Optimal electrode placement for noninvasive electrical stimulation of human abdominal muscles

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Optimal electrode placement for noninvasive electrical stimulation of human abdominal muscles. J Appl Physiol 102: 1612–1617, 2007. First published December 26, 2006; doi:10.1152/japplphysiol.00865.2006. — Abdominal muscles are the most important expiratory muscles for coughing. Spinal cord-injured patients have respiratory complications because of abdominal muscle weakness and paralysis and impaired ability to cough. We aimed to determine the optimal positioning of stimulating electrodes on the trunk for the noninvasive electrical activation of the abdominal muscles. In six healthy subjects, we compared twitch pressures produced by a single electrical pulse through surface electrodes placed either posterolaterally or anteriorly on the trunk with twitch pressures produced by magnetic stimulation of nerve roots at the T10 level. A gastroesophageal catheter measured gastric pressure (Pga) and esophageal pressure (Pes). Twitches were recorded at increasing stimulus intensities at functional residual capacity (FRC) in the seated posture. The maximal intensity used was also delivered at total lung capacity (TLC). At FRC, twitch pressures were greater with electrical stimulation posterolaterally and magnetic stimulation at T10 and smallest at the anterior site (Pga, 30 ± 3 and 33 ± 6 cmH2O vs. 12 ± 3 cmH2O; Pes 8 ± 2 and 11 ± 3 cmH2O vs. 5 ± 1 cmH2O; means ± SE). At TLC, twitch pressures were larger. The values for posterolateral electrical stimulation were comparable to those evoked by thoracic magnetic stimulation. The posterolateral stimulation site is the optimal site for generating gastric and esophageal twitch pressures with electrical stimulation.

PEOPLE WITH HIGH-LEVEL SPINAL CORD INJURY (SCI) ARE UP TO 150 TIMES MORE LIKELY TO DIE FROM PNEUMONIA, AT ANY TIME AFTER THEIR INJURY, COMPARED WITH THE GENERAL POPULATION. RESPIRATORY COMPLICATIONS ARE THE MAJOR CAUSE OF DEATH IN ACUTE SCI PATIENTS (22). REDUCED ABILITY TO COUGH AND THE SUBSEQUENT BUILDUP OF PULMONARY SECRECTIONS RESULT IN RESPIRATORY COMPLICATIONS, INCLUDING ATELECTASIS, SPUTUM RETENTION, PNEUMONIA, AND PLEURAL EFFUSION.

The abdominal muscles are the major group of muscles that develop expiratory force, required to cough. Although functional electrical stimulation (FES) has been widely used to assist paralyzed limb muscles to regain function, there are fewer reports of the use of electrical or other types of stimulation on paralyzed human abdominal muscles, and so far they have had limited success in producing an effective cough (6, 10, 12, 14, 16, 17, 20, 21, 30, 31, 33).

There have been several studies investigating the use of electrical stimulation over the anterior abdominal wall near the midline to measure the ability to generate expiratory flow or pressure (12, 18, 21, 30, 31). The most successful of these studies increased mouth pressure by 33 cmH2O during a tetanically stimulated maximal expiratory maneuver in tetraplegic subjects (21).

As an alternative to electrical stimulation on the anterior wall of the abdomen, other groups have used magnetic stimulation over the T10 spinous process to activate the spinal nerve roots around this level (T8–T12). The benefit of magnetic stimulation is that it is relatively painless and activates a larger portion of the abdominal muscles (10, 13, 17, 18, 20, 26, 29). Using closely spaced pulses, magnetic stimulation of paralyzed muscles is able to generate much larger abdominal pressures than is electrical stimulation (10, 17, 20). Despite the relative success of the magnetic stimulation of abdominal muscles, the magnetic stimulators are bulky, expensive and contraindicated with implanted metal objects and are not a viable alternative for a portable stimulator device for personal use.

Therefore, in this study, we compared directly the twitch pressures generated by stimulation through electrodes on the anterior abdominal wall, twitch pressures generated from electrodes in a more posterior location, and twitch pressures generated by magnetic stimulation over T10. We chose to stimulate in a more posterior location because the anatomy of the trunk would suggest that the stimulus would activate more of the nerves that supply the abdominal muscles. The aim was to determine which electrode position or stimulation type has the greatest potential to assist cough. This is an initial step to developing a protocol for improving cough in people with high-level SCI using noninvasive FES applied to abdominal muscles. These data have appeared in abstract form (15).

MATERIALS AND METHODS

Studies were performed on six healthy able-bodied subjects with normal lung function (4 men, 38 ± 6 yr (range 23–60 yr), 173 ± 3 cm (range 164–182 cm), 70 ± 6 kg (range 52–86 kg); means ± SE). Subjects gave informed written consent to the procedures, which were approved by the local ethics committee. All procedures were well tolerated. No subject found that the stimulus intensities used here painful, and we did not note any local erythema after the studies.

Subjects were seated, breathed through a mouthpiece, and were stimulated at three sites (2 electrical, 1 magnetic stimulation) in random order. Single stimuli were delivered twice at each intensity (5 s apart) usually with the subject relaxed at functional residual capacity (FRC) and the airway blocked by an external shutter to maintain lung volume. The data from the two responses were averaged.

Stimulation. Three pairs of high-conductivity gel-skin plate electrodes (Split 1180, 3M HealthCare, St. Paul, MN) were placed on each subject (Fig. 1A). One electrode (electrode A; 4 × 18 cm long) was placed from the midline, angled diagonally downward, 2 cm below and parallel to the costal margin, toward the anterior superior iliac

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spine on each side of the abdomen. A second electrode (electrode B; cut shorter, 4 × 14 cm long) was placed parallel ~3 cm below the first pair, starting from the midline. A third electrode was directed from the midaxillary line at the T4 level obliquely down toward the posterior superior iliac spine, overlaying the lower four ribs and many of the nerves supplying the abdominal muscles (electrode C; 4 × 18 cm long). The length of electrodes B and C was cut shorter to fit if necessary. Electrical stimulation between electrodes A (cathode) and B (anode) was termed “anterior” stimulation. Stimulation between electrodes C (cathode) and A (anode) was termed “posterolateral” stimulation. The final position of the posterolateral electrodes was determined in a pilot study. The electrodes were positioned symmetrically on both sides of the abdomen. The single electrical stimuli (200-µs pulse width; DS7, Digitimer, Welwyn Garden City, UK) were delivered bilaterally at the two sites at increasing intensities from 50 to 450 mA (50-mA increments).

The single magnetic stimuli were delivered via a circular coil (130 mm outer diameter; 200 Magstim, Magstim, Dyfed, UK) placed flat on the posterior midline of the subject, over the 10th thoracic spinous process, with the handle perpendicular to the spine (Fig. 1A) (12). Stimulation was delivered at 60–100% stimulator output.

Additional stimuli were delivered at the highest intensities [450 mA electrical (anterior and posterolateral) and 100% magnetic at T10] with the subjects seated at total lung capacity (TLC), and supine at functional residual capacity (FRC). At TLC, additional measurements were made with the shutter open to measure the peak expiratory flow when the stimuli were applied.

Measurements. The force generated by the stimuli was measured as twitch pressure using a gastroesophageal catheter with one pressure transducer in the stomach to measure the abdominal or gastric pressure (Pga) and the other transducer 20 cm rostrally in the esophagus to measure the thoracic or esophageal pressure (Pes) (CTG-2, Gaeltec, Dunvegan, UK). The pressure signals were digitized (1401 Plus, CED, Cambridge, UK) and stored on a computer.

One-way repeated-measures ANOVAs were used to compare the maximal pressures produced by the three types of stimulation. The pressures generated by increasing stimulation intensity (50–450 mA), and the pressures produced when subjects were seated and supine at FRC and seated at TLC, were compared using a two-way repeated-measures ANOVA with Student-Newman-Keuls post hoc pairwise comparisons. Data are expressed throughout as means ± SE. Statistical significance was set at the 5% level.

RESULTS

Resting twitch pressures at FRC. As stimulus intensity increased, there was a steady rise in the twitch pressures (Pga and Pes) elicited at the three stimulation sites in all subjects. Figure 2 illustrates the mean (±SE) increase in pressure with the increase in stimulus intensity for the group data. Across all the intensities, Pga and Pes twitches were greater when stimuli were delivered at the posterolateral site than the anterior site. The difference was significant at 250–450 mA for Pga and 150–450 mA for Pes. Typical twitch pressures at the highest intensities are shown in Fig. 1B. The Pes-to-Pga ratio was similar for all three types of stimulation across all intensities (on average 0.48 ± 0.01, 0.41 ± 0.03, and 0.43 ± 0.02 for magnetic, posterolateral, and anterior stimulation, respectively). This suggests similar transfer of twitch pressures to the thorax for the three types of stimulation.

Figure 3 shows the data for each subject normalized to their maximal twitch pressures at the posterolateral stimulating site for Pga. From Fig. 3, it is clear that for all subjects at most stimulus intensities, the twitch pressures were greatest when stimuli were delivered to the electrodes in the posterolateral position; i.e., the values for normalized abdominal pressures evoked via the anterior electrodes were less than one. Magnetic stimulation produced higher maximal twitch pressures (>1) in some subjects and lower maximal twitch pressures (<1) in others. As the stimulation intensity increased from 50 to 450 mA and from 60 to 100% magnetic stimulator output, twitch pressures
pressures continued to increase. We reached maximal abdomin al twitch pressure (the pressure at which further increases in stimulus intensity produced no further increases in twitch pressure) in only one subject with magnetic and posterior electrical stimulation and in five subjects with anterior electrical stimulation. Thus the posterior stimulation has potential for even larger pressures than were achieved here. The largest Pga and Pes twitches evoked in each subject (taken from all data regardless of stimulation intensity) were significantly higher for twitches evoked by posterolateral electrical and magnetic stimulation compared with anterior electrical stimulation (Table 1).

At the highest intensities of stimulation (450-mA electrical and 100% magnetic stimulator output), the amplitude of the twitch pressures for Pga was on average 2.5 times greater for both posterolateral electrical and magnetic stimulation than for anterior electrical stimulation at FRC, seated (Table 1, Fig. 2A). Pes was greater with posterolateral stimulation and magnetic stimulation compared with anterior stimulation but was only significantly larger for magnetic stimulation (Table 1, Fig. 2B). In two of the subjects (the shortest 2 of the group), at the highest intensity of stimulation (magnetic for 1 subject and posterior for the other), Pes twitches became more variable and slightly negative. There may be some stimulus spread to inspiratory muscles in these cases.

Effects of lung volume and posture. Twitch pressures generated at TLC were greater than those evoked at FRC at the same intensity (450 mA), but the difference was not significant for Pga and Pes (P = 0.054 and P = 0.106, respectively; Table 1, Fig. 2). However, the pressures produced at TLC were significantly greater with the posterolateral and magnetic stimulation than with anterior stimulation (Table 1, Fig. 2). Additional observations showed that when delivered at TLC with the shutter open, the peak expiratory flow generated by the single stimulus in the posterior position and the magnetic stimulus was ~1.7 times greater than for the anterior position (P < 0.05; data not illustrated).

Application of the highest intensity stimulation at the usual end-expiratory level when subjects were in the seated and supine position did not significantly change twitch pressure (Pga or Pes) for any of the stimulation types (Table 1, Fig. 2).
DISCUSSION

Effects of stimulation site. This study provides the first data on the twitch pressures generated by electrical stimuli in the posterolateral position of the abdomen. The data show that the posterolateral stimulation site is 2.5 times better for producing Pga via abdominal muscle contraction than the anterior position and as good as magnetic stimulation of the nerve roots.

The main reason for the improved abdominal twitch pressures from the posterolateral site is the location. The electrodes lie directly over the nerves that supply the abdominal muscles in the midaxillary line. In addition, we have used large surface electrodes (18 × 4 cm) that cover a greater surface area than the smaller electrodes used previously (e.g., Refs. 12, 14, 30, 31). The greater coverage allows stimulation of a greater number of nerve fibers and hence generates a greater twitch pressures. The underlying nerves innervate all the target abdominal muscles involved in expiration; the internal and external obliques, rectus abdominis, transverse abdominis, and some of the intercostal muscles. The muscles that contribute most to abdominal pressure in dogs are the external oblique and transversus abdominis (7). Positioning of the electrodes more posteriorly was unsatisfactory for two reasons: subjects would not be able to apply the electrodes themselves, and placement over paraspinal muscles increased inadvertent spinal extension. In contrast, electrodes placed in the anterior position activate fewer abdominal muscles, and in this anterior position, the major muscles activated are the rectus abdominis and parts of the external and internal oblique muscles. Contraction of rectus abdominis does not contribute significantly to intrabdominal pressure (7). Most muscles can only be partially activated by electrical stimulation in the anterior position (5, 7). Studies in the dog and more recently in a SCI subject suggest that the largest abdominal muscle contractions are evoked by nerve root stimulation (6–9).

The abdominal muscle twitch pressures produced by single pulse posterolateral electrical stimulation (30 ± 3 cmH2O) are comparable to the twitches produced by magnetic stimulation over T10 (33 ± 6 cmH2O). This suggests that posterolateral stimulation is as effective as nerve root magnetic stimulation. Because we compared only single electrical and magnetic pulses, the gastric twitch pressures produced by a magnetic stimulus were smaller than those reported previously produced in able-bodied control subjects by double pulses delivered via magnetic stimulation at T10 (~75 cmH2O; Refs. 10, 13). However, much higher forces will be generated using trains of electrical stimuli to produce force fusion. The twitch-to-tetanus ratio for human toe and hand muscles averages ~1:5 (23, 32), and the ratio is similar for the diaphragm (2). Thus we would expect that the maximal evocable abdominal pressure by a train of 50-Hz pulses at 450 mA would be ~150 cmH2O. This is comparable to the reported maximum voluntarily generated abdominal pressure, which ranges between 100 and 200 cmH2O (11, 13, 24, 29). We did not stimulate with trains of pulses in this experiment because the main aim was to find the optimal stimulation site for producing abdominal muscle contraction at rest. Optimal twitch pressures are likely to be a good indicator of the optimal electrode placement for tetani.

The abdominal muscles are the most important muscles for the active expiration required in a cough (3), but the best indicator for cough efficacy in humans is not clear. The positive Pga generated by stimulation is a good parameter to indicate the strength of the expiratory muscles and therefore is likely to correlate well with cough efficacy in humans (26, 27). Therefore, the data from the present study suggest that the posterolateral electrode position will generate the highest Pga twitch pressures and that this would also be the optimal site for future studies of the generation of an effective cough in people with SCI. Some studies have assessed the outcome of stimulated assisted cough in terms of pressures generated at the mouth or expiratory flow (12, 14, 16, 19–21, 30, 33). However, these are not always reliable measures because factors such as partial of full closure of the glottis can affect pressures generated in mouth and the expiratory flow, particularly during multiple stimuli delivered to the abdominal muscles. Large differences in expiratory flow during cough can occur between subjects, even with the same Pga values. This is likely due to differential narrowing of the glottis (26).

At very high intensities of stimulation, inappropriate stimulus spread may occur. In two of the subjects (the shortest of the group), at the highest intensity of stimulation (magnetic for one subject and posterior for the other), Pes twitchs became more variable and slightly negative. This suggests some inadvertent (direct or reflex) activation of inspiratory muscles. Hence, in small subjects, care should be taken to reduce the size of the electrode so that it reaches only to the eighth intercostal space rostrally. This may explain why posterolateral-evoked Pes twitchs were not significantly higher than anterior evoked Pes twitchs at the highest stimulus intensities but were significantly higher when the highest pressures for each subject were compared. However, the Pes-to-Pga ratio was the same for the three stimulation types across the full range of stimulus intensities. This suggests similar transfer of Pga to the thorax and argues against a major role for increased activation of...
inspiratory muscles by any of the stimulation types. The slightly higher ratio for magnetic stimulation may be due to stiffening of the chest wall by activation of intercostal muscles (4).

Effects of lung volume and posture. In the present study, most measurements were made at the end of quiet expiration when all respiratory muscles are close to being fully relaxed and the thoracic and abdominal pressures are in equilibrium. This ensures that the Pga and Pes twitches measured at each stimulus intensity were generated solely from the effects of the stimulus. However, because coughs are normally generated at higher lung volumes, we also tested the effect of the three types of stimuli at TLC. Lung volume has a significant influence on the pressure-generating capacity of the expiratory muscles (13), and our study confirms that this although the differences were not quite statistically significant. The increases in twitch pressure at high lung volumes may be due to a number of factors, including increased elastic recoil of the rib cage at very high lung volumes (1); the increased fiber length of the abdominal muscles at high lung volumes so that they are closer to the optimum for generating force; or a lack of relaxation of the diaphragm at TLC, which would increase Pga and reduce Pes (25). Nevertheless, the expiratory pressures were largest when the abdominal muscles were activated by either the posterolateral electrical or magnetic stimulation at T10 rather than stimulation over the anterior abdominal wall. Similarly, peak expiratory airflows at TLC were largest with posterolateral stimulation, although these flows were also contributed to by chest recoil pressure when the subjects relaxed with the glottis open.

Posture had no significant influence on the peak Pga or Pes twitches using any of the three stimulation types. This confirms previous results (26). However, small differences may be attributed to changes in the length-tension properties of the abdominal muscles in seated and supine positions (3, 28) because abdominal muscle length may be slightly increased supine compared with seated. Although the electrodes were placed on the torso by experimenters, the subjects could have positioned the electrodes themselves. Individuals with spinal injury or their caregivers would be able to position the electrodes correctly. Successful translation of these results to individuals with SCI injury will depend on a number of factors including the effectiveness of tetanic stimulation in the posterolateral position, that the nerves to be stimulated are uninjured, and that the sensory consequences of tetanic stimulation over the torso can be tolerated.

In conclusion, electrode placement exerts a major effect on pressure-generating capacity of the expiratory muscles for a given stimulus intensity. The present data shows electrode placement in the posterolateral position achieves significantly greater Pga and Pes twitches than similar electrodes placed on the anterior abdominal wall. Stimulation at the posterolateral position produces twitch pressures similar to those generated through activation of the motor nerve roots by magnetic stimulation at the T10 spinous process. The results suggest that the placement of the stimulating electrodes will be a crucial factor in the future development of a noninvasive system to assist cough in people with high-level SCI.

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GRANTS

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REFERENCES