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SYMPATHETIC RESPONSES TO HAND-ARM VIBRATION AND SYMPTOMS OF THE FOOT

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ABSTRACT

Vibration syndrome is generally considered to consist of disorders in the upper extremities which are directly exposed to vibration. However, it has been shown that vibration syndrome patients have circulatory disturbances in the foot as well: several chain-saw operators, who were little exposed to vibration of the foot, had Raynaud's phenomenon of the toes, and those with frequent attacks of vibration-induced white finger (VWF) had a higher prevalence of coldness felt in both the hands and the feet, and the patients with VWF had lower skin temperature of the toes as well as the fingers. Moreover, arterial pathological changes like medial muscular hypertrophy have been observed in both the fingers and the toes of the patients. Hand-arm vibration elicits a sympathetic nervous reflex, leading to vasoconstriction of the four extremities. Long-term repeated vasoconstriction may result in such arterial changes and then circulatory disturbances of the feet.

Key Words: Vibration, Foot symptom, Circulatory disturbances, Sympathetic nervous system, Vasoconstriction

INTRODUCTION

It is well known that hand-arm vibration causes circulatory disturbances, sensory and motor nervous disturbances, and musculoskeletal disturbances in the upper extremities which are directly exposed to vibration from hand-held vibrating tools such as chain saws, rock drills, and chipping hammers. But hand-arm vibration can evoke a sympathetic nervous reflex causing vasoconstriction of not only the upper extremities but also the lower ones, which may affect the feet. Such effect has not been confirmed yet in hand-arm vibration syndrome. However, we should consider the indirect effect of hand-arm vibration through the sympathetic nervous system as well as the direct effect.

CIRCULATORY DISTURBANCES IN THE FOOT

1. Cases reported with Raynaud's phenomenon of the toes

There are several reports of vibration syndrome patients with Raynaud's phenomenon in the toes (Table 1).[1–6] The first case was reported by Mills in 1942.[1] The patient's main complaint was numbness and a dead feeling in the left foot. He was a powder man for a road construction and used a pneumatic hammer in drilling rock. During the drilling, he pressed the drill down with his left foot. Therefore, Mills considered that use of the air hammer must have contributed to the left foot disorders. Like Mills's case, the patients reported had been mostly exposed to vibration of the foot, and the direct exposure to vibration of the foot is considered to be the main

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cause of Raynaud's phenomenon of the toes. However, there are several cases of chain-saw operators who have been little exposed to vibration of the foot.[4,6]

Table 1. Reported cases with Raynaud's phenomenon of toes in vibration-exposed workers.

Mills (1942)[1]	one pneumatic hammer operator
Suzuki et al. (1966)[2]	one rock driller
Gomibuchi and Ohi (1967)[3]	one chain-saw and wood collecting machine operator
Hashiguchi et al. (1988)[4]	three cases: a chain-saw operator, a rock driller, a stone crusher operator
Hedlund (1989)[5]	six cases of twenty-seven miners
Toibana and Ishikawa (1990)[6]	ten cases: three chain-saw operators, three rock drillers, and others

2. Symptoms of coldness felt in the lower extremities

Even when patients with vibration syndrome do not have Raynaud's phenomenon of the toes, they are likely to complain of coldness in the foot as well as in the hand.[7,8]

The authors analyzed subjective symptoms of patients with vibration syndrome in relation to frequency of attacks of vibration-induced white finger (VWF): almost daily, occasionally, never, and previously.[8] The subjects were 229 patients, who had used mainly a chain saw, in their 50s and 60s without complication, selected from 1,687 patients collected. The age was almost similar among groups (data not shown, see ref. 9). But patients with almost daily attacks of VWF had longer total operating times and shorter treatment period.

Prevalence of coldness felt in the fingers and legs was higher with the increase in frequency of VWF attacks (Table 2). In other words, patients with more frequent attacks of VWF are likely to have circulatory disturbances in the feet as well. With the progress of VWF attacks, circulatory disturbances might develop in both the upper and lower extremities.

Table 3 shows prevalence of symptoms according to total operating time of chain saw (TOT). Prevalence of VWF and coldness of fingers significantly increased with TOT. Prevalence of coldness of legs did not show significant differences, but the prevalence tended to increase with TOT slightly. This may suggest that hand-transmitted vibration itself affects the foot, though the effect on the foot does not seem to be as strong as the effect on the hand.

Table 2. Prevalence of symptoms in chain-saw operator patients with vibration syndrome according to frequency of VWF attacks. (From Ref. 8)

	VWF frequency			
	Daily (N=24)	Occasionally (N=138)	Never (N=32)	Previously (N=35)
	N(%)	N(%)	N(%)	N(%)
Numbness of fingers				
Almost daily	24(100)**	72(52.6)	18(56.3)	23(65.7)
Occasionally	0(0.0)	65(47.4)	14(43.8)	11(31.4)
Never	0(0.0)	0(0.0)	0(0.0)	1(2.9)
Previously	0(0.0)	0(0.0)	0(0.0)	0(0.0)
Coldness of fingers				
Almost daily	20(83.3)**	72(52.6)	18(56.3)	23(65.7)
Occasionally	3(12.5)	65(47.4)	14(43.8)	11(31.4)
Never	1(4.2)	0(0.0)	0(0.0)	1(2.9)
Previously	0(0.0)	0(0.0)	0(0.0)	0(0.0)
Awakening at night due to numbness of arms				
Almost daily	14(58.3)*	43(31.2)	8(25.0)	10(28.6)
Occasionally	9(37.5)	83(60.1)	18(56.3)	21(60.0)
Never	1(4.2)	8(5.8)	6(18.8)	2(5.7)
Previously	0(0.0)	4(2.9)	0(0.0)	2(5.7)
Coldness of legs				
Almost daily	20(83.3)**	47(34.1)	10(31.3)	12(34.3)
Occasionally	3(12.5)	64(46.4)	14(43.8)	15(42.9)
Never	1(0.0)	26(18.8)	8(25.0)	7(20.0)
Previously	0(0.0)	1(0.7)	0(0.0)	1(2.9)
Numbness of legs				
Almost daily	14(58.3)**	20(14.5)	4(12.5)	8(22.9)
Occasionally	6(25.0)	63(45.7)	11(34.4)	9(25.7)
Never	4(16.7)	51(37.0)	17(53.1)	15(42.9)
Previously	0(0.0)	4(2.9)	0(0.0)	3(8.6)

* $p<0.05$; ** $p<0.01$; statistically significant differences among groups classified according to frequency of VWF attacks exclusive of the "previously" VWF group by x^2-test. "Numbness of finger" was uncertain in one subject.

Table 3. Prevalence of symptoms in chainsaw operator patients according to total time operating chainsaw (TOT). (From Ref. 8)

	TOT (h)			
	−9,900 (N=85)	10,000− (N=103)	20,000− (N=41)	Total (N=229)
	N(%)	N(%)	N(%)	N(%)
VWF				
Almost daily	3(3.5)	9(8.7)	12(29.3)**	24(10.5)
Occasionally	53(61.6)	68(66.0)	17(41.5)	138(60.3)
Never	18(20.9)	11(10.7)	3(7.3)	32(14.0)
Previously	11(12.8)	15(14.6)	9(22.0)	35(15.3)
Numbness of fingers				
Almost daily	49(58.3)	61(59.2)	27(65.9)	137(60.1)
Occasionally	35(41.7)	41(39.8)	14(34.1)	90(39.5)
Never	0(0.0)	1(1.0)	0(0.0)	1(0.4)
Previously	0(0.0)	0(0.0)	0(0.0)	0(0.0)
Coldness of fingers				
Almost daily	31(36.5)	45(43.7)	27(65.9)**	103(45.0)
Occasionally	46(65.9)	48(46.6)	12(29.3)	106(46.3)
Never	7(8.2)	6(5.8)	2(4.9)	15(6.6)
Previously	1(1.2)	4(3.9)	0(0.0)	5(2.2)
Awakening at night due to numbness of arms				
Almost daily	27(31.7)	31(30.1)	17(41.5)	75(32.8)
Occasionally	49(57.6)	62(60.2)	20(48.8)	131(57.2)
Never	8(9.4)	6(7.8)	3(7.3)	17(7.4)
Previously	1(1.2)	4(3.9)	1(2.4)	6(2.6)
Coldness of legs				
Almost daily	29(34.1)	40(38.8)	20(48.8)	89(38.9)
Occasionally	38(44.7)	44(42.7)	14(34.1)	96(41.9)
Never	18(21.2)	18(17.5)	6(14.6)	42(18.3)
Previously	0(0.0)	1(1.0)	1(2.4)	2(0.9)
Numbness of legs				
Almost daily	16(18.8)	17(16.5)	13(31.7)	46(20.1)
Occasionally	31(36.5)	44(42.7)	14(34.1)	89(38.9)
Never	38(44.7)	36(35.0)	13(31.7)	87(38.0)
Previously	0(0.0)	6(5.8)	1(2.4)	7(3.1)

** $p<0.01$; differences statistically significant from the "less than 9,900 h TOT" by x^2-test."Numbness of finger" was uncertain in one subject.

3. Skin temperature of the toe

Vibration syndrome patients also have lower skin temperature of both fingers and toes.[9,10]

Skin temperature of index fingers and great toes was measured in 3-min immersion of the right foot in cold water at 10°C.[10] The subjects were 11 patients with VWF, 12 patients without VWF, and 20 healthy controls not exposed to vibration. Patients were all male chain-saw operators. The age was similar in these groups (data not shown, see ref. 10). Patients with VWF had longer total exposure times than those without VWF. Those with VWF had a higher prevalence of coldness in both the upper and lower extremities (data not shown, see ref. 10).

Skin temperature of both fingers and toes was lowest in patients with VWF, and highest in the references even before the immersion of the right foot in cold water (Table 4). The room temperature ranged from 20° to 22°C. VWF patients may have responded more sensitively to the cold than the referents, showing lower skin temperature of both fingers and toes.

Correlation coefficients of skin temperature between fingers and toes before immersion revealed a positive relationship (Table 5), which indicates that if a subject has low skin temperature of the finger, the skin temperature of the toe is also low. Patients with VWF are apt to have low skin temperature of both fingers and toes.

Asaba et al.[11] measured dermal blood flow of the upper and lower limbs with the ^{133}Xe wash-out methods. Their data also revealed that vibration syndrome patients had lower dermal blood flow in both the upper and lower limbs than healthy controls. Toibana and Ishikawa[12] measured skin temperature of the finger and the toe of patients with Raynaud's phenomenon of fingers and toes, and obtained the similar findings.

Table 4. Mean ± standard deviation (°C) of skin temperature of fingers and toes in 3-min immersion of the right foot in cold water at 10°C. (From Ref. 10)

	Patients with VWF (N=11)	Patients without VWF (N=12)	Referents (N=20)
Right great toe:			
Before immersion	25.8 ± 4.1	27.1 ± 5.3	29.1 ± 5.4
At the end of immersion	13.5 ± 1.9	13.2 ± 1.5	14.5 ± 1.8
5 min after immersion	17.6 ± 2.3	17.7 ± 2.4	19.3 ± 3.0
10 min after immersion	18.4 ± 2.5	18.7 ± 2.6	20.2 ± 3.0
Left great toe:			
Before immersion	25.6 ± 3.5*	26.9 ± 4.7	29.4 ± 5.2
At the end of immersion	25.6 ± 3.6*	25.8 ± 5.1	29.2 ± 5.1
5 min after immersion	25.5 ± 3.7*	26.5 ± 4.7	29.1 ± 5.1
10 min after immersion	25.6 ± 3.9*	26.5 ± 4.8	29.0 ± 5.2
Right index finger:			
Before immersion	28.8 ± 2.9*	30.6 ± 2.5	31.8 ± 3.1
At the end of immersion	28.3 ± 2.7*	29.9 ± 2.6	31.0 ± 2.9
5 min after immersion	27.8 ± 2.6**	29.6 ± 3.1	31.5 ± 3.3
10 min after immersion	28.0 ± 2.7**	29.7 ± 3.5	31.6 ± 3.5
Left index finger			
Before immersion	27.4 ± 3.5*	30.7 ± 2.1	30.5 ± 3.4
At the end of immersion	26.9 ± 3.2*	30.0 ± 2.1	29.7 ± 3.1
5 min after immersion	26.8 ± 3.2*	30.0 ± 2.8	29.9 ± 3.5
10 min after immersion	27.2 ± 3.5*	30.2 ± 2.7	30.2 ± 3.7

* $p < 0.05$; ** $p < 0.01$; differences statistically significant from the referent values by Student's t-test.

Table 5. Correlation coefficients among skin temperature of fingers and toes before immersion. (From Ref. 10)

	Right finger	Left finger	Right toe	Left toe
Right finger	–	0.878*	0.408*	0.454*
Left finger		–	0.464*	0.491*
Right toe			–	0.949*
Left toe				–

* $p<0.01$, statistically significant difference (N=43).

These findings all indicate that patients with vibration syndrome, especially those with VWF, have circulatory disturbances not only in the hands but also in the feet. And the circulatory disturbances in the feet seem to correlate with the disturbances in the hands, i.e., patients with severe circulatory disturbances in the upper limbs may have circulatory disturbances in the feet as well.

VASOCONSTRICTION OF THE FOOT INDUCED BY HAND-ARM VIBRATION THROUGH THE SYMPATHETIC NERVOUS SYSTEM

The subjects shown above were all chain-saw operators. They are hardly exposed to vibration of the foot. Therefore, direct vibration exposure of the foot can not be the main cause of circulatory disturbances in the foot. Hand-arm vibration itself may affect the foot through the sympathetic nerve system.

1. Skin temperature changes of the digits caused by hand-arm vibration

Skin temperature of index fingers and great toes were examined when the right hand was exposed to vibration of 125 Hz, 10 g for 5 min.[13] The subjects were 10 healthy males aged 21 to 35. Vibration exposure of one hand lowered skin temperature of both the exposed hand and the unexposed contralateral hand, and moreover the feet (Fig. 1). In this way, vibration exposure of one hand can cause vasoconstriction in the four extremities. Table 6 shows coefficients of correlation in skin temperature changes between the right finger and the other three digits. There was a significant positive correlation between the right exposed hand and the unexposed left hand, and also both toes. In response to vibration exposure of the hand, a subject showing greater reduction in skin temperature of the finger also shows great lowering of toe skin temperature.

2. Blood flow changes in the foot during chain saw operation

Skin blood flow of the finger and the toe were measured during chain-saw operation.[14] The subjects were 5 healthy men aged 27 to 50. Fig. 2 demonstrates a typical example of skin blood flow changes in the finger and foot during chain-saw operation. The figure on the left is the result when a subject just stood hearing the noise of a chain saw which another person operated nearby. In this case blood flow of the finger and foot decreased slightly. The middle figure is the finding when the subject held a chain saw but did not operate it, while hearing the noise of the same type of a chain saw another person operated nearby. Blood flow reduced much more in the finger than in the foot. Holding a chain saw affected blood flow in the finger very much, but slightly in the foot. The figure on the right is the blood flow change when the subject held a chain saw and operated it himself. Blood flow of both the finger and the foot greatly reduced.

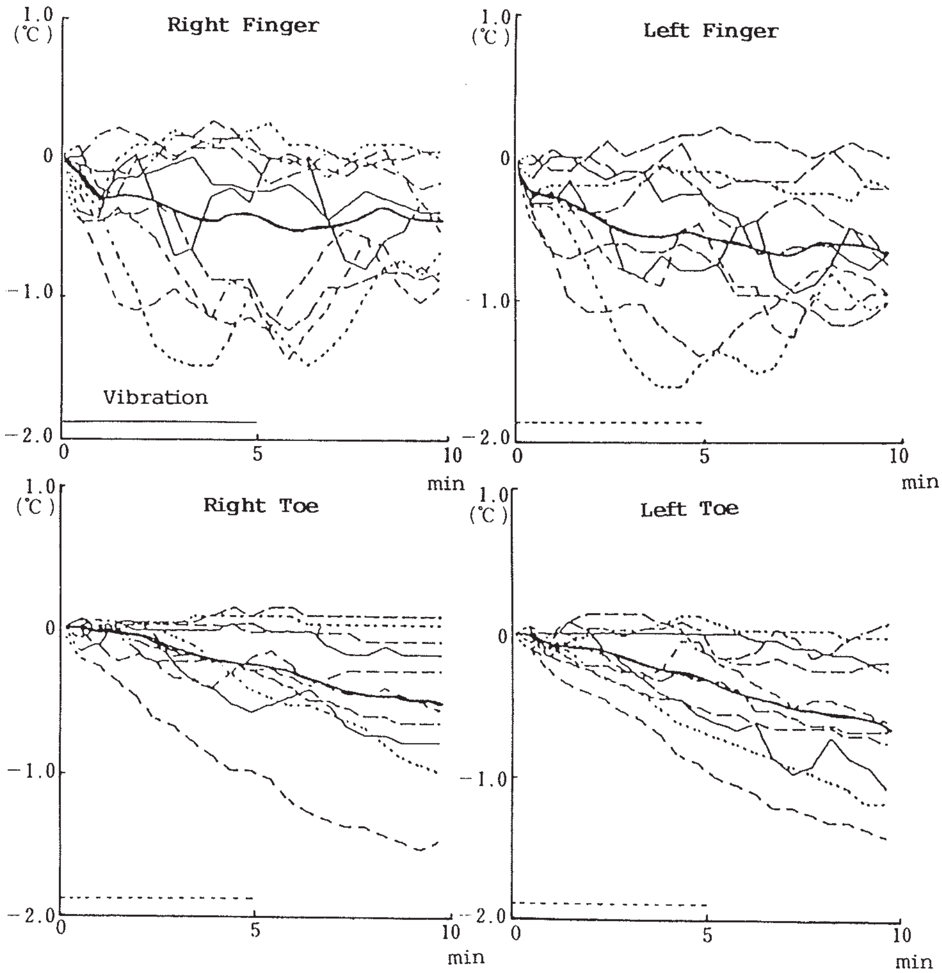

Fig. 1. Skin temperature changes of the fingers and toes due to exposure to vibration (125Hz, 10g) of fthe right hand for 5 min. (From Ref. 13)

Table 6. Correlation coefficient in skin temperature changes between the right finger and the other three digits in response to 5-min vibration exposure of the right hand. (From Ref. 13)

	Left finger	Right toe	Left toe
150th second after S[a)]	0.932**	0.486	0.751**
E[b)]	0.839**	0.698*	0.600*

* $p<0.05$, ** $p<0.01$, statistically significant difference (N=10).

[a)] skin temperature change from the beginning to 2.5 min after the bigenning of vibration exposure.

[b)] skin temperature change from the beginning to the end of 5-min vibration exposure.

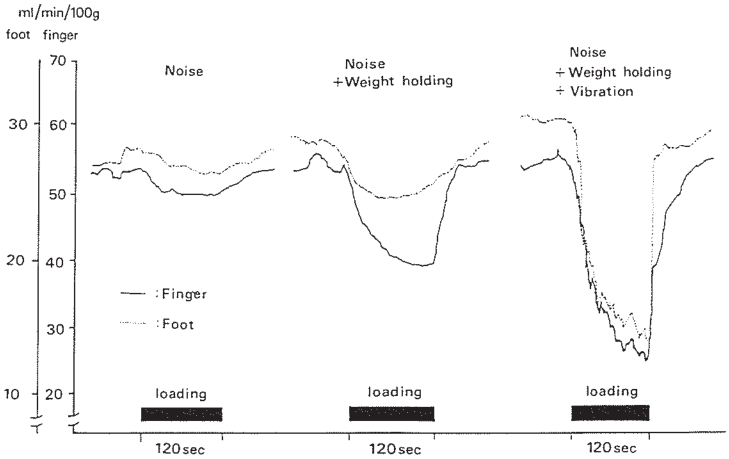

Fig. 2. A typical example of skin blood flow changes in the fingers and foot during a chain-saw operation. (From Ref. 14)

Hand-arm vibration caused considerable reduction of blood flow in the foot. Thus, operation of a chain saw can cause vasoconstriction of the foot.

Fig. 3 shows the mean values of the results from 5 subjects. Finger blood flow was reduced much by holding a chain saw and exposure to vibration of the hand. On the other hand, foot blood flow decreased greatly by exposure to vibration of the hand. Vibration exposure of the hand caused vasoconstriction of the foot most.

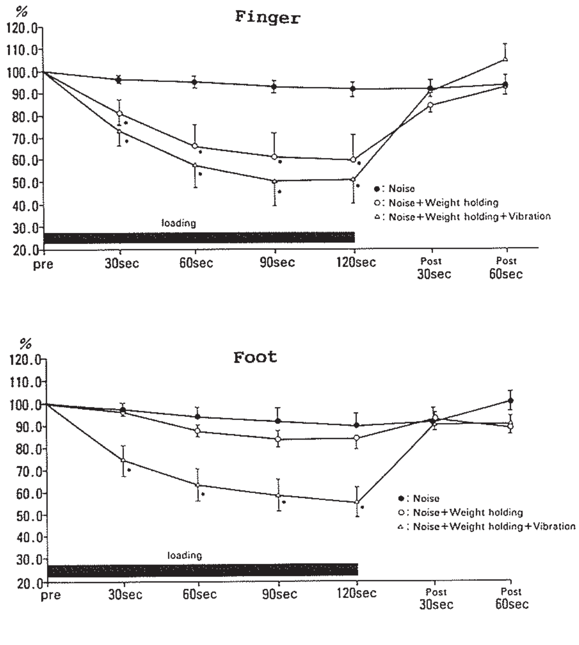

Fig. 3. Mean values (±S.E.) of skin blood flow of five subjects during a chain-saw operation. (* P<0.05, compared with 'noise'. From Ref. 14)

3. Skin sympathetic nerve activity in the tibial nerve during vibration exposure of the hand

The authors also recorded skin sympathetic nerve activity (SSNA) from the tibial nerves innervating the foot.[15] Fig. 4 is a record example of SSNA from the tibial nerves of the right leg when vibration of 100 m/s^2 at 60 Hz was applied to the left hand for 1 min. SSNA was recorded by inserting a microelectrode percutaneously into the skin nerve fascicles at the popliteal fossa of the right leg without anesthesia. When vibration was applied to the hand, SSNA in the tibial nerves increased remarkably. And perspiration increased according to the level of SSNA. The amplitude of plethysmogram of the toe also decreased slightly.

The summary of 5 subjects recorded was shown in Table 7. SSNA responses to vibration exposure differed among subjects, but each showed an increase in SSNA and a decrease in amplitude of toe plethysmogram.

Thus, hand-arm vibration evokes SSNA in the leg nerves and causes vasoconstriction in the foot. Okada et al.[16] have revealed that hand-arm vibration elicits SSNA and leads to vasoconstriction in the contralateral unexposed hand. Bini et al.[17] recorded sympathetic bursts from different skin nerves simultaneously: the left median in the arm and the right peroneal nerve in the leg; the right and the left median nerve; the left antebrachial and the left superficial radial nerve. These records demonstrate that skin sympathetic bursts are synchronous in different nerves of the arm and the leg. And electrical skin stimulation induces sympathetic bursts in the arm and leg nerves almost simultaneously. These suggest that skin sympathetic nerve activity synchronizes in the four extremities and the vasoconstrictor tone in the feet is closely linked to that in the hands. Burton[18] has also shown a similar finding measuring plethysmography of fingers and toes. Hand-transmitted vibration induces skin sympathetic nerve activity and then causes vasoconstriction of the four limbs.

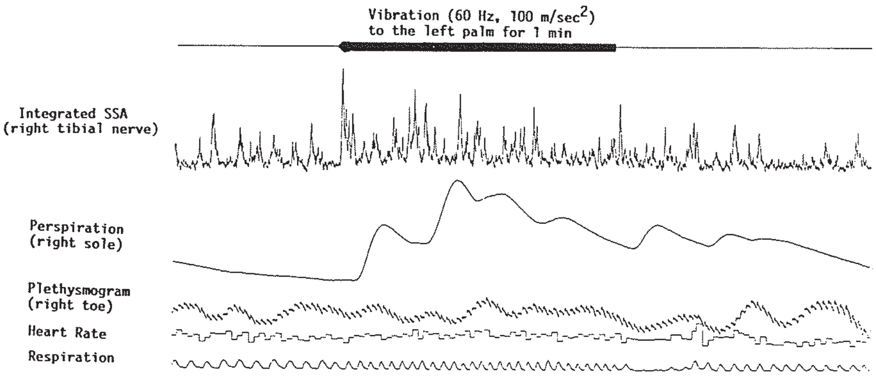

Fig. 4. A record of skin sympathetic nerve activity from the right tibial nerve when vibration was applied to the left palm. (Subject K.K. aged 23. From Ref. 15)

Table 7. Changes of skin sympathetic nerve activity (SSNA) from the right tibial nerve, right toe plethysmogram and right sole perspiration caused by vibration applied to the left palm. (From Ref. 15)

Age of subject	Perspiration on the sole	Total integrated SSNA[a] from the tibial nerve			Mean amplitude[b] of toe plethysmogram		
		Before	Exposure	% increase	Before	Exposure	% increase
20	−	64.5	209.1	+224.2	5.3	4.0	−24.5
	−	42.0	146.6	+249.0	9.0	5.6	−37.8
21	−	136.7	142.6	+4.3	13.9	12.2	−12.2
	−	129.6	149.2	+15.1	15.4	13.6	−11.7
22	−	37.9	51.8	+36.7	4.2	2.7	−35.7
	−	38.3	52.1	+36.0	3.4	2.9	−14.7
23	+	67.4	128.7	+90.9	5.1	4.5	−11.7
	+	67.5	108.5	+60.7	4.8	4.7	−2.7
23	−	61.6	116.6	+89.3	7.7	7.6	−1.3
	−	75.2	87.7	+16.6	8.0	7.1	−11.4

a) Total integrated SSNA means the sum total of burst amplitude of integrated SSNA for 1 min before or during vibration exposure

b) Mean amplitude of toe plethysmogram means the average amplitude for 20s before vibration exposure or for the last 20s of the exposure

HAND-ARM VIBRATION AND CIRCULATORY DISTURBANCES OF THE FOOT

Arterial pathological changes like medial muscular hypertrophy have been often observed in the finger biopsy probes from vibration syndrome patients.[19,20] The medial muscular hypertrophy is thought to be a typical pathological change in vibration syndrome, but similar arterial changes have been also found in the toes of patients.[21,22]

Ashe and Williams[21] investigated arterial biopsy from uranium mine workers who operated jack drills. They examined both finger and toe arteries in some subjects. They indicated medial muscular hypertrophy in the pedal arteries of all patients examined. And the wall/lumen ratio of the pedal arteries was roughly parallel to that seen in the digital arteries in the same patients. We also examined pathological changes of the finger and toe arteries of vibration syndrome patients.[22] Similar arterial changes were found in both the finger and the toe even in chain-saw operators.

Arterial changes like medial muscular hypertrophy in the finger are considered to be due to repeated constriction of the digital arteries. Hand-arm vibration can also constrict the foot arteries through the sympathetic nervous system. Hence, long-term repeated vasoconstriction of the foot may result in pathological changes of the toe artery. These arterial changes can lead to arterial stenosis, and possibly local hormonal abnormality such as endothelium-derived releasing or constricting factors,[23] and reduction of blood flow of the foot.

The circulatory disturbances of the foot might be also associated with hypersensitivity of the patients to cold. Cold activates skin sympathetic nerves and induces vasoconstriction of the extremities. Patients with VWF reportedly have hypersensitivity to cold. The patients have lower

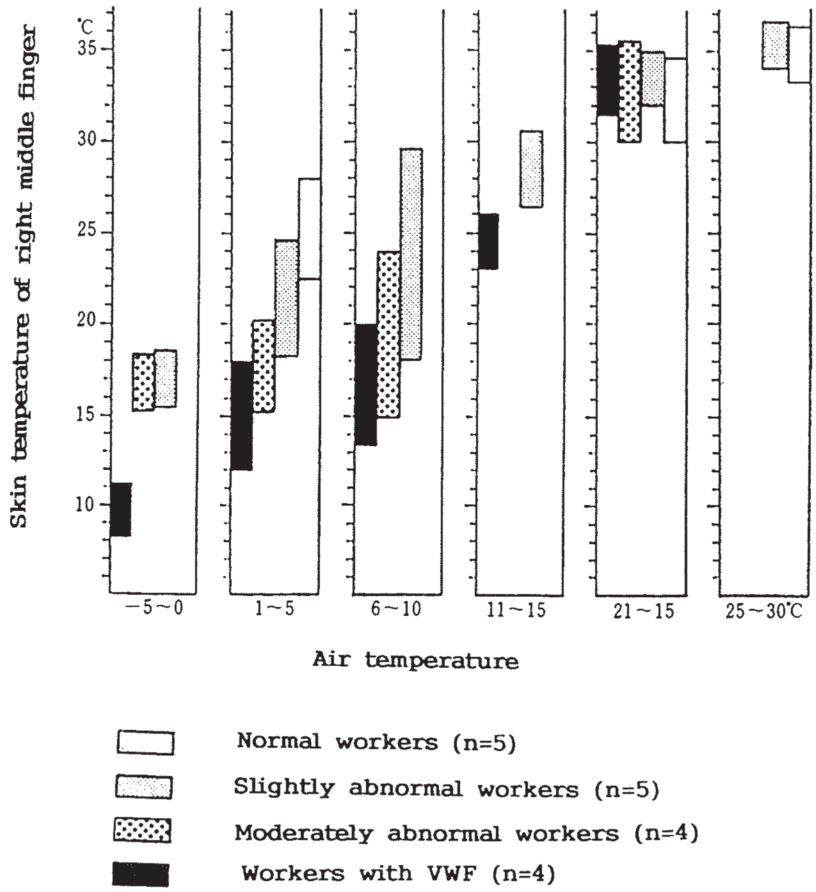

Fig. 5. Range of finger skin temperature measured during forest work at various air temperature. (From Ref. 24, modified)

skin temperatures in response to cold. Fig. 5 by Yamada et al.[24] shows that skin temperature decreased more in patients than healthy controls in colder circumstances. Nakamoto[25] pointed out that under cold circumstances the concentration of plasma norepinephrine increased in VWF patients more than in controls. Vibration syndrome patients seem to have systemic hypersensitivity to cold, which might possibly relate with circulatory disturbances of the foot.

In conclusion, vibration syndrome patients have circulatory disturbances of the foot as well as the hand, and the disturbances of the foot can result from vibration exposure of the hand by causing vasoconstriction of the foot through the sympathetic nervous system. The indirect effect of hand-arm vibration through the sympathetic nerve system should be considered in hand-arm vibration syndrome.

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