Experimental Study of Vascular Reactivity in the Fingertip: An Infrared Thermography Method

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***Abstract*—Vascular reactivity (VR) test has been proved to be an effective method to predict the risk of future cardiovascular disease. A most common technique used to study VR is to analyze the hyperemic response after an ischemia through an arterial occlusion. Current techniques to monitor hyperemic response rely on monitoring blood flow parameters. As tissue temperature is directly impacted by blood flow, in this paper, an infrared thermograph method was used to investigate the variation of fingertip temperature during VR test. Subsequently, an image processing algorithm was developed to extract the temperature of special parts of the sequential thermal images. The measured results of temporal temperature variation clearly characterized the thermal state of a subject (vasoconstriction, vasodilation, and thermoneutral) as well as perfusion. Finally, a lumped parameter thermal model was employed to explain the experimental results.**

Keywords-vascular reactivity (VR); digital thermal monitoring (DTM); hyperemic response; dynamic infrared thermal imaging; sequential image processing ; Biothermal model

I. INTRODUCTION

Cardiovascular disease (CVD) is known to be the leading cause of human death with high morbidity and high mortality. Developing methods to easily and effectively predict cardiovascular events has become an important task. However, the prediction work remains difficult and expensive because many patients are asymptomatic.

There are a lot of studies concerned with the physiological factors of CVD and cardiovascular risk prediction. Evidence has accumulated that impairment of vascular endothelial function is the initial step in the development of cardiovascular complications [1]. Measures of endothelial dysfunction can be used to stratify cardiovascular risk in peripheral arterial disease (PAD) [2]. Studies testing endothelial function are referred as vascular reactivity (VR) tests. Typically, in a VR test, arterial occlusion was performed by using a pneumatic cuff. The test focuses on analyzing the magnitude of the hyperemic response after occlusion, which is known to be reduced at any arterial level in patients with endothelial dysfunction [3].

Several techniques are available to directly monitor VR, such as high-resolution ultrasound [4], plethysmography [5], laser Doppler flowmetry (LDF), and near infrared laser speckles. However, the search for a simple, noninvasive, and widely applicable test that can be applied routinely in a clinical setting is not straightforward.

Numerous studies have shown that tissue temperature is directly impacted by blood flow. In order to monitor transient alterations in blood volume arriving to the finger during a VR test, Carlier et al. [6] developed an indirect method of continuously recording fingertip temperature in response to arterial occlusion and reperfusion, which is called digital thermal monitoring (DTM). With plentiful experiments, Ahmadi [7] give a conclusion that vascular and neurovascular dysfunction measured by DTM is associated with the presence and extent of coronary artery disease measured by CT angiography. During the DTM test, the fingertip temperature first drops as a result of the arterial occlusion or lack of blood flow, and then it increases once the arterial occlusion is released and post-occlusive hyperemia is experienced. The temperature rebound (TR) in the period of hyperemia is reduced in the presence of endothelial dysfunction (Fig. 1).

Ley et al. [8, 9] performed experimental studies of the DTM test by using T-type thermocouples and heat flux sensors connected to a data acquisition system. Parametric studies were also performed to analyze the effects of blood perfusion alteration, as well as any environmental contribution to fingertip temperature, which indicates the important effects of initial temperature and thermal trend.

To investigate the effect of blood flow on peripheral temperature, He et al. [10, 11] proposed a one dimensional thermoal-fluid model of blood circulation in the human upper limb, which can simulate blood pressure, blood flow and blood temperature in different vessels. It was observed that the contribution of blood flow in the larger arterials to the tissue temperature was as important as that of the blood perfusion. The modeling work firstly built the relationship between blood circulation and peripheral temperature.

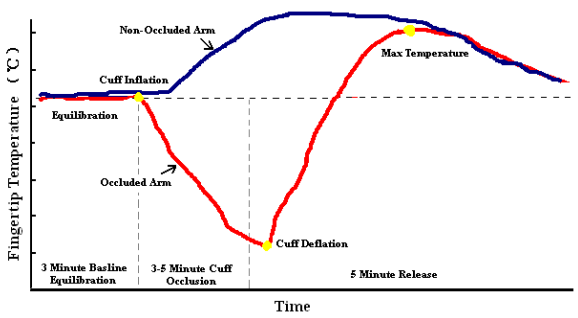

Figure 1. Example of Fingertip Thermal Response.

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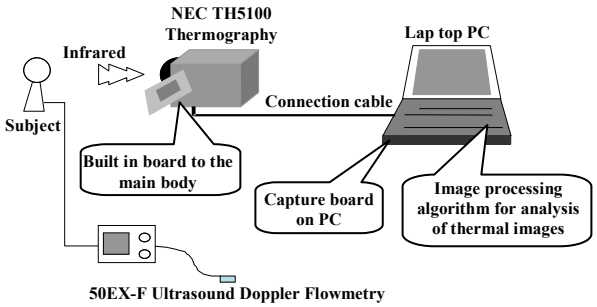

Figure 2. The experimental system.

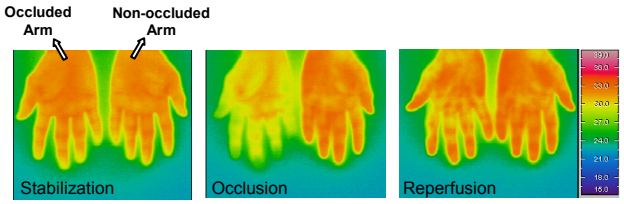

Figure 3. Infrared images during the DTM test.

This paper presents an experimental study of the DTM test by using an infrared thermography method. The variation of fingertip temperature during the VR test was recorded by using an infrared thermography (TH5100, NEC), and an image processing algorithm was developed to extract the temperature of special parts of the sequential thermal images.

II. Experimental Method

Fig. 2 shows the schematic diagram of the experimental system. Five participants between 20~30 years of age volunteered as subject for this study. All experiments were carried out in a room which has a temperature of 18 ℃ and a relative humidity of 40%RH. Studies were conducted after an overnight fast of at least 10 hours (water was permitted) and abstinence from tobacco, alcohol, caffeine, vasoactive medications, exercise, high-fat foods and vitamin C. The measurements were obtained with the subjects sit up and after 30 minutes of rest in the constant temperature and humidity laboratory to arrive at a thermoneutral condition [12]. The protocol consisted in the following steps:

Step 1: Each subject's blood pressure in the right arm was recorded in a sitting position for 5 minutes before the DTM test.

Step 2: The volunteer was seated with the right arm resting on a support placed at the heart level, and a pneumatic cuff was attached on the upper arm to perform an arterial cuff.

Step 3: DTM of both hands was continuously obtained during 3 minutes stabilization; 3.5 minutes cuff inflation to 50 mmHg higher than systolic blood pressure; and 4.5 minutes deflation using an infrared thermography imager.

The thermal images of hands were taken by a NEC TH5100 thermography and transferred to the Lop top PC at the rate of 5s per frame. Fig. 3 shows 3 infrared images which respectively represent the temperature of two hands at a moment of the stabilization, inflation and deflation stage during the DTM test.

III. Image Processing Method

The size of the thermal images is 239 × 256 unit8 and the gray levels are from 0 to 255. In order to obtain the temperature variation of different parts of the hands, automatic analysis of acquired infrared images were implemented in a MATLAB based platform. The procedures of the image processing are as follows:

Step 1: Segmentation of targets (two hands) from background images.

Step 2: Extraction of fingertip and palm regions.

Step 3: Computation of temperature variation in palms and fingertips.

A. Segmentation of Hands

The Otsu algorithm [13] was used for automatic detection of threshold. It is considered that the optimal threshold T should be the value which enables the gray difference between the target and background become the maximum. Generally, maximum between-class variance is employed to be the criteria. However, this method is not sufficient for some special cases.

As the fingertip gray value of the occluded hand in some images during the occlusion and pre-reperfusion stage is much lower than that of the non-occluded hand, the fingertip may be wrongly detected to be the background by using the Otsu method. Hence, we developed an improved algorithm to detect the threshold of target for the images in this case [14]. After the optimal threshold is obtained, the original image is converted into binary image BW according to the threshold map. That is, if the gray level in the original image is less than the threshold in the corresponding area, the pixel would be set to 0; otherwise, the pixel would be set to 1.

The above image processing algorithm is based on the premise that the target gray is above the background gray. For some images in which the target gray is close to the background gray, the information of fingertip will not be recorded in the image, and then a template matching method should be applied for segmentation.

An image from the same image sequence is taken as the source of template. As preparatory work, the template and target are segmented into binary images using the improved Otsu method. With the definition of a large structure element, the template is eroded to only obtain the binary image of palm BW_palm. Then by a subtraction between BW and BW_palm, the template finger $BW_fingers$ can be obtained through judging connected domain.

$$BW_fingers = BW \,\&\, (\sim BW_palm) \tag{1}$$

For the images whose fingertip information is lost, the edge-canny operator and two-dimensional Laplace transform

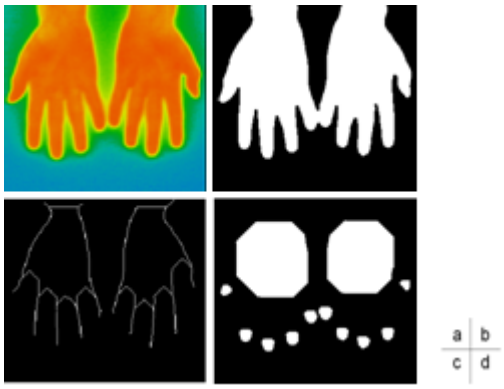

Figure 4. Primary processes of the image processing method. (a) Original image; (b) Binary Image; (c) Bones of the hands; (d) the target of palms and fingers.

is operated, and then after the threshold segmentation and thinning operation, the boundary of the target is obtained to be matched by the template.

The main method used in the template matching process is a voting algorithm similar to the generalized Hough transforms [15].

B. Extraction of Fingertips

In this step, mathematical morphological image processing is performed. Three character values are employed: the length of the noise I_n (1~3 pixels), width of the finger w_f (15~20 pixels), and width of palm w_p. Using disk-shaped structure element whose diameter is greater than I_n and less than w_f, morphological opening is carried out in the binary image and the noise in the background and heaved points at the edge could be deleted. Subsequently, morphological closing is performed using the same structure element to delete the noise in the palm and concaved points at the edge. The palm is extracted by opening operation with disk-shaped structure element whose diameter is less than w_p and greater than w_f.

The fingertip can be extracted by using thinning operation. While performing thinning operation, if the pixel is an end point, which means there is only one neighbor pixel in its 8 neighborhood, or if the connectivity of the image will be changed by deleting the pixel, the pixel will be retained. After several times of thinning to the binary image, the image with single lines of fingers is obtained. Therefore, the end point of the line is considered to be the position of the fingertips, then the fingertips areas can be extracted by dilation operation. Fig. 4 shows the primary processes of the image processing method.

C. Computation of Fingertips Temperature Variation

According to the correlation between gray value and temperature, the average temperature variations with time in the fingertips are thus obtained from the processed images.

Fig. 5(a) gives one subject's experimental results of average temperature variations in the occluded hand during

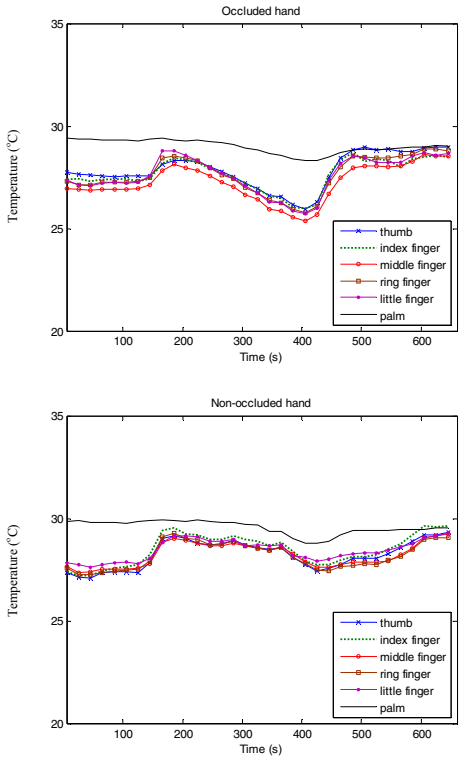

Figure 5. (a) Temperature variations in the occluded hand; (b) Temperature variations in the non-occluded hand.

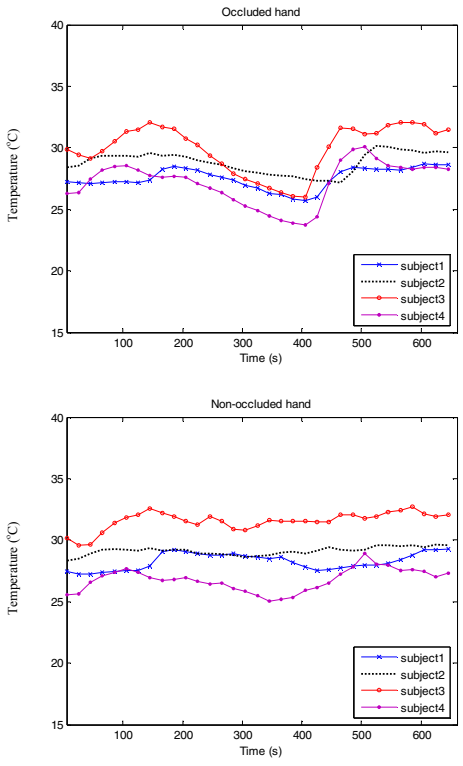

Figure 6. (a) Mean fingertip temperature variations in the occluded hand of four experimental subjects; (b) Mean fingertip temperature variations in the non-occluded hand of four experimental subjects.

DTM test. Fig. 5(b) gives the same information of the non-occluded hand.

The results clearly indicate the temperature rebound measured by DTM. During the stabilization period, the fingertip temperatures all remain a relatively smooth trend. During the cuff inflation period, an obvious temperature drop can be observed in the occluded hand. Conversely, the fingertip temperature in the non-occluded hand demonstrated a increasing trend to the baseline temperature. During the dilation period, the fingertip temperatures all experience an increasing trend because of blood reperfusion. The temperature of palm has no obvious change during DTM test, one possible reason is that the temperature detected by infrared thermography is skin surface temperature, vessels in the palm is mostly beneath the muscles, thus the blood temperature has a relative small influence on skin temperature.

The other four subjects' results are showed in Fig. 6 for comparison. The fingertip temperature variations during the three periods of DTM test are of the same trend. As there are differences in the subjects' physiological conditions, the initial temperature and temperature variation level are different for each subject.

IV. A LUNMPED PARAMETER MODELING STUDY

In the experimental study of this paper, the maximum temperature observed during reperfusion period is not much higher than the baseline temperature. To give a reasonable interpretation, a lumped parameter thermal model by Ley [9] was used to investigate the effect of variation in ambient temperature T_{air} and initial temperature T_0 over the fingertip temperature during VR test.

TABLE I. PARAMETERS VARIED TO STUDY THE EFFECT ON FINGERTIP TEMPERATURE DURING HYPEREMIA

Parameter	Base Case Value	Variation
β	3	
τ_h (s)	120	
t_{dw} (s)	45	
h_{air} (W/m^2 K)	6	
T_{air} ($^\circ$C)	24	18, 20, 22
T_A ($^\circ$C)	37.5	
T_0 (°C)	30	26.25, 27, 28.5

TABLE II. THERMOPHYSICAL PROPERTIES

Properties	Tissue	blood
ρ(kg/m^3)	1085	1069
C_p(J/kg K)	3680	3650
k(W/mK)	0.47	
ω^*_{max}(m^3/s)	7.8503e-10	

The governing equation used in the model is expressed as

$$\rho C_p V \frac{dT}{dt} = h_{air} A(T_{air} - T) + \rho C_{pb} \omega_b^*(t)(T_A - T) \quad (2)$$

Where ρ indicates the tissue density, C_p is the specific heat of tissue, ρ_b and C_{pb} represent the density and specific heat of blood, and $\omega_b^*(t)$ indicates the volumetric blood perfusion and its temporal variation during the VR test.

Blood perfusion per unit time is expressed for two stages, vascular occlusion (Stage I) and reperfusion (Stage II). During stage I, the blood flow exponentially falls, following a relationship of the form

$$\omega_b^{SI}(t) = \omega_{b0}^* \exp(-t/\tau_0), t \le t_{occ} \quad (3)$$

Where ω_{b0}^* represents the initial blood flow, τ_0 is a constant approximately 5 s related to the time which the blood flow is occluded rapidly, t_{occ} represents the occlusion time ($3\min \le t_{occ} \le 5\min$). The variations in the blood flow in the reperfusion stage are approximated by the following relationships

$$\omega_b^{SII} = \begin{cases} \omega_{max}^* \sin^2(\pi(t - t_{occ})/2t_{dw}), t_{occ} \le t \le (t_{occ} + t_{dw}) \\ (\omega_{max}^* - \omega_{b0}^*)\exp((t_{dw} + t_{occ} - t)/\tau_h) + \omega_{b0}, t > (t_{occ} + t_{dw}) \end{cases} \quad (4)$$

Where ω_{b0}^* and t_{occ} represent the same quantities described in stage I, ω_{max}^* represents the maximum hyperemic blood perfusion volume and is defined as $\omega_{max}^* = \beta\omega_{b0}^*$, where β denotes the hyperemic blood perfusion volume ratio. t_{dw} is the time required to reach the maximal hyperemic blood flow, and τ_h indicates the rate at which blood flow returns to its normal value.

Parameters and thermophysical properties used for the mathematical model are showed in table 1 and table 2 [8]. In this paper, only the ambient temperature and the initial temperature are studied, because they are the parameters which can be controlled during the experiment.

The effect of the surrounding air temperature can be seen in Fig. 7(a). Calculations show that the lower the surrounding temperature, the higher the heat loss from the finger, and smaller the thermal response or the rebound temperature. According to the model, surrounding temperature should be maintained such that it is high enough (greater than 20°C) that the researcher can see the sole effect of the reactive hyperemia on the thermal response. The fingertip temperature response to changes in initial temperature is presented in Fig. 7(b). It can be seen that the lower the initial fingertip temperature, the higher the hyperemic temperature

rebound (TR) observed. In our experimental study, the experimental room temperature was 18 ℃ because of the winter season, and the subjects' initial temperatures were varied at a low level between 25℃ and 30 ℃. Fig. 8 gives the calculation results of the four subjects in Fig. 6(a), which is consistent with the experimental results. It can also be observed that the effect of initial temperature is limited when the ambient temperature is below 20 ℃.

V. CONCLUDING REMARKS

In this paper, an infrared thermography method was used to perform DTM test. In the experiment, we developed an automatic image processing method and the temperature variation in a specific part of hand can be extracted automatically. The infrared thermography method can more easily and accurately detect the skin tissue temperature, and the measured results of temporal temperature variation clearly characterized the thermal state of a subject (vasoconstriction, vasodilation, and thermoneutral) as well as perfusion. In order to explain the experimental results, the lumped parameter thermal model by Ley [8] was used to investigate the effect of variation in ambient temperature T_{air} and initial temperature T_0 over the fingertip temperature during VR test.

Further research is necessary in building up a one dimensional thermal-fluid model of human upper limb to phenomenologically reproduce the experimental measurements.

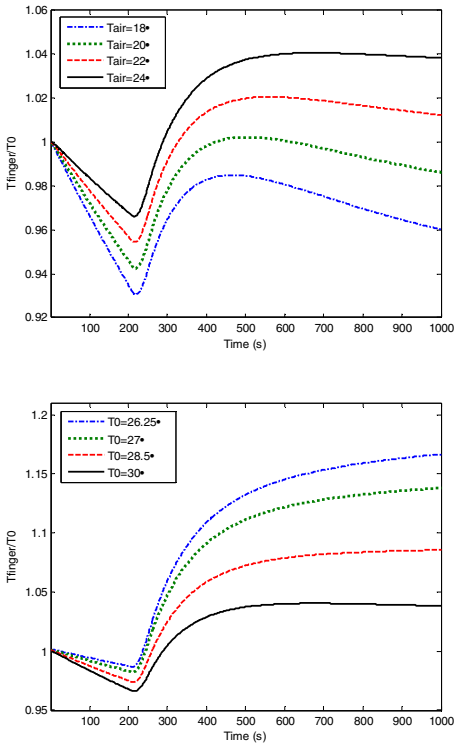

Figure 7. (a) Effects of variation in ambient temperature over fingertip temperature; (b) Effects of variation in initial temperature over fingertip temperature.

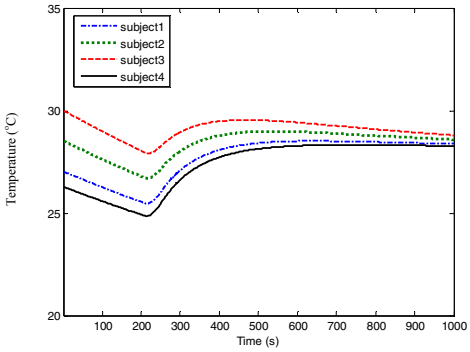

Figure 8. Calculation results of the four subjects in Fig. 6(a).

REFERENCES

[1] D. Behrendt, P. Ganz, "Endothelial function: From vascular biology to clinical applications," J. Cardiology, American, 90(10), pp. L40-L48, Nov, 2002.

[2] G. Brevetti, A. Silvertro, V. Schiano, "Endothelial dysfunction and cardiovascular risk prediction in peripheral arterial disease: additive value of flow-mediated dilation to ankle-brachial pressure index," Circulation, 108(17), pp. 2093-2098.

[3] F. Charbonneau, "Use of measure of endothelial function to stratify risk," Can. J. Cardiol., 17, pp. 18A-19A.

[4] C.J. Hartley, A.K. Reddy, S. Madala, "Noninvasive ultrasonic measurement of arterial wall motion in mice," Am. J. Physiol. Heart Circ. Physiol. 287 (3) (2004) H1426–H1432.

[5] Y. Higashi, M. Yoshizumi, "New methods to evaluate endothelial function: method for assessing endothelial function in humans using a strain-gauge plethysmography: nitric oxide-dependent and -independent vasodilation," J. Pharmacol. Sci. 93 (4) (2003) 399–404.

[6] Carlier, S.G. Jamieson, M.J. Gul, "Digital thermal monnitoring: the clinical utility of a new noninvasive , nonimaging device for cardiovascular risk assessment," Eur. Heart J., 27_Suppl.1_, 2006.

[7] N. Ahmadi, V. Nabavi, V. Nuguri, "Low fingertip temperature rebound measured by digital thermal monitoring strongly correlates with the presence and extent of coronary artery disease diagnosed by 64-slice multi-detector computed tomography," Int J Cardiovase Imaging (2009) 25:725-738.

[8] O. Ley, C. Deshpande, B. Prapamcham, "Lumped parameter thermal model for the study of vascular reactivity in the fingertip," J. Biomechanical Engineering, 130, 031012-1, June 2008.

[9] O. Ley, C. Deshpande, "Comparision of two mathematical models for the study of vascular reactivity," Computers in Biology and Medicine, 39, 579-589, 2009.

[10] Y. He, H. Liu, R. Himeno, "a one dimensional thermal-fluid model of blood circulation in the human upper limb," Int. J. Heat and Mass Tranfer, 47, 2735-2745, 2004.

[11] Y. He, H. Liu, R. Himeno, "Numerical and experimental study on the relationship between blood circulation and peripheral temperature," J. Mechanics in Medicine and Biology, 5, 39-53, 2005.

[12] C. Jessen, "Temperature regulation in humans and other mammals," Springer, New York, pp. 37-46, 2000.

[13] N. Ostu, "A threshold selection method from gray-level histograms," IEEE Trans. Syst. Man Cybern. Vol. SMC-9 (1), PP. 62-66, 1979.

[14] H.D Zhang, Y. He, X. Wang, "Dynamic infrared imaging for analysis of fingertip temperature after cold water stimulation and neurothermal modeling study," Comput. Biol. Med. (2010), doi: 10.1016/ j.compbiomed. 2010.05.003.

[15] L.J. Yao, W.M. Ding, S.Q. Zhao, "Applications of the generalized Hough transform in recognizing occluded image," Transactions of the Chinese Society of Agericultural Engineering, 24(12), 2008.