Relationship between Electrical Activity of the Diaphragm and Ventilation.* (27652)

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In the course of ventilation studies it was necesary to monitor ventilatory volume without recourse to the measurement of inspired or expired air. For various reasons other indirect measurements of ventilation such as integrated phrenic nerve action potentials, pneumographic technics and body plethysmography were not suitable. Since the electrical activity of the phrenic nerve is directly related to the activity of the respiratory center(1), it seemed reasonable to assume that the electrical activity of the diaphragm could be used as an index of ventilation. A study of the relationship between the integrated electromyogram of the diaphragm and tidal volume was undertaken to determine whether the assumption was correct.

Methods and materials. Twenty-two cats weighing between 3 and 4 kg were studied. Under ether anesthesia the trachea was cannulated. Both external carotid arteries were ligated to minimize blood loss during craniotomy. Through a parietal craniotomy an intercollicular decerebration was performed. Hemostasis was secured with silver clips and Oxycel®. The animal was then allowed to breathe room air for 90 minutes in order to eliminate most of the ether. In the initial experiments inspiratory flow was recorded with a pneumotachograph and a Statham strain gauge (resistive transducer). The signals were integrated electronically for volume measurements. In later experiments tidal volume was measured with a "Wedge" spirometer (Med-Science Electronics, Inc.). The diaphragmatic electromyogram (EMG) was recorded from 2 insulated unipolar electrodes inserted transabdominally under vision. The abdominal incision was sutured following placement of the electrode. The EMG and the integrated EMG were recorded together with inspiratory airflow or tidal volume on a multichannel cathode ray oscillograph. As an index of diaphragmatic activity, both the height and the average slope of the integrated EMG were measured. The slope was measured with the aid of a Gerber variable scale ruler.

Results. The incidence of movement artifacts or electrode displacement during deep inspiration was studied in 4 animals. After the animals were paralyzed with succinylcholine artificial ventilation with a stroke volume varying from 20 ml (approximately normal tidal volume) to 100 ml did not produce spurious signals. The importance of the location of the electrodes was studied in 4 other animals. In these animals electrical activity was simultaneously recorded from several areas of the diaphragm as the tidal volume was increased by rebreathing. It was demonstrated that although the amplitude of the integrated electromyographic activity varied in different areas, the changes in activity produced by rebreathing were proportionate at each site. Therefore, once the electrode is placed it is necessary that the position not be changed during a given experiment. In 14 animals the change in tidal volume produced by rebreathing was compared with the change in height and average slope of the integrated EMG. Rebreathing increased the height and the average slope of the EMG integral (Fig. 1, 2). This increase in diaphragmatic activity was linearly related to the increase in

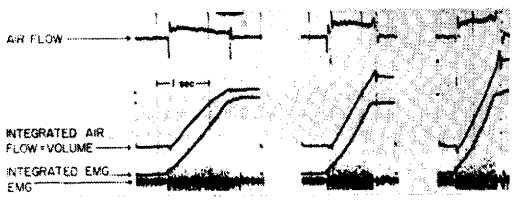

FIG. 1. Comparison of increase in integrated air flow and integrated EMG during rebreathing. Air flow measured with a pneumotachograph.

* Supported by USPHS grant.
† Work performed during tenure as a trainee, USPHS grant to Dept. of Anesthesiology.

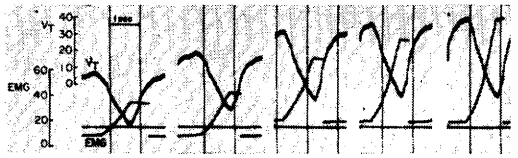

FIG. 2. Comparison of increase in tidal volume and integrated EMG during rebreathing. Tidal volume recorded with a spirometer and measured in ml. Height of EMG measured in mm. Time scale is one second between vertical lines.

tidal volume when measured by either the pneumotachograph or the spirometer. The relationships between the EMG and the tidal volumes from one experiment are depicted in Fig. 3. It can be seen that the tidal volume is proportionate to both the height and the average slope of the integrated EMG. The correlation co-efficients of this relationship (tidal volume and average slope of integrated EMG) in each of 14 experiments ranged from 0.85 to 0.99 with a mean value of 0.93 (S.D. 0.04).

Discussion. Early attempts to correlate the electrical and mechanical activities of muscle met with little success. Rosenblueth, Wills and Hoagland(2), working with the cat satorius, and Loofburrow(3) with the tibialis anticus of the cat, found that the action potential amplitude could not be quantitatively related to the tension developed in the muscle. The absence of a correlation between mechanical activity and amplitude of action potential is not surprising since Adrian and Bronk(4,5) showed that the strength of contraction of the cat diaphragm depended not upon the amplitude of action potentials but upon the number of motor units active and their frequency of discharge. This point was further amplified by Gesell, Atkinson and Brown(6) who showed that in 3 individual diaphragmatic motor units the frequency of discharge of each was unrelated to the tidal volume. However, the total number of action potentials of all 3 motor units was roughly related to the tidal volume.

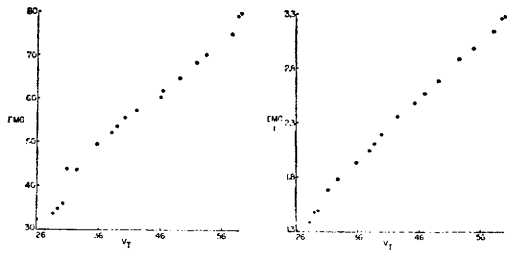

FIG. 3. Left, correlation between tidal volumes and integrated EMG; right, correlation between tidal volumes and avg slope of the integrated EMG. Both from the same experiment during rebreathing. Note better correlation on the right, when avg slope of the integrated EMG was used. Tidal volume measured in ml. EMG measured in mm. EMG/t measured in mm/time in seconds with paper speed of 25 mm/second.

In 1952 Lippold(7) showed that the integrated action potentials of the human calf muscles were linearly related to the tension produced by a voluntary isometric contraction. The correlation co-efficients of 30 experiments varied from .93 to .99. Inman *et al.*(8) in the same year compared the action potential amplitude or direct EMG, the integrated EMG and the isometric tension developed during the voluntary contraction of the human biceps brachii. The tension developed during isometric contraction was unrelated to the amplitude of the direct EMG but correlated well with the integrated EMG. However, there was no correlation between the mechanical tension and the integrated EMG if the muscle was allowed to vary in length. These authors attributed this lack of correlation to the change in the length which occurs during isotonic contraction. But two years later Bigland and Lippold(9) in human calf muscle demonstrated a linear relationship between the integrated EMG and tension exerted during both shortening and lengthening provided the change in length occurred at a constant velocity. This proportionality of electrical activity and mechanical effect during isometric as well as isotonic contraction and Pitts' correlation of phrenic nerve activity and tidal volume(1) led us to suspect a correlation between tidal volume and the integrated EMG of the diaphragm. The present study appears to substantiate this supposition.

In our early experiments the tidal volume was compared with the magnitude of the EMG integral. However, it was noted that the best correlation was always obtained when a time factor was introduced. This is illustrated in Fig. 3, in which the tidal volume is plotted against the EMG integral as such and the av-

erage slope of the EMG integral. The correlation co-efficient of the former was .93 and that of the latter, .98.

It appears that under the conditions of this experiment the integrated EMG of the diaphragm can be used as an indirect quantitative measure of ventilation. There are however some problems with the technic of diaphragmatic electromyography. In this study the position of the electrode was verified by direct inspection. In some instances the electrodes were sewn into the diaphragm to insure against displacement. We have also been able to insert the electrodes blindly through the lower intercostal space using the characteristic inspiratory discharge from the monitoring loud speaker as a guide. With this technic, however, the needles may become displaced during a long experiment. Although as previously shown the relative change of activity is the same in different areas of the diaphragm, the absolute activity may vary and thus a new base line must be used if the needle is moved. Another limitation of the method is that respiratory obstruction alters the diaphragmatic activity and its relationship to tidal volume. An extreme example is the marked activity seen in total obstruction. An unobstructed airway must therefore be assured. This discrepancy between tidal volume and EMG activity during obstruction provides a method for the study of graded obstructions on the electrical output of the diaphragm and tidal volume(10).

Some of the applications of the diaphragmatic EMG include: (1) the determination of apnea points by the disappearance of electrical activity of the diaphragm(11,12), (2) the comparison of tidal volume and electrical activity of the diaphragm during graded obstruction(10), and (3) the measurement of ventilation in unanesthetized, unrestrained animals with chronically implanted diaphragmatic electrodes (Fink, B. R., unpublished data).

Summary. The use of the integrated electromyogram of the diaphragm as an index of ventilation was studied in 22 animals. The increase in electrical activity of the diaphragm and the tidal volume, produced by rebreathing, were linearly related. Under the conditions of these experiments—spontaneous breathing with an unobstructed airway and a constant position of the diaphragmatic electrode—the integrated electromyogram of the diaphragm provides an indirect quantitative measure of ventilation.

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Received June 20, 1962. P.S.E.B.M, 1962, v110.