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Detection of Breathing Phases*

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Abstract: The electrical stimulation systems, for the needs of artificial ventilation are in the grater or lesser extent, in commercial use since 1970's. Apart from development of new methods of stimulation and hardware solutions, the key role in development of such systems is reliable detection of phases during breathing. This paper gives the review of stimulation methods, physiology of respiratory system and one of the possible solutions, proposed by the authors.

Keywords: Functional electrical stimulation, Detection of breathing phases, Artificial ventilation, Stimulation methods, Physiology of respiratory.

1 Introduction

Respiratory complications are the leading cause of illness and death in patients with spinal cord injuries. In patients with spinal injuries in cervical level, all four limbs are affected, resulting in tetraplegia with increased risk of respiratory complications for nature of this injuries result also in partial or complete paralysis of the breathing muscles. This can lead to reduction of flow during cough, which affects the ability of cleaning the airways, leading to increased probability of respiratory infections in patients with chronic tetraplegia.

2 Physiology of Respiratory System

Because of its gas exchange function, respiratory system is one of the most important physiological systems in human body. Gas exchange is considered crucial for the elimination of unhealthy gases, which are produced by burning the oxygen on the cellular level and enrichment of the blood with oxygen.

Energy for the gas exchange process is obtained by actions of two groups of muscles, so-called inspiration and expiration muscles. Contraction of the inspiration muscles leads to increase in tidal volume and decrease of the pressure, so the air enters the lungs. Main muscle of inspiration is the

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diaphragm, which provides the biggest changes in volume and pressure, of thoracal part by its movement. When the complete breathing process is done only by the movement of diaphragm, this kind of breathing is called quiet breathing and it represents the normal gas exchange process, which happens daily. Apart from diaphragm, inspiration muscles are also the external intercostals and some neck and head muscles. Expiration muscles are mainly inactive during quite breathing. This group of muscles is solely used during intensive air discharges, for an example cough or sneezing. The main expiratory muscles are abdominal muscles but the internal intercostals are also used during expiration. Respiratory muscles are shown in Fig. 1.

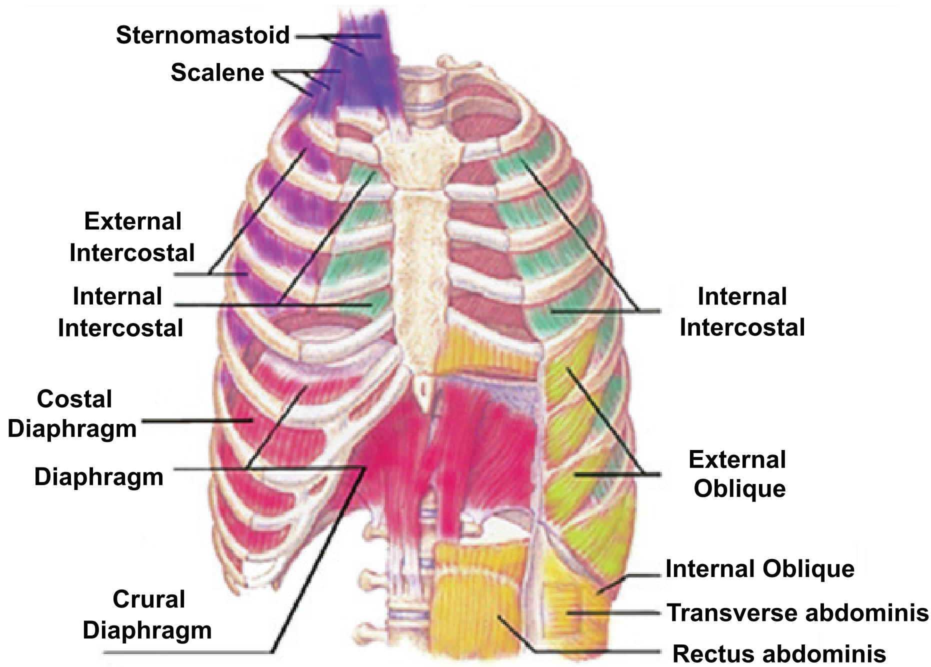

Fig. 1 – *Respiratory muscles* [10].

3 Neural Breathing Prothesis

For the artificial ventilation dependant patients, with injuries at C1-C2 levels, technique of phrenic nerve (which innervates the diaphragm) stimulation is developed. This technique improves breathing function and gives patients independence of mechanical ventilation, which automatically reduces the risk of respiratory infections. However, this technique is often not applicable in tetraplegic patients with injuries on levels just below C2, due to the minor motor-neural damage of the phrenic nerve, which is innervated between third and fourth cervical level.

In this case, stimulation of intercostals can be an alternative or additional way of improvement of breathing process. Combined functions in inspiration and expiration of the intercostals can be an obstacle in gaining satisfactory tidal volumes by stimulating this group of muscles. In addition, both of these methods are hard for implementation by transcutaneous techniques and require implantable stimulation electrodes.

Patients with tetraplegia, which have lesions on lower levels, are usually capable of voluntary breathing, and are mostly independent of mechanical ventilation. However, their breathing capacity is further reduced due to paralysis of inspiratory and expiratory muscles. Paralysis also affects the abdominal muscles, which are the main expiratory muscles, and their capacity to forcefully expire is reduced.

It was shown that stimulation of abdominal muscles during expiration can improve respiratory function. This technique can amplify coughing, for contraction of respiratory muscles leads to increase of respiratory pressure, which consequently leads to increase of expiration. Stimulation of abdominal muscles is most often used in patients that have voluntary breathing ability, although this technique is used also in patients who cannot breathe spontaneously. One of the great advantages of this method is that the stimulation is performed by surface electrodes placed on the skin.

The only stimulation method (of those previously described) that is commercially available today is phrenic nerve stimulation method, while the other two are still in testing phase.

Although all three methods have different stimulation techniques and stimulation regions, they have one mutual flaw the asynchronous work of the stimulator. Disadvantage of this kind of approach is mainly in constant parameters of stimulation, not regarding the patient’s momentary needs i.e. without following physiological parameters of breathing.

4 Detection of Breathing Phases

Reliable detection of phases during respiratory process, by using the simple sensors, would provide enormous amount of possibilities in projecting future systems for artificial ventilation. Under detecting phases during breathing, it is mainly considered expiration and inspiration, or detection of their start, end and duration and certain characterization of these processes. In addition, it would be useful if certain sub-phases and current events during inspiration could be isolated (such as moment of maximum flow during expiration). Any reliable information on these sub-phases and events would be of great importance when designing systems that would have the role of support and assistive breathing systems. If they would show satisfactory reliability of sensory information in the detection and prediction of these stages, the results would have great significance for the creation of advanced automated systems that would be able to monitor the physiological process of breathing and synchronize their work with spontaneous respiration.

This kind of information is required when creating algorithms for such systems and greatly contributes to their reliability and accuracy. Another important issue in this case would be the differentiation of phenomena such as coughing or sneezing, which are also associated with the process of breathing, but they should be well separated from normal inspiration and expiration. Otherwise, it could cause the wrong action of the device, thereby undermine the process of breathing, and cause discomfort. It is also important to detect the patient’s speech, because the speech itself may be treated as a phase of breathing. Relevant fact regarding speech is that in these moments there is no breathing, so constant stimulation during the speech led only to inconvenience of the patient. All of the above results in ideas and motivation for research and further advances in this field for designing comfortable (as less tying for the patient's daily activities and easy to use), non-invasive, clinically attainable and commercially competitive device, with simple and easily applicable sensor systems.

5 Different Methods of Detection of Phases during Breathing

Currently, phase detection of the breathing process is being done only spirometer, the device for direct measurement of the flow. All systems that use FES to improve breathing function, for validation of their results, or possibly synchronous stimulation are using this device. This method has the advantage of a direct measurement of airflow, which is actually the parameter of interest, since with it we may differ phases of speech and cough [16]. However, the disadvantage of this device is a mask that is placed on the face, so the patient is unable to speak or eat during measurements; also, the dimensions of the device are not small. Therefore, there is a need for developing new techniques that would be more mobile and gave the patient greater comfort in everyday life.

Currently, the newest research in this field include the development of systems for the detection, which would be realized by using measurements of blood oxygen saturation using pulse oximetre and systems based on electromyography (EMG), i.e. electrical activity of muscles. During the last decades, surface EMG of respiratory muscles has been used in several research and clinical studies, both in animals and in humans [17, 18]. Monitoring activities of diaphragm and the intercostal muscular system is one of the most direct methods for collecting information about the function of respiratory muscles [19]. There are also developed algorithms to detect each cycle of breathing in experimental animals [20].

6 System for Detection of Phases during Breathing

Given all the previously mentioned, we come to the conclusion that it is necessary to develop a system that would be as simple as possible, mobile, and which minimally interferes with the patient during normal daily activities: eating, talking, etc.. One possible solution is a system (Fig 2.) of three sensors that will be explained below.

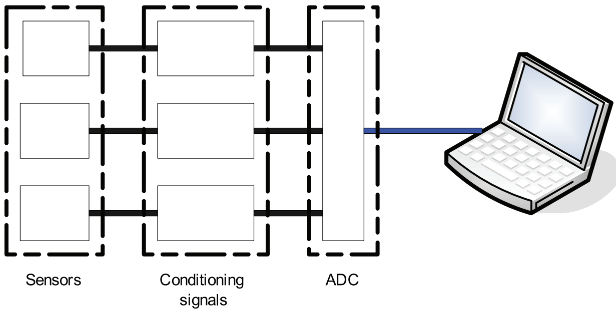

Fig. 2 – *Block scheme.*

In order to keep the mouth of the patient "free" (without the mask, for everyday use), it is impossible to apply direct measurement of the flow, so other physiological breathing properties, which can characterize phases of breathing, must be analyzed. Therefore three sensors are selected, where each has a task to detect a possible phase of the breathing. For this purpose we selected pressure sensor, thermistor - temperature sensor and microphone. Temperature sensor is used to detect breathing, using the fact that the inhaled air is cooler than the air exhaled. Scheme of the circuit in which thermistor is used is given in Fig. 3.

Pressure sensor is used as an indirect flow meter, that pressure and fluid flow are related in Bernoulli's equation (1):

$$p + \frac{\rho v^2}{2} + \rho g h = \text{const.}, \qquad (1)$$

with

p – Pressure; ρ - Fluid density; g - Gravitational acceleration;

v - Velocity of fluid; h - Distance.

In pressure measurements detection of cough or sneezing is determined by the appearance of sudden changes of pressure, and therefore the flow, which is typical for these situations [16]. Circuit scheme of pressure sensor, provided in Fig. 4.

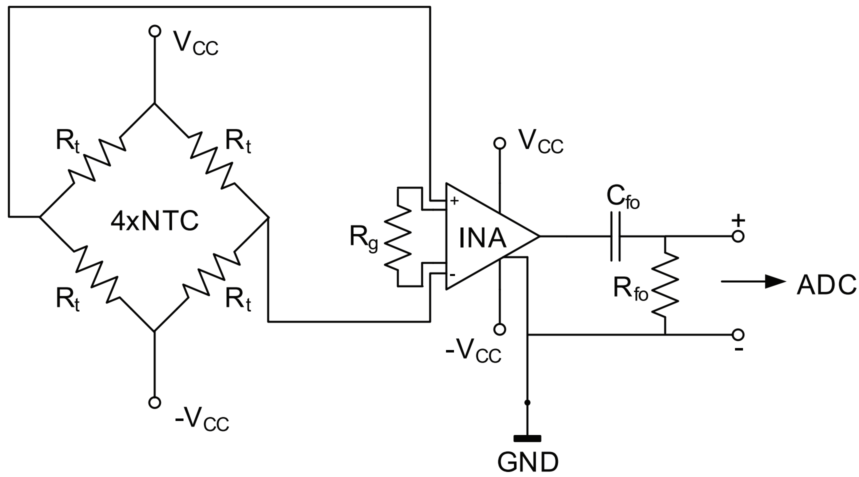

Fig. 3 – *Circuit with thermistors.*

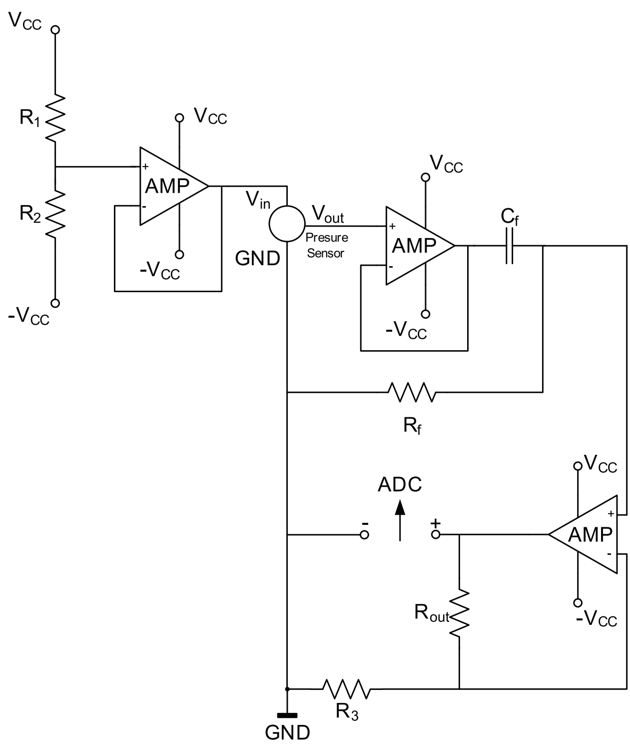

Fig. 4 – *Circuits scheme with pressure meter.*

As patient does not wear facemask, it means that it is necessary to also detect moments of talking and block the stimulation at these moments. Detection of speech is particularly demanding problem, because the noise during measurement is large and comes from many different sources. Part of the noise is the breathing itself, which may be in audible domain of the spectrum, or any sound that does not derive from the patient, as well as cases of coughing and sneezing. Therefore, it is necessary to make high-quality microphone placement near the patient's mouth, and to apply quality filtration of the signal with proper band selection before further use. Particular attention should be paid to the fact that occurrence of signal on the microphone, does not necessarily point to the existence of speech, so results of the pressure measurements should be considered first to determine that there has been no occurrence of coughing. Circuit scheme with the microphone is given in Fig. 5.

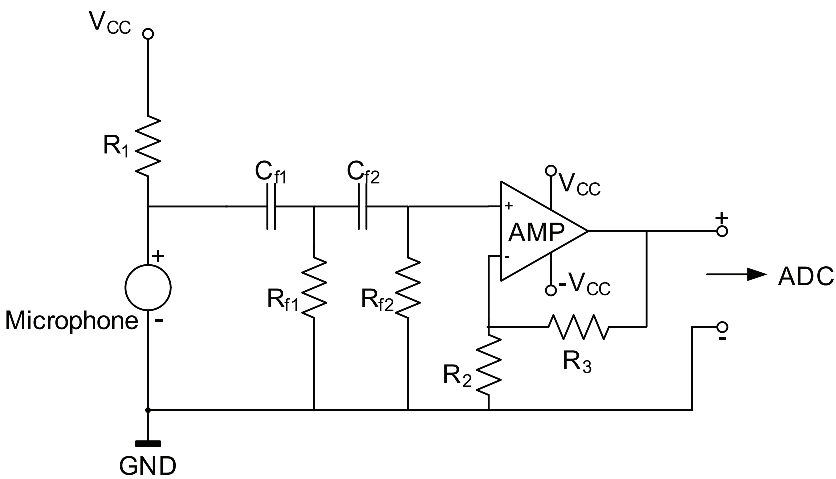

Fig. 5 – *Circuit with microphone.*

7 Results

Results obtained using the described hardware is shown in Fig. 6. Recordings were made on the healthy subject with the ability of spontaneous breathing

Signals shown in Fig. 6 are signals recorded during breathing using a pressure sensor, thermistors and microphone. In the picture are also presented the moments in which the subject speaks (thick black line on the *x*-axis) and the moments in which the subject coughs (thick gray line on *x*-axis). The rest of the recorded sequence is normal breathing. Figure shows that the thermistor and pressure signals are in phase during breathing, due to the fact that the temperature and pressure increase with expiration and decrease during inspiration. During the speech, as expected, there is no breathing, and cough occurs after the sudden change in pressure. Based on all parameters, there is a very easy way to make the difference between each phase of breathing, which is also shown.

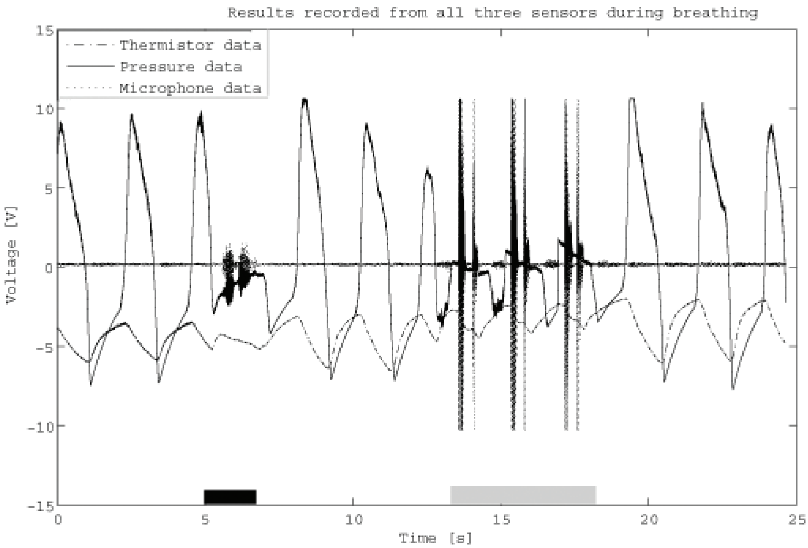

Fig. 6 – *Results recorded from all three sensors during breathing*.

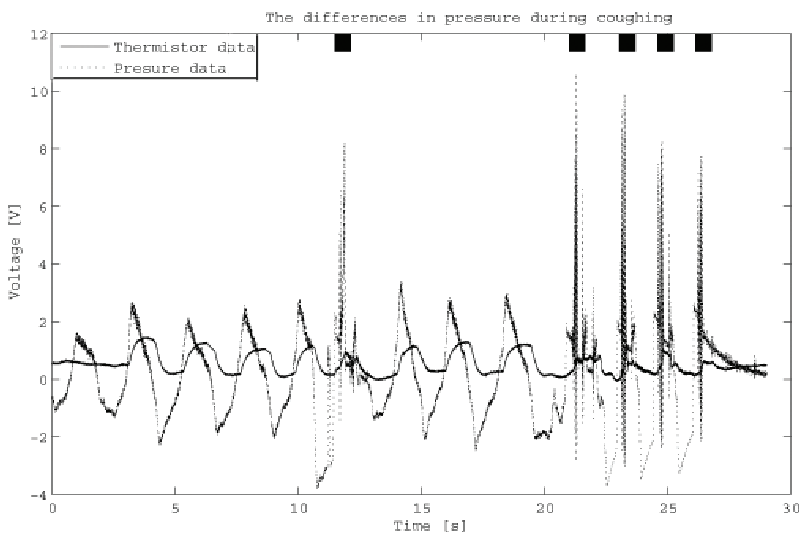

Fig. 7 – *The differences in pressure during coughing*.

Fig. 7 presents only signals from the thermistors and pressure sensor in order to see more clearly the changes of pressure at the time of cough initiation (fields marked with black spot on top of the figure). The signal from the thermistors is represented in blue and pressure with green line.

8 Conclusion

In the case of spinal cord injury leading to the loss of respiratory function it is extremely important to ensure normal functioning of the breathing process. Studies have shown that life after injury lasts to three times longer than in the case when the breathing process isn't supported. Currently, the main part of the research in the area of developing systems for the stimulation of the respiratory muscles is related to the detection and recognition of phases during breathing. The results show that the complete detection of breathing can be done using simple sensors, easy to use and small in size and weight. System of this kind would be minimally intrusive and would allow easier patient adjustment. Quality of detection is very good, errors are rare, and new solutions in the implementation could further increase the reliability and applicability of such a system. With well-selected pressure threshold, the system can, without any problems detect coughing and sneezing. Errors may occur (although rarely) during the speech and immediately after coughing, but they are short and quickly corrected (not a single case in which missed more than one pulse in the series noticed). Probably the most important characteristics of this system is that it does not include measurements on the patient's mouth, which allows normal speech, food and water intake that would significantly improve the life quality of its eventual users.

Further development of the system includes integration, minimization and preparation of mask which will carry sensors without obstruction of the mouth, and testing of the system on real patients.

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