1985

Electroventilation

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ABSTRACT

Electroventilation is a term used to describe the production of inspiration by applying rhythmic bursts of short duration stimuli to extrathoracic electrodes to stimulate motor nerves to the inspiratory muscles. In the dog, the optimum site for the electrodes was found to be on the upper chest wall, bilaterally. The inspired volume increased with increasing current intensity. The maximum tidal volume attainable was about four times resting tidal volume. The ability of electroventilation to maintain arterial blood oxygen saturation without the production of cardiac arrhythmias was demonstrated in pentobarbital-anesthetized dogs. The technique has several potential applications and offers promise in emergency and critical-care medicine.

Key words: device, electrical stimulation, opioid overdose, respiratory arrest, respiratory failure, respiratory pacemaker, sedative drug overdose, ventilation, ventilator

(American Journal of Emergency Medicine 1985, Vol. 3, pp. 337-339)

INTRODUCTION

Electroventilation is the name we have given to a new technique for producing inspiration by stimulating the inspiratory motor nerves with chest-surface electrodes. Selection of the proper stimulus parameters is crucial to avoid cardiac arrhythmias. This paper describes preliminary results in which artificial ventilation was produced in a canine model using extrathoracic, skin-surface electrodes. The objectives of this feasibility study were 1) to determine the optimal site for inspiratory muscle stimulation; 2) to characterize the relationship between stimulus intensity for electroventilation and tidal volume; and 3) to test the ability of electroventilation to maintain arterial blood oxygen saturation.

Dr. Babbs is supported by Research Career Development Award HL-00857 from the National Heart, Lung, and Blood Institute, Bethesda, Maryland.

METHODS AND RESULTS

Animal Model

In this study, electroventilation was used to produce artificial respiration in six pentobarbital anesthetized dogs in which arterial pressure, the electrocardiogram (ECG), oxygen saturation, and the volume of air inspired were recorded. Blood pressure was monitored via a fluid-filled catheter placed in a femoral artery and connected to a Statham P23Db transducer. The volume of air breathed was recorded from an oxygen-filled spirometer containing a carbon dioxide absorber. An electronically derived signal, proportional to spirometer volume, was inscribed on the graphic record. Prior to applying electroventilation, respiratory arrest was produced by stimulating the afferent vagal fibers to simulate activation of the Hering-Breuer stretch receptors in the lungs. Selective afferent vagal stimulation was accomplished by exposing the right and left vagal trunks in the neck, attaching encircling bipolar electrodes, and tightly ligating the nerve distal to the electrodes to eliminate cardiac effects.

First the chest was mapped with l-cm diameter electrodes to find the optimum location for producing inspiration. Then 3-cm diameter, stainless steel electrodes were applied to the optimum location on the left and right chest, and artificial ventilation was produced in subsequent studies by delivering rhythmic bursts of short-duration stimuli to these electrodes.

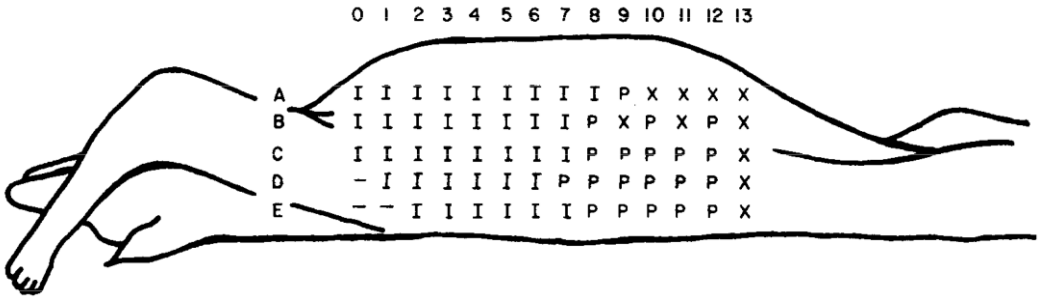

FIGURE 1. Regions on the chest where inspiration (I), expiration (X). or paradoxical breathing(P) were obtained.

Chest Mapping

The thorax of each dog was shaved, and a grid of points (1 x 1 inch) was marked with an indelible pen. Stimulating electrodes (l-cm diameter) were held bilaterally over each point, and l-second bursts of 100 μsec stimuli (with a frequency of 60 pulses/second) were applied. At each point on the chest, the current was increased to obtain a response. The response at each point was marked I for inspiration, X for expiration, and P for paradoxical motion (i.e. both inspiratory and expiratory muscles were contracted). Figure 1A illustrates these regions on the dog chest and demonstrates that inspiration is produced with upper-chest electrodes.

Next, the optimum inspiratory points were located. These are defined as the sites where the maximum volume of air is inspired per milliampere of current. The volume of air inspired was measured with a spirometer connected to the cuffed endotracheal tube. Figure 1B illustrates the optimum site (10 ml air/mA current), which is slightly anterior to a midaxillary line and about at the level of the fourth rib. This point was similar in most dogs; in a few the point was 2 to 3 cm more anterior. The coefficient (ml air/mA current) varied considerably among the dogs, ranging from 2 to 10 ml/mA for the stimulus parameters used.

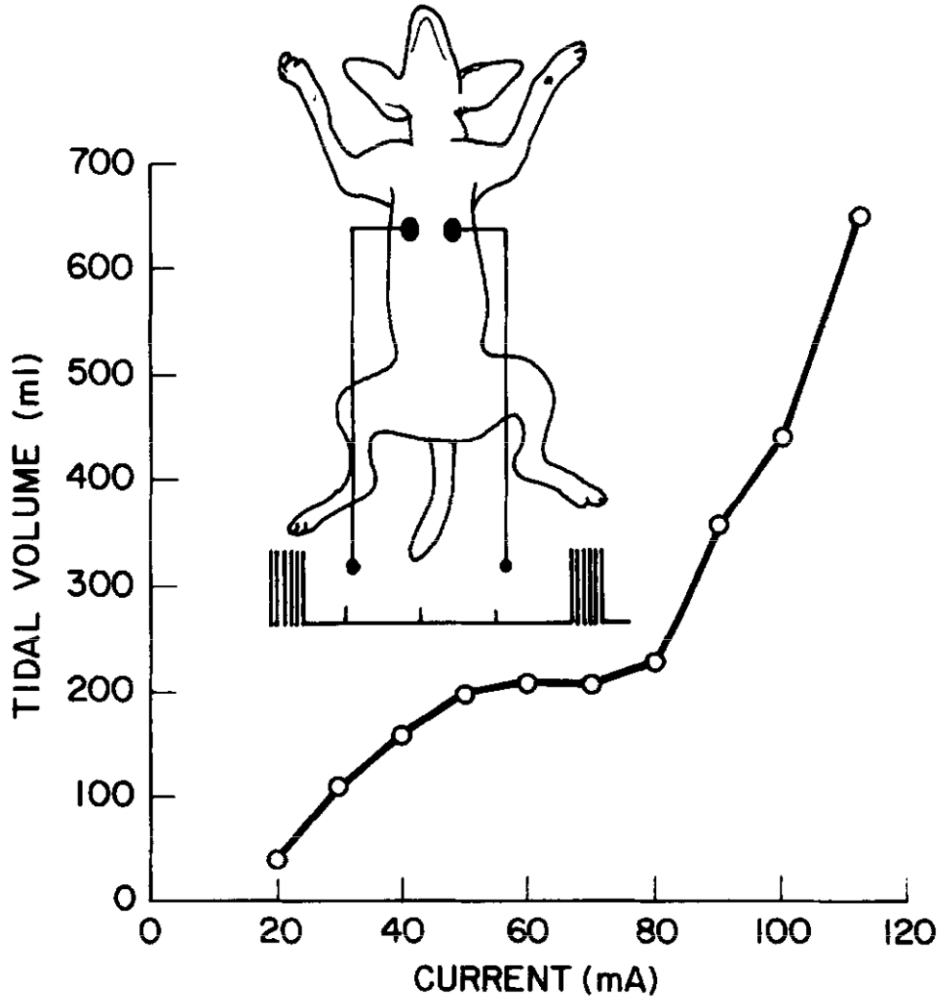

FIGURE 2. Volume of air moved versus stimulating current in a typical animal with transthoracic electrodes located as shown.

Inspired Volume Attainable

With electrodes at the optimum sites on the dog chest, the volume of air inspired was measured for l second pulse trains (60/second, 100 μsec duration) at different current levels. Figure 2 presents results in a typical animal and shows that the volume of air inspired increases with increasing current. This animal exhibited a spontaneous tidal volume of 150 ml; the same volume was achieved with about 40 mA. Notice that as the current is increased, the volume of air inspired increased dramatically, ultimately reaching a tidal volume of 650 ml. It may have been that, with the higher current levels, the phrenic nerves were stimulated, thus recruiting the diaphragm. This point is under investigation.

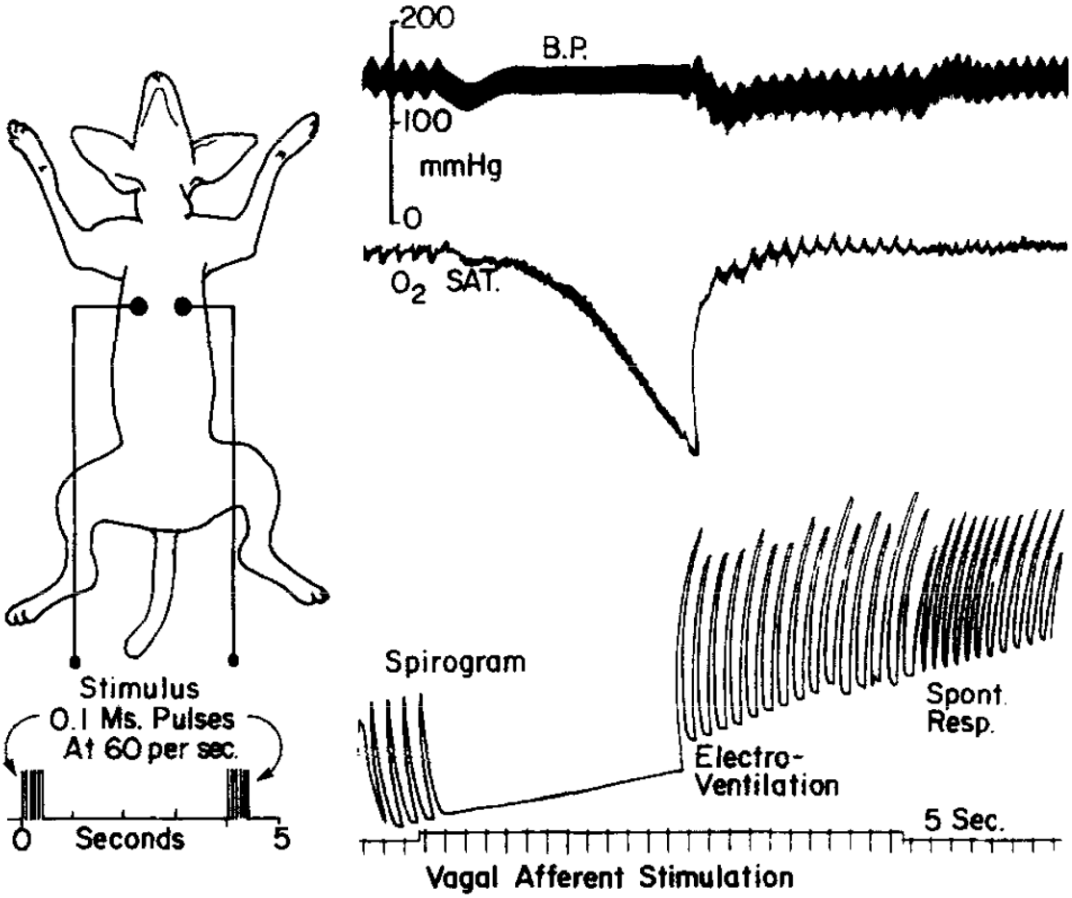

FIGURE 3. Blood pressure. (channel 1), oxygen saturation (channel 2) and tidal volume (channel 3) under control conditions, respiratory arrest. electroventilation, and spontaneous breathing. The oxygen saturation scale is uncalibrated in this record: the deflection seen in this channel was subsequently determined to be approximately 20% using a Lexington Instruments $LexO_2Con^{®}$ device.

Arterial Blood Oxygenation

Although the foregoing experiments illustrate the movement of air into and out of the trachea, the value of any artificial-respiration system lies in its ability to oxygenate the blood. To demonstrate the ability of electroventilation to oxygenate the blood, oxygen saturation was recorded continuously with a flow-through oximeter in an arteriovenous shunt. Figure 3 illustrates a typical record. On the left, the animal was breathing spontaneously. In the center, respiratory arrest was induced by afferent vagal stimulation and maintained until oxygen saturation fell by about 20%. At this point, electroventilation was applied, and within about 5 seconds (two to three breaths), the oxygen saturation returned to the control level. After about 1 minute of electroventilation, respiratory arrest and electroventilation were discontinued, and the dog resumed spontaneous breathing at a slightly higher rate and with a slightly reduced tidal volume, but with no change in oxygen saturation.

Potential Applications

We see several potential applications of electroventilation in clinical medicine. In the emergency department the method may be convenient for treating respiratory depression from sedative drug overdose. In the post-operative setting the method offers potential as a rapidly and easily applied means to assist ventilation and to prevent or reverse atelectasis. Most intriguing is the possibility of combining an electroventilator with a respiratory monitor to create a demand respirator that would function in a manner analogous to that of a demand cardiac pacemaker.

Perhaps the most valuable theoretical advantage of electroventilation is that it produces inspiration by negative intrathoracic pressure, thereby minimally altering pulmonary vascular resistance, and it also produces no deleterious effects on cardiac output. These aspects of electroventilation will be investigated further in the future.

With respect to the safety of electroventilation, several points are worthy of note. For example, because of the difference in membrane time constant of cardiac muscle (2 msec)[1] and motor nerve (0.01 msec)[2] the strength-duration curves for stimulation differ. The strength-duration curve for cardiac muscle rises above rheobase at a longer stimulus duration than does that for motor nerve. Therefore, the choice of a very short-duration pulse for electroventilation minimizes the risk of encountering cardiac arrhythmias. To date, we have never encountered a cardiac arrhythmia in the dog. An even wider safety margin may be secured by using stimuli shorter than 100 μsec for electroventilation. Further studies on the safety of electroventilation are underway.

Although the chest configuration of dogs is somewhat different from that of humans, and the relative contributions of thoracic and abdominal breathing may differ in dog and man, we believe that electroventilation has considerable potential for human application. As prototype devices for electroventilation are perfected, efficacy and safety studies will become possible, first in primates and then in human patients.

REFERENCES

1. Pearce JA, Bourland JD, Neilsen W, et al. Myocardial stimulation with ultrashort duration current pulses. PACE 1982;5:52-58.

2. Ritchie A. The electrical diagnosis of peripheral nerve injury. Brain 1944;67:314-330.