PERIPHERAL BLOOD CIRCULATION UNDER THE INFLUENCE OF OCCUPATIONAL EXPOSURE TO HAND-TRANSMITTED VIBRATION

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ABSTRACT

Changes in skin blood circulation in human subjects were examined by occlusive plethysmography, rheography, thermometry, sphygmography, capillaroscopy, and palestesiometry [sic]. Decrease of skin blood flow in fingers to 6.3 ml/100 grams of tissue per minute, increase of peripheral resistance to 12.5 kgR, and drop of skin temperature were observed. This confirmed an observed increase in skin arterioles tonus. Also observed was an increase of rheographic quotient by 50%, and the basic time of the pulse wave was prolonged by 27%. Also observed was a drop of pulse wave velocity by 10%, indicated by a lowering of tonus of the muscular and elastic vessels.

During functional thermal testing, the controls reacted by opposing changes in cutaneous and muscular circulation; the vibration-exposed group did not show this reaction. Disorders of thermoregulating function of skin circulation seem to be the cause of vibration disease.

Changes observed increased with work duration, but individual sensitivity is decisive. The manner of work and of using the tool modifies the effects of exposure. Higher values of threshold of vibration sensitivity in women (i.e., 8 dB in the frequency range of 63 to 800 Hz) indicates the importance of sex differences.

INTRODUCTION

Due to the wider and increasingly diverse application of new technologies involving vibratory hand tools, occupational hazards associated with their use have increased considerably. Hence, occupational medical researchers have become increasingly more involved in this area. Results of research in Poland and elsewhere have defined or are defining the occupational characteristics of hand-arm related vibration diseases. However, differences in the pathogenesis of disturbances to the human hand due to vibration still exist and are not well defined.

The clinical picture of vibration syndrome comprises, basically, disturbances to the circulatory, nervous, and osteoarticular systems, with particular attention to the circulatory system that, in our view, is mainly responsible for the rapid development of pathological conditions and their irreversibility.

Clinically, the first warning sign from the patient is paroxysmal blood circulation (disturbances in the palmar digital arteries), and typical symptoms include paling, at times combined with cyanosis. Subjective complaints are described as "pins and needles" (i.e., tingling), numbness, or pain in the affected area, which can last from several minutes to several hours. Coldness is commonly believed to contribute to the occurrence of these symptoms. Heat, as a rule, appears to shorten the time duration of these vascular attacks.

Disturbances to the paroxysmal blood circulation in the fingers have been described by a multiplicity of terms (e.g., Raynaud's phenomenon, dead fingers, white fingers, occupational vasomotor traumatic neurosis, traumatic vasospastic disease (TVD)), which only serves to point out the great difficulties encountered in determining the pathogenesis of changes in the circulatory system due to vibration.

PERIPHERAL BLOOD FLOW STUDY

Peripheral blood flow clinical examinations were performed on the following workers—Vibration exposed group: (a) 10 pneumatic drill operators and (b) 10 manual grinder operators (using the "Biax" type grinder). Reference (i.e., control) group: 10 workers working under similar microclimatic conditions, not exposed to vibration.

These workers were examined at ambient room temperature, consistently at 6:00 a.m. (to minimize circadian rhythm effects), for 2 consecutive days, lying on a table with arms resting level with the heart. The following tests were performed: occlusive plethysmography, volumetric plethysmography, rheography, sphygmography, phonocardiography, and electrocardiography. The results of these tests were recorded on a Cardirek-6 recorder. Figures 1 and 2 illustrate these recordings. Capillaroscopic examinations and skin thermometry were also performed. Arterial blood pressure was determined using auscultation and graphic recordings of Korotkov murmurs.

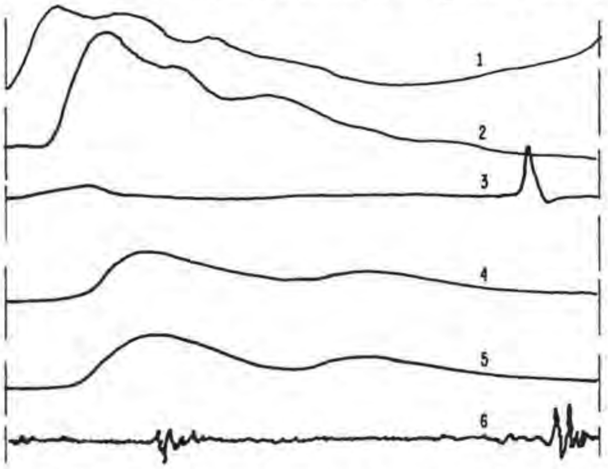

Figure 1. Polycardiographic recording of peripheral arterial pulse. 1, sphygmogram of the left carotid artery; 2, sphygmogram of the left femoral artery; 3, electrocardiogram; 4, rheogram of the left leg; 5, rheogram of the right leg; 6, phonocardiogram. (Recorder speed, 200 mm/sec)

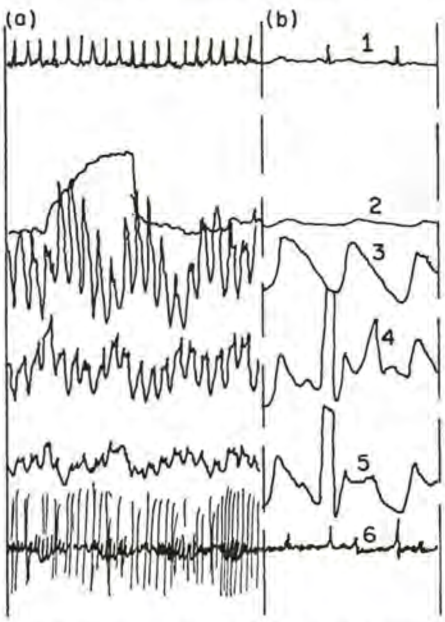

Figure 2. Polycardiographic recording of a cooling functional test. (a. speed at 5 mm/sec; b. speed at 25 mm/sec). 1, electrocardiogram; 2, occlusive plethysmogram; 3, volumetric plethysmogram; 4, rheogram of the left forearm; 5, rheogram of the right forearm; 6, phonocardiogram.

The results of these tests indicate that vascular attacks occurred in five of the pneumatic drill operators and eight Biax grinder operators. The attacks affected only the left hand of the drill operators, whereas four out of the eight symptomatic grinder operators were affected in both hands. Those subjects exhibiting vascular attacks complained of cold conditions (i.e., cold morning, or damp work gloves, or both). Three of the drill operators and four of the grinder operators reported arthritical complaints of equal intensity in both left and right upper arms. Both the objective examination results and the results of the routine analytical examinations did not exceed standard values in all the examined individuals.

In the reference group, the mean skin blood (left hand, third finger pulp) amounted to 19.8 ml/100 grams of tissue per minute under rest conditions (Figure 3). The pneumatic drill operators exhibited

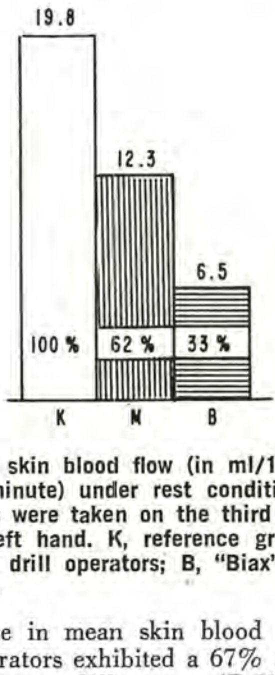

Figure 3. Mean skin blood flow (in ml/100 g of tissue per minute) under rest conditions. Measurements were taken on the third finger pulp of the left hand. K, reference group; M, pneumatic drill operators; B, "Biax" grinder operators.

a 38% decrease in mean skin blood flow, whereas the grinder operators exhibited a 67% decrease. Statistically significant differences ($P<0.01$) between reference and each exposed group were observed; significant differences between the exposed groups were also present ($P<0.01$).

Figure 4 indicates that the mean arterial blood pressure decreased only slightly in the exposed groups. Figure 5 indicates that the skin blood flow relative resistance in the reference group was 4.5 kgR. In contrast, when compared with the reference group, the pneumatic tool operators exhibited a 60% increase and the drill operators exhibited a 177% increase.

Figure 6 indicates sphygmographic detectable changes in the femoral arteries of the subjects. It ap-

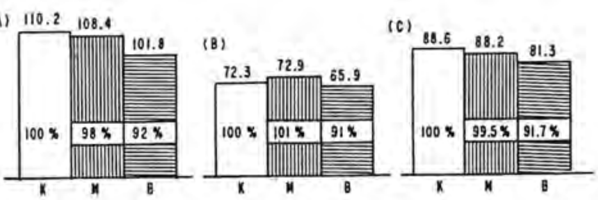

Figure 4. Arterial pressure, in mm Hg (A, contraction; B, diastole; C, mean) by means of a graphic method under rest conditions. K, reference group; M, pneumatic drill operators; B, "Biax" grinder operators.

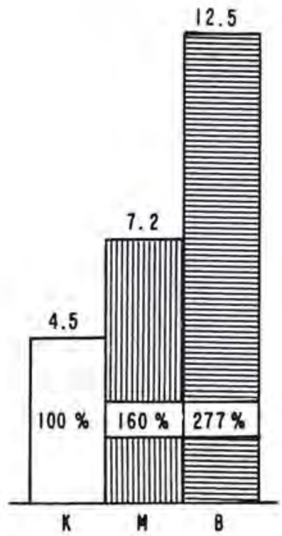

Figure 5. Skin blood flow relative resistance, in kgR, under rest conditions. K, reference group; M, pneumatic drill operators; B, "Biax" grinder operators.

pears that a long duration of the basic arterial oscillation (Figure 6A) is accompanied by a smaller dicrotic pulse wave index (Figure 6B), and a smaller pulse wave velocity (Figure 6C). The greatest changes and differences appeared between the grinder operators and the reference group.

Capillaroscopic examinations performed on capillaries of the subjects' fingernail walls did not produce a clear distinction between reference and exposed groups. In all three groups, the capillaroscopic picture was one of very thin contorted capillaries, with capillaries widening all along the walls.

To define the character of the blood flow disturbances, a thermal function test was carried out. Figure 7 depicts mean skin blood flow values obtained during the tests. Initial values of the index are designated as "0." The values within the 0 to 10 range indicate changes due to 10 minutes of cold stimulus and values ranging from 10 to 20 indicate changes occurring during recovery (i.e., after cooling). Figure 7 indicates that mean skin blood flow values were smaller throughout the test period in pneumatic drill

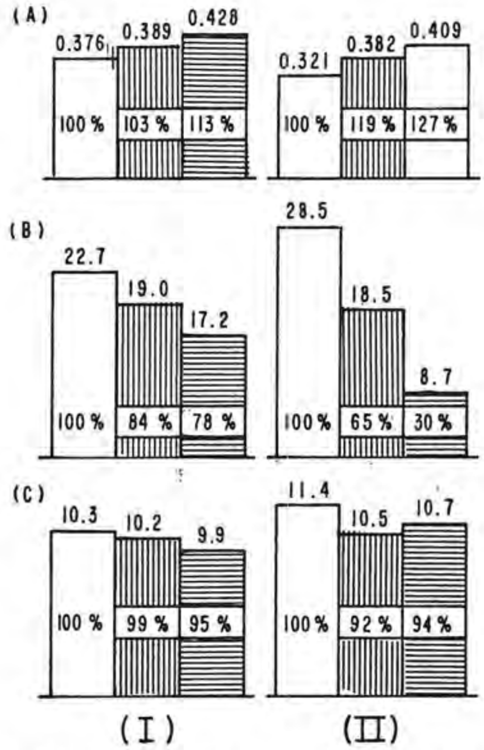

Figure 6. Sphygmographic indices of femoral arteries under rest conditions. K, reference group; M, pneumatic drill operators, B, "Biax" grinder operators; A, time of basic arterial oscillation, in seconds; B, dicrotic pulse wave index, in percent; C, pulse wave rate, in m/sec; I, left limb; II, right limb.

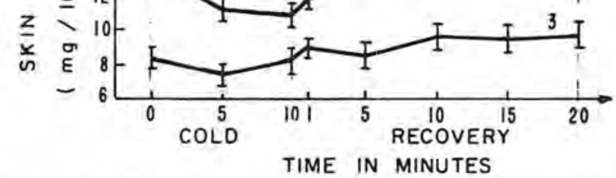

Figure 7. Mean blood skin flow during cooling function test. Measurements were taken in the third finger, left hand, during cooling. Vertical sections represent mean standard error. 1, reference group; 2, pneumatic drill operators; 3, "Biax" grinder operators.

and Biax grinder operators as compared with the reference group.

The percentage increase in pulse volume measured during cooling in left- and right-hand fingers was smaller in pneumatic drill and grinder operators than in the reference group (Figure 8).

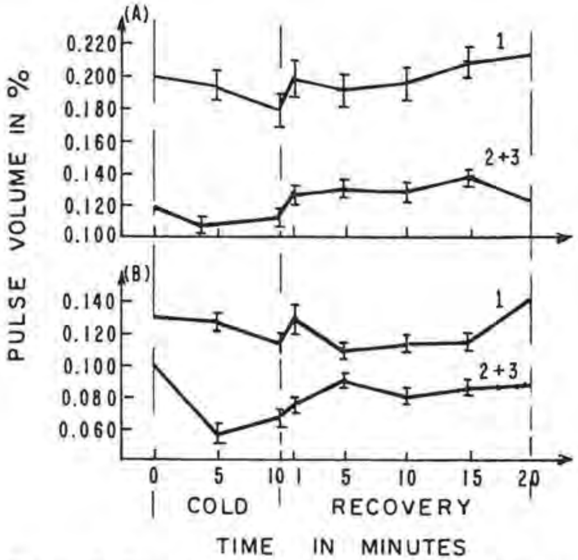

Figure 8. Percentage increase of pulse volume measured during cooling functional test. Measurements were taken on the third finger: A, left hand while cooled; B, right hand, no cooling. Vertical sections represent mean standard error. 1, reference group; 2, pneumatic drill operators; 3, "Biax" grinder operators.

It should be pointed out that during cooling two pneumatic drill operators and two Biax operators had a drop of skin temperature below +24°C in their finger pulp; a drop in percentage pulse volume less than 0.1%; and a reduction in skin blood flow below 4.0 ml/100 grams of tissue per minute. At examination time, these subjects did not report any blood flow disturbance attacks in their fingers; however, 6 months after this initial examination these subjects first reported disturbances. Thus, it appears that this test has potential merit as a prescreening test.

Figure 9 depicts rheographic quotient mean values of pneumatic drill operators and grinder operators. Their values appeared greater than those of the reference group during the cooling test. By contrast, heart rate during cooling (Figure 10) was smaller in both exposed groups than in the reference group.

ANALYSIS OF DISTURBANCE MECHANISMS OF PERIPHERAL BLOOD CIRCULATION

The basic disturbance found in persons occupationally exposed to vibration, in relation to skin blood flow in their fingers, is a reduction of blood flow resulting from either the mean arterial pressure drop or from an increase in skin flow relative resistance. Our simultaneous recordings of arterial pressure and

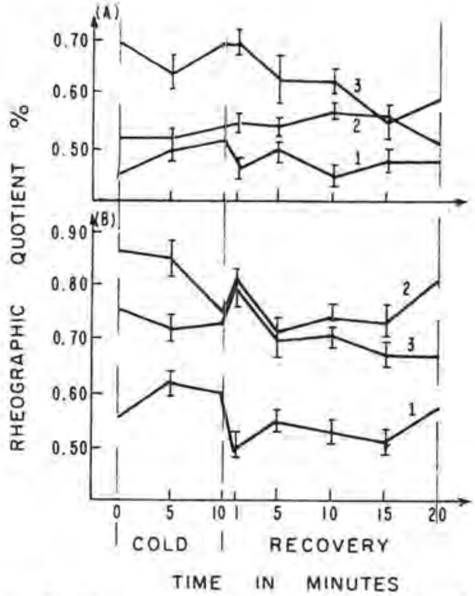

Figure 9. Rheographic quotient during cooling functional test. Measurements taken in the half next to the forearm: A, left arm, being cooled; B, right arm, no cooling. Vertical sections represent mean standard error. 1, reference group; 2, pneumatic drill operators; 3, "Biax" grinder operators.

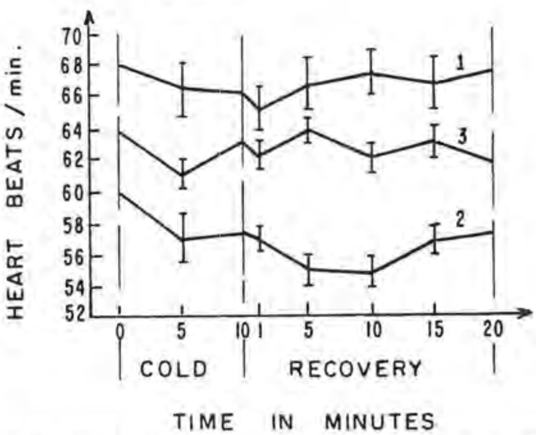

Figure 10. Heart rate during cooling function test. Vertical sections represent mean standard error. 1, reference group; 2, pneumatic drill operators; 3, "Biax" grinder operators.

skin blood flow indicates that there was a small drop in mean arterial pressure while the skin flow relative resistance in both exposed groups increased in a statistically significant manner. We can only conclude that the reduction of the skin blood flow in the fingers of the vibration-exposed workers must be related to an increase in the skin blood flow relative resistance.

Our examinations indicate that the skin temperature of pneumatic drill operators' and Biax grinder operators' fingers dropped by 3°C on the average compared with the reference group. Similarly, a percentage reduction of the pulse-volume increase was also found.

We can only conclude that there is a decrease of skin blood flow as a result of occupational vibration exposure. The left hand appears more affected under vibration, and this is not surprising since the applied vibration intensity was greater on the left hand compared with the right hand. Thus, it appears that the direct effect of vibration on the tissues closest to the vibratory source significantly contributes to peripheral blood disturbances.

There exist, however, numerous hypotheses concerning the mechanism of such blood disturbances. Some writers think a direct effect of vibration on the blood vessel muscular coat determines the development of disturbances; others stress the effect of vibration on the adventitia containing numerous coils of sympathetic nerves. On the other hand, still others attribute the main role in producing skin blood flow disturbances to the spinal vasomotor reflex. The results of our own research presented here did not provide sufficient grounds to determine which of the above opinions is, indeed, fact. Vibration, as a mechanical stimulus, affects both specific receptors and a number of other receptors and, at the same time, affects the muscular coat of the vascular wall. In the light of new research, the latter mechanism assumes particular significance. Johansson* thinks the vessel muscular coat has a high level of self-control and an ability to synchronize the reaction with a stimulus supplied by nerves. The transfer of a neurogenic reaction originated by a mechanical stimulus to deeper layers of the muscular coat is equally important. It seems the role of this mechanism of blood flow disturbances has been insufficiently determined in earlier attempts to explain the reaction to vibration.

The mechanism of direct vibration effect on the vessel muscular coat may induce organic disturbances. In our own research, only the effects upon those tissues directly absorbing vibration energy might indicate the development of changes of this kind. Even after a 20-minute heating period in water at +45°C, about 30% of the Biax operators with low skin temperature in their finger pulps failed to obtain +34°C temperature. The results allow speculation as to the organic disturbances that appear in the blood vessels of fingers of people occupationally exposed to vibration. The disturbances may originate from microinjuries of tissues caused by vibration energy absorption.

Research conducted by Romanov provides interesting data on the resonance between mechanical vibration and such subcellular structures as the actinomyosine filaments and ATP particles. The phenomena could be the direct cause of changes resulting from

Physiologically, the single most important problem is to determine the probable mechanisms of functional disturbances of blood flow resulting from vibration. Disturbances of this type generally precede vibration energy absorption by tissues closest to the source.

*References were not supplied with this presentation.

irreversible organic changes. Early disturbances often remain latent under relaxation conditions; nonetheless, there is an additional burden on the blood flow.

Our own analysis of the disturbances and changes in the examined indices during the cooling test showed greater sensitivity to cold in people exposed to vibration. Thus, in trying to establish mechanisms of this phenomenon, one must take into consideration the direct effect of cold upon the blood vessel wall (i.e., myogenic control) and the reflex reaction controlled by the vasomotor center (i.e., neurogenic control).

Abramson emphasizes a direct effect of cold upon the blood vessel wall as the most important single element for producing a vasomotor reaction. The results of our own examinations show, however, that the vasomotor reaction to cooling is more pronounced in both hands (i.e., the cooled one and noncooled one) of pneumatic drill operators and Biax operators. Also reported was a lower heart rate during cooling. There is no doubt that the vasomotor center contributes to reactions of this kind. The obtained results suggest that the cooling sensitivity demonstrated by the vasomotor center of people occupationally exposed to vibration is greater than in nonexposed people. This conclusion is confirmed by others and by our own observations, which prove that although it is often difficult to produce "dead finger" symptoms by means of local cooling of the hand using water at even 0°C, it is very easy to produce if we cool the whole body using air of +10°C temperature. This test does not produce any vascular attacks in healthy people.

The quoted data enable us to say vibration leads to disturbances of neurogenic control over skin blood flow during cooling. Greenfield et al. believe the sympathetic system determines the control level in skin vessels. Taking into consideration their research results and our own work, one must say that the increase of skin blood flow relative resistance in people exposed to vibration is due to an increase of tension of the filaments narrowing blood vessels, which accounts for the term "vasoconstriction attack" applied to "dead fingers."

There are many differences concerning the contribution of various types of skin blood vessels to these vasoconstriction attacks. Mayer-Brodnitz attribute it to the capillaries; interpretation of our own capillaroscopic examinations, however, seems to indicate that although capillaries change because of vibration, these changes do not correspond to the vasocontraction neurogenic reaction. Contracted capillaries appear not to be responsible for the characteristic paleness of the skin during attacks. Furthermore, if the capillaries actually did play a significant part in the attacks, trophic disturbances would occur more often. It seems a lack of such disturbances must be first of all related to the minimum metabolic needs of the skin. Burton found skin blood flow of 0.8 ml/100 grams of tissue per minute sufficient to meet this need. In pneumatic drill operators and Biax operators, the skin blood flow dropped to 0.3 ml/100 grams of tissue per minute during cooling. Under relaxation conditions, the skin blood flow was dozens of ml/100 grams of tissue per minute. Such large skin blood flow in fingers may only be explained by the thermocontrol function of the skin flow. From this point of view, the flow reduction may well greatly affect this significant function of skin flow (i.e., thermal control).

Based upon research into skin blood flow in the fingers, one may assume that occupational exposure to vibration results in myogenic and neurogenic vasomotor tension of arterioles and venules and simultaneous increase of neurogenic tension of arteriovenous shunts. The increased tension of the arterioles leads to a considerably higher skin flow relative resistance; with the growth of arteriovenous shunts, this tension apparently results in lumen closure. In this way, the organism is deprived of the advantages of its thermal control mechanism. Reduced heat transfer occurs with arterioles and venules contracted. Since their condition determines skin coloring, their contraction accounts for paleness of the fingers during vasculo-contraction attacks. The accompanying pain may be caused by poor oxygen supply to the peripheral nerves owing to worsened blood flow. Irritation of nerve sensory ends may also be caused by metabolites appearing in the tissue damaged by coldness. Under physiological conditions, the skin is protected by an oscillating opening of arteriovenous anastomoses so that large quantities of heat are supplied to the skin together with blood. A closure of an arteriovenous anastomosis destroys this protective mechanism. Actually, our own examinations showed either a lack or deterioration of the blood vessel opening reaction in pneumatic drill operators and Biax operators with a cold factor present.

One must also stress the point that the range of vasoconstriction attacks actually corresponds to the area where arteriovenous anastomoses occur. One must not neglect the frequent occurrence of such anastomoses in the vicinity of specific receptors of high frequency vibration; these take the form of Vater-Paccini corpuscles.

The mechanism presented here is an attempt to explain the genesis of vasculo-contraction attacks and related complaints. However, blood flow disturbances are not limited to the skin blood flow zone in fingers, though symptoms found there are the most pronounced and determine many subjective complaints.

The results of rheographic and sphygmographic tests point to disturbances and changes of the large arteries, both elastic and muscular. High values of rheographic quotient in people exposed to vibration are related to a larger rheogram amplitude. According to Kaindl, Polzer, and Schufried, a high rheogram amplitude points to reduced tensions of the examined artery walls. Thus, we can interpret the rheographic test results as a reduction of artery wall tension of the forearms and legs. The results differ from those obtained by Ross, Fusca, and Paoli who found the rheogram amplitude in people occupationally exposed to vibration was reduced. Only Malinska and coworkers found an increase of the forearm rheogram amplitude.

One cannot exclude the possibility that various methods and different exposure conditions brought about the discrepancies. It was decided to check this by simultaneously recording the pulse wave in the radial arteries by means of a sphygmograph. (Sphygmograms of the arteries, like rheograms, characterize some indicators of wall tension reduction, namely: dicrotic wave notch reduction, prolonged basic oscillation time, and pulse wave velocity rate reduction. Similar changes were found in arteries distant from the exposure site.) In this way, results obtained by means of rheography were confirmed but a prolonged exposure to vibration appears to reduce the vasomotor tension of elastic and muscular arteries.

All the obtained results allow us to suggest that there exists reduced vasomotor tension of large arteries and a simultaneous growth of the skin blood flow tension in the fingers of people occupationally exposed to vibration.

This partially accounts for the discrepancies of the results reported by others. They are due mainly to examining one flow zone and indirectly drawing conclusions concerning other blood flow conditions in the remaining zones. Such procedures are risky at best since there are significant differences in the control of separate blood flow zones.

In seeking conditioning mechanisms to varying reactions to vibration as presented by the skin and muscular flow blood vessels, one must take into account several elements. Disturbances of collagen synthesis and decomposition may lead to reduced tension of the elastic artery walls. According to Tyburczyk et al., vibration in rats results in an increased content of hydroxyproline in a water soluble protein fraction and a decrease of hydroxyproline in a nonsoluble fraction. This may produce reduced tension of the vascular wall. Kadlec even offered a hypothesis that reduction of arteriole wall elasticity may lead to compensating growth of vasomotor tension.

One must also consider the possible role of serotonin in producing peripheral blood flow disturbances. According to Markiewicz and Markowska, rats exposed to vibration had an increased blood serotonin content. Perhaps, the increased content of serotonin is the cause of the skin blood vessel contraction with a simultaneous dilatation of muscular vessels.

Prolonged exposure to vibration (similar to the action of other mechanical stimuli) may also lead to appearance of a dominant excitation focus in the cerebral cortex and, thus, to disturbances of the organism's functional balance. The disturbance may cause an insufficiency of the blood circulatory system during cooling.

Based on our polycardiographic examinations, we can draw the following conclusions: (a) occupational exposure to vibration increases the skin blood flow vasomotor tension in fingers but reduces the wall tension of elastic and muscular-type large arteries, (b) disturbances of thermal control functions of skin blood flow in fingers within the artery-vein anastomoses appear, and (c) organic changes appear in arterioles of the tissues directly exposed to vibration. The research allows us to draw several methodological conclusions: (a) polycardiography, as one method among other bloodless methods, allows one to examine the blood flow objectively and should be used to examine the functional disturbances of the peripheral blood circulation system, (b) the results of the comparative analysis of research methods points out the advisability of applying volumetric plethysmography and skin thermometry to mass examinations of people exposed to vibration, and (c) capillaroscopic and electrocardiographic tests do not reveal any changes typical of vibration and may be regarded as supplementary examinations to the above mentioned methods.

DIAGNOSTIC EXAMINATIONS OF VIBRATION EXPOSED WORKERS

A group of 300 people working as pneumatic drill operators, grinders, cast iron cleaners, moulders, metal workers, and saw machine operators were examined using a selected method. The average age and occupational experience of the reference group and groups exposed to vibration did not differ greatly statistically ($P<0.05$).

Complaints such as paroxysmal paleness of fingers were mainly reported by pneumatic drill operators (24.3%) and moulders (20%), less frequently by grinders (8.1%) and metal workers (5.3%). Cast iron cleaners did not complain. Pins and needles as well as numbness of fingers ranked first among the complaints reported by pneumatic drill operators (54.1%) and moulders (40%). Grinders and metal workers complained somewhat less often (26.3% and 5.8%, respectively).

The percentage increase in the pulse volume recorded plethysmographically in groups occupationally exposed to vibration never amounted to the level of the values obtained in the reference group (Figure 11). The differences are statistically significant under relaxation conditions ($P<0.01$), heating ($P<0.05$), cooling ($P<0.01$), and very significant in the 10th and 20th minute of the recovery period ($P<0.001$).

Attention was paid to a less efficient recovery of this index after completing the thermal test in those people exposed to vibration in comparison with the reference group.

When the results obtained in the reference group are compared with the results of the other occupational groups (Figure 12), the greatest differences in values of the pulse volume percentage increase are found in the group of metal workers, grinders, cast iron cleaners, and saw machine operators, whereas slightly smaller differences were revealed in the group consisting of moulders and pneumatic drill operators.

Values of skin temperature on the fourth finger pulp

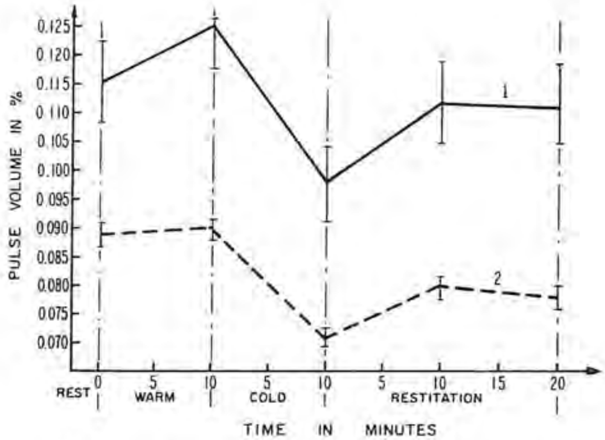

Figure 11. Percentage increase of pulse volume measured during thermal test. Vertical sections represent mean standard error. 1, reference group; 2, group exposed to vibration.

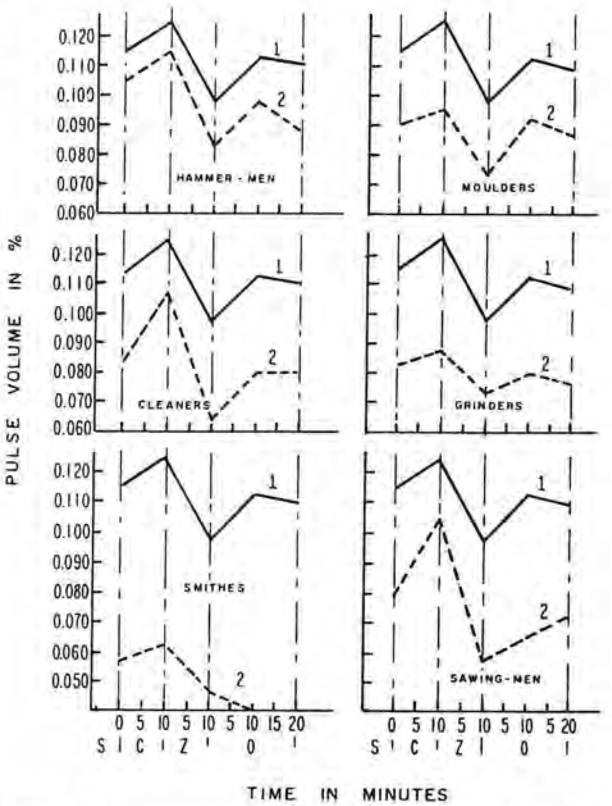

Figure 12. Percentage increase of pulse volume during thermal testing. S, rest; C, heating; Z, cooling; O, recovery period; 1, reference group; 2, individual groups occupationally exposed to vibration.

of the left hand, determined during thermal testings, were found to be smaller in the exposed group than the values obtained in the reference group (Figure 13). The skin temperature values of the left hand fingers were lower than the corresponding values for the right hand fingers (Figure 14).

Subjects whose skin temperature did not reach +34°C during a heating phase (despite a 10 minute heating using water at +45°C) are suspected of suffering from organic changes in their vessels, precluding physiological dilatation due to heat. On the other hand, a very short period of necessary heating favorably indicates the efficiency of the peripheral blood flow reaction to thermal stimuli.

The cooling phase provides a measure that provokes disturbances resembling a vasoconstriction attack typical of that elicited during vibration. Features pointing to a defective peripheral flow control mechanism while cold stimulus is present were also observed.

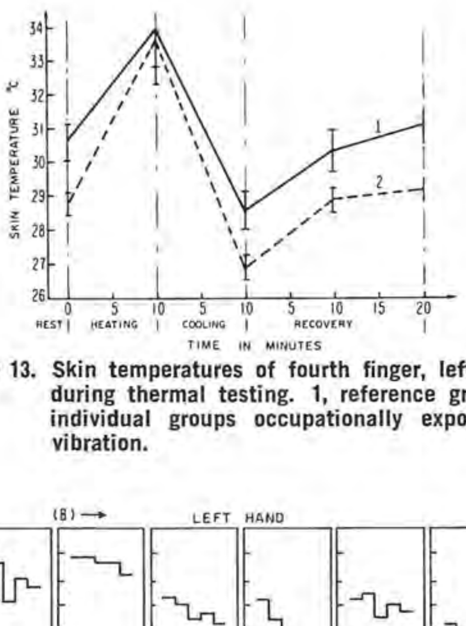

Figure 13. Skin temperatures of fourth finger, left hand, during thermal testing. 1, reference group; 2, individual groups occupationally exposed to vibration.

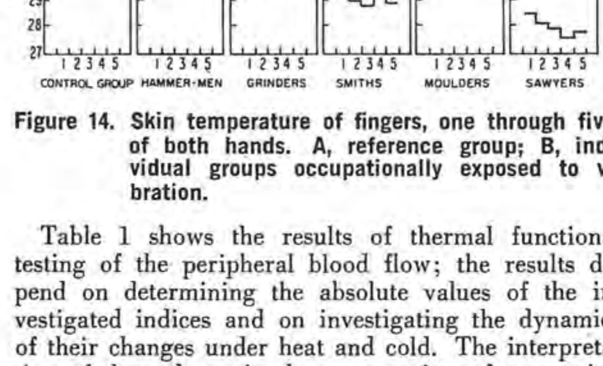

Figure 14. Skin temperature of fingers, one through five, of both hands. A, reference group; B, individual groups occupationally exposed to vibration.

Table 1 shows the results of thermal functional testing of the peripheral blood flow; the results depend on determining the absolute values of the investigated indices and on investigating the dynamics of their changes under heat and cold. The interpretation of these dynamic changes consists of comparing the values obtained in the patient during various phases of the testing.

Table 1. Standard values of blood flow indices in thermal function testing

Examined index	Test phase			
	Resting	Heating	Cooling	Recovery
Increase in pulse volume, %	0.063-0.167	0.074-0.176	0.052-0.144	0.068-0.154
Skin temperature, °C	26.5-33.7	34.0	25.5-31.7	28.2-34

THE ANALYSIS OF CHANGE IN PERIPHERAL BLOOD FLOW DEPENDING ON WORK EXPERIENCE OF PEOPLE EXPOSED TO VIBRATION

Some researchers relate the increased intensity of disturbances produced by vibration to the worker's exposure to vibration. However, there has been no confirmation of this hypothesis.

We analyzed this relation with the use of a group of pneumatic drill operators who, with the lapse of time, exhibited a gradual reduction in the percentage increase in both pulse volume values and skin temperature (Figure 15).

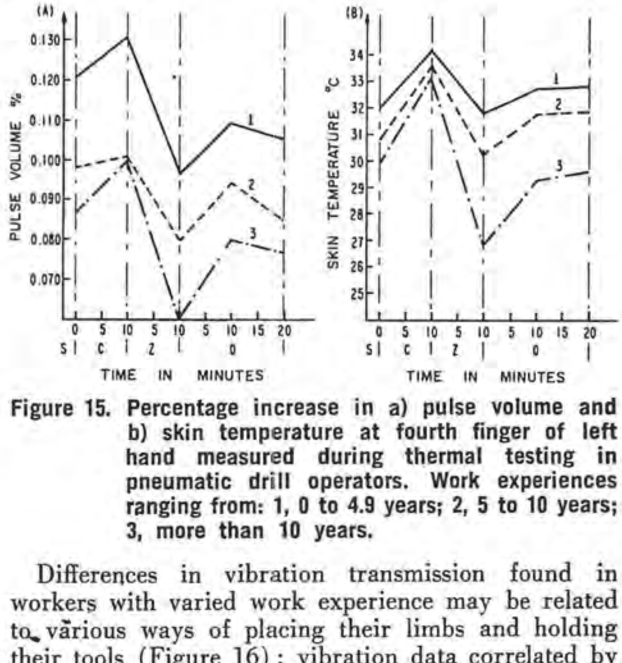

Figure 15. Percentage increase in a) pulse volume and b) skin temperature at fourth finger of left hand measured during thermal testing in pneumatic drill operators. Work experiences ranging from: 1, 0 to 4.9 years; 2, 5 to 10 years; 3, more than 10 years.

Differences in vibration transmission found in workers with varied work experience may be related to various ways of placing their limbs and holding their tools (Figure 16); vibration data correlated by an analysis of films seem to confirm these assumptions. Experienced workers tend to stabilize the position of their upper limb joints and, therefore, their body and the tools; this facilitates a characteristic vibration transmission. Inexperienced workers who have not developed a dynamic stereotype for handling the tool set their joints freely and continually change position; they thereby impart a large part of vibration energy into the small area of the hand tissue. Physiologically, this fact must be considered harmful

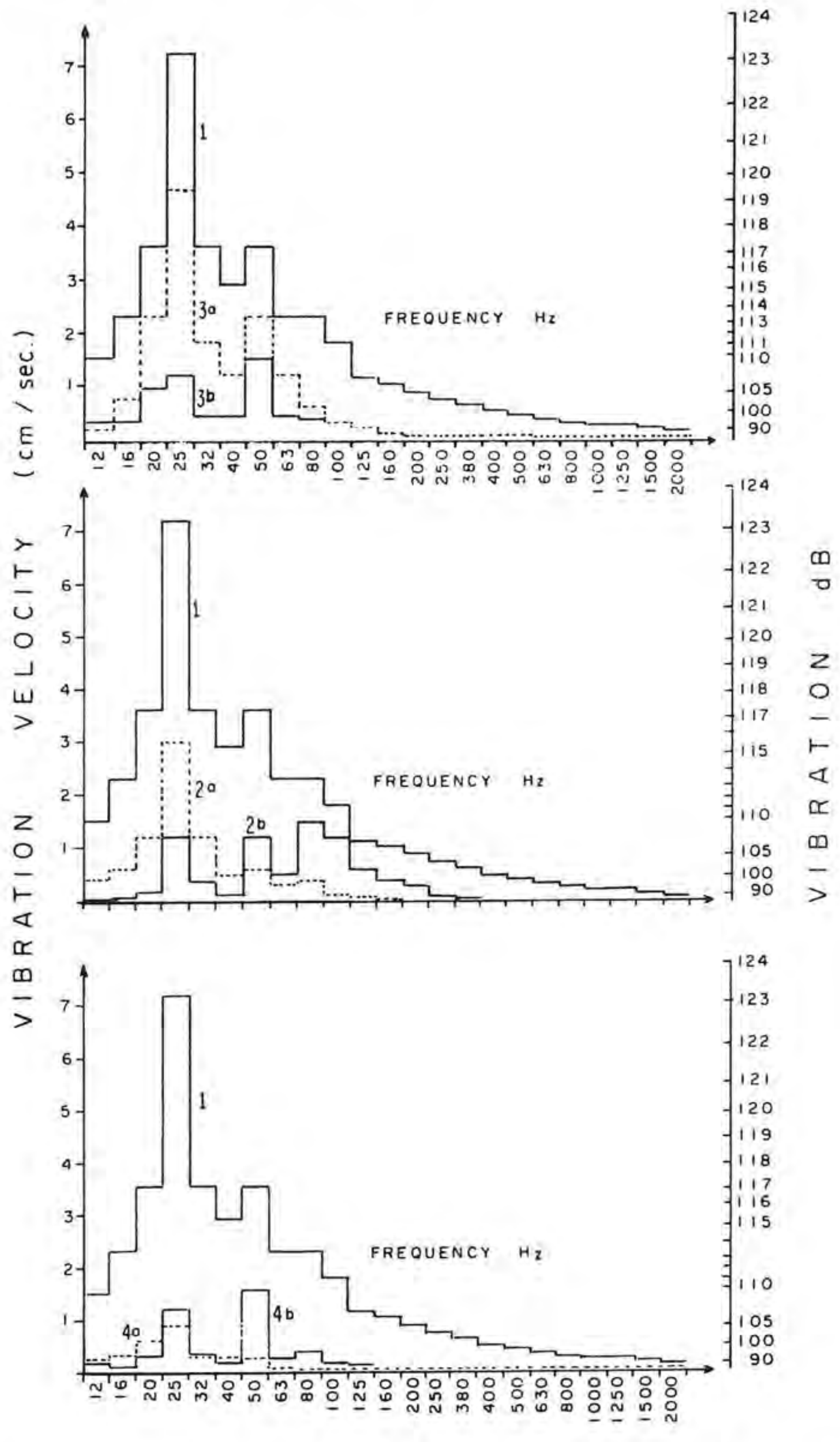

Figure 16. Values of vibration velocity as a function of frequency while operating a pneumatic drill to clean cast iron. 1, on the drill handle; 2, on wrists; 3, elbow; 4, shoulder; a, experienced worker; b, inexperienced worker.

since vibration effects depend in part on the amount of energy absorbed by the body cells. Thus, correct instructions to workers that will minimize poor work positions and shorten the working time in a bad position may prevent absorption of large amounts of energy by the worker's hands.

VIBRATORY SENSITIVITY CHANGES

In people occupationally exposed to hand-transmitted vibration, we find the vibratory sensitivity threshold generally increases. This may be determined by calculating the arithmetic mean of the vibratory sensitivity threshold for the second, third, and fourth fingers at frequencies of 250, 400, and 500 Hz, separately for the right and left hands. We use the following criteria (Table 2) in estimating the level of vibratory sensitivity disturbances applying mean values of the vibratory sensitivity threshold (in dB) for frequencies of 250, 400, and 500 Hz:

Table 2. Vibratory sensitivity disturbances resulting from occupational exposure to hand-transmitted vibration

Correct vibratory sensitivity	Negligible disturbances	Medium disturbances	Significant disturbances
up to 85 dB	86-90 dB	91-100 dB	above 100 dB

According to our work, the vibratory sensitivity threshold changes may be secondary in relation to the blood flow disturbances. It was found that (see Figure 17): (a) the values of the vibratory sensitivity threshold increase with falling skin temperature; (b) the greatest changes are observed at frequencies 400, 500, and 640 Hz; (c) individual differences in vibratory sensitivity increase with vibration frequency.

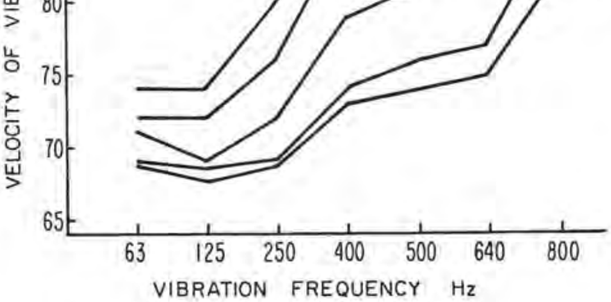

Figure 17. Curve of vibratory sensibility determined for different skin temperatures on the fingertips.

Vibratory sensitivity threshold values in women are greater than those found in men (Figure 18) particularly in the frequency range of 63-400 Hz (usually 5-10 dB), and to a lesser extent in the frequency range 500-800 Hz (usually 2.5-5 dB).

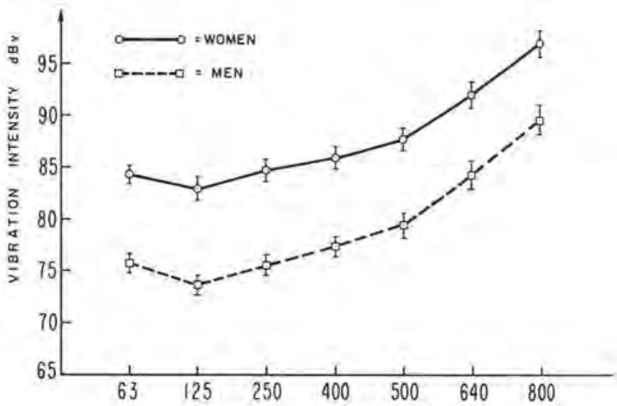

Figure 18. Values of vibratory sensibility threshold determined on the second finger, left hand, in men and women at an average temperature of 26°C.

ANALYSIS OF HOW INDIVIDUAL FACTORS CONNECTED WITH HANDLING IMPACT TOOLS (VIBRATION, NOISE, STATIC WORK) AFFECT THE WORKER

While operating or handling a vibratory impact tool (e.g., a pneumatic drill), the worker is exposed to basically three harmful factors: vibration, noise, and static loads. As far as biological effects are concerned, sometimes these factors operate synergistically, sometimes they do not—a fact of significance for disturbances occurring in the worker.

It appears that noise accompanying vibration produces considerable effects in the worker apart from its specific effect on the hearing organ. As far as its effects on the skin blood flow are concerned, we find effects resembling those produced by vibration, namely: increase in vessel wall tension and in peripheral blood flow resistance, thus greatly reducing the skin blood flow.

Handling a tool such as a pneumatic drill involves static loading in the worker due to: (a) the necessity of holding a heavy tool in the hands; (b) pressing it in order to perform a job; and (c) maintaining a bent body position.

Static work is especially harmful physiologically as it leads to disturbances of the tissue blood supply and changes of the osteo-articular system. Having considered a number of study results, we advocate that a prolonged static load should not exceed 15% of the maximum force of the group of muscles under examination. According to the data published by Assmussen et al., an average force exerted by the upper limb muscles on the tool in a horizontal direction amounts to 22.9 to 36.8 kG, depending on the height and age of the subject. Therefore, the permissible value of 15% of the maximum force is 3.4 to 5.5 kG. However, handling presently manufactured pneumatic drills requires pressures of about 20 kG, and this may be a causal factor in intensifying the adverse changes produced by vibration and noise in the worker.

Our data concerning the effect of vibration, noise, and static load indicate that all these factors have a specific adverse effect on the worker, after they have exceeded the permissible level, but their individual contribution to the development of the changes found in people handling impact tools remains unknown. Tool designers should be made aware of these parameters in designing new tools.

We designed a series of experiments to estimate the load on the worker produced by static work and noise separately.

The static work experiment consisted of holding a pneumatic drill in a working position and pressing against an electric dynamometer. Both the pressure force (50% of the maximum force) and the work-rest protocol (5 working seconds followed by 5 seconds rest) were used. In addition, a longer work-rest schedule was used: 60 minutes of work, 10 minutes of rest, followed by 60 minutes of work.

The separate noise loading experiment was performed by playing prerecorded magnetic tapes (using a Telefunken tape recorder) with actual noise recorded while operating a pneumatic drill to clean cast irons. The distance between the loudspeaker and the subject corresponded to the actual distance between the worker and his tool. Subjects were provided with hearing protection and performed activities such as counting and drawing while listening to the tape.

A combined series of experiments was aimed at determining worker reaction to a combined exposure of both noise and static work and then to three factors (noise, static work, and vibration) experienced in the working environment.

The combined load of noise and static work was obtained as follows: subjects statically pressed the tool (50% of the maximum force) while in a noise-filled room.

The three-combination situation of noise, static work, and vibration was obtained at an experimental stand, where the subject worked on a steel sample 9 mm thick with a pneumatic drill.

Experiments were performed on six healthy students (each age 20). They were divided into two groups depending on their physical fitness (assuming this could affect their response to the work environment factors). Group A had poor physical fitness (low maximal oxygen uptake, VO_2 max) and Group B, good physical fitness (high oxygen uptake, VO_2 max).

The results of the experiments (Figures 19 and 20) show differences in reactivity to vibration and noise both in individuals having good and in those having poor physical fitness. During both the combined and selective exposure to the factors, the individuals having good physical fitness reported contractions of the skin flow blood vessels and dilatation of their muscular vessels. On the other hand, people of poor physical fitness reported contraction of both skin flow blood vessels and muscular vessels. Contractions of this type may produce significant increases in peripheral blood circulation resistance and contribute to an increased loading of the heart muscle. Thus, it appears that the effect of the investigated factors upon the circulatory system in people of poor physical fitness is potentially more harmful than in the group of people with satisfactory physical fitness. The good maximum oxygen uptake criterion may be regarded as useful for selecting workers who will handle impact tools.

The results of our experiments indicate that larger loads on the worker were produced during combined exposure to vibration, noise, and static work as compared with a selective exposure to noise or to static work. Greater values of energy expenditure (Table 3), higher heart rates, and a pronounced reduction in force and muscular endurance indices accompanied by a greater hearing threshold curve were observed.

Table 3. Energy expenditure of human subjects under static work, noise, and vibratory loads

Physical fitness of group	Subject		Expenditure of energy in Kcal/min		
			Static work	Static work and noise	Static work, noise and vibration
A, poor	N.A.		3.19	3.44	4.99
	Z.M.		3.65	4.19	3.40
	K.K.		2.40	2.53	5.00
		$\bar{x}$	3.08	3.39	4.46
		S^2*	0.40	0.69	0.85
B, good	Ch.I.		3.57	3.66	5.00
	P.T.		3.23	3.53	4.96
	Ka.K.		2.77	4.39	5.00
		$\bar{x}$	3.19	3.86	4.99
		S^2*	0.16	0.21	0.0005

*S^2 = variation estimate.

On the other hand, disturbances to the peripheral circulation under combined and selective exposure to the above factors, particularly in the group of those of satisfactory physical fitness, were quite similar. A pronounced increase of the skin blood vessel wall tonus was found with a decrease in the muscular blood vessels. It may be assumed that under the 2-hour experimental exposure conditions to the factors being investigated, noise effects prevailed over effects

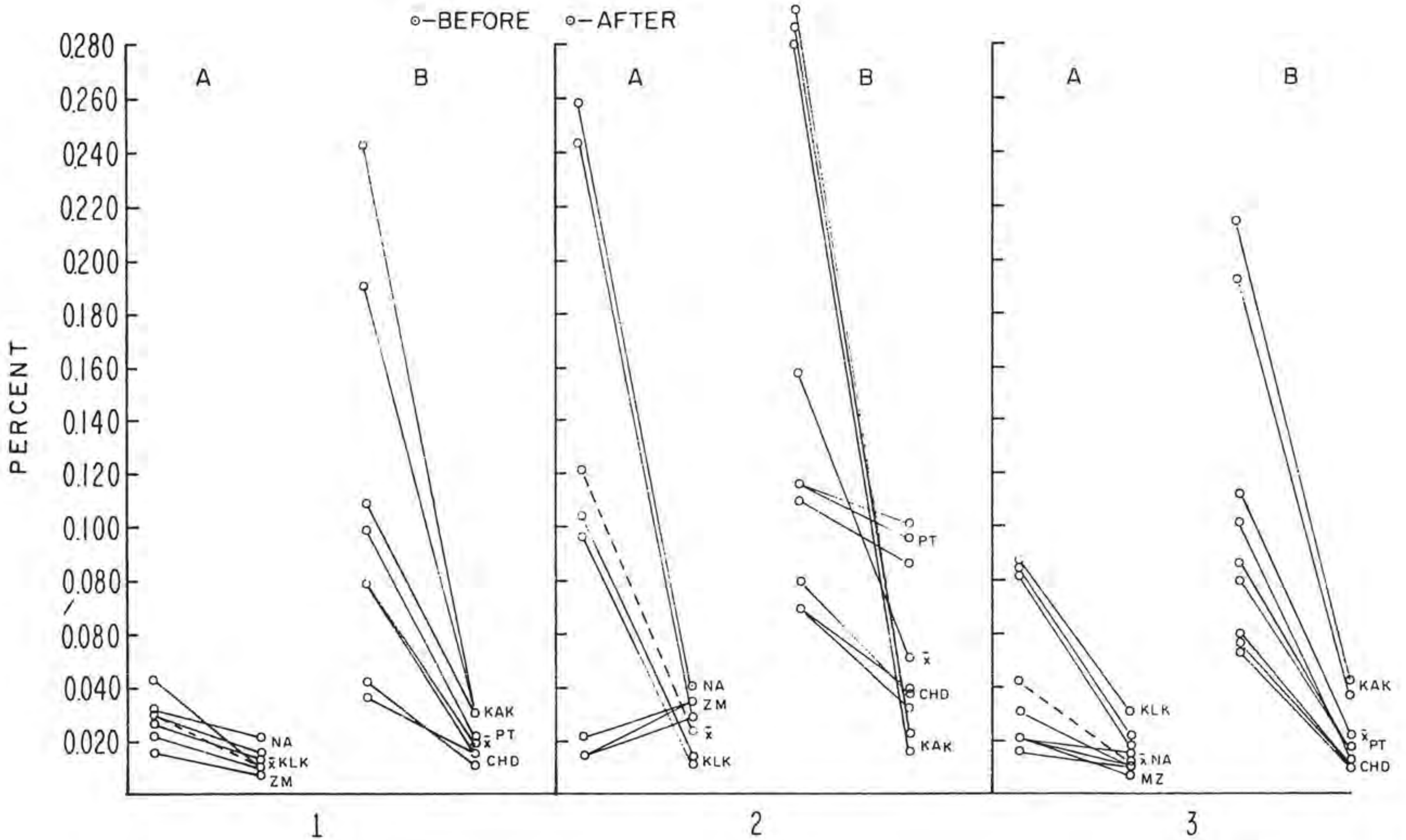

Figure 19. Changes in pulse volume (percentage increase) in the subjects in group A (with poor physical efficiency) and group B (with good physical efficiency) caused by: 1, noise; 2, noise and static work; 3, noise, static work, and vibration.

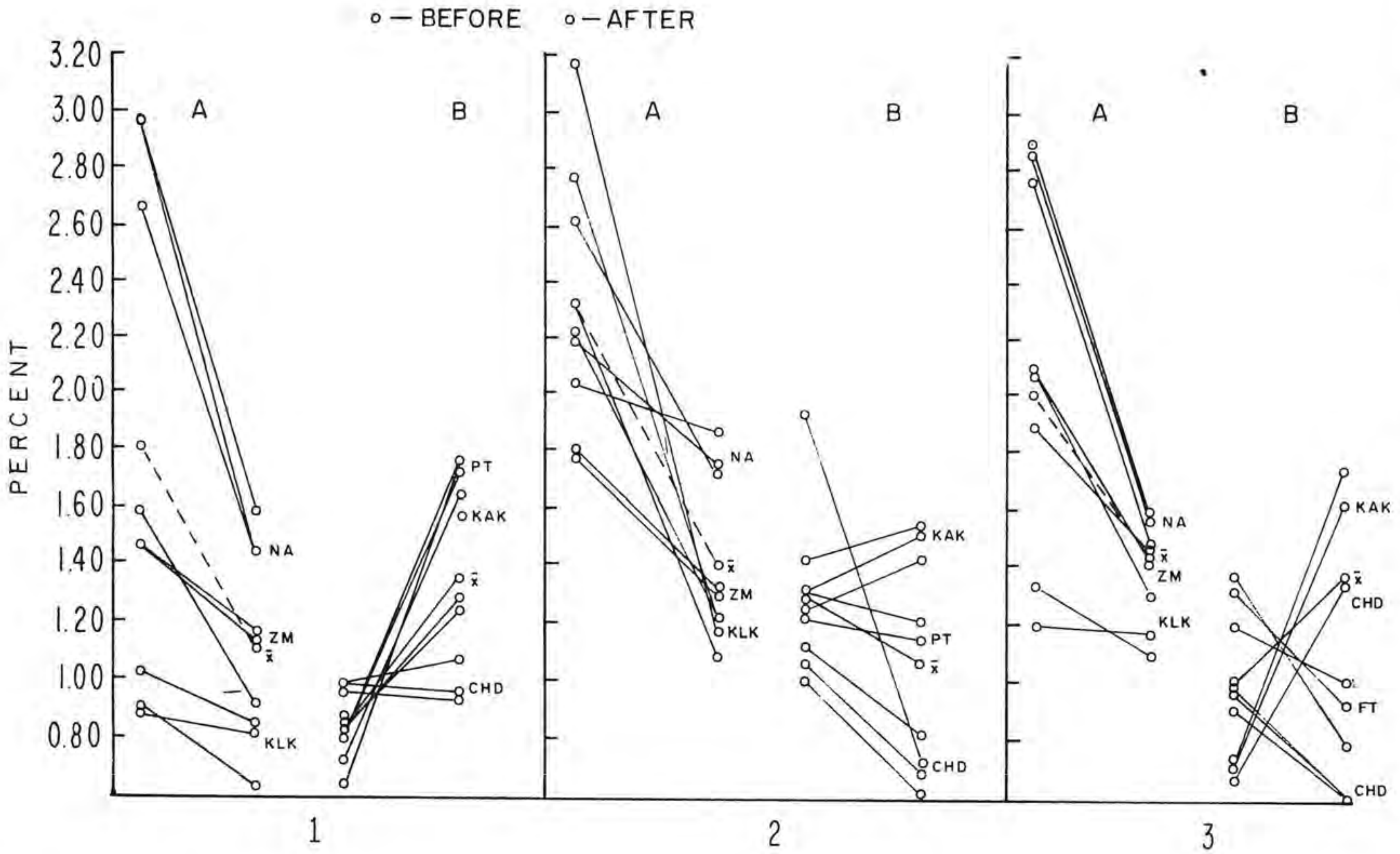

Figure 20. Changes in relative pulse volume in the left forearm of the subjects in group A (with poor physical efficiency) and group B (with good physical efficiency) caused by: 1, noise; 2, noise and static load; 3, noise, static load, and vibration.

of vibration and those of static work; after prolonged occupational exposure, apart from noise-produced disturbances, we find disturbances produced by vibration and static load. This appears to give a more complete picture of disturbances typical of vibration syndrome.

A word of caution, however; we must not draw the conclusion that perfect physical fitness and a suitable working position prevent harmful effects of vibration, noise, and static load. The basic preventive measure still is finding technical solutions to reduce the intensity of such factors. Temporarily, recommendations of proper work hygiene and physiology may constitute an important measure of preventing vibration syndrome.

NEW VIBRATION TOOL DESIGNS FROM THE POINT OF VIEW OF WORK PHYSIOLOGY AND HYGIENE

Based on our investigations, a number of new prototypes of vibration tools with reduced vibration intensity have been developed.

The prototypes were developed from the point of view of work physiology and hygiene. Performance tests were conducted on the following pneumatic tools: cutting hammers, moulder's hammers, riveting hammers. Conventional and new design prototypes were used. The tools were operated for 2 hours with a 10-minute break after the first hour. The measurements taken while operating the pneumatic tools revealed changes in a number of physiological indices, and differences occurred while operating the new types of hammers as compared with operating the older ones. The expenditure of human energy in operating the old type cutting hammer was greater (5 kcal/min) than the expenditure needed to operate the new type (3.88 to 3.93 kcal/min). The muscular force and endurance were slightly smaller while operating new types of tools (force, by 1.5 kg, endurance by 6 seconds). The threshold values of vibratory sensitivity increased while operating new tools by 5.5 db on the average, and by 7.5 db while working with an old tool. The percentage increase of pulse volume was considerably reduced when working with an old type of tool—up to 13% of rest values in comparison with 50% of rest values when working with a new prototype.

Measurements taken while operating moulder's hammers showed a smaller expenditure of energy while working with new prototypes (about 3.75 kcal/min) than while operating older tools (5.28 kcal/min). Similarly, a smaller decrease in muscular endurance during work on prototypes (18% of rest values) was observed as compared with the decrease observed while operating a hammer of the older type (31.5%). The number of errors of tremometric examinations was smaller while working with new types of tools (192) in comparison to the number of errors recorded while operating old tools (268).

Measurements taken while operating riveting hammers represented a negligible load on the worker. The expenditure of energy amounted to 3.54 kcal/min, and endurance was reduced by about 1.8 seconds on the average. The percentage increase of pulse volume dropped to 23% of rest values, and the pulse relative volume underwent slight changes.

Based on this series of experiments, we can draw the following conclusions: (1) The peripheral blood circulation index plethysmogram, rheogram, vibratory sensitivity threshold, muscular endurance, and expenditure of energy may be considered the most useful indices of estimating the loads suffered by the worker while operating vibrating tools. Values of the percentage drop of the pulse volume increase, a rise of the threshold vibratory sensitivity curve, muscular endurance decrease, and increased expenditure of energy can be taken as criteria of a comparative estimation of tools from the point of view of their potentially harmful effects. (2) Vibration tools developed with the aid of physiological designs point to the need for reducing not only the vibration level but the level of noise and static load as well. This was evidenced by smaller changes of load indices determined during a 2-hour exposure period imitating ordinary tool operation conditions.

CONCLUSIONS

In final conclusion, we can say that vibration produces changes of the organism reactivity. The most sensitive index of the organism reactivity found so far is functional testing based on vasomotor responses. All the examinations pointed to a reduction of the skin blood flow index values with a simultaneous increase in the muscular flow indices and slight changes in blood arterial pressure.

An analysis of response to functional testing was more important than the rest condition data in estimating organism functions. This study revealed a different type of peripheral blood circulation control in healthy people as compared with workers exposed to vibration. In the group of healthy people, we observed a contrary course of changing skin blood flow index values and muscular flow index values in reponse to thermal stimuli (Figure 21). Heat caused an increase of skin blood flow index values and a reduction in muscular blood flow index values. With a cold stimulus, we found a drop of skin flow index values connected with a simultaneous increase in muscular blood flow index values in the nonexposed group. In the group of workers occupationally exposed to vibration, this type of contrary change does not occur. Reactivity to thermal stimuli was very small both as far as skin flow and muscular blood flow are concerned. This indicates that there exists a stiff control characteristic for the pathological adaptation of the organism, when a reaction to a stimulus is not proportional to its intensity. We think this phenomenon is a vital factor in producing blood flow

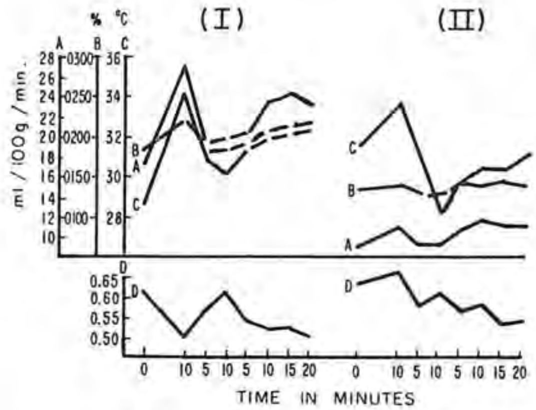

Figure 21. Peripheral blood flow reactions to local thermal stimuli in: I, healthy people; II, those occupationally exposed to vibration. A, skin blood flow index; B, pulse volume increase; C, skin temperature; D, relative pulse volume in forearm (muscular flow).

disturbances resulting in workers chronically exposed to vibration and noise.

QUESTIONS, ANSWERS, AND COMMENTARY

Question (W. Taylor, University of Dundee): Could I ask that you give us the group figures and the group graphs? Have we figures for individuals? How do we compare individuals? With the objective tests that many of us are familiar with, we are now able to separate groups readily, but when it comes to individuals we are in trouble. If you will just say a word or two about that.

Answer: Yes, we have some conclusions relating to individuals. In Poland, we have something like standardized curves for rest, heating, warming, cooling, recovery time, plethysmograms and skin temperature. And the same for vibration sensitivity. So, looking at all of these indices, we can determine an individual diagnosis. The individual changes—change among persons—are large. We often find men working with pneumatic hammers, for example, for 11 years without any change, and all is OK. Then, we find in this same workplace, men working for 11 months and having vibration syndrome. These tests of individuals help provide a set of prescreening measures for workers entering jobs.

We can find some people who possibly have some tendency towards vibration syndrome. And in a few cases, we find changes in pulse volume, skin temperature, and skin blood flow in men who have clinical symptoms. And after 1 year, they have come and told us there is something wrong with their fingers. So, these are some of the prophylactic methods now used in Poland. These methods are used in industry. Hopefully, within the next few years we will gain some practical experience. Hopefully, all people working with vibratory tools will have this type of examination. So, I think that we must wait to be sure that the laboratory methods are shown to be practical.

Question (F. Dukes-Dobos, NIOSH): We have seen a great number of different tests, and we understand that there are great individual differences: some lack of change in workers who are exposed for long time periods and some changes that occur very soon in other individuals. If we want to evaluate the individual's state of vascular disease, which test, out of the many you use, would you think is most reliable for an individual diagnosis?

Answer: I would choose the following techniques in this order: skin blood flow, pulse volume by plethysmography, skin temperature, and vibration sensitivity.

Question (F. Dukes-Dobos): Are you saying that you think the probability of obtaining a better diagnosis is greater with a large number of tests than with only one test?

Answer: Well, not in all cases; often when you use a smaller number of tests then this is better. But in the diagnosis of a vibration syndrome, I think a large battery of tests is better—principally relating to blood skin flow. However, these are experimental methods, and we must be sure before giving them to the industrial medical people. They are not very difficult, but they are experimental. Correlation with venous occlusion plethysmography and pulse volume appears to be very good; similarly, about angiography and pulse volume. The correlation between pulse volume and skin temperature is good, too. But there are very important test conditions: for example, temperature of the room, time of day the measurement was taken, skin temperature before, etc. Vibration sensitivity is also very good. We also have done some vibration measurements from 80 to 800 Hz.

Question (H. Von Gierke, Aerospace Medical Research Laboratory): Did I understand you correctly? Noise is synergistic with vibration, and that from noise alone you do not get a vibration syndrome?

Answer: No, I don't think so. Remember, this was an experimental situation. What we have is 2 hours, under experimental conditions—noise, noise and static load, and vibration—using healthy young men. And during these 2 hours you have a stress situation. And in this situation, noise is one of the main factors. But when we have normal conditions, (i.e., long-time workplace exposure) the changes in blood flow under the influence of vibration would be different from the changes in a laboratory situation. We believe the same to be true using noise.

Question (H. Von Gierke): Did you do your three tests—skin blood flow, skin temperature, and vibration sensitivity—on chronically exposed noise workers, not exposed to vibration?

Answer: Yes, we did it a few years ago, and we found differences between the control and exposed groups. This, however, is not a normal situation since vibration and noise occur simultaneously.

Question (H. Von Gierke): But you can have the situation where noise alone is present.

Answer: Yes. As I have said, but not clearing work with vibration tools. In this experimental situation, we used noise from a tape recorder. This may not be ideal, however, since you do not have a perfect noise generator, and thus, the noise spectrum is not perfect. There are differences in low frequency and high frequency spectra. Thus, it is not quite the optimum experimental situation.

Comment (A. Zweifler, University of Michigan): There have been a number of questions about tests. And what tests do you do for what. One of the things that I want to make clear is that three different kinds of questions are being asked. One question is, how do you diagnose TVD or vibration disease? Another question is, how bad is it? And the third question is, why does it occur? What are the mechanisms that underlie the development of this problem? Now these are interlocking questions as far as I am concerned, but I want to be sure that we had some consensus. I understood that there is no difficulty in diagnosing the problem. It seems to me that it is a clinical diagnosis.

The next issue is, how bad is it? And how do you quantitate the problem? And I think that the second question is one that may well be answered by something that you have going on in Poland. What is the natural history of this problem? How bad is it?

Now the third one is, why does it occur? And we have addressed that. We better be sure we are talking about the same things when we ask for tests.

Answer: In our study, all examinations were performed in the factories on men who were asymptomatic of vibration syndrome. All of them were exposed to vibration, but they were apparently healthy men. We did not look at a special group of workers who had vibration syndrome. The purpose of this examination was to find a means of early diagnosis of peripheral circulation disturbances for all workers. This is why we did a functional probe and looked at these parameters.

We tried to find early prescreening and diagnostic technicians as well as follow-up diagnostic techniques. All of them started working with these types of vibraing tools. About 30% of the workers had subjective complaints; all were clinically asymptomatic of vibration disease.

With regard to mechanisms, I think that it is interesting to observe the difference between skin blood circulation and muscle blood circulation. Of course, I am aware that there are a variety of blood flow measures that are not all the same.

Comment and Question (A. M. Ehrly): Apparently, you tried to find early symptoms of disease that could develop and you found similar changes in noise and in vibration. The problem is, in my opinion, that only a very few percent of all the people who handle vibrating tools will become vibration diseased. And some will have developed some disease symptoms and yet not develop the disease per se.

A second problem is one of diagnostic methods. Again, I think that if you do a cold exposure or you do a noise exposure, you will have the same reaction, namely a sympathetic vasoconstriction, a normalization of blood from the skin, centralization of blood flow, and you will have to show contralateral decrease in the skin blood flow. But this blood flow of the skin is not the so-called nutritional blood flow; it is blood flow necessary for thermoregulation. I have some doubt that this blood flow is for thermoregulation since if this level is decreased, it may be a symptom of necrosis or tissue ischemia, later on.

Answer: I think that it is important to realize that the vibration produced a change in thermal function of the peripheral circulation, not in metabolic function. It is not the same as when we think we have some necrosis or other problem. It is very difficult to precisely determine changes in thermal function of the peripheral circulation to the same point at which vibration syndrome occurs.

Comment (W. Taylor): I do not think we would all agree with you, but it is a point of view.

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Public Health Service
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