Subsequently the surface stimulation was performed from 0.1 to 1 A to obtain the relationship between Pga, and M-wave amplitude of each abdominal muscle. The subjects then performed a series of sit-ups to quantify the task-specific abdominal muscle use.

**Data Analysis**

All data were recorded on a PC at a sampling frequency of 2,000 Hz for the EMG and of 500 Hz for the other measurements.

The number of twitches and the coefficient of variation of Pga, are expressed as mean ± SD (Table 1). The other data are reported as mean ± SEM. Values were compared by paired t test, Wilcoxon’s signed rank test or one-way repeated measures analysis of variance (ANOVA) when appropriate. A p < 0.05 was considered statistically significant.

**RESULTS**

All subjects could easily endure the twitch stimulation of the abdominal wall, and they rated the discomfort comparable to that of phrenic nerve stimulation. By contrast, the tetanic stimulation induced severe discomfort and could be endured by two subjects only.

Typical recordings of Pga, and of four abdominal muscle EMGs during the twitch abdominal wall stimulation as obtained by increasing the stimulus current intensity progressively from 0.1 to 1 A are shown in Figure 3. At first, Pga, increased linearly with stimulus intensity and then reached a plateau at 0.8 A. Supramaximality of the stimulation was thus confirmed by Pga, A iso, M waves of all four muscles appeared on top of the stimulation artifacts and reached plateaus at the same current intensity; this was so for the recti even though the stimulation electrodes were not directly placed over them. A verage supramaximal current intensity used in the study amounted to 0.9 ± 0.03 A.

![Figure 4](image-url) Figure 4. Typical recording of Pga, Pes, and Pdi during supramaximal abdominal wall stimulation at TLC with the subject relaxing against a closed glottis (top panel), and its corresponding Konno-Mead diagram (abdominal circumference [AB] versus lower rib cage circumference [RC]) (bottom panel). Because Pdi just after deep inspiration to TLC was not stable, the first Pga, was not taken into account in the data analysis in this measurement. When upper RC was used instead of lower RC, the line during the stimulation was up and to the left as usually observed on an isovolume curve (not shown).

Typical recordings of Pga, Pes, and Pdi during supramaximal twitch abdominal wall stimulation, along with the chest wall configuration, are shown in Figure 4. The baselines of the three pressures remained constant. The fact that the baseline of Pdi between the stimulations was the same as that at FRC indicated good relaxation at TLC. Similarly, after inspiration to TLC the subject relaxed stretching his abdominal muscles as evidenced by the large displacement of AB to the right. Mean individual, fresh Pga, was 36.1 ± 3.0 cm H2O. The coefficients of variation of Pga, (expressed as standard deviation over mean value multiplied by 100) were 3.0 ± 2.1 to 4.8 ± 2.0%, averaging 3.9 ± 1.8% combining all data (see Table 1). This was smaller than the coefficient of variation of Pdi, (6.6 ± 3.2%).

During the twitch potentiation studies after three Pmax maneuvers Pga, increased by 44% (p = 0.006) at 1 min, by 36% (p = 0.005) at 2 min, and returned to control levels in all subjects at 10 min after Pmax (Figure 5).

The rise in Pga, as obtained by the short trains of supramaximal stimulations at TLC and its corresponding pressure-frequency curve in one subject, is shown in Figure 6. Because the trains were short, Pga did not reach a plateau, particularly during low-frequency stimulation. Neither did the pressure-
frequency curve. Thus, it is likely that longer stimulation at a higher frequency would have led to even higher pressures. Because measured voluntary $P_{\text{E}}_{\text{max}}$ at TLC of this subject was 185 cm H$_2$O, and the rise in Pga at 100 Hz was 186 cm H$_2$O, 100% of $P_{\text{E}}_{\text{max}}$ was reached, evidencing a recruitment during the stimulation as great, if not greater, than during the voluntary maneuvers.

During sit-ups Pga swings reached ~100 cm H$_2$O (Figure 7). The EMG showed activation of all four abdominal muscles during both lying down and sitting up. The average number of sit-ups the subjects performed was 86 ± 20.

After the sit-ups Pga decreased by 25% at 1 min ($p < 0.001$) and by 37% at 30 min ($p < 0.001$) after sit-ups (Figure 8). There was a significant difference of Pga between 1 min and 10 min ($p = 0.004$) or 30 min ($p = 0.010$) after the sit-ups, likely caused by twitch potentiation induced during the sit-ups. After the sham protocol (no sit-ups while supine for the same duration as during the sit-ups) Pga values were not different from control values (34.2 ± 3.0 and 36.2 ± 2.5 cm H$_2$O, respectively).

Mean individual, fresh $P_{\text{E}}_{\text{max}}$ at TLC and FRC were 185 ± 12 and 144 ± 14 cm H$_2$O. After the sit-ups $P_{\text{E}}_{\text{max}}$ at TLC and FRC decreased by 15% ($p < 0.001$) and 11% ($p = 0.017$) at 1 min, and by 8% ($p = 0.036$) and 9% ($p = 0.030$) at 30 min, respectively (Figure 9). During maximal voluntary expulsive maneuvers in all subjects, in all circumstances superimposed stimulation never led to twitch occlusion, indicating submaximal activation of the abdominal wall.

Figure 5. The effect of maximal voluntary expulsive maneuvers on Pga (twitch potentiation [a transient augmentation of twitch tension after a vigorous muscular contraction]) (n = 5, mean ± SEM). *$p < 0.05$, **$p < 0.01$, different from the control value.

Figure 6. Changes in Pga by the short trains of supramaximal stimulation of the abdominal wall and its pressure-frequency curve in one subject. 1 Hz means a single twitch. Because these stimulations were strong and painful, they had to be kept short (~0.2 s). The number of the stimulations at 10, 20, 50, and 100 Hz was thus 3, 3, 7, and 16, respectively.

Figure 7. Pga and EMGs of four abdominal muscles during sit-ups. The EMG clearly showed activation of all four muscles during sitting up, and Pga swings reached 100 cm H$_2$O. There was also activity when lying down after sitting up, indicating eccentric muscle activity. The duration of one sit-up was 2 to 3 s. Expiration was performed during sitting up, and inspiration was after sitting up.

Figure 8. The pressure-frequency curve of the abdominal wall muscles during volitional voluntary expulsive maneuvers and short supramaximal stimulation. The pressure-frequency curve was determined in a subject during voluntary expulsive maneuvers and short supramaximal stimulation. The mean of the pressure-frequency curve was determined in one subject during voluntary expulsive maneuvers and short supramaximal stimulation.
Mean fresh MVV was 177 ± 13 L/min and 105 ± 6% of predicted value (18). MVV tended to be lower after the sit-ups (-4% at 1 min \( p = 0.094 \) and -2% at 30 min \( p = 0.438 \)), but the effect was not statistically significant (Figure 10). During the MVV maneuvers breathing pattern parameters such as frequency, tidal volume, mean expiratory flow, and duty cycle were not changed after the sit-ups.

Pdi decreased by 8% at 10 min \( p = 0.317 \) and by 17% at 30 min \( p = 0.008 \) after sit-ups (Figure 11), whereas Pimax at FRC remained unchanged.

**DISCUSSION**

**Main Findings**

The primary aim of this study was to develop an objective method to quantify abdominal muscle contractility, strength, and fatigue. We showed that twitch gastric pressure by percutaneous supramaximal electrical stimulation of the abdominal wall (Pgat) can indeed be used to measure contractility. As such it seems a good objective indicator of abdominal muscle strength and it is sensitive to low-frequency fatigue of abdominal muscles. Respiratory muscle fatigue (19) may play a role in acute respiratory failure (20) but most studies of respiratory muscle fatigue have concentrated on the inspiratory muscles (7, 21, 22). The sit-ups successfully induced abdominal muscle fatigue as well as some diaphragmatic fatigue, but, interestingly, this had an insignificant effect on maximal breathing capacity.

If abdominal muscles have a lot of reserve during breathing this would explain why fatigue did not influence breathing frequency, tidal volume, mean expiratory flow, and duty cycle during MVV. Because expiratory flow becomes limited at expiratory muscle pressures that are a small fraction of those available, it would take considerably greater fatigue than we

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**Figure 8.** Changes in Pgat (closed circles) and twitch Pes (open circles) by supramaximal abdominal wall stimulation (n = 6, mean ± SEM). Twitch Pes was quite parallel to Pgat. Control (open square). ***p < 0.001, different from control; †p < 0.05, ††p < 0.01, different from the value at 1 min after sit-ups.

**Figure 9.** Changes in Pimax at TLC (closed circles) and FRC (open circles) after sit-ups (n = 6, mean ± SEM). Pimax tended to recover. Control (open square). ***p < 0.001, *p < 0.05, different from control.

**Figure 10.** MVV at 1 min (left panel) and 30 min (right panel) after sit-ups compared with control (circle, individual values; square, average value) (n = 6, mean ± SEM).
produced to decrease flow below that limited by dynamic airway compression. Although 2 min of sustained MVV may produce abdominal muscle fatigue (9), abdominal muscle fatigue does not decrease MVV. Similarly, exercise can lead to inspiratory muscle fatigue (23), but inspiratory muscle fatigue has only minimal effects on ventilatory control and exercise performance (24, 25).

**Superimposed Twitches**

A critical corollary finding of this study is the observation that during the maximal voluntary expulsive maneuvers PEmax always showed a small increase with superimposed twitches. It follows that the abdominal muscles are never fully activated during such contractions, even in strongly encouraged, young, healthy, trained, and motivated subjects.

A possible explanation for lack of full activation of abdominal muscles during expulsive efforts is that their strength is much greater than that of rib cage expiratory muscles. We speculate that during a PEmax maneuver the force of the abdominal muscles during expulsive efforts is that their strength is much greater than that of rib cage expiratory muscles. We speculate that during a PEmax maneuver the force of the abdominal muscles matches that of the intercostals in order to prevent eccentric contraction.

**Abdominal Muscle Function and Fatigue**

Recent research has indicated that the contribution of the expiratory muscles to breathing is more important than originally thought and that, apart from their obvious role during expiration, they may also play a role during inspiration as accessory muscles (17, 26). The abdominal muscles are recruited at the onset of even minimal exercise; their contribution increases progressively as exercise power increases; they reduce end-expiratory lung volume in exercise, and their gradual relaxation during inspiration minimizes rib cage distortion and unloads the diaphragm, permitting it to act as a flow rather than as a pressure generator (27). Expiratory muscle activity is increased and prolonged in patients with airflow limitation (6), during CO2 rebreathing (2, 3), or during inspiratory loaded breathing (3, 4). Their recruitment preserves the ventilatory response to CO2 and exercise performance after inspiratory muscle fatigue (22, 26). The abdominal muscles not only play a role in respiration but are also postural muscles that move the trunk, protect the abdominal contents, and increase abdominal pressure necessary for vomiting, defecation, and parturition.

Like other respiratory muscles, abdominal muscles are potentially subject to fatigue (8). We tried many ways to fatigue them, but not other muscles, before we decided to use sit-ups with a rolling motion with hips flexed and knees bent. This loaded all four muscles and caused large Pga swings (Figure 7). The sit-up protocol was the best we found to produce substantial fatigue of the abdominal muscles, while minimizing the impact on other muscles. Although Pdi decreased, indicating mild diaphragmatic fatigue, Pmax was unaffected.

**Technical Considerations**

Athough there are several indirect methods to assess muscle fatigue, by definition (28) the best and the most direct method to quantify a fall in force and/or velocity of contraction. Measuring maximal muscle force can be done by maximal voluntary contraction or by stimulating supramaximally. In the former, an unknown central factor potentially introduces bias. Supramaximal stimulation overrides the subject’s volitional control and therefore measures peripheral fatigue directly. Furthermore, this technique can identify central fatigue and transmission failure (25). Twitch Pdi resulting from phrenic nerve stimulation has become the gold standard for the evaluation of diaphragmatic fatigue. Because it may not be feasible to stimulate the nerves to a muscle, the muscle itself is often stimulated percutaneously (29–31). This is thought to activate the muscle through nerve endings since, similar to isolated muscle preparations, high intensities or long stimulus durations are required (32). Thus, percutaneous stimulation requires much higher intensity than the motor point stimulation (33).

Mier and colleagues (10) percutaneously stimulated the rectus abdominis and the external oblique separately. Because they were mainly interested in describing the mechanical action of the various abdominal muscles on the rib cage they used submaximal tetanic stimulation and made no attempt to describe the contractile properties. Gandevia and colleagues (34) stimulated the abdominal wall with large plate electrodes to examine the transmission of pressure across the passive and active diaphragm. Recently, magnetic twitch stimulation of the nerve roots supplying the abdominal muscles was reported (9). Although this may be a good evaluation method, the stimulation was not supramaximal and the stimulation site had to be found for every measurement, hence inducing potential reproducibility bias. As far as we are aware, ours is the first study to electrically stimulate the abdominal muscles supramaximally, percutaneously, to assess their contractility. We
stimulated all four abdominal muscles bilaterally with two pairs of electrodes at the same time. All four are supplied by the same ventral branches of the lower six thoracic nerves and/or the first lumbar nerve (35). We attached the stimulation electrodes (Figure 1) so that all four muscles would be activated maximally and simultaneously, including the recti, though the electrodes were not placed over it. Supramaximality was achieved since there were plateaus in Pga and M-waves of the four abdominal muscles as a function of intensity (Figure 3). The fact that we could reach $\approx 100\%$ of PEmax in two subjects with a short stimulation train at 100 Hz, without full tetanization (Figure 6) indicates that activation was greater than during the PEmax maneuver. A third, in which we cannot fully exclude that some portions of the muscles may not have been reached, we are confident our stimulation method assesses contractility of the four muscles as a whole.

Because it is impossible to measure human respiratory muscle force in vivo, pressure is measured instead. We thus evaluated the abdominal muscles with Pga. Because the muscles shortened with contraction the relationship between pressure and force may not have been linear. Nevertheless pressures are universally accepted as the output of the respiratory muscles since ventilation is generated by transpulmonary pressure. We thus believe that the present method provides the best available estimate of in vivo human abdominal muscle contractility.

Low- and High-Frequency Fatigue

High-frequency fatigue of the diaphragm Pdi, normally recovers in 30 min (36). We did not observe any recovery of Pga, however (Figure 8). There was, in contrast, a tendency to recover PEmax, Pga, was still reduced 6 h after sit-ups in one subject, though PEmax had returned to the control value by 3 h. Similarly, after expiratory loaded breathing PEmax gradually recovered from the initial decline (8). If PEmax is a measure of high-frequency fatigue and Pga is that of low-frequency fatigue, then sit-ups led to significant low-frequency but little high-frequency abdominal muscle fatigue. Because low-frequency fatigue lasts longer than 24 h and because it is the predominant type of fatigue that was induced in these experiments, we conclude that the appropriate way to measure it is by Pga, rather than by PEmax.

Twitch Potentiation

Twitch potentiation of Pga after PEmax maneuvers was universal. The maximal increase in twitch amplitude averaged $44 \pm 9\%$ of control at 1 min after three PEmax maneuvers, and it gradually diminished and disappeared by 10 min. Mador and colleagues (13) reported twitch potentiation in Pdi, after Pdi was induced that disappeared after sustained expiratory breaths on the second day. Similarly, in our study, Pga measurement in the first minute and the Pga measurement in the tenth minute after the end of sit-ups, it is unlikely that the Pga max maneuver affected the Pga measurement or that the PEmax maneuver affected the Pga measurement. By contrast, it is likely that twitch potentiation induced by the strong contractions of the abdominal muscles during the sit-ups explains why Pga in the first minute after sit-ups was significantly higher than Pga, at 10 and 30 min (p = 0.004 and p = 0.010, respectively). It has been reported that changes in calcium ion release or myosin phosphorylation after vigorous muscular contraction may cause twitch amplitude to be augmented, but the exact mechanism of twitch potentiation is still not clear (37). Whatever the mechanism, when using twitches to assess contractility, one must make sure that twitch potentiation does not bias the results.

It should be noted that Pga is a simple, reproducible, and precise measure of abdominal muscle contractility and it can be used to quantify abdominal respiratory muscle force. The respiratory system appears to be minimally sensitive to significant abdominal muscle fatigue when assessed with a short maximal breathing capacity test. Whether such fatigue would affect breathing in patients or in healthy subjects during exercise remains an open question.

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