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Review Article

Human response to vibration stress in Japanese workers: lessons from our 35-year studies
A narrative review

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Abstract: The occupational uses with vibratory tools or vehicles provoked health disorders of users. We reviewed narratively our articles of 35 yr studies and their related literatures, and considered the pathophysiology of the hand-arm vibration disorders. Concerning the risk factors of health impairments in workers with vibratory tools, there are two conflicting schools of the researchers: The peripheral school emphasizes that vibration only makes predominant impairments on hands and arms, showing typically Raynaud's phenomenon in the fingers. In the systemic school, the health disorders are produced by combination with vibration, noise and working environment, namely vibratory work itself, leading to diversified symptoms and signs in relation to systemic impairments. Our 35 yr studies have evidently supported the systemic school, including disorders of the central and autonomic nervous systems. The genesis is vibratory work itself, including vibration, noise, cold working environment, ergonomic and biodynamic conditions, and emotional stress in work. Because the health disorders yield in the whole body, the following measures would contribute to the prevention of health impairments: the attenuation of vibration and noise generated form vibratory machines and the regulations on operating tool hours. In conclusion, this occupational disease results from systemic impairments due to long-term occupational work with vibratory tools.

Key words: Hand-arm vibration stress, Clinical pictures, Systemic impairments, Autonomic nervous system, Diagnosis and treatments

Introduction

In the present day, various vibratory tools and vehicles are widely used in the working fields as well as living fields. In general, the employers pursue the economic efficacy with the introduction of vibratory machines, and also the workers want to use the vibratory machines because of low muscular powers. Most people in daily work operate several vibratory tools just like tipping hammers, jackhammers and chain saws, and various vehicles such as tractors, power shovels and bulldozers. When these machines are operated, vibration and noise are necessarily generated from the machines, and transmitted to the hand-arm system or whole body of users.

The first report about Raynaud's phenomenon (RP) due to vibration was by Loriga G in 1911. He described RP of stonemasons in Roma. After then, Hamilton A, USA, described health disorders of the stonecutters in detail in 1918[1]. The health disorders caused by occupational exposure to vibratory machines are divided into hand-

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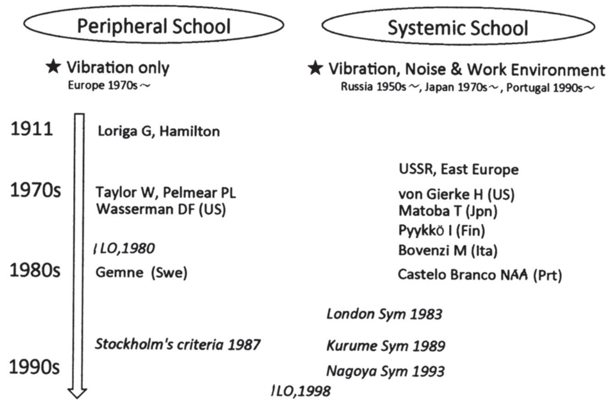

Fig. 1. Two schools of research approaches in hand-arm vibration syndrome.

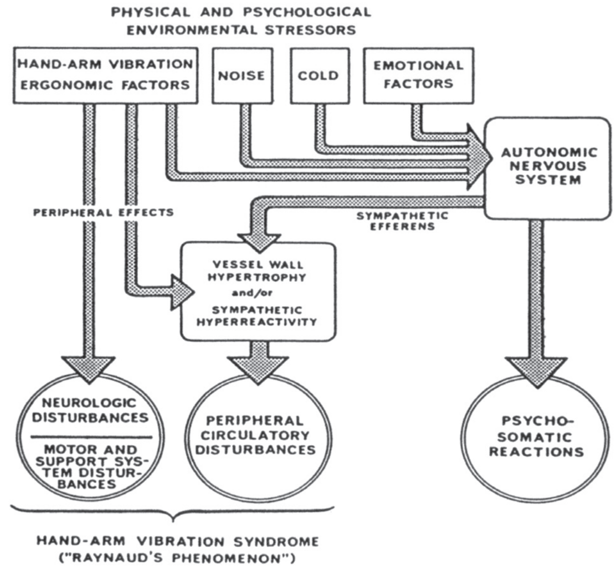

Fig. 2. The consensus of the London Symposium on non-hand/arm effects of local vibration, 1983[32].

arm vibration (HAV) and whole-body vibration (WBV) by means of the transmission sites of vibration shock[2, 3].

In HAV, there are two schools of the researchers: peripheral school and systemic one (Fig. 1). In the peripheral school, the cause of health disorders is due to vibration only. In the systemic school, the health disorders result from vibration, noise and working environment, the view of which has been taken by Russia in 1950s, Japan in 1970s and Portugal in 1990s. The Ministry of Labor, Japan, in 1970 defined the health impairment by HAV as follows: the health disorders are elicited by working with hand-held vibratory tools for a long-term, and the genesis includes vibration, noise, cold, ergonomic and biodynamic conditions, and emotional stress in work. This definition can be sound judgment as the systemic school. In 1998, International Labor Organization (ILO) recognized newly the both schools of HAV, although it had recognized the peripheral school alone in 1980.

A question that the major cause of the health disorders due to HAV is vibration with or without other factors such as noise and namely work itself, has been discussed for a long time, not coming to an agreement until now since London Symposium 1983. Having careful consideration, the operation of vibratory machines is associated with less than 500 Hz of low frequency noise as well as vibration, inducing impairments in the acoustic and vestibular systems[4–9]. According to the combined effects of vibration and noise, the investigations of von Gierke[10], and Portugal group[11] proposed the name of vibration impairments as "vibroacoustic disease", the naming of which was attained in noisy factory fieldworks. As the combination of vibration and noise is the major factors for health disorders, we would consider it to be a reasonable naming.

A long-term occupational usage of vibratory tools brings about health disorders of most workers, complaining of diversified symptoms and signs due to impairments of the peripheral nervous and circulatory systems, the joint and muscular systems as well as the autonomic nervous system (ANS)[12, 13]. As for the disorders of the autonomic and central nervous system, it has been an enduring controversy even if a lot of articles have been presented[14–30]. In this issue, there is an urgent need for further researches into this most difficult area of investigation for confirmatory evidence[31]. Various clinical pictures include palmar hyperhidrosis, irritability, insomnia as well as numbness, coldness and Raynaud's phenomenon in the fingers[13, 14]. It suggests that the ordinary medical check should be included systemic examination, even if it is in the early stage. Robert Murray, a chairperson of International Commission of Occupational Health (ICOH), summarized the consensus of London Symposium on non-hand/arm effects of local vibration in 1983[32] (Fig. 2). He referred to ANS disorders as a great factor for the health disorders in workers with vibratory machines. Thus, the major cause of the health disorders would be actually defined vibration, noise, working environments included cold and working behaviors, namely vibratory work itself[13], although some investigators have emphasized that the cause includes vibration alone[33].

We would chiefly review clinical and experimental data of our 35 yr studies and of their related articles in hand-arm vibration syndrome (HAVS) and consider the perspectives.

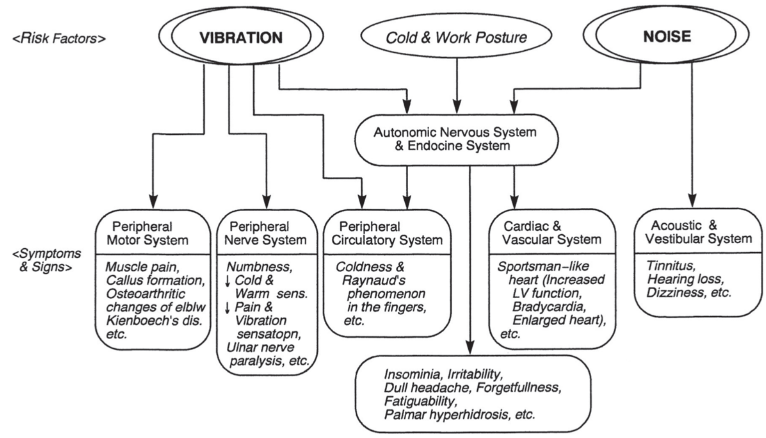

Fig. 3. Pathophysiology of disorders due to hand-arm vibration work (modified from Ref. [15, 19]).

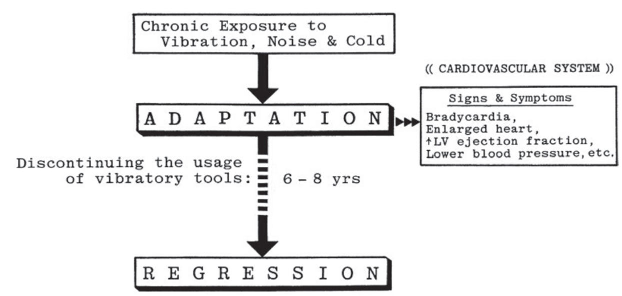

Fig. 4. Adaptation to vibration stress and regression[34].

Subjects and Methods

We searched the PubMed and MEDLINE for studies published between January 1970 and September 2013, and our articles of 35 yr studies. We also sought additional studies by reviewing the reference lists included as articles, reviews and monographs, and bibliographies of expert advisers. The articles were included clinical pictures, pathophysiology, diagnosis and treatments, and prevention of vibration disorders. The searches were limited to mainly English-language articles as well as Japanese-language ones.

Pathophysiology

We have summarized the pathophysiology of health disorders due to HAV on the basis of our 35 yr studies (Fig. 3). The vibratory tools generate vibration and noise, the users of which have worked in extremely stressful working environment. Therefore the major causes of vibration health disorders could provide vibration, noise and particularly cold environment[13]. Also, vibratory work actually accompanies working posture and emotional stress. These risk factors of health disorders affect each system in the whole body, bringing about various symptoms and signs. The disorders of the ANS and the endocrine system should be notable in particular[14–30]. Thus, occupational work with vibratory machines evokes the disorders of the peripheral motor, nervous and circulatory systems as well as the whole body system in relation to impairments of cardiac and vascular systems, acoustic and vestibular systems, and also the ANS. As we mentioned above, it is quite obvious that the cause of HAVS could not be vibration alone.

Adaptation

Adaptation to vibration stress in the cardiovascular system could be strongly formed during a long-term work with vibratory machines, although direct cardiovascular injuries due to vibration stress were obscure. The obtained adaptation disappeared gradually after cessation of work using vibratory tools[34] (Fig. 4). Chronic exposure to WBV on rat experiments produced spontaneous remission of hypertension[35].

Cardiovascular response

In the clinical fields, several attractive data were observed. The cardiac functions by the echocardiography in chain-saw workers showed an increase in ejection fraction and stroke volume, enlarged left ventricular diastolic dimension, and reduction of heart rates with a statistical significance[34]. In the electrocardiograms (ECG), however, there were no significant differences except of a flat T wave in precordial lead V_6[36], the ECG response of which showed that the 8 Hz vibration frequency was the resonance frequency of the heart[37]. Blood pressure values were comparatively lower than the controls[34]. In the human body responses during chain-saw work, the whole body reaction revealed an increase in the heart rate and hormonal values of ACTH, cortisol, adrenaline, and noradrenaline[16] (Fig. 5). The administration of sulpiride® (dopamine$_2$ receptor inhibitor) and propranolol (β-blocker) suppressed the increases of those parameters, suggesting that chain-saw work affected the whole body[16].

The external vibration affected contractile protein and reduced the left ventricular (LV) function, leading to the reverse or tolerance of LV to a sudden reduction of myocardial contractility[38]. In the conscious rate, the vibration frequency less than 16 Hz increased sympathetic nerve activity in cardiovascular responses[39].

Immunological changes

Immunological changes related to vibration stress were observed. The immunoglobulin of IgM, IgA and IgG increased in proportion to the severity[40–42]. An increase in sister chromatid exchanges was suggested to be a reason of high incidence of this disease[43]. An increase in T cell lymphocytes of CD4 and CD8 were observed[44, 45], and up-regulated genes in cDNA microassay might be injured by vibration stress[46]. Those evidences proved to be reaction of whole-body affected by vibration stress.

Animal experiments

Some interesting animal experiments demonstrated several novel findings. In the experiments of unconscious animals, WBV to the extracted rabbit heart revealed a decrease in contractile force, cardiac output, aortic flow, and left ventricular peak systolic pressure[47]. In the heart synchronized WBV to dogs, coronary flow increased by 15%, and in case of non-synchronous hearts the coronary flow decreased by 34%. The oxygen consumption increased by 21% (non-synchronous heart: −51%)[48]. WBV loaded in an anesthetized dog showed an increase in myocardial blood flow by 10% on 120 Hz vibration stress and a decrease by 9% on 50 Hz vibration[49]. Hormonal values were changed by a frequency of vibration: Adrenaline, cyclic AMP and cyclic GMP were enhanced by 50 Hz, and opposite responses were shown in 120 Hz[49]. In chicken embryo given by WBV, the anomaly rate was observed by 94% and higher mortality rates[50]. WBV reduced blood flow in the peripheral vascular system of rabbits[51].

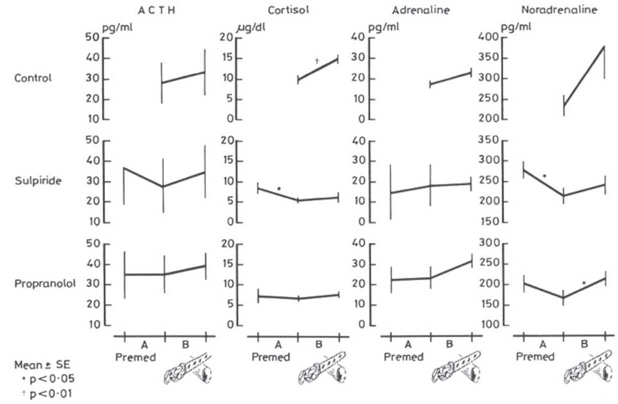

Fig. 5. Changes of hormonal levels induced by chain saw work[16].

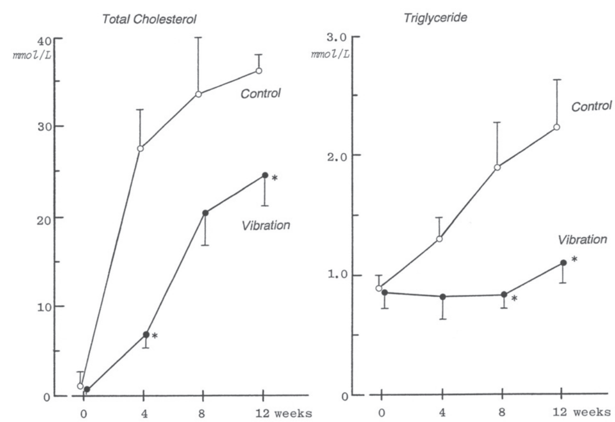

Fig. 6. Changes of serum lipid values in rabbits fed with cholesterol-rich diet with or without vibration loads[52]. The asterisk shows statistically significant difference: *p*<0.05.

Atherosclesosis

We performed animal experiments using conscious rabbits loaded with WBV[52, 53]. The methods were as follows: 14 New Zealand white rabbits were divided into 2 groups, 7 of the controls and 7 of vibration group. They were fed with 1% cholesterol-rich food of 100 g/day for 14 wk. Two weeks after feeding with special diet, WBV with 10 ms^{-2} of magnitude horizontally and 30 Hz of frequency was given during 60 min/day for 12 wk. The control group was placed at close to the vibrator. Noise was 68 dB (A) at the inside of the cage on the vibrator, and 58 dB (A) at the outside of the cage. The parameters for observation were body weight, serum total cholesterol and triglyceride, and calcium, magnesium, copper, zinc and coenzyme Q values in myocardial tissues. The levels of serum total cholesterol and triglyceride were suppressed by vibration stress with a significant difference ($p<0.05$) (Fig. 6), and the ratios of calcium/magnesium and zinc/copper ($p<0.05$) were also

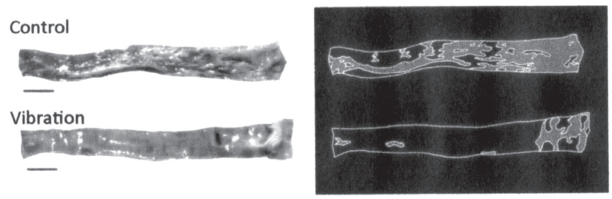

Fig. 7. A typical figure of atherosclerotic changes with and without vibration stress.

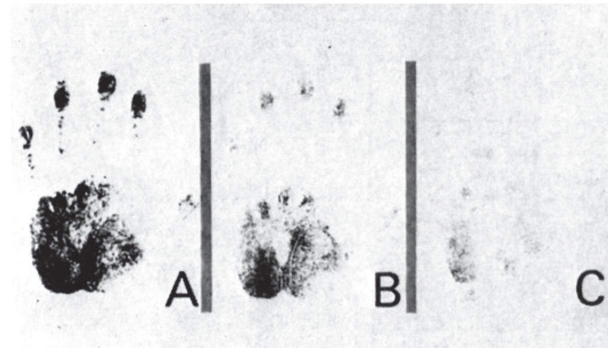

Fig. 8. Changes of palmar hyperhidrosis given by sulpiride® before (A), 1 wk after (B), and 2 wk after (C)[13].

inhibited. Speaking of a novel finding, the atherosclerotic plaque formation was markedly suppressed by WBV under the visual observation and the thickness of intima and media of the aorta and arterioles in the sole was also were suppressed by vibration[53] (Fig. 7).

The morphological changes in capillary vessels and arterioles were observed by vibration loading[54, 55]. In particular, the media of arterioles thickened, being similar to the arteriosclerotic change.

Clinical Pictures

The occupational usage of vibratory tools such as chain saws and stonecutters occurs hand-arm vibration syndrome (HAVS). In patients with HAVS, diversified symptoms and signs are observed on the impairments of the peripheral nervous, circulatory and muscular systems as well as the whole body included ANS[14]. Occupational noise exposure rises up blood pressure[56–58] and induces hearing loss[4–9], the etiology of which could relate to the autonomic nerve activity.

As for the disorders of the ANS, we had a meeting of Kurume University Symposium on Vibration Stress and the Autonomic Nervous System in 1989[59]. The participants agreed to the ANS disorders with fruitful discussion. Also, Nagoya symposium was also held in 1993[60], the topics in which included ANS responses with much discussion.

The findings of the plethysmography and thermography combined with auditory stimuli proved to be in a close relation to the autonomic nerve activity and vibration stress[61–63]. In the patients with HAVS, the autonomic nerve activity was augmented.

Clinically, about 70% of patients with HAVS suffered from palmar hyperhidrosis[13]. In relation to the progress of the severity, palmar sweating increased, and then it decreased in progressing to the severity IV[13, 15]. The administration of a dopamine$_2$ receptor inhibitor (sulpiride®) to the patients with marked hyperhidorosis reduced dramatically sweating 2 wk after (Fig. 8). The findings suggested that increased palmar sweating was caused by the excitation of the higher center of the ANS[64–67]. Also, the change of skin blood flow could be related to the ANS[68].

According to clinical experience, the autonomic nervous activity increased initially in exciting, and then declining the tones in the progress of the severity[69]. Many symptoms and signs originated in the whole body were evoked by vibration stress. Adaptation for working stress would be formed in similar to endurance athletes[34]. In cardiovascular system, it includes bradycardia at rest, enlarged heart, and an increase in left ventricular ejection fraction as indicated in Fig. 4.

The severe inpatients complained of various symptoms and signs[13]. The prevalence rate of complaints increased more and more in proportion to the severity[69]. Psychologically, they might include the symptom-induced symptoms. The symptoms and signs concerning whole body were observed in even the early stage. The variation of symptoms and signs should be carefully examined in the medical check-up[70].

A typical electroencephalographic pattern was notable spindle-formed fast activity in the frontal region in 18.0% of the patients[13, 71] (Fig. 9). The typical patterns included a frequency of 25–30 Hz, less than 30 μV of amplitude, and 0.3–1.0 s of duration. The waves differed from the light stage of sleep or epilepsy. The notable spindle-formed fast activity tended to appear continuously or sporadically. It would relate to the higher center of the ANS. The accurate mechanism was not clear, however.

Diagnosis and Staging

In general, large noise would generate when vibratory

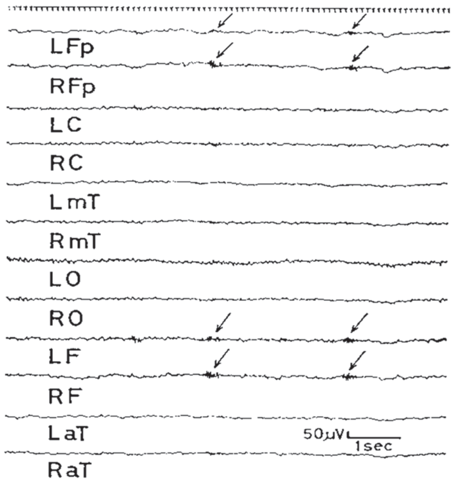

Fig. 9. Notable spindle-formed fast activities in electroencephalogaram. A 43 yr old chain saw worker.

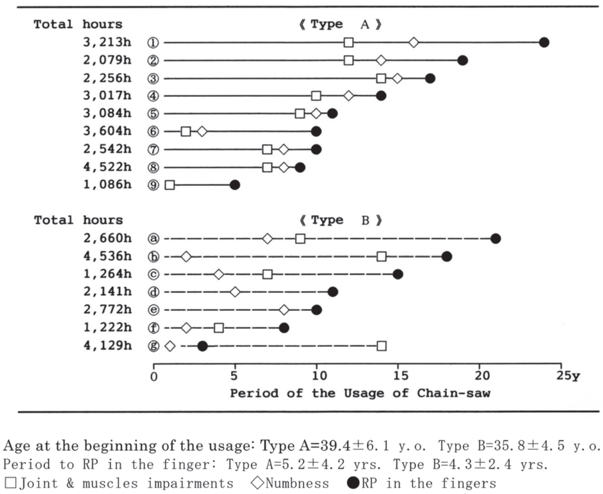

Fig. 10. Several pattern of the onset symptoms of the peripheral disorders in workers[70].

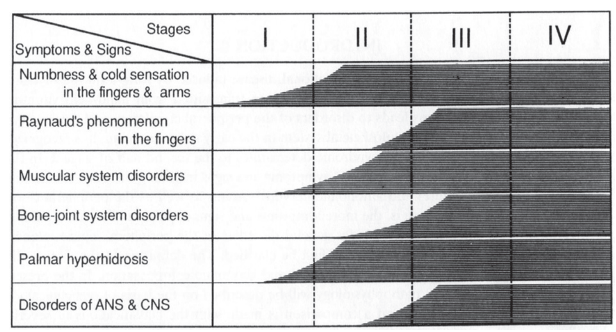

Fig. 11. Onset of symptoms and signs in each stage. The disorders of ANS and CNS occur at the middle of stage[14].

machines are operated. Its loudness is 80 to 120 dB (A), the strength of which excites the activity of the ANS. The exposure to noise could produce hearing loss associated with tinnitus, and disorders of the vestibular system[4–9]. Chronic exposure to noise leads to be hypertension[57, 58]. In consideration of the effect of noise, the health disorders of workers with using vibratory machines would chiefly result from the combined effects of noise and vibration[5, 8]. However, it is not obvious which factors would have much influence in the human body. Whichever vibration, noise or both may be effective is a big question. A detailed occupational history taking is necessary and useful for the differential diagnosis and the stage determination. In medical consultation, the workers should be examined whole body. In the initial stage, there were two types of the occurrence disorders[72]. The initial disorder was the joints and muscular impairments or sensorineural disturbance (numbness), and lastly evoked Raynaud's phenomenon (RP) in the fingers (Fig. 10). Thus, the first occurrence of symptoms and signs indicated the individual difference.

In a viewpoint of staging, the stages were divided into four[14, 69] (Fig. 11). This classification of the stage was clinically useful for examining whole body conditions comprehensively. We noticed that numbness was firstly felt; following it RP in the fingers occurred in the middle of stage 2. Those processes ran, and finally all workers complained of RP. About 70% of patients with HAVS had suffered from palmar hyperhidrosis[13]. This phenomenon suggested being an increase in the autonomic nerve activity, the increase of which was gradually subsiding near at the stage 4[15, 70, 72].

Taylor & Pelmear classification (1975)[73] included the severity of blanching of fingers as a marker, developing to Stockholm's criteria in 1987[74]. In the criteria, the severity of symptoms and signs has tended to be limited to RP and its accompanied sensorineural symptoms in the fingers. Some investigators have criticized the Stockholm' criteria, not encompassing the full range of disease and difficult interpretations of some words[75–78]. The Royal College of Physicians criticized Stockholm's criteria that the technical words were not adequately defined and objective tests should be used[79]. According to our classification, systemic symptoms and signs were systemically classified into 4 stages, as being not able to see the wood for the trees like a proverb[70].

We proposed a new criterion of revising Stockholm's criteria, although Stockholm's criteria was likely to be insufficient in particular[70, 72] (Fig. 12). The peripheral disorders restricted divided 3 categories: sensorineural,

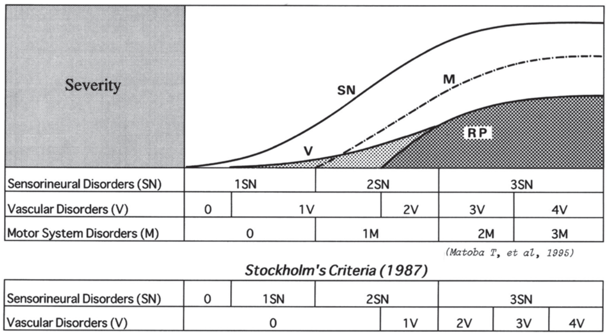

Fig. 12. A scheme of our new criteria of stages[72]. A lower column shows Stockholm's criteria.

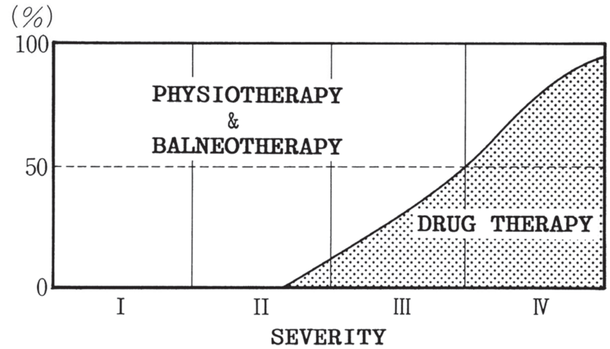

Fig. 13. Relation of severity to each therapy[83].

vascular and muscular disorders. Each category included 3 or 4 stages. Stockholm's criteria took a serious view of RP. However, the prevalence of RP differed from sex and race. The European people showed higher prevalence of RP than other races. The prevalence rates in European population survey were 10% in male and 21% in female[80], but in Japanese peoples it was 2.7% in male and 3.4% in female[81], although there were several differences in the prevalence of RP by the investigators[82]. We should notice sex and racial differences in consultation.

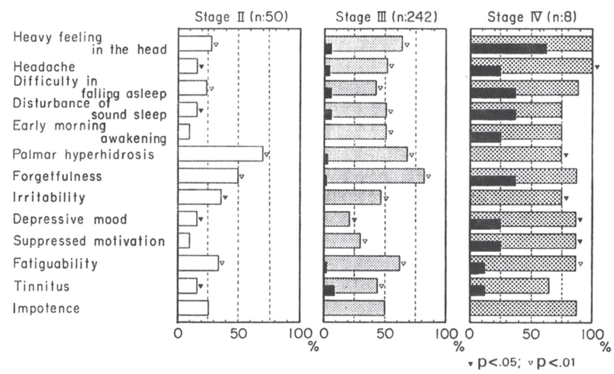

Fig. 14. Changes of prevalence rates of subjective symptoms before and after treatments[19].

Treatments and Prevention

The measures for diagnosis of vibration disease should be employed according to the physical examination of a whole body. In the early stages, we should notice the symptoms of the peripheral nerve and joint-muscular systems as shown in Figs. 10 and 11[70]. The precise occupational history taking should include the kinds of vibratory machines, the duration of the occupational usage of tools, limited working hours and working environment. The grading of the severity of the disorders could be necessary for treatments and prevention. Empirically, therapeutic effects were scarcely observed in the severely affected workers, resulting in the prolonged therapeutic course[40].

The physiotherapy and balneo-therapy were effectively employed for the disorders of whole body including the ANS[83] (Fig. 13). According to medicaments, a vasodilator such as diltiazem hydrochloride, was effective for peripheral vascular disorders[84, 85]. The most effective way was to administer it when cold sensation or blanching in the fingers was felt[81]. For tinnitus, the remedy of stellate ganglion block was useful for relief from tinnitus[86]. Those combined therapies proved to be sufficiently effective for vibration health disorders to subside even symptoms and signs of the ANS impairments (Fig. 14).

The disease can be prevented by means of some measures. The most important resources are vibration attenuation and noise reduction of machines, and improvement of working environmental[87]. The preventive policy by the Forestry Agency of Japan was administered in 1980s, including the restricted chain saw use hours to 2-h per a day, mechanical improvements of vibratory tools, the arrangements of working environment, and education programs for workers, resulting in a marked decrease in the incidence rate of patients[87].

Conclusion and Perspectives

There are two schools, peripheral and systemic ones, in the research approaches for HAVS internationally. One is the peripheral school resulted from vibration alone, leading to upper digital disorders, especially Raynaud's phenomenon in the fingers. The disorders would provide the limited body area. The other is systemic school included not only peripheral disorder but also whole body. The vibratory work itself with vibration, noise and working environment affects the whole body, provoking various systemic symptoms and signs[8]. The systemic school was evidently supported by the data of our 35 yr studies and other researchers.

Of importance, the occupational use of vibratory machines affects the workers not only digital organs but also whole body. The Ministry of Labor, Japan, in 1970 defined this disease as disorders elicited by working with hand-held vibratory tools for a long-term. And the genesis included vibration, noise, cold, ergonomic and biodynamic conditions, and emotional stress in work. It is a reasonable explanation, we consider. Consequently, even if the worker suffers from digital complaints by using vibratory tools, the physician should examine the whole body. Moreover, careful history taking, including the kind of tools, working hours per a day, and working environment, could provide very important information. It is quite natural that the clinical pictures are modified by age, sex and racial differences, and the kind of tools.

The perspectives in a future research will be proposed from the pathophysiological viewpoints. First, an occupational physician should perform systemic examination, as the patient with HAVS is impaired systemically. Second, the definition and stage of HAVS in Stockholm's criteria should be reevaluated on the basis of pathophysiology, when it will be needed the comprehensive consideration and views. Third, the data of good designs for animal and human experiments could contribute to make the detailed evidence of pathophysiology, and to attain an appropriate naming, for instance, "vibroacoustic disease".

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