INDEPENDENCE OF WORKING HYPEREMIA OF RHYTHMICALLY CONTRACTING MUSCLE OF THE APPLIED LOAD

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Acute experiments on cats have shown that the degree and duration of working hyperemia developing in the rhythmically contracting gastrocnemius muscle are unchanged despite an increase in the load from 50 g to 3 kg and, consequently, that they are independent of the magnitude of the physical work performed by the muscle during contractions.

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In previous communications the writers have shown that the intensity and duration of working hyperemia accompanying contractions of the cat gastrocnemius muscle are independent of the physical work performed [2, 3, 5]. This conclusion was reached by comparing the magnitude of the peak blood flow (the maximal blood flow immediately after contraction) and the duration of the postcontraction hyperemia (i.e., the period between the end of contraction and recovery of the initial value of the blood flow) for contractions evoked by pulses of the same frequency, but performed under auxotonic or isotonic conditions. It could be concluded from the fact that the intensity of working hyperemia is independent of the physical work performed by the muscle that vasodilatation was independent of the metabolic cycles responsible for the reaction of the contractile system to the resistance to shortening. However, the validity of this conclusion may be disrupted if it is remembered that during contractions evoked by pulses of higher frequency, the blood supply to the muscle is limited [2, 3, 5].

When the frequency of the stimulating pulses exceed 16/sec, the muscle fibers compress the vessels. In the present experiments stimulation of the nerve was continuous, and throughout the period of contraction the inflow of blood was partly or completely limited. The muscle therefore worked "in debt." These conditions could affect the values of the peak blood flow and the duration of the postcontraction hyperemia.

The intensity of working hyperemia during stretching of the muscle by loads which differed considerably in weight was compared during rhythmic contractions when the periods of limitation of the blood flow were of short duration.

EXPERIMENTAL METHOD

Cats were anesthetized with urethane and chloralose (0.5 and 0.05 g/kg body weight) and the outflow of blood from the gastrocnemius muscle was measured by means of a photoelectric drop counter [4]. Blood from the hermetically sealed drop counter flowed into the femoral vein of the other limb. The velocity of the blood flow was recorded by means of an intervalograph [6] and by an electromechanical drop counter (for every 5 sec) on an ink-writing polygraph, on which the pressure in the carotid artery and amplitude of the muscle contractions (by means of a rheostatic sensor) also were recorded. The limb was fixed in a holder in a position of complete extension by means of steel pins inserted through the bones, and maximal isometric contraction of muscle was produced and its strength measured by means of a tensometric sensor [1, 7]. For this purpose the peripheral end of the sciatic nerve (or branches of which had been divided, except those supplying the gastrocnemius muscle) was stimulated with supermaximal square pulses (0.05

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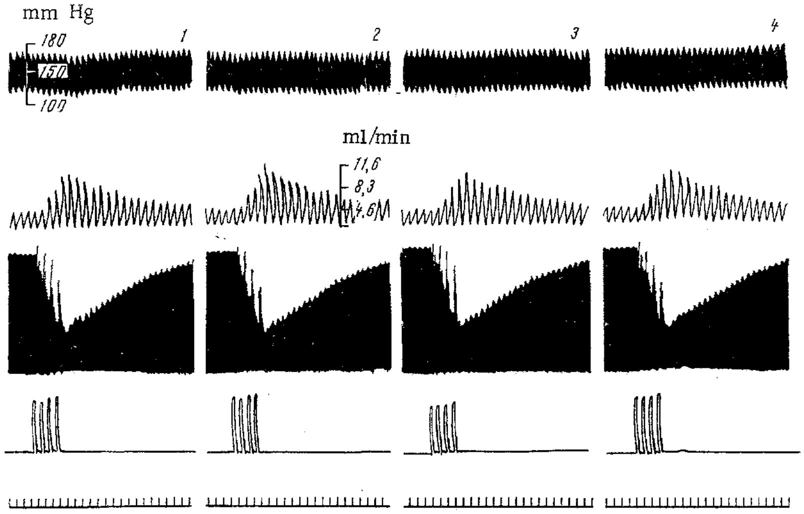

Fig. 1. Equal increase in blood flowing during four repetitions of cycles of rhythmic tetanic contractions of a loaded (3 kg) muscle. From top to bottom: arterial pressure, blood flow (recordings of drop counter and intervalograph), myograph, time marker (5 sec).

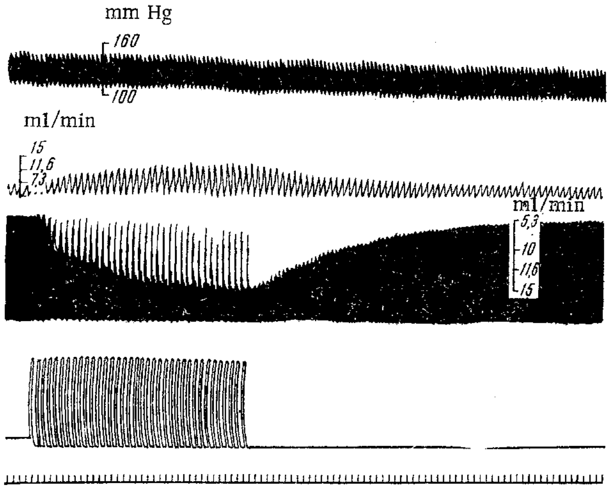

Fig. 2. Stability of amplitude of rhythmic tetanic contractions of loaded (3 kg) muscle. Order of curves as in Fig. 1.

msec, 32/sec, 1-1.5 sec). Next, while reducing the amplitude of the pulses, contractions of the muscle continued to be evoked until their strength reached half of the maximum. The amplitude and frequency of the pulses were subsequently unchanged. The muscle tendons were connected to the sliding contact of the rheostatic sensor. A thread, which passed over a pulley, was attached to this sliding contact, and a weight hung from the thread. By means of a time relay, contractions lasting 2 sec separated by intervals of 3 sec were produced. During the first cycle of stimulation (with a load of 3 kg on the muscle) tetanic volleys were repeated 36 times. At the end of the reactions of the vessels the cycle of stimulation was repeated, but a weight of 50 g was used. The load was then again changed to 3 kg and a new cycle of 12 tetanic contractions evoked. After restoration of vascular tone this cycle was reproduced again, but using a load of 50 g. A third cycle of 4 contractions was then carried out, the first time with a weight of 3 kg and the second with a weight of 50 g.

During analysis of the curves, besides the values of the peak blood flow and duration of postcontraction hyperemia, the value of the additional blood supply to the muscle (Q_Σ) for this period was obtained by means of the formula: $Q_\Sigma = (Q_1 + Q_2 + \ldots Q_n) - Q_x \cdot T$, where $Q_1, Q_2, \ldots, Q_n$ represent the readings of

TABLE 1. Increase in Blood Flow (in percent of initial value) during Rhythmic Tetanic Contractions of Loaded and Unloaded Muscle (mean results of 7 experiments)

No. of cycles of tetanic contraction	Load	
	50 g	3 g
4	119	106
12	168	171
36	219	242

TABLE 2. Mean Values of Peak Blood Flow (ΔQ), Duration of Postcontraction Hyperemia (P), and Additional Blood Supply (Q_Σ) during Rhythmic Tetanic Contractions of Loaded and Unloaded Muscle, and Level of Significance (P) of Differences between Mean Values

Load	No. of tetanic contractions	ΔQ (in ml/min)	P	T (in sec)	P	Q_Σ (in ml)	P
3 kg	36	7,5± 1,3	$<0,5$	355± 67,6	$<0,5$	15,4± 4,6	$<0,5$
50 g	36	6,8± 0,8		320± 82,3		12,3± 4,2	
3 kg	12	5,3± 0,7		197± 33,0		6,4± 1,6	$<0,2$
50 g	12	5,2± 0,5	$<0,5$	166± 28,5	$<0,2$	5,0± 0,9	
3 kg	4	3,3± 0,5		111± 9,3		2,7± 0,4	$<0,2$
50 g	4	3,7± 0,4	$<0,5$	104± 11,5	$<0,5$	2,3± 0,3	

the drop counter every 5 sec, exceeding the value of Q_X, the blood flow before contraction; T represents duration of postcontraction hyperemia (the value of T was corrected by reference to the intervalograph curve).

EXPERIMENTAL RESULTS AND DISCUSSION

Since the strength of stimulation of the nerve was submaximal, in the first experiments the reproducibility of the working hyperemia effect was verified during repeated cycles of contractions with the same load. Repeated rhythmic tetanic stimulation of the muscle loaded with a weight of 3 kg was accompanied by equal working hyperemia (Fig. 1). No signs of fatigue of the muscle were observed during the production of 36 contractions (Fig. 2). During the contractions of the muscle its blood supply was reduced, but in the intervals the blood flow increased without limitation (Figs. 1 and 2). The blood flow increased considerably after only 4 rhythmic contractions (Fig. 2). However, as Table 1 shows, with an increase in the number of contractions the value of the peak blood flow showed a tendency to become stabilized. There must apparently be some limit to the dilatation of the muscle vessels, the attainment of which is determined not by the load applied to it, but entirely by the number of contractions.

A load of 50 g was insufficient to restore the initial length of the contracted muscle rapidly. Delayed recovery of length of the unloaded muscle after tetanic contraction was observed by Ernst [10]. However, this phenomenon did not prevent measurement of the amplitude of the shortening of the muscle with sufficient accuracy to allow calculation of the physical work.

Shortening of the muscle, loaded by a weight of 50 g and 3 kg, in three experiments averaged 0.5 and 1.47 cm, respectively. This threefold difference is explained by the fact that in the second case the muscle was stretched in its initial position, whereas in the first case it was shortened as the result of separation from the distal point of attachment. For loads of 50 g and 3 kg, the physical work (allowing not only for the load, but also for the mean weight of these three muscles, namely, 37 g) was thus 43.5 and 4494 g · cm, respectively. With a load of 3 kg it was at least 100 times greater than the work performed by the muscle loaded with a weight of 50 g. Yet the ratio between the values of the peak blood flow measured immediately after contractions of the loaded and unloaded muscle (Table 1) differed by not more than 10%. Statistical analysis shows that this difference is not significant (Table 2), and leads to the conclusion that the intensity of vasodilatation is dependent neither on the load nor on the physical work, nor on the amplitude of shortening of the muscle. A similar conclusion is reached by analysis of the mean values of duration of postcontraction hyperemia and of the additional blood supply (Table 2).

The factor determining the intensity and duration of vasodilatation (for a constant number of contracting fibers and constant frequency of stimulating pulses) is thus the number of tetanic contractions, i.e., the total number of pulses during the period of stimulation. In this respect rhythmic muscle contractions are indistinguishable from continuous [1, 2, 5]. In these experiments the pulse frequency was varied but the duration of contraction remained constant. Other investigators [8, 11, 12, 15] have also concluded that the degree of vasodilatation (for an assigned pulse frequency) is determined by the number of contracting fibers and not by the magnitude of the load.

This concusion that the intensity and duration of vasodilatation are independent of the magnitude of the physical work conflicts with results obtained by workers who found that the additional blood supply of human muscles is a linear function of the work performed [9, 13, 14, 16]. In fact, however, this contradiction is purely apparent. To perform a specified physical work, man "chooses" a definite flow of impulses in motor fibers, i.e., a definite number of motor units had a definite pulse frequency. The indices of working hyperemia are evidently functions of these values, and not of the physical work [2, 3, 5].

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