Role of Volume-Conductor Properties of Muscles in the Formation of Evoked Contractions during Stimulating Electrical Impedance Myography

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Experiments on the preparation of frog sartorius muscle showed that electrical impedance myogram of evoked muscle contractions is the sum of electric processes accompanying contraction of some muscle fibers or muscle regions. Inverted muscle response probably results from heterotopic excitation of distant muscle regions under conditions of reduced excitability of muscle fibers adjacent to the electrode. During centrifugal propagation of contractions, especially in altered muscles, the negative wave on the myogram corresponding to impedance decrease is sometimes followed by a positive wave. The possibility for recording of heterotopic contractions indicates that the impedance of the electrode-muscle interface produces no considerable effects on the shape of electrical impedance myogram. These results hold much promise for the diagnostics of neuromuscular diseases.

Key Words: *stimulating electrical impedance myography; induced contractions; volume-conductor properties; impedance of the electrode-muscle interface; animals*

It was shown that stimulating electrical impedance myography can be used to study dysfunction of the muscle system, including suprasynaptic, synaptic, and subsynaptic disorders of the motor unit [1,2]. This method is based on visualization of electric processes accompanying and preceding contractions. Direct stimulation of the muscle and recording of evoked contractions (EC) are performed using the same needle electrode.

For the most part, muscle contractions are accompanied by a decrease in the electrical impedance recorded as the negative half-wave. Sometimes positive or biphasic EC is recorded due to tonic contraction or contracture of muscle fibers [11]. However, our studies on humans and warm-blooded animals revealed that ischemic contracture can be accompanied by decreased amplitude or absence, but not inversion of the response. Moreover, positive response is also observed in intact muscles.

The inversion of muscle responses can be due to unpredictable changes in the impedance of the electrode-muscle interface and centrifugal propagation of contraction along the muscle possessing the volume-conductor properties.

The physiological nature of inverted muscle response recorded during electrical impedance myography was analyzed to estimate the effects of volume-conductor properties of muscles and impedance of the electrode-muscle interface on electrical parameters of EC.

Here we studied the role of localization of muscle contractions in relation to the position of the active electrode: nomotopic (NEC) and heterotopic (HEC) evoked contractions recorded at the point of the electrode and at some distance from it, respectively). We also examined the effects of ion channel blockade and disturbances in myoneural synaptic transmission on the pattern of electrical impedance myogram. The role of summation of electric processes induced by NEC

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and HEC in the formation of negative and positive waves on electrical impedance myogram was evaluated.

MATERIALS AND METHODS

Experiments were performed on frog sartorius muscle with preserved innervation and blood flow [3]. NEC were produced by stimulation of the muscle with threshold and suprathreshold electric currents (1 Hz, 0.01 msec) delivered via a needle electrode. To induce HEC, filter paper (1 mm^2) soaked with 2% hexenal or novocain was placed (under a microscope) on the muscle near the contact with needle electrode. After the disappearance of contractile responses, the current strength was gradually increased to induce contractions of distant fibers of the same or adjacent muscles. In some experiments an additional electrical stimulator was used. In this case, 2 recording systems had common reference electrode.

During the blockade of ion channels, fatigue, or hypoxia of the muscle, focuses of heterotopic excitation are formed due to leakage of stimulating current to adjacent motor units, because nonmyelinated nerve fibers in this region are more excitable than muscles. To confirm this assumption, 0.2% fluxedil, a competitive blocker of neuromuscular transmission, was applied to HEC region.

Summation of electric processes accompanying muscle contraction was studied by decreasing the interval between 2 contractions in the same or various muscles induced by direct stimulation and having the same or opposite directionality.

The results were analyzed by χ^2-test. All presented data are statistically significant.

RESULTS

A gradual increase in the amplitude of stimulating current after the blockade of contractile responses induced HEC (Fig. 1) and was accompanied by inversion of muscle responses. These waves corresponded to increased resistance to high-frequency currents in the contracting muscle.

In the majority of cases, HEC were suppressed by the blockade of myoneural synapses.

When the interval between 2 EC in the same muscle or in adjacent muscles decreased to zero or became very short, we observed algebraic summation of 2 electric processes in electrical impedance myogram: subtraction of the amplitudes of opposite processes and addition of amplitudes of codirected processes (Fig. 2).

Combination of various phases in electrical impedance myogram during summation yielded a biphasic response. If the distance between electrodes was small, heterotopic contractions were recorded by the 1st electrode as monophasic negative waves. Thus, electrical impedance myogram reflects the summation of electric processes in muscle fibers. In this case, the muscle displays volume-conductor properties.

In pathologically altered muscles, the positive phase of the contractile response can be due to heterotopic excitation of distant muscle regions against the background of reduced excitability of muscle fibers adjacent to the electrode during hypoxia, atrophy, or degeneration. Centrifugal propagation of contractions, in particular, in altered muscles, produced a positive half-wave after negative wave on the myogram.

Recording of electrical impedance myogram by an electrode positioned at a distance from the contracting region in the same muscle, as well as the recording of contractions induced by stimulation of other muscle,

Fig. 1. Evoked contractions during blockade of synaptic transmission and suppressed excitability of muscle fibers (paper speed 5 mm/sec). *1*) heterotopic muscle responses recorded after excitation of the nearest synaptic zone with stimulating current loops. Needle electrode is placed in nerve-free region of the sartorius muscle; local and heterotopic contractions formed with the increase in current strength are shown on the left and right side of figure, respectively; *2*) application of fluxedil to the region of heterotopic contractions; suppression of positive responses; *3*) novocain-induced suppression of excitability of muscle fibers adjacent to the electrode; appearance of heterotopic responses; *4*) at the beginning: reactions similar to those in (*3*); recording speed 25 mm/sec. Then: periodic activation of heterotopic focuses of excitation, local responses; recording speed 5 mm/sec. Here and in Fig. 2: stimulation frequency 1 Hz, pulse duration 0.01 ms.

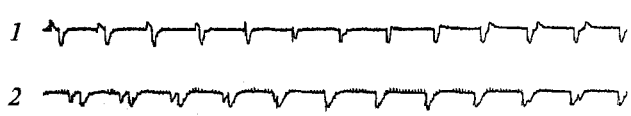

Fig. 2. Summation of contractile responses; paper speed 50 mm/sec. *1*) superposition of heterotopic (positive wave) and nomotopic (negative wave) contractions; decreased total amplitude during complete superposition and biphasic response during partial superposition of contractions; *2*) convergence of 2 stimulating electrodes; codirected nomo- and heterotopic responses; summation of the amplitude during complete superposition.

indicated that the electrical equivalent of contractions evoked by direct stimulation reflects the properties of muscle tissue and is not associated with changes in the impedance of the electrode-muscle interface.

Hence, inverted, biphasic, and alternating (by the amplitude and duration) muscle responses visualized by stimulating electrical impedance myography can be caused by denervation, disturbances in myoneural synaptic transmission, acute and chronic ischemia of muscles, and other factors. These data will improve the diagnostics of damages to the peripheral neuromuscular apparatus.

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