ELECTRICAL ACTIVITY OF THE RESPIRATORY MUSCLES IN MAN DURING BREATH HOLDING

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Voluntary breath holding is widely used in clinical practice and in athletics as a function test. Many investigations have been made of the changes arising in the body in such conditions, some of which have shown that during voluntary breath holding the respiratory muscles do not remain fully at rest throughout the period of apnea. In most people irregular contractions of the respiratory muscles begin to appear shortly after the beginning of voluntary apnea, and continue until the end of breath holding [1-12]. The workers cited above consider that involuntary contraction of the respiratory muscles during continued apnea arises from the fact that the level of excitation of the respiratory center is raised by nervous and hormonal influences and the excitation is transmitted to the respiratory muscles.

In order to analyze the functional state of the respiratory center during voluntary apnea in greater detail, we studied the dynamics of the electrical activity of the respiratory muscles throughout the period of breath holding. Experiments were carried out on four healthy persons aged 19-24 years.

EXPERIMENTAL METHOD

The action potentials of the respiratory muscles were picked up by electrodes placed on the skin and recorded on a "Disa" electromyograph. The electrodes were applied to the 7th intercostal space and to the right of the xiphoid process (inspiratory muscles), and also over the external oblique muscle of the abdomen (expiratory muscle). Breath holding was carried out after inspiration and expiration, the subject lying on his back, the nose being compressed by a special clamp.

EXPERIMENTAL RESULTS

The course of voluntary breath holding is not the same in all subjects. In some during apnea the contractions of the respiratory muscles cease completely and the pneumogram is represented by a smooth line. In others the period of voluntary breath holding is divided into two distinct phases: initially, a resting state of the respiratory muscles – a phase of complete inhibition, followed by a phase of involuntary contraction of the respiratory muscles during continued apnea. In the second phase periodic waves appear on the pneumogram, corresponding to the involuntary movements of the muscles. Pneumograms such as these were observed in our subjects during voluntary apnea.

We attempted to examine the behavior of the electrical activity of the inspiratory and expiratory muscles characterizing the whole period of both types of apnea. The problem was complicated by the fact that when the action potentials were recorded from surface electrodes fixed to the skin, during ordinary breathing the electrical activity of the respiratory muscles was very weak. During the phase of inspiration the amplitude of the action potentials reached 10-20 μV, but even when maximum amplification was used, amplitudes of 30 μV often could not be detected. However we did succeed in recording the electromyogram (EMG) in more than 50 cases of voluntary apnea, showing the characteristic features of each type of apnea.

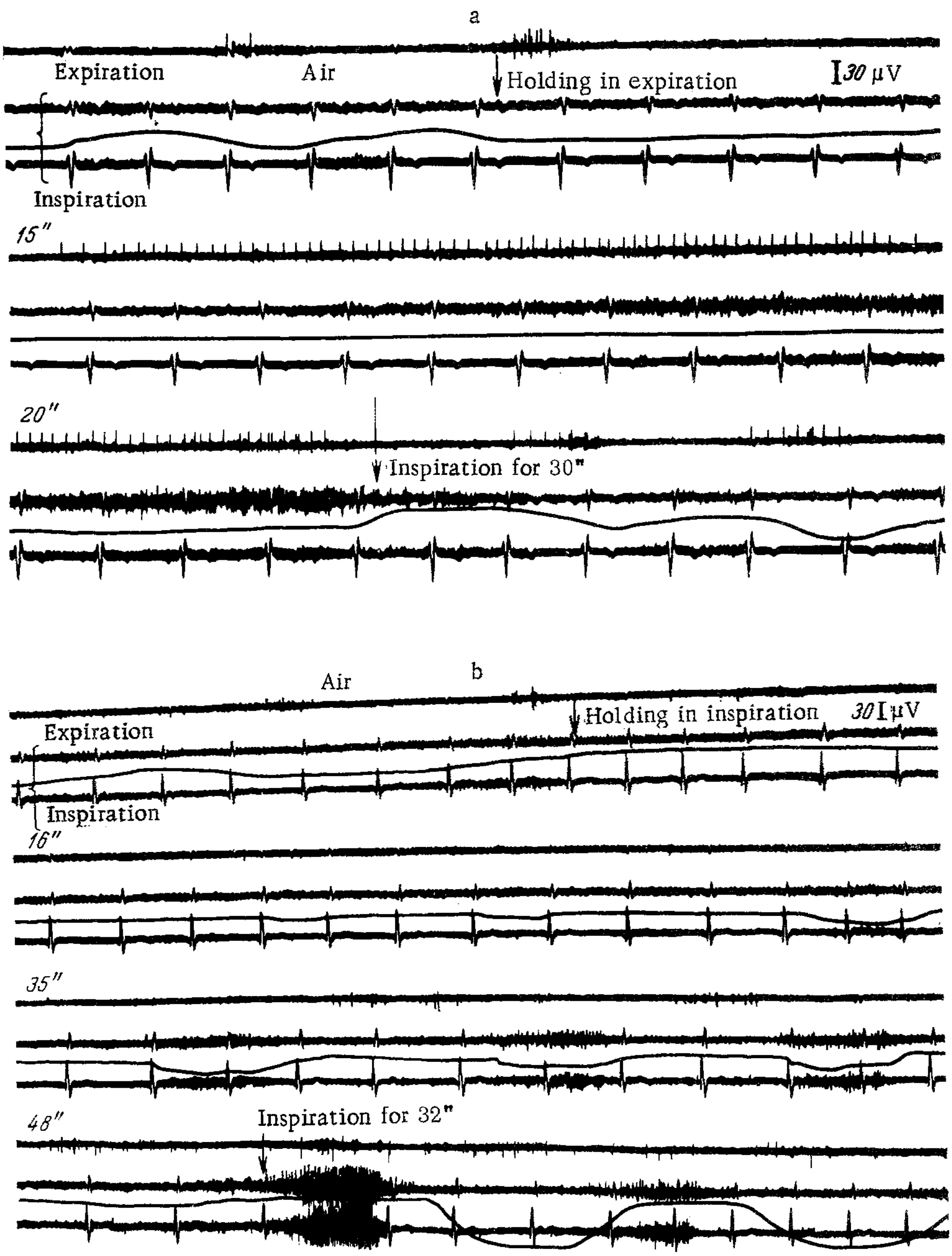

Fig. 1. Pneumogram and EMG of the expiratory and two inspiratory muscles during breath holding following an ordinary expiration in subject P. (a) and an ordinary inspiration in subject M (b).

When a smooth line was observed on the pneumogram during voluntary apnea, the EMG had the appearance shown in Fig. 1a. At the beginning of breath holding the action potentials were absent for a short time. Not until the 16th second of apnea did single discharges begin to appear, at first in the expiratory muscle, and soon after in the inspiratory muscles. The frequency and amplitude of the potentials rose quickly and simultaneously in both the inspiratory and expiratory muscles, in the form of a continuous stream of impulses. As soon as the apnea ended, the reciprocal character of the coordination between inspiration and expiration was at once restored and periodic waves appeared corresponding on the pneumogram.

An EMG of a different character was observed in those persons whose pneumogram during the second phase of apnea showed periodic waves corresponding to the involuntary movements of the respiratory muscles. In Fig. 1b, is shown a typical EMG of this type of apnea.

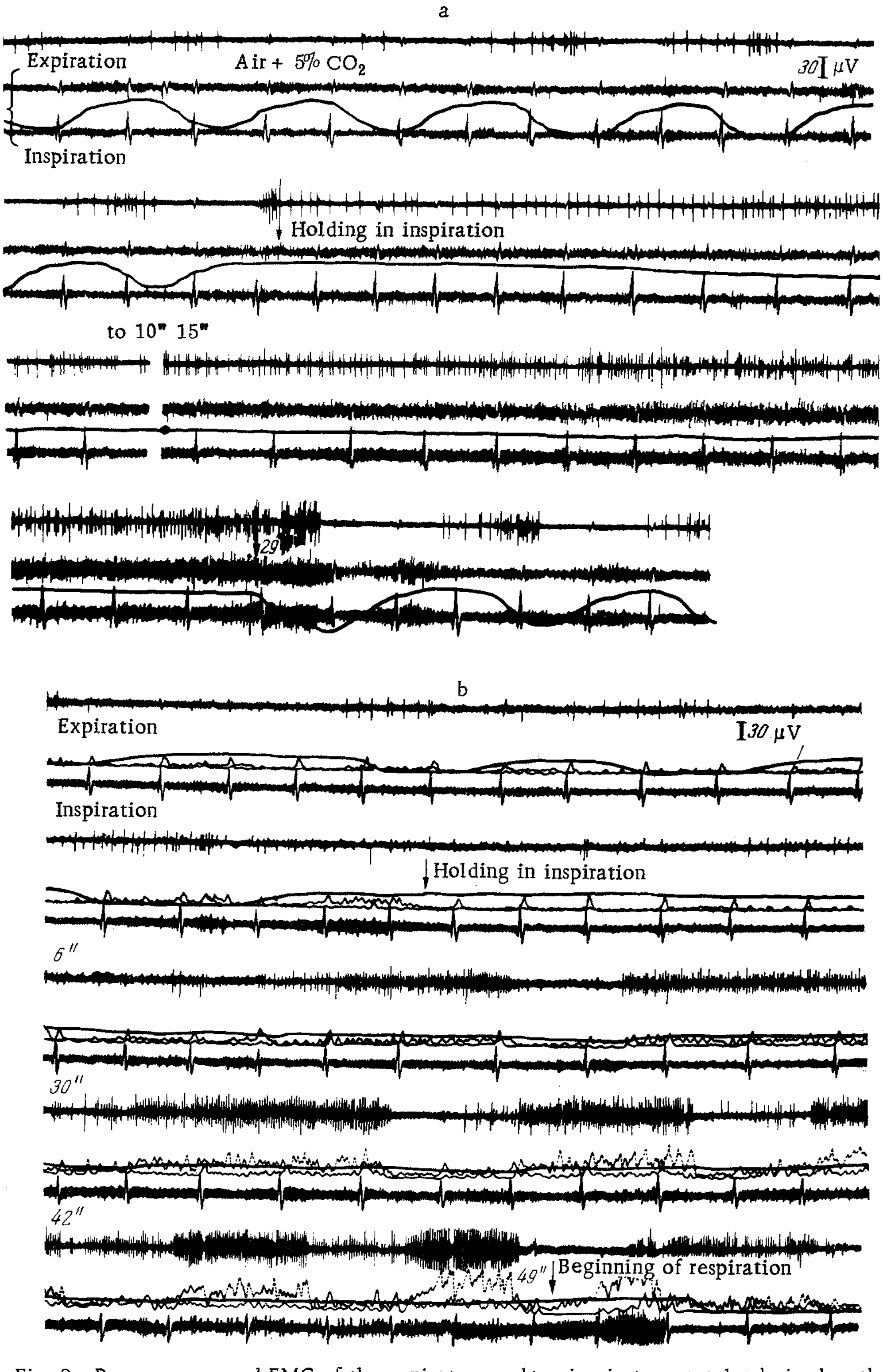

Fig. 2. Pneumogram and EMG of the expiratory and two inspiratory muscles during breath holding in inspiration by subject P. (a): pneumogram, EMG of expiratory and inspiratory muscles and integrated electrical activity of these muscles in the form of two curves during breath holding in inspiration by subject M. (b).

At the beginning of breath holding action potentials likewise were absent, but at the 19th second of continuing apnea a rhythmic inspiratory and expiratory electrical activity reappeared. The impulses followed one another in volleys, reciprocally, corresponding to the phases of "inspiration" and "expiration." As the apnea continued the

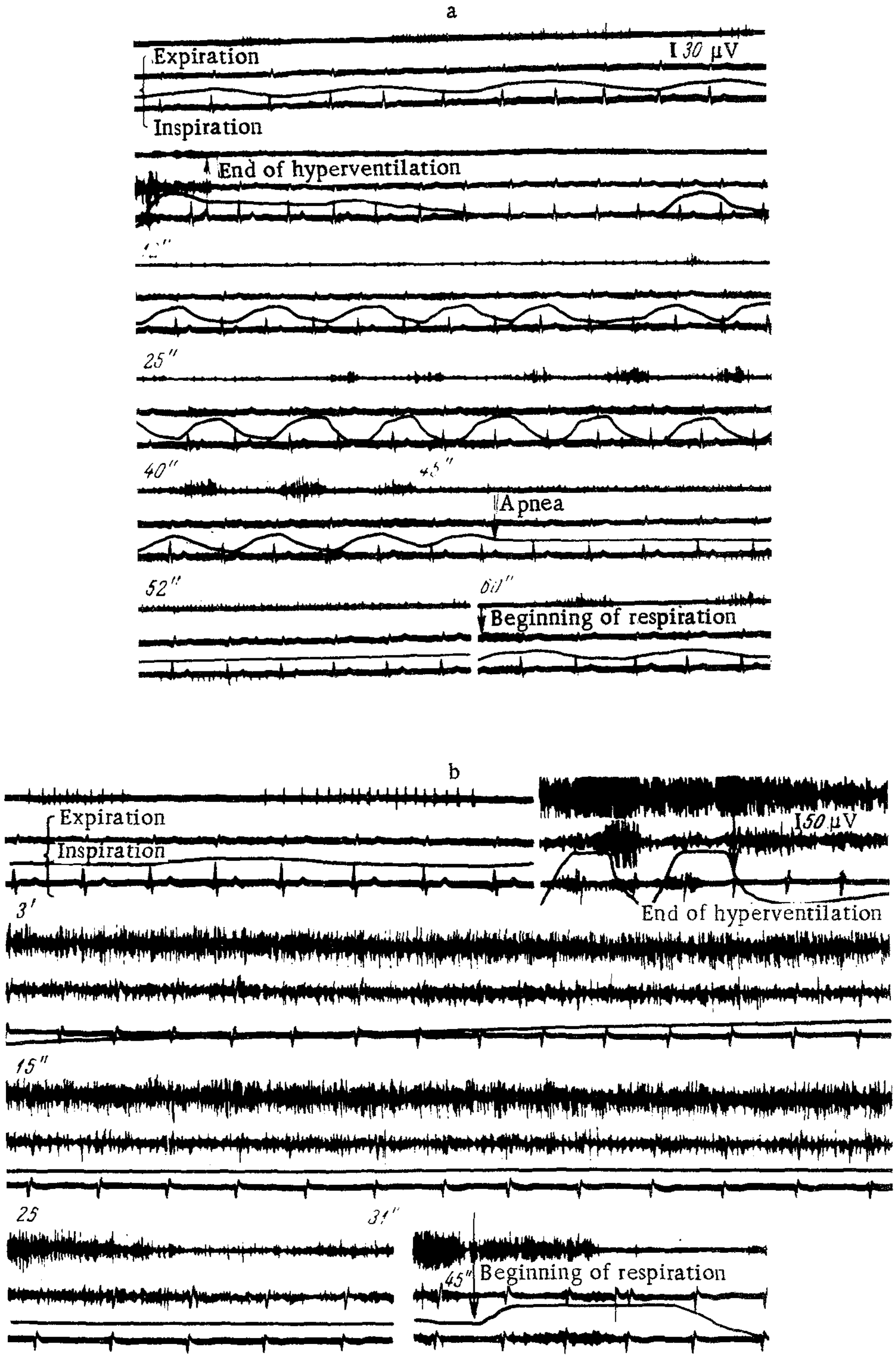

Fig. 3. Pneumogram and EMG of the expiratory and two inspiratory muscles during involuntary apnea: after voluntary, and then after involuntary hyperventilation in subject P. (a); after voluntary hyperventilation for 3 min in subject P. (b).

amplitude and frequency of the potentials increased. Synchronously with the increasing electrical activity in the inspiratory and expiratory muscles, the respiratory movements recorded on the pneumogram also became stronger.

Since the "respiratory movements" during apnea resulted from a change in the position of the diaphragm when the rima glottidis was closed, this led to a mechanical displacement of the "phases of respiration" on the pneumogram: inspiration corresponded to the electrical activity in the expiratory muscles, and "expiration" to the electrical activity in the inspiratory muscles. With the resumption of respiration the order of the phases on the pneumogram and EMG became coordinated.

To obtain a precise background of electrical activity of the respiratory muscles and hence, by comparison with it, to judge the changes developing during voluntary apnea, the subjects were instructed to breathe a gas mixture (air + 5% CO_2). The pulmonary ventilation increased during the period of breathing the gas mixture from 7 to 14 liter/min. Breath holding was then carried out against this background in inspiration and expiration. As is clear from Fig. 2a, during breath holding by subject P a continuous flow of impulses was observed simultaneously in the inspiratory and expiratory muscles from the very beginning of apnea.

The increasing inspiratory and expiratory electrical activity was not accompanied by movement of the respiratory muscles, and as in Fig. 1a, a smooth line was recorded on the pneumogram until the end of the period of apnea. With the resumption of respiration the reciprocal character of the coordination of inspiration and expiration was restored, corresponding to the periodic waves of the pneumogram.

The EMG of the inspiratory and expiratory muscles of subject M during the period of apnea after breathing the gas mixture (air + 5% CO_2) was different in character. As is shown in Fig. 2b, at the beginning of breath holding no action potentials were present, but at the 7th second of apnea the flow of impulses was restored, at first in the expiratory, and then in the inspiratory muscle. The impulses followed each other rhythmically, in volleys, and increased in amplitude and frequency (the integrated electrical activity of these muscles is shown in Fig. 2b, in the form of two curves). The renewed electrical activity in the inspiratory and expiratory muscles was reflected in the pneumogram in the form of periodic waves corresponding to "inspiration" and "expiration."

Hence, the dynamics of the electrical activity in the inspiratory and expiratory muscles during apnea preceded by inhalation of a gas mixture (air + 5% CO_2) differed from that during apnea in ordinary conditions by the intensity of the electrical activity in these muscles. The individual character of the electrical impulses in the inspiratory and expiratory muscles remained unchanged in all the subjects tested. Our results agree with those obtained by Agostoni [11], who recorded action potentials from the diaphragm and the oblique muscle of the abdomen during apnea.

The dynamics of the electrical activity in the inspiratory and expiratory muscles during voluntary breath holding is a more accurate indicator of the functional state of the respiratory center during apnea than the pneumogram. It was found, for instance, that absence of respiratory oscillations on the pneumogram throughout the period of apnea does not imply absence of action potentials in the respiratory muscles. A smooth line on the pneumogram from the beginning to the end of apnea likewise does not imply absence of excitation in the respiratory center.

Analysis of the electromyographic data showed that voluntary apnea possesses two phases, regardless of how it is reflected on the pneumogram. In the first phase the electrical activity in the inspiratory and expiratory muscles is completely suppressed, and action potentials are absent – the phase of central inhibition of the activity of the respiratory center.

In the second phase the voluntary apnea, in some subjects the increasing excitation in the inspiratory and expiratory centers is manifested by renewal of the reciprocal electrical activity in the inspiratory and expiratory muscles and by the involuntary contraction of these muscles corresponding to the phases of "inspiration" and "expiration." This indicates that in these cases the rhythmic character of the automatism of the respiratory center is not suppressed.

In the other subjects investigated, in the second phase of apnea the rhythmic character of the automatism of the respiratory center was disturbed, but its inspiratory and expiratory zones were in a state of progressively increasing, continuous excitation. This excitation was transmitted simultaneously to the inspiratory and expiratory muscles and was manifested by the static tone of these muscles.

Attempts were subsequently made to examine the changes in the electrical activity in the inspiratory and expiratory muscles during involuntary apnea. In man, involuntary apnea arises rarely after voluntary forced ventilation and the development of hypocapnia. Often, in fact, the converse is true and after voluntary hyperventilation an involuntary hypercapnia is observed. This was observed in one of our subjects. After hyperventilation for 3 min, an involuntary hypercapnia developed in subject P, lasting 45 sec and terminating in expiratory apnea (Fig. 3a). During apnea, the electrical activity in the inspiratory and expiratory muscles did not disappear, but impulses followed one another without interruption until respiration was resumed.

In subject P., after forced hyperventilation for 3 min apnea developed and lasted for 45 sec (Fig. 3b). From beginning to end of apnea strong, continuous potentials were recorded in the intercostal and external oblique muscles.

With the resumption of respiration, the reciprocal character of the coordination of inspiration and expiration was immediately restored.

Hence, the development of hypocapnia during involuntary apnea led to a disturbance of the rhythmic activity of the respiratory center and caused increased and continuous electrical activity of the respiratory muscles. The latter demonstrates that the respiratory center during involuntary apnea was in a state of continuous excitation. The electromyographic data obtained in experiments on human subjects are in full agreement with the results previously obtained by M. E. Marshak and T. A. Maeva [4] in experiments on animals. These workers showed that apnea after hyperventilation does not imply absence of excitation in the respiratory center, as it has been customary to accept, but, on the contrary, absence of inhibition therein.

Hence the results of experiments conducted on both animals and man indicate the important role of CO_2 in the production of the various phases of the respiratory act.

SUMMARY

A study was made of the dynamics of electrical activity in the inspiratory and expiratory muscles during voluntary and involuntary breath holding in 4 persons. However it appeared on the pneumogram, voluntary apnea was biphasic. During the first phase the electrical activity was completely suppressed in both the inspiratory and expiratory muscles and action potentials were absent. In some persons investigated the second phase of voluntary apnea was attended by restoration of the rhythmic electrical activity in both the inspiratory and expiratory muscles and involuntary muscular movements appeared. Other persons, investigated during the second phase of apnea, presented disturbed rhythmic automatism of the respiratory center. Its increasing excitation was transmitted simultaneously to the inspiratory and expiratory muscles, being manifested in their static tension.

In involuntary apnea, against the background of marked hypocapnia the disturbed rhythmical activity of the respiratory center continuously gave rise to intensified electrical activity in the respiratory muscles. This indicates that during involuntary apnea the respiratory center is under constant excitation.

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