Cardiovascular Reflexes during Vibration Stress

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Summary: Vibration disease due to hand-held vibratory tools has various symptoms and signs which can be characterized by the severity. They include disorders of the central and autonomic nervous systems, as well as peripheral system disorders. The mechanism of Raynaud’s phenomenon in vibration disease is proposed to be: Vibration and cold affect the local vessels and nerves directly, leading to enhanced release of chemical vasoconstrictors. Vibration, noise, cold, ergonomic and biodynamic conditions, and emotional stress during work result in disorders of the central and autonomic nervous systems. In the early stages, the autonomic nervous system may be stimulated, and in the later stages it is suppressed. When local vessel injuries and disorders of the central and local autonomic nervous mechanisms controlling the vessels occur, vasoconstrictions in the fingers develop when the whole body is exposed to cold. The cardiovascular system, other than the peripheral circulatory system, may adapt to vibration stress. The adaptation subsides 7 to 8 years after discontinuation of the use of hand-held vibratory tools.

Key words: adaptation — cardiovascular reflexes — Raynaud’s phenomenon — vibration disease

Introduction

Workers operating hand-held vibratory tools are exposed to vibration and mechanical noises generated by the machines. Hand-arm vibrations transmitted from hand-held tools to local and distant organs lead to disorders of the peripheral circulatory and nervous systems, as well as injuries of the bone-joint system. When vibration disease was recognized as an occupational disease, the patients were found to have many symptoms and signs including disorders of the central and autonomic nervous systems, as well as disorders of the peripheral circulatory, nervous and muscular systems (Matoba et al. 1975a, 1977a). The symptoms and signs of vibration disease due to the use of hand-held vibratory tools were characterized by the severity of the disease. The more severe the patient was, the more symptoms and signs that appeared. It has been a point of controversy whether the autonomic nervous disorder occurs in workers who habitually operate vibratory tools. To resolve this problem, the definition of the disease must first be clarified. In the Ministry of Labor in Japan, the disease entity is defined as disorders elicited by working with hand-held vibratory tools. This definition of the disease entity is reasonable for an occupational disease. Consequently, the genesis includes vibration, noise, cold, ergonomic and biodynamic conditions, and emotional stress in work (Matoba, 1979). It should not be restricted to vibration alone, although some investigators have emphasized the vibration (e.g. Dupuis and
Gemne, 1985). In the present paper, a selective review of the cardiovascular reflexes during vibration stress will be described with particular reference to the central autonomic nervous system.

1. Pathophysiology of Raynaud’s phenomenon due to hand-held vibratory tool work

The pathophysiological mechanisms of Raynaud’s phenomenon have not yet been clarified. Raynaud in 1862 suggested that the vasospasm was mediated through central sympathetic nervous impulses (Raynaud, 1862). Contradictory to this, Lewis (1929) advanced a theory that an attack of Raynaud’s phenomenon was produced only by defects in the nerve endings with no role of central sympathetic nervous impulses (Lewis 1929). The sympathetic nervous system provides the predominant control of cutaneous blood flow and is responsible for the large variations which occur during thermoregulatory adjustment to different environmental conditions. Exposure to cold or emotion results in selective vasoconstriction of arteriovenous anastomoses. The contraction of the vascular smooth muscle within the vessel wall of shunts is mediated by sympathetic stimuli and facilitated by activity from the vasomotor nuclei in the medulla oblongata, which are continuously adjusted by the thermoregulatory center in the anterior hypothalamus.

Long-term use of hand-held vibratory tools has been recognized as a cause of Raynaud’s phenomenon since 1911 (Loriga, 1911). Many theories for the pathogenesis have been proposed, but none have been proven. Needless to say, it is impossible to find methodologically direct evidence for the pathogenesis of vibration-induced Raynaud’s phenomenon except from biopsy findings of arteries and nerves in the fingers (Ashe et al. 1962; Hashimoto and Craig, 1980; Takeuchi et al. 1984). Research should be conducted to find circumstantial evidence concerning the true pathogenesis of vibration disease.

Seven possible mechanisms for vasospastic attacks were proposed by Olsen (Olsen, 1987). The digital arterial closure in response to cold exposure might be due to 1) central sympathetic reflexes, 2) anatomic changes of the arterial wall or lumen, 3) local nervous mechanisms, 4) circulating vasoactive substances, 5) locally released vasoactive substances other than those released from nerve endings, 6) intrinsic myogenic mechanisms, or 7) intrinsic passive mechanisms. In particular, both a hyperreactivity of the central sympathetic nervous system and a dysfunction of the peripheral sensory nerve fibers may be related to the occurrence of Raynaud’s phenomenon (Olsen and Petring, 1988). Both a central and a local component must occur.

Pyykkö et al. (1982a) described a hypothetical mechanism for vasospasms in vibration-induced white finger on the basis of their investigations. Noise, body cooling, and vibration induce a strong response in the central nervous system, which increases the efferent activity to the vessels, leading to vasoconstriction. It is plausible that the afferent reflex arc for the vasoconstrictor reflex is triggered by activation of the Pacinian corpuscles. Locally applied vibration causes a strong alerting response in the central nervous system and may trigger vascular reflexes, which could operate through the spinal cord as well as through higher centers in the central nervous system. The combination of noise and vibration directed at the abdomen of a conscious rabbit enhanced the brain activity, including the midbrain reticular and frontal motor cortex (Pyykkö et al. 1982b). The increase was strongest at a vibration rate of 120Hz. An excess of vasomotor tone secondary to sympathetic hyperactivity was also hypothesized to exist in workers affected with Raynaud’s phenomenon in their fingers (Drogitchina and Metlina, 1967).
From a history of vibration disease and finger-pulse plethysmography during vibration exposure, the vasospasms in workers using chain saws were triggered by body cooling and chain-saw noise (Hyvärinen et al. 1973). In the present experiments, digital plethysmography combined with auditory stimuli indicated that the patient with vibration disease associated with Raynaud's phenomenon had some disorders of the central sympathetic nervous system (Matoba et al. 1975b, 1981). After confirming the stabilization of the amplitude of the digital plethysmogram, auditory stimuli at a noise level of 90dB were given to the subjects through headphones for 10 seconds. With reducing amplitudes the responses to auditory stimuli began at 2.9 sec from the commencement of the stimuli in the controls and at 3.1 sec in the patients. In the controls, the reduced amplitude rapidly reverted to the prestimulation level. However, the recovery of the patient was delayed (Fig. 1). Theoretically, the hypothalamus and the limbic lobe in the brain are excited by auditory stimuli, leading to an increase in nerve impulses and arterial constriction. The vasoconstriction could reduce the amplitude of the digital plethysmogram. Consequently, changes of the amplitudes of the digital plethysmogram by auditory stimuli may reflect the sympathetic nervous tone. This hypothesis was supported by some pharmacological results. The excitation of the brain by L-DOPA resulted in a greater reduction of the amplitude of the plethysmogram in response to auditory stimuli, lasting after the cessation of the auditory stimuli. On the contrary, sulpiride, a blocker of dopamine receptors (D2), suppressed the decrease in amplitude by the auditory stimuli because of an inhibition in the hypothalamus. Thus, this method can estimate the level of sympathetic activity. The patterns of the responses to auditory stimuli were classified into 4 types. The N type was normoreactive, the I and D types were hyperreactive, and the P type was hyporeactive. This classification paralleled the concentrations of urinary catecholamines. The D type had the highest, and the P type had the lowest.

The relationship between the activity of the sympathetic nervous system and skin temperature was observed using thermography with auditory stimuli.

![Fig. 1. A typical digital plethysmogram induced by auditory stimuli in a control subject (A) and a patient with vibration disease (B). In the patient, the amplitude was reduced by the auditory stimuli and did not recover within 60 sec.](image-url)
In healthy men, the skin temperature, which was reduced by the auditory stimuli, recovered rapidly after cessation of the stimuli. In contrast, the recovery in patients with vibration disease was delayed. Administration of L-DOPA suppressed the recovery of skin temperature, and sulpiride enhanced the recovery of skin temperature. Fig. 2 shows the relationship between changes of skin temperature, expressed as percent changes in total radiant power, and the sympathetic nervous tone or the incidence of Raynaud's phenomenon. The slow recovery of skin temperature after the auditory stimuli was related to an increase in the sympathetic tone (D type) and moderately related to the incidence of Raynaud's phenomenon (B type). The poor recovery type was related to the hyporeactive type of autonomic nervous tone and had a high incidence of Raynaud's phenomenon. These findings indicate that the autonomic tone becomes hyperreactive and then falls into the hyporeactive range with the advancing severity of the disease (Matoba et al. 1975c). There was a significant correlation between the N, D and P types, the level of autonomic activity, and A, B and C in the incidence of Raynaud's phenomenon (p<0.05).

Recently, Vayssairat et al. (1987) concluded that Raynaud's phenomenon in chain saw users may be elicited by both a central nervous system dysregulation due to cold, noise, and vibrations, and an abnormal cold vascular tone of the digital arteries caused by a local defect.

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![Fig. 2. The relationship between changes of skin temperature and autonomic nervous tone (A) or the incidence of Raynaud's phenomenon (B). The patients with hyperreactivity of the autonomic nervous system or moderate Raynaud's phenomenon had a slow recovery of skin temperature after cessation of the auditory stimuli.](image-url)
Thus, several studies over the last few years have strongly supported the concept that the disorders in the central autonomic nervous system are similar in patients with Raynaud's phenomenon and in patients with vibration disease.

The decrease in digital blood flow can result from many local factors. A decreased luminal area of the digital artery may be induced by enhanced alpha adrenergic responses, anatomic luminal occlusions, and local mediator abnormalities (Smith et al. 1985). Local mediator abnormalities include relaxing factors and constriction factors. A decrease in relaxing factors, such as endothelium-derived relaxing factors (EDRF) and prostacyclin, and an increase in constricting factors, such as thromboxane A₂ and endothelin (Yanagisawa et al. 1988), a newly discovered potent vasoconstrictor peptide derived from the vascular endothelium, may be related to the occurrence of Raynaud's phenomenon.

Physiologically, vibration enhanced the responses of canine femoral arterial strips to noradrenaline, particularly after cessation of the vibration load (Azuma et al. 1982). In the assessment of animal experiments, however, responses to vibration may differ for each species and each artery.

Ekenvall et al. (1988) described the relationship between blood flow and pain. Patients with vibration-induced white finger had higher pain thresholds than controls during vibration exposure to their index fingers. The changes of blood flow to mechanically and thermally induced pain were prominently different in patients with vibration white finger and healthy controls. The controls demonstrated vasoconstriction in response to pain stimulation, whereas the patients had no or weak vasoconstriction in response to the stimulation. It was concluded that sympathetic vasoconstrictor nerves or receptors were affected in vibration disease. It is natural to include central and local sympathetic nervous dysfunctions.

Histological abnormalities were noted in the arteries and nerves of the fingers (Takeuchi et al. 1984). The muscular layers of the arterioles had intense thickenings with considerable hypertrophy of individual muscle cells without intimal fibrosis. Periarterial fibrosis and collagen formation were also noted. In the peripheral nerves, there was demyelinated neuropathy with a remarkable loss of nerve fibers that were replaced by collagen fibers and an increase in the number of Schwann cells with large amounts of collagen formations. The electron microscopic study revealed almost the same findings in the vascular endothelial cells and nerves (Hashimoto and Craig, 1980). A significantly decreased number of capillaries was also observed in the chain saw operators with Raynaud's phenomenon, as compared to the control subjects (Vayssairat et al. 1987).

A theoretical scheme for the pathogenesis of Raynaud's phenomenon in vibration disease can be proposed, as shown in Fig. 3. In the first step, vibration and cold affect the local vessels, directly. Disorders of the central and local autonomic nervous systems may be induced by the vibration, noise, cold, and other stressors during work with vibratory tools. In the peripheral vessels, repeated exposure to these stressors produces histological injuries and ischemia of tissues and organs. Under these conditions, the chemical substances for vasoconstriction may readily be released from the intima of the affected vessels. In the second step, vasospasm of the affected vessels may be provoked by cold exposure, associated with the enhanced release of chemical substances from the endothelium. No regulation from the central and local autonomic nervous systems was noted. In conclusion, the vasospasm in vibration
diseases can occur as a result of disorders of the central and local autonomic nervous systems in addition to the histological injuries of the local vessels and nerves.

2. Clinical features of cardiovascular reflexes during vibration stress

Cardiovascular reflexes other than the peripheral vasospasm will be reviewed. The left ventricular ejection fraction (EF) calculated from the end-diastolic and end-systolic dimensions in the echocardiogram expresses a comprehensive left ventricular function. A significantly increased EF was observed in patients with vibration disease, as compared to the controls (79±4% vs 75±6%; p<0.01). The cause was an increase in the left ventricular end-diastolic dimension (Matoba et al. 1983). The increase in EF was proportional to the sympathetic nerve activity. The EF for the hyperreactive type was the highest, and for the hyporeactive was the lowest. The stroke volume index in the patients was also significantly higher than in the controls (24.2±6.9 vs 16.4±4.9 ml/beat/m²; p<0.001).

Boventi (1986) described a significant inverse relationship between urinary free catecholamines and the duration of the left ventricular ejection time index (LVETI) under resting conditions. In workers with Raynaud’s phenomenon, the concentration of urinary catecholamines was the highest and the LVETI was the shortest. This result indicates that the level of sympathetic nerve activity is higher in vibration-exposed workers than in controls.

The prevalences of ST segment depression and negative T waves in the electrocardiograms of subjects with vibration disease were significantly lower than in the population survey (3.0% vs 11.6%) (Matoba et al. 1977; Kimura et al. 1979; Miyamoto et al. 1984). In 481 workers occupationally exposed to vibration and noise, the prevalences of left axis deviation and incomplete right bundle branch block were significantly greater than in controls. Prolonged PQ intervals and low QRS amplitudes were significantly less frequent in the workers (Idzior-Walus. 1987). The ratio of T waves to R waves was significantly greater than in the controls (Matoba et al. 1983).

Fig. 3. A hypothetical scheme representing the pathogenesis of Raynaud’s phenomenon due to the habitual use of hand-held vibratory tools.
According to clinical data from 300 patients with vibration disease (Matoba et al. 1977), the prevalence of hypertension was 7.7%. Nerell and his collaborators reported an incidence of 8.9% (Nerell, 1974), and Bogolepov et al. (1978) reported a rate of 4.3%. These prevalences were significantly lower than those in the general population in Japan and other countries. In contrast, the mean systolic blood pressure in 1780 workers was significantly higher than the pressure in the national survey of Japan (Kurumatani et al. 1988). The patients with vibration disease had comparatively low pressures: Systolic and diastolic blood pressures in the vibration patients were $123 \pm 8$ (mean $\pm$ SD) mmHg and $74 \pm 7$ mmHg, respectively, whereas blood pressures for the controls were $135 \pm 19$ (mean $\pm$ SD) mmHg for systole and $79 \pm 7$ mmHg for diastole. This was a statistically significant difference ($p<0.001$).

An enlarged heart, confirmed radiologically, was found in 20.0% of the subjects. Sinus bradycardia (less than 50/min) at rest was noted in 12% of the patients. Kurumatani et al. (1988) reported that bradycardia showed a rate of 6.7% in 953 chain saw workers, which was 2 to 5 times higher than in the general Japanese population.

Thus, the cardiovascular features include sinus bradycardia, an enlarged heart, an increased left ventricular ejection fraction and a shortened left ventricular ejection time index at rest. Blood pressure is usually lower than normal. These symptoms and signs of the cardiovascular system are similar to those frequently observed in endurance athletes (Scheuer and Tipton. 1977). Overall, vibration stress may not injure the cardiovascular organs very much.

Bodily reactions during chain saw work were studied in 14 subjects (Matoba et al. 1985). The subjects were divided into three groups (control, sulpiride, and propranolol) who continuously cut logs with a chain saw for seven minutes. At the start of the sawing period, there was a pronounced increase in heart rate which persisted during the period. The control of heart rate is modulated centrally by an interaction between the hypothalamus and the medulla. The groups taking sulpiride, which inhibits the action of the hypothalamus due to blockade of dopaminceptors ($D_2$), or propranolol had smaller increases in heart rate than the controls. The fact that the rate of increase was suppressed with sulpiride and propranolol indicates that the chain saw work stimulates the central sympathetic nervous system. The chain saw operation resulted in an increase in all hormones (adrenocorticotropic hormone (ACTH), cortisol, adrenaline, noradrenaline and dopamine).

A comparison of the values before and after operating the chain saw showed that the increases of cortisol, adrenaline and noradrenaline concentrations were highest for the controls, intermediate for the propranolol group, and lowest for the sulpiride group. These findings indicate that chain saw work has an influence on the whole body, including the hypothalamus and the limbic lobe in the brain. From circumstantial evidence concerning the effect of vibratory tool work on the whole body, some investigators have reported increased urinary catecholamines (Boventi, 1988; Une and Esaki, 1988), significantly increased serum catecholamines (Kondo, 1988) and little heart rate variation in the workers (Harada et al. 1989).

The electroencephalogram revealed a specific pattern of spindle-shaped fast activity, 20-30 Hz in frequency and 0.3-1.0 sec in duration, in approximately 25% of the patients (Matoba et al. 1975a; Arikawa et al. 1978). Approximately 82% of the activity was distributed in the anterior part of the scalp, such as the frontal and central, to which regions the activity of the brain stem may have projected. The level of consciousness before and after the ap-
44% of the subjects, whereas the appearance of non-spindle fast activity was clear in 74% of the subjects. The activity paralleled the severity of the disease. The treatments resulted in the disappearance of the activity. The diffuse and slow alpha waves and the drowsy pattern were observed with high incidences (Sasaki et al. 1987). Theta activity and a poor reaction to flicker were also frequently observed (Petrov, 1969). Direct observations of the brains in the patients with vibration disease will be obtained by positron emission tomography.

3. Follow-up study

Fifty one patients with vibration disease induced by chain saws, ranging in age from 43 to 62 years, were followed for about four years (Matoba et al. 1980, 1982). The average duration of chain saw use was 10.9±4.2 (mean±SD) years, and the period between discontinuation of chain saw use and the final examination was 6.7±3.1 years. Assessment of blood pressure at the initial and final examinations showed that the incidence of normotension decreased, and the incidence of hypertension increased from 7.8% to 22.9% (p<0.05). The increased incidence of hypertension was particularly associated with increased and persistent complaints of lesions of the joints and muscles induced by the vibratory tools. These lesions were difficult to treat. The patients were psychologically and socio-economically impaired. By the time of the final follow-up examination, the incidence of resting bradycardia (less than 50/min) decreased from 15.7% to 9.8%. At the initial examination, eleven of the subjects were diagnosed from the electrocardiogram as possessing left ventricular hypertrophy. This had regressed to within normal limits by the time of the follow-up. The level of autonomic nerve activity, as measured by digital plethysmography with auditory stimuli, showed that the proportion of the normoreactive type had increased from 17.5% to 65.1% by the follow-up period. Thus the autonomic imbalances were improved.

These changes of the clinical picture during the follow-up study are indicative of the adaptive responses of the cardio-
vascular system in vibration disease (Fig. 4). Chronic exposure to vibration, noise, and cold during habitual operation of vibratory tools can lead to adaptation to the stressors. With regard to the cardiovascular features of the disease, sinus bradycardia at rest, an enlarged heart, increased left ventricular function, low blood pressure and other symptoms can appear. These findings are similar to the results of studies on endurance athletes (Scheuer and Tipton, 1977). The adaptation should disappear after discontinuation of the use of vibratory tools for approximately 6 to 8 years. Also, the adaptation of well-trained athletes regresses after training ceases. Finally, the cardiovascular symptoms and signs in patients with vibration disease are similar to those frequently observed in endurance athletes, which represent an adaptive response of the cardiovascular system.

Conclusion

Our expanding knowledge of the cardiovascular reflexes during vibration stress in the past several years has been presented. The occurrence of Raynaud’s phenomenon must be related to disorders of the central and local autonomic nervous systems, as well as to histological injuries of the local vessels. The release of chemical mediators for vasoconstriction and vasodilation may be modulated by the conditions inducing the injuries of the local vessel walls. Thus, cardiovascular reflexes during vibration stress may be elicited by excitation of the central and local autonomic nervous systems, as well as by the injuries to the local tissues. The cardiovascular symptoms and signs are similar to those frequently observed in endurance athletes. The adaptation obtained disappears after the discontinuation of vibratory tool work for 6 to 8 years. In clinical investigations, direct and clear-cut evidence can often not be obtained. Circumstantial evidence from many sources will lead us closer to the true pathophysiological basis of vibration disease.

References


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