

GERHARD A. BAER and GERHARD EXNER (eds.)

Functional Electrical Stimulation in Paralysed Respiratory Muscles
Proceedings of the Workshop held in Hamburg 11-12 November 1999

Editors

Gerhard A. Baer, M.D., Ph.D.
Tampere University Medical School (Anaesth.)
Gerhard Exner, M.D., chief
Centre for Spinal Cord Injured, BG- Traumahospital Hamburg

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University of Tampere
Sales Office
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Foreword
Proceedings of the
Workshop on Functional Electrical Stimulation of Respiratory Muscles
FESAM

It is more than 200 years from mentioning of phrenic nerve stimulation as a possible aid for resuscitation (1), more than 150 years from introduction of a functioning device for electrophrenic ventilation (2), 70 years from publication of the first series of resuscitated newborns (3), 50 years from ventilation for some days of polio victims by transcutaneous electrical stimulation of the phrenic nerves (4), and more than 30 years from the first use of a diaphragm pacer (5). The last 35 years are obviously the longest period of continuous use of phrenic nerve stimulation for ventilation of respiratory device-dependent patients; some patients have been continuously paced for more than 20 years (6).

Use of continuous electrical stimulation has become possible because of implantation of the stimulation electrodes, which circumvents possible pain and burns at the stimulation site and the cumbersome daily search for the best stimulation point. Inductive feed of energy and information to the implanted stimulator (7;8) made easier to adapt the system to the patient's needs than cardiac pacers at the same time and is still in use. The whole system for diaphragm pacing has been developed by the group lead by William W.L.Glenn at Yale University. The goal had been to free the patient from the mechanical ventilator "long-term full-time", which is possible for all suitable patients after introduction of achievements of basic muscle research (9) into clinical use (10). Certainly professor Glenn is more widely known as a pioneer (11) and expert of cardio thoracic surgery (12) and one of those involved in the development of cardiac pacing (13); diaphragm pacing is a "spin off" of this involvement.

Knowing the procedures of implantation (14) and conditioning (10) is not enough for successful diaphragm pacing. Equally necessary are a real voluntary consent of a really informed patient and his supporting group and a social back ground that guarantees future care and service. The concept of "total patient care" (6) should be reflected upon by all those simply planning "implantation of a diaphragm pacer".

Thirty years of success, if not depending on good luck mean a preceding life of professionalism. Age is no disease, but life leaves its marks. Professor Glenn participated in this workshop in giving advice on themes to cover and participants to invite but unfortunately was unable to come. He also indirectly participates in the editing of these proceedings in having left marks on the way of the editors' thinking about treatment of respiratory device-dependent patients. Professor Glenn's personal attendance at the meeting might have lead to better agreement among the participants about what to aim at and what to achieve with phrenic nerve stimulation.

At the workshop it was intended to cover all kind of muscle stimulation for respiratory use the goal being to enlarge the group of patients that can be freed from mechanical ventilation. Unfortunately participants of some groups were missing. Some will also miss in this volume the contributions of the Yale and the Liverpool Group. Professor John Elefteriades represented the clinical experience of the former group and professor Stanley Salmons the expertise in muscle stimulation. Their presence and contributions at the workshop, which helped to the success of the meeting, are gratefully acknowledged. Because both recently published large reviews of their work (15;16) it was agreed upon to avoid a duplication of their papers in this volume. On the other hand, especially worth mentioning additionally to her participation in the workshop is the contribution in this volume of professor Debra Weese-Mayer that covers in one place the development, achievements, and standards (17) of diaphragm pacing for treatment of central hypoventilation syndrome in pediatric patients.

We thank all contributors to this volume for sticking to the editors' rules and (almost to) the timetable and hope that all participants find useful the time spend for and at the meeting. We gratefully acknowledge the facilities provided by and financial support from the Foundation of Berufsgenossenschaftliche Krankenkassen, Hamburg and from Atrotech Co., Tampere for both, the workshop and the publication of the proceedings. The sponsorship of the University of Tampere allowed publishing this volume in her series.

Tampere and Hamburg, July 2000

Gerhard Baer Gerhard Exner

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Possible Indications

Baer G.A

Glenn used the term “respiratory-dependent patient” to name the patients who might profit from diaphragm pacing. In Finland we managed to get the term “respiratory device-dependent patient” into the appropriate Finnish law. I would suggest to use this term. Thus we all could agree that for a respiratory device-dependent patient a respiratory device is indicated, otherwise the patient would die.

However, we do not agree with equal certainty about the indication of a special device or method for a special patient. Whether we use a sophisticated respirator, a simple ventilator, a cuirass-type ventilator, a self-inflating breathing bag, a rocking bed, or a respiratory muscle-stimulating device, the patient will stay alive with all of these devices. Respiratory device-dependent patients even stay alive for long periods without a device once they have learned to breath by aid of their accessory muscles in the neck(1) or by frog breathing(2). All respiratory device-dependent patients should learn these methods. They are useful during nursing and may save precious time in case of failure of the respiratory device. However, both methods need voluntary effort. Thus this way of breathing means “living for respiration”. That is why patients don’t like these and other methods, which occupy most of their mental capacity.

At the time being we have no rules that could guide us to choose a special device for a certain patient. The reason is that we have no evidence-based data on the consequences of employing the different devices. During this workshop we concentrated on the evaluation of electrophrenic ventilation in comparison to IPPV. There are several aspects to evaluate when choosing the device for a special patient. Patient preference should be one. Patients like to get rid of the ventilatory tubes, of the tracheostoma, of the mechanical ventilator, which makes them prefer PNS to IPPV. However, both methods inhere objective special benefits and risks. The risk and the benefit are of different values for each patient. For one patient, two hours a day without mechanical ventilator seem to be such a big advantage that he willingly takes all risks of implantation. In most cases, only full-time electroventilation would be worth to abandon mechanical ventilation and to take the risks of implantation.

Unfortunately in most countries those who care for respiratory device-dependent patients still lack basic training in respiratory physiology and technology. Those who know about respirators, like me, lack knowledge of care for chronic patients. When choosing electrophrenic ventilation both groups have additionally to learn about stimulation neurophysiology. We hear a lot of expert opinions, read about trends in the results of the rare controlled trials and realise, in our opinion, obvious advantages of one method over the other. However, we lack evidence-based data.

Objectively a possible benefit is difficult to show because our patients form a real minority. There are two controlled studies(3;4), the results of both not being significant because of too low patient numbers in both studies, and additionally because of selection bias in the later study(4). Especially those who provide the money for devices like to see hard data and are rarely convinced by opinions, even of experts. Duration of survival, costs caused by infections, incidence of complications, costs needed for helpers, ability to care for one self might be something every body could understand. However, no data is available because there are no controlled trials of sufficient power.

Additionally, for electrophrenic ventilation, we should be able to tell the patient numerically the risk of loosing the nerve, the risk of infection of implanted devices, the risk of re-operations. These numbers are available from three previous retrospective studies, but the studies include patients from the real begin of the learning curve (5-7). Thus, the results look bad. However, we can calm down: we even lack reliable data on the risk of living with a tracheostoma.

During the following session we will hear different opinions on how to choose and what. Hopefully, we will agree on some facts. And I hope, we all will agree at least on one thing: that we urgently need evidence-based data for decision making on the indication of different respiratory devices for individual respiratory device-dependent patients.

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PNS: Indications

Meindl R.Ch, Bötzel U

In Bochum we have been very reluctant to implant electrical stimulation systems in paralysed persons although technically we are able to do it. We always ask, whether the implantation means benefit for the patient.

One motive for this may be the experience with the implantation of a diaphragm pacer 8 years ago. This ventilator-dependent patient - dens fracture in the age of 27 years - never used the pacer, although it worked well. The young man - bodyweight about 120 kg - preferred the ventilator, because he always felt dyspnoea with the pacer. He died five years after his accident. The autopsy did not reveal any lung disease caused by the ventilator.

We want to present our results with ventilator-dependent tetraplegic persons treated without functional electrical stimulation of the paralysed respiratory muscles questioning, whether the electrical stimulation causes a benefit or not. Is there any improvement of quality of life? In discussions of papers already presented the pacer can provide more mobility and independence, may reduce pneumonia and may allow the patient to speak and shout normally. We ask, whether these aims could not be reached using a ventilator, too. May be that we will be convinced, that we should implant more pacemakers after this congress. We hope, that our presentation causes an effective and spirited discussion.

Since the possibilities of resuscitation after accidents have improved markedly during the course of the last 15 years, the number of spinal cord injured patients with long lasting respiratory insufficiencies has increased steadily.

37 patients with posttraumatic ultra high tetraplegia had to be reintegrated in there formal social surroundings during the last 10 years. How did we manage without the pace-maker?

1989-1999	n=37
25 persons tetraplegia C 0-C 3	with ventilator dependency
12 persons tetraplegia C 4-C 6	with temporary ventilator dependency

accident

8 children: 2,2/2,3/3/5/6/6,5/7/8 years old	8 polytrauma
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7 adolescents: 17-22 years old	5 car accidents 1 mountain biking 1 diving accident
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10 adults: 40-70 years old

8 car accidents

1 fallen from a ladder

1 stroke

The table above shows the survey of our patients. The mechanical ventilator systems without heating using only humidity filters provide more mobility. The ventilator dependent person should drink sufficiently. The children received tea during night by a percutaneous gastric-tube. Therefore we do not see atelectasis due to mucus, which hardly can be removed. The ventilator does not disturb the propelling of the electric wheelchair. All our patients are able to manage the mechanisms by mouth. As soon as possible, our patients are removed from the ICU. 10 years ago the treatment in the ICU was about 4 1/2 month, now the average stay in the ICU is only two to three weeks. As soon as possible we train our patients to be ventilated by a tube without cuff. This tube allows speaking and shouting, eating and swallowing normally. Our logopaedist starts to train the patients for normal speaking under mechanical ventilation from the first days of treatment in the ICU. With these cases we did not see any complications in respect of pneumonia or aspiration. Our well-trained staff - including nurses and doctors, physiotherapist, logopaedist and psychologist, occupational therapist and also teachers - goes even to the swimming-pool with these patients with a tube without cuff. Actually we have four ventilator dependent children, who like to go swimming, and who compete to be under water with eyes and head.

In our department of spinal cord injury the survival rate for children is high as all children still are alive. Three of the adolescents died after five years, two of them by pulmonary complications, one from pneumonia and another from lung-abscess. In the adult group the survival rate is markedly lower. Nearly half of the adults died 1 1/2 year after trauma, but we could not find a relationship between death and lung diseases caused by the mechanical ventilation.

In the whole group we found unexpected functional recovery of the phrenic-nerve in some cases. The initial medullary lesion shown by the MRI did not allow to predict, whether the function might recover or not. For example, three of our children achieved a slight or a good functional recovery of the diaphragm. The time and extend of recovery was very different. One child achieved 12 hours of ventilator independency 6 years after the initial training starting with some minutes. His mother was training him all the years. His initial MRI was worse than the MRI of a girl, who only managed 20 minutes of ventilator independency. Thus, there is only a weak relationship between imaging results and functional recovery. One boy is able to breath on his own for one hour. All children had lesions at C 0 or C 1. Also in the groups of adolescents and adults unexpected recovery of diaphragm-function could be observed. Therefore the question has to be raised, at what time a diaphragm pacer should be implanted.

Additionally it has to be questioned whether phrenic nerve pacers should be implanted in growing children as electrode disconnections have been observed.

Phrenic Nerve Pacing - Indications

Thoma H, Girsch W**, Holle J*

Department of Biomedical Engineering & Physics, University of Vienna

*Department of Plastic and Reconstructive Surgery, Wilhelminenspital, City of Vienna

**Department of Plastic Surgery, University of Vienna

1. Introduction:

Under certain conditions phrenic nerve stimulation (PNS) is regarded as an alternative to the respirator. Therefore, PNS very seldom has a clear and imperative indication in the clinic. Today the electrodes of a phrenic pacemaker (PPM) are mostly placed into the thorax, which usually means a big operation (left and right thoracotomy or medium sternotomy). For this reason a long-term application is requested. Initial costs of a PPM are high; in the course of time costs are decreasing, compared to the costs caused by the respirator including the necessary service. Last but not least technology, function, and advantages of the PPM are not generally known, which, in turn, keeps the number of patients implanted with a PPM small, though this method has been known for more than 40 years.

The discussion will be improved if we look upon PNS from the view of rehabilitation: the respirator needs an open tracheostoma, whereas the PPM usually does not, i.e. – closed tracheostoma or none. Phrenic pacing is not noisy. Further more, Phrenic pacing needs no big tube to the throat, but an electric cable to the transmission coil fixed on the thorax or stomach area. The patients with PPM may speak nearly normal, can smell and taste food, and usually our patients gain weight during the first year after implantation. Rehabilitation of patients with PPM is much easier, ranging from an electrical wheelchair to complex devices e.g. a computer system. In the public a patient with PPM may not be identified, whereas the respirator patient is so at any time. This situation leads to the following indications.

2. Indications

The following indications to implant a phrenic nerve stimulator are based on the present state of research and development in medicine, as well as biomedical engineering.

Three main questions have to be answered for indication of a phrenic pacemaker:

1. Is it possible to stimulate both phrenic nerves and at least the right phrenic nerve and intercostal muscles?
2. Are we sure that the present situation is stable and there will be NO restitution of spontaneous breathing, as well as no denervation of the phrenic nerves because of the disease?
3. Is the patient ready to co-operate?

In case of negative results of testing the nervi phrenici via surface electrodes it is recommended to expose surgically the nervi phrenici in the neck. If we have positive results we may position the stimulation electrodes in this area, especially if we are not really convinced of our present diagnoses (fig. 1).

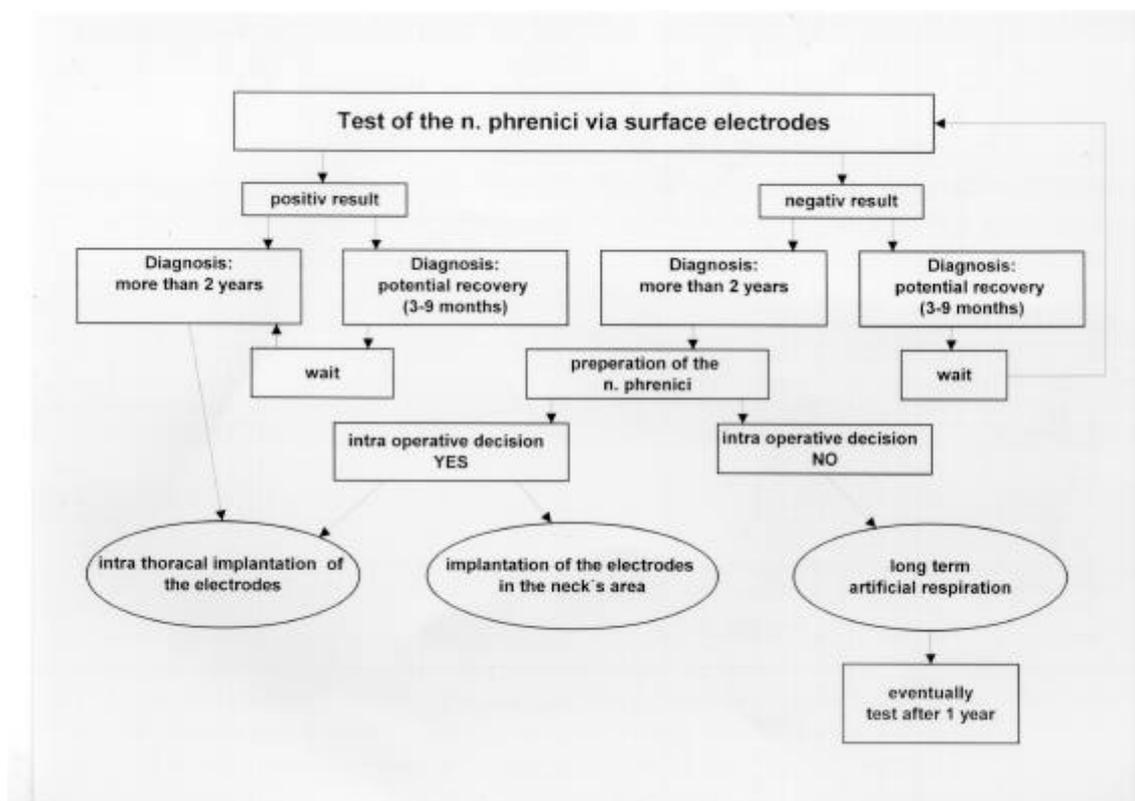


Fig. 1. Flowchart, implantation of a phrenic pacemaker (Univ. Vienna)

To be sure that a restitution of breathing by the patient will not appear we usually have to wait for up to one year to implant the phrenic pacemaker. Such delay is a big serious disadvantage for the patient.

Despite of these limitations in application for a phrenic pacemaker, we should consider the following points:

- the service of training the patient at least 6 month after operation
- status of lung function (severe pulmonary diseases may lead to a contraindication)
- lack of rehabilitation possibilities (alarm, telephone, environment control, communication aids, use of a computer,.....)
- psychic diseases, e.g. autoaggression of the patient
- risk of a nerve damage, e.g. in small children
- ecology

It is to be hoped that with the improvement of research and development in medicine as well as biomedical engineering it will be possible in the near future to reduce the waiting time for the patient by improvement of diagnosis methods and technology of the phrenic pacemaker.

3. Discussion

The indications mentioned above are the result of our work in the field of PNS. Other groups may have other indications. The indication criteria are focused to SCI – patients. Children or patients with other diseases e.g. Pickwick syndrome may have other criteria for indication.

In 1984 we started the closure of the tracheostomy in the first patient. Meanwhile tracheostomy has been closed in 7 patients each about one year after implantation. But these patients have been trained for an auxiliary breathing of 0,5 – 2 hours /Mayr 1993/. In all of these patients we never have had severe problems with the closed tracheostomy. The closed tracheostomy is one of the quality criteria of rehabilitation.

To avoid the big operation, we operated on a patient in 1996 using endoscopic surgical technique /Thoma 1999/. Another improvement concern development and test of a fully implantable 8-channel stimulator /Lanmüller 1997/.

It is to hope that these improvements will lead to a better acceptance of PNS.

Author's address:

Univ. Prof. Dr. Herwig Thoma

Institute of Biomedical Engineering & Physics, AKK- Vienna

A- 1090 Vienna, Währinger Gürtel 18-20 / 4L

Tel: +43 1-40400-1986, Fax: +43 1-40400-3988

e-mail: h.thoma@bmt.p.akh-wien.ac.at

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Nov. 1999, Abstract

Phrenic Nerve Stimulation – Indications

Exner G, Hirschfeld S
Hamburg

Summary:

Since 1987 PNS is used in the SCIC in Hamburg. PNS is one method of artificial ventilation, not the only one. There are some excluding criteria like disorders of the peripheral motoneuron, lung tissue diseases, severe brain dysfunction, and poor chances of social reintegration. In carefully selected patients PNS improves the ability to speak, provides nearly physiological ventilation, improves mobility and increases the patient's independence from medical institutions.

Key-words: ultrahigh tetraplegia - artificial ventilation - PNS
- excluding criteria list.

Acute stage:

PNS was developed to provide the possibility to get rid of mechanical ventilation for patients with ultrahigh (C0 to C2) lesions of the spinal cord (1). Due to the rapid development of the German emergency care system we see more and more patients with a lesion above C 4 since about 15 years. Before that time such patients died within or after the accident. Nowadays everybody has learned the technique of mouth-to-mouth-ventilation. Early intubation and mechanical ventilation is available. Thus such patients survive and are admitted to our special centres. Because of the fact that we cannot predict the extent of recovery all these patients have to be treated according to the rules of modern traumatology. Fixation of the unstable spine is necessary, a decompression of the spinal cord should be performed and the whole programme of early mobilization and rehabilitation is initiated. So the patients are treated with intensive chest physiotherapy combined with a mobilization programme. They are supported with electrically powered wheelchairs, which they are able to control with a joystick mechanism via an individually tailored chin- or tongue adaptator. They are transferred to an open ward to have all possibilities of reintegration within and outside of the hospital.

Indication and experiences in Hamburg:

When it is sure that there will be no recovery of spontaneous respiration we have to decide how to continue artificial ventilation. There are two possibilities: mechanical ventilation and electrical stimulation of the phrenic nerves with the implantation of a stimulation device. We have experience in both fields, in the

latter one since 1987 when we implanted our first patient. We checked the nerves percutaneously, found them perfectly working and decided to implant. Actually, we should confess that, except for the nerve check, during decision making in this patient we did all possible mistakes, which may negatively influence the outcome; details are given below. So we learned in this one case that deciding on this indication is to do very sophisticatedly and cautiously and that all information of all members of the caring team are important. Information must be collected and evaluated precisely. In any case of doubt specialists should be involved. Today we try to make our conclusions with all team-members present. However, the final decision has to be done by the head of the spinal-cord-injury-centre (SCIC) because of his general responsibility.

Exclusion criteria:

Several years ago we agreed to wait five month after injury for recovery of respiration. At the same meeting we made a statement, that PNS is only one possibility of artificial ventilation and that there is no absolute medical necessity for an implantation in cases of a spinal cord lesion above C 4. We still agree with this statement, even today. But we think of PNS as a proper treatment in cases, which should be selected carefully under several points of view. First of all we have to check the medical and biological situation of the patients. Thus the first and most important point of a list of excluding criteria is a disorder of the lower motoneuron. Before starting any preliminary preparations for implantation it is necessary to check the nerves of both sides in the neck percutaneously. According to our experience it makes no sense to increase the current above 9 to 10 mA. Within these current limits we found diaphragm contractions on stimulation in all patients with an intact lower motoneuron. We have no experiences with open stimulation of surgically exposed nerves. We do not recommend this method because of the possibility of damaging the nerves.

The second important exclusion criterion is any kind of pulmonary tissue pathology. One should check this very carefully. One of our patients, a young lady, survived the implantation for four months only. She died due to severe pneumonia caused by chronic hypostasis of the lungs, which had developed and relapsed intermittently over years before she had suffered her SCI. Our evaluation of her presurgical status concerning this point was to optimistic. Another important point on the list of exclusion criteria is any kind of cerebral dysfunction not only of the cortex but of the cranial nerves, too. The patient should be able to use the vocal cords. He should be able to swallow; otherwise complications will appear due to aspiration when the tracheal tube has been removed. Cooperation of the patient is needed during all phases from implantation to full-time use of the stimulation system. Thus a critical decision is necessary whether and when a patient with a high lesion in combination with any sort of cerebral defects should be supported by PNS or not.

As mentioned above in 1987 we implanted the device the first time. The patient caught a C2-lesion when jumping into shallow water and almost drowned at the event. Therefore he also suffered from hypoxic brain damage with malfunction of cranial nerves. He could not use his vocal cords because of some kind of laryngeal convulsion when intending to speak. And he was not able to swallow without aspirating. Thus he was not able to use one of the most important benefits of PNS: he could not talk. Finally, suffering also from several other complications, he gave up himself deeply depressed and died.

Finally we have to check the future possible conditions of the patient. If there is no possibility for him or her to achieve reintegration into the family or other social systems, which are comfortable enough and additionally able to use a sophisticated system of artificial ventilation, then PNS should be avoided.

But even the best social condition and well-chosen equipment cannot guarantee a successful treatment. One of our patients was transferred back to his family into a well prepared home, supported by a nursing group and equipped with a strong insurance system. Nevertheless he could not adapt himself to his new situation. Having fallen in depression he suffered several pulmonary complications and died due to an abscess of the lower part of his lungs. Looking back to his development we have to confess that we failed in our indication.

Possible indications:

We think that PNS is a good method and works properly in all patients who suffered their SCI by trauma. Most of our patients are trauma patients and our best results are with these patients. In disease-caused cases we have to check very cautiously the possible future development. If, e.g., the lesion is caused by tumour surgery we should know something about the prognosis concerning life expectance. This in general is a big problem. One of our patients died within five months after the implantation due to a relapse of his medullar tumour. His surgeon had convinced us that he had done the excision very radically. Thus we had followed a wrong assumption. Going on in our list we think of central sleep apnea as a disease that can be treated with PNS, which we did in two cases. Central sleep apnea can be treated with PNS also when presenting in combination with trauma or other diseases. But one should know facts about the other origins very exactly because of possible complications caused by the underlying condition. For a more complete list of indications we refer to a publication of Baer et al. (2). Professor WEESE-MAYER gives more information concerning this field elsewhere in this volume.

Also worth mentioning is the problem of bilateral or unilateral implantation. We have experiences only in one person with a unilateral pacing-system. The right phrenic nerve did not work and the left side worked insufficiently. Thus we did an implantation to the left side and were very successful. The young lady is stimulated 12 - 18 h daily enjoying all benefits of the method. During the night she

is uses mechanical ventilation with the intention thus to prevent atelectasis of the right lung. We have no experiences in unilateral pacing and normal function of the other side. This topic is covered by the contribution of Drs Watt and Soni.

Conclusion:

We conclude that PNS can be used in SCI patients able to use their vocal cords and to swallow. Additionally the patient should not only accept but want the device and should know that there may be only very small benefits concerning quality of life. His possible reintegration should be affirmed, be it in his family or in any other social group, which should be able to help the patient to use his equipment efficiently after discharge. Of course the therapeutic team should be experienced and well trained in all methods of pacing and rehabilitation, too. In such case we can expect to achieve the ability to speak, approximately physiological ventilation, improved mobility, an independent status from hospital or other medical institutions. In some rare cases it might be possible to close the tracheostoma.

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Correspondence:

Gerhard Exner, MD
SCIC
Bergedorfer Straße 10
D-21033 Hamburg

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Phrenic nerve stimulation versus mechanical ventilation

Wenck B, Exner G
Hamburg

Summary:

When compared to mechanical ventilation phrenic nerve stimulation improves verbal communication and personal mobility. The patient appears to be less handicapped without ventilatory tubes and machinery. These facts improve the patient's social acceptability and make reintegration easier, which in turn improves the patient's comfort and satisfaction with life.

Key-Words: PNS; MV; quality of life; comfort

Medical indications for phrenic nerve stimulation (PNS) are discussed in separate chapters. In some contributions the usefulness of PNS for spinal cord injured patients has been questioned generally. It is our experience, too, that there is no difference in functional and medical outcome between both methods. Survival time and complications rate are identical.

In this presentation we want to show a quite different view on thinking about the indication of different methods of ventilation. that we should extend our thinking over indication under complete different points of view. We think it is important to consider the patient's emotional being well and his satisfaction with life, which in turn depend on his social integration.

We would like to present three points of view. The first one is the patient's being well under the impact of the function. The second one concerns visual aspects. The third is on risks and possible dangers.

At the end we would like to summarize the most important facts that make life comfortable for these patients. In our opinion these aspects have to be included in discussions about indications of PNS.

When using PNS for artificial ventilation we can expect to achieve
the ability to speak
a technically supported mobility and
independence from the hospital

We agree totally that these are goals that can be achieved with mechanical ventilation-technique, too. But there are differences when concerning patient comfort.

1) Function

a) quality of communication

Talking with the PNS system is more physiological. The voice sounds quite normal. In contrast to speaking during MV the characteristics of the individual voice are preserved restoring an important part of the pre-incident individuality. The disturbing noise of mechanical ventilation is absent. Verbal communication improves. It is easier for everybody to talk with patients on PNS than with patients on MV.

b) quality of mobility

As mentioned above the patients should be mobile. There is no doubt that they can be mobilised with mechanical ventilation devices, too. However, simply when considering the difference in size and weight of both ventilating systems one will understand our experience that PNS is more accepted than MV by all team-members, the patient included. Due to the difference in size the range of mobility is increased, too.

c) quality of nursing

Nursing is easier because all kinds of transfers are easier to perform when PNS is in use. The patients artificial ventilation system is fixed to his skin, not to his neck and trachea. During patient transfer there is no need for an additional person transferring the device and monitoring the tube connections. Washing and dressing are less complicated.

2) Visual aspects

Social re-integration and community re-entry are easier achieved for “normal” looking persons than for strange looking persons. Nobody looks normal and for some people even looks frightening when being equipped with the tubes and machinery of MV. The noise of the ventilator is disturbing and may also be frightening. No special device is visible and no strange noise is heard when using PNS: the handicap appears to be less total.

3) Risks and danger

When travelling and during all kinds of transfer the danger of disconnection is present when using a mechanical ventilation system. It should not be denied that every transfer might cause some trouble to PNS users, too, but not such life threatening events like disconnection.

Additionally, when using PNS it is much easier and safer to perform suction when travelling outside of the clinical environment because ventilation has not to be interrupted for this procedure.

4) Conclusion

One of our patients told us that after implantation of the PNS-system he felt like starting a new life. This patient had previously been dependent on mechanical ventilation for about four years. Thus he was really able to compare both methods of ventilation.

Concerning satisfaction with life there are profound differences. People supported with the PNS-system appear less handicapped visually and therefore are easier integrated socially. Social re-entry is also better because partners have a quite „normal“ access. Their communication is quite normal, not bothered by disturbing noises, produced by a ventilator. They look like „normal“ people sitting in a wheelchair without such frightening supports like tubes or other parts of a mechanical ventilation device.

In summary, we think the PNS-system is a device that is much more comfortable for the patient than any system of MV and improves the patient's satisfaction with life. Even if there are no differences evident from the strict medical point of view between the different methods of artificial ventilation, when concerning satisfaction with life and social reintegration PNS is obviously preferable to mechanical ventilation.

Correspondence:

Barbara Wenck, P.T.

SCIC

Bergedorfer Str. 10

D-21033 Hamburg

FESAM ventilatory support

Kandare F, Stanic U, Jeray J, Pedotti A, Exner G
University Clinic of Respiratory and Allergic Diseases GOLNIK, Slovenia

Abstract

Functional electrical stimulation of abdominal muscles (FESAM) is a potential new method of ventilatory support. This paper presents the theoretical background and physiological principles of this new method. The experimental results clearly show ventilatory effects of FESAM in normal and SCI subjects, and support the potential clinical importance of this novel mode of ventilatory support. The results support the hypotheses that FESAM augments pulmonary ventilation in normal subjects and in SCI patients and suggest that this method could be clinically important in the cases of ventilatory pump insufficiency for short periods of time. Additional technical modifications suggest possible prolongation of support over longer periods of time. These results suggest several lines of subsequent investigation.

Introduction

Noninvasive ventilation refers to artificial ventilation without the need for an invasive interface between the ventilatory device and the patient. Noninvasive positive pressure ventilation is currently the preferred mode of noninvasive ventilation for most applications, and there is a substantial literature on this topic. However, other modes have been investigated in the past (e.g. negative pressure ventilators, abdominal displacement ventilators, diaphragm pacers etc.). This study investigates the novel use of 'electrical' modification of abdominal displacement method of ventilatory support, and is termed functional electrical stimulation of abdominal muscles (FESAM). Both theoretical background and experimental data will support the potential usefulness of FESAM as a means of ventilatory support.

Theoretical background

To understand the principles of FESAM augmented pulmonary ventilation, the role of respiratory muscles and mechanical events during normal breathing must be re-examined in detail from a slightly different perspective. In the respiratory gas exchange chain (from environment to the cells and vice versa) two active systems are involved: pulmonary ventilation and blood circulation. In both processes the active component of the process is represented by respiratory muscles (inspiratory) and heart muscle, respectively. All other parts in the respiratory gas exchange chain are passive, without energy consumption. From a clinical point of view, the first time that either of these active systems draw our attention is at the moment of their failure.

Ventilation is a process in which a certain amount (tidal volume - V_T) of fresh air enters alveolar space during inspiration and, depending upon the metabolic status of the organism, an identical amount leaves the alveolar space during expiration. The active mechanism in this process is the respiratory muscles. The contractions of these muscles, in conjunction with the structure of bones and joints, produce volume changes. The muscles contract and relax based on neural signals from the respiratory centers in the CNS. Ventilation involves a number of muscles. For optimal respiratory gas exchange, in addition to the volume of air inspired, the distribution of fresh air in alveolar space is very important for efficient gas exchange. All muscles involved must be carefully orchestrated, conducted so to speak, by the CNS, which processes rich information coming from different central and peripheral sensors to create optimal muscle contractions, which provide optimal conditions for gas exchange. There are numerous muscles involved in respiration. These muscles can be conveniently divided into to expiratory and inspiratory muscles according to the phase of respiratory cycle they are predominantly functionally involved (Table 1). For distribution of inspired volume the local conditions in different lung compartments are very important.

From a physiological point of view the chest wall is defined as all those structures outside the lungs which take part in breathing movements, including rib cage, diaphragm, abdominal contents and abdominal wall. The unique volume of the trunk is divided by the diaphragm into two compartments, one compressible (rib cage with lungs) and another non-compressible (abdomen with viscera) compartment. These compartments influence each other with volume and pressure changes. At the point where the elastic properties of the chest and lungs are equal and in equilibrium (FRC level) breathing is performed with minimal energy expenditure. By changes in elastic properties of lungs or the chest wall, the level of the FRC can be changed and with this expiratory reserve volume can be modulated. Body position has a pronounced effect on FRC level.

Table 1.

	Primary	Accessory
Inspiratory muscles	<ul style="list-style-type: none"> • diaphragm • mm. intercostales externi • mm. intercostales interni (pars parasternalis) • mm. scaleni • m. triangularis sterni 	<ul style="list-style-type: none"> • mm. sternocleidomastoidei • mm. pectoralis major et minor • mm. serratus anterior • mm. serratus post. sup. • mm. trapezius • mm. latissimus dorsi • mm. levatores costarum breves et longi
Expiratory muscles	<ul style="list-style-type: none"> • Abdominal muscles <ul style="list-style-type: none"> – mm. recti abdominis – mm. transversi abdominis – mm. obliqui interni et externi • mm. intercostalis interni • mm. serratus posteriores inf. 	

Above the level of FRC the inspiratory muscles are active, they must overcome the resistance of the lungs and as the total lung capacity level is approached, chest wall elastic resistance must also be overcome. Expiration is to a great extent passive, in some cases minimal activity of expiratory muscles is observed. In the case of increased ventilation or increased resistance in airways the activity of expiratory muscles is increased {Morris et al. 1990}. From the point of respiratory aids, tidal volume is increased with positive pressure ventilators and phrenic nerve stimulation (PNS) above FRC, whereas FESAM increase tidal volume below FRC (Figure 1.).

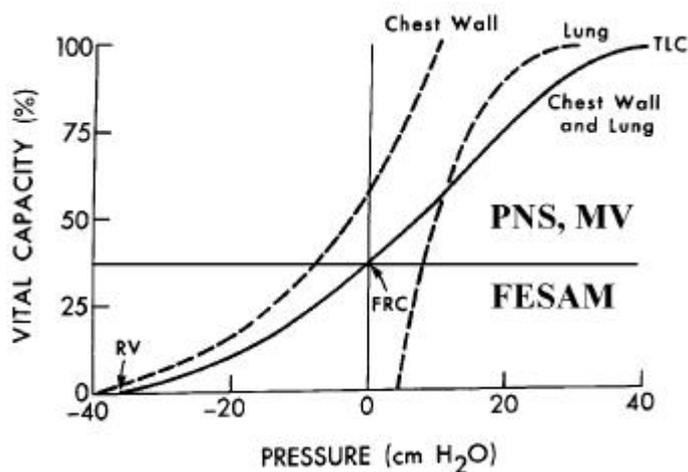


Figure 1.

The abdominal muscles represent a group of muscles composed of mm. recti abdominis, mm. transversi abdominis and mm. obliqui interni et externi. They are classified as expiratory muscles. They are involved in numerous function others than respiratory (e.g. singing, coughing, voiding, defecation, delivery, and posture) {Abe et al. 1996}. Their respiratory function is enhanced by shortening of the AP (antero-posterior) diameter of the rib cage and decreasing abdominal volume. Because abdominal content is essentially non-compressible, the abdominal pressure increases and the diaphragm is passively pushed into thorax causing additional expiration. Their effect on tidal volume is dependent on the value of expiratory reserve volume (ERV), therefore also on the level of FRC. During FESAM the chest is compressed below FRC level and in the beginning of next inspiration it passively expands to the level of FRC, where inspiratory muscles begin to exert function.

Figure 2 summarizes the concept of tidal volume augmentation by FESAM. Trace "a" represents volume changes during normal breathing, trace "b" represents impaired breathing with reduced tidal volume and trace "c" trace indicates tidal volume increased by FESAM below FRC.

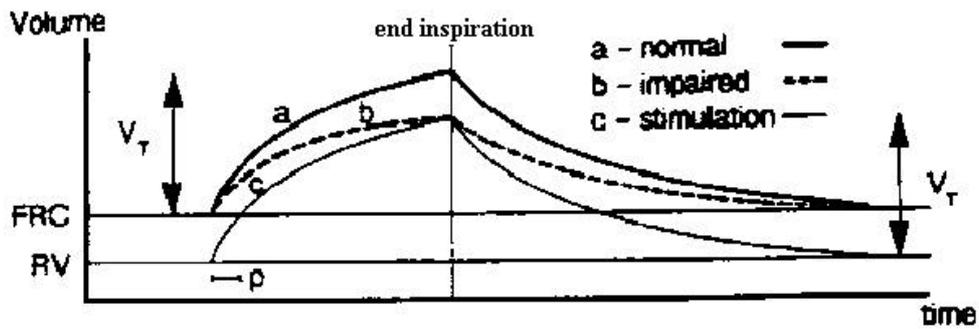


Figure 2.

The initial part of the inspiration would be assisted as a secondary effect of FESAM and therefore passive (bar marked "p"). The theoretically maximal FESAM tidal volume augmentation is equal to expiratory reserve volume.

Review of FESAM effects on ventilation

In addition to mechanical ventilation there are several different non-invasive respiratory aids to augment pulmonary ventilation in patients with ventilatory insufficiency {Simons 1996}. All potential methods of ventilatory support are typically compared to these existing methods. In order to evaluate the benefits achieved by FESAM during expiration, a comparison was made to manual abdominal compression. This is a significant comparative evaluation of the effects of FESAMs {Sorli et al.1996}. In this comparison, no significant difference in pulmonary ventilation was found between these two methods of augmenting ventilation. However, a significant increase was observed compared to normal breathing in healthy subjects (17.5 ± 6.5 l/min, 18.3 ± 8.0 and 10.3 ± 2.7 respectively). During FESAM breathing rate was elevated by approximately 3 breaths per minute.

Stimulation of different abdominal muscle groups (mm. recti abdominis and lateral abdominal group of muscles - mm. transversi and mm. obliqui abdominis) showed no significant differences in V_T increase between muscle groups stimulated {Kandare et al. 1997}. On the other hand prolongation of stimulus duration increases V_T and decreases breathing rate, the ventilation being unchanged. V_T changes observed during FESAM in normal subjects were practically equal in both standing and sitting positions, but lower in the supine position. Through an optoelectronic method (ELITE), breath by breath volume changes of the trunk were determined in normal subjects in standing, sitting and supine positions {Kandare et al. 1996}. Partial trunk volumes (upper and lower thorax, upper and lower abdomen) were calculated as percentage of tidal volume. The contribution of the abdominal compartment to tidal volume was greater in standing and supine position (avg. 53% and 59%). The differences observed between different body positions are primarily due to opposite volume changes of upper thorax and lower abdomen. During FESAM partial volumes of the trunk were increased proportionally to initial values. In spinal cord injury patients the trunk volume

changes during normal breathing differ compared to normal subjects, in that volume changes are mainly seen in the upper abdominal and lower thoracic regions. During FESAM the volume distribution become similar to distribution in normal subjects during quiet breathing {Stanic et al. in press}.

These results were obtained in experiments of short duration (on the order of a few minutes) of FESAM. In prolonged experiments with up to 3 hours of FESAM, observations in the first ten minutes showed initial significant increase of pulmonary ventilation up to 90 % above the quiet breathing value, with subsequent exponential declined to a plateau value of about 30 % during the rest of the time of experiment. The effects of FESAM are similar between the groups of stimulated muscles. Irrespective of the underlying mechanism(s) for these observations, the results indicate possibility of applying FESAM to different abdominal muscles groups in order to prolong the initial increase in pulmonary ventilation.

Conclusions

FESAM augments pulmonary ventilation in normal subjects and in SCI patients. The results suggest that this method could be clinically important in cases of ventilatory pump insufficiency for short periods with possible prolongation of support if more extensive technical possibilities are exploited. There is a need for additional future experiments to determine potential target groups of patients where FESAM could be used to compensate for ventilatory deficits, to improve stimulation technology for routine clinical application, and to improve control principles of this method.

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Chairman's comments

Bötel U

Functional Electrical Stimulation in Paralysed Respiratory Muscles Morning session: "Indications", Thursday 11-11-99

Discussion:

According to indications for functional electrical stimulation of the phrenic nerve some misunderstandings could be revealed and cleared, as the approach to patients with ventilation problems is quite different in the American and the German group of participants. The American participants mainly treated children with congenital central hypoventilation syndrome (Ondine's curse) and sleep apnea, but the German groups mainly treated tetraplegic patients above C 4. The indication and gain of quality of life for patients with congenital central hypoventilation syndrome is quite obvious and was not put in question, but the indications for sleep apnea are not as clear and have to be decided individually.

Long discussion arose about the indication for diaphragm pacers for tetraplegic patients either by trauma or by disease. According to the ASIA-classification system most of the tetraplegic cases are incomplete at least in the time of onset so that a clear prognosis of the ventilatory deficit cannot be given in the first weeks and months. It was agreed that diaphragm pacing should not be installed earlier than 9 to 12 months after the onset of high tetraplegia.

The restoration of oral communication is a most important aim of treatment and can be achieved with functional electrical stimulation of the phrenic nerve in most of the cases, but speaking also is possible for most of the mechanical ventilated patients with unblocked tracheostomy tubes as the Bochum - group could show.

Only a few tetraplegic children have been implanted with diaphragm pacers. In some cases adverse reactions have been observed contrary to the experiences in children with Ondine's curse. Doubtless nursing is easier with paced patients, but dependence on a ventilation aid is the same. A pacer may improve mobility.

The closure of the tracheostomy depends on the ability of expectoration. By safety measurements a clear advice for tetraplegic patients could not be given although in some cases the closure of the tracheostomy was possible successfully.

The question, whether diaphragmatic pacing is more physiological thus preventing secondary lung failures, could not be answered finally, because also in long-term mechanical ventilation a higher incidence of lung fibrosis could not be detected.

It was pointed out, that patients with diaphragm pacers feel less disabled, as the ventilation aid is less visible as a mechanical ventilator and works without noise. Economical reasons do not give a prevalence for one or the other system, as an additional mechanical ventilator is necessary in every case.

In summary it was pointed out, that diaphragmatic pacing is the therapy of choice in cases with congenital central hypoventilation syndrome, whereas the indication for functional electrical stimulation of the phrenic nerve has to be decided on a very individual base in all other cases.

U. Bötel, Chairman

Implantation technique

Exner G
Hamburg

Surgical approach is through the second intercostal space in both sides {Glenn1985}. We do a resection of a short part of the second or third rib parasternally to improve view and access {Wetstein1987}. The nerves were easily identified in nearly all cases. When starting our method in 1987, we used a cuff electrode. This was changed to a Teflon© fabric two strip electrode. One strip should be placed in front of, the other behind the nerve. In order to avoid touching the nerve itself we developed a method of preparing subpleurally two pouches, one for each strip of the electrode, also named pouch-technique (Exner, 1998). It is of great importance not to touch the nerves in order to avoid direct (distraction, pressure) and indirect (lesions to the vascular supply of the nerve) trauma {Glenn1985}. In modern rehabilitation there is no time to wait weeks or months for recovery of a traumatised nerve.

The strips are pulled to their exact position with the help of sutures fixed to their ends. Each strip is armed with two electrode buttons, which should be placed symmetrically and directly to the nerve. When the procedure is finished the nerve is surrounded by four electrodes fixed by two Teflon© strips. Additional suturing of the strips is not necessary. Before closing any approach the threshold currents of each of the four electrode combinations is checked and documented, as is the position of the cut-off edge of the electrode matrix in relation to the nerve.

We insert thoracic drains at the top of the rib cage. When closing the thoracic approach a small whole is left for outlet of the stimulator cable. Larger subcutaneous pockets are needed for placement of the receivers. In patients with “no” subcutaneous fat these are best placed over the abdominal wall, in patients with plenty of surplus they are better placed laterally over the ribcage. The connecting cables are drawn through subcutaneous tunnels.

Using this technique it was always possible to stimulate successfully all electrode combinations after wound closure and even to check the tidal volume a first time using 4-pole sequential stimulation. The latter is rarely possible when sutures have been placed near to the nerve, which almost always means a mini trauma of the nerve.

After a short stay in the recovery room the patient can be transferred to the ward.

On an average two hours are needed for this implantation procedure. After some experience the procedure can be performed as mini-invasive one.

Correspondence:

Gerhard Exner, MD

SCIC

Bergedorfer Straße 10

D-21033 Hamburg

The Vienna Phrenic Pacemaker System, Technical Aspects

Thoma H, Holle J*, Lanmüller H, Stöhr H

Department of Biomedical Engineering and Physics, University of Vienna,
* Wilhelminenspital, City of Vienna, Austria

1. Introduction

Today, all phrenic pacemaker systems have basically the same structure: (1) the RF powered and controlled implant with electrodes for nerve stimulation and (2) the external battery powered control device with the RF antenna for power transmission and control. In addition, all producers have to implement a quality management system according to ISO 9001 or FDA. Even the cost of all systems is on the same level.

The main differences – relevant for patients – are (1) the number of stimulation channels (stimulation mode) and (2) design of the electrodes. In the following the (system) components of the Vienna pacemaker system will be described.

2. System components of the Vienna Phrenic Pacemaker

In fig. 1 the components of the Vienna Phrenic Pacemaker are shown:

1. battery-powered control for 8 stimulation channels
2. external RF transmission coil for control and power supply of the implant
3. electronic implant with receiving coil and connector pairs for 8 channels
4. 4-channel electrode leads with connectors and ring-shaped electrodes
5. annular electrode tips

Peripheral Devices:

6. mains supply
7. car battery supply
8. trigger unit for the respirator (during training)



Fig. 1. The Vienna Phrenic Pacemaker System (see text)

2.1. Epineural electrodes and leads

In 1973 we developed the so called „epineural electrode“. This stainless steel 316 electrode with 12 x 50 μ filaments is ring shaped (1 mm diameter) and sutured directly to the epineurium of the nerve by a 8-0 prolene suture.

In fig 2. an electrode two years after implantation in a patient with attached prolene suture is demonstrated. All four electrode leads are spiralized, isolated by a silicon tube and connected to the plug of the electronic implant. Close to the electrode four spiralized single leads are distributed to enable a flexible suturing of the electrode to the peripheral nerve (fig. 3). A histology staining – cross section of the electrode -, two years after implantation in a patient shows: (1) connective tissue, (2) round – cell infiltration, (3) liquid, (4) pseudo sheet and (5) not isolated electrode of 1 mm in diameter (fig. 4). In general a minimum of tissue connection compared to cuff – electrodes is observed.

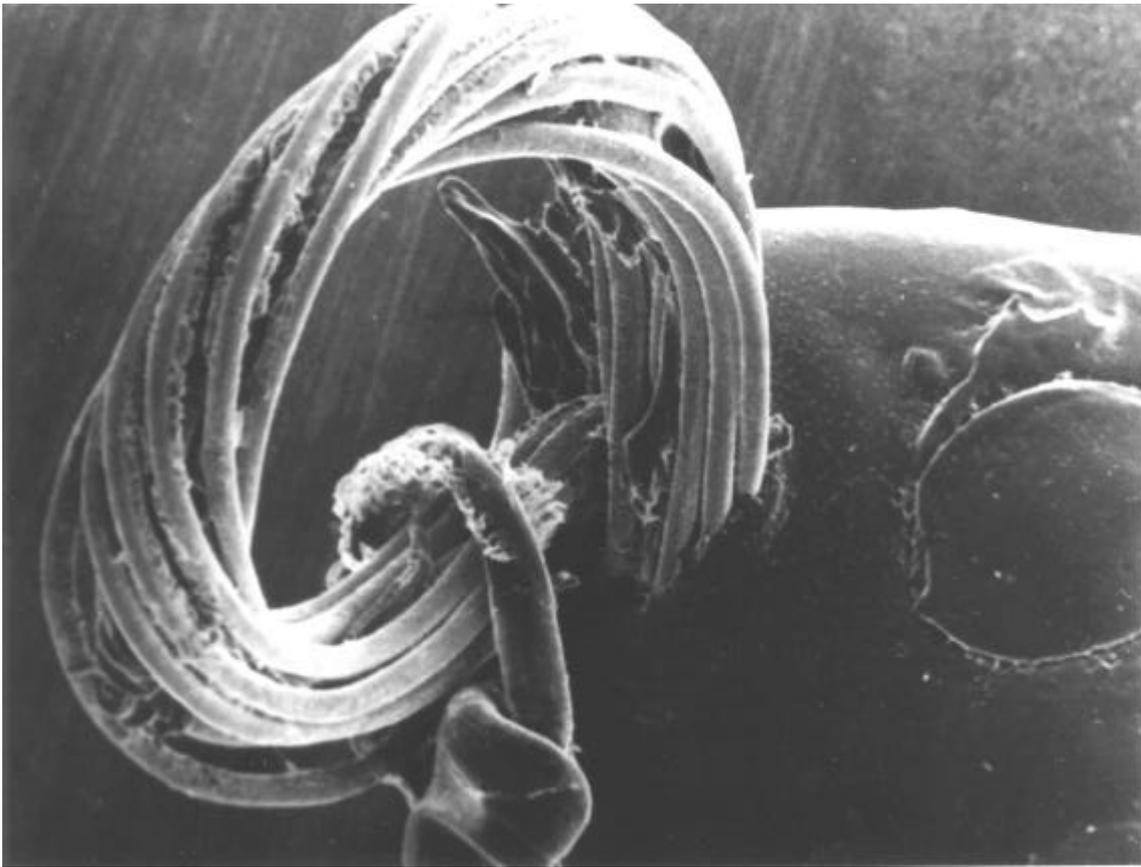


Fig. 2. Magnification of an epineural electrode (see text)

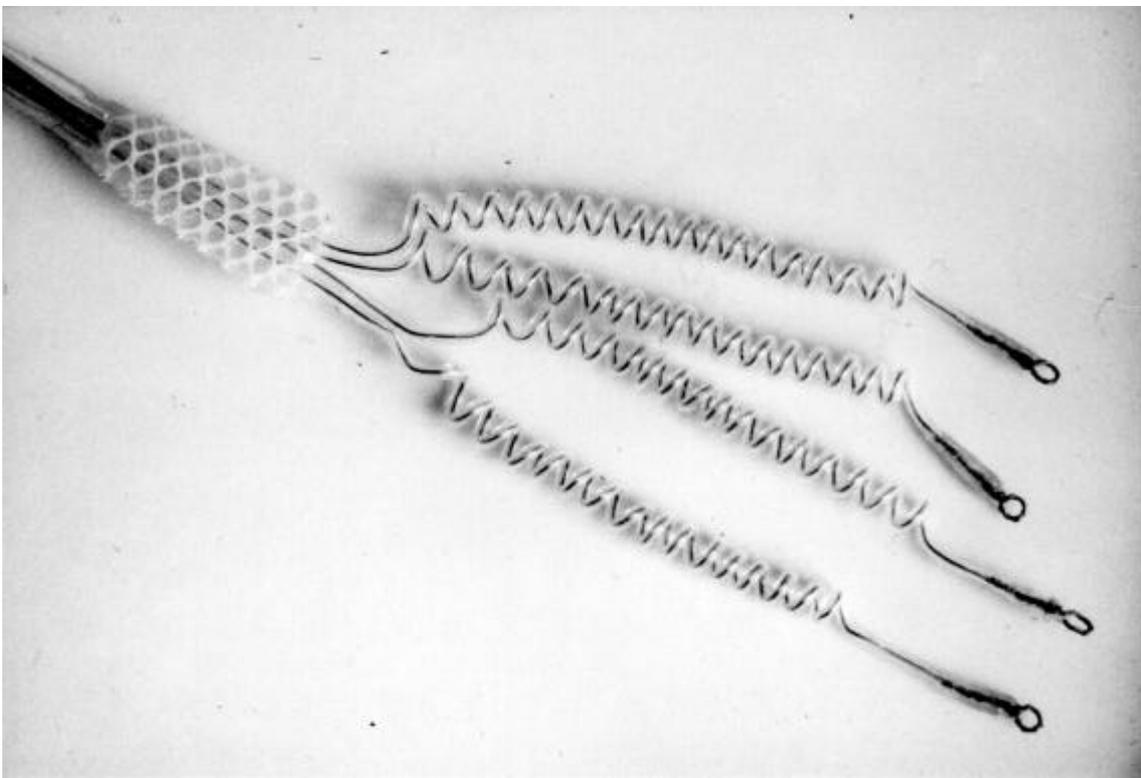


Fig. 3. Electrode lead, distributor and 4 single electrodes

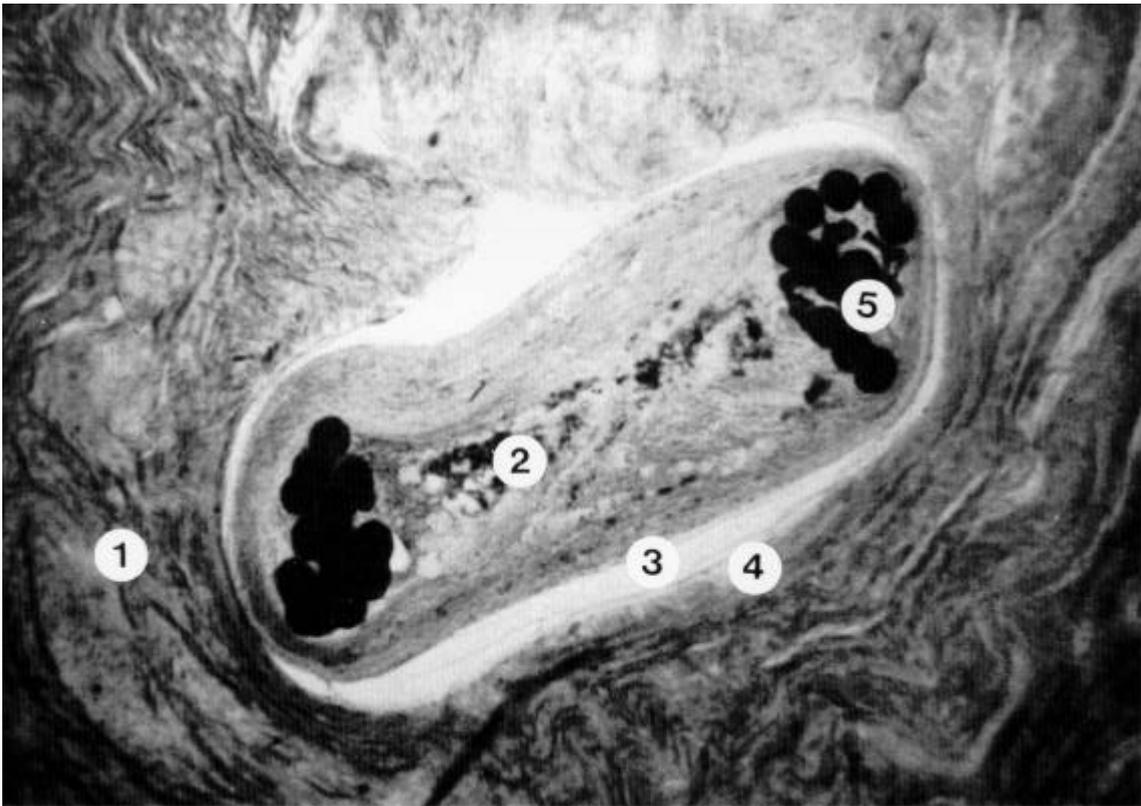


Fig. 4. Histology staining of epineural electrode (see text)

Results

In the course of time we have had two episodes with epineural electrodes and leads:

In 1992 some electrodes burned out in patient with a more than five year - old implant. Most likely the decoupling condensators of the implant have had a short for DC current. We put the condensator in a separate metal housing and have had no problems up to now.

The second episode did concerned the electrode lead. We have had excellent results – more than 600.000 cycles on the testbank - with straight not spiralized electrode leads. After a couple of months of implantation a failure between stomach and breast area occurred. At this time all implants have been positioned in the stomach area. We have had to return to the multichannel spiralized electrode lead.

In 1980 /Rosenkranz 1980/ up to 1993 /Girsch 1993/ different animal studies were started to get statistical data of a potential lesion of the nerve due to the epineural electrodes. Results were excellent, e.g. 1% fibre lost after one year of an observation period.

Despite the two events, we have never had problems with a function or a biocompatibility of the electrodes.

As a result of the first endoscopic placement of our epineural electrodes in a patient in 1996, our present research efforts are focused on the development of new electrodes which can easily be placed on the phrenic nerves.

2.2. The electronic implant

In 1974 we developed, tested and subsequently patented /Thoma 75/ the so called „carrousel stimulation“ to avoid fatigue of the diaphragm muscles. For this method an 8-channel implant in thin film technology was developed in 1980 and tested in animal experiments and then implanted in human being for the first time in 1982. In 1984 another patient was implanted, the tracheostoma could be closed because of the excellent results in stimulation 24 h / day, together with the rehabilitation strategies of the W.Wicker Rehabilitation Center, Bad Wildungen, Germany.

During the first years we have had a limited life time (2-6 years) and some dropouts of our 8-channel implant. Later, all electronic components were encapsulated in a metal housing and we have had no dropout until today.

Due to penetration of water in Hysol, the inductivity of the receiver coil changed up to 15% of the initial value. This induced some discomfort if the implant was positioned subfascially, more than 3-4 cm, or inclined to the skin. In the new version, the receiver coil is arranged in a ceramic holder. With this feature we have no relevant changes of inductivity.

The result of failure and success of the implant may be seen in fig. 5, patients schedule 1983 – 1999. The first failure has been documented in 1988 the last two in 1993. With the new concepts mentioned above we have had no failure up to now /Mayr 93/.

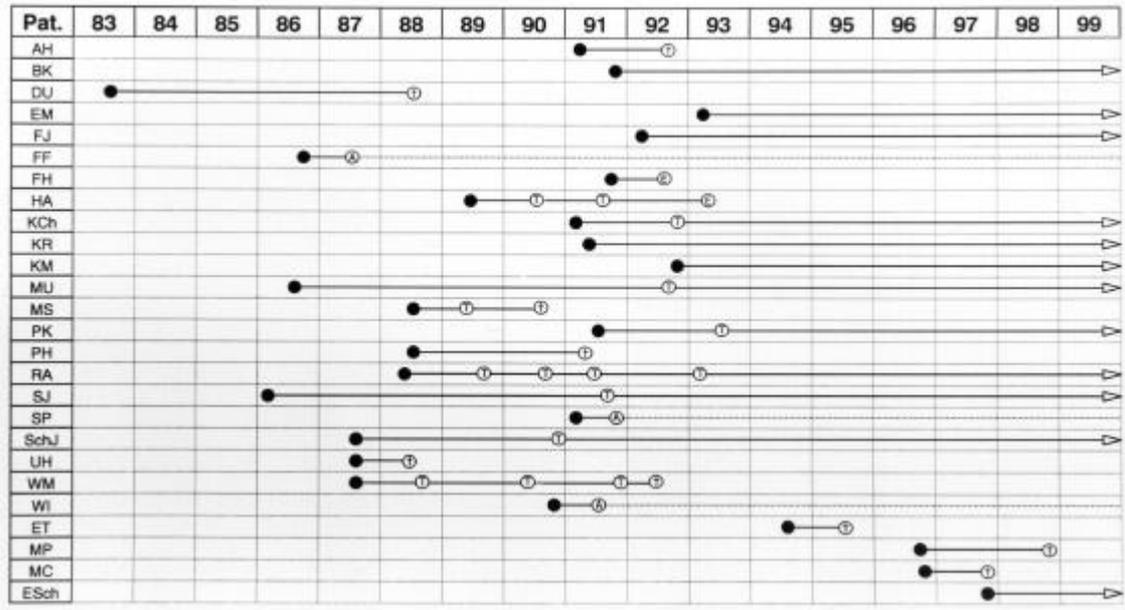


Fig. 5. Patients schedule 1983 –1999

- * black point: implantation
- * cross: deceased
- * T: change of the implant
- * A: stop of stimulation
- * E: explanation

Since the very beginning in about 1975 including the new developments we have always had the same connectors. The reason is, that we have long and good experience. The connector is sealed by silicon rubber SK 43. While changing the implant, the silicon rubber is removed by a scalpel and all two of four connectors are detached by special tool. With this standard in one patient the implant has been changed unfortunately four times but without problems with a connector.

Development

In 1990, we started to develop a 20-channel implant in thick film technology which is hermetically isolated by a niobium housing (fig. 6). This implant has been tested in 8 sheep during a cumulative time of 4.5 years.

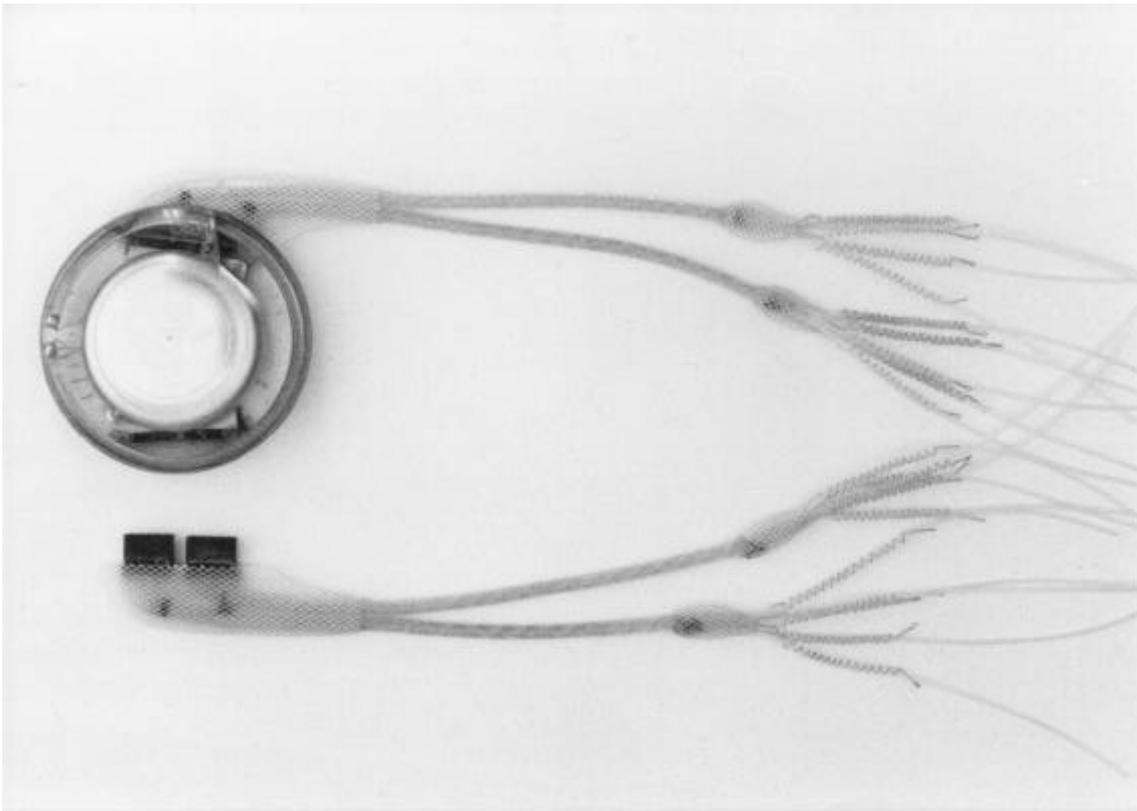


Fig. 6. 20-channel implant

The 8-channel version of this implant is presently tested for its CE-conformity. The updated version of our phrenic pacemaker will hopefully be available on the market in 2000.

In 1994 we started the development of a fully implantable system including a battery sufficient for 3-5 years (fig. 7). This microprocessor controlled 8-channel implant is pre-programmed externally by a Laptop computer. First models were tested in animal studies and are now undergoing a lifetime test. A new feature of this development is the possibility of controlling the respiratory rate by a biologic signal.

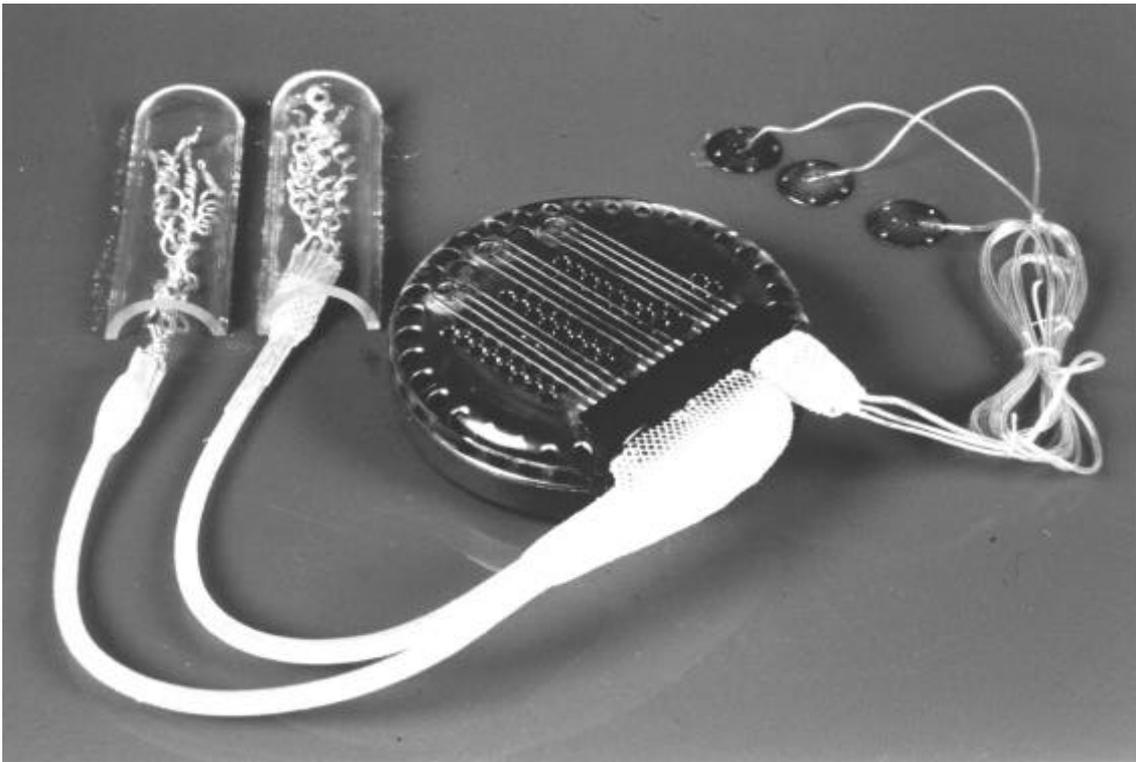


Fig. 7. Fully implantable 8-channel implant

2.3. The battery – powered control unit

The control unit in the present version has been developed in 1980. According to the carousel method, 16 combinations of switching modes: electrode to plus, electrodes to minus or not is pre-programmed. For individual adaptation to the patient for each of the 16 right and left combinations the initial threshold and desired breathing volume has to be adjusted manually. The implant is a constant current generator which is more stable compared to constant voltage applications during the first month. The ramp for smooth inspiration is pre-programmed.

In addition, the patient parameters: the length of inspiration (duration) and the number of breathing cycles per minute must be adjusted. For the adjustment of other FES parameters, e.g. of the impulse duration or FES –frequency the service staff is responsible.

The power supply is safe: 2 rechargeable batteries work independently each for at least 12 hours. If both batteries fail (very rare), an external 12 Volt supply may be connected (car battery). Batteries are loaded via 220 Volts power supply. This charger may be used for continuous not limited time to supply the control unit (preferred by our patients during night). Low battery voltage is alarmed acoustically.

The display shows (1) patient's parameters, (2) left and right adjustment, (3) left parameter only or right parameters only in case of programming, (4) number of the

pre-programmed combinations (0-16) and the battery status (visually). Many other features are possible via the service connector on the backside of the device, e.g. the synchronisation with a respirator during training.

In the updated version (fig. 8) the housing is of aluminium, produced by CNC milling. Programming is done by a Laptop PC due to safety reasons and easier documentation. Connectors are protected against mechanical stress. The electronics has been adapted to present standards (SMD,...). Depending on the software the control may be used for 8 channel implants and 10 / 20 channel implants.

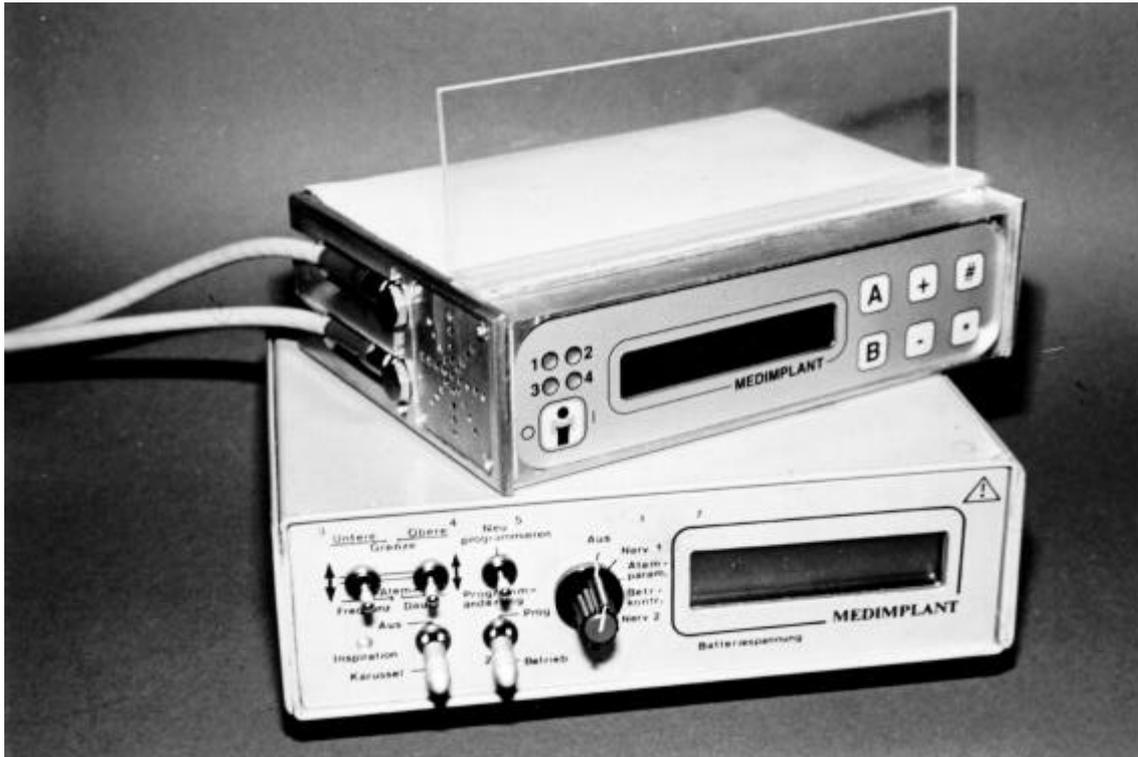


Fig. 8. Update of the control unit

2.4. External RF – Transmission coil

The external RF – Transmission coil (fig. 1) for control and power supply of the implant is connected by cable to the control unit. Different to other producers, the RF is generated in the coil which is casted in Hysol. This has the advantage to enlarge the cable up to 10 meters, e.g. good for swimming. The RF transmits signals and power up to a distance of 8 cm to the implant. One disadvantage is, if the coil is very close to the implant – less than 1 cm – the control may not work (overspeaking). We solved this problem in the updated version.

3. Discussion

The phrenic pacemaker is a product which needs a lot of service. This may be one of the reasons that bigger companies, e.g. coming from the heart pacemaker, do not like this highly efficient medical product. The result of this marketing strategy is that only smaller companies are present on the market. But these companies have problems to investigate all the modern technology of a modern phrenic pacemaker (fully implanted). In addition, they are strictly inhibited due to different rules: MPG, ISO, FDA, GMP, etc.

The other disadvantage is still the acceptance with all consequences of rehabilitation, e.g. close of tracheostoma. Not least also the small number of patients is a problem.

This was also our limit for the necessary updated version of our phrenic pacemaker. To get on the EC market without problems only changes are allowed.

We have a good experience with our strategies (e.g. only two surgeons operate all patients in Europe), with the long term service in Germany (Fa. Börgel, Limburg) and with the clinical results (no failure since 1983/84, no severe problems for a patient in connection with the pacemaker in all the years).

We are looking for partnership, to establish the fully implantable phrenic pacemaker on the market.

Author's address:

Univ. Prof. Dr. Herwig Thoma

Institute of Biomedical Engineering & Physics, AKK-Vienna

A-1090 Vienna, Währinger Gürtel 18-20 / 4L

Tel: +43 1-40400-1986, Fax: +43 1-40400-3988

e-mail: h.thoma@bmt.akh-wien.ac.at

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FESAM

Stanic U, Kandare F, Pedotti A, Aliverti A, Delacca R
Institute Jožef Stefan, Ljubljana, Slovenia; University Clinic of Respiratory and
Allergic Diseases GOLNIK, Slovenia

Abstract

Functional electrical stimulation (FES) was developed in the early 1970s as a new method for rehabilitation of functional movements in paretic and paralyzed subjects. The long standing experience and technological development of stimulators has been the background for the development of the custom-made four-channel stimulator used in experiments involving functional electrical stimulation of abdominal muscles (FESAM). This paper provides a technical description of the stimulators, parameters of stimulation, electrode sites, and control principles. In these experiments, the effects of duration of stimulation train were systematically studied. It was shown that with prolongation of stimulation, tidal volume increases and breathing rate decreases (after an initial transient rise). These two changes result in a significant and constant increase of ventilation. For practical reasons related to possible problems of muscle fatigue and battery power consumption, stimulation duration of 1 second was determined to be most appropriate.

FES technology background

Functional electrical stimulation (FES) was developed in early 1970s as a new method for rehabilitation of paretic and paralyzed subjects. The central idea was to provide a bypass from the intact central nervous system (CNS) via a muscle under volitional control that provided a signal to an electronic stimulator, which, in turn, delivered stimulation pulses to paralyzed muscles that were not under the direct control of the CNS in order to re-establish functional movements, such as manipulation and walking. The emerging transistor technology, and later integrated circuit technology, enabled production of smaller battery powered portable stimulators that have been used therapeutically and orthotically. The main target populations for FES based treatment were patients with stroke, head trauma, cerebral palsy children, multiple sclerosis, and spinal cord injury. A wide range of personal and clinical, surface and implantable, single-channel and multi-channel stimulators have been developed and have been used in routine clinical practice and research. Among many different impairments, FES has been applied to correction of drop-foot during walking, standing and grasping in spinal cord injury (SCI) patients, and wound healing. These are among the most frequent applications; there are many others.

Stimulators and parameters

The first experimental stimulator for functional electrical stimulation of abdominal muscles has been developed by Jaeger {1996}. It was a microprocessor controlled dual-channel stimulator with an a/d converter and current output stages that delivered stimulation via surface electrodes. The pulse train was ramped up from 25 μs pulse width with linear increase to 350 μs over a 1s burst of stimulation. An airflow sensor triggered the stimulation, with stimulation beginning at 15% of maximal expiratory flow obtained during normal breathing. Stimulation amplitude was up to 100 mA, with a constant pulse rate of 50 pulses per second. In order to perform multi-center experiments, a portable custom made four-channel stimulator has been constructed on the basis of a commercially available drop-foot stimulator (Microfes) by Jeraj {1998}. This stimulator had four independent output stages, powered by four 1.5 V batteries. Stimulation was triggered by thermocouples with adjustable onset. There were two modes of stimulation, four-channel simultaneously or dual-channel alternating. The parameters of this stimulator could be adjusted over the following ranges:

- pulse rate: 15 to 80 pulses per second
- pulse train duration: 0 - 3 sec
- rectangular, balanced, asymmetrical, biphasic current pulses of 150 μs
- amplitude up to 100 mA
- Size: 12 cm x 13 cm x 4 cm
- Weight: 255 g

In figure 1 the block diagram of the stimulator is shown schematically.

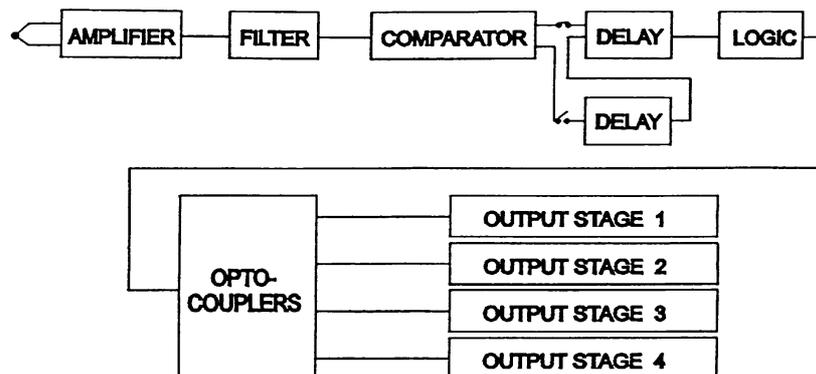


Figure 1.

Electrodes and sites

In Figure 2 a schematic diagram is shown with the approximate position of electrodes for stimulation of mm. rectus abdominis and lateral abdominal muscle groups. Typically self-adhesive electrodes (9x5 cm, rectangular) were used.

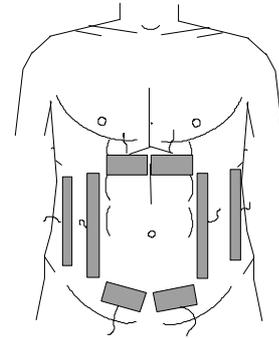


Figure 2.

Stimulation Sequences (Duration, Timing)

In order to determine the optimal duration of FESAM, a series of experiments was performed in normal subjects, where stimulation trains of 1 second duration, 1.5 s and 2 s were delivered. In Figure 3, tidal volume, as a function of duration of stimulus train is shown.

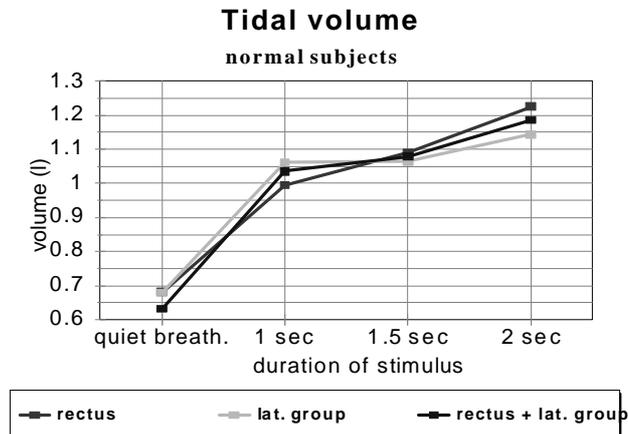


Figure 3.

In Figure 4, the breathing rate is shown as a function of duration of stimulus train.

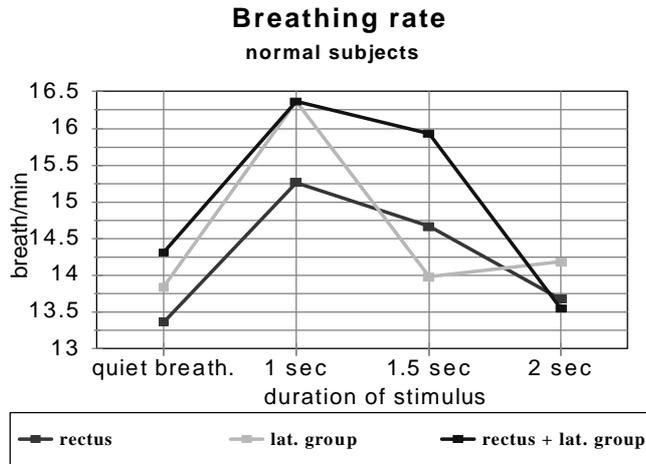


Figure 4.

In Figure 5, ventilation is shown as a function of duration of stimulus train.

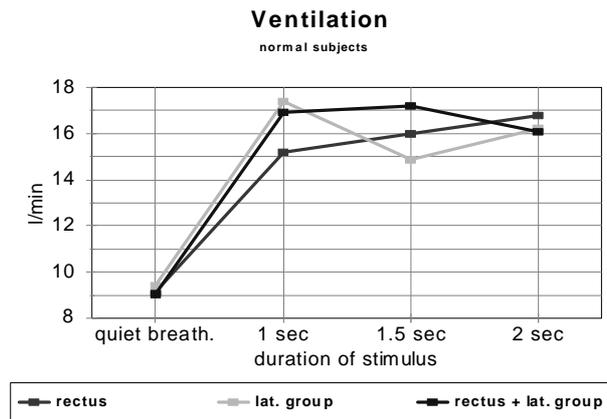


Figure 5.

With prolongation of duration of the stimulus pulse train, tidal volume increases, breathing rate decreases (after an initial transient rise). This results in a significant and constant increase of ventilation independent of the duration of stimulus pulse train. For practical reasons related to possible muscle fatigue problems and battery power consumption, the duration of 1 second has been chosen as most appropriate for the stimulus pulse train.

Measurement techniques

There are several standard measurement techniques and devices used in measurements of pulmonary function values, such as volume measurements. These include the pneumotachograph, triple V system, mass flow system, and others. Recently a new noninvasive measurement technique has been developed that is based on a 3D optical measurement system which directly measures the spatial positions of a number of markers on the surface of the trunk. This new system enables measurements of partial volume measurements of the trunk. For measurements of respiratory gas exchange O₂ and CO₂ analyzers are used, whereas differential manometers enable pressure measurements at different sites. All of these devices are useful in determining the effects of FESAM on pulmonary mechanics.

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Personal Situation and Situation at Home of respiratory-dependent Patients with Tetraplegia: electrophrenic versus mechanical ventilation

Wolf C, Meiners Th., Eisenhuth J

1. Introduction

During the last 20 years we have treated nearly 90 patients with tetraplegia demanding continual artificial respiration. 19 out of those patients received a phrenic nerve stimulator system.

Our objective in the treatment of patients with tetraplegia and paralysis of respiratory muscles following spinal cord injury is to discharge them into an environment that ensures a high standard of medical and nursing care. Also encouragement to cope with the handicap is needed. After discharge, though, patients tend to disappear out of sight of the attending doctors.

2. Material and Methods

We made an enquiry to learn more about the quality of life and the situation at home of our patients demanding artificial respiration. 28 patients were requested to fill in a questionnaire. Half of them used phrenic nerve stimulation (PNS), the others were in a mechanical ventilation scheme (MV), using a portable respirator.

In the „MV“ group three patients could not be considered, because they were in the meantime able to breathe spontaneously for an average of 16 hours per day or longer. One patient with „PNS“ never made use of it. So he was counted in the „MV“ group. Out of the 14 patients with „PNS“ one patient had not left hospital and two others did not answer the questionnaire. Thus eleven patients of each group were included in the study. After conclusion of the study one of the „PNS“ patients had to undergo abdominal surgery and stopped using stimulation; another patient of this group died.

3. Results

Only one patient lived in a nursing home, all of the others lived at their own homes. The patients were aged 11 to 60 years in the „MV“ group and 20 to 42 years in the „PNS“ group. They had been paralyzed between two and more than ten years in each group. The average daily time of spontaneous breathing was 37 min. („MV“) versus 57 min. (PNS).

Demography

	Mechanical Ventilation (MV)	Phrenic Nerve Stimulator (PNS)
Age	11-60	20-42
More Than 10 Years Paralyzed	4	5
5-10 Years Paralyzed	4	3
2-5 Years Paralyzed	3	3
Mean Time of Spontaneous Respiration	37min	57min

Figure 1

Fig. 2 shows the average daily time on phrenic nerve stimulation. Seven persons make use of PNS for 24 hours per day, the others between ten and 22 hours. Seven patients breathe via tracheostomy tube. Four breathe via their nose and use a nasal mask combined with a respirator when needed.

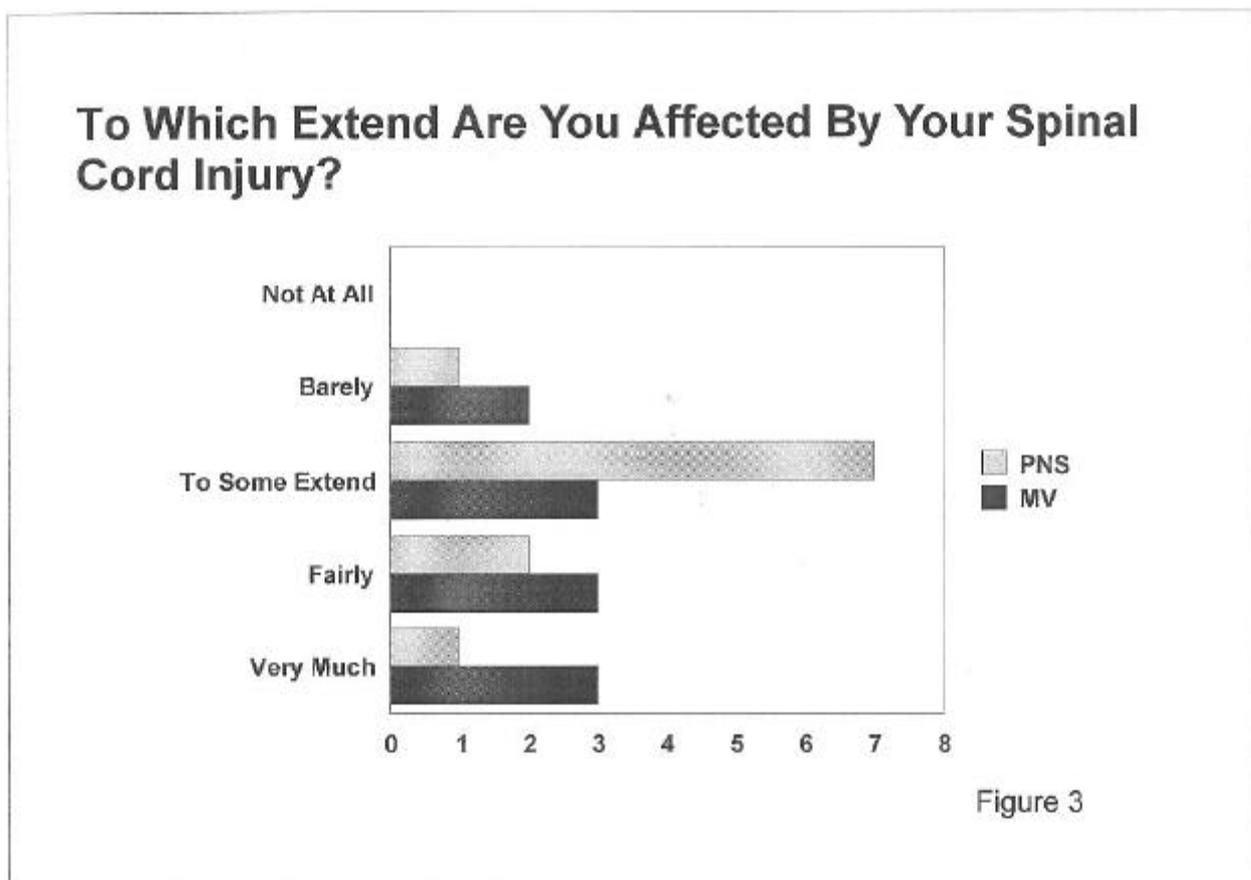
Mean Time of Stimulation Per Day

24h	7 Persons
22h	1 Person
21h	1 Person
13h	1 Person
10h	1 Person

Plus Spontaneous Breathing And/Or Mechanical Ventilation

Figure 2

The following results were obtained in our enquiry concerning the personal situation and situation at home. Eight out of eleven „PNS“ patients felt they were „barely“ or „to some extent“ affected by their spinal cord injury. The statements of the „MV“ group ranged evenly from „barely“ to „very much“ (Fig. 3). Accordingly, all of the „PNS“ patients said, they coped „well, rather well or not too bad“ with their impairment, whereas most of the patients on respirator scheme answered in a more moderate way (Fig. 4) .



How Do You Cope With The Fact of Your Spinal Cord Injury?

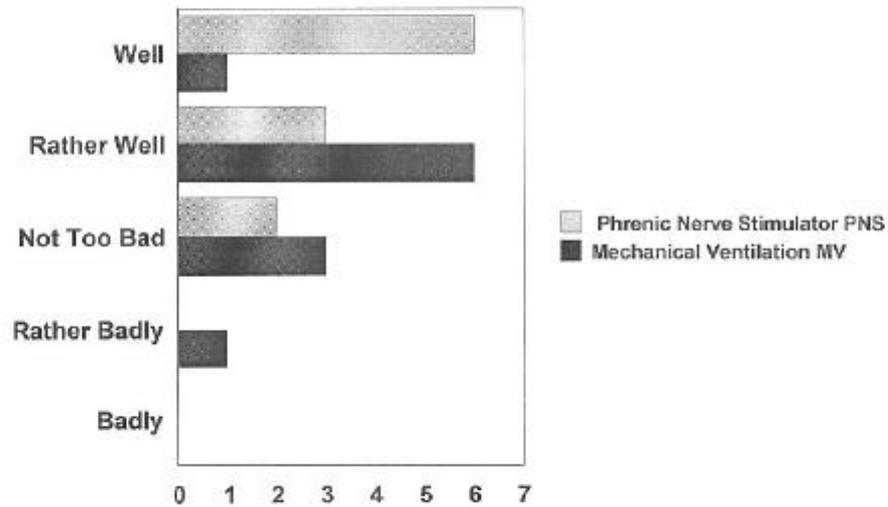


Figure 4

Specifying their problems, both groups equally complained about their dependence on others and lack of privacy. Physically troubling were the lack of bladder and bowel control and lack of sensory perception. Less patients of the „PNS“ group reported about problems with transportation and social contact, while this seemed to be a more severe problem in the „MV“ group. Only three patients of each group found themselves void of meaningful occupation. (Fig. 5). In the domestic field reading, watching TV and computing were favorite pastimes. But also a number of outdoor activities were mentioned, such as vacations, visits to the cinema or pubs, short trips, watching football matches, photography, music, pen-friends, fishing, visiting wine-festivals etc.

Which Problems Do Trouble You?

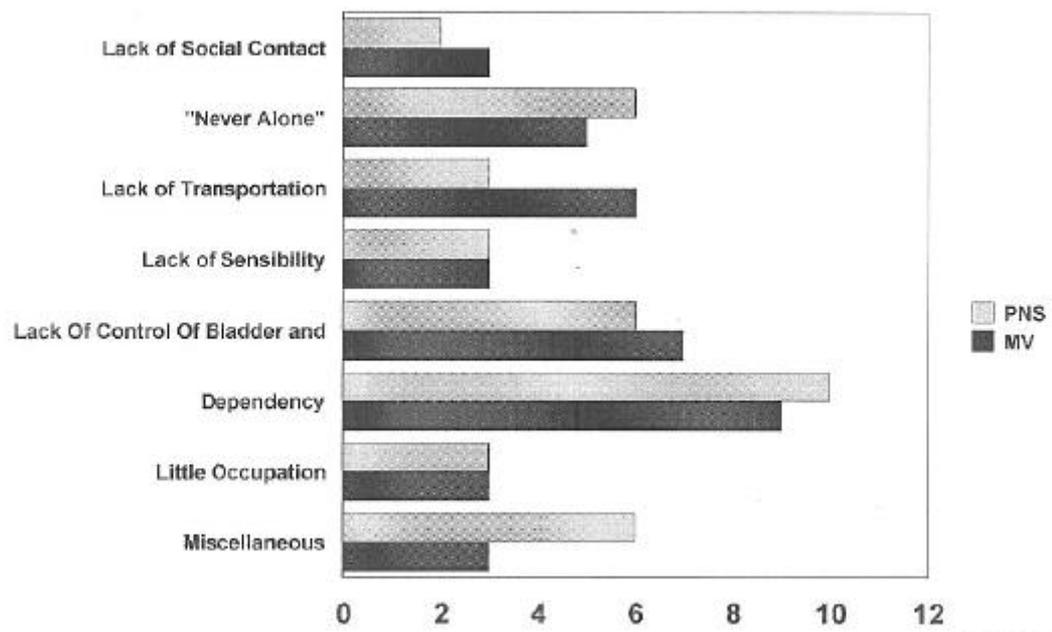


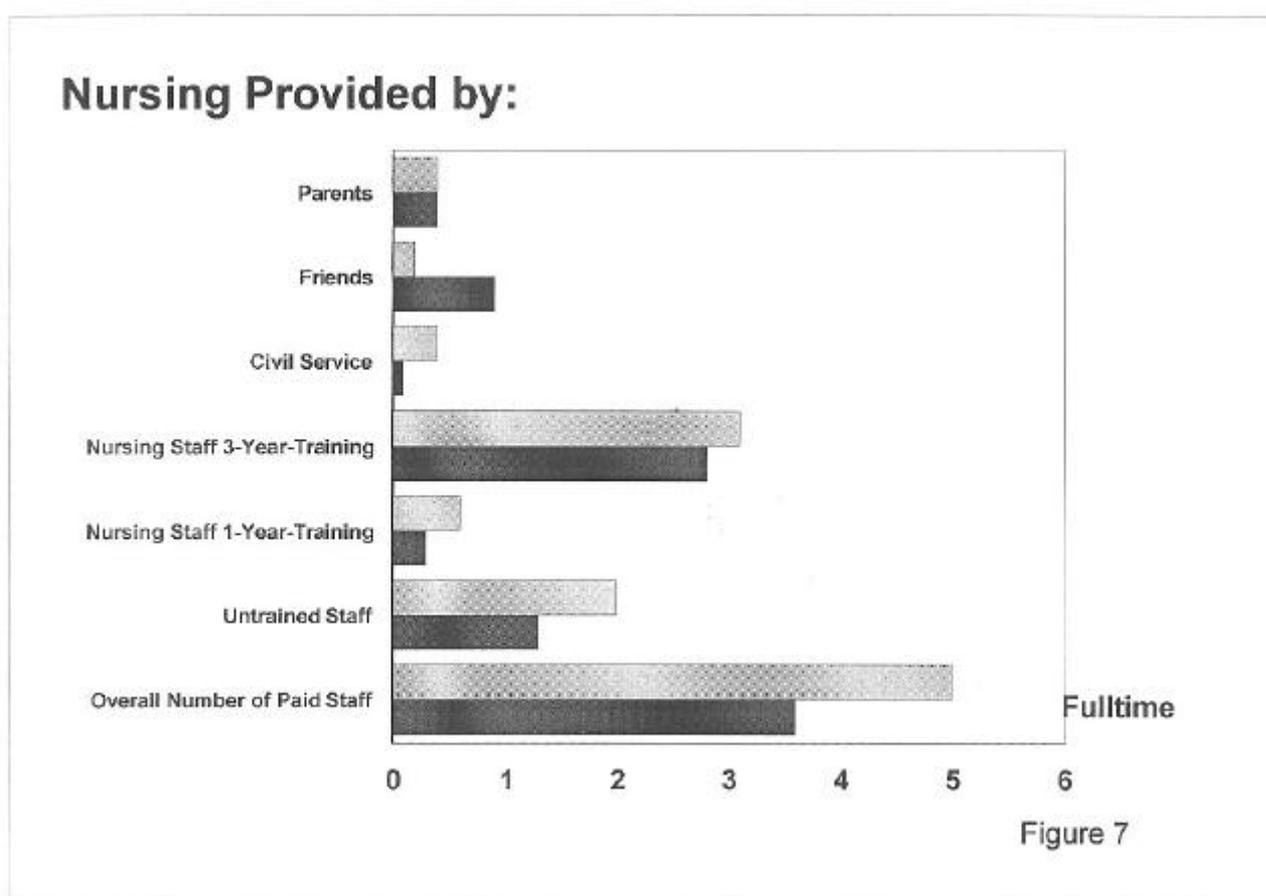
Figure 5

Seven patients in the „MV“ and three in the „PNS“ group visited school or university or attended to an occupation or training. The occupations ranged from clerk, secretary, and computer specialist to social pedagogics (Fig. 6).

	MV	PNS
Occupation	3	1
School	3	1
Training	0	1
University	1	0

Figure 6

Another aspect of the enquiry dealt with medical and nursing care. A widespread range of persons provides nursing. Each patient with mechanical ventilation is cared for by an average of 3,5 paid attendants, versus five in „PNS“ patients. In the majority of the cases, staff consists of nurses with a full training, but untrained staff is employed as well as parents (Fig. 7). Both groups judged the nursing as excellent or fairly well. Nobody was dissatisfied with the care he or she was given (Fig. 8). New members of the team were trained by experienced staff or by the patients themselves. The training on the technical devices was partly conducted by the personnel of the supplier.



Contentment With Domestic Nursing ?

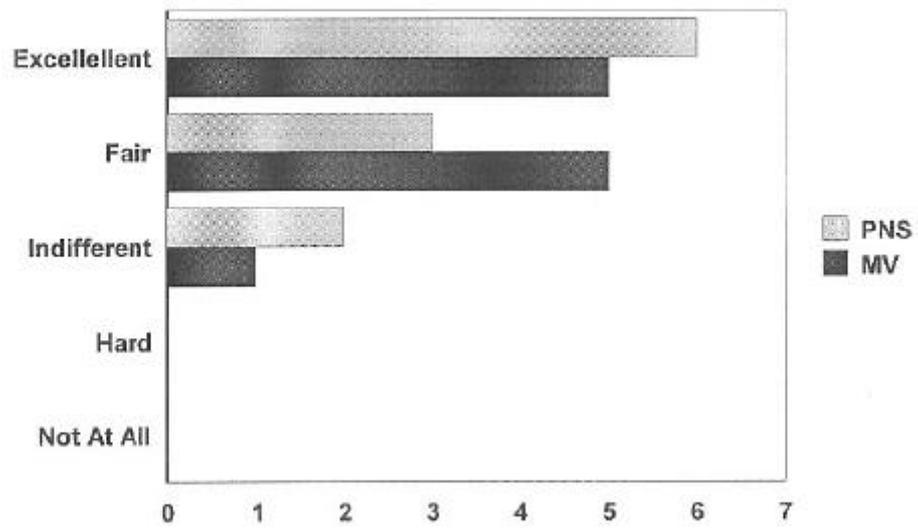
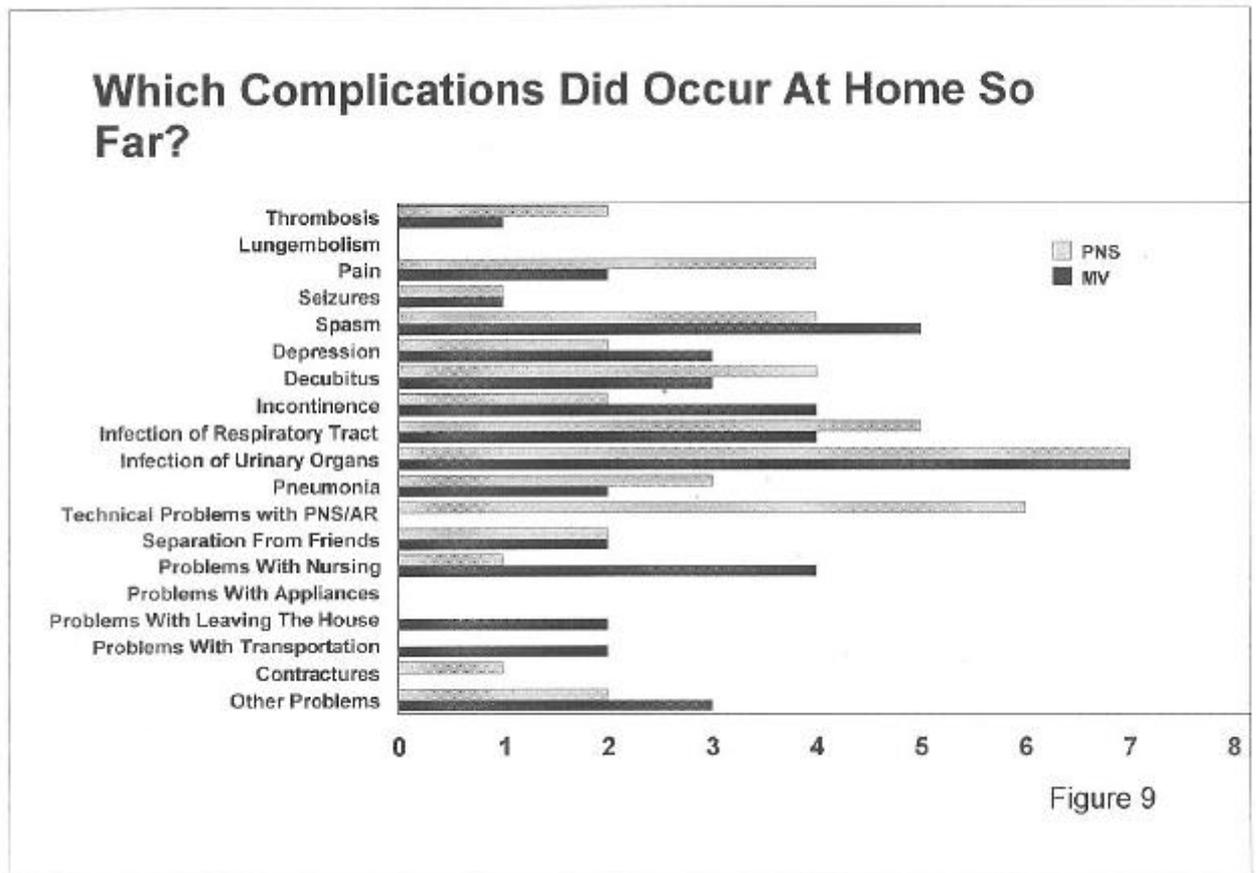


Figure 8

Complications mainly occurred as infections of the urinary or respiratory tracts. Also other specific problems such as spasms, pain, incontinence, and pressure sores were listed in both groups. Problems related to nursing, transportation and outdoor activities were only mentioned in the „MV“ group (Fig. 9). However, six out of eleven patients had experienced technical problems with their phrenic nerve stimulator system. Incidents related to the artificial respiration were rather rare in both groups. Problems mentioned here were defects of the respirator and dislocation of the tubes (Fig. 10).



Which Incidents Did Occur Under PNS/MV?

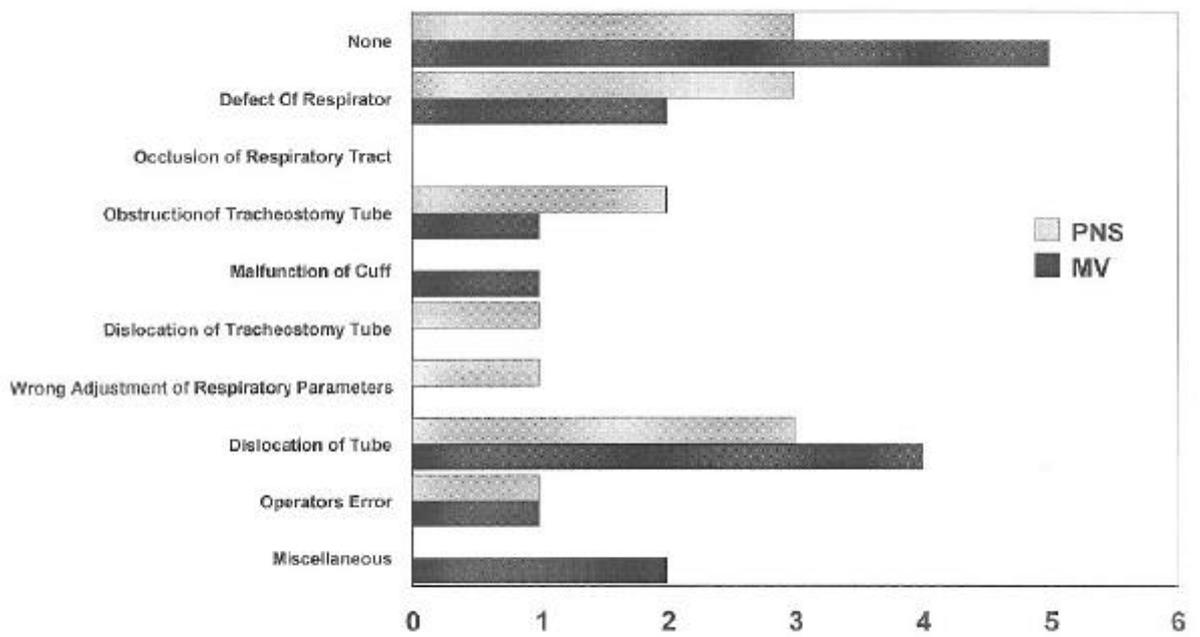
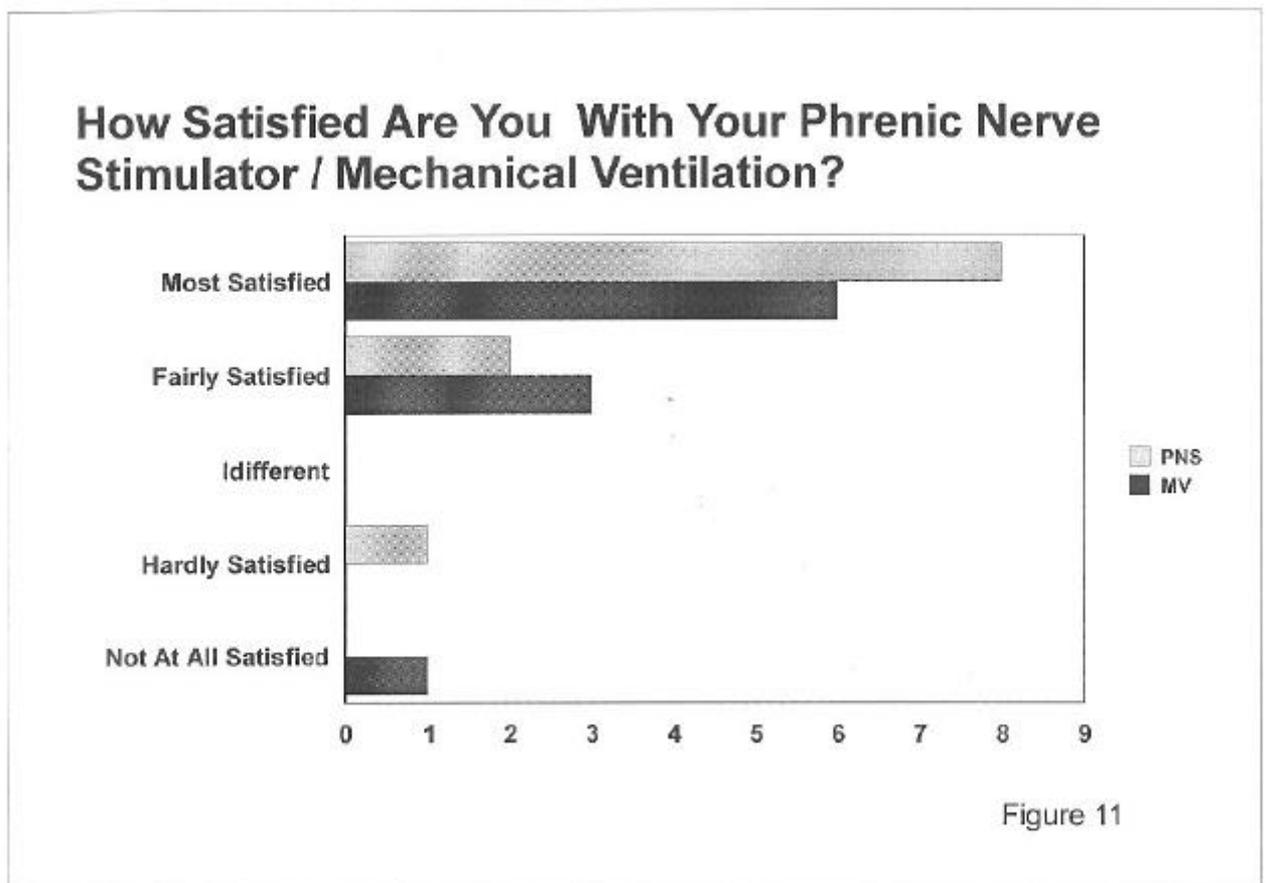


Figure 10

Both groups stated they were „most“ or „fairly“ satisfied with their respiration scheme. Only one patient of each group was discontented (Fig. 11). At last we asked the „PNS“ group to compare their present situation with the previous situation under mechanical ventilation. All of them reported they were „much better“ or „better“ off than before (Fig. 12). Benefits became apparent in respect to health, transportation and social and professional activities. The „PNS“ patients claimed, that PNS restored their self-assurance. Their voice was stronger and more articulate than before. They felt they were not stared at so much as the respiratory deficiency was not so obvious to others. Finally, mucus could be removed more easily. Mechanical ventilation left patients feeling helpless, insecure, and dependant. As a disadvantage of PNS was seen that there are no alarms in case of malfunction of the device and that the capacity of the accumulator was too short.



Please Compare Your Present Situation With Phrenic Nerve Stimulator To Your Situation Under Respirator Scheme? Situation With PNS Is...

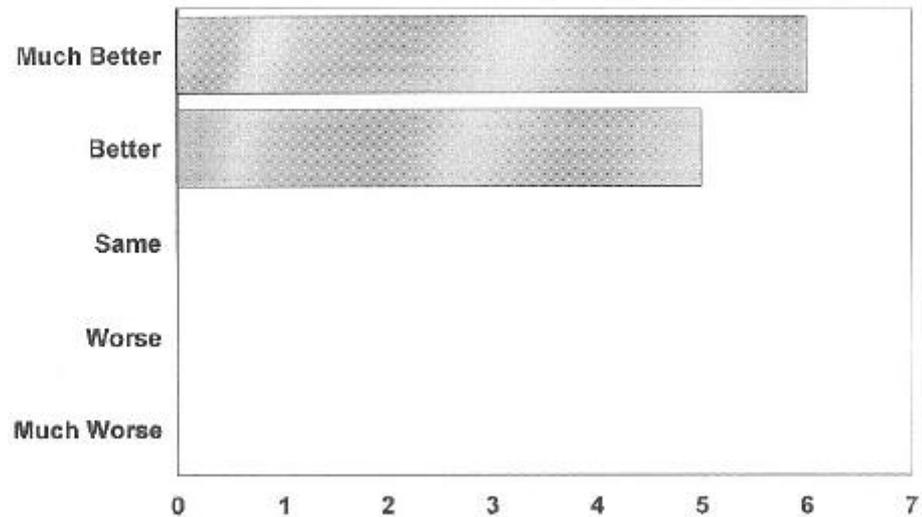


Figure 12

4. Summary

We learned that the majority of patients with tetraplegia and respiratory deficiency live at their homes and receive sufficient nursing and medical care. They take an active, self-confident and responsible outlook on their lives despite their handicap. In either group patients were content with their respiration scheme. Especially „PNS“ patients were, despite of some technical shortcomings, very satisfied and prefer PNS to a respirator scheme, because it offers them better comfort and more personal freedom.

Address:

Dr. Cornelia Wolf
Zentrum für Rückenmarkverletzte
Werner Wicker Klinik
Im Kreuzfeld 4
D-34537 Bad Wildungen

Phrenic Nerve Stimulation: Results Based on Selection Criteria

Caldirolì D*, Rocco G**

*Dept. of Anesthesia and Intensive Care and **Dept. of Thoracic Surgery
Azienda Ospedaliera E. Morelli, Sondalo, Italy

Introduction

The prerequisites of diaphragmatic pacing are well-established (i.e., normal phrenic nerves, diaphragm muscles, and lungs)¹. In addition, age, disease progression, life expectancy, level of self-awareness, and home care facilities all have to be taken into account in the decision-making process.

According to these criteria patients with organic lesions of the craniospinal tract or functional derangements of the respiratory center can be included in the Phrenic Nerve Stimulation (PNS) protocol. However, the prolonged length of stay and conditioning time in an institution and the morbidity and mortality of these patients have to be carefully weighted against the possible improvement of the quality of life in those patients whose neurophysiological inclusion criteria are marginal.

Still controversial is the timing of implantation concerning the possibility of recovery of spontaneous breathing².

Methods

Between January, 1989 and July, 1999, thirty-two patients with chronic respiratory failure have been evaluated for PNS. These patients were either ventilator-dependent or carried malfunctioning stimulators implanted elsewhere.

Neurophysiologic inclusion criteria, implantation timing, recovery of spontaneous breathing, and success of stimulation (hours/day) have been evaluated with relation to the disease pattern.

Results

Ten out of 32 patients (32%) were deemed eligible to PNS according to the inclusion criteria. They were all quadriplegic patients; eight of them (39%) had a history of cervical cord injury, one (3%) suffered a complication at birth, and one (3%) had quadriplegia following odontoidectomy of the epistropheus. Of the two patients with non-traumatic neurological compromise (cord ischemia, Guillain-Barre syndrome, cervical myelitis) neurophysiologic inclusion criteria were absent for 6 consecutive months. Among the 10 patients undergoing implantation eight were operated on after more than six months whereas the remaining two had the implantation done within four months from evaluation (Tab.1).

Complete weaning (24h/day) from mechanical ventilation was obtained in three patients; one of these had the tracheostoma cannula removed. The remaining six patients are still ventilator-dependent, four only at night and two all daylong. The reasons for ventilator dependency in the last two patients are abdominal muscle spasticity evoked by diaphragmatic contractions and severe tracheomalacia associated with poor cooperation in a patient with Down syndrome. None of the

patients with cord injury recovered spontaneous diaphragmatic breathing after PNS. However, two of these patients are now able to breath spontaneously for over six hours by using the accessory muscles of the neck. The patient undergoing implantation (< 4months) following birth trauma recovered some diaphragmatic function together with upper limb motility short after implantation.

Among the 22 patients excluded from the PNS protocol, 14 (64%) recovered spontaneous breathing or require nocturnal ventilatory assistance only. Nine of them had a history of cervical cord injury and five had concurrent neurological disease (Tab.2).

Implanted components had to be removed in three patients. Infection of implanted components occurred ten years after implantation in one (fortunately meanwhile) non-ventilator-dependent patient; an entrapment of the phrenic nerve occurred within two months from implantation in a second patient and was successfully surgically cured followed by re-implantation in the neck eight months later; a third patient wanted his receivers changed when he heard of a “more modern” model. Reconditioning lasted significantly longer than after the first operation in the two patients who had replacement of implanted components and were mechanically ventilated for four and six months. Two patients on PNS died two and five years from implantation (Tab. 3). The cause of death was lack of home care in one patient and is still unknown in the other, who died during stimulation.

Discussion

PNS was successful (at least 12 h/day) in all patients younger than 55 years of age presenting all neurophysiologic inclusion criteria for at least six months associated with an uncompromised cardio respiratory condition and high level of cooperation. Several causes for PNS failure in ventilator-dependent patients were identified. In the 14 years old Down patient with sequelae after odontoidectomy for treatment of pseudarthrosis of the epipistropheus, the following lead to a failure of PNS:

1. Incomplete compliance to neurophysiological criteria (PNCT> 14ms with poor muscle response);
2. Lack of cooperation;
3. Inadequate timing of implantation (< 4months) while the patient showed a partial recovery of his upper limb and diaphragmatic motility.

In a second patient the main reason for failure was an unpredictable severe spasticity of the abdominal muscles elicited by diaphragm contractions. Worth to note is the percentage of patients not deemed eligible according to inclusion criteria, who partially or completely recovered spontaneous breathing (82%). This occurred on all patients with ischemic (i.e., thrombosis of the anterior spinal artery) or infectious (G.B.S.) neurological conditions.

In our experience, insufficient emphasis on the timing of the steps preceding implantation has been the reason for failure of PNS in some cases. Early recovery of spontaneous breathing in one patient with functioning PNS may be related to inadequate timing or to insufficient compliance to neurophysiologic criteria.

Analysing the results and the inclusion criteria for PNS, some of the indications for PNS have proved questionable. In conclusion, an inadequate performance of PNS is likely to be attributed to a misleading interpretation of neurophysiologic criteria, to a lack of consideration of concurrent criteria, and to an inappropriate timing.

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Table 1
 Patients evaluated for diaphragm pacing from 1989 to 1999 at
 Azienda Ospedaliera E. Morelli, Sondalo, Italy

	Patients evaluated	Matched criteria for pacing (PNS)	No criteria for pacing	<i>Time from evaluation to implantation</i>
n (%) (%)	32 (100)	10 (31)	22 (69)	
Cord injury	25 (78) (100)	8 (32)	17 (68)	> 6 months
Cord ischemia Guillain-Barre S. Cervical myelitis	5 (17)		5 (100)	
Birth complication	1 (3)	1(100)*		< 4 months
Odontoid surgery	1 (3)	1(100)*		< 4 months

* Referred from other hospital with implant in situ.

Table 2
 Recovery of spontaneous breathing and use of mechanical ventilation in patients
 selected for (PNS, n=10; 100%) and patients excluded from (No PNS, n=22;
 100%) diaphragm pacing.

	Recovery of Spontaneous Breathing		Mechanical Ventilation	
	PNS	No PNS	PNS	No PNS
n (%)	3 (30)	14 (64)	3 (30)	7 (32)
Cord injury	2 (accessory muscles)	9 (64)	2 *	5
Cord ischemia Guillain-Barre S. Cervical myelitis		5 (36)		2
Birth complication	1 (diaphragm)			
Odontoid surgery			1 **	

* One patient impossible to stimulate because of severe spasticity of
 abdominal muscles during stimulation

** Down syndrome; phrenic nerve conduction time >14ms; no cooperation
 during conditioning.

Table 3
Descriptive data of the PNS population

Patients Age (yrs.)	Disease	Follow up	Tracheo- stoma	hrs./day on PNS	MV	Company	Implantation Site
MA (18)	C1-C2	10 yrs	open	24 ⁺	0	Avery, Atrotech	Neck, [§] Thorax
MR (18)	C1 – C2	9 yrs	closed	24 ⁺	0	Avery	Thorax
BD (14)	C1 – C2	7 yrs	open	0 [⊠]	24	Avery	Neck
FA (51)	C1 – C2	7 yrs	open	16 ⁺	8	Atrotech	Thorax [@]
TG (54)	C1 – C3	2 yrs (died)	open	12 ⁺	12	Atrotech	Thorax
SM (18)	C1 – C2	3 yrs	open	24 ⁺	0	Atrotech	Thorax
KA (5)	C1 – C2	1 yr (conditioning)	open	8 ⁺	16	Atrotech	Thorax [#] , Neck
CJ (18)	C1 – C2	8 months (conditioning)	open	0 ⁺	24	Atrotech	Thorax
MD (2) *	C1 – C2	5 yrs (died)	open	16 ⁺	8	Avery	Thorax
PD (1) *	Birth complic.	8 months	open	6 [⊠]	18	Avery	Neck

* Referred from different hospital

§ Reimplantation because of infection

Reimplantation because of nerve entrapment

@ Receivers substituted when changing electrode?

+ Implantation > 6 months from incident

⊠ Implantation < 4 months from incident

**Diaphragm Pacing in Infants and Children: Learning from the Past to Plan
for the Millennium**

Weese-Mayer DE

Professor of Pediatrics

Rush University

Chief, Pediatric Respiratory Medicine

Rush Children's Hospital at Rush-Presbyterian-St. Luke's Medical Center

Chicago, Illinois

U.S.A.

Corresponding author information:

Debra E. Weese-Mayer, M.D.

Chief, Pediatric Respiratory Medicine

Rush Children's Hospital at Rush-Presbyterian-St. Luke's Medical Center

1653 West Congress Parkway

Chicago, IL 60612

E-mail: dweese@rush.edu

Phone:

312-942-2723

Fax:

312-942-3087

Historic Background

Electrical stimulation of the phrenic nerves to initiate diaphragm pacing was first proposed over 200 years ago when Hufeland applied the treatment to asphyxiated newborns (1=Schechter 1970). Nearly one hundred years later (1872), Duchenne de Boulogne supported artificial ventilation with a pacing technique (1=Schechter 1970). Modern forms of diaphragm pacing began to emerge in the middle of the 20th century when Sarnoff et al described a method of percutaneous phrenic nerve stimulation that allowed for sustained support (2=Sarnoff 1951). Dr. Glenn moved the use of diaphragm pacing into the public eye in 1964 when he reported his first results (3=Glenn 1964). Since 1966 he and Dr. Elefteriades have paced more than 100 patients with chronic ventilatory insufficiency (3-6=Glenn 1964, van Heeckeren 1966, Judson 1968), representing the world's largest experience of diaphragm pacing in adults. In 1976 Dr. Hunt established a program in Chicago to pace infants and children. Drs. Weese-Mayer and Silvestri have developed this Center into the world's largest program for diaphragm pacing in the pediatric population (7-16=Hunt 1978, Weese-Mayer 1992, Ilbawi 1985, Brouillette 1988, Weese-Mayer 1989, Marzocchi 1990, Brouillette 1983, Weese-Mayer 1988, Silvestri 1995, Weese-Mayer 1996). Now in the year 2000, diaphragm pacing has become a reasonable alternative and/or adjunct to mechanical ventilation for the adult and child with alveolar hypoventilation due to inadequate central respiratory drive or high cervical cord injury (17-24=Mellins 1970, Glenn 1973, McMichan 1979, Coleman 1980, Oakes 1980, Ruth 1983, Cahill 1983, Fodstad 1987).

Global Perspective

To put the overall pacer experience with the monopolar electrode system into perspective, one must turn to the report by Glenn et al (25=Glenn 1986) describing 477 paced patients (>90% adults) implanted between 1966 and 1986. The diagnoses among these patients included cervical cord and brainstem lesions, central alveolar hypoventilation, and hypoventilation due to peripheral causes. Notably, ~65% of patients were implanted and followed outside of Centers with recognized expertise in diaphragm pacing. At the time of that report, 59% of the Center patients were alive. Curiously, the most common approach for adults was unilateral pacing, potentially using one side for 12 hours then the other side for 12 hours to sustain continuous pacing. Bilateral simultaneous, but not continuous, pacing was fairly standard for infants and children who were not wheelchair dependent. A tracheostomy was placed initially in all pediatric patients and > 90% of the adults with the intent to allow for mechanical ventilation or to avoid pacer-induced airway obstruction. At the time of that publication the longest pacing experience was 18.3 years of unilateral (left side only) pacing and 15.6 years of bilateral and full-time pacing, both in adults.

Pediatric Experience with Diaphragm Pacing

Monopolar Electrode System. Diaphragm pacing has now been successfully used in pediatric patients for nearly three decades (7-25). Although most reports typically include study of one or two children, we have previously summarized our experience with, at the time of that report (1975-1991), our first 37 patients paced in the Chicago program using the monopolar electrode system. At the time of that report an additional ~30 children were identified in the literature, again as case reports. The diagnoses among our patients is most typically Idiopathic Congenital Central Hypoventilation Syndrome (CCHS). CCHS is a rare entity with ~100 published cases, again typically in case report format. It is characterized by generally adequate ventilation while the child is awake but with alveolar hypoventilation with typically normal respiratory rates but diminished tidal volume when the child is asleep (26-30=Weese-Mayer 1999, Weese-Mayer 1992, Silvestri 1992, Pine 1994, Silvestri 2000). More severely affected children with CCHS demonstrate alveolar hypoventilation asleep and awake, necessitating artificial ventilatory support 24 hours per day. It is these children who are completely ventilator dependent who can benefit the most from diaphragm pacing, for they can participate in age-appropriate activities (in moderation) without the cumbersome mechanical ventilator during the day. Other patients in whom diaphragm pacing has been applied include those with late onset CHS, Chiari II malformation, acquired hypoventilation, and tetraplegia. Notably, ~30% of patients are from outside of Centers with recognized expertise in diaphragm pacing. At the time of our 1992 publication, 73% of the Chicago Center paced patients were alive. All but one of these children were paced bilaterally and had a tracheostomy. Among the children reported in that study, the longest pacing experience is >18 years of unilateral use (alternating right-left-right) and >18 years of bilateral use with 12-15 paced hours/day.

Quadripolar Electrode System. Subsequent to 1990, we and others have initiated use of the Atrostim pacing system which relies on a quadripolar electrode. The initial report (16=Weese-Mayer 1996) of use between 1990-1995 included 36 pediatric and 32 adult patients enrolled in 14 countries around the world. The two primary diagnoses were CCHS among the pediatric patients and tetraplegia among most adult and some pediatric patients. At the time of that publication, all of the pediatric patients were alive. The patients were typically paced bilaterally. More than 80% of the patients had a tracheostomy. At the time of that report the longest use of the quadripolar system was >5.2 years. Subsequently the quadripolar electrode system has been successfully used in pediatric patients for >8 years.

Pediatric-Specific Limitations to Continuous Pacing (24 hr/day)

Although adults have often been paced 24 hours each day, these are typically tetraplegic adults with limited ventilatory needs and no ambulatory capability. The active child with CCHS is somewhat more complicated and therefore not typically paced continuously. First, the infant and child have a very compliant rib cage, thus requiring bilateral pacing to support ventilation. Second, the immature patient has an increased required alveolar ventilation (due to the increased metabolic rate corrected for body weight (31=Wohl 1983), necessitating bilateral pacing to achieve adequate ventilatory support. Third, an ever present concern for diaphragmatic fatigue in these children who are facing a life-time of artificial ventilatory support necessitates conservative management. For those able to support periods of spontaneous breathing, there is always concern for surgical trauma to the phrenic nerve which could render the child entirely ventilator dependent. Encouragement regarding continuous pacing in children comes from our earlier animal data studying continuous low frequency pacing in a puppy model (32=Marzocchi 1990). We demonstrated that one month of unilateral diaphragm pacing 24 hr/day with settings similar to those used in our clinical care did not impair diaphragm function and actually converted muscle fiber type to a uniform population of fatigue-resistant Type I fibers (high oxidative enzyme activity).

Patient Selection Criteria

The ambulatory child with CCHS who requires artificial ventilatory support 24 hours each day is the ideal pacer candidate. Likewise, the child should be without intrinsic lung disease or supplemental oxygen requirement, and should have preservation of the cervical roots that comprise the phrenic nerve (C3, C4, C5). Much of our success with diaphragm pacing in children comes from rigorous patient selection criteria. These include the following:

- Ventilator dependence 24 hr/day
- Absence of intrinsic lung disease
- Phrenic-nerve-diaphragm axis integrity
- Tracheostomy
- Potential to improve quality of life
- Stable family environment

Recommended Age for Pacer Implantation

Another factor that has augmented our success with diaphragm pacing is related to careful selection of an appropriate age for surgical implantation.. The children with CCHS are not usually implanted until that are at least 12 months of age. This will give them the maximal benefit of mobility since children with CCHS typically have delayed motor milestones despite the potential for excellent

intellectual outcome. Also, children with CCHS often have multiple complicating symptoms that can occur in the first several months of life including seizures, hypoglycemia, dysphagia, and severe constipation. The delay in surgical implantation allows the infant and family ample time to recover from these symptoms and acclimate to the child's diagnosis. The child who is tetraplegic, though not the typical patient we would pace in Chicago, should be observed for a minimum of six months to allow ample time for spontaneous recovery from the initial trauma inducing the tetraplegia.

Assessment of Phrenic Nerve-Diaphragm Axis Integrity

It is essential to validate an intact phrenic nerve-diaphragm axis before considering a child for surgical implantation of a diaphragm pacer system. This can be determined by diaphragm fluoroscopy to look for diaphragm excursion of at least 1-2 rib spaces with voluntary breaths. For those infants who do not take adequate respiratory effort, even briefly for the period of the fluoroscopy, percutaneous stimulation of the phrenic nerve is another option. This technique involves application of a bipolar stimulating electrode on the neck posterior to the lateral border of the sternocleidomastoid muscle. The electrode is moved superiorly and inferiorly along the body of the anterior scalene muscle to stimulate the phrenic nerve. The simulator is set to deliver 1 msec pulses of 1 to 15 mA current. Conduction time and diaphragmatic action potential amplitude are measured on an oscilloscope from signals obtained by surface EMG electrodes placed on either side of the costal margin (superior and inferior) in the mid clavicular line bilaterally. The phrenic nerve conduction time should be 7ms. The diaphragmatic action potential amplitude varies with the site of the surface electrodes but is typically 0.4mV.

Surgical Implantation and Subsequent Parameter Adjustment of the Pacer System

The description of surgical implantation was deleted from the presentation in Hamburg because it has been described by other presenters.

The primary goal of setting the pacer system is to minimize electrical stimulation, yet achieve adequate ventilation and oxygenation. This can be achieved by setting the different variables as detailed below:

- Stimulus current: threshold & volume for each individual electrode
- Slope adjusted bilaterally to achieve a smooth contraction
- Interpulse interval: 40-120 ms
- Inspiratory time: ~0.6 seconds
- Respiratory rate: 14-40 bpm

These parameters were determined after studying how best to deliver current during inspiration in order to optimize the inspiratory contraction. Specific settings will vary from evaluation to evaluation in a given child, and from child to child. The pacers should be evaluated every six months for the first two years of use (at a minimum) in a Center with recognized expertise in pediatric diaphragm pacing. Consolidation of experience with diaphragm pacing will allow for improvement in the pacing systems and allow the child the benefit of the most trained staff available.

Life Table Analysis of Implanted Pacer Components with the Monopolar Electrode System

The diaphragm pacing experience with the monopolar electrode in children in our Chicago Center has been published previously (11=Weese-Mayer 1989) among the first 33 successfully paced pediatric patients. The experience included 192 system-years and 96 patient-years. The categories for failure are shown below:

- Receiver failure
- Electrode wire or insulation breakage
- Infection
- Mechanical nerve injury

The mean time to failure of implanted components was 56.3 months with a total of 26 failures of the Avery system (Avery Laboratories, Glen Cove, NY). The symptoms of failure included absent diaphragmatic movement, intermittent function, or pain at the receiver site or ipsilateral shoulder.

Receiver failure. Receiver failure accounted for 15 of the 26 internal component failures. The mean time to receiver failure was 62.6 months. Failure was due to fluid penetration of the epoxy encapsulation or receiver wire breakage. The treatment requires subcutaneous pocket entry to replace the receiver.

Electrode failure. Electrode failure accounted for 6 of the 26 internal component failures. The mean time to receiver failure was 19.0 months. Failure was due to breakage in the silicone rubber insulation or breakage in the electrode wire. Unfortunately electrode or electrode wire failure require thoracic surgery for component replacement.

Infection. Infection accounted for 3 of the 26 internal component failures. These infections occurred at 38 days, 72 days, and 50 months. The organisms identified included *Staphylococcus Aureus* alone and in combination with *Moraxella* species, and *Pseudomonas Aeruginosa*. Symptoms at presentation consistently

included cellulitis over the implanted receiver. These children required intrathoracic surgery to remove all of the implanted components except for the actual electrodes attached to the phrenic nerves. These are left intact but the wires cut as close to the electrodes as possible to avoid traumatizing the phrenic nerve while minimizing the amount of foreign body left in the chest. In addition each child received up to 12 weeks of intravenous then oral antibiotics directed toward the identified organism. An additional period of up to 12 weeks is allowed off of antibiotics while the child is vigilantly followed for any sign of infection. Finally, ~6 months after the initial treatment for the infected pacer components the entire system can be replaced. We are aware of one child who reportedly developed symptoms of cellulitis but responded to vancomycin and cefotaxime without surgical intervention.

Mechanical nerve injury, no paced electrical injury. This condition occurred in two of the 26 implanted component failures. One child presented after 7.5 years of pacing with the phrenic nerve entrapped in a cuff electrode that is no longer used. The other child presented 2.8 years after pacer implantation at one month of life, with the phrenic nerve tethered by a monopolar electrode. In the first case the electrode was removed and in the second case the nerve was re-anastomosed. In both children pacing resumed in <12 months from the onset of pacing dysfunction. As a result of these cases, the cuff electrode is no longer used and even with the monopolar electrode (and subsequently the quadripolar electrode) the surgeon allows for redundant wire in the chest for growth coupled with a delay for initial surgical implantation until >12 months of age.

Life Table Analysis of Implanted Pacer Components with the Quadripolar Electrode System

The diaphragm pacing experience with the quadripolar electrode in children in our Chicago Center has been published previously in part (16=Weese-Mayer 1996) among the first 68 successfully paced patients. The experience included 280 system-years and ~149 patient-years. The categories for failure are shown below:

- Receiver failure
- Electrode wire or insulation breakage
- Infection
- Mechanical nerve injury

The total number of failures of the Atrostim system (Atrotech Oy, Tampere, Finland) was 17. The symptoms of failure included absent diaphragmatic movement, intermittent diaphragm flutter or function, and pain at the receiver site or ipsilateral shoulder.

Receiver failure. Receiver failure accounted for 6 of the 17 internal component failures. Five were for unidentified technical malfunction and one for altered

integrated circuit function. The treatment requires subcutaneous pocket entry to replace the receiver.

Electrode failure. Electrode failure accounted for 4 of the 17 internal component failures. Failure was due to unspecified failure in 2 cases, nerve entrapment in 1 case, and a broken pin and insulation in one case. Several other patients had periodic flutter noted. For the flutter, it is possible in programming the system to turn “off” select electrodes. For the other cases of failure, thoracic surgery is indicated for component replacement. Because of these early failures, we worked with the Atrotech company to re-design the connectors for the pacemaker system and in so doing minimize the potential for electrode and wire failure.

Infection. Infection accounted for 4 of the 17 internal component failures. These infections occurred at 0.25, 0.6, 1.7, and 2.8 years after surgical implantation of the pacemaker system. The organisms identified included *Staphylococcus Aureus* in 2 children, *Streptococcus Pneumoniae* in one child, and an unidentified organism in one child. Symptoms at presentation consistently included cellulitis over the implanted receiver, and were typically preceded by a report of minor trauma to the site. These children required intrathoracic surgery to remove all of the implanted components except for the actual electrodes attached to the phrenic nerves. These are left intact but the wires cut as close to the electrodes as possible to avoid traumatizing the phrenic nerve while minimizing the amount of foreign body left in the chest. In addition the child received up to 12 weeks of intravenous then oral antibiotics directed toward the identified organism. An additional period of up to 12 weeks is allowed off of antibiotics while the child is vigilantly followed for any sign of infection. Finally, ~6 months after the initial treatment for the infected pacemaker components the entire system can be replaced.

Mechanical nerve injury, no paced electrical injury. This condition occurred in one of the 26 implanted component failures. This patient had the phrenic nerve entrapped in an electrode. In this case the electrode was removed and pacing resumed in <12 months. Of interest, before the pacemakers were even implanted 3 phrenic nerves were noted to be traumatized in the hands of surgeons unfamiliar with diaphragm pacing. This observation serves to emphasize the need for pacemakers to be implanted in recognized Centers with expertise in the surgical implantation and management of diaphragm pacemakers. It is imperative that each patient, and children in particular, have the best possible opportunity for success in pacing.

Clinical Lessons of Diaphragm Pacing

During the years of extensive experience in diaphragm pacing among infants and children we have learned several important clinical lessons. First, the family should have a pulse oximeter that allows them to see the pulse waveform and hemoglobin saturation as well as an end tidal carbon dioxide monitor that allows them to see the exhaled waveform and carbon dioxide values. These measures should be assessed in the home on a regular basis if the child is paced awake and

should be measured continuously if the child is paced during sleep. Second, is recognition of the potential for electromagnetic interference. If the child requires a cardiac pacemaker, the system should be bipolar in order to minimize interference from the diaphragm pacer. If the cardiac pacemaker is a bipolar system and the diaphragm pacemaker is a quadripolar system, the risk for interference should be minimized. Also with regard to electromagnetic interference, the child with a diaphragm pacemaker should not have an MRI. If cranial imaging is necessary then a CT will need to suffice. Finally, the active child with CCHS who relies on diaphragm pacing while awake will need close supervision during exercise as the pacers do not provide a feedback system for the child with CCHS who will become hypercarbic and hypoxemic with modest exercise (15=Silvestri 1995).

Physiological Lessons of Diaphragm Pacing

We have previously reported on the study of 24 hr/day pacing of the left hemidiaphragm in immature beagle puppies using stimulus parameters typical of clinical practice (32=Marzocchi 1990). These stimulus parameters include a pacer frequency of 11.1 Hz, inspiratory time of 0.81 ms, respiratory rate of 20 bpm, and a stimulus current of 130% of that used to attain the maximal diaphragmatic action potential amplitude. We demonstrated that paced tidal volumes and airway occlusion pressures were unchanged at low (<15 Hz) stimulus frequencies and were reduced at high (>20 Hz) stimulus frequencies. Although encouraging, this information must be extrapolated with caution to the clinical condition in human infants and children.

Histochemical Lessons of Diaphragm Pacing

Using the same puppy model described above (32=Marzocchi 1990), the histochemical effects of one month of continuous pacing were studied. The diaphragm appearance was normal but on histochemical evaluation conversion from a mixture of Type I (54%) and Type II (46%) fibers to a uniform population of Type I fibers with high oxidative enzyme activity was observed. We noted transformation of muscle fiber type as assessed by gel electrophoresis. Fast and slow isomyosin bands were identified in each control hemi-diaphragm specimen. However, slow isomyosin only was identified in the paced hemi-diaphragm specimens.

Long Term Outcome of Paced Children at Chicago Center

Monopolar system. Among 37 children implanted with the monopolar electrode pacer system, 23 are living. Four of the children are no longer paced because of severe obesity in one, diaphragmatic atrophy post encephalitis in one, and ventilator preference in two tetraplegic children. When 11 of these patients had

repeated internal component failure with the monopolar system, each was re-implanted with the quadripolar electrode system.

Quadripolar system. Among 17 children implanted with the quadripolar electrode pacer system, 15 are living. All have been successfully paced (14 daytime pacing and 3 night time pacing).

Advantages and Disadvantages of Diaphragm Pacing

The advantages of diaphragm pacing in children with CCHS is quite apparent with the afforded mobility compared to mechanical ventilation if the child requires artificial ventilation awake and asleep. Pacing allows for elimination of daily use of a mechanical ventilator if the child is supported during sleep only. Of necessity, the child requires a back-up pacer transmitter as well as an at-home mechanical ventilator. A potential (though limited) exists for tracheostomy removal in the rare child who might pace with an intact airway awake and use Bi-Pap mask ventilation asleep. To date, this potential has not been realized in our Center.

The advantages are less apparent for the child with tetraplegia. Some children report that they perceive themselves as “more normal”. The possibility of training of the diaphragm to prevent atrophy in the case of any diaphragmatic function should be considered.

The potential disadvantages of diaphragm pacing include cost, time for surgical implantation and pacer initiation/follow-up, and discomfort due to the initial surgery and repeated surgeries in the event of pacer dysfunction.

Future Directions In Diaphragm Pacing

Parents and children will consistently report that diaphragm pacing allows them freedom they could not have had with a mechanical ventilator. Although families are typically discouraged with component failure, they remain enthusiastic and hopeful for improved technology. To actually move diaphragm pacing for infants and children into the next millennium it is essential that funding be directed to improvement in the durability of the technology and the total implantability of a feed back diaphragm pacer system. Only then will the field surpass a technology that has advanced little in the past 10 to 20 years. Through the collaborative efforts of Centers with recognized expertise in diaphragm pacing coupled with the engineering effort of pacemaker manufacturers this goal will hopefully be realized.

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12 years of Experience with Phrenic Nerve Stimulation (PNS)

Hirschfeld S, Exner G, Wenck B

From 1987 to 1999 we treated 30 spinal cord-injured patients with a functionally complete lesion of the spinal cord at the levels C0 to C3 and respiratory device dependency. 18 persons received implantation of an Atrostim Phrenic Nerve Stimulator (PNS), 12 were supported with a conventional mechanical ventilator. We report about the 18 patients treated with PNS.

We treated six female and twelve male patients with an average age of 33,8 (8-59) years. 16 persons got their lesion by trauma, 2 by disease.

Implantations were performed on an average 10,5 (3-50) months after onset of SCI. For all implantations we used the thoracic approach (1). Our method to place the electrodes is described elsewhere in this book (Exner). The conditioning time ranged from four to 28 weeks, with an average of 6,8 weeks, confirming previous results with four-pole sequential stimulation (2).

Primary results

During the first check three months after implantation 10 patients were stimulated continuously and were independent from the ventilator, eight used alternating the stimulator and the ventilator. All had been equipped with special tubes enabling them to speak.

Additionally they were mobilized and supplied with electrically powered wheelchairs and other aids with various computer control systems. Thus, being independent from intensive care, they were transferred to an open ward with all possibilities of reintegration within and outside of the hospital.

COMPLICATIONS during treatment in the ICU and on the ward

We had no acute surgical complications during implantations. Postoperatively thoracic haemorrhage had to be treated once on one side using drainage and suture. Obviously the surgical risk is low if a well-trained surgeon performs the implantation. Severe problems arose during the later follow-up.

First we want to mention technical defects and failures concerning the device. In our first patient both receivers had to be exchanged because of malfunction. Later (since 1991) there were no defects at all of implantable parts.

Most technical failures of the extra corporal parts can be avoided by regular exchange of wearing parts. Such parts are cables, which we exchange four times a year, and coils, which we check at the same intervals and exchange if necessary. A longer standing time of these parts is welcome.

Several patients suffered complications not related to the devices. In our first case we found that the patient could not swallow and had no function of his vocal cords because of defects in the brainstem. Another patient got a basal atelectasis of the left lung. A subsequent abscess needed surgical treatment. After the operation the function of the lung improved. One patient died from his original disease 6 months after implantation.

LEARNING CURVE:

In two cases we caused nerve damage during surgery for implantation. In one case we sutured together the electrode strips to ensure good electrode fixation. The nerve lost function because of the constriction but regained function after surgical decompression. In a second case we saw good nerve function in both sides during surgery and immediately thereafter. At the onset of the conditioning period the function of the left side was gone. During a second look surgery we found constricting scars and performed a decompression. Within 6 months the nerve recovered. The patient is now stimulated 24 h daily. He needed the longest conditioning period of 28 weeks.

COMPLICATIONS after discharge:

We noted seven complications after discharge. One pneumonia and two cases with an atelectasis needed temporary mechanical ventilation. Two pulmonary abscesses and two pressure sores were surgically treated.

MORTALITY

Seven of the 18 implanted patients died. Case 1 and 4 died from resignation because of functional and social difficulties. Case 2 died from a basal pulmonary abscess. Case 3 died from his original disease 6 month after implantation. Case 5 died from pneumonia shortly after readmission in our hospital. Case 6 died from sepsis because of a pressure sore. The seventh patient was found dead by her husband but still ventilated by the phrenic nerve stimulator. No explanation was found during the post mortem examination, which included histological studies.

Thus we lost two patients because of disorders in quality of life, two from pulmonary disorders, one from tumour relapse, and one from sepsis. The reason for the last death is still unknown.

FOLLOW-UP

11 of our patients are still alive. Our second patient now lives eight years after implantation. Concerning ventilation we have

- seven patients with sufficient four-pole-stimulation using the mechanical back up only in case of respiratory infections.
- three patients who alternately use mechanical ventilation and stimulation because of special indications and
- one patient who's spontaneous respiration recovered.

SOCIAL STATUS

Of the 18 implanted patients, we discharged

- 10 patients to their previous home
- 1 patient into a nursing home
- 1 patient into boarding school and
- 6 patients stayed in general hospitals.

The present state (October 1999) of the surviving 11 patients is as following:

7 patients are still at home using PNS 24h daily

2 patients are now in the boarding school (one was just transferred from a hospital) and

2 patients are still in a general hospital.

Of the 18 patients three were discharged with a closed tracheostoma. Two of them died, but not from complications caused by the closed tracheostoma. Of the 11 living patients one patient has his tracheostoma closed because he recovered spontaneous respiration.

The average survival-time is 2,4 years with phrenic nerve stimulation and 3,0 years with mechanical ventilation.

Concerning quality of life (3) we checked three items, the degree of

- patient activity,
- achievement of patients' expectations, and of
- independence from hospitals.

17 patients increased their activity having received

- an improved ability to speak,
- independence from the mechanical ventilator, and

- increased mobility.

The expectations concerning stimulation were achieved in 14 cases.

Independence from nursing institutes (hospitals) was achieved by 12 patients.

CONCLUSIONS

1. Sequential four-pole-stimulation in high tetraplegic patients provides

- the possibility to speak and
- to be independent from mechanical ventilators and medical institutions

These are the only points of interest for the patient concerning quality of life.

2. Medical improvements are:

- almost physiological breathing and
- the possibility to close the tracheostoma.

These points are only of interest for the medical staff.

3. Results and functional outcome differ largely. Thus the indication to implant a phrenic nerve stimulator should be the result of a sophisticated decision process. Therapeutic concepts should be clear, goals well defined and criteria lists complete. The staff included in the process should have experienced good and bad outcomes and should be always prepared to stand bad results.

4. Our duty is not only to rescue and to save but to take care for the future of these highly disabled patients, too!

5. From our point of view the first aim should be to find an individual 24 h care-unit for every patient, against all obstacles and restrictions set up and invented by insurance companies and officials. Our aim should be to discharge the patient where he belongs: home.

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Sven Hirschfeld, MD
Spinal Cord Injury Center
Workmen's Compensation Hospital
Bergedorfer Str. 10
D- 21033 Hamburg

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Two Successful Outcomes from Unilateral Diaphragm Pacing after high Tetraplegia

Watt J.W.H, Soni B.M

Summary

The incidence of permanent unilateral diaphragm paralysis after cervical spinal cord injury is between 1 and 3% and presents with recurrent chest infections or with frank respiratory insufficiency. If the paralysed hemi-diaphragm has an upper motor neurone lesion, stimulation of its phrenic nerve will cause it to contract whilst the contralateral intact diaphragm functions as normal. Two such patients are described, one in the sub-acute phase of spinal cord injury, the other having been rehabilitated some years previously. The conditioning period was less than 4 weeks in the latter case, but about 6 months for the former on account of diaphragmatic pain which appeared 2 weeks after pacing onset, persisting for another 6 weeks. It remains unproven whether this was related to asynchrony between the 2 diaphragms. Visual and audio signal were used in both cases to try to assist their coordination but the intact diaphragm usually lagged behind the paced side in this patient, and the two hemi-diaphragms were frequently out of synchrony in the second case. A triggering device could be of benefit even although both cases had a good clinical end result. Techniques for assessing synchrony are also discussed. The first patient was prone to obstructive sleep apnoea and retained a tracheal stoma.

Introduction

Diaphragm pacing is now a well established means of providing assisted respiration after high cervical cord injury¹ and in central hypoventilation². However, there is little experience of pacing in unilateral diaphragmatic pacing when the other diaphragm continues to function, as in tetraplegia with persistent unilateral paralysis. The condition was described by Carter in 1980³ with 5 cases out of 821 tetraplegics pointing towards an incidence of permanent unilateral diaphragm paralysis of 0.6% . Sixteen cases had transient unilateral paralysis recovering within 10 weeks. Another retrospective review of 96 patients requiring assisted ventilation after acute cervical spinal cord damage between 1981-1998 produced 4 cases with permanent unilateral and 21 with permanent bilateral paralysis⁴. There were also 12 cases with initial bilateral diaphragm paralysis, of whom 7 patients had a mean time to initial diaphragm recovery of 143 days and could be weaned from respiratory support, whereas the 5 with a mean time to recovery of 290 days continued to have partial respiratory dependency. Thus pragmatically, one should await at least 6 months before concluding that a unilateral diaphragm paralysis will not recover or before undertaking implantation, whether unilateral or bilateral.

At the outset there were a few uncertainties relating to practical aspects of the pacing and conditioning which have not previously been covered in published reports so warranting the publication of our experience of unilateral diaphragm stimulation in 2 of the 4 patients in our series who had unilateral diaphragm paralysis.

Case histories

1. The first case to be described is of a lady who was first seen at Southport at the age of 30, 13 years after she had sustained a gun-shot injury resulting in a C2 Brown-Séquard incomplete tetraplegia, with a paralysed right hemidiaphragm, a vital capacity of 600ml and a respiratory rate of 26. Although originally ventilated after the acute injury she had had few respiratory problems, had later given birth and more recently had a hysterectomy under anaesthesia. However, in the last 6 years she had been having increasingly frequent and serious chest infections despite normal blood gases in between times, and she depended upon theophylline and the use of the flutter valve as well as the usual assisted coughing for mucous clearance.

Her phrenic nerves were stimulated under light general anaesthesia to produce 3 cm of excursion on each side, with a conduction time of 10 ms on the paralysed side compared with 7 ms on the intact side, and a voltage response of 370 mcV compared with 333 mcV.

She therefore had a unilateral implantation of a quadripolar electrode (Atrostim) through the second right intercostal space and remained on intermittent positive pressure ventilation for the next 4 weeks. By this time her intact diaphragm was quite weak with only 300 ml and an independent respiratory rate of 36 breaths per minute. The paced diaphragm produced 400 ml, and was set at a respiratory rate of 26 bpm, and conditioning was commenced with 5 minutes in the hour, whilst the respiratory impedance waveform was used as a visual cue and the fm radio used to provide an audio cue to aid diaphragmatic coordination. By the end of 2 weeks, she was able to pace for 60 minutes and the pacing rate was reduced to 16 which was about half her independent breathing rate. As the pacing period progressed and extended into night, she was monitored but found not to have obstructive sleep apnoea so her tracheostomy was decannulated and she was discharged from hospital 6 weeks after the start of pacing conditioning.

2. The other case is of a 14 year old boy who had a C3/4 fracture dislocation overseas after a diving accident and required immediate assisted ventilation. He was transferred back to this country and a weaning programme pursued. He was referred to this centre at the point when he was apparently ventilator independent, yet still oxygen dependant despite having good lung expansion, and in fact he had gross morning hypercapnia with associated symptoms. He was then transferred to Southport 6 months after injury for assessment for suitability for

unilateral phrenic nerve pacing by means of phrenic nerve stimulation. Screening under light general anaesthesia confirmed his suitability for this procedure and he was able to have a right sided quadripolar electrode implanted through the second intercostal space 2 months later, being supported by positive pressure ventilation in the meantime.

Conditioning was commenced 3 weeks after surgery, at 5 minutes in the hour for 4-5 sessions per day using visual and audio aids as described in the previous case. The paced diaphragm volume was 700 ml at the start and for the next 4 weeks. After 2 weeks, he could pace for 60 minutes continuously, and for the following two weeks, this pacing period was maintained whilst mobilising him in his wheelchair in the upright position. At the end of the first month, he started to develop intractable cramps in the right diaphragm after pacing for more than 15 minutes and the tidal volume was around 450 ml. The symptoms persisted despite attempts to alter the pacing parameters including setting the stimulus level at only 30%. In response to the cramps, pacing was restricted to 10 minutes whilst he breathed oxygen-enriched air and used the visual and audio cues once again. He finally became free of cramps after another 6 weeks after which time his pacing time could be increased once again till he was pacing full time, and ventilator free, 17 weeks after the initial start of conditioning. His pacing volume remained at 400 ml, although the sigh volume was 750 ml. This patient commented that he found the sigh breath upsetting to the rhythm of his intact diaphragm and this function is not programmed in for him.

Monitoring during sleep demonstrated a significant degree of obstructive sleep apnoea so he was provided with a cosmetic type of sleep apnoea tube, plugged off during the day, and over which a condenser humidifier was placed at night time. It had been evident that whether the right diaphragm was paced at 15 or 12 breaths per minute, the intact left diaphragm lagged behind the right, even though not out of phase. Sleep studies confirmed that the lag time for the left diaphragm was up to 2 seconds compared with no more than a second in the day.

Comments.

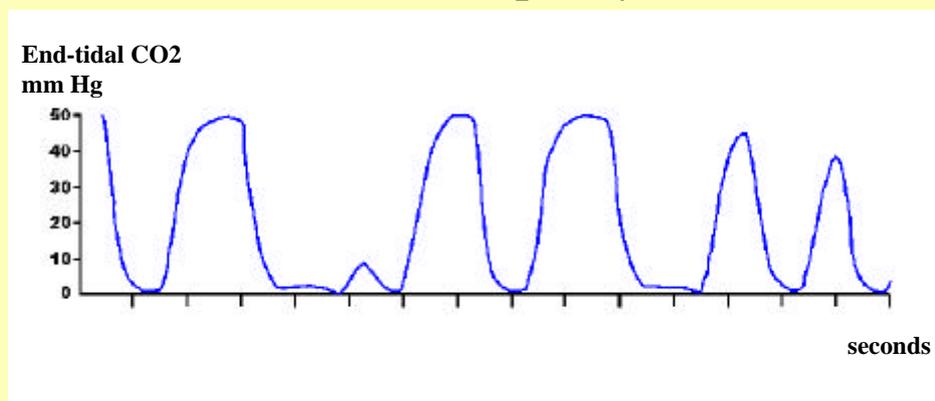
It is evident from these two case studies that an intact diaphragm may indeed contract out of phase from a stimulated diaphragm whether or not the paced diaphragm is slower than the intact side (first case), or faster (second case).

The clinical importance of this is not fully established though it was observed in the first case that on the subsequent occasion of coincidental major surgery, requiring a day or two of mechanical ventilation, weaning was initially impaired due to the gross asynchrony of the two diaphragms. If the paced diaphragm could in some way be triggered by the intact side this should in theory be better both with respect to breathing, but also to other functions such as swallowing, and it may help to prevent obstructive sleep apnoea if the genioglossal muscle tone increases just before the onset of contraction of the intact diaphragm⁵.

Assessment of diaphragm synchronisation.

Capnography. If the end-tidal carbon dioxide is monitored either by means of nasal cannulae or via breathing hose connectors, it is relatively easy to identify diaphragmatic asynchrony. The illustration shows a capnogram from the first patient who was under very light general anaesthesia for a separate procedure at a later date (Fig 1). The downstroke marks the start of inspiration and it is possible to see that at a pacing rate of 16 breaths per minute, she tends to take an additional independent breath in between.

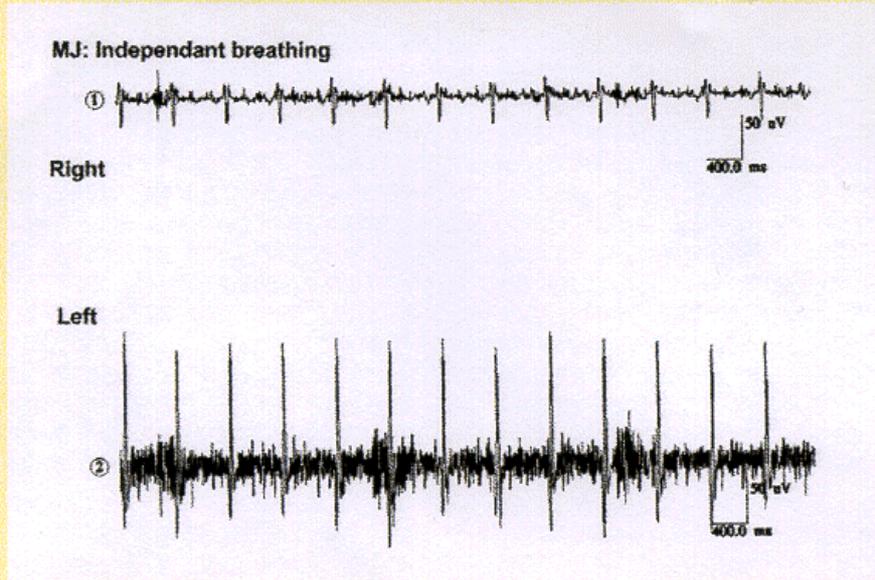
Fig. 1. Capnography during pacing for unilateral paralysis



Electromyography.

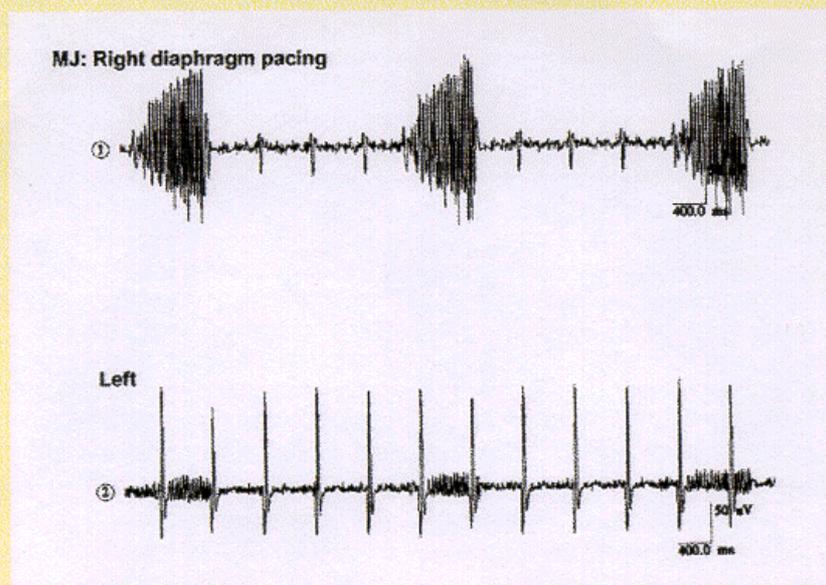
It is generally easy to record the diaphragmatic EMG by means of surface electrodes in patients with tetraplegia who lack voluntary intercostal muscle activity. The first EMG illustrated shows a muscle action potential in phase with respiration from the intact left diaphragm when the pacer was switched off, though there is some background non-phasic intercostal muscle tone also evident in this patient (Fig 2).

Fig 2. ELECTROMYOGRAPHY FOR UNILATERAL DIAPHRAGM PARALYSIS: NO PACING



When the pacer was switched on, there is a good signal from the right diaphragm and the impression that the left diaphragm is also contracting in phase (Fig 3).

Fig 3. ELECTROMYOGRAPHY DURING PACING FOR UNILATERAL DIAPHRAGM PARALYSIS



However, EMG studies of another patient with bilateral phrenic nerve implants clearly shows that the stimulus artefact from one diaphragm may be recorded simultaneously from the contralateral side during unilateral pacing (Figs 4 & 5). This implies that it will not be possible to compare the times of onset of inspiration of a paced and an intact diaphragm by means of surface EMG, though needle electrodes may be better able to differentiate the onset times of each side.

Fig. 4. DW. Bilateral pacing

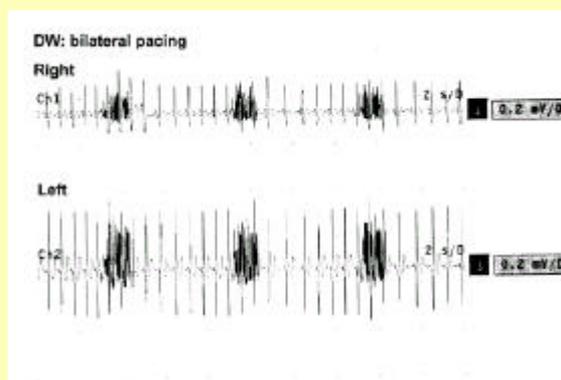
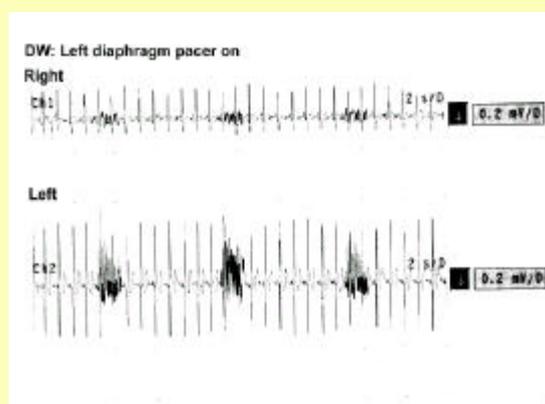


Fig. 5. DW. Pacing on left only



Respiratory impedance waveform.

Surface electrodes used to monitor the ECG are able to produce a respiratory impedance waveform in a suitably configured multifunction monitor. Not only can this be a convenient way to help patient visualise their breathing, but it can enable the clinician determine the relative onset times of diaphragmatic contractions semi-quantitatively, as well as their relative contributions. The intact diaphragm in the second patient was rather quiescent during sleep, unless the tracheostomy tube was plugged off to partially obstruct the breathing, in response to which the intact diaphragm was seen to contract more vigorously producing a larger waveform.

Conclusion.

The good clinical outcome in two cases of unilateral phrenic nerve stimulation should encourage the identification of other suitable subjects, and aspects of diaphragm asynchrony should be systematically studied in any future cases for future comparisons of outcomes.

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Phrenic Nerve Stimulation: Results

Meindl R.Ch, Bötzel U

We present problems of a child with ultrahigh posttraumatic tetraplegia. The boy was 2 years and 2 month old, when he was hurt in a car accident. He was sitting on the back seat without safety seat or belt. Initially he was treated in another hospital. A diaphragmatic pacer was implanted 7 month later in a children's hospital in Munich using the Finnish Atrotech system. The boy was admitted to our department at the age of three, not being discharged earlier than the age of six due to the course of rehabilitation but mainly due to the difficulties to organise an adequate housing and a well trained nursing group.

He had trained nurses at home around the clock nevertheless having much fun in outdoor activities, visiting friends and relatives and even travelling to Turkey, his home-country, by plane. His mother and his aunt told us some advantages and experiences with the pacer according to their individual point of view:

- Transfer and mobility are improved by the size of the pacer in comparison to the heavy mechanical ventilator, so that it is easy to leave the house for all sorts of activities.
- They feel safe, because pacer and MV can be used alternatively.
- Travelling with the pacer is easier, especially by plane.
- They were disappointed that they had not been told, that nobody had much experience with the implantation of diaphragm pacers in children with tetraplegia less than three years of age, and that their boy probably was the first in Europe.
- Nevertheless and despite some complications they would agree to an implantation again.

In comparison to the other children treated in our unit the boy developed severe spasticity causing high pressure alarm of the ventilator many times during night or day. A severe rotational scoliosis developed too at a time much earlier than expected. We found a marked rotation of the pelvis disabling the sitting position additionally to an extreme lordosis of the lumbar spine.

Initially the pacer worked 12 hours daily, although the relatives aimed at a complete independence from the ventilator. This was impossible for several reasons. When expanding the pacer time it was found that the pulmonary mucus became sticky and could not be removed adequately especially in the winter time. The spasticity increased steadily. So the pacer time had to be reduced to ten hours using the ventilator for the rest of the time with heating and humidity filters. This concept was successful for some years.

Then problems arose, as the electrodes on the left side did not work sufficiently. Additionally the insurance-company wanted the restoration of the pacing system, because they did not want to pay the nursing staff around the clock arguing that the boy could breathe himself with the pacer not needing any further medical observation around the clock. This certainly is a weak argument, as also electrical stimulation needs thorough control around the clock being nothing else than an artificial ventilating system using the patient's muscle force instead of compressed air for mechanical ventilation. But also the relatives strongly resisted a re-operation, since investigations showed that the left diaphragm did not contract adequately despite changes of the stimulation parameters.

After extended discussion with Dr. Baer and after x-rays showed suspicious details according to which the nerve contact of the left electrode was lost we decided to perform intrathoracic surgical revision mainly trusting the neurophysiological examination according to which the left phrenic nerve still could be stimulated from the cervical portion proximal to the very distal intrathoracic electrode. The electrode was covered with scar tissue and could not be removed without danger of damaging the nerve following the recommendation even to avoid the attempt. Even the leads had been caught in scars and had to be cut near the electrode after insulation of the remaining leads and removal of the rest. Exposure of the trunk of the phrenic nerve more proximal was possible and the new electrode and leads could be placed. After wound-healing and firm position of the new electrode stimulation could started again but was restricted to 6 to 8 hours daily.

During general anaesthesia and before starting stimulation again scoliosis and hyperlordosis disappeared nearly totally but worsened again during stimulation. The effects of the electrical phrenic nerve stimulation clearly can be demonstrated in a video, which has been presented during the session. The severe spinal deformity resulting in increasing problems with the sitting position will require surgical stabilization soon.

To our knowledge similar sequelae of phrenic nerve stimulation have not been published yet. We are very interested in the experiences of other groups especially in diaphragm pacing of tetraplegic children as doubtless some improvements can be achieved, if as worse reactions as in our case can be avoided.

Prerequisites for Follow-up: where did we come from?

Baer G.A

“A medical doctor who does not write does not improve.” Obviously Hypocrite 2500 years ago already knew that clinical experience without proper documentation means relying on the relicts in our memory of the last 3 to 4 similar successfully treated cases. However, in the average unstructured patient record the essential information, if available, frequently is hidden between lots of useless words. From the largest retrospective study on our matter we can learn that documentation in most cases was not complete, in some cases even absent(1). Two other retrospective studies comprise fewer black holes because of case selection(2;3). The three studies provide data about the special risks of phrenic nerve stimulation but do not compare these risks to those arising from mechanical ventilation for the same patient group. I was astonished when I realised that even manufacturers of respiratory devices rarely receive all the data officials order to provide from each patient. The generally low quality of retrospectively collected data is mostly due to large differences in what is recorded and how. We either have large numbers and no significance because of incomplete data, or no significance because of low numbers in prospectively performed studies. Quality control in commercial managing means sticking to agreed rules. The first step is always to agree and write down the rules. I would like to suggest a prospective multi centre study to compare phrenic nerve stimulation (PNS) and mechanical ventilation (MV) in respiratory device-dependent patients. Participants in the study should strictly agree to collect the same set of data for each patient at the same time points.

The design of a multi centre study should be simple. However, the description of the patient’s situation when taken into the study should be precise to enable to control the bias caused by the patients’ individuality. If we had hundreds of patients, the large number would compensate for the differences between individual patients. However, even in large centres, where one might assume that most of the treatment is similar in similar cases, large patient numbers are unachievable, because similar simple cases are rarely seen. Therefore we need written rules on how to collect data in every participating centre in a reproducible way, see appendix. Then we can compensate for the small numbers by weighting patient data with the special features of each patient. I hope we will agree during this workshop on the essential data we need from every patient we might enrol in a future prospective multi centre study.

I made a more detailed print out of what I think is needed to start from. I would like to ask you to wipe out what you think to be unnecessary, add the necessary, write down your comments and suggestions, and to return the forms. We then will try to produce a version that should satisfy most of us and thus might be

generally acceptable. From all patients who participate we also need the special data needed for evaluation of the results with PNS, see appendix.

Let us now assume we have a well-documented state of each patient who participates in the study. We would like to compare the fate of patients using PNS with that of patients using MV. There are some difficulties with this approach. Patients should be randomised to either form of treatment. However, they are already treated, otherwise they would not have survived. Patients should give informed consent to randomisation. However, it is difficult to imagine how they might receive unbiased information because, in each institution, there is a well-proven way to handle the patient's problems. I figured out a possible solution, but I agree with you, this would be difficult to put into practice. Informed consent would be obtained one month after injury; patients would agree to randomisation for PNS or MV; data would be collected every month; evaluation would be after one year by an independent researcher. Even if performed as a multi centre study sufficient patient numbers would be difficult to achieve.

An easier to perform approach might be more successful. We could compare the situation of the patient before and after our intervention, whatever the intervention is, instead of comparing different interventions. We then would compare the improvement achieved with the intervention, in our case PNS and MV. In this way we would have results for both groups within a short time after intervention. Later in the future we could use obligatory check ups to collect our data at certain intervals.

The technical experts of the EU and the FDA force us to have a check-up once a year of the device of respiratory device-dependent patients. The aim of these check ups is to assure proper function of the respiratory device. These agencies are not else interested in the patients. The international society for paraplegia recommends check-ups in a special institution once a year for every paraplegic patient, life-long. For patients with central alveolar hypoventilation check ups at regular intervals are also recommended (4). I think, we all agree with these requests. The check ups could be used to register also data that may show the efficacy of our interventions.

Next we have to agree on what to measure (5). Patients may survive for decades. Thus survival rate, though being a clear outcome, is not a practical measure. Upper airway infection and pneumonia are precisely defined, but practically the precise diagnosis is rarely done. I would like to suggest two simple measures on quality of life, the degree of independency.

For the patients with respiratory muscle palsy, RMP, traumatic tetraplegic patients in most cases, the measure would be "minutes without a professional helper". I learned this measure from a colleague with high paraplegia sitting in a wheel chair at a congress on paraplegia. When I asked for his advice on how to measure the quality of life of patients with high tetraplegia who are forgotten

below the bottom of all published scales on quality of life, he said: "That's simple, it is every minute without a professional helper, ask them." So I did, and all tetraplegic patients I met agreed.

The second group comprises patients with CAH, central alveolar hypoventilation or central hypoventilation syndrome (CHS (4)). In the typical case the patient is a child with inborn central apnoea. A similar measure as for RMP would be, how often a week or a month the child sleeps being monitored by other persons than the patients or professional helpers. To use both measures no special training is needed and, I suppose, both are important outcomes, no surrogates. Both outcomes measure also the possibility to save money: less professional help means less money to pay for the helpers. Therefore these outcomes are important for discussions with those who purchase the respiratory device.

Correspondence:

Gerhard A.Baer, MD, PhD

Kasvitarhankatu 5

FIN-33500 Tampere

Tel. +358 3 2611 002

Fax +358 3 2611 128

gbaer@sci.fi

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Appendix

Draft ! Respiratory Device Dependency (RDD): Questionnaire on Quality of Life

Whenever possible, please give exact data, but at least one mark on each line.

Institution	
Department	
Dr. in charge	
Chief Dr.	
Study contact:	
Postal address	
Street address	
Telephone	
Telefax	
e.mail/web	

Patient's

Family name				
Surnames				
Date of birth	D	M	Y	Gender: M F
ID	Hospital:		Soc.Sec.	

Weight (kg)		anorectic	slim	normal	overweight	obese
Height (cm)		small	below	mean	above	long
Profession						
Employment						
Marital state						
Children?						

Degree of respiratory insufficiency	Full time	Sleep apnoea
Reason for respiratory insufficiency		
Other diseases/abnormalities		
Phrenic nerves, conduction time	left:	right:
Diaphragm muscles, tetanic displacement	left:	right:
Lung parenchyma normal/impaired (specify)	left:	right:

SCI

		Date of estimation
Functional level of injury		
Complete/incomplete		
Frankel(ASIA)-Grade		

Surgical interventions	Procedure
- in primary hospital (Date, place)	
- in specialized hospital	

Day of injury	
Day of diagnosis (causing RDD)	
Begin of rehabilitation (day)	
Duration of stay in primary ICU	
Duration of stay in special ICU	
Duration of stay in primary hospital	
Duration of stay in special centre	
First day at final place of living	
Complications	

SCI and CHS

Artificial airway	Begin (Date)	End (or continuous)
Intubation tube		
Tracheostoma		
Cuffed tube, no speaking leak		
Cuffed tube, speaking leak		
Uncuffed tube/button		
Nose-, face mask		
Artificial airway unnecessary		

Respiratory devices		
Final respiratory device	Device	Use hours/day
MV (specify)		
PNS (specify)		
Other (specify)		
Begin of continuous use		
Back up device		

Device performance	Device	Date
Scheduled services/year		
Unscheduled services		
Replacement		
Failure causing back up use		
Other (specify)		

Single use equipment		Starting date	End of period
Suction catheters	Pieces:		
Gloves	Pairs:		
Other (specify)	Items:		

Quality of life

Independence				
Unit of measure	min/24h	times/24h	times/week	times/month
Alone				
Without professional helper				
Use of telephone				
-“- computer				
Having guests				
Working				
Outside of room				
Outside of house				
Outside of town				
Outside over night				
Participation in social events				
Visiting theatre, film, football, etc.				
Social events				
Other (specify)				

Medical complications during observation period			
Observation period	Starting day	End of period	
Upper airway infections			
Pneumonia			
Other infection (specify)			
Other complication (specify)			
Unscheduled interventions			
Unscheduled in institution			

Management of Life-long Follow-up after Discharge

Luetjens A

Inherently, breathing is vital to life. The deployment of a phrenic nerve stimulator is an invasive measure, which has social, psychological and medical effects beyond those of merely inhaling and exhaling. The person involved requires more attention than those of purely technical nature.

Our company, Börgel PTY LTD, has had a pioneering role in the field of home ventilation in Germany. We began this work approximately 15 years ago, working together with various hospitals specializing in the treatment of tetraplegia.

Through discussions with patients and their families, clinical staff, health insurance authorities, home nursing companies, social workers and others, we attempt to assist in the successful transition of patients from hospital wards, back into society.

Quality of life is a major issue, is however associated with many compromises. If people are rescued and rehabilitated after trauma it cannot be enough to make them clinically fit and then abandon them once they leave the hospitals.

Our role begins in the hospitals and continues in the domestic environment, as a partner in regard to maintenance of respiration equipment, education of home nursing staff and solution finder for a multitude of problems and considerations that arise.

We consider it important to give feedback to the retrospective hospitals; to encourage the patients again and again to get a grip on their lives. In many cases it is helpful to stay in contact and in fact to establish contacts to other patients in similar situations.

For the last 6-7 years we represent 2 manufacturers of diaphragm stimulation systems. Medimplant, Vienna and Atrotech, Tampere.

Technical routine checks at home include maintenance of all external parts of the diaphragm stimulators. We also look at the magnetic link between antenna and implanted stimulator.

A complication that occasionally arises is the breakdown of the magnetic link due to movement of the implanted stimulator, particularly with obese patients. This can of course be corrected through surgical intervention. It is becoming apparent that the site for placement of stimulators is best over a firm supporting structure such as the lower ribcage. In the case of young females, their prior consultation may be beneficial to overall cosmetic acceptance afterwards.

Ventilation parameters checked include tidal volume, its distribution, (left and right diaphragm), to avoid long-term chest deformities and the risk of atelectasis. Threshold and tidal volume power requirements to the individual electrodes are adjusted if necessary. (Generally we find the power requirements stabilize within one year after implantation). Oxygen saturation and carbon dioxide elimination values are noted along with tidal and minute ventilation levels in sitting and lying positions.

A phenomena some patients confront us with, usually some time after hospital discharge, is the gradual lessening of tidal volume in the sitting position whilst threshold and maximum power adjustments appear to be set at an optimum. The reason for this may be the long-term decline of abdominal muscles which no longer return the diaphragm to its original resting position. The use of an abdominal supporting strap can improve tidal volumes quite dramatically. We have been using external muscle stimulation equipment to strengthen abdominal wall muscles in a couple of severe cases, with promising results.

Communication between the patients, the hospitals and us is all-important. Due to the low number of diaphragm stimulated patients it is beneficial to all that the hospitals involved are few but dedicated.

In the past, 2 still living patients with functioning equipment were implanted in hospitals which otherwise have no commitment in this field. We do not know whom we can confront when problems requiring surgical intervention arise. In one case this problem is currently acute.

The number of patients equipped with these systems is still very low so that meaningful statistical data is not realistic. In our yet limited experience we have however been able to do away with some popular beliefs. I.e. patients who have had no diaphragm function for 3 years and more can in fact be successfully adapted to stimulation.

It is not always a main goal to seal a tracheotomy. This is more the aim of surgeons than of patients. During discussions with patients who ask about possible tracheotomy closure it becomes apparent that their first objective is safety. The second is vocalization and the third, also important cosmetic appearance. If they can be provided with a hygienic and cosmetically “sound ” solution the wish to seal a tracheotomy is no longer of vital importance. With a customized cannula, whenever possible without a cuff and with suitable placement of phonation openings, plugged during the day and open via filter during sleep, suctioning can be minimized, vocalization enhanced and safety reassured. The cosmetic appearance cannot be stressed enough.

A critical comment towards the surgeons involved: I would suggest that particular attention be paid to the tracheotomy so that there is no air leakage around the cannula. This is a major issue for the success of rehabilitation in the

long run. Another point is the need to train such patients and stress the need to maintain the capability of emergency breathing by use of the accessory respiratory muscles in the neck.

Criteria assessed in regard to indication of stimulator implantation are generally of medical nature. In our experience it is also important to look at the social environment.

Many questions need to be addressed and cleared up beforehand. Such as:

Does the patient understand what a diaphragm stimulator is?

What are the pros and cons?

Where is the patient going to live? Institutionalized or at home?

Can adequate care be provided?

Is he/she a child? If so, can he or she perceive any PNS induced deficiency?

(Children require particular care in regard to normal growth and safety).

Mechanical ventilators are fitted with alarms that are inherently more apt to give warning of potential ventilation deficiencies than a diaphragm stimulator. The latter will only warn of empty batteries but otherwise will, like a cardiac pacemaker, continue to technically function regardless of its host's condition. We observe in some patients the capability to adapt to poor ventilation without real awareness. They become energy drained and have some symptoms similar to patients with Duchenne's disease. Hence the need for good medical surveillance on the part of the caregivers.

The guarantee for good care and observation after being released from hospital must be ascertained prior to implantation.

Institutions often do not have the personnel required, especially at night, to accommodate the vital care and surveillance requirements of such persons.

The adherence to medical legislation is a factor often left completely unconsidered!

We have had cases of patient dismissal from the ward directly into institutions where the administrative staff had ensured that they can provide adequate care. Obviously they gave more thought to monetary considerations than to the actual capability of their well meaning but overworked nursing department, with lethal outcome.

A problem we have in our daily work regards the doctor at home. Medical practitioners in the field usually have little or no experience with tetraplegia, let alone tracheostomized, ventilated patients. The patients' specific medical and psychological requirements can be more time consuming and demanding than many practitioners are willing or able to meet. Typical effects are; Respiratory infections are often indiscriminately bombarded with one antibiotic after another instead of microbiotic secretion analysis and specific drug selection.

Many patients suffer functional reduction of the digestive system rendering them susceptible to occlusion.

This susceptibility can be adversely affected through the side effects of drugs.

Currently we have a patient with reduced bowel passage and inflated abdomen, possibly due to his prescribed medication. This patient, implanted in 1995, had a diaphragm stimulated tidal volume potential of up to 1.5 liters. Over the last half year the maximum possible tidal volume decreased dramatically as his abdomen has enlarged. During this time high dosage benzodiazepine as well as a long list of drugs including muscle relaxants has been administered. Recently we have asked the patient's nurses to let the practitioner review this prescription.

I have mentioned this case to underline the need for consultation about the patient management between the specialist hospital and the doctor at home.

In conclusion let me make the following remarks.

Much has been achieved in the field of home ventilation if one reviews the changes over the last 15 years.

Better technical apparatus improves quality of life through more efficient ventilation and safety.

The weak links in the chain are usually people. People such as ourselves, who owing to the pressures of modern society find it hard to take the time needed to ensure best possible care for our patients.

If we accept this to be a problem we will be closer to a solution.

I believe that better communication between all involved will take us a step further.

Andrew Luetjens 12.11.1999.....BÖRGEL GmbH

Future Developments and Opportunities

Stanic U, Kandare F, Pedotti A, Exner G

Severe SCI with a remaining disorder of the spinal cord above C4 is a major life event and changes dramatically all circumstances of life. We would like to discuss aspects of quality of life (if you can say so!) of these persons.

Targets

For these patients there are only three main points of beneficial outcome: the ability to speak, a very restricted sort of mobility, and, at least, independency of hospitalisation. From a medical point of view a PNS system does not provide more benefits than other systems of ventilation, especially mechanical ventilation. But concerning the aspects of comfort we think PNS provides a better physical and emotional state of well being as demonstrated elsewhere in this volume. However, we also think PNS to be a system that works properly under technical aspects but not yet good enough concerning all of the patients' physical and emotional needs. As clinicians with experiences in medical and functional outcome and additionally with the knowledge about the individual fate of several persons using this device we have to ask for improvement. It is not enough to get nearly physiological ventilation with the possibility of using a sigh at different intervals. And it is no advantage for the patient that he needs other persons to change the parameters of stimulation. Concerning our goal, the greatest possible independency, we fail. The patients' possibility to influence his ventilation himself is not given. He is not able to change the system according to the activities of his daily life. Changing his position from sitting to lying, raising his voice, prolonging his sentences, coughing - nothing is possible for him doing it himself. Thus, how could we improve the system?

Improvements

We have to think of

1. improvement of hardware. Research and technical development are going on. Hopefully we think of the future, remembering the past. Cables and connections are now easier to use. Receivers got smaller and smaller, improvement can be seen during the last ten years. And it will go on.
2. We have to improve the software. The stimulation seems to be very rough. Shaking and shivering of the diaphragm are to be seen very often. Modulation of the impulses should be improved. The movement of the diaphragm should begin and continue more smoothly. Another idea to solve this problem might be a stimulation system that permits the survival of all

kinds of muscle fibres of the diaphragm to allow for a very physiological stimulation-answer.

3. The patient should have the possibility to change the stimulation parameters himself not only when changing his position but also to adapt his ventilation to other activities. The best solution would be some sort of automatic assessment of the ventilatory need with a feedback to the stimulator. Such system would provide the patient with more independency.
4. Concerning independence we would like to see the combined stimulation of the diaphragm and other ventilatory muscles. Our experience with the combination of diaphragm pacing with the extra-corporal stimulation of abdominal expiratory muscles is encouraging. We ask the technicians to develop such systems and to transfer the stimulation of the abdominal and muscles of the chest wall to an implantable system. But this should be done with only a few electrodes and cables, to avoid new complications from an over-sophisticated technical system.

The aim of such combined system could be to enable the patient to cough. The most dangerous complication of PNS is atelectasis of the base of the lungs and subsequent infection. Coughing is the most efficient method of bronchial drainage, also for persons on artificial ventilation.

5. Improvement could also be achieved by incorporating the energy-sources into the implant. The induction coil system has become smaller and easier to use during the years but is still cause of much trouble.

Correspondence

Gerhard Exner, MD

SCIC

Bergedorfer Straße 10

D-21033 Hamburg

Possible Future Developments and Opportunities

Väänänen J
Tampere University of Technology
Tampere, Finland

Abstract

Functional electrical stimulation (FES) will benefit from the technical evolution and advancement in microelectronics, radio frequency (RF) modules and implantable power sources. This paper provides a technical discussion of the possible future configurations, usage and power consumption of the planned Totally Implantable Stimulator (TIS).

TIS Configuration

Some of the most important requirements for the new generation FES system can be listed as follows:

Requirements	Projected Solutions
More convenient to use	No more energy transfer coils and cables The stimulus controller does not have to be present all the time
Easier to program	Semi-automatic or automatic threshold seeking Sophisticated programming module
Keeping track of parameter changes	Sophisticated programming module
Increasing battery lifespan	Modern microelectronics

Table 1. Requirements and solutions of the new generation FES system.

A totally implantable Phrenic Nerve Stimulation (PNS) system would be the ultimate solution to the above requirements, most of all because of its user-friendliness (Fig. 1.). In today's microelectronics, it is feasible to make the individual components of a system as intelligent as possible. Effective miniaturization makes it possible to build complex systems whose size remains virtually the same [3]. However, typically the most advanced miniaturization technology is aimed at the mass market (consumer electronics) because of the high initial cost.

Two-channel PNS system

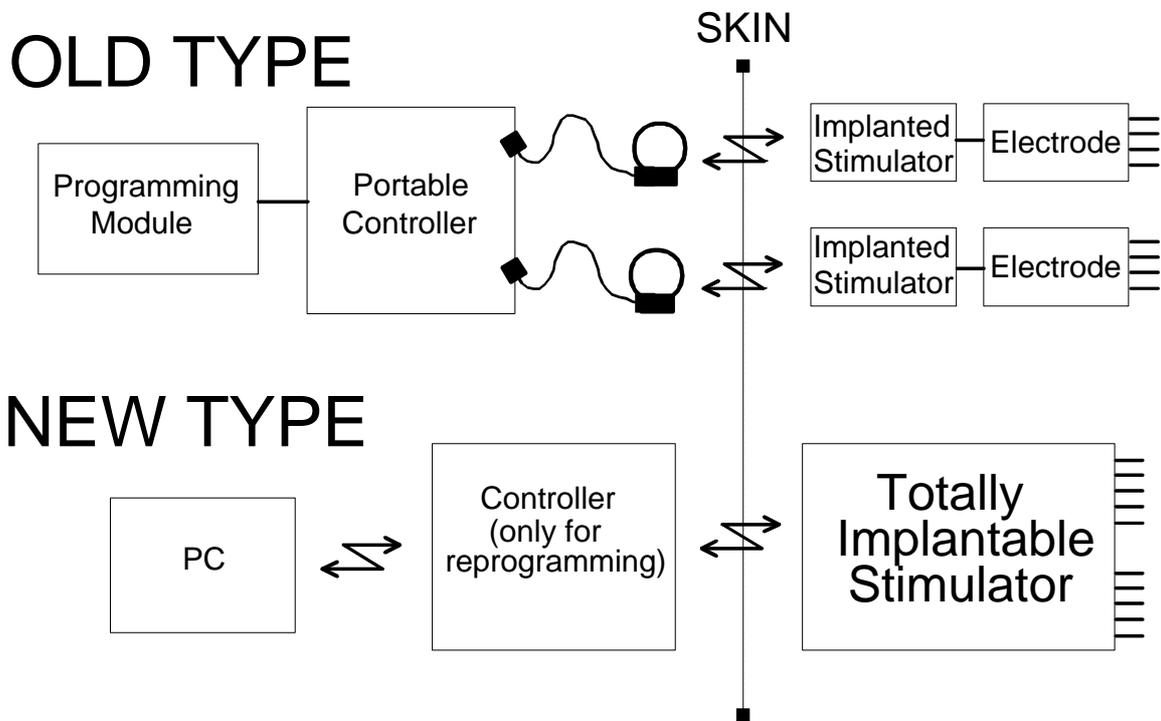


Figure 1. Comparison of the old and new PNS systems.

One of the key features of the new system is to make obsolete the external cables and coils of the current PNS systems. Another important feature is that the future stimulus controller will not have to be present during the normal use. It will be needed only during reprogramming.

An implantable battery provides the means of powering the whole implant. At the moment, there is a limited technical choice of batteries. All are based on lithium chemistry, and a rechargeable implantable battery is under development [4].

Communication with the implant is performed using either:

- the current inductively coupled link system, or
- a short-range radio frequency transceiver.

If the inductively coupled link system is retained, it can possibly be used also to charge the implanted battery.

TIS Usage

The new generation stimulators should be easier to use. The initial threshold seeking procedure during surgery should be automated. This would be performed in two steps. In the first development stage there will only be an open-loop control. The operator must give an OK-signal when the threshold is achieved. In the second stage the whole procedure will be automated. This will require a closed-loop control.

As before, two parameter levels will be maintained:

- Stimulus Controller: Patient-level parameters
- Programming Module: Doctor-level parameters

A portable personal computer (PC) will replace the old programming module. This would bring within reach the powerful data processing capabilities of a modern personal computer. Patient document control and connection to the outside world will be enabled within the stimulation system itself. Parameter change history logfiles and time stamps will be automatically generated. This would make the documentation much easier and reduce human errors. Remote diagnostics would be possible.

TIS Power Management

Power management is, obviously, the most challenging feature of the new stimulator. The only way to achieve an ultra-low average operating current is to use advanced microchip technology with as low clock frequency as possible, and to suspend the operation of the central processing unit (CPU) as often as possible.

Application Specific Integrated Circuits (ASIC), custom-made chips tailored for one specific application, must be used for low power consumption and miniaturization. Their only practical drawback is the very high cost for low production volumes.

The generation of FES stimulus pulses consumes more power than, for example, cardiac pacing. This is mostly because of the complex pulse train which must be generated for each inspiration. The pulse train has several adjustable parameters, and their adjustment resolution, or accuracy, must be high. This makes a high clock frequency and more powerful signal processing necessary.

Moreover, the stimulus pulse train itself contains a considerable portion of the allowed power consumption. The following chapter contains calculations about how much of the allowed average operating current is consumed in the nerve-electrode interface.

TIS Power Management Calculation

At the moment, a battery capacity of 2Ah can be implanted feasibly [4]. Therefore, the average current of the entire device must not exceed 46 μ A if we want five years of continuous stimulation¹.

On the other hand, with the nominal parameters, the average output current of the Atrostim PNS system is 11.3 μ A². This current flows through the nerve-electrode interface and is not negotiable.

This will leave approximately 34 μ A average current for operating the implanted device. This is a great challenge, but not an impossible one. As a comparison, the total current drain of a modern cardiac pacemaker is 19.2 μ A, even including its output current³.

¹ If we want to stimulate for five years without surgery for battery exchange, the average current can be calculated as $2\text{Ah} / (5 \times 360 \times 24) \text{h} = 46\mu\text{A}$.

² Atrostim PNS pulse train: Nominal parameters: Pulse amplitude 3mA; pulse width 200 μ s; all four combinations active; Bilateral mode; Inspiration Duration 1.5s; Rate 15/min; Pulse Interval 40ms [1]

One inspiration: inspiration duration 1.5s; average pulse interval 40ms
=> the number of pulses bilaterally: $2 \times (1.5\text{s} / 0.040\text{s}) = 75$ pulses (per inspiration)
One minute: $15 \times 75 = 1125$ pulses (per minute)
Total charge of the 1125 pulses: $Q = It = 1125 \times 0.003\text{A} \times 200\mu\text{s} = 675\mu\text{C}$
Average current: $I_{\text{ave}} = Q/t = 675\mu\text{C} / 60\text{s} = 11.3\mu\text{A}$

³ Medtronic Thera: 510 ohm load, 100% pacing, BOL (Beginning Of Life), mode DDD [2]

Conclusion
The Future

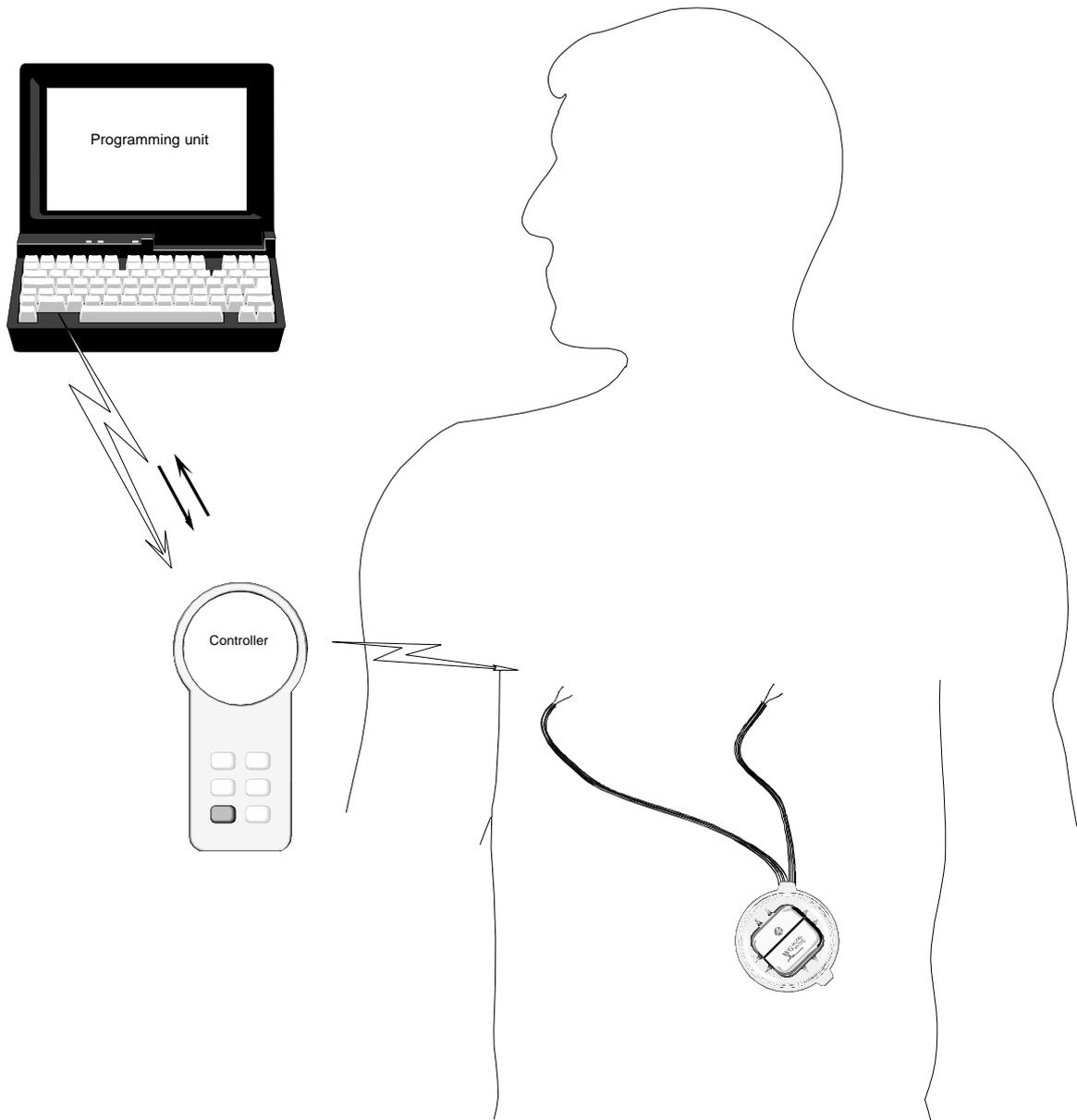


Figure 2. Overview of the new generation PNS system.

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Compartmental Analysis of Breathing and Optimization of Respiratory FES

Stanic U, Kandare F, Pedotti A^{1,2}, Aliverti A^{1,2}, Delacca R^{1,2}

¹ Dipartimento di Bioingegneria, Politecnico di Milano, Italy

² Centro di Bioingegneria, Fond. Don Gnocchi IRCCS and Politecnico di Milano, Italy

Introduction

Up to now, artificial ventilation considers almost exclusively intermittent positive pressure ventilation (IPPV), both in intensive care medicine and in the prolonged treatment of chronic ventilatory failure. However, alternative methods like functional electrical stimulation of respiratory muscles can be used as an alternative to the commonest conventional method of ventilatory support, i.e. mechanical ventilation. Implanted systems for the electrical stimulation of the phrenic nerve ('diaphragm pacemakers') have been used in the last decades, since the first application reported by Glenn et al. in 1964 [1], to restore breathing in patients with high quadriplegia causing respiratory paralysis and patients with central alveolar hypoventilation.

Functional electrical stimulation of expiratory abdominal muscles (FESAM) has been scarcely used in the past. Recently it has been introduced to enhance cough in tetraplegic patients [2, 3]. Another possible application could be the combination of FESAM and phrenic nerve stimulation (PNS), to optimize ventilation or to assist spontaneous ventilation [4].

Recent optoelectronic techniques have been proved of great potentialities for the noninvasive kinematic analysis of the chest wall movements during respiration. The introduction of Opto-Electronic Plethysmography (OEP) allows not only to measure with high accuracy the 3D displacements of the chest wall, but also to estimate the volume changes of the different respiratory compartments [5, 6, 7]. The combination between accurate measures of the volumes of the different compartments and pressure measurements, allows also to assess rib cage distortion [8] and respiratory muscle action [9].

The understanding of respiratory mechanics during ventilation based on PNS, FESAM or both can be enhanced by using OEP, which can provide useful data for optimising patient adaptation to these ventilatory assistance devices. In order to verify this hypothesis, we preliminarily analysed a spinal cord injury patient with OEP during PNS and FESAM under different conditions. The results will be shown in this paper.

Methods

We studied an 11-year-old boy with complete quadriplegia due to traumatic high cervical cord lesion (C2). Our analysis was performed three years after injury, and two years after implantation of a phrenic nerve stimulator (Atrostim, Atrotech, Tampere, Finland). The daily ventilatory assistance was mechanical ventilation (12 hours/day) and PNS (12 hours/day). Before the analysis, the patient was adapted to a multi-channel electrical stimulator for surface FESAM, developed at the Jozef Stefan Institute of Ljubljana, Slovenia. The stimulator was synchronized with the expiratory or inspiratory phase by a flow signal coming from a screen-type pneumotachograph. Abdominal muscle stimulation was delivered via pairs of surface self-adhesive electrodes placed on the transversus (T), rectus (R), or both muscles.

We considered the following conditions:

- PNS alone (bilateral stimulation, 13 breaths/min, pulse interval 45-55 ms);
- PNS combined with FESAM applied during expiration;
- PNS combined with FESAM applied during inspiration.

All the measurements were repeated in two different postures: seated on a wheelchair and supine on a bed. In the supine position, FESAM was combined to PNS during inspiration alternatively to transversus or to rectus abdominis. In the seated position, FESAM was also applied alone for a short period (about 30 seconds).

Chest wall kinematics and compartmental volumes were noninvasively measured by optoelectronic plethysmography. With this technique, a set of reflective markers is placed over the chest wall from the clavicles to the pubis. Each marker is tracked in 3D by at least two dedicated CCD cameras. A dedicated image processor measures the motion of each marker; OEP approximates chest wall surface by a finite set of triangles connecting the markers and, using Gauss' theorem, the volume of the chest wall (V_{cw}) and of its compartments can be calculated. As proposed by Ward et al. [10], a three-compartment model of the chest wall (pulmonary rib cage or upper thorax, UT, diaphragmatic rib cage or lower thorax, LT and abdomen, AB) is considered. The sum of the volume of each compartment equals the chest wall volume: $V_{cw} = V_{ut} + V_{lt} + V_{ab}$.

In this study we analyzed kinematics of breathing in two different postures (seated on a wheelchair and supine on a bed) where the back of the subject is not visible. Therefore the posterior surface of the chest wall was defined by a number of 'virtual' markers assumed to lie on the supporting plane (back support of the wheelchair or bed). The positions of these virtual points were determined by projecting the lateral markers' initial frontal co-ordinates (from the first acquired image frame) onto the reference plane.

We used 45 reflecting markers placed on the anterior thoraco-abdominal surface as reported in figure 1. For the analysis in the supine position (fig. 2, left), each

marker was tracked in 3D by four video cameras, positioned about 2 meters above the subject and inclined downward [11], while for the analysis in the seated position (fig. 2, right) four cameras were placed in front of the subject at a distance of about 2 meters, two on the right and two on the left; the height was about 2 meters for one couple of cameras (one on the right and one on the left) and about 0.5 meters for the other couple.

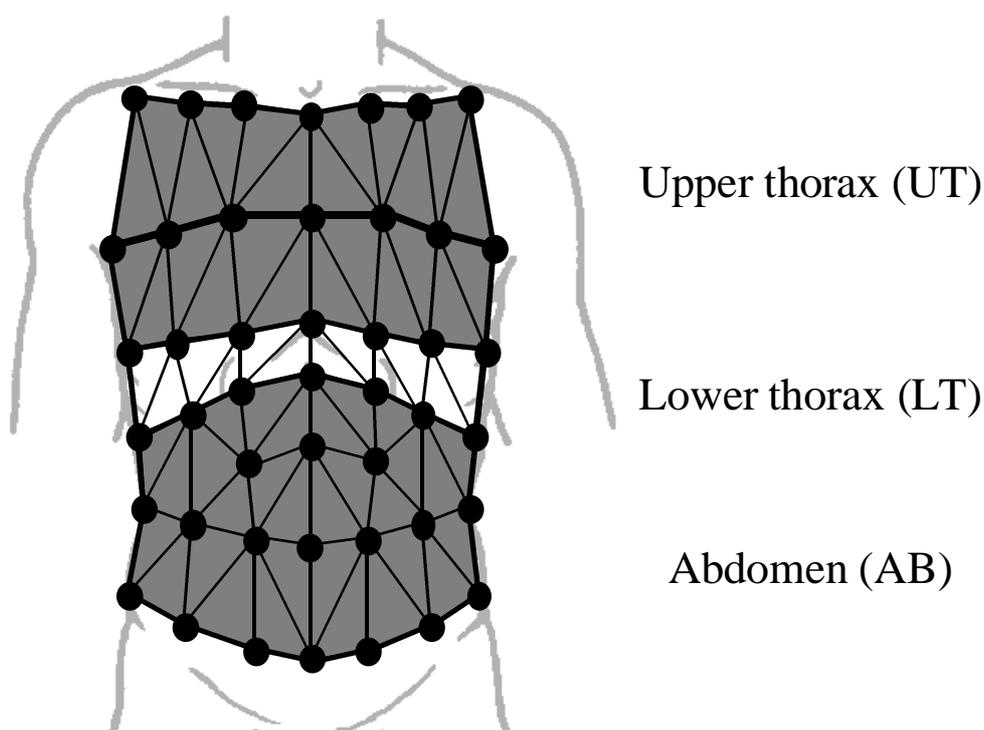


Fig. 1 – Markers' positions and chest wall compartments for optoelectronic plethysmography. Transversal lines: clavicular line; manubrio-sternal joint (angle of Louis); xiphoid process; lower costal margin; upper abdomen (3 markers); umbilical level; anterior superior iliac crest. Axial lines: two midaxillary lines; two midclavicular lines; two parasternal lines (extended to the abdominal region); midsternal line (extended to the abdomen). Chest wall compartments: upper thorax (UT) or lung-apposed pulmonary rib cage; lower thorax (LT) or diaphragm-apposed abdominal rib cage; abdomen (AB).

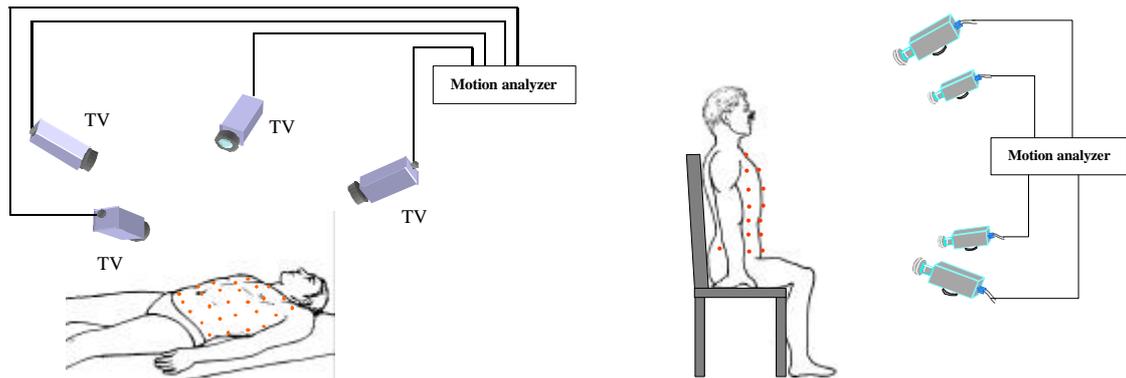


Fig. 2 – Experimental set-up for the analysis in the supine (left panel) and seated (right panel) position.

In the case of the supine position, this procedure was extensively validated in a previous study [11] comparing the total chest wall volume changes measured by OEP (ΔV_{CW}) with lung volume changes measured by pneumotachography or spirometry (ΔV_{PNT}).

For the same purpose, in this study we measured airway flow by the same screen-type pneumotachograph used for PNS/FESAM synchronization (see above), in order to compare ΔV_{CW} with lung volume changes obtained from flow integration (ΔV_{PNT}) in our experimental conditions. Then, the absolute (diff) and percentage (diff%) discrepancies between these two measurements were calculated as follows:

$$diff = (DV_{CW} - DV_{PNT})$$

$$diff\% = \frac{DV_{CW} - DV_{PNT}}{DV_{PNT}} * 100$$

Results and discussion

The results of the comparison between ΔV_{CW} and ΔV_{PNT} during different maneuvers are reported in table 1. In the supine position, the results are similar to those previously obtained on normal subjects and sedated and paralyzed patients during mechanical ventilation in intensive care unit [11]. Percentage discrepancies were lower than $\pm 5\%$ also in the seated posture, apart from during phrenic nerve stimulation and PNS combined with FESAM during expiration, where we found an average discrepancy of 9.6%. In this experimental condition, two possible sources of difference between ΔV_{CW} and ΔV_{PNT} could be either trunk motion artifacts during electrical stimulation of abdominal muscles or blood shifts from the trunk to the extremities. The value of discrepancy is however small ($<10\%$) and therefore also in this case ΔV_{CW} can be used as a good estimation of lung volume changes.

	SUPINE		SEATED	
	diff (liters)	Diff%	diff (liters)	diff%
PNS	-0.012 ± 0.021	-2.7 ± 4.5	0.008 ± 0.014	2.2 ± 3.4
PNS + FESAM during expiration	-0.023 ± 0.016	-4.9 ± 3.4	0.050 ± 0.014	9.6 ± 2.8
PNS+ FESAM during inspiration	-0.013 ± 0.021	-3.1 ± 4.8	-0.007 ± 0.03	-1.7 ± 7.4

Table 1 – Absolute and percentage values (mean \pm SD) of the difference between chest wall volume variations from OEP and lung volume changes obtained from flow integration during different maneuvers and postures.

Figures 3 and 4 show short periods of volume changes of the different chest wall compartments obtained for the patient receiving different ventilatory supports, in the supine and seated position, respectively.

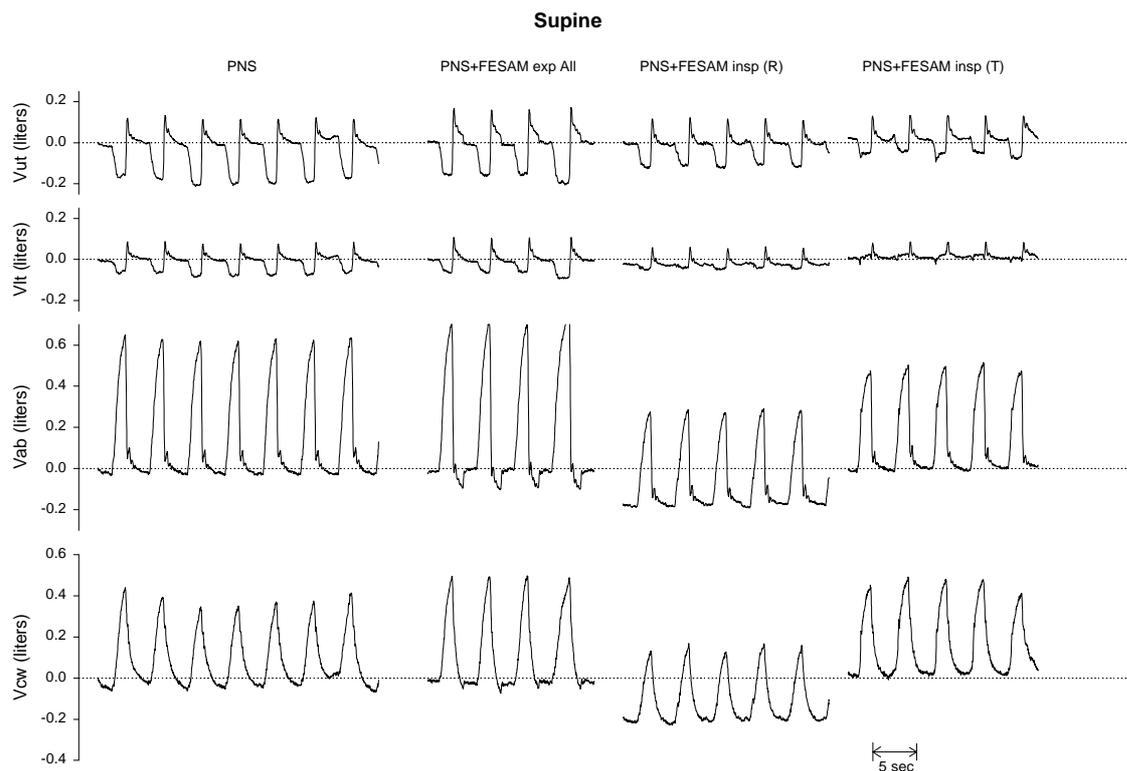


Fig. 3 – Compartmental volume changes in the supine position during (from left to right): phrenic nerve stimulation, PNS combined with abdominal muscles pacing during expiration, PNS combined with abdominal muscles (rectus) pacing during inspiration, PNS combined with abdominal muscles (transversus) pacing during inspiration.

In the supine position (fig. 3), during PNS a strong paradoxical motion of the upper and lower thorax is present. Therefore, the changes in V_{cw} are smaller than the changes in V_{ab} and an important part of the generated pressure does not contribute to lung expansion and is wasted into rib cage distortion.

In the same posture, the application of FESAM during expiration increases tidal volume only slightly, because of the paradoxical motion of the rib cage during expiration. The inspiratory paradoxical motion of the rib cage is instead reduced during PNS combined with FESAM applied during inspiration, and this effect is more evident during stimulation of the transversus alone.

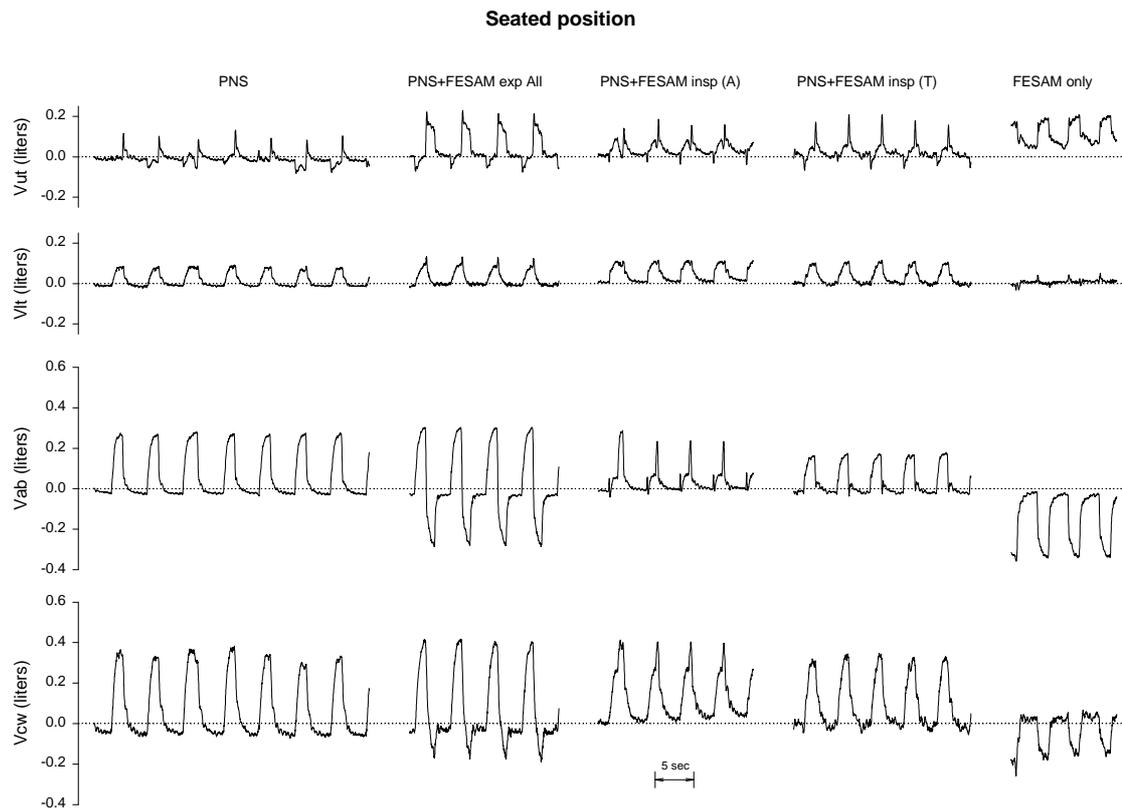


Fig. 4 – Compartmental volume changes in the seated position during (from left to right): phrenic nerve stimulation, PNS combined with expiratory muscles pacing during expiration, PNS combined with expiratory muscles pacing during inspiration, PNS combined with expiratory muscles (transversus) pacing during inspiration, FESAM alone.

In the seated position (fig. 4), PNS alone does not induce a significant paradoxical motion of the upper thorax, while lower thorax is in phase with the abdomen. The effect of FESAM during expiration is similar to that obtained in the supine position and the paradoxical motion of the rib cage during expiration still limits the increases in tidal volume. The combination between PNS and FESAM during inspiration allows a more physiological distribution of chest wall volume variations, with both thoracic compartments now in phase with the abdomen. This effect is also not dependent on the stimulated muscle.

In the seated posture, finally, ventilation can be obtained by applying only FESAM. In this case, total chest wall volume changes (about 200 ml) occur below FRC. The stimulation of abdominal muscles produces a decrease of abdominal volume and an increase of upper rib cage volume. Inspiration is then obtained by passive relaxation of the chest wall to FRC.

Figure 5 summarizes these results and shows the percentage contribution of the different compartments to total chest wall volume changes in the seated and supine positions.

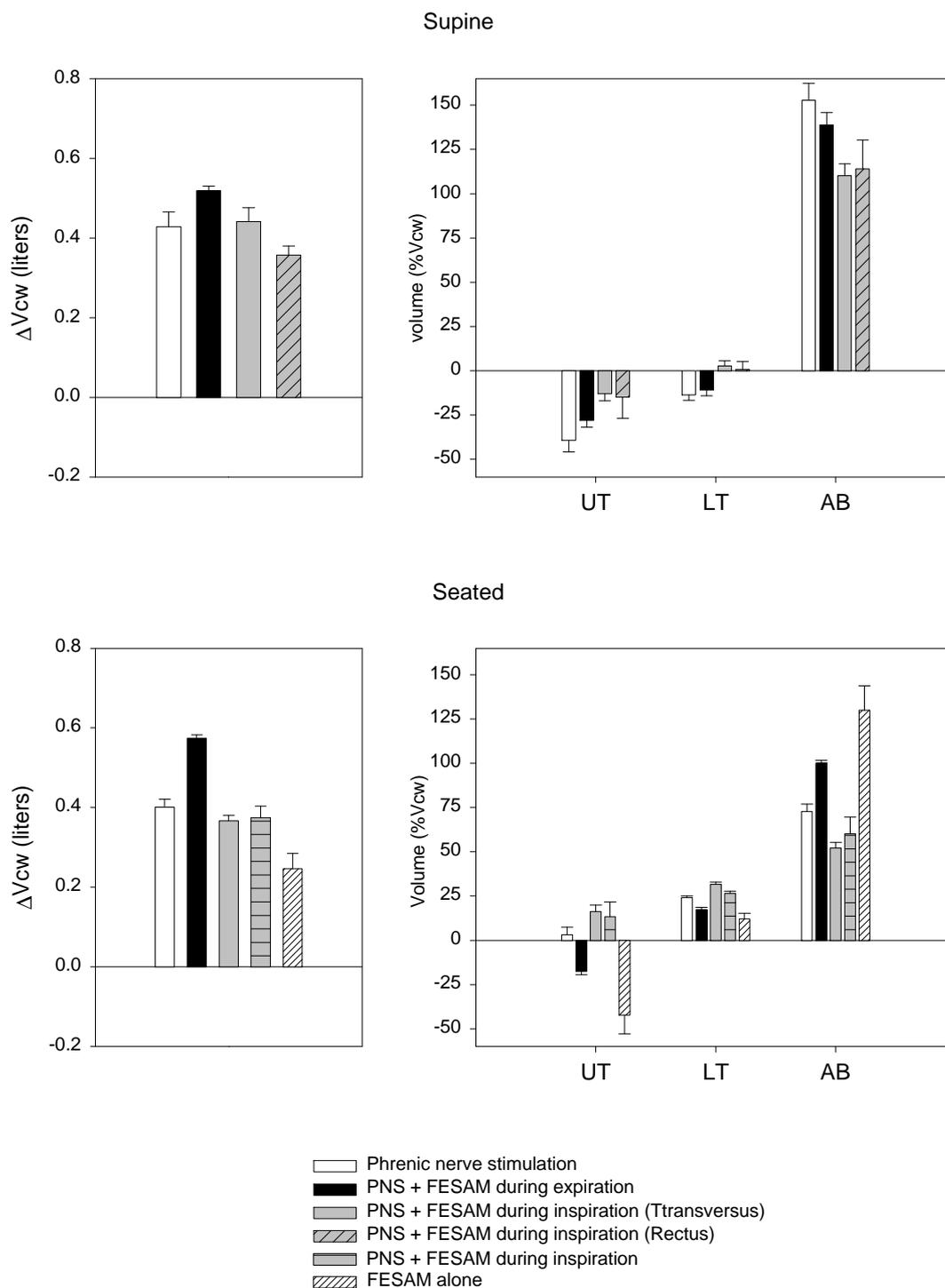


Fig 5 – Total chest wall volume changes (left panels) and percentage contribution of the different compartments (right panels) during different ventilatory supports in the supine(above) and seated (below) postures.

Conclusions

In conclusion, optoelectronic plethysmography is a reliable method to quantify volume distribution in the different chest wall compartments during phrenic nerve stimulation, FESAM or both, which can provide useful data for optimizing patient adaptation to these ventilatory assistance devices. In our spinal cord injured patient, we found that in the seated position, FESAM can be combined with PNS to enhance volume distribution among the different chest wall compartments, preventing the paradoxical motion of the upper thorax during inspiration and allowing a more physiological distribution of chest wall volume variations. In the supine position, a strong paradoxical motion of the upper thoracic compartment is present, but this effect can be reduced by applying FESAM during inspiration. Future studies will be addressed to study the implications of these findings on a long term basis and on a larger population of spinal cord injured patients.

Acknowledgements

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