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Circulatory adaptation during static muscular contractions. A review.

by Kilbom Å

Affiliation: National Board of Occupational Safety and Health, 10026 Stockholm 34, Sweden.

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Circulatory adaptation during static muscular contractions

A review

by ÅSA KILBOM, M.D.[1]

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Key words: static contraction, isometric contraction, cardiac output, heart rate, blood pressure, central circulation, regional blood flow, occupational work, blood flow distribution.

The circulatory response to dynamic muscular exercise is well known from a number of studies (3). This knowledge has been successfully put to use in the study of circulatory adaptation in many occupations where dynamic muscular exercise constitutes an important part of the total work load (3). The traditional laboratory methods are often employed in a modified form even at the work site. Thus realistic studies at the work site are possible, and good opportunities exist for measuring the circulatory load in physically heavy work of a dynamic nature.

As a result of rationalization and mechanization, many classically heavy occupations are continuously changing in character. The increased use of machines and mechanized hand tools has led to the disappearance of many physically demanding tasks, even if brief steps which cannot be automated often remain and impose heavy demands on the oxygen transport organs. However, the operation of controls and hand tools may instead call for sustained muscular contractions with an extremely limited range of movement, and thus dynamic work is replaced by static muscular activity. Static muscular activity is common not only in classically heavy occupations but also in the rapidly growing service sector. Office work, for example, may impose static loads on the back, neck, and shoulders, mainly because of unsuitable work positions. Such strain may indeed be modest in intensity, but it may still be very fatiguing because of its protracted nature. The care of sick and elderly people frequently entails considerable amounts of static muscular activity of great intensity, as in the lifting of patients.

Although static loads are thus common in many occupations, physiological adaptation has been studied far less in static muscular contractions than in dynamic muscular exercise. The present report provides a summary of some of the findings to date on the circulatory effects of static work loads. Regional and central circulatory adaptation in isolated, sustained isometric muscular contractions, as well as in combinations of static and dynamic activity, is described. Finally the assessment of circulatory strain during the static components of occupational activities is discussed.

[1] National Board of Occupational Safety and Health, Stockholm, Sweden.

Reprint requests to: Dr. Åsa Kilbom, National Board of Occupational Safety and Health, 100 26 Stockholm 34, Sweden.

DEFINITIONS

"Static muscle work" can be defined as sustained, isometric muscular activity. In contrast to dynamic work, the contraction is performed without any appreciable change in the length of the muscle. In dynamic muscle work contraction is performed with simultaneous lengthening (excentric or negative work) or shortening (concentric or positive work) of the muscle. Thus an isometric contraction produces an intermediate condition between the two forms of dynamic muscle contraction. The circulatory adaptation which occurs during isometric contractions is often compared to that which occurs during dynamic muscle work. The comparisons usually refer to concentric dynamic work which, in respect to circulatory response, differs in many ways (such as in mechanical efficiency) from excentric muscle work (4). In this review, "dynamic muscle work" will henceforth be taken to mean concentric work.

Since the activity performed in static and dynamic muscular contractions is not measured with the same parameter, comparisons of the circulatory response must be interpreted with caution. The amount of external work performed in dynamic activity is measured in joules; and the power, in watts. In static contractions the force exerted is measured either in absolute values, i.e., in newtons, or in relation to the maximal force of contraction (percentage of maximal voluntary contraction, MVC). The initial length of the involved muscle group and the position of the joint must be defined with great accuracy when force is expressed in either absolute or relative terms, as these factors affect both force and endurance (3), and maybe also circulatory adaptation. These demands can be met in the laboratory, but the difficulties become exceptional in complicated activities where the static contraction constitutes only part of the total load.

The designation "static muscular work" is often used as a synonym for static muscular contraction. Since the nature of the contraction is mainly isometric, the inclusion of the term "work" is by definition incorrect. "Work" usually requires movement, and muscular work is equal to the product of the force exerted times the alteration in the length of the muscle. There are, however, some reasons why the use of the term static "work" is likely to continue in the future, at least when the static components of occupational activities are discussed. Static muscular activity is locally more fatiguing than dynamic activity and is therefore perceived as "work." Moreover, the worker is scarcely in a position to distinguish between muscular contractions producing a change in length and those which fail to do so. Static muscular contractions demand energy and increase oxygen uptake to some extent, although not to the same degree as dynamic work.

Myophysiological conditions in static contractions have yet to be fully elucidated. Activity in the different muscle fibers probably changes during the course of contraction. It is possible that individual fibers actually shorten periodically during a contraction and thereby perform true work. However, since no external work is performed in static contractions, mechanical efficiency cannot be calculated. The energy supplied is converted to heat, which, in combination with the partially occluded circulation in static contractions, results in a rapid increase in muscular heat (17).

In the description of a static muscular contraction, the time dimension can be introduced by multiplying the force exerted by the duration in seconds. Some myophysiologists have introduced a new definition of "work" in static contraction. This definition expresses "work" as the product of torque (or force) and time. A close relationship has been found between this expression of static "work" and the time integral of the myoelectric signal (27).

The borderline between static and dynamic muscular activity is not easily defined. For example, many occupations contain sustained muscular activity in which muscle length alters slightly during contractions. Also an isometric contraction must have a certain minimum duration in order to be described as static. Repeated short-lasting contractions are more accurately described as dynamic. However, the length of time an isometric contraction must last in order to be regarded as static and the contraction rate at which activity acquires a more dynamic character have yet to be defined.

REGIONAL CIRCULATORY ADAPTATION DURING STATIC CONTRACTIONS

Regional blood circulation during static contractions can be measured with plethysmography or the isotope technique. In venous occlusion plethysmography the total blood flow in a segment of an extremity can be measured at rest and during static contraction. This technique provides information on circulation in both muscle and skin. The error of the method is relatively slight at rest but increases considerably during static activity. Regional circulation in resting or contracting muscles can be assessed with the isotope technique, but this method encompasses a large methodological error and provides only a semi-quantitative measure of the flow at a given contractile intensity. One advantage is the fact that the method can be employed with many muscle groups, such as those of the trunk, not accessible with other flow measurement techniques. It can also provide some idea as to the relative intensities at which circulation is completely occluded. Direct flow measurements employing, e.g., the dye-dilution method have only been performed with human subjects to a very limited extent (35).

Most determinations of local blood flow during static contractions have been performed on the forearm during sustained handgrips with the use of venous occlusion plethysmography (7, 19, 33, 36, 39, 40). Detailed studies of both local and central circulatory response to static contractions have been performed by Lind et al. (16, 41, 43). Their emphasis was on static forearm contractions in the form of handgrips of varying intensities, expressed as the percentage of MVC. Calf muscle work (dorsal or plantar flexion of the foot) has been employed in some studies (8, 19, 40), but methodological problems with respect to measurements of regional circulation and control of experimental conditions are more difficult than in studies of forearm contractions.

Fig. 1 shows the blood flow in the forearm, as measured by Lind and McNicol (39) with venous occlusion plethysmography, at contraction intensities varying from 5 to 30 % of MVC (5 % of MVC in the form of a handgrip corresponds to about 30 N and 30 % to about 200 N in healthy men) (6). At low intensities (less than 15 % of MVC) blood flow in the forearm rapidly rises to a level maintained throughout the continued duration of contraction. This leveling off probably indicates that the blood supply is adequate for the metabolic requirements of the muscle. At about 15 % of MVC the flow tends to increase throughout the 3-min contraction period. At 20 % and 30 %, respectively, the increase in flow during contraction is even more pronounced. At even higher contraction intensities the blood flow declines and is completely arrested at about 70 % of MVC (33). Peak values during ongoing contraction fail to exceed 20—25 ml/min x 100 ml of tissue in the forearm. Thus the blood flow at the end of contraction is related to the intensity only at contractions corresponding to less than 20 % of MVC. When the contraction intensity exceeds 15 % of MVC, endurance declines rapidly and amounts to about 1 min at 50 % of MVC.

Thanks to studies conducted by Rohmert (54), among others, endurance in a static contraction has long been known to be related to intensity (fig. 2). Contractions lasting more than 8 to 10 min can only be attained at intensities corresponding to 15 % of MVC or less, i.e., at the low

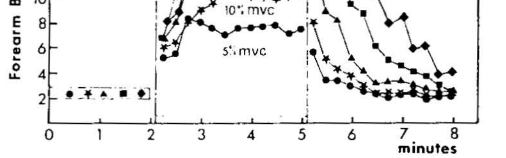

Fig. 1. Forearm blood flow in response to static contractions (handgrip) at intensities from 5 to 30 % of maximal voluntary contraction (MVC). The contraction was started after 2 min and terminated after 5 min. Note the sharp further rise in blood flow at the termination of contractions at 20 and 30 % of MVC. Data from nine healthy male subjects. [Reprinted from LIND, A. R. and MC NICOL, G. W. *J. physiol.* 192 (1967) 575—593.]

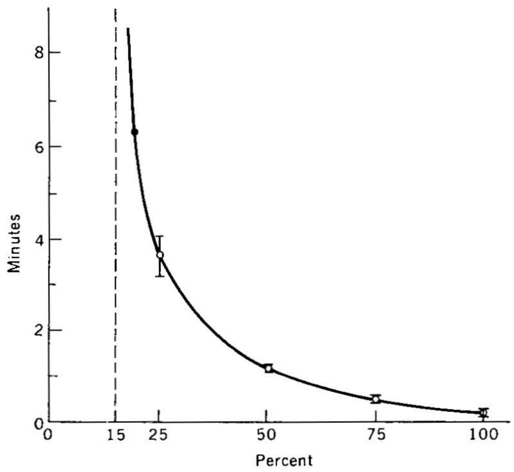

Fig. 2. Maximal endurance in static contractions of intensities from 15 to 100 % of maximal voluntary contraction. Average of results obtained from different muscle groups of 21 subjects. [Reprinted from ROHMERT, W. *Int. Z Angew. Physiol.* 18 (1960) 123—164.]

intensities at which blood supply is adequate for the requirements. Poor endurance at high intensities is probably caused by the blood supply being inadequate for the energy need of the muscle, as these requirements can be satisfied by anaerobic processes only for a very limited period of time. More support for the insufficiency of muscle blood flow (MBF) during sustained contractions is obtained by the sharp further rise in blood flow at the cessation of a contraction above 15 % of MVC (fig. 1).

During muscle contraction oxygen tension decreases, metabolites accumulate, and the pH of the muscle declines. These changes in the chemical environment constitute the most important causes of the local vasodilation arising in an active muscle (32). A considerable increase in MBF can be attained during dynamic muscle work through the combination of this local vasodilation and an increase in cardiac output. Studies conducted by Wahren (60), for example, have shown that blood flow to the dynamically working forearm is closely related to work intensity up to nearly maximal work loads. Blood flow amounting to about 50 ml/min x 100 ml of tissue have been observed in dynamic muscular work, i.e., far higher flow rates than in static contractions (23).

Thus there is a considerable difference between static and dynamic muscular activity in terms of local circulatory response. The poor capacity for the increase of blood flow in static contractions is probably due to the greatly elevated intramuscular pressure which can be recorded during an ongoing contraction. Edwards et al. (17) have shown that intramuscular pressure in the quadriceps muscles exceeds systolic arterial pressure at 25 % of MVC. Naturally the intramuscular pressure also rises during each contraction in dynamic work, but flow can be maintained as a result of the drop in pressure occurring in every muscle relaxation. This has been clearly demonstrated in the calf, in which the fluctuations in intramuscular pressure are further amplified by the muscular pump. The exact site of this vascular compression is not known for certain, but according to animal studies by Gray et al. (26) the vessels are pinched on their way in and out of the muscle.

The importance of MBF has also been investigated by measuring the endurance in static contractions with and without arterial occlusion. It has been demonstrated in different muscle groups that arterial occlusion decreases endurance at intensities varying from 20 to 70 % of MVC (8, 9, 29, 39, 58). The capacity for blood flow increase in a muscle during sustained contractions thus varies from one muscle group to another. For example, Barcroft and Millen (8) found no increase in calf blood flow during plantar flexion of the foot at 20 % or more of MVC. One reason for regional differences in blood flow during contraction may be variations in the anatomical construction of different muscle groups.

As previously mentioned, venous occlusion plethysmography gives the aggregate blood flow in both musculature and skin. Measurements of MBF suggest that the blood flow here is unable to increase to the same degree as total blood flow in an extremity segment. Employing the isotope technique, Bonde-Petersen et al. (9) measured MBF in upper arm flexors and extensors and dorsal extensors. A relationship between MBF and intensity was demonstrated in contractions requiring less than 15 to 22 % of MVC. However MBF was of no importance to endurance at intensities ranging from 25 to 50 % of MVC. There were relatively large differences between the three muscle groups examined.

CENTRAL CIRCULATION DURING STATIC MUSCULAR CONTRACTIONS

A rapid increase in heart rate can be noted at the onset of a static muscular contraction (fig. 3) (16, 24, 30, 43, 59). The speed of this increase and the absolute level attained after a contraction lasting for a few minutes are related to contraction intensity expressed as the percentage of MVC (43). Heart rates as high as in dynamic work have not been reported in conjunction with static contractions. A stable heart rate is attained, as in the case for regional blood flow, only if the relative intensity is less than 20 % of MVC.

The increase in cardiac output during static contractions parallels the increase in heart rate (fig. 3) (43). Thus the increment is continuous throughout the entire duration of contraction with intensities at or above 20 % of MVC, and very high values, although not as high as in heavy dynamic exercise, can be obtained immediately before the contraction is arrested because of local muscular fatigue. Measurements of cardiac output in conjunction with static contractions have been made in only a few studies, but the results are in close agreement (5, 22, 43, 45). Stroke volume remains essentially unchanged throughout contraction; a drop in stroke volume has however been noted at very high intensities (fig. 3) (43).

Values for the arteriovenous oxygen difference display no changes during static contractions, whereas oxygen uptake increases somewhat. Thus the relationship normally found between cardiac output, arteriovenous oxygen difference, and oxygen uptake during dynamic muscular exercise is disrupted during static contractions, and the circulation becomes hyperkinetic (43, Kilbom and Brundin to be published).

The increase in oxygen uptake is rather modest during static contractions of the forearm (43, Kilbom and Brundin to be published). A more pronounced increase in oxygen uptake, related to contraction intensity, has been reported by Wald and

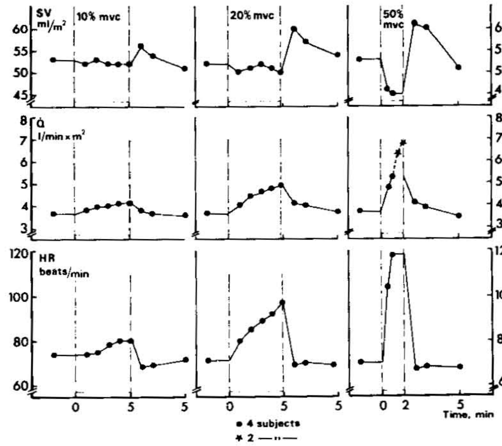

Fig. 3. Stroke volume (SV), cardiac output (Q̇), and heart rate (HR) before, during, and after static forearm contractions (handgrip) at different intensities expressed as the percentage of maximal voluntary contraction (MVC). Stroke volume and cardiac output are expressed per m² of body surface area. [The figure has been drawn from data of Lind et al. (43).]

Harrison and by Royce in static contractions of other muscle groups (arm and trunk muscles, leg extensors) (56, 61). In these cases the mass of active musculature was large, and the measured increments in oxygen uptake probably reflected the activity in the muscles responsible for the exerted force. However in static contractions of high intensity adjacent muscles which contribute nothing to the force measured are without doubt activated and induced to perform contractions of lower intensity. When a subject does not have firm support for his entire body during an experiment, muscle activity, particularly in the trunk musculature, increases in order to stabilize the body during the increasing load. Thus the increase in oxygen uptake during static contractions need not be due to increased oxygen utilization in the muscles whose force is being studied.

The regional distribution of the cardiac output between different tissues during static contractions has been discussed, but has not as yet been clarified (19, 43, 50). As previously mentioned, the increase in flow to muscles performing sustained contractions is restricted because of the increase in intramuscular pressure, and it does not account for more than a small

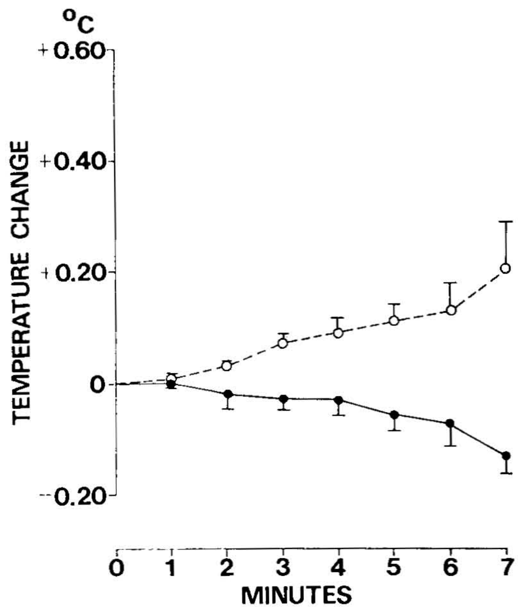

Fig. 4. Change in temperature of mixed venous blood (filled symbols) and skin (unfilled symbols) during 7 min of a static forearm contraction (20 % of maximal voluntary contraction). Mean values and the standard error of the means from four healthy men. Blood temperature was measured with a thermistor-equipped Swan-Ganz catheter no. 7 positioned in the pulmonary artery, and skin temperature was measured with a thermistor catheter inserted subcutaneously on the chest. [Data were taken from Brundin (10) and the unpublished results of Kilbom and Brundin.]

part of the total increase in cardiac output. Part of the increase in flow supplies the myocardium, whose energy consumption rises considerably due to the increments in heart rate and blood pressure (31). However the unchanged arteriovenous oxygen difference suggests that the increase in cardiac output in static contractions is mainly directed to inactive tissues. Eklund et al. (19) have shown that blood flow to the contralateral forearm increases during static forearm contraction but static calf muscle contraction does not produce any corresponding increase in the contralateral calf. Nor is there any increase of leg blood flow in a leg performing dynamic exercise during simultaneously performed forearm contraction. Therefore the increase in blood flow does not seem to be evenly distributed over the body. Studies by Nowakowska (49) have disclosed that skin blood flow increases in static contractions. In measurements of temperature in mixed venous blood and in the skin, Brundin (10) has demonstrated that the temperature of the blood declines concomitantly with an increased skin temperature during static contractions (fig. 4). Since the circulating blood tends to equalize temperature differences between different body tissues, these findings suggest that peripheral parts of the body, the skin in particular, are the main recipients of the increased blood flow during static contractions.

One of the most dramatic circulatory changes induced by static contractions is the pronounced increase in blood pressure (figs. 5 and 6) (16, 50, 59). Both systolic and diastolic pressures increase continuously during a contraction, and the increase in blood pressure becomes more rapid as the relative intensity increases. Only at low intensities is a steady-state level actually achieved, and the blood pressure response after a given period of contraction is related to the percentage of MVC employed (21, 43). The elevated blood pressure is brought about by an

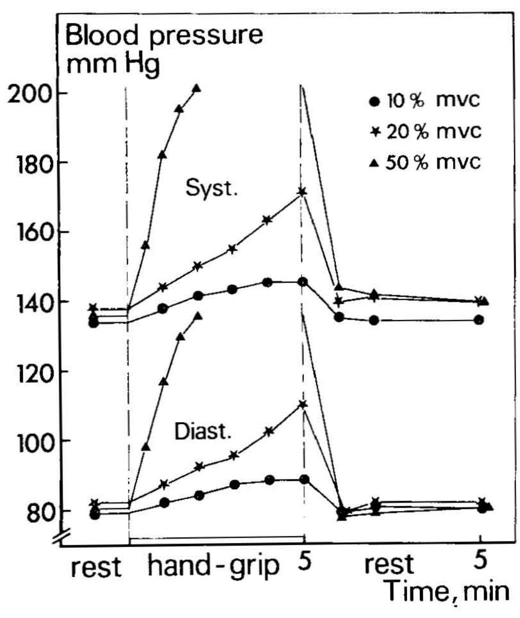

Fig. 5. Intraarterial blood pressure during sustained handgrips of 10, 20 and 50 % of maximal voluntary contraction. Mean values of four subjects. [The figure has been drawn from data of Lind et al. (43).]

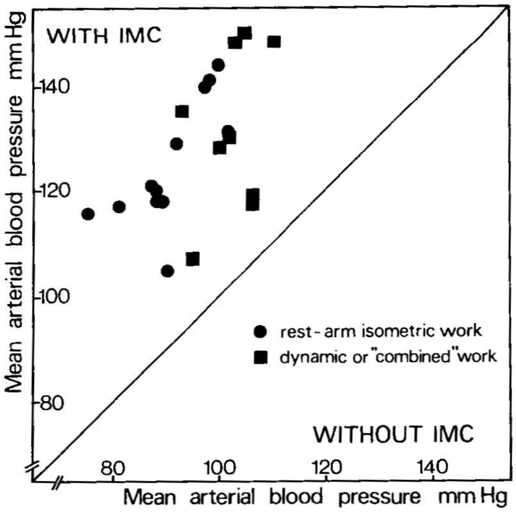

Fig. 6. Effect of static forearm contraction (handgrip) at 20 % of maximal voluntary contraction on mean intraarterial blood pressure. On the abscissa individual values from young men during either supine rest or after 6 min of dynamic leg exercise (100 W) are presented. Results obtained when an isometric contraction (IMC) was added are presented on the ordinate, i.e., blood pressures in the same subjects after 6 min of either isolated IMC or IMC combined with the dynamic leg exercise (= "combined" work). The diagonal is the line of identity. [The data have been taken from the unpublished results of Kilbom and Brundin.]

increase in cardiac output and probably also by an increased peripheral resistance (20, 45, 46).

Thus the most obvious hemodynamic effects of static contractions, i.e., the increase in heart rate and blood pressure, can be observed without the increase in oxygen uptake which normally accompanies the corresponding circulatory changes induced by dynamic muscular exercise. Even if some increase in oxygen uptake can be demonstrated, this increase is far less than that which occurs for the same heart rate or blood pressure response during dynamic exercise. Comparisons between circulatory response during static and dynamic muscular activity may be misleading since dynamic muscle work is usually studied during exercise with large muscle groups, as in running or cycling, whereas most hemodynamic studies of static activity have been made on forearm contractions. As shown by Åstrand et al. (2), there are major differences in the relationship between oxygen uptake and heart rate or blood pressure response when dynamic exercise is performed with small and large muscle groups (fig. 7). In exercise with small muscle groups, like those of the arms, heart rate and blood pressure at a given percentage of maximal aerobic power are much higher than in leg exercise. However, the difference in the size of the muscle groups active in static contractions is probably of limited importance to the central circulatory response. Thus Lind and McNicol (40) claim that the increase in heart rate and blood pressure is identical at any given relative contraction intensity, irrespective of whether small or large muscle groups are contracted.

The effect of age and sex on circulatory response during static muscular contractions, as well as reproducability and interindividual variations, has been examined in some studies (21, 48, 51, 52). Petrofsky

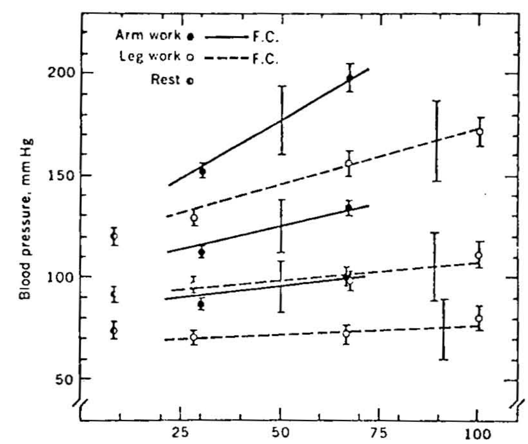

Fig. 7. Effect of dynamic exercise on arterial blood pressure. Regression lines of arterial systolic, mean, and diastolic blood pressures, respectively, in relation to oxygen uptake (in percentage of maximum) during arm and leg exercise in the sitting position for 13 subjects. F.C. = femoral artery catheter. The figure summarizes data from 23 submaximal and 13 maximal work loads with arm work (cranking) and 44 and 13 experiments, respectively, with leg work. The vertical heavy lines represent a standard deviation of ± 1 around the regression line. The dots and thin lines represent the mean ± 1 standard error of the mean for three groups of values at different levels of oxygen consumption. [Reprinted from ÅSTRAND, P.-O. and RODAHL, K. *Textbook of work physiology.* McGraw-Hill, New York, N.Y. 1970. 669 p. The data have been taken from Åstrand et al. (2).]

and Lind (52) showed that young people displayed a more pronounced heart rate increase than older people during forearm contraction corresponding to 40 % of MVC. The older subjects however had larger increases in systolic blood pressure. There were no sexual differences regarding heart rate response, but young men displayed a greater increase in systolic blood pressure than female subjects of the same age (51). However McDermott et al. (48) found no age differences in blood pressure and heart rate response in handgrips employing one-third of MVC. Differences in response between these different studies may be explained by the fact that Petrofsky and Lind performed their measurements during contraction to exhaustion, whereas McDermott measured these variables after 5 min in all subjects.

Although combinations of dynamic and static muscle work are very common in everyday life, as well as in many occupations and sports, the hemodynamic effect of different types of combined muscular activity has hitherto attracted little interest (28, 34, 40, 53). Lind and McNicol (40) studied heart rate and blood pressure response to handgrips (employing 10 %, 20 % and 50 % of MVC) superimposed on dynamic leg exercise (walking) with oxygen uptake varying from 1.1 to 2.8 l/min. The same heart rate and blood pressure response for a given handgrip was observed both at a low and intermediate oxygen uptake. However, the response was less accentuated at the highest level of oxygen uptake, at which the heart rate in particular was already elevated due to dynamic exercise. In another study (Kilbom and Brundin, to be published) circulatory adaptation to handgrips performed at 20 % of MVC, both isolated and combined with dynamic leg exercise demanding an oxygen uptake of about 1.6 l/min, was studied. The heart rate increase was less marked when the static contraction was combined with dynamic work than when it was performed in isolation. However the elevation in blood pressure was just as great in isolated forearm contraction as when this activity was combined with dynamic leg exercise (fig. 6). Thus the sharp rise in blood pressure induced by a static contraction was added to the modest increase produced in dynamic work; the result was very high blood pressure levels. Leg blood flow was measured in the same study, both in combined static and dynamic activity and in isolated dynamic leg work of the same intensity. Despite the considerable blood pressure elevation found in combined static and dynamic activity, blood flow to legs performing dynamic exercise was unchanged as compared to the blood flow level recorded in dynamic activity alone. Therefore the local vasodilation produced in leg muscles by dynamic activity must have been counterbalanced by the powerful sympathoadrenergic activation with increased vascular resistance arising in conjunction with static activity, as discussed later. However hemodynamic conditions in combined activities and the possible modifying effect of one kind of muscular activity when superimposed on another type of activity are not known in detail and merit further study.

REGULATION OF CIRCULATION DURING STATIC CONTRACTIONS

The mechanisms which control hemodynamic adaptation in static muscular contractions have not yet been fully clarified. One essential question is whether the increase in heart rate and blood pressure induced by muscular contractions is initiated via a reflex, triggered in the contracting muscle, or whether hemodynamic effects are initiated in the central nervous system (24, 30, 47). If the reaction is triggered by muscle receptors, then the fast onset of the initial heart rate increase suggests that the receptors are stimulated by mechanical stretching (fig. 8). Even involuntary muscular contractions induced by electrical stimulation of the motor nerves cause the same rapid heart rate response and thereby lend support to the theory of a reflex (30). Neither receptors nor afferent nerves have yet been identified. There are however some studies suggesting that the hemodynamic effects of static contractions may be initiated centrally or at least modified from higher centers in the nervous system (25). Thus the mere intention to perform a muscular contraction triggered an increase in the blood pressure and heart rate of subjects whose muscles

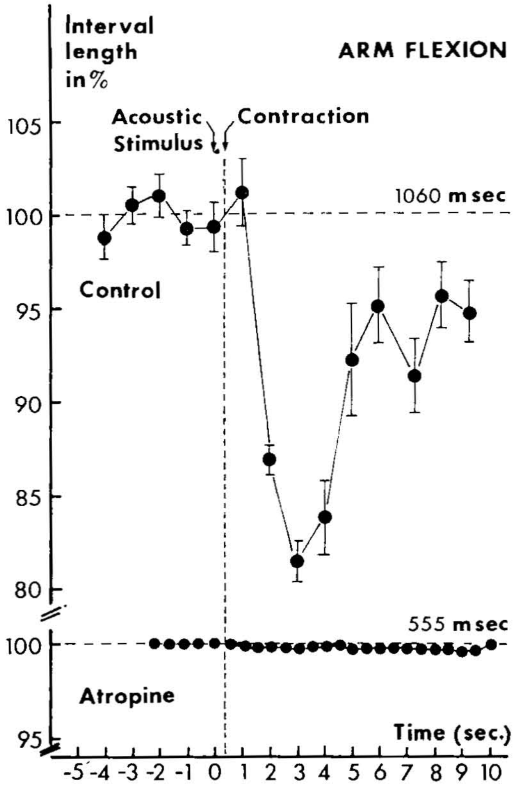

Fig. 8. Effect of maximal isometric arm contraction on heart rate before and after blockade with atropine. On the ordinate beat by beat R-R intervals (measured from ECG tracings) are presented as percentage of average resting values in the presence and absence of atropine. An increased heart rate thus gives a downslope of the curve. Before the atropine the average R-R interval was 1,060 ms, i.e., 57 beats/min, and after atropine it was 555 ms, i.e., 108 beats/min. The contraction was started after an acoustic stimulus. Note the fast increase in heart rate after the onset of contraction. [Reprinted from HOLLANDER, A. P. and BOUMAN, L. N. *J. appl. physiol.* 38 (1975) 272—278.]

were paralyzed with succinylcholine (24). The efferent nerves which govern the hemodynamic response to static contractions are apparently not the same for the responses to heart rate and blood pressure. Thus the increase in heart rate induced by static contraction does not develop after blockade with atropine but is unaffected after beta-receptor blockade with propranolol (30, 45). This result suggests that the pulse increase is mediated via a vagal withdrawal (fig. 8). During more longlasting contractions an increased sympathetic activity may be responsible for the elevated heart rate (46). Since the vagal activity is already partly withdrawn in dynamic exercise (18), the heart rate response to a superimposed static contraction, discussed earlier, will probably be less marked. A stimulation of cardiac beta-receptors is probably required to retain an unaltered stroke volume concomitant with heart rate increase. This view is supported by the fact that after propranolol blockade static contractions only produce a very slight increase in cardiac output, as compared to the increase normally recorded (45, 46). The increase in sympathoadrenergic activity during static contractions is demonstrated by the very marked increase in plasma catecholamine levels (37). Through this mechanism the peripheral resistance increases, and thereby the blood pressure is further elevated. This increase in peripheral resistance is mediated via stimulation of sympathetic alpha-receptors since blockade of the receptors with phentolamine produces a much less pronounced increase in blood pressure during static contractions (24, 46).

Another problem that needs clarification is the mechanism which interferes with or modifies the ordinary baroreceptor response to a sudden increase in blood pressure. Normally such an increase will trigger a peripheral vasodilation and a slowing of heart rate. During static contractions these effects are not obtained, possibly due to interference from higher cerebral centers.

STATIC LOADS IN OCCUPATIONAL ACTIVITIES

As already pointed out in the introduction, static loads are very common in most occupations, where they often constitute a very important cause of local muscular fatigue. Some countries have guidelines and limit values for static loads in, e.g., lifting, carrying, treading on pedals, etc. These guidelines have been worked out mainly on the basis of studies of local myophysiological conditions, such as maximal muscular force, modified with respect to differences in body size (11, 12, 13, 15). Thus consideration is seldom paid to the circulatory stress in static work, even though laboratory experiments have shown that the stress on the heart, mainly in the form of elevated blood pressure, is considerable.

Realistic measurements of the circulatory load due to static muscular contractions during occupational work have hitherto been performed in only a few studies (1, 42, 61).

Åstrand et al. (1) compared circulatory adaptation in arm work (nailing) performed at three heights: at ceiling, shoulder and bench levels (fig. 9). The actual hammering of a nail consists of dynamic work, but a static load is imposed on the back, shoulder, and forearm muscles as the work height increases. In this case work was performed on the three different levels with the same energy expenditure. Efficiency (number of nails used per minute) was found to be poorest in work at the ceiling height. Heart rate, intraarterial blood pressure, and blood lactate concentration were all significantly higher in work at the ceiling level than at the bench level. Undoubtedly the additional circulatory load produced by work at the ceiling level presents an increased risk to the elderly and to people with heart conditions.

Lind and McNicol (42) measured circulatory response (heart rate and blood pressure) in an experimental series in which a weight was carried either in the hands or with the aid of a shoulder harness. Both endurance and the maximum weight that could be sustained were greatly improved when the load was supported by the more powerful muscles of the shoulders, as was the case when a shoulder harness was used. The authors also pointed out that a fatiguing work load (i.e., where severe local muscular fatigue developed) coincided with the load at which a nonsteady state was obtained for heart rate and blood pressure, i.e., a continuous increase was recorded for these variables throughout the duration of contraction. They proposed that the upper limit value for static contractions performed with the hands, arms, and shoulders should be set at the heaviest weight or load at which a steady state for blood pressure is maintained.

Since oxygen consumption also displays a steady state in nonfatiguing contraction, it may be possible to measure oxygen up-

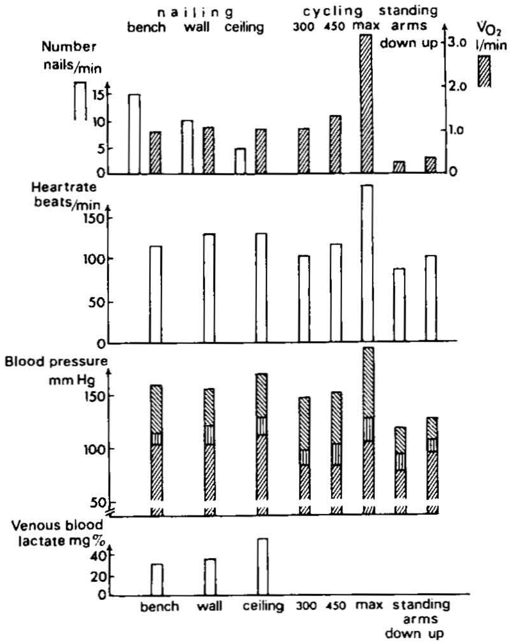

Fig. 9. Circulatory responses to arm exercise (nailing) on different heights as compared to dynamic leg exercise and standing. Nailing was performed at bench, wall, and ceiling levels. Blood pressure was measured intra-arterially, and blood for lactate analysis was sampled from a cubital vein of the working arm. [The results were obtained in eleven skilled carpenters by Åstrand et al. (1).]

take to ensure that circulatory strain is not excessive (14, 56, 61).

If static contractions of high intensity are to be performed for a long period of time, the periods of contraction must be reduced in duration, and pauses must be introduced. Aiming at a circulatory steady state, Rohmert (54, 55,) drew up detailed guidelines for the minimum duration of pauses between static contractions of varying duration and intensity. He specified a continuous heart rate increase of no more than 0.1 beats per minute as tolerable for an 8-h work day. For example, a contraction requiring 30 % of MVC and lasting for 1 min should be followed by a break lasting twice as long. With appropriate breaks it should be possible to repeat such contractions for many hours and retain a circulatory steady state. Local muscular fatigue increases exponentially as the duration or intensity of the contraction increases, and therefore a given reduction in duration or intensity may result in greatly improved endurance. Whether these guidelines, when followed, will really preserve a circulatory steady state and protect against local muscular fatigue in static contractions has however not been sufficiently demonstrated.

With the present knowledge, guidelines can probably be devised for the largest acceptable circulatory stress in static muscular contractions during occupational work. However a detailed assessment of circulatory strain and local muscular load is much more difficult to obtain outside the laboratory. As previously noted, values for heart rate, blood pressure, and oxygen uptake are related to the intensity of the contraction only when circulatory steady state is attained. During more strenuous contractions, heart rate or blood pressure measured at random cannot be related to local muscular load since no steady state exists. In addition since local circulatory adaptation varies from one muscle group to another, there is reason to assume that central circulatory variables (heart rate and blood pressure) may display varying patterns of adaptation during static contractions in different muscle groups. In those very common situations where static and dynamic muscular activities are combined, the heart rate response gives no information regarding the circulatory strain caused by the very high blood pressure. Muscular force exerted locally is often impossible to measure in occupational work. Electromyography is somewhat difficult to register at the work site, and the recordings display wide interindividual variations. However, more advanced methods for the assessment of electromyographic results are being published and should be available in the not too distant future (27). These methods can then be used, e.g., in order to obtain a measure of local static muscular load (44).

For some time now sustained isometric contractions have been used to provoke circulatory stress in patients during cardiological examinations (20, 22, 38, 57). Potentially hazardous blood pressure elevations have been recorded during such tests in patients with hypertension, and signs of left ventricular insufficiency have been found in patients with hypertension and cardiac enlargement (20, 22). Signs of impaired left ventricular function with an elevated end-diastolic pressure in the left ventricle were found during isometric contractions by Krayenbuehl et al. (38) in patients with left ventricular strain or coronary insufficiency. These findings justify increased caution in those phases of occupational activities where static contractions occur, since many patients with latent ventricular insufficiency or hypertension are still active in their occupations (50). Circulatory stress is often overlooked by the individual himself, since muscular discomfort predominates in fatiguing static contractions. It is generally accepted that elderly people and patients with hypertension or mild cardiac insufficiency should not be employed in occupations in which heavy, dynamic muscular exercise is included. However such individuals are often seen carrying out heavy, static contractions erroneously assessed as being relatively light. Thus increased awareness about static load is necessary in work site evaluations. With the aid of ergonomic guidelines, the strain in such activities can often be reduced without excessive cost or the alteration of work routines.

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