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Short Communication

Cold Stress Dynamic Thermography for Evaluation of Vascular Disorders in Hand-Arm Vibration Syndrome

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Exposure to hand-transmitted vibration can cause a variety of disorders collectively known as the Hand-Arm Vibration Syndrome (HAVS). Its neurovascular component is Vibration-induced White Finger (VWF), a type of secondary Raynaud's phenomenon (RP), which manifests itself as episodic blanching of the fingers in response to cold. Due to the episodic nature of this condition, an occupational health physician rarely observes the blanching; thus, VWF has often been diagnosed based only on patient's history together with a history of occupational exposure to vibration and the exclusion of other known causes of RP[1)].

For the assessment of VWF, measurements of finger skin temperature (FST) and finger systolic pressure (FSP) in response to cold stress are most widely used[2–4)]. The FST-based assessment relies on the principle that the pattern of FST following cooling reflects the degree of cold-induced vasoconstriction in the digital blood vessels[5)]. The rise in FST during recovery reflects the increase in blood flow in the investigated skin area. Abnormal rewarming times indicate different patterns of vascular dilatation following vasomotor responses to cooling[6)]. A lower FST is expected to reflect a persistent abnormality of blood flow in patients with HAVS[2, 7)].

Merla *et al.*[8)] described a technique that used infrared imaging to record the thermal recovery and produced images which visualized the τ times of individual pixels, assuming an exponential rewarming process (τ being the time needed for rewarming to 63% of the total temperature change). The damaged areas exhibited a slower recovery and longer τ time. This was a novel approach in that it used dynamic parameter (Tau) imaging, but the parameter was derived as a cutoff-value, not from all the available rewarming data. Using a non-imaging infrared-based device, Foerster *et al.*[9)] also reported that a rewarming pattern could be described using the τ value. According to Darton and Black[10)], thermographic images of the hands and rewarming curves after cold provocation show characteristic differences among patients with primary and secondary RP, and normal subjects. We propose a novel method of dynamic infrared thermography for assessing the dynamic response of the microcirculation during rewarming.

Methods

The subject examination procedure is based on cold provocation (CP) in a controlled environment (room temperature 22 ± 1°C) followed by thermographic recording of the rewarming process. After CP (the hand with a latex glove immersed up to the wrist into water at 8°C for 5 min), the glove is removed, the subject puts his hand in a specially designed support, and a sequence of thermograms on the volar side is recorded by a thermographic camera connected to a laptop computer. A thermogram is recorded every 30 s during a 30 min session. Since the adjustable support keeps the hand fixed in position during recording, these thermograms are directly used to reconstruct the rewarming process for each pixel individually. An application was written in the Mathcad® environment, for importing, processing, and visualization of the recorded data. As the rewarming process generally conforms to the exponential law[8, 9, 11)], the analysis includes curve fitting of the measured time series of temperature $T(t)$ to the exponential form $T(t)=T_0+\Delta T(1-e^{-kt})$ for each pixel, producing an optimal exponential curve through nonlinear regression. This produces k (rewarming rate), T_0 (initial temperature) and ΔT (total temperature change) for each pixel separately.

As the value k quantifies the dynamics of the rewarming process (greater k implies more rapid rewarming), it is useful to produce a "k map," i.e. to visualize the spatial distribution of this parameter over the volar side of the hand (Fig. 1). In a grayscale palette, darker regions represent slower (lower k values), while lighter ones represent faster rewarming (greater k values). In practice, color palettes are used. In grayscale, background pixels are black, while clear white represents regions with poor exponential conformance, warranting further investigation by observing the recorded rewarming curves.

Results and Discussion

Examples of k maps are shown in Fig. 1. Informed consent was obtained from the subjects. Fig. 1(a) is a typical k map of a healthy subject, never exposed to

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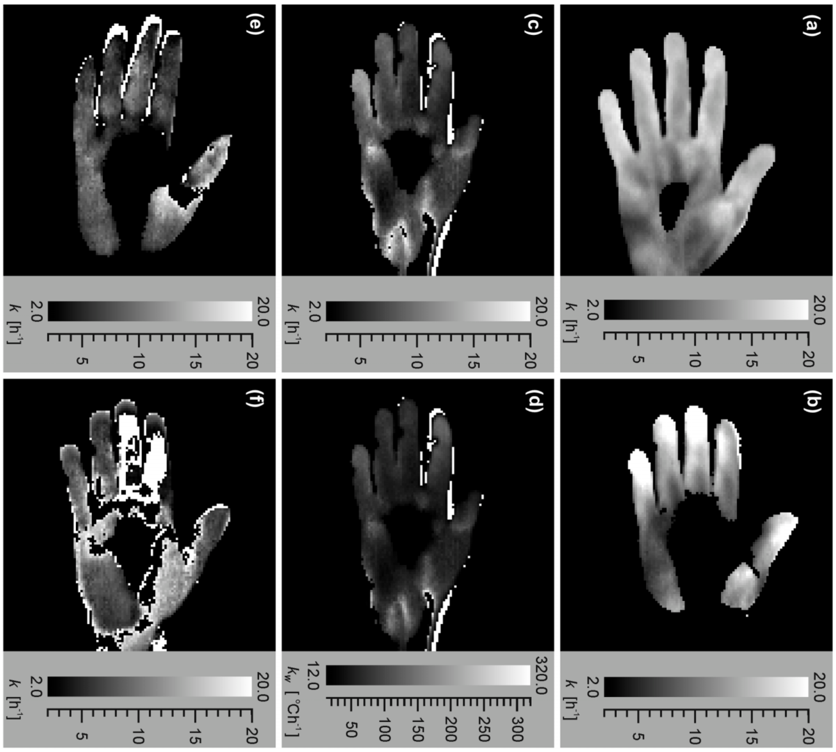

Fig. 1. Examples of k maps: (a) Normal subject; (b) Subject with initial pathological changes due to vibration exposure; (c) Non-weighted and (d) weighted k-map of the same subject; (e) Pathological k map showing slow rewarming in acral regions and clear white areas due to tremor; (f) Pathological case with slow and irregular rewarming, requiring analysis of rewarming curves.

occupational vibrations. The pattern of the distribution of *k* shows high rewarming rates at the fingertips, as well as on the finger bases. The exponential fitting succeeded completely, without movement artifacts. The subject had good motor control, no tremor and exhibited quick and complete thermal recovery. Figure 1(b) shows differences in rewarming rates over the different fingers in this vibration-exposed subject. The fact that the finger most exposed to occupational vibrations (index finger) exhibited lower rewarming rates was indicative of the onset of pathological changes, namely impaired vascular reactivity in cutaneous microcirculation. According to Gautherie[12], the observed asymmetry of the responses to cold between individual fingers can be useful in differential diagnostics of HAVS. Figures 1(c) and 1(d) illustrate the need to introduce “weighted k maps” to better understand the condition of this vibration-exposed subject. In this case, the k map in Fig. 1(c) suggests faster rewarming of the little finger relative to the other fingers. However, the total temperature change ΔT was smaller in that finger than in the others. Introducing a weighted k map, basically means replacing visualization of *k* with visualization of the $k\Delta T$ product. Since, in this subject, the ΔT was small in the little finger, the $k\Delta T$ product was also smaller, so it did not differ much from the other fingers when viewed as a weighted k map (Fig. 1(d)). The k map in Fig. 1(e) was recorded in a subject with impaired peripheral blood flow. The rewarming rates were lower at the fingertips, and somewhat higher at the finger bases, but were generally low, while the presence of artifacts (white areas around fingers) was due to tremor. The k map of the vibration-exposed subject shown in Fig. 1(f) demonstrates major changes in the peripheral vascular system. The k map reveals slow and irregular rewarming patterns, consistent with peripheral vascular disorders, while the asymmetry between rewarming patterns among the fingers suggests primary RP is not the cause. In this case, the k map is not entirely clear: the critical regions where the vibration-induced damage is most commonly encountered (index and middle finger) are covered in white, indicating inadequate exponential conformance. In such cases, it is useful to plot and analyze the rewarming curves in the areas of the distal and proximal phalanges of the index and middle fingers (also possible with our software) to investigate why the rewarming process could not be modeled as an exponential. This can happen for a number of reasons, from delayed rewarming (very slow, almost linear initial rewarming, followed by a rapid exponential "relaxation," i.e. sudden increase of the blood flow) to various oscillations during very slow rewarming. These reasons are immediately visible upon inspection of the rewarming curve. For the case shown in Fig. 1(f), the corresponding rewarming curves reveal low rates of temperature change, curve irregularities and small differences between initial and final temperatures. Also, the final temperatures (after 30 min) are far below pre-cooling values, which offer enough grounds to conclude there are severe impairments in the peripheral vascular system. In such cases, it is recommended to plot the curves for the finger tips and bases of the ring finger and the little finger too, to observe asymmetries.

Presently, none of the proposed tests for circulatory impairment, including the one accompanying VWF, are completely satisfactory[5]. There is a need for further development of methods to gain better insight into VWF patient conditions. Thermography can assess the entire hand simultaneously, which was found useful in differential diagnostics of HAVS[11, 12] and, unlike contact thermometers, it does not introduce perturbations. For imaging purposes, we introduce the parameter *k*, directly proportional to the rewarming rate, obtained through nonlinear regression, utilizing all available temperature data collected throughout the rewarming process. This reduces errors due to temperature oscillations and is less sensitive to minor deviations in certain time intervals. This parameter characterizes relative temperature changes and thus tolerates small bias errors. The influences of emissivity and background temperature are also reduced. Additionally, the weighted *k* value was introduced to deal with cases in which the final temperature did not reach the pre-cooling value. The method proposed here can be useful as a follow-up test in individual diagnostics of HAVS.

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