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MUSCULAR REFLEX STIMULI TO THE CARDIOVASCULAR SYSTEM DURING ISOMETRIC CONTRACTIONS OF MUSCLE GROUPS OF DIFFERENT MASS

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SUMMARY

1. The cardiovascular responses to voluntary isometric contractions performed by human subjects are determined by the proportion of maximal tension achieved by the muscles contracting, and not by the mass of the contracting muscles, nor by the absolute tension achieved (Lind & McNicol, 1967; confirmed here). When two or more muscle groups contract simultaneously at different relative tensions, the increments in heart rate and blood pressure are the same as when the muscle group at the higher relative tension contracts alone at that tension (Lind & McNicol, 1967). It is known that there are both central and reflex stimuli to the cardiovascular system in exercise, and the present study examines whether the muscular reflex stimuli are related to the proportion of maximal tension achieved or to the mass of contracting muscle.

2. Isometric hind-limb contractions were induced in anaesthetized dogs and cats by stimulation of spinal ventral roots. Pressor responses to contraction of both hind limbs were greater than responses to contractions of either hind limb alone. No differences were observed between heart rate responses to single or combined hind-limb contractions.

3. When human subjects perform isometric contractions, a pressor response can be maintained beyond the conclusion of the exercise by occluding muscle blood flow. This response is generally attributed to a reflex set up in the muscle by the action of chemical factors on afferent nerves. When comparable pressor responses were evoked by comparable proportional efforts with either the whole hand or the little finger, it was found here that the pressor responses remaining during the period of post-exercise occlusion were greater when the greater mass of muscle had been exercised.

4. It is concluded that the muscular reflex drive in isometric exercise is related to the bulk of contracting muscle.

INTRODUCTION

When human subjects perform sustained hand-grip contractions at tensions above 15 % of the maximum attainable, the heart rate, cardiac output, and systolic and diastolic arterial pressures all increase, and the magnitude of these increases is determined by the intensity of the contraction and its duration (Lind, Taylor, Humphreys, Kennelly & Donald, 1964). It has been suggested that the physiological advantage of these responses is the increased flow which is possible in the contracting muscle group when the blood pressure rises (Humphreys & Lind, 1963).

There are certain peculiar features of the cardiovascular responses to such isometric contractions. For example, when two or more muscle groups contract at the same proportion of their maximal tension, the increments in blood pressure and heart rate are the same whether they contract separately or together (Lind & McNicol, 1967). Or, when two or more muscle groups contract simultaneously at different relative tensions, the increments in heart rate and blood pressure are the same as when the muscle group at the higher relative tension contracts alone at that tension (Lind & McNicol, 1967). These findings hold true even when the muscle groups involved are of quite different total mass.

Isometric exercise has been used in experiments on the nature of the stimuli to the cardiovascular system in exercise. These stimuli include 'irradiation' of the cardiovascular control centres by elements of the command signals descending from higher centres to the contracting muscles (Goodwin, McCloskey & Mitchell, 1972), and reflex stimuli originating in nerve endings in the contracting muscles (Coote, Hilton & Perez-Gonzalez, 1971; McCloskey & Mitchell, 1972). It is not known whether both central and reflex stimuli are related to the proportion of maximal tension achieved rather than to the mass of muscle involved in the contraction. Nor is it known whether these two components of the cardiovascular drive contribute similarly in similar relative contractions of different muscle groups.

In the present study the reflex contributions to the cardiovascular drives during isometric contractions of muscle groups of different masses have been investigated in animals and in man. In the animal experiments isometric contractions of hind-limb muscles were induced by spinal ventral root stimulation, as this allows the reflex part of the cardiovascular drive to be seen alone. In the experiments on human subjects, reflex circulatory effects were investigated by using occlusion of the blood supply to the contracting muscle. This causes the maintenance of a pressor response beyond the conclusion of the exercise for as long as the occlusion persists (Alam & Smirk, 1937). This is generally attributed to a reflex set up in the ischaemic muscle by the action of chemical factors on sensory nerve endings. Such a reflex is probably part, and perhaps the whole, of the muscular reflex element of the cardiovascular drive in exercise, and can be observed when it is the sole drive to the cardiovascular system. Our results indicate that the muscular reflex component of the cardiovascular stimulus in isometric exercise is related to the mass of the muscle group performing the contraction.

METHOD

Animal experiments

Experiments were performed on nine cats (1·8–3·8 kg) anaesthetized with pentobarbitone sodium (Nembutal: Abbott, 40 mg/kg, I.P.), and on six dogs (6–14 kg) anaesthetized with chloralose (α-chloralose: British Drug Houses, 80 mg/kg I.V.), after thiopentone induction. A tracheal cannula was inserted low in the neck. Blood pressure was recorded from the axillary artery through a saline-filled nylon catheter connected to a Statham P23AC transducer, and was recorded on a Grass polygraph pen recorder. On another channel of this recorder either the electrocardiogram or heart rate was recorded using a Grass 5P4D pre-amplifier.

A laminectomy was performed to expose the sacral and lower lumbar segments of the spinal cord. Animals were fixed in a prone position on a table by pins driven into the iliac crests and through the knee joints, and the ankle joints were firmly clamped to prevent movement. A pool was made over the laminectomy with paraffin warmed to 37° C and bubbled with 95 % O_2 + 5 % CO_2. The spinal cord was exposed by a lengthwise incision through the dura. The ventral roots of L 6, L 7 and occasionally S 1 were cut close to their exit from the spinal cord on each side and were placed over pairs of Ag–AgCl electrodes. Stimulation of the ventral roots at 20–50 Hz with square wave pulses of 0·2–0·5 msec duration, delivered by an isolated stimulator, were used to elicit sustained isometric contractions of the hind-limb muscles. The voltage used for maximal contractions was twice motor threshold. Periods of contraction of 10–40 sec were used. The exposed spinal cord and nerve roots were washed every 30–40 min with warmed Ringer solution bubbled with 95 % O_2 + 5 % CO_2 (cf. Brown, Lawrence & Matthews, 1969). Rectal temperatures were maintained at 36–38° C throughout.

Human experiments

Ten normal volunteer subjects (eight male and two female), aged between 19 and 26 yr, acted as experimental subjects. The experiments were performed with the understanding and consent of the subjects.

Subjects were required to perform isometric contractions using muscle groups of the preferred hand or forearm. Usually, handgrip contractions and 'trigger-pulling' contractions of the little finger of the same hand were compared. Three subjects performed combined contractions of the index and middle finger of the same hand, attempting to close the extended digits in a scissors-like action on the strain gauge: this form of contraction, when undertaken, was used instead of the contraction of the little finger for comparison with the hand-grip. Contractions were performed at about 40 % of the maximal voluntary tension for 1–1½ min. Handgrip contractions alternated with contractions of the smaller muscle group, and there were rest periods of at least 10 min between contractions. During contractions the subject could see only the tension gauge against which he was pulling, and the face of an oscilloscope on which were displayed the achieved tension and a target beam for alignment.

All other equipment, and the experimenters, were out of sight, and the room was kept silent. Five seconds before the conclusion of each contraction a sphygmomanometer cuff was inflated above the elbow on the experimental side to a pressure of 250 mmHg, and was kept inflated after the conclusion of the effort for a further 1–1½ min. The first contraction in a series was always neglected for purposes of analysis, and served only to familiarize the subject with the experimental procedure.

Blood pressure was measured continuously through a short Teflon catheter inserted through the skin into the radial artery of the resting arm. This catheter was connected to a Statham P23Dc transducer, and blood pressure was recorded on a Grass polygraph pen recorder. Heart rate was obtained through a Grass 5P4D preamplifier from the radial pulse, and was also recorded. The tension achieved during the isometric effort was recorded on a third channel of the polygraph.

RESULTS

Animal experiments

In all the animal experiments the pressor and heart-rate responses to maximal induced contractions of one hind limb alone were compared with the responses to maximal contractions of both hind limbs together. In all but two experiments the pressor response to combined contractions exceeded the response to contraction of either limb contracting alone. In these thirteen experiments the maximal increase in blood pressure on contraction of a single hind limb ranged from 10 to 35 mmHg for individual animals, and the maximal pressor response for combined hind-limb contractions ranged from 20 to 50 mmHg. When the maximal increase in pressure for combined contractions was expressed as a percentage of the maximal increase in response to contraction of a single hind limb in the same animal, the range for individual experiments was 150–230 %. In the remaining two experiments, both done on cats, the maximal pressor responses to single and combined hind-limb contractions were of similar magnitude: in both experiments these were small (10 and 15 mmHg). In all experiments, the reflex nature of the responses observed was confirmed when the responses were abolished by cutting the spinal dorsal roots from L 5 downwards. After cutting the dorsal roots there were often small transient changes in blood pressure at the start of a contraction, possibly due to mechanical alterations in peripheral resistance, and slight reductions in pressure at the conclusion of contractions, possibly due to reactive hyperaemia in the exercised muscle. Bilateral ventral root stimulation was performed in two dogs and one cat which had been paralysed with gallamine, and this induced no changes in blood pressure or heart rate. Typical pressor responses to single and combined hind-limb contractions are shown in Fig. 1.

Heart rate increased in response to hind-limb contractions in all experiments. The increases were variable in magnitude, and never exceeded 20 %

of the resting heart rate. We were unable to demonstrate any differences between heart rate responses to single or combined hind-limb contractions in any animals.

In five experiments submaximal limb contractions were investigated. In all five experiments (three cats and two dogs) there was a smaller pressor response to a maximal contraction of one hind limb than to a similar contraction of that hind limb combined with a submaximal

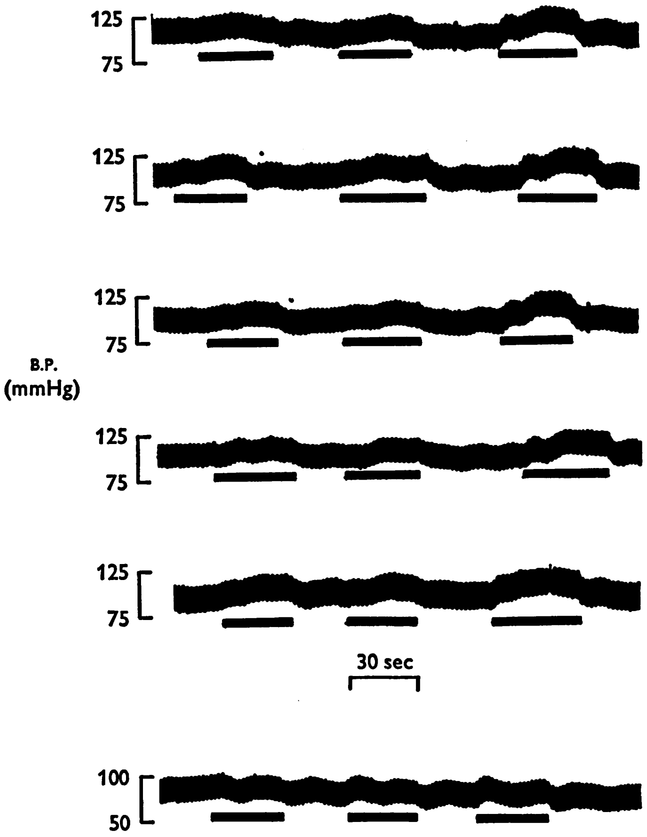

Fig. 1. Records of systemic arterial pressure in a cat anaesthetized with pentobarbitone. Maximal isometric hind-limb contractions were induced by ventral root stimulation at each marker. In each panel the sequence of contractions shown is: left hind limb alone, right hind limb alone, both hind limbs together. In the upper five panels all dorsal roots were intact, and reflex pressor responses occurred. The pressor responses to combined maximal hind-limb contraction were greater than the responses to either hind-limb contracting maximally alone. The lowest panel shows the effects of cutting the spinal dorsal roots from L5 downwards: hind-limb contraction was associated with only transient alterations of blood pressure.

contraction of the other hind limb. Fig. 2 shows typical responses. Again we were unable to demonstrate any relation between mass of contracting muscle and increase in heart rate in any experiment.

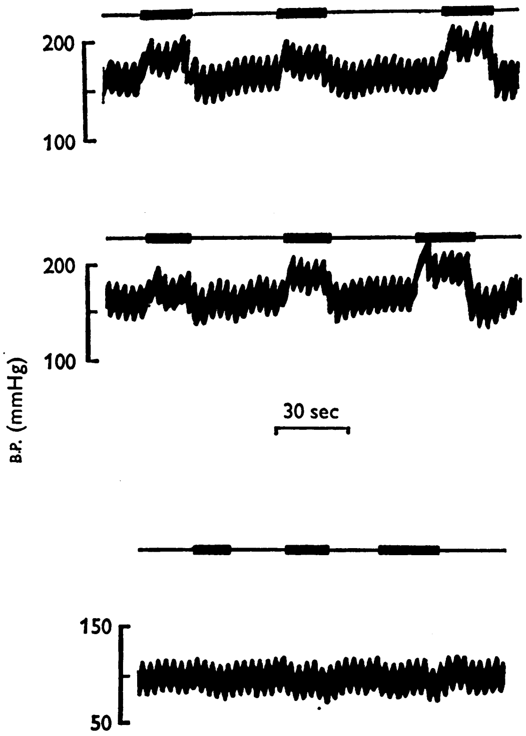

Fig. 2. Records of systemic arterial pressure in a dog anaesthetized with chloralose. Hind-limb contractions were induced by ventral root stimulation at each marker. The upper two panels show reflex pressor responses when the dorsal roots were intact. In the top panel the sequence of contractions was: left hind limb alone, right hind limb alone, both hind limbs together; in the second panel the sequence was right hind limb, left, then both together. In each sequence the left hind limb contracted maximally and the right submaximally. The pressor responses to combined maximal and submaximal hind-limb contraction were greater than the responses to either hind-limb contracting alone. The lowest panel shows the sequence of contractions of the top panel repeated after cutting the spinal dorsal roots from L 5 downwards.

Human experiments

Handgrips and contractions of a smaller muscle group of the same arm were performed alternately by all subjects, with rest periods between. Usually there were three or four contractions of each type. We aimed to produce increases in systolic pressure of the same magnitude during each form of contraction: this was achieved by altering the magnitude of the effort required of the smaller muscle group. Handgrip contractions of 40 % of the maximal voluntary contraction (MVC) were always used, and efforts producing similar pressor responses were within the range 35–45 % MVC for the smaller muscle group.

TABLE 1. Comparison of mean systolic arterial pressure and heart rate response to sustained handgrip contractions and to contractions of smaller muscle groups

			During isometric effort		During post-exercise occlusion	
Control systolic pressure (mmHg)	Control heart rate (beats/min)	Muscle group	Systolic pressure (mmHg)	Heart rate (beats/min)	Systolic pressure (mmHg)	Heart rate (beats/min)
105	65	Hand	155	82	140	72
		Finger	150	80	112	78
115	76	Hand	140	95	132	70
		Finger	148	104	120	72
115*	55	Hand	160	80	134	50
		Finger	160	74	118	56
120	60	Hand	172	92	146	64
		Finger	176	88	130	56
122	80	Hand	156	124	146	86
		Finger	152	120	134	82
122	62	Hand	190	76	178	54
		Finger	182	82	148	56
128*	66	Hand	165	90	144	70
		Finger	172	88	138	72
134*	85	Hand	184	104	160	90
		Finger	192	100	148	84
138	72	Hand	166	102	152	60
		Finger	170	110	144	62
140	68	Hand	170	96	158	58
		Finger	174	98	148	64

* All subjects used flexion of the little finger as the effort with a small muscle group, except those marked * where a scissors-like contraction of the index and middle fingers was employed.

Occlusion of the circulation through the exercising forearm was commenced 5 sec before the end of the exercise. When the contraction stopped, there was typically an abrupt fall in blood pressure and heart rate, which had risen during the exercise. Often the blood pressure began to rise again slowly after this initial fall, sometimes stabilizing some 15–45 sec after the end of the contraction. Consistent changes were not observed in heart rate during the post-exercise occlusion period.

We compared the increases from control levels of blood pressure and heart rate in the last 15 sec of the voluntary effort, and between 45 and 60 sec of the post-exercise occlusion period. Table 1 summarizes the results. Systolic arterial pressure in each experimental condition was taken as the mean of systolic pressure throughout one or two complete respiratory cycles, so as to minimize the influence of respiratory fluctuations in blood pressure. In each subject the mean of these systolic arterial pressures, and the mean heart rate, for the three or four efforts in each category were determined, and are set out in Table 1. Typical responses from one subject are shown in Fig. 3. In all subjects, the blood pressure was higher during circulatory occlusion after handgrip contractions than after contractions of the smaller muscle group. Heart rate was not elevated during the post-exercise occlusion in any subject for either form of contraction: in some subjects, the heart rate was slower in comparison to the control level during this period.

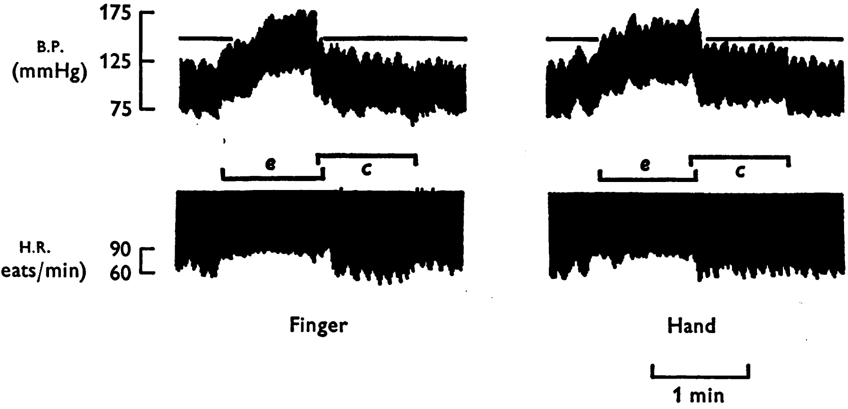

Fig. 3. Records of blood pressure and heart rate from a normal human subject performing isometric contractions. On the left are shown the responses to efforts made by flexing the little finger at 40 % of its maximal tension, and on the right, the responses to a handgrip contraction at 40 % of maximum. In each case the duration of the voluntary effort is marked *e*. The pressor responses to both efforts were comparable in size. Just before the conclusion of each voluntary effort, an occlusion of the blood supply through the exercising muscle was applied: the duration of the period of vascular occlusion is marked *c*. During the period of post-exercise occlusion part of the pressor response was maintained. This maintained part of the pressor response was greater for the larger muscle group, as can be seen by reference to the line drawn across the blood pressure record.

DISCUSSION

In this study, using muscle groups of quite different total mass and strength, we have confirmed the finding of Lind & McNicol (1967) that the pressor and heart rate responses to isometric contractions are related to the proportion of maximal tension achieved rather than to the bulk of the contracting muscle group. The muscular reflex component of the stimulus to the pressor response, however, does not conform to this relation: our experiments in animals and in humans indicate that the muscular reflex drive is proportional to the bulk of contracting muscle.

The animal experiments reported here simply illustrated the interactions of pressor reflexes elicited during muscular contractions. While there was considerable variability in the extent of interaction, all but two of our fifteen experiments showed some additive drive when the bulk of contracting muscle was increased, and this was so whether the added muscle was contracting maximally or submaximally. The human experiments were a less direct approach to the question, examining the reflex drives only after the isometric efforts were completed. When circulatory occlusion is applied at the end of a period of contraction induced by ventral root stimulation in animals, the pressor response which is maintained is not the full response which was achieved during the contraction (McCloskey & Mitchell, 1972). This may mean that intramuscular mechanoreceptors contribute part of the reflex drive during induced contractions. Such mechanoreceptors would not be the muscle spindles or tendon organs, however, as these have been shown not to contribute to the cardiorespiratory drives in exercise (McCloskey & Mitchell, 1972; McCloskey, Matthews & Mitchell, 1972). It must be conceded that the reflex stimuli we investigated in man were probably only part of the total reflex drive present during contractions and that the value of the human experiments is the confirmation they provide of the observations made in the animal experiments of this study.

The arguments above refer only to the pressor responses to isometric contractions. In none of our experiments, whether in animals or in humans, were we able to relate the reflex increases in heart rate to the bulk of the muscle group exercising. This might lead to the simple conclusion that primary muscular reflex effects upon heart rate are not related to the mass of contracting muscle. While this conclusion may be quite correct, it should be recognized that other factors also operate upon heart rate. In particular, the baroreceptor–cardiodepressor reflex may be of importance here. In studies in man, Cunningham, Petersen, Peto, Pickering & Sleight (1972) showed that the baroreflex is reset and its sensitivity reduced during isometric handgrips, but that the sensitivity is substantially restored during periods of post-exercise occlusion. We have found also that in isometric hind-limb contractions induced by ventral root stimulation in the dog the baroreceptor–cardiodepressor reflex is reset, but we found no evidence that its sensitivity is reduced (K. A. Streatfeild & D. I. McCloskey, unpublished observations). These observations open the following possibilities. During a voluntary isometric effort the heart rate rises partly because the baroreflex sensitivity is reduced (presumably the sensitivity is reduced by some factor operating during voluntary contractions, but not during the post-exercise occlusion period, nor during induced contractions in animals). When the isometric effort is concluded, the baroreflex regains a great deal, or all, of its sensitivity so that if a pressor response is maintained, then the heart rate is slowed by the baroreceptor reflex. This would explain why the heart rates during the periods of post-exercise occlusion were often slower than the control heart rates in this study and in the experiments of Cunningham *et al.* (1972). While there is a powerful primary cardio-acceleratory reflex set up in the exercising muscle, its effects are often wholly or partly masked by the baroreceptor reflex. Our conclusions regarding the influence of muscle mass on heart rate must therefore be much less definite than those regarding the pressor responses.

In view of our results there is now an apparent paradox. The pressor response to a voluntary isometric effort is related to the proportion of maximal tension achieved, and not to the mass of muscle contracting, but the muscular reflex component of the stimulus for the pressor response *is* related to the mass of muscle contracting. If one were to believe that the total stimulus in exercise is the simple sum of contributing stimuli, one would be forced to the conclusion that pressor stimuli other than those of a muscular reflex kind are inversely related to the bulk of muscle involved in a contraction. This is a conclusion which we find unattractive. There is no reason to assume that the cardiovascular stimuli in exercise simply summate to produce their effects. It is possible that a considerable element of occlusion exists. Irradiation of the central command is an important cardiovascular stimulus in exercise (Goodwin *et al.* 1972), and its interaction with the muscular reflex stimulus may be of a largely occlusive kind. Present knowledge would be accounted for if the effective cardiovascular stimulus were whichever one of irradiation or muscular reflex was the greater, and if the potency of irradiation as a stimulus were related to the proportion of maximal effort attained.

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