CORRELATION ANALYSIS OF ELECTRICAL ACTIVITY OF HUMAN MUSCLES OF RESPIRATION

L. E. Sapuntsov

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A special analog computer was used for correlation analysis of electromyograms recorded from the external intercostal muscles. The results indicate a special (synchronized) system of operation of the motor units of the respiratory muscles which differs from the program of operation of other skeletal muscles.

Although classical mathematical analysis has demonstrated the irregularity of most physiological processes, some of their statistical properties are nevertheless stable in time, as can be shown, in particular, by correlation analysis. In the field of medicine this method was first used at the beginning of the 1950s to analyze encephalograms [4]. It was shown in 1963 that if electromyograms (EMGs) are recorded from two symmetrical muscles of opposite limbs, the correlation function is virtually zero [2].

Because of the unique character of the supraspinal innervation of the intercostal muscles and preliminary findings regarding their electrical activity [3], it was decided to make a systematic correlation analysis of the EMGs of the respiratory muscles.

Interference EMGs were recorded from the external intercostal muscles in man using bipolar surface electrodes measuring 12 × 6 cm, located 20 mm apart. The skin was first treated with alcohol and ether, the electrodes were then fixed to it with adhesive plaster, and secured in position by a firm rubber belt. The electrodes were coated with a special electrolytic paste to ensure reliable electrical contact between them and the skin. Two EMGs were recorded simultaneously, either in the 6th and 8th intercostal spaces on the right side or in the 8th intercostal spaces on the right and left sides. Healthy young subjects aged from 17 to 30 years were used for the tests.

Muscle action potentials were amplified by a "Disa" electromyograph and recorded simultaneously on photographic paper and, by means of a two-channel tape recorder, on magnetic tape. By the use of the tape recorder the data could be fed into a correlometer without the need for conversion in any form. Electrical activity of the muscles recorded from healthy subjects during quiet breathing is low, and when it is recorded the electrical activity of the heart is superposed on it and must be excluded for computer analysis of the data. A special device was therefore used which would stop the recording of the EMG temporarily during the QRS complex of the ECG. The recording was made only during inspiration, and discontinued during expiration.

After the recording had been made on magnetic tape, the tape was joined into a ring and reproduced repeatedly to obtain values of the correlation function for different values of the delay time τ. The correlation functions were calculated on a correlometer designed by the All-Union Research Institute of Medical Instrumentation [1]. The following formula was used for the analysis:

$$R(\tau) = \frac{1}{T}\int_0^T f_1(t)\cdot f_2(t-\tau)\,dt,$$

where $f_1(t)$ and $f_2(t)$ are the recorded EMGs. The integration time T was 20 or 30 sec.

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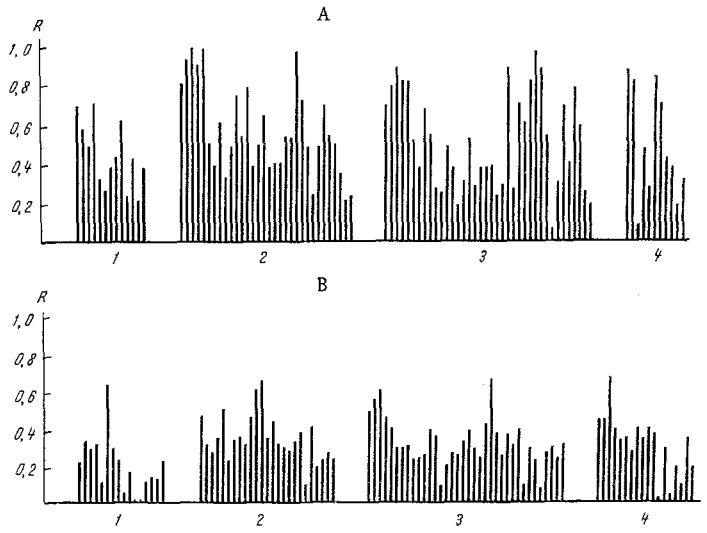

Fig. 1. Coefficients of cross-correlation during recording from right side of chest (A) and from both sides (B): 1) during quiet breathing; 2) during inhalation of mixture of air with 5-6% CO_2; 3) during voluntary forced breathing; 4) during breathing with resistance to inspiration.

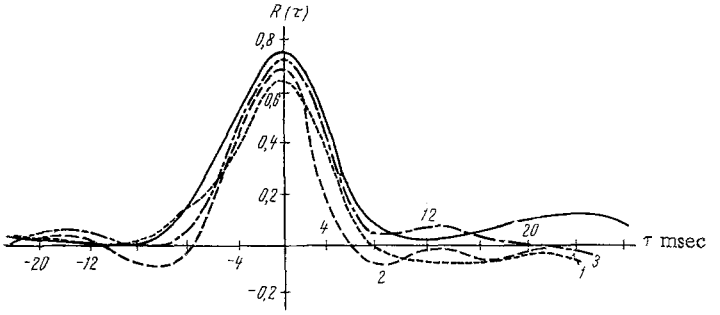

Fig. 2. Cross-correlation functions of EMGs of intercostal muscles in 6th and 8th intercostal spaces on the right side of the chest during quiet breathing (1), breathing with resistance to inspiration (2), voluntary hyperventilation (3), and inhalation of a mixture of air with 6% CO_2 (4).

Besides the tests during quiet breathing, recordings were also made during three types of forced breathing: 1) breathing a mixture of air with 5-6% carbon dioxide; 2) voluntary forced breathing; 3) breathing with resistance to inspiration.

EXPERIMENTAL RESULTS AND DISCUSSION

The correlation functions obtained in 187 tests can be represented as the products of a cosine curve and an exponential with various decay times. The maximum value of the cross-correlation function (the coefficient of cross-correlation R) reflects the degree of association between the processes studied, while the shift of the maximum along the $\tau = 0$ axis shows the time by which one process is delayed relative to the other.

It is clear from Fig. 1, which shows the values of R obtained in different tests, that R is quite high. For readings from the right side of the chest, R = 0.72 during quiet breathing, rising to 1.00 sometimes during tests with forced breathing (Fig. 1A). In recordings from both sides the value of R was slightly lower (0.64 during quiet breathing and 0.76 during forced breathing; Fig. 1B). Typical correlogram curves obtained in different tests are shown in Fig. 2.

TABLE 1. Mean Values of Coefficients of Cross-Correlation in Different Types of Investigations (M±m)

Conditions of test	Recording from both sides of chest		Recording from one side of chest	
	number of tests	R	number of tests	R
Quiet breathing	16	0,21±0,04	13	0,46±0,05
Voluntary hyperventilation	35	0,33±0,02	37	0,52±0,04
Inhalation of mixture of air with 5-6% CO_2	25	0,35±0,02	32	0,58±0,04
Resistance to inspiration	18	0,32±0,03	11	0,51±0,09

It follows from the results in Table 1 that marked correlation exists between the EMGs of the intercostal muscles. The coefficients of cross-correlation were significantly higher ($P_0 < 0.01$) with recordings from one side of the chest than in those from both sides. The maximum values of the cross-correlation functions were observed when $\tau = 0$, and lower values were obtained even with small values of τ.

The presence of high coefficients of cross-correlation for the work of the intercostal muscles is evidence of the high level of synchronization of activity of the various motor units composing these muscles. Synchronization of muscles of one side was more marked than synchronization of muscles on different sides of the chest. In every case synchronization of the electrical activity of the different motor units took place without a time shift.

It will be recalled that in Person's investigations on the limb muscles [2], no synchronization was observed. In the present investigations, results indicating a unique pattern of work of the respiratory muscles were thus obtained.

Such striking differences called for additional control tests to rule out any possible artefacts.

The use of a device to stop the recording of the EMG temporarily during waves of the ECG could introduce artefacts due to the presence of a nonzero R. This is because both channels are disconnected simultaneously, and in the event of transitional processes, the correlation of these processes as they accumulate on the myogram will be recorded.

Person's investigations on the biceps brachii muscle [2] were repeated, but the recording was stopped in expiration and also during waves of the ECG, just as in the principal experiments. The cross-correlation functions obtained did not deviate from the zero line by more than the permissible error of the instruments used. The disconnecting device was thus not the source of interference which could have changed the type of correlation function.

If a pair of electrodes is placed close together, electrical activity from the same motor units can be induced in them, and this will subsequently give high values of R. To test the effect of this factor in the present investigations, a correlation analysis was made of potentials generated during voluntary contraction of the pectoralis major muscles. These muscles were chosen because, like the intercostal muscles, they are situated on both sides of the chest and at about the same distance from the heart. During the investigation, as in all other cases, the recording was discontinued during the ECG waves and during expiration. The values of the cross-correlation functions obtained in these tests were virtually equal to zero.

These control experiments indicate that when the EMG of the respiratory muscles was recorded by this particular technique, no instrumental interference distorting the results of the test was introduced.

The values obtained for the cross-correlation functions of the external intercostal muscles differed from values obtained for the limb muscles and indicate a high level of synchronization of the activity of their motor units.

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