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Acousticmyogram Measured with Electrostimulation During Muscle Fatigue

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SYNOPSIS

The acousticmyogram (AMG) is a mechanical phenomenon recorded at the surface of an active muscle. It is used to monitor force production, fatigue, and contractile properties of muscle. In this study, the new electrode with accelerometer for electrostimulation and acoustic detection. It consists of Ag-AgCl active electrode and solid-gel annular ground, and a very light piezoresistive accelerometer. The recorded AMG waveform depends on the pulse amplitude and duration of stimulation current and its lag from the electroatimulation is about 7 ms. The strength-duration (S-D) curve (the threshold current for stimulation vs. pulse duration) describes the excitability of muscle. The left forearm is electrostimulated by using the same electrode and the muscle vibration (AMG) is recorded with accelerometer. During the muscle fatigue, the S-D curve changes and the current threshold increases under the same pulse duration. The rheobase of S-D curve increases gradually but the chronaxie hardly changes during muscle fatigue.

1. INTRODUCTION

Muscular sound is a mechanical phenomenon detectable at the surface of an active muscle. The phenomenon of sound emission from contracting muscle has been recognized since early in the nineteenth century. Recently this signal has attractive for monitoring the mechanical aspects of muscle contraction, because of the availability of reliable electronic sensors (piezoelectric transducers, condenser microphones, piezoceramic membranes, or accelerometers) and of computerized signal processing techniques (1). The signal detected at the muscle surface has been given different terms by different researchers. These terms are acousticmyogram, phonomyogram, soundmyogram, or vibromyogram. The former three terms refer to the recording of the sound emitted by the active muscle and the latter is considered as the source of the skin oscillations. In this study, we use the term of acousticmyogram (AMG).

The physiologic mechanism of the AMG is not well understood. Sounds emitted by contracting skeletal muscle have been used *in vivo* to monitor force production, fatigue, and contractile properties of muscle (2). Individual motor units can be resolved acoustically, and the sounds have diagnostic potential in pediatric neuromuscular disease. The mechanism of sound production is lateral movement of the whole muscle, and the sounds are linearly related to lateral acceleration of the muscle *in vitro*.

This paper deals with the fatigue influence on the AMG properties evoked by electrostimulation. A more detailed investigation of the strength-duration curve for chronaxie is also carried out during sustained isometric contraction.

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2. ELECTROSTIMULATION

2.1 Stimulation waveform

Though stimulation waveforms such as decaying exponentials, sinewaves or trianglewaves have been used, the sensation caused by these pulses is imperceptible (3). In this study, a negative rectangular pulse is used for electrostimulation. Monophasic pulse, however, results in charge accumulation at the electrode-muscle interface. As the charge accumulation by the negative pulse in this electrostimulation is performed for a short duration, the sensation is not very painful. The stimulation pulses from the drivers are with a pulse duration of 0.02 – 100 ms and an interval of 1 s. The amplitude of stimulation current increases gradually until it yields a muscle acoustic signal, which is detected with accelerometer placed on a stimulation electrode. Fig.1 shows the basic current waveform of stimulation pulse. The used current driver apparatus for electrostimulation is CHRONAXIE (CX-2, OG GIKEN Co. Ltd.).

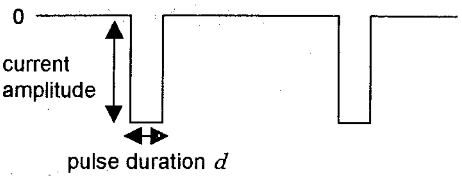


Fig.1 Current pulse of electrostimulation.

2.2 Stimulation electrode

We have developed a new electrode with accelerometer for electrostimulation and acoustic detection. The electrode consists of Ag-AgCl active electrode with a solid-gel and annular large ground shown in Fig.2. The active electrode is 10 mm in diameter and 5 mm apart from the ground. The annular electrode limits the spread of current to the surface of the skin and does not stimulate the other deeper muscle. A solid-gel electrode pad for low-frequency electro-therapy apparatus (OMRON, HV-BIGPAD) is adapted to the annular electrode. We use the flexor carpi radialis of left forearm as the location of stimulation. The active electrode contacts with a motor point of the muscle. The pricking pain can be reduced by ensuring that the electrode has adequate contact with the skin (1). First we have wash the skin surface so that it reduces its dry resistance and current density through the skin. Then we achieved much more comfortable stimulation.

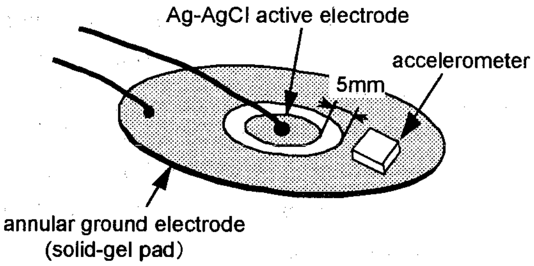


Fig.2 Stimulation electrode.

To record the acousticmyogram, a very light accelerometer (IC SENSORS, 3031 002) is applied to the stimulation electrode with the use of a double-stick tape. It is a piezo-resistive transducer and its frequency response is DC to 2540 Hz. The use of larger piezoelectric contact sensor restricts an acoustic response because of the ratio between its mass and that of the muscle investigated. The sensor mass must not induce the distortion in the muscle surface. It also varies the frequency response of the sensor because of mechanical coupling to the muscle surface. The transduced or electrical signals were led to an electronic amplifying system with a filter bandpass of DC-30 Hz.

2.3 Static exercise

In order to examine the possibility of monitoring muscle fatigue by the analysis of acousticmyogram detected by the accelerometer, the static exercise of holding a weight of 1 kg within 30 min is applied to the left forearm shown in Fig.3. The arm was held close to the body with the elbow flexed at 120 degrees. The forearm was supinated and parallel to the floor. The wrist joint was at a 180-degree position. With the hand open and the palm facing up, the weight was supported by the hand. Accordingly, the flexor carpi radialis muscle was isometrically contracting against a steady load. 5 % of the maximal voluntary contraction (MVC). The subject was encouraged to relax, not to tense other muscle groups, and remain immobile as much as possible during data acquisition. The acousticmyogram is measured on the forearm at rest and during exhausting contraction, when the motor point of flexor carpi radialis of forearm is electrostimulated.

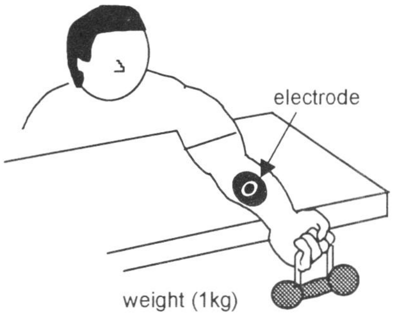


Fig.3 Static exercise.

3. MEASUREMENT OF ACOUSTICMYOGRAM

3.1 Electrostimulation and AMG

When the pulse amplitude of stimulation current increases gradually, the muscle contraction begins and the acousticmyogram appears shown in Fig.4 at about 7 s, 2 mA. The current pulse is s negative rectangular pulse, the pulse duration is 1 ms, and the pulse repetition rate is 5 Hz. The AMG is recorded on the flexor carpi radialis muscle of left forearm by using the accelerometer.

Fig.5 shows graphically the evoked AMG spectrum as a function of time when the current amplitude increases. The spectrum had two prominent peaks occurring at 10 and 15 Hz. The analysis of STFT (short time Fourier transform algorithm) is carried out with 128 data points by shifting 64 points. This analysis is possible to avoid the effect of an involuntary physiological tremor at times.

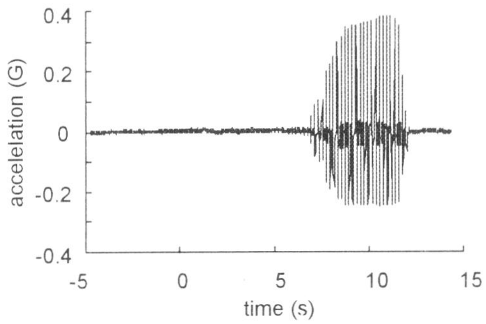


Fig. 4 Acousticmyogram in case of increasing the pulse amplitude.

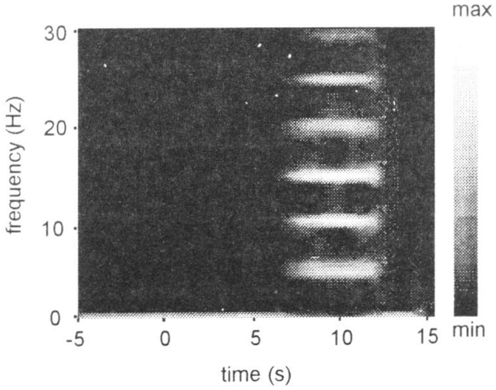


Fig.5 AMG spectrum in case of increasing the pulse amplitude.

3.2 Acceleration waveform of AMG

Fig. 6 shows the unidirectional current pulse for electrostimulation and the AMG waveform evoked by it. The pulse duration is 1ms, the repetition rate is 1Hz, and the current amplitude of negative pulse is 4.72mA. The recorded AMG lag from the electrostimulation is about 7 ms. Two AMG waveforms are recorded on the flexor carpi radialis muscle in relax and in sustained isometric contraction, respectively. Muscle twitches produce a biphasic acoustic waveform that rise sharply from the baseline, reaches a peak, slowly declines, crosses the baseline, and then returns to the baseline. This slow, biphasic waveform has small, higher frequency oscillations superimposed on it (4-6). The acoustic waveform has two components – a large, low-frequency (<10Hz), biphasic waveform and smaller, higher frequency (>25 Hz), superimposed oscillation. The large, slow muscle movement is due to bulk

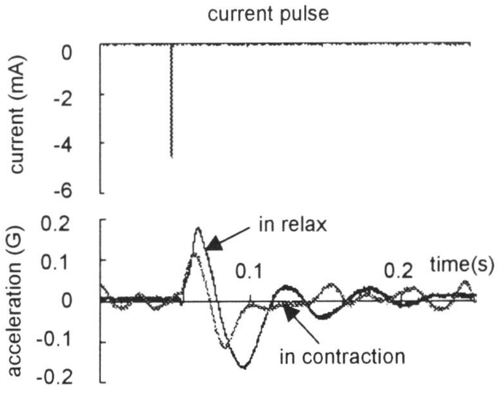
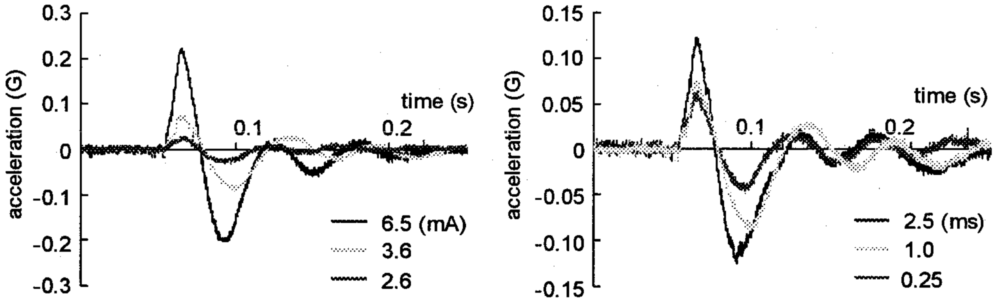


Fig.6 AMG waveform at the electrostimulation.

movement of the muscle and may be simply due to asymmetrical distribution of muscle fibers and nonsimultaneous contraction of fibers. As the muscle is electrostimulated, the muscle belly moves away from the accelerometer, producing a downward deflection of the waveform (a positive acceleration). During relaxation after electrostimulation, the muscle belly moves toward the accelerometer, producing an upward deflection. The smaller, higher frequency oscillations are due to resonant vibrations of the muscle and they appear to represent the natural mechanical response of the muscle to a step function input. The resonant frequency is related to stiffness, mass, length, and viscosity of the muscle and the surrounding medium. During an isometric twitch, in sustained isometric contraction, however, the change in muscle stiffness is much greater than the change in any of the other parameters and may dominate the change in resonant frequency. As the resonant frequency is proportional to the stiffness of the muscle, the resonant frequency becomes higher in a muscle contraction and the fundamental period of AMG waveform decreases.

Fig.7(a) and (b) show AMG waveforms evoked by the stimulation current with pulse amplitude 2.6, 3.6, 6.5 mA and pulse duration of 0.25, 1.0, 2.5 ms, respectively. The AMG waveforms are recorded on the same muscle at rest. The acoustic signal is proportional to the pulse amplitude shown in the figure (a). In case of pulse duration shown in the figure (b), it is found that the acoustic signal period changes. The muscle stiffness which influences the resonant frequency of muscle may change due to the pulse duration.



(a) pulse amplitude (b) pulse duration

Fig.7 AMG waveforms in case of different pulse duration and amplitude.

4. CHRONAXIE AND MUSCLE FATIGUE

4.1 Strength-Duration curve

The strength-duration curve is a plot of the lowest (threshold) current (*i*) required for stimulation vs. pulse duration (*d*); it forms the basis for describing the excitability of a given tissue. It is extremely useful in all manner of studies in which excitable tissues are stimulated because it describes the manner in which the current required is changed when the pulse duration is changed. Moreover, it can be used to determine the charge and energy-duration relationships (7). Fig. 8 shows the strength-duration (S-D) curve which is hyperbolic-like, with the current required increasing with decreasing pulse duration; the expression (Weiss-Lapicque law) for the S-D curve is

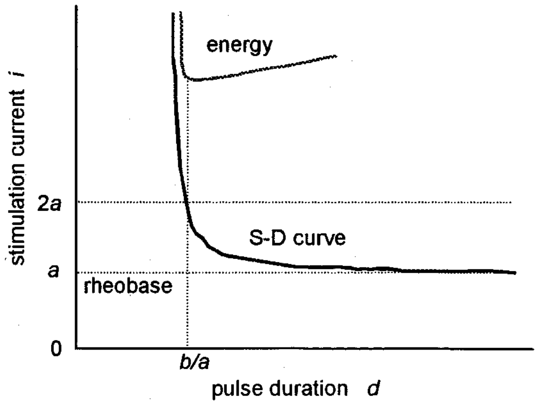


Fig.8 Strength-duration curve.

$$i = a + b / d \quad (1)$$

$$\tau_c = b / a \quad (2)$$

where b is a constant that depend on the type of excitable tissue. The long-duration asymptote a and a special duration τ_c (the chronaxie), where the current for excitation is twice the rheobasic value. The chronaxie is the factor that describes where the strength-duration curve rises with decreasing stimulus duration. In practice, it is usually difficult to determine the chronaxie because it is not easy to determine the long-duration current asymptote, because with very long-duration current pulses the excitability of tissue is not stable. In general the value of chronaxie in skeletal muscle is 0.1 to 0.3 (ms). In this study, the S-D curve is used for an evaluation of muscle fatigue (8).

4.2 S-D curve and fatigue

In order to evaluate muscle fatigue, the S-D curve was measured at left forearm during the sustained isometric contraction as mentioned above, every 10 min for 50 min. The subject held a weight of 1kg within 30 min and afterwards the weight was removed from the palm. The forearm was kept in the same posture at rest. The current amplitude for electrostimulation increases gradually at the pulse duration of 0.02, 0.1, and 1 ms. The muscle vibration starting that indicates the current threshold is detected by using the accelerometer of the above electrode.

Fig.9 shows the changes of S-D curve during muscle fatigue, which is drawn by fitting a least squares regression curve of Eqn.(1) to the strength-duration data. The vertical axis is normalized with the rheobase of the S-D curve at 0 min (just after). When the muscle became fatigued gradually, the current threshold increases under the same pulse duration (after 10, 20, 30 min), and it returns slowly to the initial amplitude after removing the weight (after 40, 50 min).

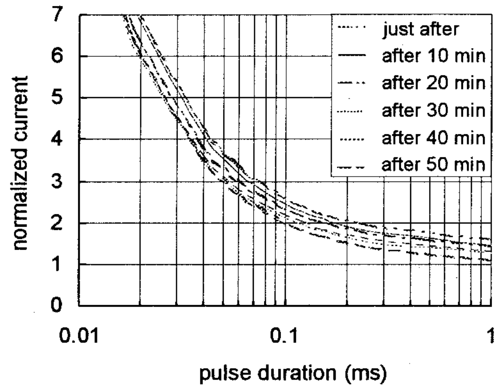


Fig.9 S-D curves during muscle fatigue.

4.3 Discussion

Fig. 10 shows the changes of a, b, τ_c in the S-D curve. Though the rheobase a and b increases gradually during muscle fatigue in sustained contraction, there is not very much change in the chronaxie τ_c. As the chronaxie describes the excitability of muscle, it may be considered that the muscle of forearm did not become fatigued in this sustained contraction for 30min. In this experiment, the subject felt fatigued a little during static exercise. Generally in clinical rehabilitation, the S-D curve is examined under reducing the muscle fatigue. We should recognize properly that the S-D curve depends on the muscle fatigue and the chronaxie hardly changes under moderate exercise.

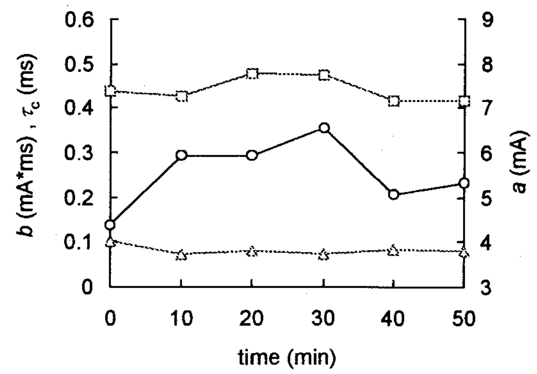


Fig.10 a,b, τ_c changes during muscle fatigue.

During sustained isometric contractions, the development of fatigue influences the motor unit activation pattern by changing the firing rate or the degree of recruitment and synchronization of the motor unit. A reliable description of these phenomena can be obtained only by means of needle EMG and/or by sophisticated decomposition techniques, which isolate and track the motor unit action potential throughout the effort [(9)].

5. CONCLUSIONS

In this study, the new electrode with accelerometer is developed for electrostimulation and detecting the acousticmyogram. The recorded AMG depends on pulse amplitude and duration of stimulation current. The S-D curve is also measured at left forearm during sustained isometric contraction. The rheobase depends on muscle fatigue but the chronaxie hardly changes in this exercise for 30min.

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