

# Changes in Cold-induced Vasodilatation, Pain and Cold Sensation in Fingers Caused by Repeated Finger Cooling in a Cool Environment

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**Abstract:** To examine how repeated cooling of fingers with a rest pause schedule at work affects cold-induced vasodilatation (CIVD), pain and cold sensation in fingers, six healthy men aged 21 to 23 years immersed their left index fingers six times in stirred water at 10°C for 10 minutes. After each cold-water immersion of the fingers, 5-minute rest pause was taken to observe the recovery process of the indicators. This cold-water immersion/rest pause test was carried out in a range of three ambient temperature conditions: 30°C (warm), 25°C (thermoneutral), and 20°C (cool) as experienced in daily life. At the ambient temperatures of 30°C and 25°C, marked CIVD response occurred and the CIVD reactivity did not significantly change upon repetition of cold-water immersion. The lowered finger skin temperature also tended to recover quickly to the pre-immersion level during each post-immersion rest period. At the ambient temperature of 20°C, however, the CIVD response weakened continuously upon repetition of immersion and almost disappeared during the final immersion. The recovery of finger skin temperature during each post-immersion rest was gradually delayed upon repetition of immersion. At every ambient temperature, finger pain and cold sensation induced by each cold-water immersion significantly decreased upon repetition of immersion and completely disappeared during each post-immersion rest period. Oral temperature during the experiment showed no significant change at the ambient temperatures of 25°C and 30°C, but it decreased significantly at the ambient temperature of 20°C. These results suggest that in a cool work environment where the body core temperature is liable to decrease, repeated finger cooling may weaken CIVD reactivity and delay the recovery of finger temperature during post-immersion rest periods. In such lower ambient temperature work conditions, subjective judgements such as the decrease in finger pain and cold sensation during repeated finger cooling and the absence of them during post-immersion rest may not be reliable indicators for monitoring the risk of progressive tissue cooling and frostbite formation.

**Key words:** CIVD (Cold-induced vasodilatation), Repeated and intermittent cooling, Pain, Cold sensation, Ambient temperature, Rest, Frostbite, Finger, Work

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## Introduction

In workers in cold environments such as refrigerated warehouses, food processing facilities and outdoors in cold weather, excessive cooling of fingers and toes have been frequently reported<sup>1, 2</sup>, even though the workers wear thick clothing to protect themselves from cold stress. Our recent case study on job-related frostbite found that some workers were affected by frostbite without noticing any subjective warning signs during work in cold environments in spite of wearing cold-protective clothing<sup>3</sup>.

In such cold work places, the workers are likely to handle frozen materials through cotton gloves or cold protective-gloves they wear, or touch a frozen fish or meat directly with their hands, or immerse their fingers in cold-water. In all cases, they are rarely kept exposed to cold stress for a long period, but, their fingers and hands are repeatedly and intermittently cooled, with rests and pauses in between<sup>4</sup>.

When peripheral parts of the body such as fingers and toes are exposed to extreme cold, cold-induced vasodilatation (CIVD) occurs as a defensive reaction that protects the extremities against excessive cooling and frostbite<sup>5</sup>. Yoshimura and Iida<sup>6</sup> developed a practical method, based on CIVD reactivity, of evaluating peripheral resistance to frostbite (local cold tolerance). Since then, many studies have been carried out using this test method to clarify the factors affecting local cold tolerance, such as occupation<sup>8, 9</sup>, gender<sup>8</sup>, age<sup>11, 12</sup>, race<sup>7</sup>, environmental temperature<sup>8, 17</sup>, body heat content<sup>18</sup>, clothing<sup>10</sup>, ambient pressure<sup>13</sup>, season<sup>8</sup> and cold acclimatization<sup>14, 15</sup>. Nevertheless, there has been little research on how CIVD occurs during short-term repeated or intermittent cooling as experienced in actual cold work. When repeating cold-water immersion for a short period with rests in between, we hardly know whether the CIVD response increases or decreases, or remains constant, and scarcely know how the ambient temperature affects it. During the cold immersion, pain and cold sensations also occur and consequently the subjective thermal loads increase, but we do not know how these subjective thermal loads change with short repeated immersions in cold water or change in post-immersion rest. As mentioned above<sup>3</sup>, we found some cases of job-related frostbite which occur unconsciously during working in cold environments. It is, therefore, important to investigate not only how CIVD response as a frostbite-resistant reaction occurs but how the cold pain or thermal sensation in the fingers varies when the fingers are repeatedly and intermittently cooled with rests or pauses in between.

The objective of this study is, therefore, (1) to examine how repeated finger cooling with rest affects cold-induced vasodilatation (CIVD) response and subjective thermal loads such as pain and cold sensation, and (2) to elucidate how the ambient temperature affects these frostbite-resistant response and subjective thermal loads. Based on the findings obtained, we discussed the characteristics of CIVD response and problems concerning subjective thermal loads induced by repeated and intermittent peripheral cooling during work in cold environments.

## Subjects and Methods

Six healthy young men aged 21 to 23 years participated in this study. The physical characteristics of the subjects are shown in Table 1. They had been well informed of the protocol and had given their informed consent before the experiment. This study was approved by the ethics committee of the National Institute of Industrial Health. In order to make clothing uniform, a T-shirt, short pants, trunks and socks were to be the clothes during the experiment. The experiment was carried out in the morning (10:00–12:00) of days between August and early September. The subjects entered an artificial climatic chamber to adapt to ambient temperature conditions at 10 a.m., and rested on chairs for 30 minutes, during which time the measuring electrodes were attached to them. After a 5-min recording of control values before cold-water immersion, the subjects immersed their left index fingers in stirred water at 10°C for 10 minutes as reported previously<sup>11, 16, 17</sup>. This immersion procedure was repeated six times. Each cold-water immersion was followed by a 5-minute rest. This cold-water immersion experiment was carried out on different days under three ambient temperature conditions in the climatic chamber with relative humidity of 50%: 30°C (warm), 25°C (neutral) and 20°C (cool).

The skin temperature of the palmar side of the immersed

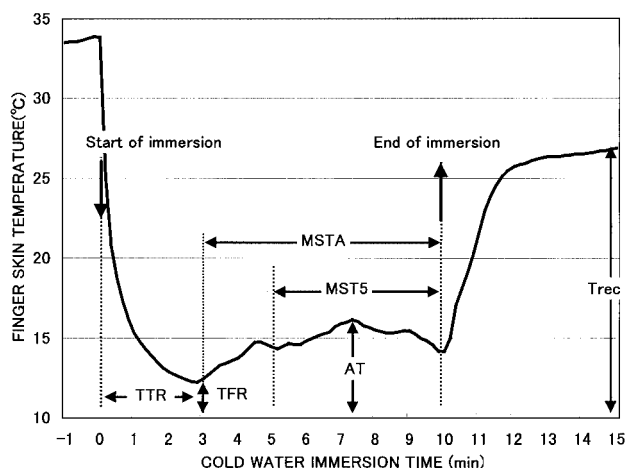
**Table 1. Physical characteristics of subjects (n=6)**

	Age (year)	Height (m)	Weight (kg)	Ab* (m <sup>2</sup> )	Body Fat** (%)
Mean	22.5	1.75	66.6	1.80	23.7
SD	0.8	0.10	6.9	0.09	3.3

\*Body surface area was estimated from Fujimoto's equation<sup>23</sup>.

\*\*Body fat (%) was measured by using a body fat meter (AD-6311, A & D).

finger tip and the oral temperature of the subjects were measured every 10 seconds with thermistor probes (ITP010-12, NIKKISO-YSI). The subjective pain and thermal sensations in the immersed finger were also reported by the subjects every minute, on a four-point scale (1: None, 2: Slightly painful, 3: Painful, 4: Very painful) and a seven-point scale (1: Very warm, 2: Warm, 3: Slightly warm, 4: Neutral, 5: Slightly cold, 6: Cold, 7: Very cold), respectively. In addition, subjective comfort and thermal sensation in the whole body were reported at the beginning and end of the experiment, on a four-point scale (1: Comfortable, 2: Slightly uncomfortable, 3: Uncomfortable, 4: Very uncomfortable) and a nine-point scale (1: Very cold, 2: Cold, 3: Cool, 4: Slightly cool, 5: neutral, 6: Slightly warm, 7: Warm, 8: Hot, 9: Very hot), respectively. To evaluate the CIVD reactivity as an index of frostbite resistance, the following parameters were used as shown in Fig. 1: TFR=temperature at first rise following the immersion; TTR=time for first temperature rise following the immersion; MST5=mean skin temperature of the finger during the last 5 minutes of immersion; AT=maximum temperature rise in the CIVD response<sup>6,8,11,17</sup>; In addition to these four parameters, the area between the temperature curve of CIVD and the base line of 10°C



**Fig. 1. Five parameters for evaluating CIVD reactivity by using a finger skin temperature curve.**

TFR=Temperature at first rise following the immersion; TTR=Time for first temperature rise following the immersion; MST5=Mean skin temperature of the finger during the last 5 minutes of immersion; AT=Maximum temperature rise in the CIVD response curve; MSTA=Section area between the temperature curve and base line of 10°C over the period from the onset of temperature rise to the end of immersion. Trec (=finger skin temperature at the end of post-immersion rest) is also included as an index of recovery rate of finger skin temperature during the post-immersion rest in the figure.

(=MSTA) was estimated by integrating the temperature values which were measured every 10 seconds over the period from the onset of temperature rise to the end of immersion. And recovery of the finger skin temperature was evaluated at the end of each post-immersion rest (Trec).

Repeated measures analysis of variance (ANOVA) was used to statistically evaluate the effect of ambient temperature and repetition of immersion on CIVD response, recovery of finger skin temperature at post-immersion rest, and pain and cold sensations. Paired t-test was employed to evaluate the difference in oral temperature between pre- and post-experiments and between ambient temperatures.

## Results

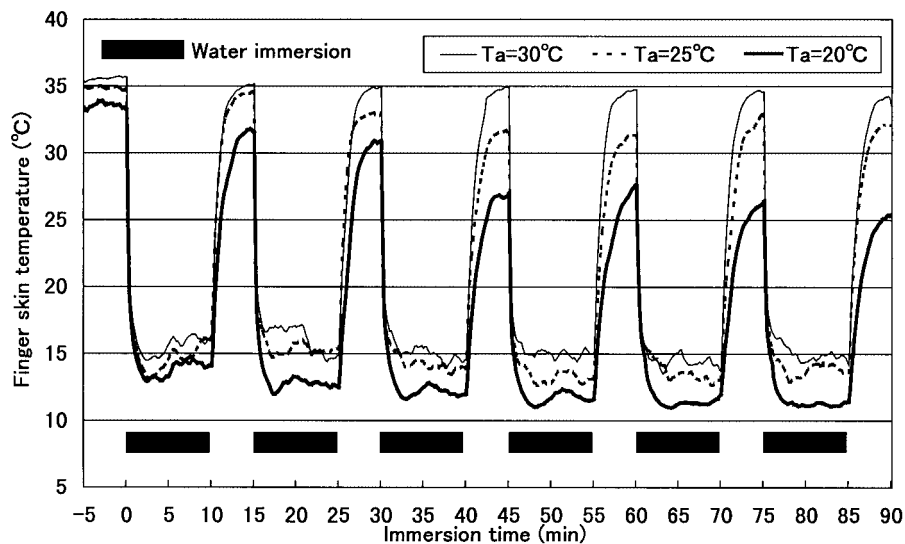
Fig. 2 shows the CIVD responses of the immersed finger during repeated cold-water immersion under the three different ambient temperature conditions. Table 2 shows the values (mean  $\pm$  SE) for each parameter of CIVD reactivity (TFR, TTR, MST5, MSTA, and AT) and recovery of skin temperature of the immersed finger at the end of post-immersion rest (Trec). All of these measured variables were significantly affected by the ambient temperature conditions. At the ambient temperatures of 30°C and 25°C, marked CIVD response occurred and the CIVD response did not significantly change upon repetition of cold-water immersion. The finger skin temperature during each post-immersion rest also tended to recover quickly to the pre-immersion level. At the ambient temperature of 20°C, however, the CIVD response which markedly occurred during the first immersion gradually weakened upon repetition of immersion and almost disappeared during the final immersion. The recovery of finger skin temperature during each post-immersion rest (Trec) also decreased significantly upon repetition of immersion (Table 2). The statistical analysis of each parameter (TFR, TTR, MST5, MSTA and AT) of CIVD response by means of repeated measures ANOVA revealed a significant decrease in MSTA, MST5 and TFR and a significant increase in TTR upon repetition of immersion at the ambient temperature of 20°C (Table 2).

Fig. 3 shows the changes in pain sensation of the immersed finger during repeated cold-water immersion under the three different ambient temperature conditions. Finger pain sensation rapidly increased during each immersion but it tended to decrease upon repetition of immersion. It also completely disappeared during each post-immersion rest period. The pain sensation during the immersion and post-immersion periods was not significantly affected by the

**Table 2.** Effect of repeated cold-water immersion on five parameters of CIVD reactivity (TFR, TTR, AT, MST5 and MSTA) and the recovery of skin temperature of the immersed finger at the end of each post-immersion rest (Trec) under three ambient temperature conditions: 20, 25 and 30°C

Ambient temperature	CIVD parameter	Repetition of cold-water immersion					
		1st	2nd	3rd	4th	5th	6th
30°C <sup>s</sup>	TFR (°C)	4.1 ± 1.62	5.5 ± 1.06	5.5 ± 1.03	4.5 ± 0.83	3.9 ± 1.06	5.4 ± 1.06
	TTR (min)	2.1 ± 0.40	1.8 ± 0.36	1.7 ± 0.38	1.6 ± 0.42	1.9 ± 0.46	2.0 ± 0.62
	AT (°C)	8.5 ± 1.25	7.9 ± 0.66	7.7 ± 0.61	6.9 ± 0.63	6.7 ± 0.98	6.9 ± 0.74
	MST5 (°C)	6.5 ± 1.28	5.8 ± 0.79	5.2 ± 1.03	4.9 ± 0.74	4.4 ± 1.12	5.2 ± 0.75
	MSTA	263 ± 86	298 ± 45	233 ± 60	242 ± 50	202 ± 62	228 ± 55
	Trec (°C)	35.1 ± 0.18	34.9 ± 0.17	34.9 ± 0.19	34.7 ± 0.17	34.6 ± 0.25	33.6 ± 1.16
25°C <sup>s</sup>	TFR (°C)	3.0 ± 1.14	5.1 ± 1.03	4.0 ± 1.11	2.5 ± 0.88	4.6 ± 1.40	2.6 ± 0.77
	TTR (min)	2.6 ± 0.44	2.0 ± 0.33	2.0 ± 0.52	2.8 ± 0.76	2.2 ± 0.73	3.1 ± 0.78
	AT (°C)	6.3 ± 1.20	7.8 ± 0.51	5.5 ± 1.11	4.3 ± 1.24	5.5 ± 1.35	5.2 ± 0.98
	MST5 (°C)	4.7 ± 0.99	5.5 ± 0.75	3.9 ± 0.89	3.1 ± 1.04	3.3 ± 1.05	4.1 ± 0.92
	MSTA	214 ± 60	251 ± 42	209 ± 54	123 ± 46	164 ± 60	151 ± 51
	Trec (°C)	34.5 ± 0.21	32.7 ± 1.28	31.1 ± 2.12	30.7 ± 2.38	32.8 ± 0.91	33.3 ± 0.50
20°C <sup>s</sup>	TFR (°C)	2.5 ± 0.94	1.8 ± 0.52	1.4 ± 0.32	0.8 ± 0.24	0.8 ± 0.33	0.8 ± 0.48 <sup>#</sup>
	TTR (min)	2.9 ± 0.55	3.0 ± 0.52	2.9 ± 0.12	4.1 ± 0.45	4.9 ± 0.92	4.7 ± 0.73 <sup>#</sup>
	AT (°C)	5.5 ± 1.17	2.3 ± 2.41	3.1 ± 0.64	2.7 ± 0.76	1.8 ± 0.50	1.9 ± 0.80
	MST5 (°C)	4.0 ± 0.88	2.9 ± 0.79	2.3 ± 0.52	1.9 ± 0.49	1.4 ± 0.43	1.2 ± 0.48 <sup>#</sup>
	MSTA	192 ± 46	138 ± 34	87 ± 18	73 ± 65	55 ± 16	53 ± 24 <sup>#</sup>
	Trec (°C)	31.3 ± 1.33	30.6 ± 1.22	26.3 ± 2.07	27.4 ± 2.26	26.2 ± 2.19	25.6 ± 2.61 <sup>#</sup>

Values are the mean ± SE. <sup>#</sup>P<0.01 (Effect of repetition is significant by repeated measures ANOVA). <sup>s</sup>P<0.01 (Effect of ambient temperature is significant by repeated measures ANOVA).



**Fig. 2.** CIVD responses during the repeated cold-water immersion under three different room temperature conditions (20°C, 25°C and 30°C).

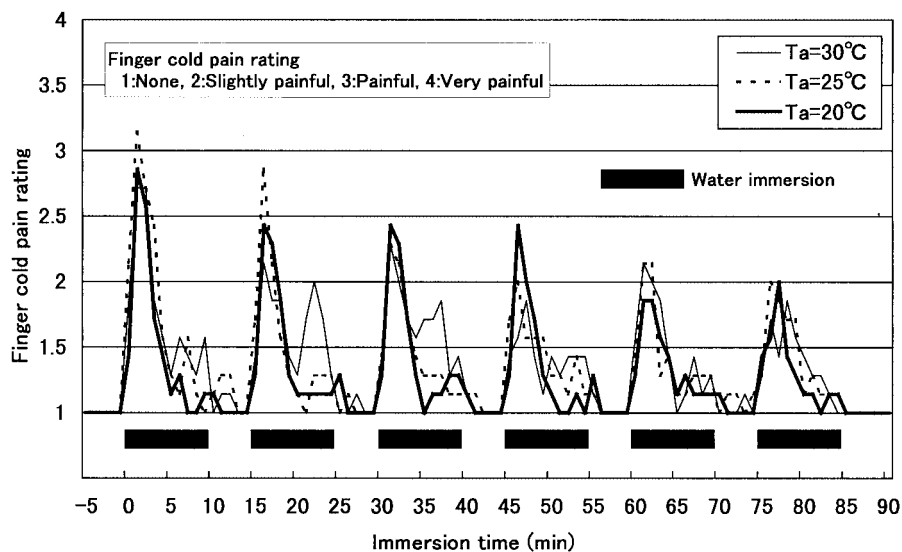


Fig. 3. Changes in pain sensation of the immersed finger during repeated cold-water immersion under three different room temperature conditions (20°C, 25°C and 30°C).

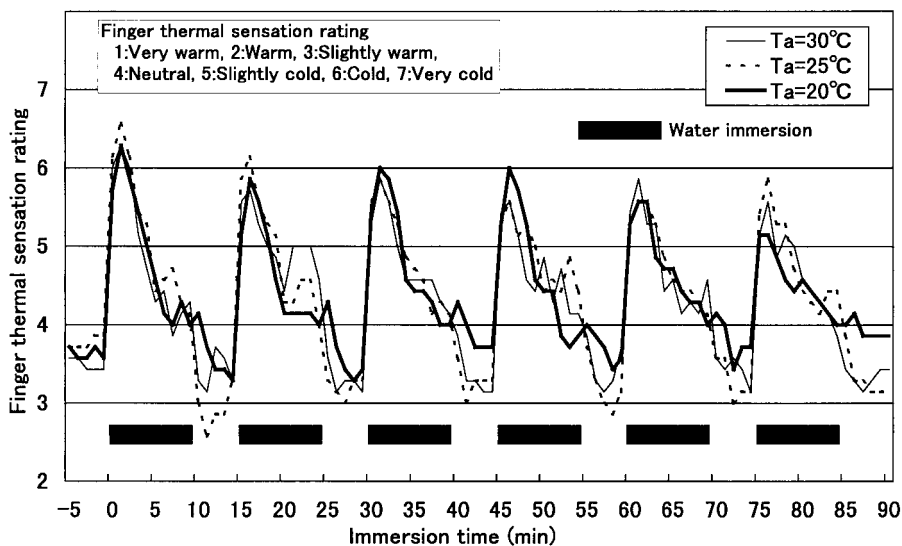


Fig. 4. Changes in thermal sensation of the immersed finger during repeated cold-water immersion under three different room temperature conditions (20°C, 25°C and 30°C).

ambient temperature conditions.

Fig. 4 shows the changes in finger thermal sensation during repeated cold-water immersion under the three different ambient temperature conditions. Finger cold sensation rapidly increased during each immersion but it tended to decrease upon repetition of immersion. Cold sensation was completely replaced by a warm or neutral sensation during each rest period. The finger thermal sensation during the

immersion and post-immersion periods was not significantly affected by the ambient temperature conditions.

Oral temperature during the experiment showed no significant change at the ambient temperatures of 25°C (from  $36.9 \pm 0.27^\circ\text{C}$  to  $36.8 \pm 0.27^\circ\text{C}$ ) and 30°C (from  $36.9 \pm 0.23^\circ\text{C}$  to  $36.9 \pm 0.23^\circ\text{C}$ ), whereas it decreased significantly from  $36.6 \pm 0.29^\circ\text{C}$  to  $36.3 \pm 0.29^\circ\text{C}$  at the ambient temperature of 20°C.

Before the experiment, the subjects tended to feel “neither cool nor warm (neutral), and comfortable” at the ambient temperature of 25°C, “warm and comfortable” at 30°C, and “slightly cool and comfortable” at 20°C. After the experiment, they tended to feel “neither cool nor warm (neutral), and comfortable” at 25°C, “warm and slightly uncomfortable” at 30°C, and “cool and slightly uncomfortable” at 20°C.

## Discussion

### *CIVD response during repeated cooling with rest*

Several previous studies have shown that the CIVD response is strongly affected by environmental temperature<sup>8, 17)</sup> or body heat content<sup>18)</sup>: the higher the environmental temperature or body heat content, the stronger the CIVD response; the lower the environmental temperature or body heat content, the weaker the CIVD response, but it has not been shown whether this is also true for repeated and intermittent cooling with rest in between. In this experiment we could observe no significant change in the CIVD response when the subject felt “neither warm nor cool (neutral), and thermally comfortable” at 25°C, or “slightly uncomfortable and warm” at 30°C, without any change in oral temperature. The present study, therefore, showed that the CIVD response changed little upon the repetition of cold-water immersion under thermoneutral or higher ambient temperature conditions (25°C, 30°C). On the other hand, this study also showed that the CIVD response tended to weaken significantly upon repetition of cold-water immersion under a lower ambient temperature condition (20°C) where the body continues to cool and the subjects feel “slightly uncomfortable and cool”.

### *Recovery of skin temperature during each post-immersion rest*

The recovery of finger temperature during each post-immersion rest was also much affected by the ambient temperature condition and the repetition of cold-water immersion; it significantly decreased with repetition of cold-water immersion under the lower ambient temperature condition (20°C), but changed little under the thermoneutral or higher temperature condition (25°C, 30°C). Since it was pointed out that the CIVD response is severely affected by the skin temperature before the immersion as well as the ambient temperature and body heat content<sup>17, 19)</sup>, the delay in recovery of the skin temperature during the post-immersion rest at 20°C is considered to be much involved in the

depression of CIVD responses induced by the next cold-water immersion.

### *Finger pain and cold sensation during repeated cooling with rest*

The pain and the cold sensations of the immersed finger were not affected by the ambient temperature conditions, contrary to the CIVD response and recovery of skin temperature during the post-immersion rest. In every ambient temperature condition, the pain and cold sensation weakened upon repetition of cold-water immersion and disappeared completely during each post-immersion rest: In the lower ambient temperature condition (20°C), the frostbite-resistant CIVD response decreased upon repetition of cold-water immersion and the recovery of the skin temperature during the post-immersion rest kept retarded. Nevertheless, cold pain and cold sensation in the fingers kept decreasing upon the repetition of cold-water immersion and they disappeared completely during each post-immersion rest.

In the recommendations for a cold exposure limit, the American Conference of Governmental Industrial Hygienist (ACGIH)<sup>20)</sup> and the Japan Society for Occupational Health (JSOH)<sup>21)</sup> pointed out that cold pain is the early warning sign of danger to cold stress and frostbite. Nevertheless, the findings obtained in this study showed that in lower ambient temperature conditions the frostbite-resistant response decreased clearly, as indicated in CIVD response, upon repetition of cold-water immersion, and showed that progressive cooling of the finger tissue occurs, increasing the risk of frostbite. Nevertheless, the pain and cold sensation in the finger continued to decrease. This suggests that cold pain is not a reliable warning sign of frostbite and progressive cooling of the finger tissue under the cool conditions.

Although the recovery of the immersed finger temperature during the post-immersion rest kept retarded under the lower ambient temperature conditions at 20°C, the cold pain and the cold sensation disappeared completely. This also implies that the progressive cooling of the fingers during post-immersion rests could not be subjectively perceived. We therefore strongly suggest that if the work-rest cycle is left to the workers' subjective judgment and the time for rest is voluntarily chosen by them, progressive cooling of the finger tissue may occur unconsciously and the risk of the frostbite may increase. In fact our recent case study of job-related frostbite showed that though workers in cold environments considered that they had sufficient protection against the cold, some of them suffered from frostbite unconsciously while working in cold environments<sup>3)</sup>.

*Validity of CIVD response as an index of frostbite resistance*

As mentioned above, Yoshimura *et al.*<sup>6)</sup> proposed a local cold tolerance test, because the CIVD reactivity is closely related to an individual's frostbite resistance. This test method has, however, consisted of 30-min immersion of fingers in ice water (0°C). Under this test condition, most of the participants have tended to feel much pain and distress, and some have either fainted or had to withdraw prematurely from the experiment. We, therefore, previously proposed a simplified and less painful test for evaluating local cold tolerance as a substitute for Yoshimura's method<sup>11,16,17)</sup>. Then we suggested that the degree of CIVD response occurring when fingers are immersed in 10°C water for 10 minutes closely reflects the equivalent frostbite resistance level obtained when fingers are immersed in 0°C water for 30 minutes. In the present study we therefore used the method of water immersion at 10°C for 10 minutes to examine how repeated finger cooling affects the frostbite-resistant response.

Nevertheless, it is controversial to evaluate individual frostbite resistance by the CIVD response observed in this cold-water immersion test. But we suppose that the CIVD response also has such other physiological effects as fingers are kept warm and prevented from excessive cooling, cold pain is diminished<sup>17)</sup>, and tactile discrimination is improved<sup>22)</sup> if CIVD response occurs. We, therefore, thought that the CIVD response observed during cold-water immersion at 10°C for 10 min would be useful in preventing finger overcooling, to mitigate subjective loads and to improve finger dexterity as well as to prevent frostbite.

Of course because it is not allowed and therefore impossible to cause frostbite experimentally in human subject, the present study does not directly prove the existence of a mechanism by which the frostbite occurs unconsciously during work in cold environments, as mentioned above. But the present study clearly shows that at work under such lower ambient temperature conditions where the body core temperature lowers, the pain and cold sensation in fingers do not work as warning signs of frostbite and progressive tissue cooling. This finding is considered to be closely connected with the above-mentioned fact that workers suffered from frostbite without any warning sign<sup>3)</sup>. On the other hand, if fingers are cooled under the thermoneutral or higher condition, we can expect that the higher CIVD response occurs regardless of the workers' subjective sensation or perception and that there may be less risk of frostbite occurrence.

*Conclusion*

The present study suggests that in cool work environments where the body core temperature is liable to decrease, repeated finger cooling may weaken the CIVD response and delay the recovery of finger temperature during post-immersion rest periods. In such lower ambient temperature work conditions, subjective judgements such as the decrease in finger pain and cold sensation during repeated finger cooling and the absence of them during post-immersion rest may not be reliable indicators for monitoring the risk of progressive tissue cooling and frostbite formation.

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