Optimal electrode placement for non-invasive electrical stimulation of human abdominal muscles

Julianne Lim, Robert B. Gorman, Julian P. Saboisky, Simon C. Gandevia and Jane E. Butler

Prince of Wales Medical Research Institute and University of New South Wales, Randwick, Sydney 2031, Australia.

Running head: Abdominal muscle stimulation

Corresponding author:
Dr. S.C. Gandevia
Prince of Wales Medical Research Institute
Barker Street
Randwick NSW 2031
Sydney Australia

Ph: Int +61 2 9399 1017
FAX: Int +61 2 9399 1027
Email: s.gandevia@unsw.edu.au
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 non-invasive electrical activation of the abdominal muscles. In 6 healthy subjects, we compared twitch pressures produced by a single electrical pulse through surface electrodes placed either postero-laterally or anteriorly on the trunk to twitch pressures produced by magnetic stimulation of nerve roots at the T10 level. A gastro-esophageal catheter measured gastric pressure (P\textsubscript{ga}) and esophageal pressure (P\textsubscript{es}). 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 greatest with electrical stimulation postero-laterally and magnetic stimulation at T10 and smallest at the anterior site (P\textsubscript{ga}, 30±3 and 33±6 cmH\textsubscript{2}O vs. 12±3 cmH\textsubscript{2}O; P\textsubscript{es}, 8±2 and 11±3 cmH\textsubscript{2}O vs. 5±1 cmH\textsubscript{2}O; mean±SE). At TLC twitch pressures were larger. The values for postero-lateral electrical stimulation were comparable to those evoked by thoracic magnetic stimulation. The postero-lateral stimulation site is the optimal site for generating gastric and esophageal twitch pressures with electrical stimulation.

Keywords: cough, functional electrical stimulation, abdomen
INTRODUCTION

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 to the general population. Respiratory complications are the major cause of death in acute SCI patients. Reduced ability to cough and the subsequent build up of pulmonary secretions, result in respiratory complications including atelectasis, sputum retention, pneumonia and pleural effusion.

The abdominal muscles are the major group of muscles which develop expiratory force, required to cough. While functional electrical stimulation 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 (7, 11, 13, 15, 18, 19, 22, 23, 33, 34, 36).

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. The most successful of these studies increased mouth pressure by 33 cmH₂O during a tetanically stimulated maximal expiratory manoeuvre in tetraplegic subjects (13).

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 (7, 9). Using closely-spaced pulses, magnetic stimulation of paralysed muscles is able to generate much larger abdominal pressures than with electrical stimulation (7). 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 spinal cord injury using non-invasive functional electrical stimulation (FES) applied to abdominal muscles. These data have appeared in abstract form.

MATERIALS AND METHODS

Studies were performed on 6 healthy able-bodied subjects with normal lung function (4 males, 38±6 years (range 23-60 years), 173±3 cm (range 164-182 cm), 70±6 kg (range 52-86 kg), mean±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 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 3 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, USA) were placed on each subject (Fig. 1A). One electrode (electrode A, 4 cm x 18 cm long) was placed from the midline, angled diagonally downwards, 2 cm below and parallel to the costal margin, towards the anterior superior iliac spine (ASIS) on each side of the abdomen. A second electrode (electrode B, cut shorter, 4 x 14 cm long) was placed parallel ~3 cm below the first pair, starting from the midline. A third electrode was directed from the mid-axillary line at the T8 level obliquely down towards the posterior superior iliac spine (PSIS), overlaying the lower 4 ribs and many of the nerves supplying the abdominal muscles (electrode C, 4 cm x 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 “postero-lateral” stimulation. The final position of the postero-lateral 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 Co., Welwyn Garden City, UK) were delivered bilaterally at the 2 sites at increasing intensities from 50 mA to 450 mA (50 mA increments).

The single magnetic stimuli were delivered via a circular coil (130 mm outer diameter; 200 Magstim, Magstim Co., 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). Stimuli were delivered at 60-100% stimulator output.

Additional stimuli were delivered at the highest intensities (450 mA electrical (anterior and postero-lateral, and 100% magnetic at T10) with the subjects seated at total lung capacity (TLC), and supine at FRC. At TLC, additional measurements were made with the shutter open in order 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 gastro-esophageal catheter with one pressure transducer in the stomach to measure the abdominal or gastric pressure \( (P_{ga}) \) and the other transducer 20 cm rostrally in the esophagus to measure the thoracic or esophageal pressure \( (P_{es}) \) (CTG-2, Gaeltec Ltd., Dunvegan, UK). The pressure signals were digitized (1401 Plus, CED Limited, Cambridge, UK) and stored on computer.

One-way repeated measures ANOVAs were used to compare the maximal pressures produced by the 3 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 mean±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 \( (P_{ga} \) and \( P_{es} \), elicited at the 3 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, \( P_{ga} \) and \( P_{es} \) twitch pressures were greater when stimuli were delivered at the postero-lateral site than the anterior site. The difference was significant at 250-450 mA for \( P_{ga} \) and 150-450 mA for \( P_{es} \). Typical twitch pressures at the highest intensities are shown in Figure 1B. The \( P_{es}/P_{ga} \) ratio was similar for all 3 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 \( P_{ga} \) twitch pressures to the thorax for the three types of stimulation.
Figure 3 shows the data for each subject normalised to their maximal twitch pressures at the postero-lateral stimulating site for $P_{ga}$. From this Figure, 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 postero-lateral 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 continued to increase. We reached maximal abdominal twitch pressure (the pressure at which further increases in stimulus intensity produced no further increases in twitch pressure) in only 1 subject with magnetic and posterior electrical stimulation, and 5 subjects with anterior electrical stimulation. Thus, the posterior stimulation has potential for even larger pressures than were achieved here. The largest $P_{ga}$ and $P_{es}$ twitch pressures evoked in each subject (taken from all data regardless of stimulation intensity) were significantly higher for twitches evoked by postero-lateral electrical and magnetic stimulation compared to 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 $P_{ga}$ was on average 2.5 times greater for both postero-lateral electrical and magnetic stimulation than for anterior electrical stimulation at FRC, seated (Table 1, Fig. 2A). $P_{es}$ was greater with postero-lateral stimulation and magnetic stimulation compared to anterior stimulation but was only significantly larger for magnetic stimulation (Table 1, Fig. 2B). In two of the subjects (the shortest two of the group), at the highest intensity of stimulation (magnetic for one subject and posterior for the other), $P_{es}$ 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 $P_{ga}$ and $P_{es}$ ($p = 0.054$ and $p = 0.106$, respectively, Table 1, Fig. 2). However, the pressures produced at TLC were significantly greater with the postero-lateral 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 ($P_{ga}$ or $P_{es}$) 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 postero-lateral position of the abdomen. The data show that the postero-lateral stimulation site is 2.5 times better for producing gastric pressure 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 postero-lateral site is the location. The electrodes lie directly over the nerves that supply the abdominal muscles in the mid-axillary line. In addition, we have used large surface electrodes (18 x 4 cm) which cover a greater surface area than the smaller circular electrodes used previously (e.g. 8, 10, 17, 18). The greater coverage allows stimulation of a greater number of nerve fibres 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 (4). 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 intra-abdominal pressure (4). Most muscles can only be partially activated by electrical stimulation in the anterior position (2, 4). Studies in the dog and more recently in a SCI subject suggest that the largest abdominal muscle contractions are evoked by nerve root stimulation (3-6).

The abdominal muscle twitch pressures produced by single pulse poster-lateral electrical stimulation (30±3 cmH2O) are comparable to the twitches produced by magnetic stimulation over T10 (33±6 cmH2O). This suggests that postero-lateral stimulation is as effective as nerve root magnetic stimulation. As 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, 7, 9). 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 around 1:5 and the ratio is similar for the diaphragm. Thus, we would expect that the maximal evocable abdominal pressure by a train of 50 Hz pulses at 450 mA would be about 150 cmH2O. This is comparable to the reported maximum voluntarily generated abdominal pressure which ranges between 100-200 cmH2O (9, 14). We did not stimulate with trains of pulses in this experiment as 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 but the best indicator for cough efficacy in humans is not clear. The positive gastric pressure 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 (15, 16). Therefore, the data from the current study suggest that the postero-lateral electrode position will generate the highest gastric 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 (8, 11, 12, 17, 19). However, these are not always reliable measures because factors such as partial or 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 gastric pressures. This is likely due to differential narrowing of the glottis (15).

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), P_{es} twitches 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 8^{th} intercostal space rostrally. This may explain why postero-lateral evoked P_{es} twitches were not significantly higher than anterior evoked P_{es} twitches at the highest stimulus intensities but were significantly higher when the highest pressures for each
subject were compared. However, the Pes/Pga ratio was the same for the three stimulation types across the full range of stimulus intensities. This suggests similar transfer of gastric pressure 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 (1).

**Effects of lung volume and posture**

In the current 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 P_{ga} and P_{es} twitch pressures measured at each stimulus intensity were generated solely from the effects of the stimulus. However, as 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 (9) and our study confirms 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 ribcage at very high lung volumes, 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 P_{ga} and reduce P_{es}. Nevertheless, the expiratory pressures as well as were largest when the abdominal muscles were activated by either the postero-lateral electrical or magnetic stimulation at T10 rather than stimulation over the anterior abdominal wall. Similarly, peak expiratory airflows at TLC were largest with postero-lateral 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 P_{ga} or P_{es} twitch pressures using any of the three stimulation types. This confirms previous results (15). However, small
differences may be attributed to changes in the length tension properties of the abdominal muscles in seated and supine positions as abdominal muscle length may be slightly increased supine compared to 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 carers would be able to position the electrodes correctly. Successful translation of these results to individuals with spinal cord injury will depend on a number of factors including the effectiveness of tetanic stimulation in the postero-lateral position, that the nerves to be stimulated are uninjured, and that the sensory consequences of tetanic stimulation over the torso can be tolerated.

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 postero-lateral position achieves significantly greater $P_{ga}$ and $P_{es}$ twitch pressures than similar electrodes placed on the anterior abdominal wall. Stimulation at the postero-lateral 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 non-invasive system to assist cough in people with high-level SCI.
ACKNOWLEDGMENTS

We are grateful to Prof. Neil Pride and Dr Nicholas Murray for their helpful comments.

GRANTS

Supported by: NSW Premier’s Spinal Cord Injury Grant Program and the National Health and Medical Research Council of Australia.
REFERENCES


<table>
<thead>
<tr>
<th></th>
<th>Seated FRC</th>
<th>Seated FRC</th>
<th>Seated TLC</th>
<th>Supine FRC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(maximal intensity)</td>
<td>(largest value)</td>
<td>(maximal intensity)</td>
<td>(maximal intensity)</td>
</tr>
<tr>
<td></td>
<td>( P_{ga} ) (cm H(_2)O)</td>
<td>( P_{es} ) (cm H(_2)O)</td>
<td>( P_{ga} ) (cm H(_2)O)</td>
<td>( P_{es} ) (cm H(_2)O)</td>
</tr>
<tr>
<td>Anterior</td>
<td>12±3</td>
<td>5±1</td>
<td>13±3</td>
<td>6±1</td>
</tr>
<tr>
<td>Postero-lateral</td>
<td>30±3*</td>
<td>8±2</td>
<td>30±3*</td>
<td>10±2*</td>
</tr>
<tr>
<td>Magnetic</td>
<td>33±6*</td>
<td>11±3*</td>
<td>33±6*</td>
<td>12±2*</td>
</tr>
</tbody>
</table>

*indicates significant differences from the respective twitch pressures produced by anterior stimulation (p < 0.05). There were no significant differences across lung volume or posture.

Maximal intensity stimulation was 450 mA for electrical and 100% stimulator output for magnetic stimulation over T10. Largest values are calculated from the highest twitch pressure for each subject for each stimulation type, regardless of stimulation intensity. Data are expressed as mean±SE.
Figure 1 Experimental set up

A. Subjects were studied seated and breathed on a mouth piece. $P_{ga}$ and $P_{es}$ were measured using an intra-esophageal catheter. Three large surface electrodes were placed on either side of the abdominal wall. Electrical stimulation was applied bilaterally. At the anterior site (left panel) current was passed between electrodes A (cathode) and B (anode); at the postero-lateral site (middle panel) current was passed between electrodes C (cathode) and A (anode). Magnetic stimulation was delivered over the T10 spinous process (right panel). B. This depicts two $P_{ga}$ twitch pressure traces overlaid from the 3 stimulus sites at the highest stimulus intensities (450 mA and 100% magnetic stimulator output) recorded at FRC from a single subject.
Figure 2 Recruitment curves for abdominal muscle activation.

Evoked pressures produced by stimulation of abdominal muscles at increasing intensities (mean±SE). A. $P_{ga}$ and B. $P_{es}$ peak twitch pressures are shown for anterior (○) and postero-lateral (●) electrical stimulation (left panels, between 50–450 mA) and for magnetic (■) stimulation (right panels, 60-100% stimulator output) seated at FRC. Data obtained seated at TLC and supine at FRC (450 mA, and 100% stimulator output) are shown to the right of each curve. * indicates significant differences between anterior and postero-lateral electrical stimulation.
Figure 3 Normalised abdominal twitch pressures for all subjects.
Data are shown from each subject for anterior (left panel), postero-lateral (middle panel), and magnetic (right panel) stimulation. The data are normalised to the maximal pressure twitch produced by postero-lateral stimulation in each subject; this is indicated by the horizontal dashed line. Each line represents a single subject with the larger filled circles depicting the mean ± SE.