TEMPERATURE SENSOR ARRAY SYSTEM FOR THERMAL DIAGNOSTICS ON HUMAN DISEASE

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Abstract-**A technique using a plane temperature sensor array to dynamically image the transient temperature response of the human skin subject to intentionally applied heating or cooling was proposed. A human disease diagnostic system with satisfactory accuracy and rapid response speed was constructed. Preliminary experiments show the potential clinical application of this device, which is simple to fabricate and thus cheap in price. Further theoretical analysis shows that the surface heat flux may serve as a better thermal index for disease diagnostics than the commonly used surface temperature, due to that it included all the thermal contributions from any abnormal tissues underneath the skin. An approach was proposed to measure the skin surface heat flux using the currently constructed temperature sensor array system.**

Keywords-**thermal diagnostic，bioheat transfer, imaging system，temperature sensor array， noninvasive monitoring, thermal diagnostics index**

I. INTRODUCTION

It has long been revealed that the body surface temperature is controlled by the blood circulation underneath the skin, the local metabolism, and the heat exchange between the skin and the environment [1-6]. Changes in any of these parameters can induce variations of temperature and heat flux at the skin surface, reflecting the physiological state of human body. For example [1], a highly vascularized skin tumor can lead to an increase of local blood flow and thus the skin temperature. Inflammation induced high metabolic rate can also increase the skin temperature. On the other hand, thrombosis or vascular sclerosis in the peripheral circulation decreases the blood flowing to the skin resulting in low skin temperature. Apparently, the abnormal temperature or heat flux at the skin surface indicates irregular peripheral circulation, which can be used in the clinical diagnosis. Unlike detection using radiation and isotope marker, thermal diagnostics does no hurt to the human body and thus becomes gradually popular. The high-resolution thermography of the skin surface has been proved to be an effective diagnostic tool [1]-[6]. However, most of the previous efforts are focused on the steady state diagnostics, which may loose valuable disease information. A critical step to improve the thermal diagnostic efficiency is through dynamic imaging.

Up to now, several thermal imaging methods have been established to diagnose the human body [5], [6]. The most commonly used approach is through infrared thermometry based on measuring the thermal radiation from the objects. Compared with the non-invasive diagnostics like nuclear magnetic resonance, microwave and ultrasound [5], infrared thermometer appears more simple and safer. However, running the infrared thermometer requires additional equipment such as cooling system so as to obtain high quality image and work safely. Due to the difficulty in calibrating the temperature sensor, extending the working temperature range of this device is not easy. The complicated methodology also makes the infrared thermometer very expensive, which may limit its widespread applications. Further, the imaging of this device is easily subject to the external factors such as the air flow, the emissivity of skin etc, which will affect the reading and thus the interpretation of the obtained data. To avoid influence from the surrounding environment, directly measuring the surface temperature may provide more reliable information. People also applied microwave to image the temperature map of the skin surface. But there is defect in its temperature measuring resolution and the response speed. This device is also very expensive. Apart from the above two kinds of devices, the liquid crystal thermometer has also been tried to image the temperature distribution on the skin surface [6]. This device is simple in operation and cheap in price. A major drawback is its poor quantification on the temperature magnitude and relying too much on the operator's judgement. Its temperature measurement range is small. Particularly, it is hard to use this method to dynamically monitor the transient temperature of the skin surface. All these situations limit the application of the liquid crystal thermometer for the disease diagnostics.

In this paper, a dynamic diagnostic system using temperature sensor array to directly image the skin surface temperature is proposed, which is simple in structure and cheap in price. It can be used as either steady state or transient imaging. The thermal couple sensor with wide temperature measurement range has high accuracy and quick response speed. It thus satisfies closely the requirement of the thermal diagnostics. Finally, the paper will also discuss the thermal index most appropriate for the disease detection.

II. SYSTEM CONSTRUCTION

As schematically shown in Fig.1, the present imaging system is mainly consisted of the plane temperature sensor array, the data acquisition system, and the computer etc. The thermoelectric cooling device made of Peliter elements was used to apply heating or cooling due to its good flexibility. The temperature information was recorded and stored in the computer and then displayed as topography image using software. As clinically revealed, when the human body is subjected to a heating or cooling, it will induce different temperature response for the tissues, healthy or diseased, or with various vascular structures. Previously, few attentions

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Abstract

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had been paid to the dynamic diagnostics. The present method will be beneficial for such clinical practice.
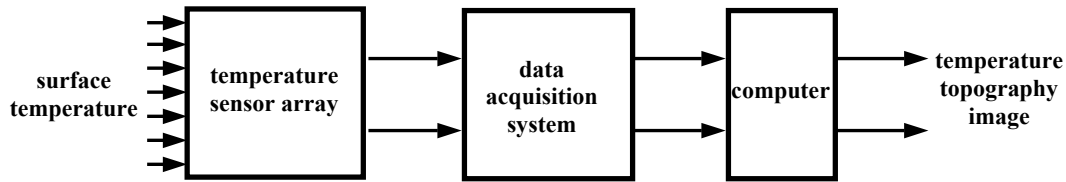

Fig.1. Signal flow chart

As shown in Fig.2(a), the T-type thermal couples were used as the temperature sensors and arranged in square array. The adiabatic base made of glass fiber reinforced plastics was uniformly drilled with microscale holes with diameter of about 100 μ m at the prescribed positions. The thermal couples were sealed at these positions and exposed to the skin surface to map its temperature distribution. The down-lead wires of the thermal couples were guided out through the bottom of the base and then packaged using the substrate made of organic glass (Fig.2(b)). In this way, a temperature sensor array was constructed. According to the area of the to be measured skin surface, different sizes for the array plate can be designed. And the distance between each thermal couple can be regulated at will and 6mm was used in the present system. Further, the amount of the thermal couples can also be determined as required. However, confined by the channels of the current data acquisition system, 6×6=36 thermocouples were used in this study. Their coordinates were stored in the computer. Once the temperatures at these positions were recorded using data acquisition system (USA, Agilent 34970A), the two-dimensional temperature topography for the skin surface can be displayed. Comparing this image with that of the normal skin surface, one can evaluate whether the detected tissue is healthy or abnormal. This system is capable of in-situ imaging the transient temperature of the skin surface, which will provide valuable information for detecting the human disease.
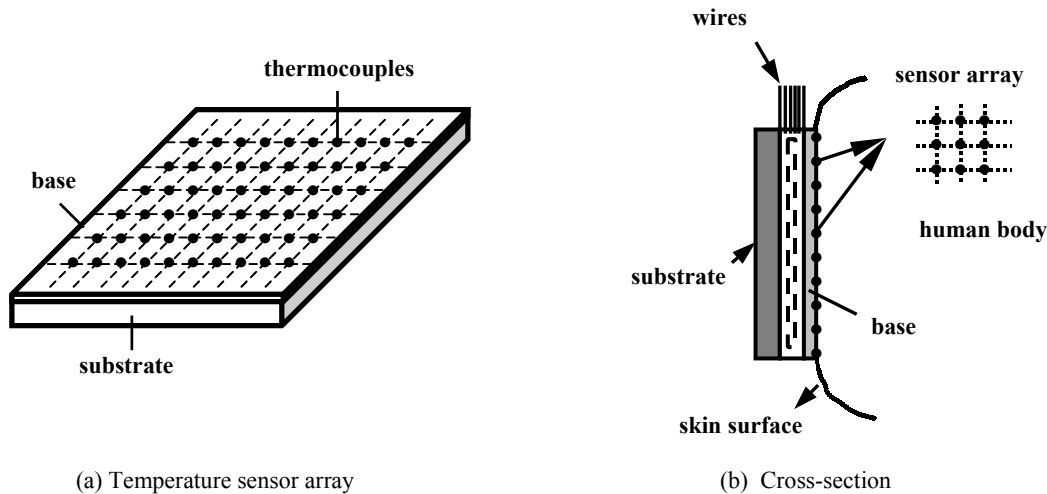

(a) Temperature sensor array   (b) Cross-section

Fig.2. Construction of the temperature sensor array

III. PRELIMINARY EXPERIMENTAL RESULTS

To calibrate the temperature sensor array, all the hot and cold ends of the thermal couples were immersed in the ice-water mixture. Then the deviation between each other was determined and the systematic error can thus be eliminated before the measurement.

When performing the steady state diagnostics, closely contact the sensor array to the skin surface. Then the two-dimensional temperature information on the skin surface can be mapped. If for a dynamic diagnostics, the skin surface should be subjected to a specific heating or cooling before imaging the temperature.

As a preliminary investigation, we performed experiments on the surface of human forearm with underneath large blood vessel transversing. Before the imaging, this skin surface was cooled using a 6cm×6cm×3cm aluminum plate pre-cooled by ice water mixture. After about

20 seconds, the cooling plate was moved away. And the sensor array was contacted to the forearm to map its transient temperature response of the skin surface. Fig.3 depicts the corresponding spatial temperature profiles for two human forearm surfaces at two different times. The irregularity of the temperature distribution is quite evident which is mainly caused by the blood flow in large vessels. This is because the convective heat transfer by the flowing blood and the heat conduction by the tissue is different in strength, which will result in different temperature response on skin surface when subject to cooling. Generally, for the healthy human body, the non-homogeneity of the skin surface temperature is mainly determined by the blood flowing in the vessel. Given the small magnitude of the temperature difference, high-resolution thermal sensors are required for this application.

It has long been revealed that existence of the malignant tumor often leads to very different skin surface temperature response. The metabolic rate in the tumor site often appears abnormally high. Comprehensive analysis on the irregularity of the abnormal thermal states of the skin surface will be beneficial for the disease diagnostics. An atlas database needs to be set up and an expert software system need to be developed to help to judge when the temperature mapping stands for disease. Clinical experiments need to be performed to investigate the most effective heating (or cooling) and imaging algorithms for the disease detection. Clearly, dynamic diagnostics will provide more information than the steady state one. Based on different thermal signals intentionally applied on the skin surface of human body, the transient temperature response can possibly be correlated with the disease. All these problems need further investigations.
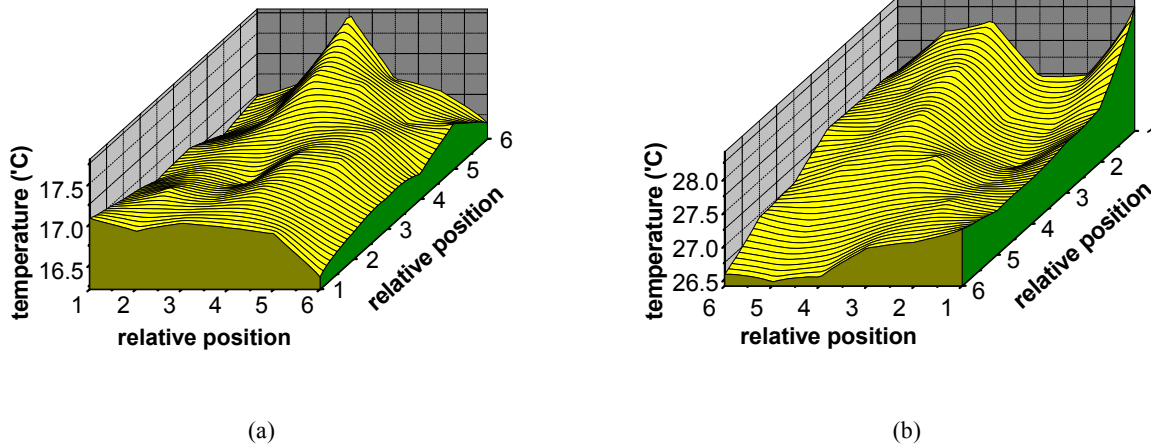

Fig.3. Temperature maps for two human forearms at two time intervals

IV. DISCUSSION

For the disease diagnostics via thermal approach, the most commonly used index is the skin surface temperature, which can be non-invasively recorded by the infrared thermometer or the present system. However, this information is not always useful. As a common experience for the clinician, the temperature mapping on the skin surface can not always reflect the right disease symptom. This is because the surface temperature is overall a contribution from all the physical or physiological behaviors inside the living tissues. In other words, the same surface temperature may represent different states of the biological bodies. Many factors such as tissue density, specific heat, heat conductivity, blood perfusion, metabolism etc. all affect the output of the skin surface temperature. So, even the diseased tissue has abnormal heat generation, it does not necessarily result in an irregular surface temperature increase, since other factors may possibly level off the contribution from such disease factors. For these reasons, finding a more suitable index for thermally diagnosing the human disease is still very necessary. As will be shown later, the heat flux is just one of such candidates, which can provide more complete information for the diagnostics than that of the surface temperature. This conclusion was drawn from the following analysis.

The well known Pennes' equation reflecting heat transfer in the skin tissue reads as [7]:

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot \left(k \nabla T \right) + \omega_b \rho_b c_b (T_a - T) + q_m \left(x, y, z, t \right) \quad (1)$$

where, ρ, c, and k denote density, specific heat and thermal conductivity of tissue; ρ_b, c_b are density, specific heat of blood; ω_b blood perfusion rate; q_m metabolic heat generation; T_a the supplying arterial blood temperature and T the tissue temperature.

Equation (1) can be written as:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial T}{\partial z} \right) + q_m^* \left(x, y, z, t \right)$$

$$(2)$$

where, $q_m^*(x,y,z,t) = \omega_b \rho_b c_b [T_a - T(x,y,z,t)] + q_m(x,y,z,t)$ can be regarded as a local apparent metabolic heat generation, which comprehensively reflects the thermal contribution from the tissues. If tissue appears as either diseased or healthy, it will results in the alternation of the $q_m^*(x,y,z,t)$. Thus if certain index capable of reflecting this behavior can be found and non-invasively recorded, it will be very useful for the thermal diagnostics. This index is proved to be the skin surface heat flux.

For simplicity, the one-dimensional problem was analyzed which is

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + q_m^*(x,t) \qquad (3)$$

Integrating this equation from the skin surface (x=0) to the body core (x=L) leads to

$$\int_0^L \left(\rho c \frac{\partial T}{\partial t}\right)\mathrm{dx} = \int_0^L \left[\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right)\right]\mathrm{dx} + \int_0^L q_m^*(x,t)\mathrm{dx} \qquad (4)$$

At the steady state, the above equation leads to

$$0 = k_x \frac{\partial T}{\partial x}\bigg|_{x=L} - k_x \frac{\partial T}{\partial x}\bigg|_{x=0} + \int_0^L q_m^*(x,t)\mathrm{dx} \qquad (5)$$

Considering that at the deep biological body, the temperature becomes uniform due to self regulation of the human body, the temperature gradient at the core position tends to be zero, i.e. $\frac{\partial T}{\partial x}\big|_{x=L} = 0$. Then (5) can be written as:

$$q = k_x \frac{\partial T}{\partial x}\bigg|_{x=0} = \int_0^L q_m^*(x,t)\mathrm{dx} \qquad (6)$$

which means that the total heat generation inside the biological body contributes to the skin surface heat flux. Clearly, any abnormal internal thermal behavior will be reflected by the skin surface heat flux. Thus compared to the temperature information, the surface heat flux is more appropriate in serving as the right tool for diagnosing the disease. To measure this surface heat flux, a highly conductive material such as copper or aluminum plate embedded with heating wires can be sandwiched between the substrate and the base. Due to with high conductivity, the temperature over this whole plate surface is almost the same, thus only a thermocouple needs to be fixed on the surface of this layer to measure its temperature T_0. Once the skin surface temperatures T_i (at position of the i*th* couple) were recorded, the skin surface heat flux at position of the i*th* couple can be obtained as $q_i = k_b \frac{T_i - T_0}{\Delta x}$ (where k_b and Δx are heat conductivity and thickness of the base, respectively) based on Fourier's law. In this way, a surface heat flux sensor array can be set up. For diagnostic purpose, a database of surface temperature and heat flux corresponding to different thermal states of biological bodies need to be established in the near future.

V. CONCLUSION

In this paper, a highly economic imaging system for thermal disease diagnostics using temperature sensor array was proposed which may replace the infrared thermometer in some degree. This system is quick in response and accurate in the temperature measurement. It can be used in a wide variety of temperatures. The device is a kind of simple diagnostics system with low price and high performance as well as good flexibility. Preliminary experiments show the promising future of this system to the thermal imaging of human body. From a theoretical analysis, it was still found that the surface heat flux appeared more appropriate for disease diagnostics than the surface temperature. All these efforts guarantee further investigation in this area using the present method to detect the human disease. And the sensor array system to measure the surface heat flux needs to be developed.

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