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Original Article

Skin temperature responses to hand-arm vibration in cold and thermoneutral ambient temperatures

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Abstract: Hand-arm vibration (HAV) from hand-held vibrating machines increases the risk of injury in the form of vasoconstriction in the fingers, commonly named as vibration induced white fingers (VWF). Cold temperature may increase that risk. This experimental study examined and compared the effects of the skin temperature of the hands during and after exposure to HAV in thermoneutral and cold conditions. Fourteen subjects were exposed to three conditions: 25°C with HAV, 5°C with HAV or 5°C without HAV. Their skin temperatures were continuously recorded for the thumbs, index fingers, palms, and back of hands. After 20 min of acclimatization, the subjects held, for five min, two handles where the right handle could vibrate at 5 m/s^2 and the left was stationary. Finally, they released their grip and stood still for 10 more min. HAV had no additional cooling effect in cold during gripping of the handles. After the subjects released the handles there was only a HAV-induced cooling effect in the left palm with on average 0.5°C colder skin temperature. A single exposure to HAV will not cause an injury such as VWF, but as the present study show: short-term exposure to HAV causes some changes in skin temperature.

Key words: Hand-arm vibrations, Cold, Exposure, Skin temperature

Introduction

In occupations such as construction or maintenance work the workers regularly use hand-held vibrating tools such as grinders, hammers, or drills which expose the worker to hand-arm vibrations (HAV). Exposure to HAV increases the risk of injuries or disorders of the vascular, neurological, as well as the musculoskeletal system of the hand and arm, also known as the hand-arm vibration syndrome (HAVS)[1, 2]. How hazardous the HAV exposure is depends on the intensity, duration, and frequency content. Other important factors are ergonomic factors such as push and grip forces that affect the transmission of HAV from the tool to the hand-arm system[3].

The vascular part of HAVS is believed to be a disturbance in the digital blood circulation causing an abnormal reaction to cold called vibration induced white fingers (VWF), which is a secondary form of Raynaud's phenomena. The cold causes a further decrease in blood flow by a vasoconstriction in the fingers, which facilitates finger cooling and causes hypoxia[3, 4]. Cold temperatures can cool the extremities, body or both. During optimal body heat balance the blood flow to the extremities sustains the

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temperatures of peripheral body parts, but if the cooling is continuous it may trigger a vasoconstriction in the extremities. The vasoconstriction increases the thermal insulation of the superficial tissues in the hand and foot[5]. Cold may not only trigger a vasoconstriction in VWF, but also increase the risk of VWF. A large cross-sectional cohort study of Swedish construction workers indicated that there is an increased risk of VWF in a cold environment among workers exposed to HAV (odds ratio 1.71, 95% confidence interval 1.42–2.06)[6]. On the other hand, studies in tropical or subtropical areas have found a very low prevalence of white fingers suggesting that temperature influences the prevalence of VWF symptoms[7, 8]. In an epidemiological survey on workers exposed to HAV in four regions of China the prevalence of VWF in the northern region was higher than in midwest or southern regions but the study lacked data on factors influencing the risk of VWF such as the amount of HAV exposure, age, and smoking[9]. Experimental studies have found that ambient temperature and HAV influence the finger blood flow (FBF) and finger skin temperature, but it is not clear how these exposures interact with FBF and skin temperature[10–14]. Earlier experimental studies found that FBF and FST decrease with vibration exposure[11, 12].

The aim of this experimental study was to examine and compare the effects on the skin temperatures of the hands in healthy subjects during and after exposure to HAV in thermoneutral and cold conditions.

Subjects And Methods

Subjects

Fourteen healthy volunteers (7 females and 7 males) served as test subjects. Their mean age was 25 (range 21–39) yr, weight was 73 (range 57–96) kg, height was 175 (range 166–187) cm, and BMI was 24 (range 19–30). The test subjects were office workers, students or unemployed with no prior history of regular or prolonged work with hand-held vibrating tools. All subjects answered a questionnaire on their occupation or studies; use of hand-held vibrating tools; tobacco and alcohol consumption; if they had injuries or earlier surgical treatment in their hand, arm, neck, shoulder, or back; any diseases such as diabetes, high blood pressure, heart disease, arthrosis or muscular disease, allergy, asthma, migraine, and; if they used any medication. Their lengths and weights were measured. The exclusion criteria were injury or disorders in the hand, arm, shoulder, neck or back. All subjects were non-smokers, but one male subject used snuff. The test subjects were informed not to use any form of tobacco products, drinking coffee/tea, or performing intense physical exercise less than 3 h before the experiment. All subjects gave their informed written consent to participate in accordance with the Declaration of Helsinki. All subjects were informed verbally and with written explanation of the purpose of the experiment. They were also informed that the participation was voluntary, that they could refuse to participate at any time, and that the result from the experiment would remain confidential. The subjects were also introduced to the experimental procedures and facilities before they gave their written consent to participate. This study was approved by the Regional Ethics Committee of the Northern Ostrobothnia Hospital District, Finland (73/2012).

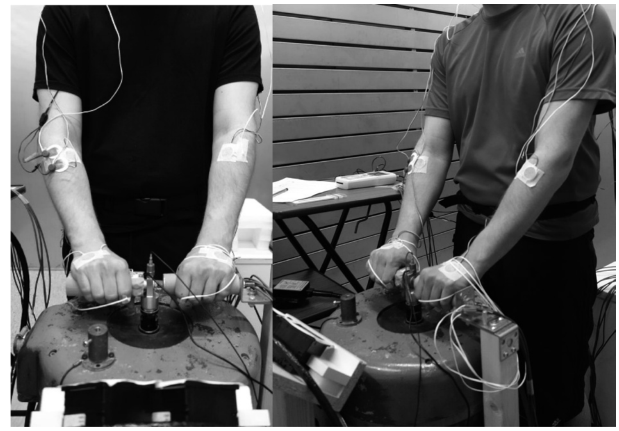

Fig. 1. The subject's position during gripping of the handles.
The right handle was attached to the vibrator and the left handle was attached to a separate pole, which was not in contact with the vibrator.

Experimental procedure

The subjects wore t-shirts, shorts, socks, shoes, and bras if they were female, during the experiment. The experiment was performed in a climatic chamber with either thermoneutral (25°C) or cold (5°C) condition. Air velocity was less than 0.2 m/s. Before entering the climatic chamber all the measurement equipment was fixed on the subjects. Equipped with the instruments the subjects entered into the climatic chamber and stood still with their hands relaxed along the sides. After 20 min of standing still inside the chamber, the subjects used their right hand and gripped the handle of an electrodynamic shaker and the left hand gripped a handle that was stationary all the time. The grip height was adjusted with wooden plates under their feet so that their arms were straight when holding the handles (Fig. 1). The stainless steel handles were covered by a single layer of adhesive tape to decrease contact cooling. Before the first exposure the subjects were instructed on how to hold the handles and control the push and grip force. After gripping the handles for 5 min the subjects released the handles and kept their arms relaxed along the sides for 10 more min. The whole experiment inside the climatic chamber lasted for 35 min.

To investigate if combined exposure to HAV and cold affects the skin temperature differently compared to separate exposures to HAV and cold, the subjects were exposed to three different types of exposure settings. The exposures were: 1) thermoneutral condition, 25°C, with exposure to HAV on the right hand (25V); 2) cold condition, 5°C with exposure to HAV on the right hand (5CV), and; 3) cold condition, 5°C, without HAV (5C). Randomized block design was used so that the order of the three exposure conditions was randomly assigned for each subject. Each subject was tested at the same time of day i.e. before lunch, after lunch or late afternoon for all three experimental conditions. There was at least 24 h between exposures to ensure that the test subjects were fully recovered before the next experiment.

HAV exposure

The grip- and push force were continuously monitored by using a pointer, which was calibrated before each test. The test subjects could see the pointers, one for each force, on a display. Each subject gripped the right handle by a force of 15 N (grip force) and pushed the handle downwards by a force of 20 N (push force). During exposure the right handle vibrated while the left handle was stationary since they were attached to separate apparatus. The grip- and push force on the left handle were not measured and the subjects were instructed to only hold the handle. The magnitude of the HAV level in the vertical direction was set to 5 m/s^2 root mean square (rms) and this vibration level corresponds to an eight-hour equivalent acceleration exposure, A (8), of 0.5 m/s^2 [15]. The HAV spectrum used in this study was recorded from an angular grinder (Hitachi G23UB, rpm 6600, Japan) by an Instant replay (360 systems, USA) attached to an accelerometer (Brüel and Kjær 4368, Denmark) and amplifier (Brüel and Kjær 2635, Denmark). The HAV in the right handle was produced by an electrodynamic shaker (Ling Altec 7/600, Denmark), by an amplifier (Ling Dynamic System 300, Denmark) connected to a low-pass filter (Krohn Hite model 3550, USA), an amplifier (Sentec PA9, Sweden) and an Instant replay (360 systems, USA). The vibration spectrum of the recorded angular grinder from the electrodynamic shaker used in this study was presented as a function of the frequency (Fig. 2). The vibration level was monitored using an accelerometer (Brüel and Kjær 4384, Denmark) attached to the vibrating handle and a level meter (Brüel and Kjær 2513, Denmark).

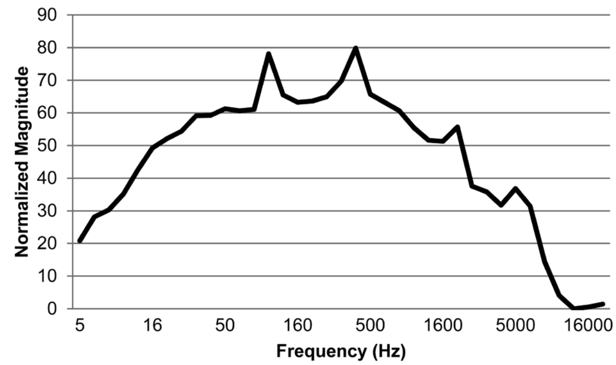

Fig. 2. The spectrum for hand-arm vibration from the angular grinder used in the experiment as a function of the frequency.

Measurement and calculation of skin temperatures

The skin temperature on the thumb, index finger, palm, back of hand, forearm, and trapezius on the left and right side was continuously measured by thermistors (YSI 427, Yellow Springs Instruments, USA) and a data logger (Squirrel 1,000 meter/logger, Grant, UK) with a sampling rate of 1 Hz. The thermistors were placed on the dorsal proximal phalanx of the thumb and on the dorsal intermediate phalanx of the index finger. The skin temperature on the forehead, chest, the left upper arm, thigh, calf, and foot, was measured by thermistors (NTC DC95, Digi-Key, USA) and a data logger (SmartReaderPlus8, ACR Systems, Canada) with a sampling rate of 0.1 Hz. The thermistors were fixed by adhesive tape (Hypafix, BSN medical GmbH, Germany) on the skin, and, data logger was placed in a bag around the subject's waist.

The skin temperature on the forehead, chest, trapezius muscles, back of both hands; left upper arm, thigh, calf, and foot was used to calculate the mean skin temperature according to international standard[16]. The skin temperature changes in the hands and fingers were calculated by subtracting the skin temperatures measured during and after hand gripping from the initial skin temperature (measured just in the beginning of hand gripping).

Statistical analysis

The repeated measurement ANOVA (analysis of variance) method was used to analyse the difference in the skin temperature changes between all three exposure settings. The skin temperature changes during gripping of handles (21–25 min inside the climatic chamber) and after releasing the hands from the handles (26–35 min inside the chamber) were analysed separately. The differences in hand and finger skin temperature changes due to the different thermal (thermoneutral and cold) and vibration (on/off) exposures and the interaction between these two exposure factors were analysed. Statistical significance was set at $p<0.05$. Mauchly's sphericity test was used and if no sphericity could be assumed then the Greenhouse-Geisser correction was used. For each measurement data the Shapiro-Wilkinson test of normality and histograms were used to study if the data had a normal distribution. All data was analysed using IBM SPSS Statistics for Windows (Version 22.0, IBM Corp., released 2013, USA).

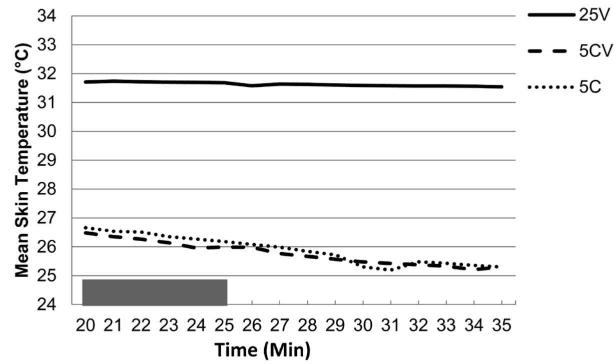

Fig. 3. The average mean skin temperature of all subjects.
In thermoneutral conditions, 25°C, with exposure to HAV (25V) and cold conditions, 5°C, with (5CV) and without (5C) exposure to HAV. The HAV exposure between 20–25 min in the right hand is illustrated as a grey bar in the figure.

Results

Mean skin temperature

During and after hand gripping (at 21–35 min inside the climatic chamber) the average mean skin temperature in thermoneutral conditions was 5.8 °C above the average mean skin temperature in cold conditions, with or without exposure to HAV (Fig. 3). The mean skin temperature decreased on average 1.1°C from 21 to 35 min in cold conditions with and without exposure to HAV.

Hand and finger skin temperatures

During the gripping of the handles

The HAV exposure of the right hand had no significant effect on the skin temperature in the thumbs, index fingers, palms (Figs 4 and 5), and back of both hands regardless of ambient temperature (Table 1).

Thermal and HAV exposures did not significantly affect the skin temperature responses in the right thumb, index finger, and back of hand ($0.2<p<1.0$, Table 1 and Fig. 5). However, there was a significant decrease in skin temperature in the right HAV exposed palm in 5CV compared to 25V ($p=0.02$, Table 1, and Fig. 4b).

In the left non HAV exposed thumb and palm the skin temperatures decreased significantly more in 5C and 5CV compared to 25V ($p<0.01$, Table 1 and Fig. 4a). In the back of the left hand, the skin temperature decreased more in 5C than 25V (Table 1). There was no effect of HAV or ambient temperature on the left index finger ($0.2<p<0.7$, Fig. 5).

During the different exposure conditions, there were some significant differences in local skin temperature between the left and right hand side. During the experimental setting of 25V the local skin temperature decreased more in the right HAV exposed palm ($p=0.01$, Fig. 4) and the left non HAV thumb ($p=0.01$) than the opposite side. The skin temperature in the back of both hands, increased but more for the left hand side than the opposite side ($p=0.03$). In 5CV the skin temperature of the left non HAV thumb decreased more than in the right HAV exposed thumb ($p=0.03$). The skin temperature decreased significantly more in 5C in the left thumb and back of hand than the right thumb ($p<0.05$) and back of hand ($p<0.05$).

After the subjects released the handles

The skin temperature in the thumbs, palms, and back of both hands decreased significantly in 5C and 5CV compared to 25V ($p<0.01$, Table 2 and Fig. 4). However, thermal and HAV exposures had no significant effect on skin temperature responses of the index fingers ($0.1<p<0.5$, Table 2 and Fig. 5).

There were no significant changes in skin temperature of the right and left hand and fingers except for the left palm between 5C compared to 5CV ($0.1<p<0.8$, Table 2 and Fig. 4a). The skin temperature changes in the left palm was on average 0.6°C lower after 5CV compared to 5C ($p=0.037$, Fig. 4a). There was a trend in the back of the left hand of a colder skin temperature after 5C than 5CV ($p=0.09$).

The skin temperature in the right palm decreased in cold and increased in thermoneutral condition (Fig. 4).

There were some significant differences in local skin temperature between left and right hand in 25V and 5CV. In 25V the skin temperature changes were higher in the left non HAV exposed back of hand than the right side

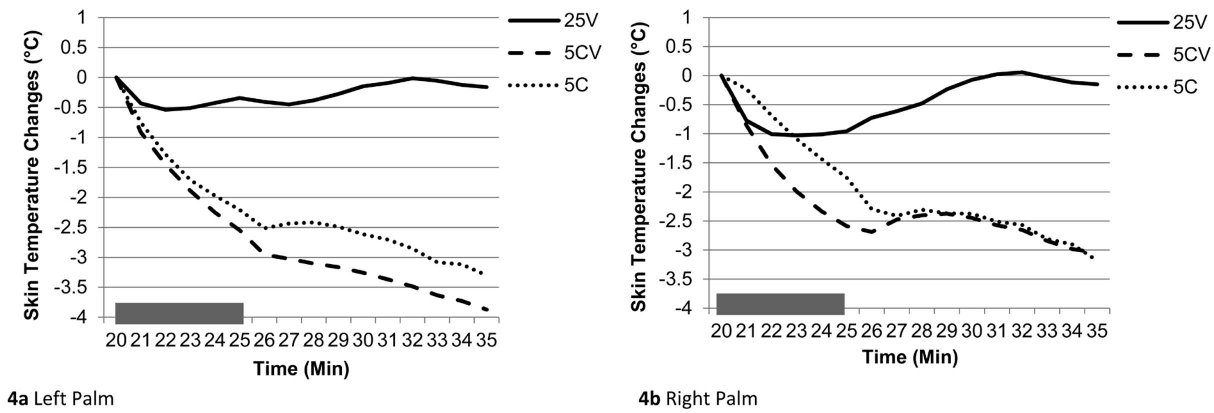

Fig. 4. Skin temperature changes in the left (4a) and right palm (4b).
Temperature when the subjects held the handles (20–25 min) and after releasing their grip on the handles (26–35 min) during thermoneutral (25V) and cold conditions without (5C) and with exposure to HAV (5CV). The HAV exposure between 20–25 min in the right hand is illustrated as a grey bar in the figure.

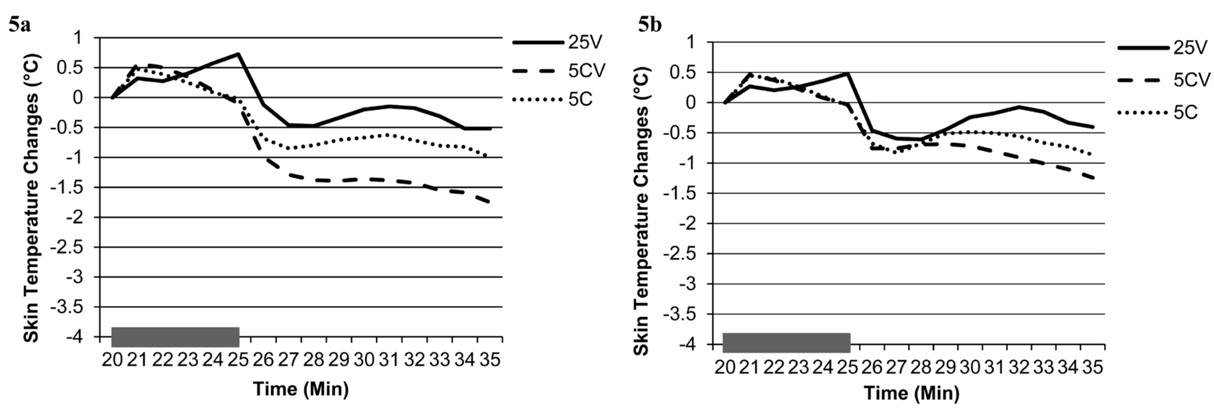

Fig. 5. Skin temperature changes in the left (5a) and right index finger (5b).
Temperature when the subjects held the handles (20–25 min) and after releasing their grip on the handles (26–35 min) during thermoneutral (25V) and cold conditions without (5C) and with exposure to HAV (5CV). The HAV exposure between 20–25 min in the right hand is illustrated as a grey bar in the figure.

Table 1. Repeated measures ANOVA analysis (*p* values) for the differences in skin temperature responses in both hands during gripping of the handles

Exposure	Factor	Thumb		Index finger		Palm		Back of hand	
		Right	Left	Right	Left	Right	Left	Right	Left
25V, 5C	Exposure	0.852	0.001	0.698	0.182	0.798	0.001	0.974	0.022
	Exposure × Time	<0.001	<0.001	0.005	<0.001	0.002	<0.001	0.001	0.025
25V, 5CV	Exposure	0.324	0.004	0.653	0.441	0.023	0.002	0.365	0.097
	Exposure × Time	<0.001	<0.001	0.007	<0.001	<0.001	<0.001	<0.001	0.017
5C, 5CV	Exposure	0.230	0.815	0.930	0.710	0.115	0.488	0.428	0.590
	Exposure × Time	0.582	0.687	0.776	0.176	0.109	0.427	0.888	0.936

25V: 25°C air temperature with exposure to hand-arm vibration (HAV); 5C: 5°C air temperature without exposure to HAV; 5CV: 5°C air temperature with exposure to HAV.

Table 2. Repeated measures ANOVA analysis (*p* values) for the differences in skin temperature responses in both hands after releasing the handles

Exposure	Factor	Thumb		Index finger		Palm		Back of hand	
		Right	Left	Right	Left	Right	Left	Right	Left
25V, 5C	Exposure	<0.001	<0.001	0.452	0.181	<0.001	<0.001	<0.001	<0.001
	Exposure × Time	0.005	0.181	0.377	0.804	<0.001	0.002	<0.001	<0.001
25V, 5CV	Exposure	<0.001	<0.001	0.254	0.061	<0.001	<0.001	<0.001	<0.001
	Exposure × Time	0.012	0.013	0.098	0.557	0.003	<0.001	<0.001	<0.001
5C, 5CV	Exposure	0.835	0.115	0.364	0.093	0.710	0.037	0.493	0.086
	Exposure × Time	0.780	0.236	0.211	0.349	0.303	0.973	0.115	0.296

25V: 25°C air temperature with exposure to hand-arm vibration (HAV); 5C: 5°C air temperature without exposure to HAV; 5CV: 5°C air temperature with exposure to HAV.

(p=0.03). In 5CV the skin temperature decreased significantly more in the left non HAV exposed thumb and palm than the right HAV exposed thumb (p=0.01) and palm (p=0.04, Fig. 4).

Discussion

The present study demonstrated a local skin cooling from HAV in cold condition only after the subjects released their hands from the handles and only on the palm of the left non HAV exposed hand. During gripping of the handles, the HAV had no effect on the local skin temperature. After releasing the handles, the local skin temperature decreased significantly in cold temperature than thermoneutral conditions except for the index fingers.

In the present study, cold temperature and exposure to HAV may have interacted on the local skin temperature, but the effect was small and was only in the left non HAV exposed hand. Earlier experimental studies have found a decrease of skin temperature with decreasing ambient temperature and with additional exposure to HAV the skin temperature decreases even more in the right HAV exposed and left non HAV exposed hand[10–12]. Thus, the cold conditions used in this study were either too cold or the HAV level was too low to affect the skin temperature. The cold conditions might have decreased the FBF to such a low level that the HAV could not affect it and the HAV could thereby not decrease the skin temperature further. In addition, it is still unclear how ambient temperature and HAV interact[10–13]. Both the present study and Scheffer and Dupuis[10] did not find any interaction between temperature and exposure to HAV in the right HAV exposed index finger. Scheffer and Dupuis[10] showed that the static load on the right HAV exposed hand had a predominant influence on the skin temperature in the right index finger. In Chao *et al.* study[13] the HAV levels may have been too low (0.0584–0.0749 m/s^2) for an interaction between temperature and HAV. Ye and Griffin[12] study found a decrease in finger skin temperature and FBF in the left non HAV exposed hand, during and after exposure to HAV in the right hand that was dependent on ambient temperature. However, they only used ambient temperatures above 20°C.

It is interesting that a cooling effect from exposure to HAV occurred in the left non HAV exposed hand. Earlier experimental studies found that HAV in one hand reduces the skin temperature and FBF in the non HAV exposed hand in ambient temperatures above 20°C[12]. Mahbub *et al.*[14] instead found an increase of FBF in the non exposed hand, although they used a vibrating plate that was kept at the same temperature regardless of the room temperature. Short term exposure to HAV has been shown to alter the blood flow in the exposed as well as non HAV exposed hand in an ambient temperature of 23–28°C[17–22]. A possible mechanism for the responses in blood flow to vibrations could be that the vibrations in one hand stimulate the sympathetic nervous system (SNS) in the exposed hand and unexposed hand as well as other extremities[18, 23, 24]. However, in the present study there was no additional cooling effect from HAV in the right hand, in cold conditions. HAV exposure might have activated the blood circulation in the HAV exposed right hand. This might explain why the average local skin temperature decreased less in the right HAV exposed thumb and palm than in the left non HAV exposed thumb and palm after the subject released the grip on the handles. Since we did not measure blood flow we cannot be certain. Experiments in warmer temperatures have found that the HAV decreases the FBF during exposure, but directly after exposure it increases and then declines again for both exposed and non exposed hands[19, 21, 22]. Maybe there is a different effect of HAV in colder temperatures on the FBF and skin temperatures. Cold ambient temperature also affects the blood circulation in the hand by stimulating the SNS and cause vasoconstriction in the arms and fingers, which accelerates the decrease in skin temperature[5].

Other influencing factors in this setup were the grip- and push force. The left non HAV exposed hand, held a stationary handle, but the grip- and push force were not monitored as it was for the right HAV exposed hand. It would have been difficult for the subject to concentrate on several monitors for both hands. The force itself acting on the right HAV exposed palm might alter the FBF on both the exposed and unexposed hand[25]. If there was a difference in grip and push force between the hands it might have caused different changes in blood flow of both hands. Another possible influencing factor was the low airflow in the climatic chamber originating from the same side as the left non-exposed hand side. The actual skin temperature in the back of the left hand was significantly lower compared to the right side when the subject held the handles ($p<0.01$) and after releasing the handles in cold ($p<0.03$) with or without exposure to HAV in the right hand. A cooler skin temperature in the left side may influence how the skin reacts to HAV exposure than the warmer right side.

The vibration exposure duration, level and frequency content affect the finger circulation and may therefore influence the results[19, 21, 22]. Earlier studies have used varied exposure duration, levels, and used frequency content with either a sinusoidal 125 Hz vibration or a broad band frequency content from operating an electric drill or chainsaw[10–13]. To better understand the interaction of HAV and cold on the hand different ambient temperatures should be tested with variation of vibration level, duration and frequency content. No earlier studies have tested high impact vibrations as seen in workers using for example rock-drills and jack hammers. Miyakita *et al.*[11] used a repeated exposure setting, but few subjects. There could be other modifying factors increasing the risk of VWF in cold such as smoking, although it is not clear if smoking increases the risk of VWF[26].

Earlier epidemiological studies suggest that temperature influences the prevalence of VWF symptoms[6–9]. In the present study a site dependent cooling effect from exposure to HAV in cold was found. It is not clear if or how these results from single short term exposure to HAV in cold environment relate to long duration exposure to HAV in cold and the risk of developing VWF. A single exposure to HAV will not cause an injury such as VWF, but as the present study and earlier experimental studies show: short term exposure to HAV causes changes in skin temperature and FBF. Still it is not clear how the physiological responses to short term exposure of HAV reflect any underlying physiological mechanism in developing VWF. Further studies are needed to evaluate if repeated exposures, typical in real life situations, have stronger effects on hand and finger circulation in different temperatures. Thus, this study and earlier experimental studies show that a short, single exposure to HAV and cold temperatures causes changes in skin temperature[10–13]. To understand the effect of HAV and cold conditions on workers, field measurements should be conducted in occupational settings.

Conclusion

Exposure to HAV decreased the local skin temperature even further in cold conditions, but it was limited to the palm of the left, non HAV exposed hand after the subjects released their hands from the handles. No HAV skin temperature cooling effect was present on any other site or during gripping of the handles. This was probably due to a greater vasoconstriction in the left non exposed hand or facilitated circulation in the right HAV exposed hand. A single exposure to HAV will not cause an injury such as VWF, but the present study indicates that short-term exposure to HAV causes some changes in skin temperature.

Conflict of Interest

The authors declare that they have no conflict of interest.

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