Proposal of a New Electrode and Modality of Electrical Stimulation for Diaphragmatic Pacemakers

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Purpose. This report describes the implantation of a new design of intramuscular electrode to the diaphragm and introduces a new modality of electroventilation for diaphragmatic pacemaker.

Description. We used 22 Large White female pigs to test 68 electrodes that were implanted in the abdominal portion of the diaphragm by videolaparoscopy. Animals were submitted to a new protocol of electroventilation with an unpolarized current and a single-channel mode with 1 electrode for each hemidiaphragm during 3 hours.

Evaluation. The electrodes were easily fixed to the diaphragm with the help of a deployment device designed for this purpose. There was no evidence of clinical complications such as pneumothorax or bleeding. No significant differences were observed in arterial blood gas analysis and serum lactate levels.

Conclusions. The designed electrodes provided an excellent performance in connection between the electrical stimulator and the muscle tissue. The proposal for using an unpolarized current proved to be effective in stimulating both hemidiaphragms simultaneously with only a single channel of the electrical stimulator.

The treatment of chronic respiratory failure caused by the loss of respiratory muscle function has been improved in recent years by efforts to reestablish the ability to contract by electroventilation [1, 2]. This method consists of the application of electrical currents to strategic points of the muscles responsible for ventilation or to the phrenic nerve to trigger an effective muscular contraction and use the individual’s own muscular system to reestablish functionality.

Great advances have been achieved in recent years regarding equipment and methodologies, with special attention being paid to the implantation of electrodes directly in the abdominal portion of the diaphragm [3]. This technique was initially described through laparotomy and later evolved to videolaparoscopy [4, 5]. A diaphragmatic pacemaker with intramuscular electrodes has been used mainly for the treatment of ventilatory insufficiency in cases of high spinal cord trauma and amyotrophic lateral sclerosis [6], with excellent results.

In this report, we describe a new design of an intramuscular electrode for electrical stimulation of the diaphragm and a new modality of electroventilation generated by the simultaneous stimulation of both domes of the hemidiaphragm with a single-channel mode (Fig 1).

Technique

We used 22 Large White female pigs weighing 25 kg in this study. The animals were treated as recommended by the World Health Organization Ethical Code for Animal Experimentation. The project was approved by the local Research Ethics Committee (No. 10-260).

Videolaparoscopy was used to implant 68 electrodes in the abdominal portion of the diaphragm. The preparation of the animals, the anesthetic protocol, and the surgical technique are described elsewhere [7].

The electrode was attached to a deployment endoscopic instrument, and the diaphragmatic domes were exploited bilaterally to locate its motor or functional point. Electrical stimuli were applied with an intensity current of...
10 mA to select the locations where a global muscle contraction was observed to then deploy the electrodes. In 10 animals, 1 electrode was implanted, and in 12 animals, 2 electrodes were implanted in each diaphragmatic dome. The lead wires of the electrodes were placed in the subcutaneous tissue of the abdominal wall for later access.

The animals were observed for 15 days and then were anesthetized and intubated following the same protocol. The wires placed in the subcutaneous abdominal wall were exposed and connected to a current generator for evaluation of the muscular contraction and measurement of the tidal volume generated during 3 hours. All animals were euthanized with an overdose of propofol, followed by lethal venous injection of potassium chloride. The diaphragm was removed for macroscopic evaluation of the position and fixation of the electrodes.

The electroventilation was produced using an unpolarized symmetrical electric current, with an intensity of 30 mA, with 20 stimuli per minute, applied through electrodes implanted in the diaphragm in single-channel mode. In those animals with 2 electrodes in each hemidiaphragm, we selected the 2 (1 on each side) that demonstrated the best muscle contraction. The animals were induced into a coma by an increase the propofol dose to 0.5 to 0.8 mg/kg and a bolus dose of fentanyl of 100 μg to inhibit the respiratory system. Electroventilation was maintained uninterrupted for 3 hours.

Arterial blood samples were collected at specific time: baseline, just after intubation; 1 hour after the beginning of the electroventilation protocol; and after 3 consecutive hours of electroventilation. These samples were analyzed for the arterial blood gas values (pH, partial pressure of arterial carbon dioxide, bicarbonate, total carbon dioxide, base excess, and partial pressure of oxygen) and the concentration of lactate with animals ventilated in room air (fraction of inspired oxygen, 21%). The expiratory volume was evaluated through an airflow sensor attached to end of the endotracheal tube.

The design of the electrode allowed it to be used in a thin and slender muscle such as the diaphragm, allowing its implantation by videolaparoscopy. The electrode is composed of a body in a nonconductive material that is used as support for the attachment with the deployment tool. Its terminal end has a helical or spiral format (corkscrew) in stainless steel, with the most distal portion sharpened to facilitate penetration into the muscle tissue. A metallic covered wire and a connector at the proximal end make the connection between the electrode and the electric generator (Fig 1). The electrode is inserted into the muscle by screwing in a clockwise direction, providing an interface between the muscle tissue and an electric generator or electromyography equipment and capturing signals of neuromuscular activity.

This design allows the electrode to be used to locate the most appropriate point for its fixation, facilitating and making the entire process faster and more efficient. The electrode design has been documented and registered by the Brazilian National Intellectual Property Institute (INPI) under No. BR2020140245214.

The Friedman nonparametric test was used for the statistical analysis of the medians, and a p value of 0.05 or less was considered statistically significant. The inter-quartile range was used to measure the data variability based on dividing a data set into quartiles. The results are shown as the range of values of a frequency distribution between the first and third quartile intervals.

Clinical Experience

All animals survived the procedure without any evidence of clinical complications such as pneumothorax or
bleeding. It was possible to identify the diaphragm motor points with the electrode and to deploy it without the use of another device or tool, making the procedure easier and more agile. The average time spent on the procedure was 86.15 ± 6.39 minutes.

The electroventilation protocol properly ventilated all of the animals. In addition, we observed an effective muscle contraction, demonstrating that the electrode provided an adequate connection between the current generator and the diaphragmatic muscle tissue. The postmortem evaluation of the diaphragm allowed us to check the positioning of the electrode and its attachment to the muscle. All 68 electrodes were attached to the muscle adequately, without evidence of any apparent muscle injury, creating a proper interface for electric conduction.

The protocol using the unpolarized electric current proved to be effective to produce a muscle contraction able to generate adequate pulmonary ventilation with an average of tidal volume of 220 ± 38.99 mL and to maintain an average minute volume of 7.49 ± 1.35 mL/kg in all animals throughout the experimental period. The values for the pH, partial pressure of carbon dioxide, and bicarbonate collected in arterial blood at baseline, 1 hour, and after 3 hours remained within a limit considered normal in all animals at the different observation times, and there were no statistically significant differences (Table 1). The average blood concentration of lactate collected at the beginning of the experiment was 0.88 ± 0.15 mmol/L and was 0.96 ± 0.1 mmol/L after 3 hours, without any significant difference (p = 1.0). The partial pressure of arterial oxygen remained above 100 mm Hg during all observation times with the animals ventilating in room air (fraction of inspired oxygen, 21%).

Comment

This study showed that the new design of an electrode developed by our group was effective in creating a proper interface between an electric stimulator and the diaphragm. An additional advantage of this system is to use the electrode itself to locate the diaphragmatic motor points very effectively. Furthermore, the new proposal of the simultaneous depolarization of both diaphragmatic domes was able to generate adequate pulmonary ventilation. Other researchers have described the simple visual observation of muscle contraction when stimulated at different points as an effective technique for locating the motor points of the diaphragm. The operating procedure of exploration of the motor points of the diaphragm by applying electric current has been extensively described by others and may be accomplished with the use of specific probes or with endoscopic forceps [8]. This is the first report of this design of electrode for diaphragmatic stimulation.

In the past, different types of electrodes have been used with different shapes and designs of deployment but have not been free from complications, such as detachment or muscle injury, during their deployment [9]. The air volume achieved with the use of the new electrode design is similar to that found in the literature [3]. The electrode’s spiral design allows for fixation onto the muscle tissue by screwing and avoiding displacement or an unexpected release. The 68 implanted electrodes were all properly attached to the muscle without evidence of any clinical complication.

The only intramuscular diaphragmatic pacemaker currently used in clinical practice consists of 4 current generators with 2 wires in each channel (2 channels in each hemidiaphragm) [7]. In our model, we successfully achieved an effective muscle contraction in both hemidiaphragms at the same time by using an unpolarized electric current with only a single channel. This electrical stimulation modality does not use a “passive” electrode, but rather 2 “active” electrodes, 1 in each hemidiaphragm, making it possible to generate a simultaneous depolarization. We believe that this finding may allow the development of a smaller electrical stimulator with lower energy consumption, which would potentially be implantable.

We observed a small decrease in muscle performance over 3 hours, demonstrated by the reduction of the arterial pH, resulting from an increase, although not significant, of the bicarbonate level and partial pressure of carbon dioxide related to less effective arterial “washing” of carbon dioxide. Muscle activation by electrical stimulation is related to premature muscle fatigue [10]. This may be explained by the limited and repeated recruitment of the muscle fibers as well as by the pattern of muscular recruitment in a reverse order, which are the factors related to the early onset of muscle fatigue.

Table 1. The Effect of Electroventilation on Arterial Blood Gases and Expiratory Volume Adjusted by Weight

<table>
<thead>
<tr>
<th>Variable</th>
<th>Baseline Median (Q1–Q3)</th>
<th>1 Hour Median (Q1–Q3)</th>
<th>3 Hours Median (Q1–Q3)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.51 (7.486–7.56)</td>
<td>7.49 (7.45–7.50)</td>
<td>7.48 (7.39–7.52)</td>
<td>0.20</td>
</tr>
<tr>
<td>PaCO₂ mm Hg</td>
<td>36.55 (34.2–41.57)</td>
<td>41.85 (37.85–46.17)</td>
<td>44.65 (38.77–49.05)</td>
<td>0.07</td>
</tr>
<tr>
<td>HCO₃⁻ mEq/L</td>
<td>30.60 (27.32–31.72)</td>
<td>30.90 (28.75–32.62)</td>
<td>31.65 (30.05–32.325)</td>
<td>0.06</td>
</tr>
<tr>
<td>PaO₂/FiO₂ ratio</td>
<td>450.5 (103.15–498.68)</td>
<td>519.04 (492–571.19)</td>
<td>489.29 (423.8–621.7)</td>
<td>0.12</td>
</tr>
<tr>
<td>Expiratory volume, mL/kg</td>
<td>7.62 (6.64–8.6)</td>
<td>7.77 (6.31–8.86)</td>
<td>7.69 (6.46–8.53)</td>
<td>0.50</td>
</tr>
</tbody>
</table>

FiO₂ = fraction of inspired oxygen; HCO₃⁻ = bicarbonate; PaO₂ = partial pressure of arterial oxygen; PaCO₂ = partial pressure of carbon dioxide; Q1 = first quartile; Q3 = third quartile.
This study has limitations that must be taken into consideration, such as the short observation period. Our study was only long enough to demonstrate the effectiveness of the electrode and the new electroventilation modality. We believe that longer periods of observation are important to observe the histologic changes of the muscle tissue and the possible ion deposition or damage caused by electrical energy near the electrode. We aimed to specifically evaluate the possibility of stimulating both hemidiaphragms simultaneously. For this reason, we did not analyze the energy consumption caused by the current generator and, consequently, the autonomy of the system.

Disclosures and Freedom of Investigation

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References


Disclaimer

The Society of Thoracic Surgeons, the Southern Thoracic Surgical Association, and The Annals of Thoracic Surgery neither endorse nor discourage use of the new technology described in this article.