

# A Review of Abdominal Muscle Stimulation for Patients with Spinal Cord Injury

GANESAN KATHIRESAN<sup>1)</sup>, KENNETH HUNTOR<sup>2)</sup>, PETER H FRASER<sup>2)</sup>,  
SENTHILKUMAR JEYARAMAN<sup>3)</sup>

<sup>1)</sup>Physiotherapy, School of Allied Health, Masterskill University College:  
G8, Jalan Kemacahaya 11, Taman Kemacahaya, Batu 9, Cheras 43200, Selangor, Malaysia.  
E-mail: gans\_therapist@yahoo.co.in

<sup>2)</sup>Biomedical Reserch Center, Central Manchester University Hospital NHS Foundation, UK

<sup>3)</sup>School of Allied Health, Masterskill University College, Malaysia

**Abstract.** [Purpose] Abdominal muscle stimulation can provide respiratory support in Spinal cord-injury patients. Stimulation may be applied by simple surface stimulation, resulting in uniform muscle contraction which can help to improve the expiratory function for coughing and breathing. [Subjects and Methods] In this review, an overview of methods and approaches available for abdominal muscle stimulation is given. Studies are discussed which show that this technique can lead to improvements in expiratory flow and tidal volume, resulting in enhanced cough and breathing functions. Approaches are introduced which aim to integrate abdominal stimulation with the subject's own voluntary breathing functions. These are illustrated with experimental results from the evaluation of automatic stimulation methods in tetraplegic patients.[Results]The results show that the effectiveness of abdominal surface stimulation can vary widely between subjects. [Conclusions] Clinical significance and applications are discussed and future developments and the direction of research in this area are reviewed.

**Key words:** Tetraplegia, Electrical stimulation, Abdominal muscle

(This article was submitted Feb. 19, 2010, and was accepted Mar. 29, 2010)

## INTRODUCTION

Spinal cord injury (SCI) often leads to an impairment of the respiratory system. The more rostral the level of injury, the more likely the injury will affect ventilation. In fact, respiratory insufficiency is the number one cause of mortality and morbidity after SCI<sup>1)</sup>. 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<sup>2)</sup>. Respiratory complications are a leading cause of morbidity and mortality in people with spinal cord injury (SCI)<sup>3–5)</sup>. People with SCI in the cervical region, affecting all

four limbs and resulting in tetraplegia, are at increased risk of respiratory complications as their injury also results in partial or complete paralysis of the breathing muscles. While high-level tetraplegia can lead to complete or partial loss of function of the diaphragm, tidal volume is further reduced by intercostal paralysis, and cough peak flow is compromised due to abdominal paralysis<sup>6)</sup>. In particular, the reduction in cough peak flow affects the ability to clear the airways<sup>7)</sup>, leading to an increased likelihood of respiratory infection in individuals with chronic tetraplegia<sup>4)</sup>. A number of approaches exist to provide respiratory support in this group of patients. This tutorial review will focus on the use of surface stimulation of the abdominal wall muscles as a technique to improve

respiratory function in general, and cough in particular. Following a review of the state of the art, an overview of methods of abdominal muscle stimulation will be given, with an emphasis on systems for automatic stimulation. The methods will be illustrated by results from experimental evaluations, followed by a discussion of the clinical implications and future directions of research in this area.

### NEED OF THE STUDY

For ventilator dependent patients with an injury at level C1-C2, phrenic nerve pacing to stimulate the diaphragm is an established technique for improving breathing function and for enabling independence from mechanical ventilators which can reduce the risk of respiratory infection<sup>8-10</sup>). This technique is, however, often not applicable in tetraplegia with injuries at a level just below C2 due to lower motor- neuron damage to the phrenic nerve which is innervated at the 3rd and 4th cervical level. In this case, stimulation of the intercostal muscles can be an alternative or additional way to improve respiration<sup>11</sup>). The combined function of the intercostal muscles for inspiration and expiration can, however, make it difficult to obtain a well-defined respiratory response when stimulating these muscles. Furthermore, both diaphragm pacing and intercostal stimulation are difficult to implement with transcutaneous techniques and therefore usually require implanted stimulation electrodes<sup>8</sup>).

People with tetraplegia who have a lesion at a lower level are typically able to breathe voluntarily and are mostly independent from mechanical ventilation. Their breathing capacity is still compromised due to paralysis of inspiratory and expiratory muscles. Because the paralysis also affects the abdominal wall muscles which are the main expiratory muscles, their capacity to forcefully expire air, e.g. during cough, is also reduced<sup>7</sup>). It has been shown that stimulation of abdominal muscles during expiration can improve respiratory function<sup>12-15</sup>).

Stimulation of the abdominal muscles during expiration can enhance cough since the contraction of the stimulated abdominal muscles leads directly to an increase in respiratory pressure and consequently to improved expiratory flow. It also reduces lung volume below the functional residual capacity, and the subsequent passive recoil during

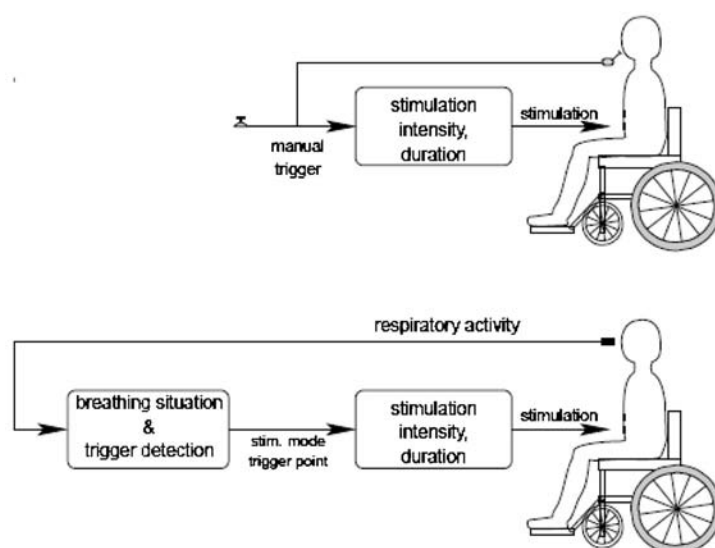
inspiration can result in an increase in tidal volume. Stimulation of the abdominal muscles is typically used in tetraplegic individuals with spontaneous breathing and it has also been applied to individuals who are unable to breath spontaneously<sup>16</sup>). The abdominal muscles are typically stimulated through surface electrodes which are easy to apply, and stimulation results in uniform, well-defined muscle responses<sup>17,18</sup>). Alternatively, stimulation can be delivered by spinal cord stimulation using epidural electrodes<sup>19</sup>) or microstimulators<sup>20</sup>), or by magnetic stimulation of the thoracic nerve roots<sup>21,22</sup>).

### NEUROMUSCULAR STIMULATION OF ABDOMINAL WALL MUSCLES

A system to augment cough and to support normal breathing activity can be implemented by applying surface stimulation to the abdominal wall muscles. In individuals with spontaneous breathing, stimulation of the respiratory muscles should generally be synchronised with their voluntary breathing activity<sup>8</sup>), although subjects may be able to adjust their breathing activity to a pre-defined stimulation pattern within a certain range. Synchronisation of stimulation with the subject's own breathing is typically achieved using a manual trigger. While some subjects may be able to use a manual button to initiate a stimulation burst, limited hand function resulting from tetraplegia often requires alternative input methods such as a chin-controlled joystick<sup>23</sup>) or a trigger which is operated by the therapist<sup>24</sup>), as illustrated at the top of Fig.1.

A manual trigger becomes unsuitable for prolonged periods of stimulation when repetitive manual activation is required. In this case an automatic system can be used which ensures that the stimulation is applied adequately. Using a measurement of the respiratory activity, the stimulation can automatically be timed in such a way that it is applied in synchrony with the subjects' voluntary breathing. The basic set up for such a system is shown at the bottom of Fig. 1.

This approach was used for the following specific respiratory situations. J. Sorli et al. focused on quiet breathing. Their system was not applicable for cough induction<sup>25</sup>). On the other, Spivak et al. focused on a system generating an automatic trigger for cough, but did not consider other breathing situations<sup>26</sup>). Gollee et al.<sup>27</sup>) extended this concept



**Fig. 1.** Set up of manual triggering (top, using a chin-switch or external button) and automatic triggering (bottom, using respiratory activity) of stimulation.

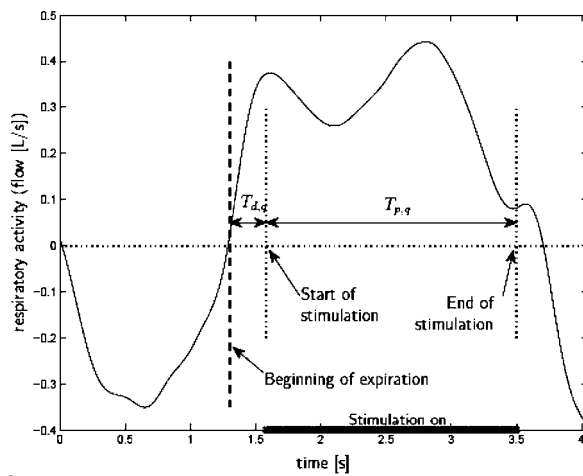
and proposed a system to automatically trigger stimulation during both quiet breathing and coughing. To determine the respiratory activity, their system uses a direct measurement of the air flow at the mouth and nose and synchronises the stimulation pattern accordingly. In experiments with four tetraplegic subjects (C4–C6, complete) it was demonstrated that this approach was suitable for delivering automatic stimulation patterns, detecting cough and quiet breathing while suppressing stimulation during other activities such as speaking. Marked increases in tidal volume and cough peak flow were observed<sup>28)</sup>, suggesting that the technique may have potential use in tetraplegia to increase minute ventilation and to improve cough clearance. While a direct measurement of the air flow at the mouth is a suitable signal for respiratory activity in a laboratory setting where it also allows the collection of spirometry data, this approach is less suitable for use outside a research environment. Spivak et al.<sup>26)</sup> suggest an EMG-activated stimulation system for abdominal stimulation independent of a caregiver. Stimulation for cough was triggered by EMG signals obtained from either the pectoralis major muscle or the deltoid. Other possible approaches for making measurements of respiratory activity include the direct observation of abdominal and chest movements. This can be achieved by using a respiratory effort sensor (plethysmographic belt) commonly employed for

the diagnosis of sleep apnoea<sup>29)</sup>. An alternative approach suggests the use of an inertial measurement unit to detect signals of abdominal movement related to respiration<sup>30)</sup>.

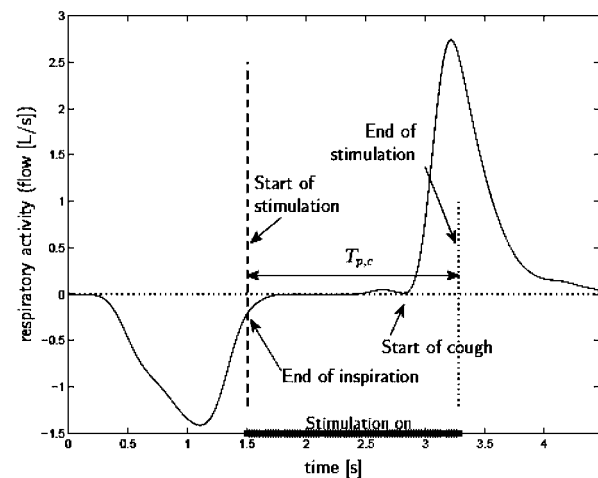
#### *Automatic muscle stimulation*

As discussed above, it is desirable to synchronise the stimulation of expiratory muscle with the user's voluntary breathing. This can be achieved either using simple manual trigger switches which require active user intervention or stimulation can be generated automatically, based on measurement of the respiratory activity. A number of basic tasks can be formulated which should be implemented by an automatic stimulation system:

- It should deliver the stimulation burst at the optimal moment relative to the subject's voluntary breathing pattern;
- It should distinguish between different breathing situations such as quiet breathing, coughing and other activities, e.g. speaking. This enables the system to adjust the stimulation timing and other parameters for a specific breathing situation since the requirements for coughing and quiet breathing will be different. It should also allow muting of the stimulation when needed in order for it not to interfere with, for example, speaking.
- It should automatically adjust stimulation parameters to accommodate fatigue, spasticity and



2a



2b

**Fig. 2.** Trigger points and stimulation during quiet breathing and for a cough, based on measurement of the respiratory activity. a: Quiet Breathing. b: Cough.

other variations in the user's response.

In this paper we will focus on the first two points. The stimulation parameters in current systems are usually set-up a-priori and adjusted manually if required.

### 1) Trigger point

In order to deliver the stimulation burst at the appropriate moment, a suitable trigger point needs to be identified. The stimulation burst may then be delayed by a time  $T_d$  relative to that trigger point so that it is delivered at the optimal moment. A possible approach is shown in Fig. 2 for a quiet breathing situation and for a cough. Each figure shows the respiratory activity (measured as the air flow at the mouth) during a single breath, starting with inspiration. Note that negative flow corresponds to inspiration while positive flow indicates expiration.

During quiet breathing the stimulation burst should support expiration. A suitable trigger point is therefore the beginning of expiration (see Fig. 2a). In term of flow this can be described as the point when its sign changes from negative (inspiration) to positive (expiration). The start of the stimulation can be delayed by an adjustable time,  $T_{d,q}$ , relative to this trigger point. A stimulation burst of duration  $T_{p,q}$  is then delivered, resulting in a contraction of the abdominal muscles and a subsequent increase in expiratory flow. This additional air flow resulting from the stimulation can be clearly observed in Fig. 2a, starting at

approximately 50 s. Note that there is a delay of nearly 0.5 s between the start of stimulation and the beginning of the flow increase which is due to the combined effects of muscle stimulation delays and the time taken for the muscle to contract and build up sufficient abdominal pressure to generate air flow at the mouth. To obtain optimal support during coughing, the stimulation should be applied at the end of inspiration. This allows the abdominal muscle contraction to increase the intra-abdominal pressure while the subject closes their airways at the end of inspiration. When the abdominal pressure has built up sufficiently the subject will open the airways, resulting in a cough. This is illustrated in Fig. 2b, showing the end of inspiration as the trigger point for the stimulation. A stimulation burst of duration  $T_{p,c}$  is then applied, resulting in an increased cough. Note that in both cases stimulation should terminate when the subject starts the next breath or when the stimulation burst is completed.

### 2) Detection of breathing situation

The difference in stimulation trigger for cough and quiet breathing necessitates that an automatic system can differentiate between these breathing situations. In order to distinguish between different breathing situations, features which characterise the breathing pattern need to be extracted from the respiratory activity signal and analysed in real time. The fundamental challenge is that the intended breathing situation needs to be predicted from past

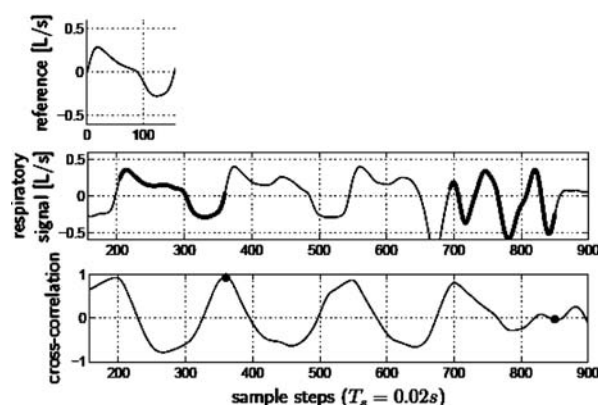


Fig. 3. Use of cross-correlation to characterise quiet breathing. The respiratory signal (middle plot) is compared to a reference breath (top plot), resulting in a cross-correlation measure (bottom plot).

observations of the breathing activity. It is possible to extract a number of fundamental characteristics which can be used to distinguish between the main breathing patterns. The breathing patterns considered here are coughing, quiet breathing and other breathing situations during which stimulation is not desirable (such as during speaking). The characterisation of the breathing situations will be discussed with respect to air flow at the mouth as the signal representing respiratory activity. It is, however, possible to adapt these approaches to different measurements of respiratory activity.

An attempt to cough is typically characterised by a large peak inspiratory flow. The trigger point for cough stimulation which is the end of inspiration can then be determined by a sudden drop in inspiratory flow. This represents itself as a peak in the derivative of air flow with respect to time. Cough stimulation can therefore be triggered by looking for a large inspiratory flow signal, followed by a peak in the derivative of flow. If the peak inspiratory flow is smaller than the cough threshold, another breathing situation is likely to be present. This can be quiet breathing or other breathing activities. For quiet breathing, the stimulation trigger is the beginning of expiration which can be detected relatively easily by observing the sign of the measured flow signal: a change in the direction of flow indicates a stimulation trigger. The limitation of this simple approach is that the change from inspiration to expiration is also present in other situations (such as during speaking) when stimulation is not desired as it would interfere with

the activity. It is therefore necessary to obtain additional features to characterise quiet breathing. One approach described in<sup>27)</sup> uses a measure of the cross-correlation between a typical (reference) quiet breath and the current breathing pattern. If the current pattern is similar to the reference breath, then the breathing situation can be classified as a quiet breath and stimulation will be delivered, otherwise stimulation will be muted. This is illustrated in Fig. 3 where a reference breath (shown in the top graph) was obtained by averaging 60 s of quiet breathing. A measured respiratory signal (shown in the middle plot) is then continuously compared to the reference breath by calculating their cross-correlation (shown in the bottom plot). If the reference breath and the current breath have a high degree of similarity and are in phase, the cross correlation signal will approach one. If both signals are very different, the cross-correlation signal will be close to zero. A value of -1 for the cross-correlation indicates that while the signals have a high degree of similarity, they are shifted relative to each other by 180°.

In Fig. 3, two breathing patterns are highlighted in the middle plot. The first pattern is similar to the reference breath, resulting in a cross-correlation value close to one (indicated by the first black dot in the bottom plot). The second highlighted pattern is very different from the reference breath and therefore results in a small cross-correlation value (indicated by the second black dot in the bottom plot). Using this cross-correlation approach, it is possible to distinguish between quiet breathing and other respiratory situations online in real-time. In particular, quiet breathing and speaking can be distinguished which makes it possible to mute stimulation when the subject attempts to speak a time when abdominal muscle stimulation would interfere with the subject's voluntary activity.

## EXPERIMENTAL EVALUATION

The automatic muscle stimulation methods described above were evaluated in experiments with tetraplegic volunteers<sup>27,28)</sup>. An overview of the main findings is given here, illustrated by example data. All experimental procedures were approved by the Research Ethics Committee of the Southern General Hospital, Glasgow, and participants gave their written informed consent.



### Methods

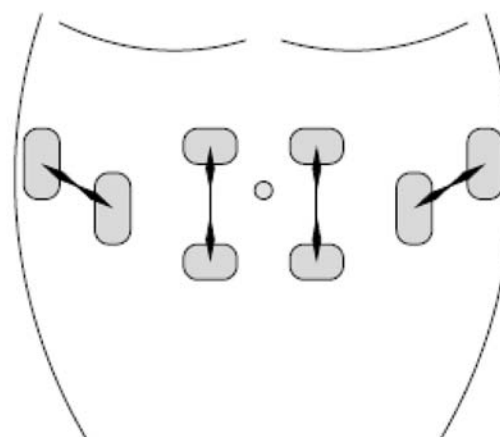
The abdominal muscles were stimulated bilaterally, using four stimulation channels such that two channels stimulated the rectus abdominis muscle, while the other two channels stimulated the lateral abdominal muscle group (mm. transversi and mm. obliqui ext. et int.) on both sides. Stimulation was delivered using self-adhesive surface electrodes (PALS, Axelgaard) connected to a neuromuscular stimulator (Motive 8, Stanmore, UK). A laptop PC was used to control the stimulator via a RS232 link, adjusting the timing and parameters of the stimulation pulses. The stimulator delivered monophasic, charge-balanced, current controlled pulses. A stimulation frequency of 50 Hz was chosen, with a constant current between 30 and 100 mA and variable pulse duration in the range of 100–400  $\mu$ s. Stimulation currents were adjusted separately for the different muscle groups and held constant throughout the experimental session. Pulse-duration was adjusted manually throughout the experiment to account for progressive muscle fatigue if necessary.

A handheld spirometer (Microloop, Micromedical, Chatham, UK) with a low dead-space full face mask (Hans Rudolph Inc., Missouri, USA) was used to record air flow at the mouth and nose of the subject as a measure of respiratory activity and to evaluate the outcome of the intervention. The spirometer was connected via a RS232 interface to the PC control the stimulator, allowing acquisition of respiratory flow in real-time. The automatic algorithms described in section III-B were implemented in Matlab/Simulink (Mathworks, Massachusetts, USA) using customised extensions for the real-time operation and hardware interface.

In addition to the air flow at the mouth and nose, a signal describing the movement of the abdomen was recorded in one subject to obtain a measure of respiratory activity. A piezoelectric respiratory effort sensor (Embletta, ResMed) was worn around the subject's abdomen and connected to the PC via a custom-made signal amplifier and a data-acquisition card (DAQCard 1200, National Instruments, Texas, USA)

#### 1) Abdominal surface stimulation results

To illustrate the functionality of abdominal surface stimulation, detailed results from a single subject (complete tetraplegia at level C4, aged 16,



**Fig. 4.** Electrode positions. The association of the electrodes with the four stimulation channels is indicated by the black lines. The umbilicus and xiphoid process are shown as landmarks.

12 months post-injury) are presented. Fig. 2a shows the results obtained during quiet breathing. The top graph (Fig. 3) shows the air flow as the respiratory activity signal, with positive flow corresponding to expiration. The bottom graph (Fig. 3) depicts the respiratory volume obtained by integrating the corresponding flow signal. The volume was re-initialised to zero for each breath at the beginning of expiration. The peak volume during each breath therefore corresponds to the maximal expiratory volume obtained. The bold horizontal lines show the periods when stimulation was applied. Fig. 4 shows data from five breaths: breaths 1, 2, 4 and 6 were made with the assistance of abdominal stimulation, while breaths 3 and 5 are unassisted. It can be clearly seen how the stimulation resulted in an additional second peak in the expiratory flow which is absent in the unassisted breaths. The corresponding levels of peak expiratory volume were considerably higher for breaths with abdominal muscle stimulation.

Results obtained during forced expiration are depicted in Fig. 5. Four breaths are shown, with the 2nd and 3rd breath being assisted by stimulation. The shape of the flow curve is similar to that obtained for quiet breathing, with a clear additional peak during expiration which is the result of the abdominal stimulation. The difference between assisted and unassisted breathing is not as considerable as for quiet breathing, although abdominal stimulation led to a marked increase in the expiratory peak volume of subject.

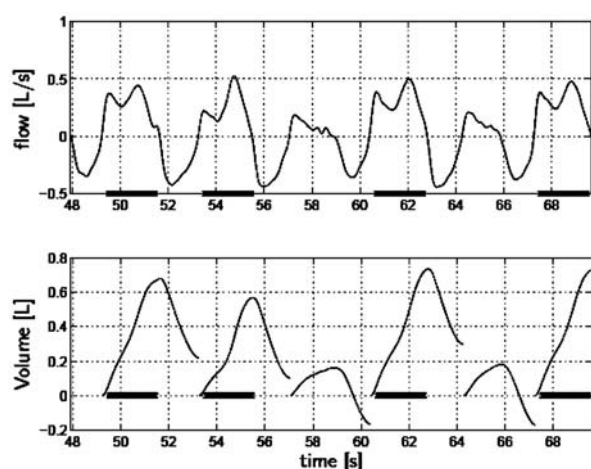


Fig. 5. Respiratory flow (top) and expiratory volume (bottom) during quiet breathing, with and without abdominal stimulation. Periods of stimulation are indicated by bold black lines.

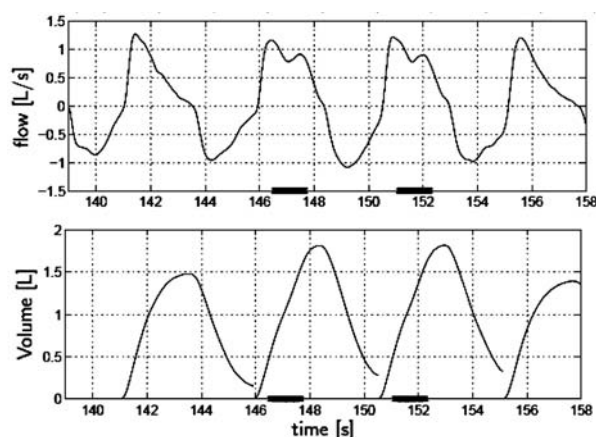


Fig. 6. Respiratory flow (top) and expiratory volume (bottom) during forced expiration, with and without abdominal stimulation. Periods of stimulation are indicated by bold black lines.

Results for abdominal stimulation during cough are shown in Fig. 6. For an effective cough, a high peak expiratory flow is of primary importance while the tidal volume achieved is less significant. For this reason only flow data are shown here. A total of 8 coughs are shown, with abdominal stimulation applied during coughs 1, 6 and 8. It is clear that these assisted coughs also resulted in the largest peak expiratory flow, indicating that abdominal muscle stimulation can lead to a more effective cough.

The results shown in Fig. 4–6 were obtained

using the automatic stimulation system described in section III-B with direct measurement of the air flow as the respiratory activity signal. Fig. 7 illustrates the use of a respiratory effort belt as an alternative way to measure breathing activity. The top graph shows the signal obtained from this sensor. Since the respiratory effort belt provides a measure of the change of the abdominal circumference, the resulting signal represents relative respiratory volume. The bottom graph in Fig. 7 shows the sensor signal differentiated with respect to time, together with the corresponding signal from the spirometer. The differentiated sensor signal now represents change of volume which is equivalent to measurement of the air flow. The differentiated sensor signal follows the flow signal closely, both during stimulated breaths (breaths 1 and 2) and unassisted breath (breaths 3 and 4).

## 2) Effectiveness of abdominal stimulation

Four subjects participated in the evaluation of the effectiveness of abdominal stimulation. All subjects had complete tetraplegia (level C4–C6, 3 months–5 years post injury) secondary to a spinal cord injury. They were aged between 16 and 49 years old. The automatic system was able to correctly differentiate between attempts to cough and quiet breathing situations in all subjects throughout the experiments, without inappropriate stimulation which would have interfered with their voluntary breathing activity. The system was well tolerated by all the subjects. We measured expiratory tidal volume together with respiratory rate and minute ventilation during periods of quiet breathing lasting up to 5 min. During these measurement periods, breathing with stimulation alternated with unassisted breathing. It was observed that tidal volume increased in all subjects when stimulation was applied, although the level of increase varied between 50 and 230 ml. The respiratory rate was generally slightly reduced however, minute ventilation still increased by between 680 ml/min to 2.07 L/min. During coughing, peak expiratory flow was measured during assisted and unassisted cough. It was observed that peak flow increased in all subjects when stimulation was applied. The level of increase varied considerably between subjects, ranging from 40 and 490 ml/s. This evaluation shows that abdominal surface stimulation can provide an

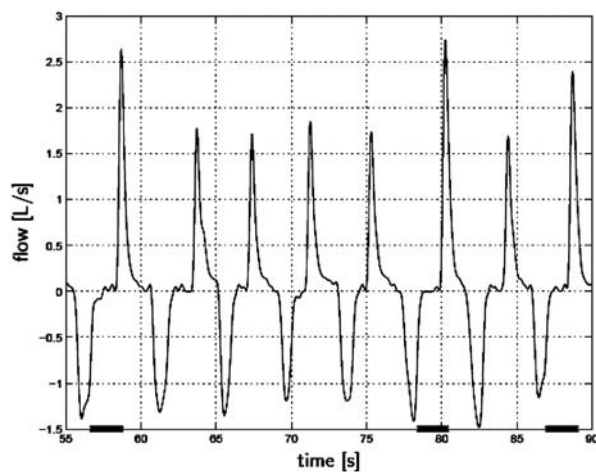


Fig. 7. Respiratory flow during coughing, with and without abdominal stimulation. Periods of stimulation are indicated by bold black lines.

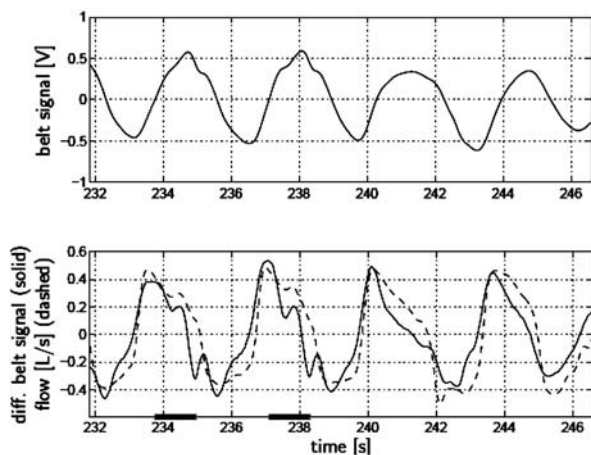


Fig. 8. Measurement of breathing activity using a respiratory effort sensor: Belt signal (top) and differentiated belt signal together with the respiratory flow (bottom). Periods of stimulation are indicated by bold black lines.

effective means of increasing respiratory function in tetraplegia. The automatic system used here allowed the precise and repeatable timing of the stimulation which is particularly important when evaluating the effectiveness of the stimulation in experiments over several minutes where manual triggering of the stimulation becomes impractical. The results show that the effectiveness of abdominal surface stimulation can vary widely between subjects. In particular, in one of the subjects, stimulation only resulted in very limited improvements in respiratory function (50 ml

increase in tidal volume during quiet breathing and 40 ml/s increase in cough peak flow). The clinical significance of such small increases remain doubtful. The remaining subjects, however, benefitted from much larger increases in respiratory function. It is clear that in these subjects the stimulation resulted in clinically significant outcomes.

## DISCUSSION

A number of studies have demonstrated that stimulation of the abdominal muscles using surface electrodes can lead to marked improvements in respiratory function in tetraplegia. As abdominal surface stimulation activates the main expiratory muscles which are typically paralysed in people with a spinal cord injury at for cervical level, its main application is in the support of cough function. It was also shown that respiration during normal breathing can benefit since the increased expiratory volume leads to expiration below the functional residual volume, with corresponding larger inspiratory volume during the following breath. Abdominal stimulation is mainly used for people who can breath voluntarily and are not ventilator dependent which poses the task of a suitable system to trigger the stimulation at the appropriate time to synchronise it with the user's own breathing. A number of approaches exist, ranging from triggering the stimulation manually to automatic systems which use real-time measurement of the respiratory activity of the user to derive the trigger timing.

### A. Clinical significance

We foresee several areas for possible clinical applications of abdominal surface stimulation within the spinal-cord injury population.

*Acute injury:* There may be scope for using the technique in acute injury, to provide ventilatory support to reduce the likelihood of more invasive techniques. Half of all tetraplegics admitted to our unit require intubation and ventilation in the early stages of injury and this treatment prolongs their hospital stay and rehabilitation time by many weeks. Early use of surface abdominal Functional Electrical Stimulation (FES) has the potential to augment patients residual capacity to breathe and to cough, and may reduce the necessity of ventilation. *Weaning:* Most patients can be weaned from the



ventilator but this is often a tedious process lasting several weeks<sup>31)</sup>. Surface FES of abdominal muscles could be used as part of the weaning program to potentially reduce weaning times and overall length of stay.

*Coughing:* Current airway clearance measures in tetraplegia include care-given assisted coughs, use of suction machinery with tracheal catheters, or in-exsufflators such as the Cough Assist device (J.H. Emerson, Cambridge, MA, USA). All these techniques rely on help from another person. It has been demonstrated that abdominal surface FES can administer a cough independently without the need for a care-giver. Using the patient's own muscles may also provide a more natural and physiological cough than the above techniques.

*Long-term ventilation:* The use of surface abdominal FES in established ventilator dependent tetraplegia remains speculative. Similar to Kandare et al.<sup>16)</sup>, we have found that the technique can provide short-lived ventilation in an apnoeic patient (unpublished observation), but it remains unclear how long such ventilation can be maintained. It seems unlikely that the technique would provide complete independence from a mechanical ventilator although it might provide short-term support with the advantage of augmented coughing. Surface stimulation could also provide at least a part-time alternative for the many patients with high tetraplegia who have damaged phrenic nerves and are therefore unsuitable for electropacing.

#### *B. Future development and directions*

Most studies have focused on evaluating the acute effects of abdominal stimulation on respiratory function. It is, however, known that the use of electrical neuromuscular stimulation can also reduce muscle atrophy and may have a training effect<sup>32)</sup>. Zupan et al.<sup>24)</sup> used a regime combining respiratory muscle training with short periods of stimulation. Lin et al.<sup>33)</sup> used magnetic stimulation to condition expiratory muscles, resulting in improved expiratory muscle strength. Lee et al.<sup>34)</sup> implemented an intensive training regime (daily 20–30 min for 4 weeks) in a case study with very promising results. It is unclear whether these outcomes can be repeated in the wider tetraplegic population, and the formulation of effective training regimes remains an open question.

From the available studies it has emerged that improvements in respiratory function can vary

widely among patients. Criteria should therefore be identified which can characterize patients who would best respond to stimulus and determine those groups of patients which may only benefit to a limited extent.

In their current form the described systems remain largely experimental and require experienced bioengineering personnel to set up and operate. Further work is necessary to improve software and hardware designs to allow a care-giver to initiate treatment after attaching electrodes and the breathing sensor. Alternatively, a simple chin-switch system such as that described by Taylor et al.<sup>23)</sup> would be most suitable for everyday use outside clinical or research environments. Until commercial systems become available usage is likely to remain within institutions. Abdominal muscle stimulation can provide a simple yet effective intervention for improving respiratory function in the tetraplegic population, potentially contributing to reducing the risk of respiratory complications in this patient group. Surface stimulation remains an attractive option as it is easy to apply by care-givers, while technological developments may lead to systems which are both functional and easy to use for the patients and their carers.

#### REFERENCES

- 1) Zimmer MB, Nantwi K, Goshgarian HG: Effect of spinal cord injury on the respiratory system: basic research and current clinical treatment options. *J Spinal Cord Med.* 2007; 30(4): 319–330.
- 2) Lindsey L: Respiratory complications in SCI. Research Review [serial online] 1: 1–4, available from <http://www.spinalcord.uab.edu>, 1999.
- 3) Cardenas DD, Hoffman JM, Kirshblum S, et al.: Etiology and incidence of rehospitalization after traumatic spinal cord injury: a multicenter analysis. *Arch Phys Med Rehabil.* 2004; 85(11): 1757–1763.
- 4) McKinley WO, Jackson AB, Cardenas DD, et al.: Long-term medical complications after traumatic spinal cord injury: a regional model systems analysis. *Arch Phys Med Rehabil.* 1999; 80(11): 1402–1410.
- 5) DeVivo MJ, Krause JS, Lammertse DP: Recent trends in mortality and causes of death among persons with spinal cord injury. *Arch Phys Med Rehabil.* 1999; 80(11): 1411–1419.
- 6) Winslow C, Rozovsky J: Effect of spinal cord injury on the respiratory system. *Am J Phys Med Rehabil.* 2003; 82(10): 803–814.
- 7) Wang Y, Jaeger RJ, Yarkony GM, et al.: Cough in spinal cord injured patients: the relationship between

- motor level and peak expiratory flow. *Spinal Cord*, 1997, 35(5): 299–302.
- 8) Creasey GH, Eleftheriades J, DiMarco AF, et al.: Electrical stimulation to restore respiration. *J Rehabil Res Dev*, 1996, 33(2): 123–132.
- 9) DiMarco F: Neural prostheses in the respiratory system. *J Rehabil Res Dev*, 2001, 38(6): 601–607.
- 10) DiMarco AF: Restoration of respiratory muscle function following spinal cord injury. review of electrical and magnetic stimulation techniques. *Respir Physiol Neurobiol*, 2005, 147(2–3): 273–287.
- 11) DiMarco F, Takaoka Y, Kowalski KE: Combined intercostals and diaphragm pacing to provide artificial ventilation in patients with tetraplegia. *Arch Phys Med Rehabil*, 2005, 86(6): 1200–1207.
- 12) Linder SH: Functional electrical stimulation to enhance cough in quadriplegia. *Chest*, 1993, 103(1): 166–169.
- 13) Jaeger RJ, Turba RM, Yarkony GM, et al.: Cough in spinal cord injured patients: comparison of three methods to produce cough. *Arch Phys Med Rehabil*, 1993, 74(12): 1358–1361.
- 14) Langbein WE, Maloney C, Kandare F, et al.: Pulmonary function testing in spinal cord injury: effects of abdominal muscle stimulation. *J Rehabil Res Dev*, 2001, 38(5): 591–597.
- 15) DiMarco AF, Romaniuk JR, Kowalski KE, et al.: Efficacy of combined inspiratory intercostal and expiratory muscle pacing to maintain artificial ventilation. *Am J Respir Crit Care Med*, 1997, 156(1): 122–126.
- 16) Kandare F, Exner G, Jeraj J, et al.: Breathing induced by abdominal muscle stimulation in individuals without spontaneous ventilation. *Neuromodulation*, 2002, 5(3): 180–185.
- 17) Bell S, Shaw-Dunn J, Gollee H, et al.: Improving respiration in patients with tetraplegia by functional electrical stimulation: An anatomical perspective. *Clin Anat*, 2007, 20(6): 689–693.
- 18) Lim J, Gorman RB, Saboisky JP, et al.: Optimal electrode placement for noninvasive electrical stimulation of human abdominal muscles. *J Appl Physiol*, 2007, 102(4): 1612–1617.
- 19) DiMarco F, Kowalski KE, Geertman RT, et al.: Spinal cord stimulation: a new method to produce an effective cough in patients with spinal cord injury. *Am J Respir Crit Care Med*, 2006, 173(12): 1386–1389.
- 20) Lin VW, Deng X, Lee Y-S, et al.: Stimulation of the expiratory muscles using microstimulators. *IEEE Trans Neural Sys Rehab Eng*, 2008, 16(4): 416–420.
- 21) Polkey MI, Luo Y, Guleria R, et al.: Functional magnetic stimulation of the abdominal muscles in humans. *Am J Respir Crit Care Med*, 1999, 160(2): 513–522.
- 22) Lin VW, Hsieh C, Hsiao IN, et al.: Functional magnetic stimulation of expiratory muscles: a noninvasive and new method for restoring cough. *J Appl Physiol*, 1998, 84(4): 1144–1150.
- 23) Taylor PN, Tromans AM, Harris KR, et al.: Electrical stimulation of abdominal muscles for control of blood pressure and augmentation of cough in a C3/4 level tetraplegic. *Spinal Cord*, 2002, 40(1): 34–36.
- 24) Zupan A, Savrin R, Erjavec T, et al.: Effects of respiratory muscle training and electrical stimulation of abdominal muscles on respiratory capabilities in tetraplegic patients. *Spinal Cord*, 1997, 35(8): 540–545.
- 25) Sorli J, Kandare F, Jaeger RJ, et al.: Ventilatory assistance using electrical stimulation of abdominal muscles. *IEEE Trans Rehab Eng*, 1996, 4(1): 1–6.
- 26) Spivak E, Keren O, Niv D, et al.: Electromyographic signal-activated functional electrical stimulation of abdominal muscles: the effect on pulmonary function in patients with tetraplegia. *Spinal Cord*, 2007, 45(7): 491–495.
- 27) Gollee H, Hunt KJ, Allan DB, et al.: A control system for automatic electrical stimulation of abdominal muscles to assist respiratory function in tetraplegia. *Med Eng Phys*, 2007, 29(7): 799–807.
- 28) Gollee H, Hunt KJ, Allan DB, et al.: Automatic electrical stimulation of abdominal wall muscles increases tidal volume and cough peak flow in tetraplegia. *Technology and Health Care*, 2008, 16(4): 273–281.
- 29) Dingli K, Coleman EL, Vennelle M, et al.: Evaluation of a portable device for diagnosing the sleep apnoea/hypopnoea syndrome. *Eur Respir J*, 2003, 21(2): 253–259.
- 30) Gollee H, Chen W: Real-time detection of respiratory activity using an inertial measurement unit. *Cont Pronc IEEE Eng Med Biol Soc*, 2007: 2230–2233.
- 31) Peterson WP, Barbalata L, Brooks CA, et al.: The effect of tidal volumes on the time to wean persons with high tetraplegia from ventilators. *Spinal Cord*, 1999, 37(4): 284–288.
- 32) Sköld C, Lönn L, Harms-Ringdahl K, et al.: Effects of functional electrical stimulation training for six months on body composition and spasticity in motor complete tetraplegic spinal cord-injured individuals. *J Rehabil Med*, 2002, 34(1): 25–32.
- 33) Lin VW, Hsiao IN, Zhu E, et al.: Functional magnetic stimulation for conditioning of expiratory muscles in patients with spinal cord injury. *Arch Phys Med Rehabil*, 2001, 82(2): 162–166.
- 34) Lee BB, Boswell-Ruys C, Butler JE, et al.: Surface functional electrical stimulation of the abdominal muscles to enhance cough and assist tracheostomy decannulation after high-level spinal cord injury. *J Spinal Cord Med*, 2008, 31(1): 78–82.