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ORIGINAL ARTICLE

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Finger cold-induced vasodilation: a review

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Abstract Cold-induced vasodilation (CIVD) in the finger tips generally occurs 5–10 min after the start of local cold exposure of the extremities. This phenomenon is believed to reduce the risk of local cold injuries. However, CIVD is almost absent during hypothermia, when survival of the organism takes precedence over the survival of peripheral tissue. Subjects that are often exposed to local cold (e.g. fish filleters) develop an enhanced CIVD response. Also, differences between ethnic groups are obvious, with black people having the weakest CIVD response. Many other factors affect CIVD, such as diet, alcohol consumption, altitude, age and stress. CIVD is probably caused by a sudden decrease in the release of neurotransmitters from the sympathetic nerves to the muscular coat of the arterio-venous anastomoses (AVAs) due to local cold. AVAs are specific thermoregulatory organs that regulate blood flow in the cold and heat. Their relatively large diameter enables large amounts of blood to pass and convey heat to the surrounding tissue. Unfortunately, information on the quantity of AVAs is lacking, which makes it difficult to estimate the full impact on peripheral blood flow. This review illustrates the thermospecificity of the AVAs and the close link to CIVD. CIVD is influenced by many parameters, but controlled experiments yield information on how CIVD protects the extremities against cold injuries.

Keywords Arterio-venous anastomoses · Cold induced vasodilation · Finger blood flow

Introduction

Millions of people are daily exposed to cold and face the challenge to maintain their body core temperature at about 37°C. Peripheral vasoconstriction is a powerful mechanism to reduce the heat loss, but results in strong cooling of the extremities. However, the extremities possess the ability to prevent the occurrence of local cold extremes. About 5–10 min after the initiation of cold exposure of the hand, blood vessels in the finger tips suddenly vasodilate, which increases the peripheral blood flow and subsequently the temperature of the finger tips. This cold-induced vasodilation (CIVD) is followed by a new phase of vasoconstriction. This process repeats itself and is called 'the hunting reaction' (Lewis 1930). Arterio-venous anastomoses (AVAs) are thought to play a major role in the mechanism of CIVD, but the exact mechanism is still subject to debate. The CIVD reaction and the related blood vessels are important issues for thermal physiologists, since CIVD is thought to reduce the risk of local cold injuries (Iida 1949). Wilson and Goldman (1970) found in their experiments that freezing did not take place when CIVD occurred. It is likely that CIVD also improves the manual dexterity and tactile sensitivity during work in the cold. Since the blood flow increases substantially in the fingers during CIVD, this increases the blood circulation in the large vessels of the forearm, with the consequence of increasing the temperature of the forearm muscles (Ducharme et al. 1991), and likely contributes to improved manual performance by improving muscle function. The increased skin temperature due to CIVD will increase the firing rate of the pressure transducers in the skin and thus increase tactile sensitivity.

CIVD can occur at several locations in the human body. The focus in this review is placed on finger CIVD, since the finger is a common site for local cold injuries and most data are available for this body part.

It is the purpose of this article to review the current knowledge on finger CIVD, to describe the effects of several parameters such as core temperature, diet and acclimatization on finger CIVD and to discuss the possible mechanisms involved.

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Definitions and terminology

CIVD and hunting reaction

Cold-induced vasodilation can be defined as vasodilation of cold-exposed blood vessels, in particular the small arteries. The term hunting reaction or hunting response (Lewis 1930) is used to describe the alternating periods of vasodilation and vasoconstriction during cold exposure. Some authors use the term Lewis reaction instead of hunting reaction (Kramer and Schulze 1948; Werner 1977).

Purkayastha et al. (1992) argue that the hunting reaction is only one out of four possible reactions of blood vessels to extreme local cold. The other responses observed in the fingers after immersion in cold water are: (1) a continuous state of vasoconstriction, (2) slow steady and continuous rewarming and (3) a proportional control form in which the blood vessel diameter remains constant after an initial phase of vasoconstriction.

The majority of the vascular responses to immersion of the finger in cold water can be classified as the hunting reaction. Daanen (2001) observed that the hunting reaction was present in 210 out of 226 investigated male subjects (93%) who immersed their finger in ice water. The reactions of the remaining subjects were difficult to classify.

Arterio-venous anastomoses (AVAs)

AVAs are thought to play a major role in CIVD. These blood vessels have a thick muscular wall and a lumen, measuring on average 10–30 μm (Gray 2000), 35 μm (Roddie 1983) or even 50 μm (Sherman 1963). Under the influence of the sympathetic nervous system, with its rich supply of non-myelinated fibres on the wall of the vessel, they are capable of complete closure. When the AVAs are open, large amounts of blood can pass. Anastomoses are not fixed structures, but may come and go on demand: they can develop when necessary and disappear when they are no longer needed. Hale and Burch (1960) observed that AVAs develop if blood requirement increases at the finger tip. Clark and Clark (1934) estimated that the formation of new AVAs requires 2–3 days.

In their studies, Hale and Burch (1960) and Clara (1939) mentioned the following sites of AVAs: the skin of the inside of the hand and foot, the nail bed, the elbow, lips, cheeks, ears and the nose. There is some discussion about the presence of AVAs in the skin of the head.

Grant and Bland (1931) found 501 AVAs per cm^2 surface area in the nail bed, 236 in the finger tip, 150 on the palmar side of the distal phalanx, 20 on the palmar side of the medial phalanx and 93 on the palmar side of the proximal phalanx. They found no AVAs on the dorsal side of the hand. However, the numbers were derived from only one index finger from only one subject, although they claim that similar results were found in three other subjects. Masson (1937) only counted three to four AVA's per cm^2 at the top of the finger and about ten in the nail bed. Clara (1939) argued that Grant and Bland (1931) counted the same AVA several times. AVAs are tortuous and they did not account for that in their counting technique.

The limited information on the number of AVAs in the fingers and the disagreement in the existing studies necessitates new research to address this topic. Moreover, there is a strong need for more accurate data on the amount of AVAs in the human body, in particular to improve current computer models on blood flow and heat transfer.

Methodology

Several methods are available to quantify the amount of vasodilation in the finger skin. Direct measurement of the diameter of blood vessels is extremely difficult, if not impossible, and therefore indirect measures are used. When the blood vessel diameter increases, the blood flow increases (if the viscosity of the blood remains the same) and this can be measured by laser Doppler flowmetry and strain gauge plethysmography. Some authors determine the blood flow by the wash out of a marker added to the blood (e.g. Coffman 1972). The increased blood flow raises the tissue temperature and thus the temperature at the finger tip. The finger skin temperature is the most frequently used method to determine CIVD. The increased finger skin temperature leads to a higher heat transfer to the environment, which can be assessed by heat flux sensors and calorimetry. The most common methods to quantify CIVD are briefly discussed below.

Strain gauge plethysmography

The principle of this technique is that a cuff is placed and inflated proximal to the measuring site in such a way that blood can enter, but not leave the measured extremity. During the obstruction a linear increase is seen in circumference due to the accumulating blood. The increase in circumference is an estimator of blood flow (Elkington 1968). Since fingers are almost free of skeletal muscle tissue, their volume changes mainly represent alterations in the blood volume in the cutaneous blood vessels (Okuda 1942).

Laser Doppler flowmetry

Laser Doppler flowmetry is a method that yields information on local skin blood flow. The emitted laser light from a small probe on the skin is backscattered from moving red blood cells or static skin structures. Light scattered from moving objects is shifted in frequency (Doppler shift) in proportion to the velocity of the moving target. A photodetector, located close to the laser beam end, measures the backscattered light.

The penetration depth of the laser in the skin is determined by the wavelength of the laser Doppler system, the fibre separation (Hirata et al. 1988) and local properties of the skin (Tenland 1982). Nagasaka et al. (1988) argues that only a minimal part of the AVAs can be "seen" by laser Doppler flowmetry using He-Ne lasers. Wollersheim (1988), however, shows that at least part of the shunt flow is included in the laser Doppler results. This issue is not resolved, but it can be expected that new laser Doppler systems will have the ability to set the penetration depth.

Skin nutritional blood flow through the capillaries is generally related to total blood flow of an extremity. For instance, Johnson et al. (1984) found a good relationship between laser Doppler flow and forearm blood flow ($r = 0.94$–0.98). However, there are also situations, such as reflex vasodilation, in which skin perfusion is regulated independently from total blood flow (Hirata et al. 1988).

Finger skin temperature

Finger skin temperature is the most commonly used measure for CIVD. A small thermocouple is generally attached to the palmar side of the distal phalanx with tape. The measured temperature is a mix of the finger skin temperature and the temperature of the surrounding cooling medium. Careful attachment of a small thermocouple to the skin minimizes the influence of the cooling medium temperature.

The nail bed is also often used as a measuring site, since it is known that AVAs are abundant there. However, Yoshimura (1966) showed that the temperature reaction measured on the pad of the finger is more sensitive and reproducible than that on the nail bed.

The measured finger skin temperature is a slow indicator of what occurs in the tissue underneath. Daanen (1997) observed that CIVD onset measured using the finger skin temperature occurred 90 (48) s later than measured using laser Doppler flowmetry.

The changes in finger skin temperature profile during cold exposure are quantified using the terminology shown in Fig. 1.

- The **minimum temperature** (T_{min}) is the lowest finger skin temperature just before CIVD starts.
- The **maximum temperature** (T_{max}) is the highest finger skin temperature during CIVD.
- The **onset time** (Δt_{onset}) is the time from immersion to T_{min}.
- The **amplitude** is the difference between T_{min} and T_{max}.
- The **peak time** (Δt_{peak}) is the time interval between T_{min} and T_{max}.
- The **mean finger skin temperature** (T_{mean}) denotes the finger skin temperature averaged over the immersion period. As a rule, the onset time is not included, since during this period the heat in the hand is removed. In practice, the first 5 min data are removed.
- The **frequency** of the hunting reaction is expressed as the number of waves (vasodilation/vasoconstriction period) within a certain time frame.

Yoshimura and Iida (1952) quantified the magnitude of the CIVD reaction using the Resistance Index for Frostbite (RIF) in which Δt_{onset}, T_{min} and T_{mean} were included. Short onset times and high minimal or mean finger skin temperatures were rated by 3 points and long onset times and low temperatures by 1 point, leading to summated RIFs from 3 to 9. This RIF index is used by many other authors, in particular from Japan.

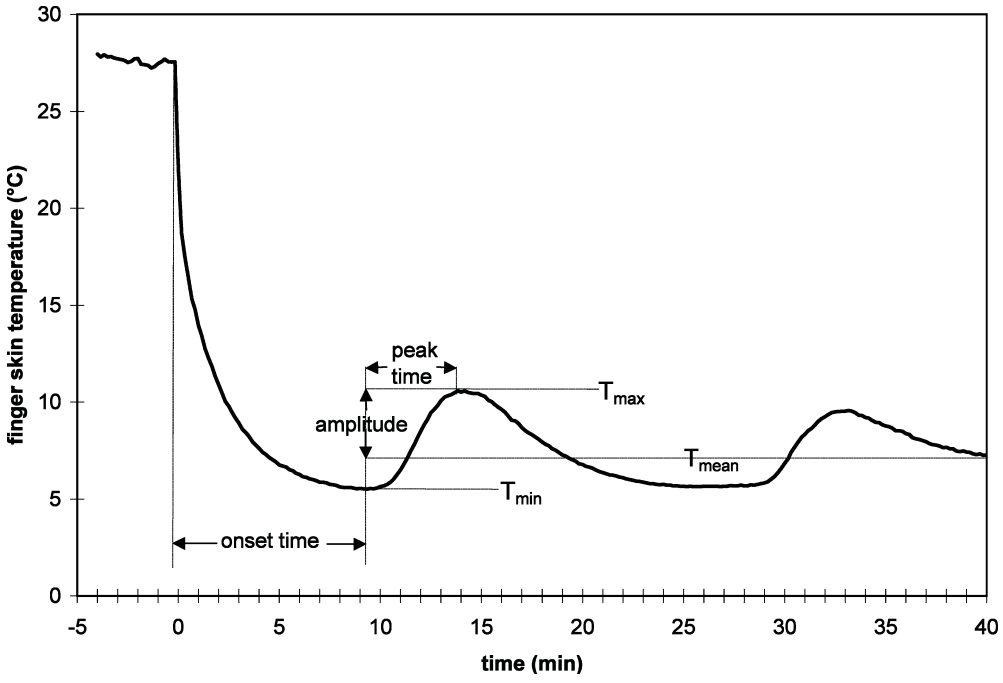

Fig. 1 Parameters derived from a temperature profile of a finger tip immersed in cold water. The onset time (Δt_{onset}) is the time from immersion to the minimum temperature (T_{min}). The amplitude is the difference between T_{min} and T_{max}. The peak time (Δt_{peak}) is the time interval between T_{min} and T_{max}. The mean finger skin temperature (T_{mean}) denotes the finger skin temperature averaged over the immersion period, excluding onset time

General reactions observed during CIVD

Reflex vasoconstriction and reflex vasodilation

When one body part is cooled, vasoconstriction also occurs in other parts of the body. This phenomenon is known as reflex vasoconstriction. Similarly, if heat is applied to another part of the body, such as a leg, the vessels open up and the hand gets warm (Gibbon and Landis 1932). This phenomenon is called reflex vasodilation. Sensors in the skin react to the external stimulus and transfer information to the vasomotor centre. This centre integrates the information and sends an adequate response to the effector organs. Pickering (1932) showed that blood temperature also plays an important role in this mechanism. He found no reflex vasodilation when the venous return of a heated hand was blocked.

Reflex vasodilation and vasoconstriction are also noted during the hunting reaction. Immersion of the feet in cold water during the hunting reaction in fingers reduced the magnitude of the hunting reaction (Keatinge 1957). Lewis (1930) observed that cooling the forearm suppressed CIVD in the fingers. Page and Brown (1953) and Livingstone et al. (1978) observed that Eskimos had less reflex vasoconstriction in the fingers upon cold water immersion of a foot than control subjects. Thus, Eskimos are able to maintain good dexterity when the feet are cold. Werner (1983) showed that reflex vasodilation or vasoconstriction not only depends on the skin and core temperatures but also on the rate of change of these temperatures.

Pain

Immersion in cold water is often a painful experience. LeBlanc (1975) and Heus and Daanen (1993) noted that the most painful period occurred during vasoconstriction, and that the vasodilation phase was often felt as a relief. The pain during strong vasoconstriction may be seen as a warning signal for exceptional cooling. Kreh et al. (1984) found a close relationship between pain intensity and degree of vasoconstriction. If the cooling continues, the tissue temperature may decrease below the threshold for nerve conduction (7–8°C, Vanggaard 1975). If that threshold is reached no information from the periphery can reach the central nervous system and the extremity feels numb. Sawada et al. (2000) observed that pain diminished after repeated cold water immersions.

Experimental factors affecting CIVD

Ambient temperature and body temperature

The regulation of blood flow to the extremities is, at low ambient temperatures, primarily determined by the thermal state of the body as a whole. Even at air temperatures below −30°C, the skin temperature of bare hands can be sustained above 21°C (Rapaport et al. 1949). Therefore, it is rather likely that the body core temperature influences the hunting reaction. In Table 1 results of relevant articles in the literature are summarized.

In most investigations the effects of body temperature were investigated by putting subjects in a relatively cold or warm room. Unfortunately, the resulting core and mean body skin temperatures were often not recorded. The general image emerging from Table 1 is that a high ambient or core temperature leads to higher mean finger skin temperatures during the hunting reaction. Also, the onset time of CIVD was observed to be shorter. Daanen et al. (1997) and Daanen and Ducharme (1999) found that onset time was mainly related to the mean skin temperature of the body and that mean finger skin temperatures were mainly related to body core temperatures.

Ambient temperature may change body core temperature, but the core temperature is also modified by exposure to ambient light and changes in melatonin variations during the day (Burgess et al. 2001), and during the year (seasonal) (Yoneyama et al. 1999). The effects of these changes in core temperature on CIVD, as reported in the literature, are:

- The hunting reaction is more pronounced in the afternoon, than in the morning or the night (Kramer and Schulze 1948).
- Schulze (Kramer and Schulze 1948) measured his CIVD each month at room temperature with his hand in a cold air box and found an average maximal finger skin temperature of 28°C in the summer and 16°C in the winter during immersion, indicating a vasoconstrictive state during winter.
- Tanaka (1971b) measured CIVD during middle finger immersion in 0°C water during summer and winter under identical ambient conditions and also observed that the CIVD reaction was more pronounced in summer.

In summary, it appears that in the afternoon and in the summer, when the core temperature is relatively elevated, the hunting reaction is more pronounced.

Cooling medium

To evoke CIVD, two media are commonly used: water and air. Immersion in cold water is used most often. The thermal conductivity of water is about 25 times higher than that of air, so cooling is rather quick.

Kramer and Schulze (1948) cooled fingers in a cold air box, and compared the results with those of other studies in which the fingers where cooled in water. The frequency of the hunting response in 0°C water showed most similarity with that in −18°C air. Kramer and Schulze (1948) observed that the frequency of the hunting reaction decreased when the air temperature in

Table 1 Influence of body temperatures on the hunting reaction. [T_{re} Rectal temperature (°C), T_{sk} mean body skin temperature (°C), T_{mean} mean finger skin temperature (°C), T_{min} minimum temperature of finger skin during immersion (°C), Δt_{onset} time from immersion toT_{min} in minutes]

Author(s)	Body temperatures			Hunting reaction		
	Induction	Measurement		Induction	Measurement	
		Variables	Results		Variables	Results
Adams and Smith (1962)	Room temp. 7 and 22°C for 1 h	–	–	Index finger for 20 min in 0°C	Finger skin temp	Δt_{onset} increased in cool subjects
Bader and Mead (1949)	Room temp. 13 and 32°C	–	–	Terminal phalanx in ice water or 0°C air	Finger skin temp. and plethysmography	Blood flow not dependent on local temp. (cold water or air) but on ambient temp.
Blaisdell (1951)	Room temp. 28, 25, 15 and 12°C for 2–3 h	T_{re}, T_{sk}	T_{re} not different between room temp. T_{sk} at 28°C: 33.1°C. T_{sk} at other room temp.: 25°C	Hand in 0, 5,10 and 15°C air	Finger nail bed temp. and plethysmography	T_{min} lower when chilled (3.8°C versus 7.8°C at 28°C room temp.), no differences in frequency and amplitude
Daanen et al. (1997)	Drinking 0°C and 43°C beverages	T_{re}, T_{sk} and T_{ear}	T_{ear} 36.5 and 37.1°C	Hand for 30 min in water of 8°C	Finger skin temp	Cold body: low hunting frequency and small hunting magnitude
Daanen and Ducharme (2000)	Whole body cold water immersion; hot water perfused suit	T_{es}, T_{re} and T_{sk}	T_{es} 36.1 and 38.0°C	Hand for 40 min in water of 5°C	Finger skin temp, skin perfusion (laser Doppler)	Cold body: long onset times, small CIVD magnitude
Edwards and Burton (1960)	Room temp."neutral" and 9–17°C	–	–	Finger in ice water	Plethysmography, calorimetry	Reduced blood flow and heat transfer in cold room
Elsner et al. (1960)	Room temp. 18°C unclothed and 22°C clothed	–	–	Hand for 30 min in water of 5°C	Calorimetry	More heat loss in warm room
Folkow et al. (1963)	Indirect warming and cooling	–	–	Hands in ice water	Venous occlusion plethysmography	More blood flow when indirectly warmed
Greenfield et al. (1951)	Room temp. 14.5°C, 20.5°C and 22.5°C	–	–	Toes in water 0–6°C	Calorimetry	More heat loss when room temp. increases
Keatinge (1957)	6°C water bath; Room temp. 5–6°C (1 h) and 17–18°C with clothing and exercise	–	–	Index finger in ice water	Calorimetry	Finger heat loss. Hot: 65% of max. Cold: 5% of max. Cold bath: 13% of max.
Kramer and Schulze (1948)	Room temp, hot drinks, daily and seasonal variations	–	–	Hands in cold air of −18 to 10°C	Finger skin temp	Mean finger skin temp. increased when warm
Lee et al. (1996)	30 min in 27°C air (N), 60 min in 20°C water (H)	T_{es}, T_{re}	N: T_{es}: 36.85°C; T_{re}: 37.02°C; H: T_{es}: 36.18°C; T_{re}: 36.29°C	Right middle finger in 4°C water	Finger skin temp	Mean finger skin temp. lower in H amplitude also lower
Spealman (1945)	Room temp.16, 24 and 32°C for 3 h	–	–	Hands for 3 h in water of 2 to 35°C	Blood flow by venous occlusion plethysmography	Blood flow higher at high ambient temp. and when water temp. is higher or lower (CIVD)than 15°C

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