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OBSERVATIONS IN MAN UPON A BLOOD PRESSURE RAISING REFLEX ARISING FROM THE VOLUNTARY MUSCLES

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This paper is concerned with the rather large changes in the general blood pressure which we observed in man during the muscular exercise of a limb when the circulation of blood through its working muscles was arrested by mechanical pressure. Our earliest observations were made in the course of experiments which were not concerned directly with the present investigation.

Method

Special large sphygmomanometer cuffs were placed round the thighs of a normal subject who was in the sitting posture, and a flat iron weight of 12 kg. was laid across the knees. During the control period the systolic and diastolic blood pressures were measured in an arm by the auscultatory method at about half-minute intervals, until constant readings were obtained. The sphygmomanometer cuffs round the thighs were then inflated rapidly to a pressure well above the subject's systolic blood pressure in order to arrest the circulation through both the legs and further blood pressure readings were taken in the arm. The subject was next instructed to raise and lower the knees. The distance traversed by the weight during each of its excursions was about 5 cm. The movement was performed using as far as possible only the calf muscles. This movement was repeated at intervals varying in the different experiments between 0·5 and 2 sec. The first experiment of a series on any one subject was usually only for the training of the subject and the results then were not recorded.

It was found that both the systolic and the diastolic blood pressures increase as a result of such exercise (Fig. 1). On stopping exercise the blood pressure usually fell only a few millimetres of mercury and remained always above the original normal level until such time as the circulation through the legs was restored by releasing the pressure in the sphygmomanometer cuffs round the thighs. If the circulation remained obstructed for more than 3 or 4 min. after the exercise ceases it was found that a further gradual rise of blood pressure often took place. In the early experiments on the legs there was no exact control of the amount or

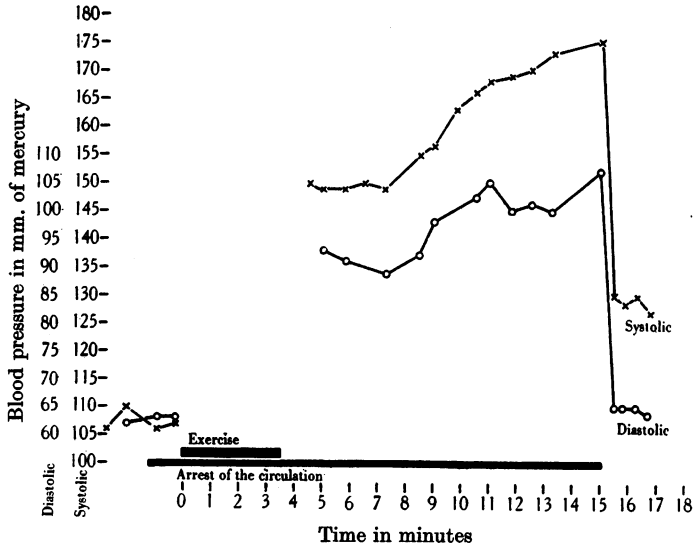

Fig. 1. The exercise was the lifting of 12 kg. through 5 cm. 120 times in 3·5 min. The calf muscles of both legs were the chief muscles involved.

rate of exercise. The degree of increase in the blood pressure which it was possible to secure by this method varied much from one subject to another but was often in the region of 25 mm. of mercury. Increases of as much as 68 mm. of mercury have been encountered.

Experiments were next performed in which the circulation through one forearm was arrested by means of a sphygmomanometer cuff placed round the upper arm and inflated to well above the systolic blood pressure. Exercise, which consisted in squeezing the rubber ball from the sphygmomanometer at intervals of 1 sec. for a few minutes, was performed with the circulation arrested. Increases in the systolic blood pressure of as much as 82 mm. of mercury were recorded. More experiments were made

upon the forearm than upon the leg. It was found that the rise of the blood pressure was established during the exercise and fell very slightly

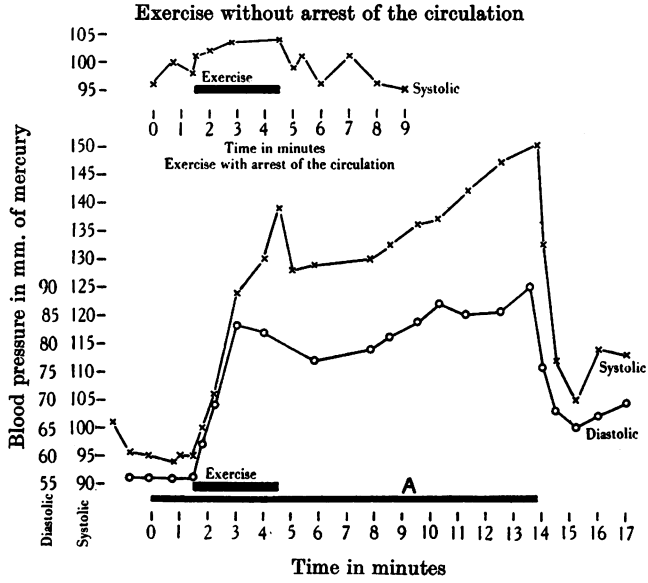

Fig. 2. *A* = period of circulatory arrest. The exercise was of the forearm muscles. 500 g. were lifted through 5 cm. 180 times in 180 min.

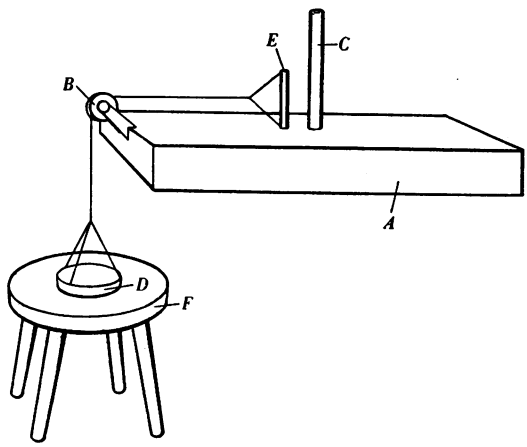

Fig. 3. Apparatus used for exercising the forearm muscles.

on cessation of exercise, but that most of the increase in blood pressure persisted until the circulation through the arm was re-established (Fig. 2).

The experiments which follow were designed to explain the rise of the blood pressure described above. For this purpose it was found necessary to measure the work done by the contracting muscles. Since the forearm is better adapted than the leg for the accurate performance of a muscular task most experiments have been performed with exercise of the forearm muscles. For this purpose the following apparatus was used. A piece of wood *A* (Fig. 3) about 70 cm. long carries a pulley *B* at one extremity and a wide rounded iron bar *C* rises vertically from its centre. A scale pan *D* carrying the desired weight hangs over the pulley by means of a rope which is attached to the handle *E*. When the scale pan rests upon the stool *F* the handle stops short of the iron bar by about 5·5 cm. The subject rests his thenar eminence and thumb against the iron bar and holds the handle by the remaining four fingers. The exercise consists in alternately raising and lowering the weight through a distance of 5·5 cm. by the action of the four fingers upon the handle *E*.

Experimental

(1) *Evidence that the maintenance of the rise in general blood pressure on exercise of muscles with their circulation arrested depends upon arrest of the circulation*

A series of experiments was arranged in which the amount of work and the rate of performance of work by the forearm muscles was the same in each of the experiments of the series. The individual experiments differed only in the duration of circulatory arrest. Each of the series of the experiments was completed on the same subject but different subjects were used. The blood pressure was measured frequently in the arm which was unoccupied by the exercise. Certain changes in the blood pressure were observed and it is evident (Figs. 2 and 4) that the presence or absence of arrest of the circulation through the working muscles of the forearm has a considerable influence upon the blood-pressure readings found in the free and resting arm. When the circulation is free the rise of blood pressure is small and the blood pressure falls to normal within a few seconds after cessation of exercise. When the forearm muscles are exercised while their circulation is arrested, the rise of general blood pressure is much greater than that obtained from equal exercise of the same forearm with the circulation free. If the circulation through the forearm is restored at the end of the exercise the blood pressure falls rapidly and is often near to the normal value in about 20 sec. In numerous other experiments obstruction to the circulation was maintained for various periods of time after cessation of the exercise. It was found that

in normal subjects the rise of blood pressure persisted so long as the arrest of the circulation persisted, and upon the re-establishment of the circulation the blood pressure always fell promptly towards the original normal level.

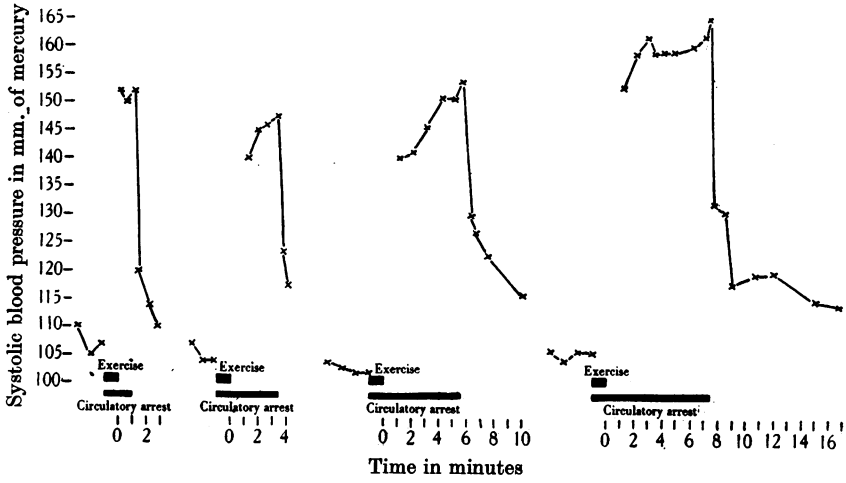

Fig. 4. The exercise was of the forearm muscles. 2 kg. was lifted through 5·5 cm. about 120 times in each experiment.

All of the results of more than fifty other experiments conducted on the same principles as those described above support the conclusion that the maintenance of the rise in blood pressure depends upon arrest of the flow of blood through the working muscle, and that exercise of the muscles of the forearm causes a much greater rise of blood pressure when the flow of blood through the exercising forearm is arrested.

(2) *Evidence that the rise of general blood pressure does not depend on the method of arresting the circulation through the working forearm*

A forearm may be devascularized and the circulation arrested by plunging it into a bath of mercury to a depth of about 12 cm. above the elbow. If the forearm muscles are exercised while the forearm circulation is thus arrested it is found that the systolic and diastolic blood pressures rise and are maintained at a high level until circulation through the arm is restored by withdrawal from the bath of mercury. It is clear therefore that the rise of blood pressure does not depend upon the manner in which the circulation through the forearm is arrested. The temperature of the bath of mercury should be between 33 and 37° C. or rapid cooling of the

forearm while in the mercury may cause changes in blood pressure which are not related to the muscular exercise. A typical result is shown in Fig. 5.

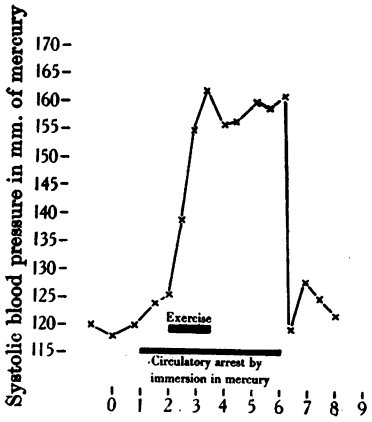

Fig. 5.

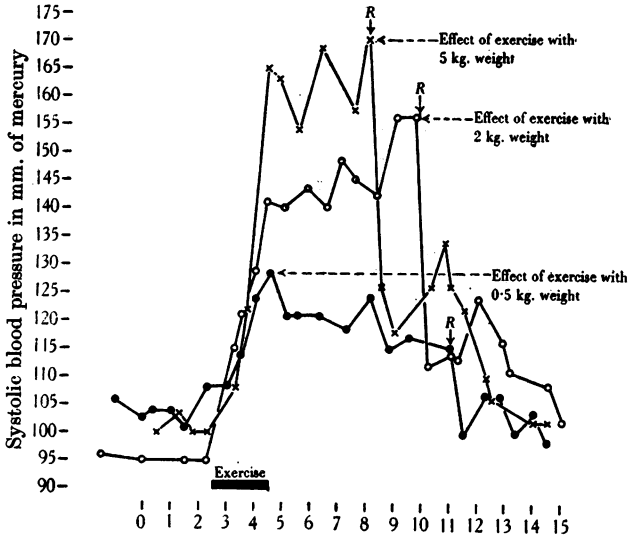

Fig. 6.

Fig. 5. The exercise was of the forearm muscles. A sphygmomanometer bulb was squeezed under mercury about 60 times.

Fig. 6. The exercise was of the forearm muscles during arrest of their circulation. The weights were lifted 60 times. Circulation through the forearm was restored at *R*.

(3) *On exercise of the forearm muscles with their circulation arrested, the extent of the resulting rise of the general blood pressure depends upon the amount of work done by the forearm muscles*

In all the following experiments the circulation through the forearm was arrested during and for some time after exercise. The number of muscular efforts and the distance through which the weight was lifted were constant through any series of experiments performed on the same subject. The weight to be lifted varied from 0·5 to 5 kg. in the different experiments of a series.

Fig. 6 summarizes results of one of the three experiments performed, and it is seen that when our observations are confined to the muscles of the forearm the rise of blood pressure increases with the amount of work done during the circulatory arrest. In over forty experiments it has been shown also that when the work done by the forearm muscles is increased by increasing only the number of muscle efforts then the greater rises of

the blood pressure are still obtained in the experiments where more muscular work is done.

(4) *Evidence that the blood pressure rises in the absence of pain and that when pain is present the extent of the rise of blood pressure is not dependent upon the degree of pain*

When a forearm is exercised during arrest of its circulation the subject experiences the following:

(1) A period without any abnormal sensation or with a sensation in the forearm muscles described variously as tiredness or heaviness but not causing appreciable discomfort.

TABLE I. The relationship between blood pressure and pain in selected subjects

	Blood-pressure measurements			
Subject	Resting	Highest without pain	During slight or moderate pain	During severe pain
G.	108/70	144/94	—	152/100
W.R.	108/60	118/70	130/80	140/88
S.	107/78	120/82	—	—
W.G.	98/69	108/75	114/82	128/88
R.	107/74	147/94	—	—
R.	112/64	150/87	158/89	186/101

Blood pressures below the usual English range are common in Egypt. All readings are made with mercury manometers. Large blood pressure increases, as in Table I, are found only in one-fourth of the normal human subjects studied.

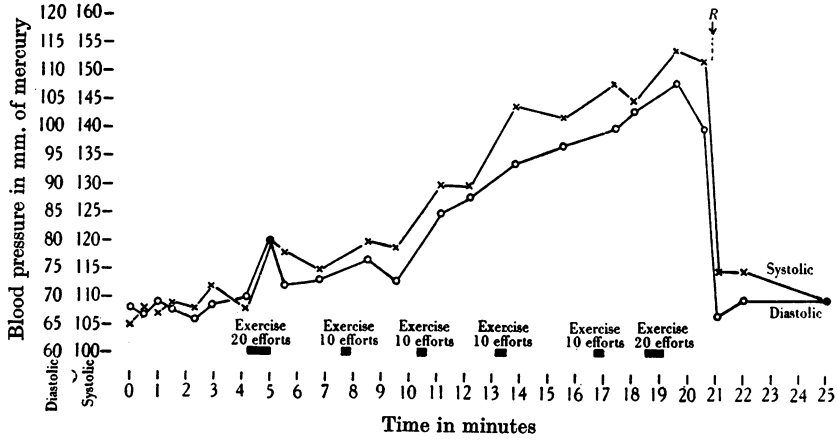

Fig. 7. The exercise was of the forearm muscles. A 2 kg. weight was lifted. The circulation through the forearm was arrested until *R*.

(2) A period where the sensation in the forearm becomes definitely aching in character and is described as pain which, however, is easily tolerated.

(3) A period with severe pain.

It is well known that many types of pain give rise to an increase of blood pressure. Therefore one must consider whether the changes in blood pressure which have been observed are due to pain. In our earlier experiments, made mainly on illiterate subjects, increases of 5–30 mm. of mercury were observed frequently at a time when the subject noticed only a sensation of tiredness or heaviness of the forearm muscles and stated that there was no pain.

A further series of experiments made on doctors, medical students and trained normal subjects confirmed the results of these earlier studies. The results obtained on medical men are set out in Table I (Fig. 7). It is concluded from these results that in the absence of pain a definite rise of blood pressure may be produced by exercise of the forearm muscles during arrest of their blood circulation. In some experiments the course of the rise of blood pressure during the progress of exercise does not appear to be influenced much by the appearance of pain in the forearm muscles (Fig. 7). It is clear that the rise of blood pressure described does not depend upon the production of pain.

(5) *Evidence that the rise of blood pressure is not due mainly to the mental effort involved in exercise*

Experiments have been described in previous sections which indicate clearly that the rise of general blood pressure which develops during the exercise of a limb with its circulation arrested persists after cessation of exercise so long as arrest of the circulation is maintained. It is clear therefore that the mental processes associated with such muscular exercise are not mainly responsible for the rise of blood pressure which takes place.

If the exercise is performed with the circulation normal, the rise of blood pressure is either absent or is much less than in exercise with arrested circulation, yet the mental processes responsible for the muscular contractions are present in both cases.

If the blood-pressure measurements are made at frequent intervals just before and just after exercise ceases, the circulation remaining arrested, it is found almost always that the blood pressure decreases by 5–10 mm. of mercury on cessation of exercise (Fig. 2). This small fall of blood pressure is not progressive and usually is complete within half a minute after the cessation of exercise. It seems likely that the small blood pressure fall is the result of the cessation of mental activity concerned with the muscular exercise.

(6) *Evidence that, with unobstructed circulation, exercise of the forearm muscles, more rapid than previously described in sections* 1–5, *will cause a rise of general blood pressure*

It has been shown already that, when the forearm muscles are exercised slowly with their circulation intact, there is little change in the general blood pressure. If the speed of work is much increased there is good reason to suppose that the flow of blood through the forearm may be insufficient to remove completely the newly formed metabolic products of the exercising muscles. Whatever may be the cause, however, the blood pressure rises appreciably during a rapid exercise of the forearm muscles such as the squeezing of the rubber ball of a sphygmomanometer as frequently as possible.

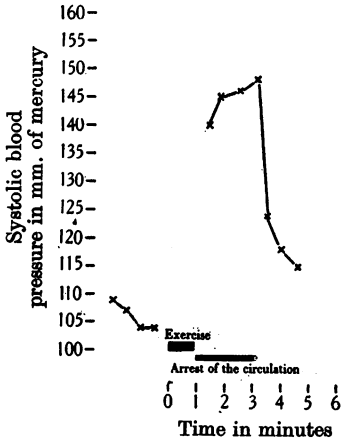

Fig. 8. The exercise was of the forearm muscles. A sphygmomanometer bulb was squeezed 40 times rapidly.

If at the moment exercise ceases the circulation through the forearm is arrested by rapid compression of the upper arm with a sphygmomanometer cuff, it is found that much of the rise of pressure established during exercise persists on cessation of the exercise. As with the experiments described in section 1 the rise of blood pressure is maintained by arrest of the circulation through the arm and falls to normal again whenever the circulation is re-established.

It is clear, therefore, that the part of the rise of blood pressure which persists on cessation of the exercise is not due to mental disturbance resulting from the performance of the exercise. It is clear also that the rise of blood pressure which was demonstrated by slow exercise of an arm with arrested circulation is obtained now by exercising rapidly an arm whose circulation is intact (Fig. 8). The rise of blood pressure thus obtained may be maintained by arresting and maintaining arrest of the circulation after the exercise has ceased.

Discussion

It is well known already that during *general* muscular exercise the blood pressure rises. Several factors may be involved in this blood pressure increase. Thus mental activity associated with the preparation for or the performance of muscular exercise is supposed to cause stimulation of the

vaso-motor centre. The release of adrenaline from the suprarenal glands is thought to play a part in raising the blood pressure during general exercise. The increased venous return to the heart during exercise also is thought to raise blood pressure by increasing the output of the heart. The liberation of acid metabolites of muscle activity into the general circulation is sometimes suggested as an explanation for the rise of blood pressure because of the stimulating action of acid metabolites on the vaso-motor centre. Since a vaso-dilator histamine-like substance is also liberated during muscle activity, the part played by metabolites on their reaching the general circulation must be regarded as doubtful.

Our observations have shown that the activity of even a small group of muscles such as those causing flexion of the little finger of the hand may give rise to an increase of even 70 mm. of mercury in the general blood pressure provided that the circulation of blood through the exercising muscles is arrested completely.

The hypotheses which have been advanced to explain the rise of blood pressure on general exercise do not explain the rise of blood pressure in our experiments. Thus the influence upon the blood pressure of the mental activity associated with muscular exercise is not a very important factor in our experiments because, after cessation of muscular activity, the blood pressure remained at a high level so long as the circulation through the arm was arrested. The mental activity associated with exercise, however, is not quite without influence upon the blood pressure. Some conception of the magnitude of the effect of such mental activity on the blood pressure may be gained from the experiments described in section 5. Increased venous return to the heart due to the greater flow of the blood through active muscles cannot explain the rise of the blood pressure obtained in our experiments since the circulation through the active muscle was arrested. For this reason also the rise of the blood pressure cannot be explained by the release of muscle metabolites into the circulation, for during the period while the blood pressure was high they were confined within the exercised muscles. The effect on the general arterial pressure of sudden arrest of the blood flow through both legs and one arm was found to be negligible in normal subjects. The obstruction was effected very near to the trunk with the object of excluding from the general circulation as much of the limbs as possible. It is clear therefore that the exclusion of a limb from the general circulation will not explain the rise of blood pressure under discussion.

The secretion of adrenaline will not explain the rise of the blood pressure which we have observed for the blood pressure falls at once when

the circulation through the limb is re-established. Moreover, the subjective sensations associated with a rise of blood pressure due to injection of adrenaline are absent from our subjects.

In these experiments the sustained rise of blood pressure which persists after exercise has ceased depends upon the previous performance of muscular exercise at a time when the supply of blood to the working muscles is arrested or when the rate of performance of the work is so great that the supply of blood to the muscles is inadequate. It seems that the maintenance of the rise of blood pressure is due to the retention in the muscle of the products of muscle activity. The rise of arterial pressure takes place when, owing to circulatory arrest, nerves form the only channel of communication between the exercising muscle and the rest of the body. It becomes evident, therefore, that the rise in blood pressure is caused by the passage of nerve impulses out from the exercised muscle. Thus the increase of blood pressure which we have observed on exercise of muscles during arrest of their circulation is due to a reflex. The stimulus which starts and maintains this reflex is the accumulation of muscle metabolites in muscles. Accumulation of metabolites has occurred also in our experiments where the rate of performance of muscular work was rapid. The reflex may be excited strongly when only a small bulk of muscle is involved, thus in one experiment a sustained rise of 70 mm. of mercury followed exercise, with arrest of the blood supply, of the muscles which flex the little finger.

Although exercise of the forearm muscles with arrested circulation causes muscular pain, it was shown that in the course of the exercise the rise of blood pressure often appeared before the pain. In some experiments it was found that exercise of both the legs with arrested circulation produced more pain and a smaller rise of blood pressure than exercise of one forearm in the same subject.

The experiments of section 2 show that the rise of blood pressure does not depend upon the method employed for arresting the circulation. If the forearm is plunged vertically downwards into a bath of mercury the circulation through the lower part of the forearm is arrested because the pressure of the mercury exceeds the systolic blood pressure. Exercise performed with the forearm muscles causes a rise of blood pressure which persists so long as the forearm remains in the mercury. When the forearm is removed from the mercury and the blood flow is re-established the blood pressure falls rapidly to normal.

The rise of blood pressure, although elicited conveniently under a pathological condition, namely, during arrest of the circulation, neverthe-

less occurs under natural physiological conditions. The rise of blood pressure takes place during rapid exercise of the forearm muscles in the absence of any interference with the natural flow of blood. It is clear that during rapid natural exercise the circulation may be insufficient to prevent the accumulation of metabolites with the development of muscle fatigue. The rise of blood pressure obtained under these physiological conditions appears to be the same as the rise of blood pressure obtained when the exercise is performed during arrest of the circulation. It was shown in section 7 that if the circulation is arrested immediately on cessation of rapid exercise performed by the forearm muscles with unobstructed circulation a large part of the rise of blood pressure persists so long as the circulation remains arrested and falls to normal on re-establishment of the circulation. Thus the accumulation of the metabolites formed during natural exercise of the forearm muscles also causes a reflex rise of the general blood pressure.

Conclusions

1. A blood pressure raising reflex arising from voluntary muscles may be demonstrated in normal human subjects by a simple clinical method. The increases of systolic blood pressure, which have been secured by this reflex, range from 5 to 85 mm. of mercury. The increases of the diastolic pressure are usually less than those of the systolic pressure.

2. The reflex is elicited when the substances liberated during muscle work are caused to accumulate in the working muscle either by arresting the circulation through the muscle during its work, or by performing the work under natural conditions but at a rapid rate so that the flow of blood through the working muscle is insufficient to prevent accumulation of the metabolites.

3. High blood pressures produced by the accumulation of metabolites in voluntary muscle may be maintained at a high level by local arrest of the circulation, thus preventing the removal of the excess of metabolites by the blood stream.

4. It seems that this reflex must be designed so that voluntary muscles, as they become fatigued, may call upon the central nervous system to regulate the supply of blood in their favour. The local vaso-dilator action of the muscle metabolites ensures that the blood vessels supplying the muscle will have the full advantage of the blood pressure increase.

5. The rather large blood pressure increases which occur with exercise of small groups of muscles, and under perfectly natural conditions, indicate that this reflex from the voluntary muscles explains in part the rise of blood pressure which is found during vigorous exercise of the whole body.