Abdominal stimulation for respiratory support in tetraplegia: a tutorial review

H. Gollee*, K. J. Hunt, M. H. Fraser, and A. N. McLean

Abstract—Neuromuscular stimulation of the abdominal wall muscles can provide respiratory support in tetraplegia, where the main expiratory muscles are affected by paralysis. Stimulation may be applied by simple surface stimulation, resulting in a uniform muscle contraction which can help to improve expiratory function for coughing and breathing. 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. Clinical significance and applications are discussed and future developments are outlined.

Index Terms—Electrical stimulation, Pulmonary function, Tetraplegia, Abdominal muscle function

I. INTRODUCTION

Respiratory complications are a leading cause of morbidity and mortality in people with spinal cord injury (SCI) [1]–[3]. 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 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 [4]. In particular, the reduction in cough peak flow affects the ability to clear the airways [5], leading to an increased likelihood of respiratory infections in individuals with chronic tetraplegia [2].

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 for 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.

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DOI:10.2298/JAC0802085G

II. BACKGROUND

For ventilator dependent patients with an injury at level C1-C2, phrenic nerve pacing to stimulate the diaphragm is an established technique to improve breathing function and to enable independence from mechanical ventilators which can reduce the risk of respiratory infections [6]–[8]. 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 [9]. 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 [6].

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 [5].

It has been shown that stimulation of abdominal muscles during expiration can improve respiratory function [10]–[13]. This technique can enhanced 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 causes a reduction of lung volume below the functional residual capacity, and the subsequent passive recoil during inspiration can result in an increase of tidal volume.

Stimulation of the abdominal muscles is typically used in tetraplegic individuals with spontaneous breathing, although this technique has been applied in individuals who are unable to breathe spontaneously [14]. The abdominal muscles are typically stimulated through surface electrodes which are easy to apply, and stimulation results in a uniform, well-defined muscle response [15], [16]. Alternatively, stimulation can be delivered by spinal cord stimulation using epidural electrodes [17] or microstimulators [18], or by magnetic stimulation of the thoracic nerve roots [19], [20].
III. ABDOMINAL MUSCLE STIMULATION

A. Overview

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 [6], 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 [21] or a trigger which is operated by the therapist [22], as illustrated at the top of figure 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 setup for such a system is shown at the bottom of figure 1.

This approach was used by Šorli et al. [23] and Spivak et al. [24] for specific respiratory situations. While the study reported in [23] focused on quiet breathing their system was not applicable for cough induction. On the other side, the study in [24] focused on a system to generate an automatic trigger for cough, but did not consider other breathing situations.

Gollee et al. [25] have extended this concept 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 airflow 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 is suitable to deliver 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 [26], 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 airflow 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. [24] 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 to obtain a measurement for the respiratory activity include the direct observation of the abdominal and chest movement. This can be achieved by using a respiratory effort sensor (plethysmographic belt) commonly employed for the diagnosis of sleep apnoea [27]. An alternative approach suggests the use of an inertial measurement unit to obtain a signal of abdominal movement relating to respiration [28].

B. 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 with the limitation that active user intervention is required. Alternatively, stimulation can be generated automatically, based on a 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 will also allow to mute 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 other variations in the user’s response.

In this paper we will focus on the first two points. The stimulation parameter 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 figure 2 for a quiet breathing situation and for a cough. Each figure shows the respiratory activity (measured as the airflow at the mouth) during a single breath, starting with inspiration. Note that negative flow corresponds to inspiration while a positive flow indicates expiration.
During quiet breathing the stimulation burst should support expiration. A suitable trigger point is therefore the beginning of expiration (see figure 2a). In terms 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 airflow resulting from the stimulation can be clearly observed in figure 2a, starting at approximately 50s. Note that there is a delay of nearly 0.5s 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 a sufficient abdominal pressure to generate a 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 figure 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 increase 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 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 airflow at the mouth as the signal representing respiratory activity. It is, however, possible to adapt these approaches to different measurements which represent 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 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 of this signal 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 this activity. It is therefore necessary to obtain additional features to characterise quiet breathing. One approach described in [25] 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 figure 3 where a reference breath (shown in the top graph) was obtained by averaging 60s 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 figure 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 when abdominal muscle stimulation would interfere with the subject’s voluntary activity.

IV. EXPERIMENTAL EVALUATION

The automatic muscle stimulation methods described above were evaluated in experiment with tetraplegic volunteers [25], [26]. 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 written informed consent.

A. Methods

The abdominal muscles were stimulated bilaterally, using four stimulation channels as illustrated in figure 4: two channels stimulated the mm. rectus abdominis, 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 50Hz was chosen, with a constant current between 30 and 100mA and a variable pulse-duration in the range of 100-400µs. 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 airflow 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 same PC which controlled 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 real-time operation and hardware interface.

In addition to the airflow 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, 12 months post-injury) are presented.

Figure 2a shows results obtained during quiet breathing. The top graph shows the airflow as the respiratory activity signal, with positive flow corresponding to expiration. The bottom graph 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. Figure 5 shows data from five breaths: breaths 1, 2, 4 and 6 are with assistance by abdominal stimulation, while breaths 3 and 5 are unassisted. It can be clearly seen how the stimulation results in an additional second peak in the expiratory flow which is absent in the unassisted breaths. The corresponding levels of peak expiratory volume are considerably higher for those breaths with abdominal muscle stimulation.

Results obtained during forced expiration are depicted in figure 6. Four breaths are shown, with the 2nd and 3rd breath being assisted by stimulation. A similar shape of the flow to that obtained for quiet breathing can be observed, 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 leads to a marked increase in expiratory peak volume in this subject.

Results for abdominal stimulation during cough are shown in figure 7. 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 cough 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 show in figures 5–7 were obtained using the automatic stimulation system described in section III-B with a direct measurement of the airflow as the respiratory activity signal. Figure 8 illustrates the use of 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 figure 8 shows the sensor signal differentiated with respect to time, together with the corresponding signal from the spirometer. The differentiated sensor signal now represents changes of volume which is equivalent to measurement of the airflow. 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, 3months – 5 years post injury) secondary to a spinal cord injury. They were between 16 and 49 years old.

The automatic system was able to correctly differentiate attempts to cough and quiet breathing situations in all subjects throughout the experiments, without inappropriate stimulation.
which would interfere with their voluntary breathing activity. The system was well tolerated in all 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 could be 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 could be observed that peak flow increased in all subjects when stimulation was applied. The level of increase varied considerably between subjects, with a range between 40 and 490 ml/s.

This evaluation shows that abdominal surface stimulation can provide an effective means to increase respiratory function in tetraplegia. The automatic system used here allows 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, benefited from much larger increases in respiratory function. It is clear that in these subjects the stimulation could result in clinically significant outcome.

V. DISCUSSION

A number of studies have demonstrated that stimulation of the abdominal muscles using surface electrodes can lead to marked improvements of respiratory function in tetraplegia. As this method activates the main expiratory muscles which are typically paralysed in people with a spinal cord injury at cervical level, the main application is in the support of cough function. It has also been 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 in people who can breathe 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 a 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 injured 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 FES has the potential to augment the patients residual capacity to breathe and to cough, and may reduce the likelihood of ventilation.

Weaning: Most patients can be weaned from the ventilator but this is often a tedious process lasting several weeks [29]. Surface FES of abdominal muscles could be used as part of the weaning program to potentially reduce weaning times and overall stays.

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 CoughAssist 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 of the 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. [14], 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 could be maintained. It seems unlikely that the technique could 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 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 [30]. Zupan et al. [22] used a regime combining respiratory muscle training with short periods of stimulation. Lin et al. [31] used magnetic stimulation to condition expiratory muscles, resulting in improved expiratory muscle strength. Lee et al. [32] 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 remain open questions.

From the available studies it has emerged that improvements in respiratory function can vary widely in different patients. Criteria should therefore be identified which can characterise patients who will best respond to the technique 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 setup and operate. Further work is necessary to improve software and hardware designs which would allow a care-giver to initiate treatment after attaching electrodes and breathing sensor. Alternatively, a simple chin-switch system such as that described by Taylor et. al [21] could 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 to improve respiratory function in the tetraplegic population, potentially contribute 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 carers.

REFERENCES


