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Thermography as a Means of Blood Perfusion Measurement

The scanning infrared camera has been used to verify an analytical model relating blood perfusion rate to skin temperature. The blood perfusion rates were measured with both the mercury strain gage and the volume plethysmograph on the human forearm. Thermograms were taken of the forearm and temperature measured using an optical densitometer. Comparison of the volume plethysmograph with the strain gage, and the thermograms with the strain gage indicate thermography to be a useful means of measuring blood flow. Thermography has the advantages of being noninvasive and can be used to measure blood perfusion in parts of the body not easily monitored with occlusive techniques.

Introduction

Thermography has been proposed as a simple fast means of blood perfusion measurement by Love and Lindsted [10]. This proposal was based on an energy balance which equates the convective heat gain from blood flow to the peripheral tissues to the heat loss from those tissues. Conventional plethysmographic methods are subjected to well known limitations and restrictions. Although thermographic techniques also involve a set of assumptions which are discussed below, it has a number of advantages for many applications. One is that the apparatus does not attach to the subject or touch the subject in any way. Another is that blood perfusion may be inferred in regions of the trunk where venous occlusion methods may not be utilized. The purpose of the current work is to compare measurements made with the scanning infrared camera and conventional venous occlusion techniques in human extremities.

Analysis

The theoretical basis for the technique presented in reference [10] is summarized as follows. The relationship has been developed through the use of widely utilized "Bio-Heat" equation [11, 13, 19] which is given in steady state form as

$$\frac{k}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right) + W_B C_B (T_{\text{art}} - \text{T}) + Q_o = 0 \quad (1)$$

The equation is solved for the steady state skin temperature using cylindrical coordinates and assuming no azimuthal or longitudinal temperature variation. However, the variables of metabolic heat generation and tissue thermal conductivity are also known. The vein temperature is used to provide additional information permitting the elimination of these variables.

In this model the tissue properties are assumed homogeneous throughout the extremity. It is recognized that the human anatomy is such that there exist the cutaneous layers, subcutaneous fatty layer, skeletal muscle and bone all separated by the various fascial layers. Although the blood supply to each layer may be identified, the major arterial supply and venous return will be common. In terms of the energy balance the cutaneous layer is so thin that skin blood flow makes very little difference in the skin temperature. Experimentally this may be observed by scratching the skin surface with a single stroke of a finger nail to obtain a red weal indicating increased cutaneous flow. This visible reddening cannot be seen in the thermogram even though it is visible to the eye. On the other hand, if a region of skin is massaged to stimulate blood flow in the subcutaneous tissue, a region of increased temperature may be observed on the thermal image even though there is no visible reddening of the skin. The blood perfusion in the bone is of course much lower than soft tissue. However, since the bone is deep to the tissue, the temperature gradients will be small and the effect of this small blood flow again will not seriously affect skin temperature. The differences in the blood flow in the subcutaneous fat layer and the muscle are somewhat more difficult to rationalize. However, if the region of concern is the extremity with a relatively thin fat layer, the perfusion determination will represent primarily that of the skeletal muscle. If the region of interest is the female breast, this computed blood perfusion represents primarily an average of the flow in the fatty breast tissue.

Equation (1) is a thermal energy model of the temperature distribution in living tissue during steady state conditions. The individual terms comprising it represent the rate of heat conduction in the radial direction, the heat transfer due to blood perfusion and the rate of heat generation due to metabolic reaction, respectively. Cylindrical coordinates have been chosen as being reasonably representative of the geometry of living tissue for many areas where skin temperatures are of interest. One boundary condition which allows for a solution is given by

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at $r = 0$, the temperature is finite. (2)

Another boundary condition is obtained by an energy balance at the skin surface, $r = R$, between the tissue and the environment given by

$$-k\frac{dT}{dr}_{r=R} = h(T - T_{\text{room}}) \tag{3}$$

This equation may be solved for a relationship involving the parameters. An additional relationship can be derived by integrating the temperature profile and assuming that the vein temperature represents an average tissue temperature in the region of interest.

The result of the analysis is represented by

$$W_B = \frac{2h}{RC_B}\left[\frac{T_{\text{skin}} - T_{\text{room}}}{T_{\text{art}} - T_{\text{avg}} + \dfrac{Q_o}{W_B C_B}}\right] \tag{4}$$

An additional simplification may be developed by noting the magnitude of these quantities. First, a simple heat transfer analysis indicates that at 21°C (room temperature), the temperature over superficial veins will be about 0.2°C cooler than the blood in the vein. In addition, an examination of usual arterial – venous blood oxygen concentration differences indicates the following magnitude for the ratio of metabolic heat generation and blood perfusion.

$$\frac{Q_o}{W_B W_C} \approx 0.2°\text{C} \tag{5}$$

Using these approximations, while noting that errors of 100 percent or more will have only a small effect on the determination, the following relationship is obtained

$$W_B = \frac{2h}{RC_B}\left[\frac{T_{\text{skin}} - T_{\text{room}}}{T_{\text{art}} - T_{\text{vein}}}\right] \tag{6}$$

Physically this equation is simply a balance of change in internal energy of the blood in the tissue to the convective loss/gain from the surrounding skin surface. While this analysis is based on cylindrical geometry a similar relationship may be derived for an infinite plane parallel geometry. Actually, the thorax, including the female breast, is more closely approximated by the cylindrical model than either spherical or plane geometry. This is particularly true when the thermal imaging is done while the patient is supine.

For estimation of blood perfusion, the heat transfer coefficient h may be calculated for known environmental conditions. For comparative studies in which symmetrical contralateral values or serial values are to be used, the following ratio is valid if the environmenal conditions are the same for each study.

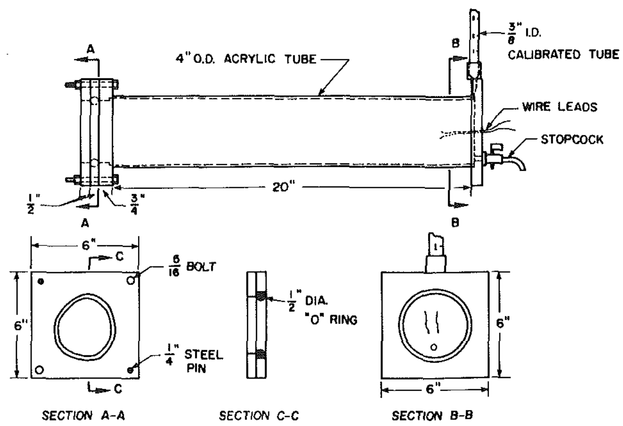

Fig. 1 Sketch of forearm volume plethysmograph

$$\frac{W_{B,1}}{W_{B,2}} = \left[\frac{T_{\text{skin}} - T_{\text{room}}}{T_{\text{art}} - T_{\text{vein}}}\right]_1 \left[\frac{T_{\text{art}} - T_{\text{vein}}}{T_{\text{skin}} - T_{\text{room}}}\right]_2 = \frac{\theta_{\text{Study 2}}}{\theta_{\text{Study 1}}} \tag{7}$$

where

$$\theta = \left[\frac{T_{\text{art}} - T_{\text{vein}}}{T_{\text{skin}} - T_{\text{room}}}\right]$$

In both relationship (6) and (7), it is important to note that judgment must be used in selecting the vein temperatures corresponding to the veins draining the region of the blood perfusion determination.

The present work involves a series of experiments which compare the results of simultaneous blood perfusion measurements in the human forearm determined by thermographic technique and a mercury strain gage venous occlusion plethysmograph.

Method

In the first study, a strain gage was calibrated using a volume plethysmograph for the hand and forearm constructed from acrylic (Fig. 1). The opening for the arm was shaped to fit the forearm. The seal around the upper forearm was designed to be airtight, yet not interfere with normal blood flow. The sealing ring was made from 1.25-cm rubber tubing bonded into a circle with silicone sealant. It was coated with solid petrolatum and inserted into a channel in the opening. Electrical leads for the mercury strain gage were placed through the walls of the plethysmograph and sealed.

In these experiments the mercury strain gage (Parks Electronics) was placed on the forearm at the midpoint between the wrist and elbow of the subjects. The length of the gage used was either 20 or 30 cm, depending on the size of the forearm. The strain gage was connected to a plethysmograph

Nomenclature

- A_C = cross-sectional area of the tissue
- C_B = specific heat of blood
- h = combined convective and linearized radiative heat transfer coefficient
- k = tissue thermal conductivity
- r = radial position
- R = distance from the center of the tissue region to the skin surface
- T_{art} = arterial temperature
- T = tissue temperature
- T_{vein} = temperature of the skin superficial to the vein
- T_{skin} = temperature of the skin superficial to the tissues from which the vein is assumed to be draining blood
- T_{room} = ambient temperature
- T_{avg} = average tissue temperature = $1/A_C \int T(r)\, dA$
- Q_o = metabolic heat generated per unit volume
- W_B = mass blood perfusion rate per unit volume
- θ = dimensionless temperature ratio = $(T_{\text{art}} - T_{\text{vein}})/(T_{\text{skin}} - T_{\text{vein}})$

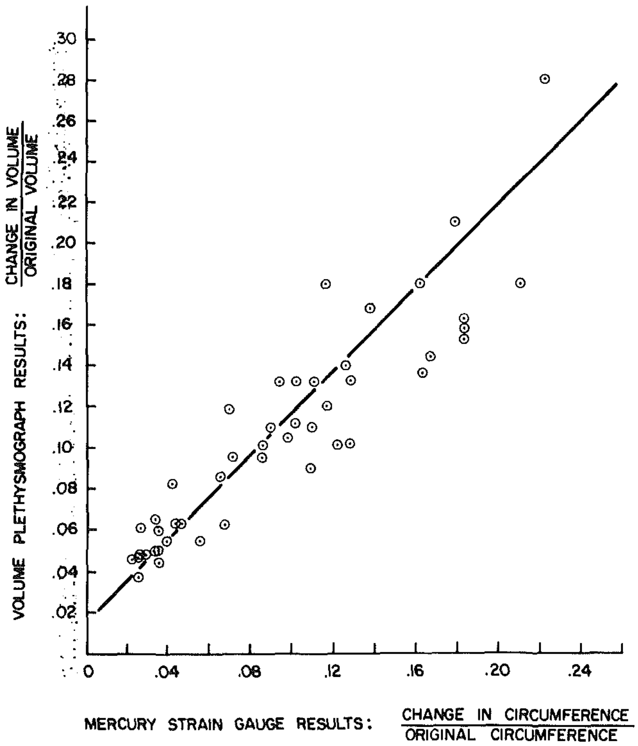

Fig. 2 Calibration curve for the mercury strain gage versus the volume plethysmograph

unit (Parks Electronics, Model 270) and recordings were made using a polygraph (Grass Model 5 DWC1).

The circumference of the arm at the point of attachment of the gage was recorded for later calculations. The volume plethysmograph was placed on the same forearm to allow simultaneous recording of total volume changes in the hand and forearm and circumferential changes in the forearm. A blood pressure cuff was placed around the upper arm which, when inflated to 70 mm mercury would prevent outflow of blood through the veins, but not inflow of blood through the arteries. After the apparatus was in position, the subject was seated in a chair with his arm and hand on a table, palm upward. The cuff was inflated and the resultant changes in volume and circumference noted. Cuff pressure was released a few seconds after inflation. This procedure was repeated four or five times at 5-min intervals. In order to obtain higher blood flow values the subject then squeezed a rubber ball 25 times without removing his hand from inside the plethysmograph. After waiting 1 min from the exercise period to allow blood flow to become maximal, the cuff was inflated and readings were again taken. This was repeated 5 min later. It should be noted that the occlusion cuff was necessary only to the mercury gage measurements.

After the mercury strain gage was calibrated to the volume plethysmograph, experiments were conducted in which blood flow was estimated simultaneously with the mercury strain gage and infrared thermography. The mercury strain gage was positioned as before. The infrared camera model 700 ("Thermlscope," Texas Instruments Company) was positioned to take thermograms of the entire forearm. The temperature of a reference heat source placed in the field of view of the camera was monitored with a thermistor, and recorded at the time that each thermogram was obtained. The cuff was placed on the upper arm, the subject was seated with his arm on the table, palm upward and the subjects oral temperature and the room temperatures were recorded. After a 15-min equilibration period, data were taken before and

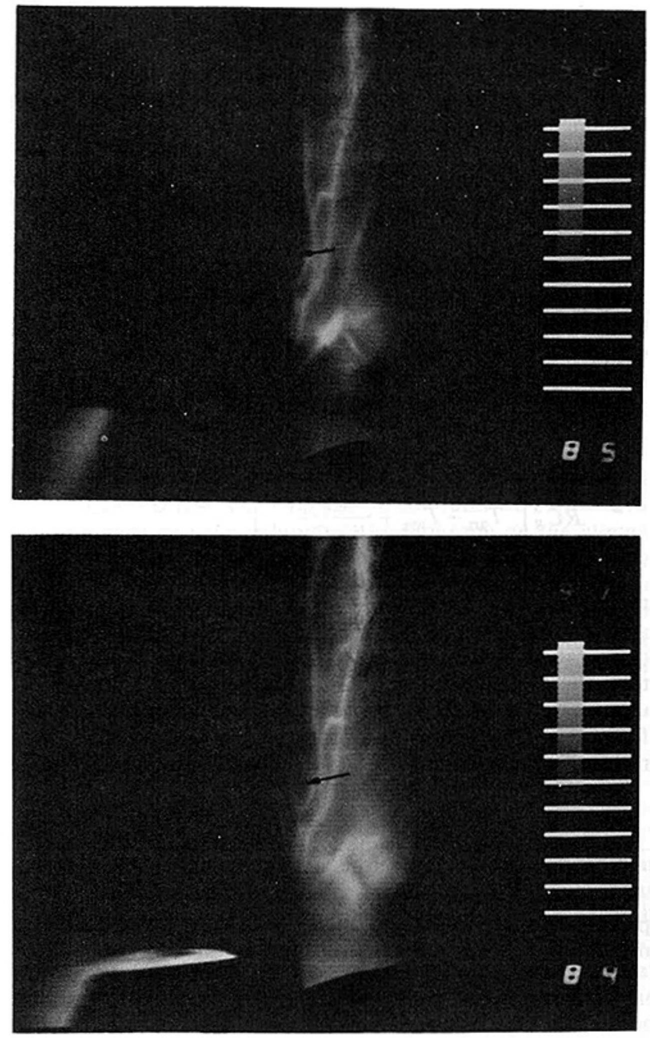

Fig. 3 Thermograms of human forearm before (*a*) and after (*b*) exercise

after exercise as previously described. Thermograms were obtained a few seconds before the cuff was inflated for blood flow measurements by the strain gage.

In order to obtain temperatures from which to estimate blood flow using thermography, ambient temperature was taken as recorded and arterial temperature was taken as the subject's oral temperature plus 0.55°C, since rectal temperature is 0.55°C higher than oral temperature. We have assumed rectal temperature is approximately arterial temperature. Vein and skin temperatures were obtained by analyzing the thermogram negatives using a Gamma Scientific Instrument's Micro-densitometer and log converter. Vein temperatures were obtained from densitometer traces taken over the vein and skin temperatures were taken from skin superficial to the tissues from which the vein is assumed to be draining blood. A reference was used to calculate the actual temperatures as the internal scale on the thermograms was not always correct. It was placed in the camera's field of view and its temperature was monitored with a thermistor with a precision of 0.1°C. Data was obtained from 15 subjects.

Results

Increased blood flow occurred in the forearm of each subject after exercise. This increase was determined using the volume plethysmograph, the mercury strain gage and thermography. A comparison of the data obtained with the volume plethysmograph and the mercury strain gage is

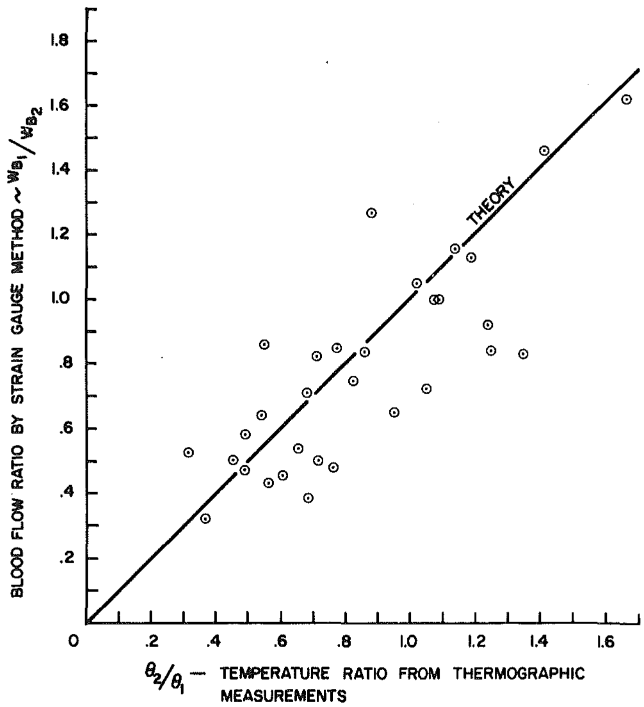

Fig. 4 Comparison of blood perfusion ratio as obtained from the mercury strain gage to the blood perfusion ratio (expressed in temperature ratios) obtained from thermography

presented in Fig. 2. Thus data at both low (at rest) and high (after exercise) blood flow rates are linearly related for these two methods, even though the strain gage measures circumferential changes at a single position on the arm, while the volume plethysmograph measures volume changes in the hand and most of the forearm.

The thermograms shown in Fig. 3 were taken before (*3a*) and after (*3b*) exercise. In these thermograms white is warm and black cool, with intermediate temperatures showing as shades of grey. The grey scale on the right side of the thermogram indicates the relationship between temperature and shades of grey. The numbers indicate the grey scale range in °F. To correct the scale for any inaccuracies a comparison is made with the controlled temperature source. In Fig. 3, the forearm was warmer after exercise (*3b*) due to the warming effect of increased blood flow. Data obtained from densitometer traces of the thermograms was plotted against strain gage data (Fig. 4). The solid line is a plot of the theoretical expression given by equation (7).

A straight line was calculated for the data using the least square methods. The correlation coefficient is 0.764 and the slope is not significantly different from 1. These results indicate the analytical model is a reasonable representation of the data.

Discussion

For several years thermography has been used in the diagnosis and evaluation of therapy of various vascular diseases [1-6, 8, 9, 12, 14-18, 20]. This has included peripheral vascular diseases such as arterial insufficiency, thrombophlebitis, varicose veins and vasospastic phenomena as well as cerebrovascular disease. It has other clinical uses that are also based on detection of blood flow such as placental localization [7]. In this paper we have reported the use of thermography in quantifying blood flow changes to support a theoretical model of blood perfusion in the human forearm.

The many uses of thermography in peripheral vascular studies along with the well known difficulties and limitations of conventional plethysmographic techniques seem to warrant the application of thermography as a means of estimating blood flow. The analytical model summarized by equation (7) has been verified in these experiments. In these studies the use of this model and the scanning IR camera has been shown to be an acceptable means of measuring relative blood perfusion rates. This new technique for measuring blood flow has the following advantages: it is noninvasive, it may be used on all parts of the body many of which cannot be monitored by the other methods, and it is less cumbersome than many of the other methods.

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