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Thermographic Venous Blood Flow Characterization with External Cooling Stimulation

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Abstract

Experimental characterization of blood flow in a human forearm is done with the application of continuous external cooling based active thermography method. Qualitative and quantitative detection of the blood vessel in a thermal image is done along with the evaluation of blood vessel diameter, blood flow direction, and velocity in the target blood vessel. Subtraction based image manipulation is done to enhance the feature contrast of the thermal image after removal of external cooling. To demonstrate the effect of occlusion diseases (obstruction), an external cuff based occlusion is applied after the removal of cooling and its effect on the skin rewarming is studied. Using external cooling, a transit time method based blood flow velocity estimation is done. From the results obtained, it is evident that an external cooling based active thermography method can be used to develop a diagnosis tool for superficial blood vessel diseases.

Keywords: Medical Infrared (IR) Thermography, External Cooling Stimulation, Skin Temperature, Superficial Skin Blood Flow, Venous Blood Activity Ratio.

1. Introduction

Human body thermoregulation with respect to the ambient environment conditions is one of the most attractive fields of study since a long time. To ensure proper metabolism of the different organs of the body, blood circulation system plays an important role in maintaining a standard core body temperature of 37 °C through vasoconstriction and vasodilation at peripheral locations. This regulates the heat transfer interaction of the outer skin with the ambient atmosphere [1][2]. Therefore, outer skin temperature changes from time to time depending upon the extent and effectiveness of heat transfer, which particularly depends on the external conditions, kind of clothing, age, sex, etc. [3]. Barcoft et al. [4] performed an invasive experiment on forearm of a human subject to study the skin and muscle temperature variation with blood flow under three different external temperature conditions: forearm under water bath, covered with a cotton cloth and open to air. The authors have found that the blood flow decreases with the decrease in water bath temperature to prevent any further heat loss from the body. A similar trend in blood flow alteration is observed for the other two cases studied. Nilsson [5] developed a nearly linear correlation between the skin blood flow and skin temperature by applying local stimuli in the form of forced convection (air) and radiative cooling. Since the experiments are done for limited thermal range, these results cannot be applied to the real-time conditions. Further, in the work of Vuksanovic et al. [6], a non-linear relationship between the skin blood flow and skin temperature is shown. The authors have also observed the memory phenomenon that relates to the hysteresis, when blood flow restored to normal condition on application of an external thermal shock. Therefore, for the given ambient

condition, any imbalance in the temperature is considered as an abnormal health condition.

This brings the usefulness of Infrared (IR) thermography in medical diagnosis and health condition monitoring [7]–[11].

It is well established that any object above absolute zero temperature emits infrared (IR) radiations. Depending upon the emissivity (ϵ) and temperature (T in K) of the object surface, the total emissive power (E in W/m^2) is calculated [12] as follows:

$$E = \epsilon \sigma T^4 \quad (1)$$

where, σ is the Stefan Boltzman constant with a value of $5.676 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$.

The emissive power provides a measure of temperature when detected with an IR detector, resulting into a thermal map called thermogram. Specific application of thermography in medical diagnosis [13]–[16] and detection of the vital health signatures such as pulse rate has been evolved with the development of image and signal processing techniques like Fast Fourier Transform (FFT) adaptive estimation [17], contour segmentation and tracking [18], multi-resolution approach [19], data adjustment scheme [20], data synchronization [21], etc. For a better visualization and quantitative investigation, an active thermography method can be adopted, wherein an external excitation in the form of thermal heating or cooling, vibration, pressure, etc. is used.

In the past, active thermography methods have been developed to visualize the microcirculation and venous blood flow over the skin tissue that relates to the effective heat

transfer between the skin and its surroundings [22][23]. In a resting arm, thermal contrast between the blood vessels and skin area is not enough to visualize the blood flow. Therefore, application of external excitation in the form of oscillatory pressure in the frequency range 0.015 - 0.03 Hz can result into better visualization as shown by Wu et al. [24]. Similarly, Bouzida et al. [25] utilized the internal blood flow excitation by the application of external pressure through an armband at a frequency of 0.03 Hz to successfully capture the veins structure of the human back hand. The authors have found a 0.35 °C drop in temperature over the vein pixels of the hand under examination. The authors have concluded that blood flow in the veins and arteries led to heat exchange through skin surface and regulates the temperature distribution in the whole body. Therefore, tracking the heat transfer through temperature mapping of the skin surface can be correlated to the abnormalities in the form of acute pathological conditions. Such a correlation between the skin microcirculation and the skin temperature can be devised through wavelet oscillations of the skin perfusion with temperature, which can be utilized to diagnose vascular disorders [26], [27].

Using thermography, a more quantitative superficial disease diagnosis (skin diseases, venous diseases, peripheral arterial diseases, etc) can be developed by measuring the velocity of blood flow in the veins. This could also complement or replace the currently available non-thermographic methods such as light based transit-time method, electromagnetic method, laser Doppler technique, near infrared spectroscopy, etc. [28], [29]. Under thermographic methods, the work by Boue et al. [30] has experimentally and analytically estimated the speed of blood flow, radius and depth of a superficial vein on a human forearm. The authors have

1 applied external thermal stimulation in the frequency range of 0.08 – 0.009 Hz to the forearm
2 skin just above the superficial vein and monitor the transport of heat by the blood in the vein
3 through thermal images acquired at a frame rate of 1 frame per second. The method employed
4 has deduced a blood velocity of 0.16 mm/sec and a vein radius of 3.1 ± 0.1 mm at a depth of 2.2
5 ± 0.7 mm. In a different subject, the same procedure evolves a velocity of 20 mm/sec for the
6 same kind of vein. Ratovoson et al. [31] studied the application of cold stress for 40 seconds
7 over the superficial vein and monitor the rewarming curve at different points in the nearby
8 area. Data point just above the blood vessel shows a quick recovery in the temperature as
9 compared to other points within the cooling zone. Further, a Pennes equation based 2-
10 dimensional numerical model is developed to validate the results. The blood flow velocity is
11 calculated to be 4.8 mm/sec which is found to be much lower than the velocity range shown in
12 the work of Pennes et al. [32] (30 mm/sec to 60 mm/sec). Jin et al. [33] estimated the blood
13 flow velocity in the superficial artery of a rabbit through an in-vivo thermographic
14 experimentation. The authors have used laser excitation to thermally stimulate the blood flow
15 and hence, monitor the time of heat transport in the blood vessel to estimate the flow velocity,
16 using an analytical model. Mahmoud et al. [34] measured the volumetric blood flow rate in the
17 superficial vein assuming blood flow in the vein equivalent to fully developed laminar flow in a
18 pipe. The authors have captured thermal images before and after the application of an ice pack,
19 hence, estimated the volumetric flow rate of 0.06 ml/sec using a heat balance model. The
20 validity of the method is verified on an in-vitro model, which agrees with the ground truth
21 volumetric flow rate.

1 From the literature studied, it can be concluded that the kind of blood flow determines the rate
2 of heat transfer to the walls of the blood vessels, which will then be conducted to the outer
3 surface of the skin. At the outer surface of the skin, convective heat transfer takes place with
4 the ambient atmosphere. The rate of heat transfer from the blood vessels to the skin is
5 dependent on the outer skin surface temperature which is dependent on the ambient
6 condition. For a given ambient condition, the skin thermal map reveals the thermoregulation
7 between the blood flow and the skin tissue. However, a thermal image generated through
8 passive thermography (without external excitation) couldn't reveal much information on the
9 blood flow in the vessel due to rather uniform diffusion to the skin. Since the temperature of
10 the tissue under scan is already at a higher temperature than ambient, it is favorable to use
11 cooling as an external excitation instead of heating. This will not only help in creating a high
12 temperature differential between the specimen and the thermal source, but also avoids the
13 error in the thermal data collected due to unnecessary reflections to the camera, as in the case
14 of heating excitation application [35]. Therefore, in the present study, a momentarily higher
15 heat transfer window will be created using localized cooling (external thermal excitation) of a
16 small section of the skin over the superficial blood vessel (minimally contact) and hence, the
17 rewarming process will be tracked using a contactless IR thermal camera. The images acquired
18 during this rewarming phase can provide a better contrast to the presence of superficial blood
19 vessels and ease the blood vessel diameter estimation. Further, using a transit time method on
20 thermal transport during the application of external excitation (cooling), the blood flow velocity
21 in the superficial blood vessel is estimated.

2. Experimental Method

2.1. Problem Statement

Potential of active thermography is studied to characterize the blood flow in the superficial vein of a human forearm. Following objectives are studied:

- a) To locate the blood vessel.
- b) To quantify the presence of blood vessel.
- c) To find the direction of blood flow.
- d) To estimate the diameter of the blood vessel.
- e) To estimate the velocity of blood flow.

2.2. Apparatus and Material

Human Subject experiments (IRB: SHS-NTU/014/2016) are performed. A small skin surface just above the superficial vein on the left forearm of 3 human subjects (males of age 24 ± 1 years) is considered as the Region of Measurement (RoM) as shown in Fig. 1. The ambient room temperature is maintained at 23 ± 0.5 °C.

Figure 1: Region of Measurement (RoM) on the forearm of a human subject

2.2.1. Thermal Camera

Temperature is monitored over the left forearm of the subjects using a non-contact IR thermal camera, VarioCam by InfraTech (Fig. 2). Specifications of the camera are given in Table 2. In the present study, image acquisition is done at the rate of 2 frames per second.

Table 1: Specification of the IR thermal camera:

Parameters	Details
Accuracy	± 2 K
Pixel	320 x 240
Detector	Microbolometer
Resolution	Better than 0.1 K
Emissivity	User Defined (0.98)
Temperature resolution	better than 0.1 K

Figure 2: IR Thermal Camera – VarioCam by InfraTech

2.2.2. Cooling Pad

For the application of primary external stimulation in the form of cooling, ice water at a temperature of 5 ± 0.5 °C is circulated through a cooling pad using a submersible pump (0.069 lit/sec). With cooling as the principal thermal perturbation in the study, it is imperative to

1 devise a cooling device that permits a uniform cooling application on the test section. The
 2 cooling system comprises of a cooling pad, thermally-insulated flexible hoses, a submersible
 3 pump, and an insulated tank (Fig. 3). Representing the primary component in the system, the
 4 cooling pad is formed from a flat copper strip as the base and clear acrylic as the peripherals on
 5 the top and walls, adhered firmly by silicone glue. The high thermal conductivity of copper
 6 enables effective cooling on the test section. On the contrary, the choice of acrylic for the
 7 remaining peripherals aims to attenuate thermal gain into the cooling pad. Additionally, the
 8 transparency will enable detection of undesirable bubble formation within the pad, which may
 9 affect the cooling.

(a)

(b)

(c)

(d)

Figure 3: (a) Dimensions of cooling pad, (b) Cooling pad with copper base and acrylic peripherals,
 c) With thermally-insulated hoses installed, (d) Overview of cooling system

2.2.3. Occlusion Cuff

A blood pressure measurement cuff (OMRON HEM-7121) is used to apply the occlusion based secondary external stimulation in Subject-1. The occlusion cuff, equipped with an automatic inflator and deflator, is wrapped around the left arm to apply a safe and secure occlusion alike to the blood pressure measurement protocol. Using a piezoresistive pressure sensor placed between the skin and the cuff, the pressure (P) applied over the time during the inflation and deflation of the cuff is measured and plotted (after normalizing with maximum pressure applied $P_{max.}$) against time as shown in Fig. 4.

Figure 4: Cuff pressure versus time

2.3. Experimental Procedure

In the present study, two different experiments are carried out. The subjects are asked to rest calmly without any physical activity for 15 minutes in a room maintained at 23 ± 0.5 °C. In the first experiment, cooling is applied for 30 seconds at the skin RoM (Fig. 5) and left open for rewarming. In addition to this procedure, in the second experiment, a cuff is wrapped over the arm and occlusion is applied just after the removal of cooling. Thermal images are captured

from start to end of the experiment. For each of the two experiments in each patient, 3 repetitions are done, and the mean value of the calculated parameter with standard deviation ($\pm$ SD) is reported.

Figure 5: Application of cooling excitation with cooling pad on the forearm

2.4. Thermal Image Analysis

Once the images are acquired, the next step would be to improve the contrast of the features captured in the image. Extraction of the temperature data over time, at specific points of interest, is performed to study various characterization outlined in Section 2.1. For the presentation purpose, the absolute skin temperature obtained at these points of interest, from the thermogram sequence, is normalized with the core body temperature ($T_{Core} = 37^{\circ}\text{C}$). To enhance the contrast of the images, a primitive noise subtraction based image manipulation is performed. To do so, the subsequent images after the removal of cooling is being subtracted from the image immediately after the removal of cooling. This proved to be an efficient way of improving the image contrast as discussed later in Section 3.1.

3. Results and Discussion

3.1. Location of the Blood Vessel

In this experiment, effect of external excitation on thermography is studied to characterize the blood vessels on the human forearm. Fig. 6a, 6b and 6c show the thermal images at various instants of the experiment. Without any external excitation, the passive thermal image is shown at $t = 0$ second (start of the experiment). It can be observed that no visible blood vessel can be detected from this image unless image manipulation is done, which is computational intensive and might need highly sensitive camera to resolve the temperature contrast in the image. Therefore, an external thermal excitation based active thermography can be used to address the issue. In the present study, to apply the external thermal excitation, the skin surface is cooled down for 30 seconds shown in Fig. 6a ($t = 30$ seconds). After the removal of cooling, at $t = 30.5$ second, there is no visible temperature contrast can be seen in the cooling zone, however, after 5 seconds from removal of cooling ($t = 35$ seconds), there is a high temperature line observed. This is basically because of the heating of the skin surface due to the presence of the blood vessel just below this line. As the time progress, this line temperature increases due to increased heat transfer over time ($t = 40$ seconds and 45 seconds). To further enhance the image contrast, a subtraction-based image manipulation is employed, wherein, the thermal image at the instant just after removal of the cooling ($t = 30.5$ second) is subtracted from images at the instants, $t = 35, 40$ and 45 seconds. This subtraction filters out all the background noise and gives only the region of interest (blood vessel in this case). The resultant subtracted images in the last rows of Fig. 6a, 6b and 6c reveal a clear demarcation of a

- 1 primary vein along with a secondary vein. Moreover, the appearance of the blood vessel
- 2 outside the cooling zone is also clearly visible with the help of this subtraction-based image
- 3 manipulation.

Figure 6a: Thermal images at various instants and its subtracted images after application of cooling (5 ± 0.5 °C) in Subject – 1

Figure 6b: Thermal images at various instants and its subtracted images after application of cooling (5 ± 0.5 °C) in Subject – 2

Figure 6c: Thermal images at various instants and its subtracted images after application of cooling (5 ± 0.5 °C) in Subject – 3

3.2. Quantify the Presence of Blood Vessel

In this section, a strategy to quantify the presence of blood vessels in a thermal image is defined. For this purpose, two points on the thermal image are taken (Fig. 8a), one over the clearly visible blood vessel and the other over the area with no blood vessel, and the temperature over these two points is monitored after the removal of cooling. Further, to quantify the behavior of the blood vessel in the presence of an obstruction, an external occlusion stimulation to the blood flow is applied just after the removal of cooling pad, using an inflation-deflation cuff. From Fig. 7, it can be observed that the rewarming curve with occlusion deviates from the one without any occlusion at the instant of occlusion application; however, its effect persists even after the completion of the deflation phase. This deviation in rewarming temperature curve is because of the absence of the heat transfer source (blood flow) for a duration equivalent to the occlusion period; hence, results in lower temperature.

Figure 7: Rewarming plot (after removal of cooling) with and without occlusion over a point on primary vein in Subject - 1 ($T_{Core} = 37^{\circ}\text{C}$)

Although the application of occlusion results in lower rate of temperature increase for a small duration of the rewarming period, this temperature evaluation is not expected to go lower than or equal to the temperature evaluation at a point where no similar superficial blood vessel is present. As shown in Fig. 8b, temperature over the skin with no blood vessel shows a lower temperature throughout the rewarming duration as compared to the temperature curve just over the blood vessel (Point A and B in Fig. 8a). This is due to absence of any heat source in the form of flowing blood at higher temperature in this zone. Further, occlusion-based temperature curve evaluated over the point just above the blood vessel lies between the other two curves because of only a temporary absence of the heat source in the form of blood flow.

Figure 8: (a) Subtracted thermal image with the location of point under consideration (b) Rewarming curve (after removal of cooling) over the point A and B for in Subject-1 ($T_{Core} = 37^{\circ}\text{C}$)

Temperature difference (ΔT_R) during the rewarming phase with respect to total rewarming time (t_R) up to a fixed reference temperature (here equal to the room temperature) is normalized with the temperature difference (ΔT_C) developed during cooling phase with respect to the cooling time (t_C), to evaluate venous blood activity ratio (AR_{RC}) given by:

$$AR_{RC} = \frac{\Delta T_R / t_R}{\Delta T_C / t_C} \quad (2)$$

Using Eq. (2), AR_{RC} value is calculated for the two points considered and the results are summarized in Table 2. For all the subjects studied, it can be observed that the value of AR_{RC} is highest for the point over the blood vessel, while it is the least for the point not above (outside)

the blood vessel. Since the application of temporary occlusion restricts the blood flow in the primary vein, it is evident from the above discussion that the value of AR_{RC} at a point over the vessel will be lesser than the case of no occlusion (Table 2). Moreover, except for Subject-1, AR_{RC} value over skin tissue with no superficial vein is found to be lower in case of occlusion application. This implies the effect of occlusion on the skin blood microcirculation which contributes to the rewarming of the skin tissue even without any major superficial vein.

Table 2: Value of activity ratio for the cases considered

Subject Studied		$AR_{RC} \pm \text{Standard Deviation (SD)}$	
		Over the Primary Vein – A	Over No Vein – B
Subject 1	No occlusion	1.28 ± 0.03	0.33 ± 0.04
	with occlusion	0.60 ± 0.09	0.34 ± 0.02
Subject 2	No occlusion	0.43 ± 0.08	0.28 ± 0.03
	with occlusion	0.31 ± 0.03	0.21 ± 0.01
Subject 3	No occlusion	0.62 ± 0.17	0.26 ± 0.09
	with occlusion	0.28 ± 0.03	0.18 ± 0.01

3.3. Direction of Blood Flow

In this section, evaluation of the blood flow direction is done from the acquired thermal image or thermogram in all the subjects. For this, as shown in Fig. 9a, three points (A, B and C) are taken along the primary vein. From the rewarming curves of the three points plotted for Subject-1 in Fig. 9b, it can be observed that point A maintains a higher temperature for the whole duration of the rewarming phase followed by point B and C. Considering the known ground truth that the blood flow is from point A to C, it is evident that the upstream point should be at the higher temperature as compared to the downstream points along the blood vessel. When blood enters the cooling zone (near upstream point), more heat is transferred

from the blood to the skin due to higher temperature difference. As the blood moves further downstream, it loses its capacity to heat the skin with the same potential due to less temperature difference between the blood and the skin and hence, the downstream point over the skin remains at a lower temperature. Hence, plotting the rewarming temperature curve along the blood vessel inside the cooling zone could help in establishing the direction of blood flow.

Figure 9: (a) Subtracted thermal image with 3 points along the primary vein (b) Temperature rewarming curve (after removal of cooling) for the 3 points for Subject-1 ($T_{Core} = 37^{\circ}\text{C}$)

To further quantify the direction of blood flow, the results for rewarming temperature from the occlusion experiment is plotted along with the no occlusion experiment. For the rewarming duration (t_r), a global temperature difference factor (μ) can be calculated as the area

intercepted between the two curves (shaded region in Fig. 10a) divided by the total rewarming time ($t_r = 90$ seconds) as given by Eq. (3).

$$\mu = \frac{\int_0^{t_r} (T_{skin}/T_{core})_{no\ occlusion} dt - \int_0^{t_r} (T_{skin}/T_{core})_{with\ occlusion} dt}{t_r} \quad (3)$$

Due to application of occlusion, the rewarming temperature curve for the upstream point is supposed to deviate minimum, followed by increasing deviation in downstream; hence results into an increasing μ value along the blood vessel. This can also be observed in Fig. 10b, where the value of $\mu \pm$ Standard Error (difference between means of with and without occlusion cases) at point A, B and C along the primary vein (within cooling zone) is plotted. The minimum and maximum standard error (SE) in means of μ derived from multiple experiments (3 repetitions for each case in each subject) is found to be 0.003 and 0.006, respectively. Given the increasing trend in μ value from point A to C, it can be derived that the direction of blood flow is from point A to C.

(a)

(b)

Figure 10: (a) Area under the two curves (Subject-1): rewarming (after removal of cooling) with and without occlusion ($T_{core} = 37^{\circ}\text{C}$) (b) $\Delta T_G \pm \text{Standard Error (SE)}$ for the 3 points under consideration for Subject-1,2 and 3

3.4. Diameter of the blood vessel

As marked in the subtracted images in Fig. 11a, the temperature magnitude is plotted along the line $a-a'$ which is perpendicular to the primary blood vessel and the high temperature zone over the blood vessel is used to mark the diameter. Although, in the work of Boue et al. [30], a similar method is used to determine the diameter using amplitude images over continuous thermal images, subtracted images, with relatively less computation involved, are found to be more suitable to determine the diameter in the present study. To mark the boundary of the blood vessel in lateral direction (along line $a-a'$), a reference zero point is marked. To do so, at each pixel along the line $a-a'$, from maximum temperature ($T_{max.}$) over line $a-a'$, a relative

difference in temperature ($T_{max} - T_{ij}$) is evaluated. Since T_{max} will fall over the region of
 blood vessel along line $a-a'$, this point is marked as reference zero. Plotting ($T_{max} - T_{ij}$) against
 the distance along the line $a-a'$ as shown in Fig. 11b, boundary of the vessel on the left and right
 side of the reference zero point is marked by the sudden change in the shape of the plot.
 Within blood vessel region, the slope of the plot is supposed to either remain zero or
 consistent. Using this method, diameter of the primary blood vessel is evaluated in each subject
 and an average value ($\pm$ SD) is summarized in Table 3.

Figure 11: (a) Subtracted thermal images with lateral line ($a-a'$) marking over the primary vein (b) plot of $T_{max} - T_{ij}$ along the line $a-a'$ in Subject-2

Table 3: Diameter of the primary vein estimated from the subtracted images

Subject Studied	Primary Vein Diameter (mm) $\pm$ SD
Subject 1	3.83 $\pm$ 0.08
Subject 2	2.63 $\pm$ 0.04
Subject 3	2.76 $\pm$ 0.14

3.5. Velocity of Blood flow

In this experiment, during the application of cooling, it is observed that the blood in the vein passing under the cooling pad gets cooled down with the application of cooling and is clearly visible in the thermal images marked by the lower temperature line outside the cooling zone as shown in Fig. 12a (for Subject 3). In the present study, a transit time method is used to evaluate the velocity of the blood flow in this vein. As shown in Fig. 12b, on the application of cooling, the heat transfer will take place from the skin to the cooling pad. Depending upon the intensity of cooling and the depth of the blood vessel, the blood in the vessel also cools down accordingly. On the application of the cooling, the skin tissue below the cooling pad will cool down (cooling zone), which provides a potential temperature difference between the cold skin tissue and hot blood entering the superficial blood vessel beneath this cooling zone; hence heat transfer will take place from blood to the skin tissue, which cools down the blood. Other than this heat transfer in the vertical direction below the cooling pad, a diffusion heat transfer from the skin tissue adjacent to the cooling pad will also take place. Therefore, the skin below and adjacent to the cooling pad will cool down in the process, along with the blood. When the cold blood in the blood vessel will flow outside the cooling zone, a heat transfer component from the skin to the blood will also arise due to the temperature difference between the cold blood

1 and the hot skin, which will cool down the skin just above the location of the blood vessel,
 2 outside the cooling zone (Fig. 11a).

Figure 12: (a) Thermal image with 4 markers outside the cooling zone in Subject-3 (legend: temperature in °C) (b) Mechanism of heat transfer on the application of cooling

Following the mechanism of heat transfer described above, the presence of the cold zone outside the cooling zone in Fig. 12a can be explained. The lower temperature zone in the immediate vicinity of the cooling pad is because of the diffusion heat transfer within the skin layer in horizontal direction, while the cold line going away from the cooling pad is because of the heat transfer from the skin surface to the cold blood. Now, if two data point markers

(marker 1 and 2, which are at distance, d) are taken over the visibly cold region line outside the cooling zone, the time delay for the temperature drop at these two markers can be used to estimate the blood velocity. However, to mark the temperature deviation instant at the two markers correctly, reference points are also required to negate the diffusion effect from the skin. As explained before, there is a uniform diffusion heat transfer happening outside the cooling zone. Therefore, two more data point markers (marker 3 and 4) are taken outside the cooling zone (not above the blood vessel), aligned but away from the first set of markers as shown in Fig. 12a. The temperature progression over these 4 markers is monitored for the duration of cooling application as plotted in Fig. 13.

Figure 13: Temperature evaluation at the 4 points outside the cooling zone (during application of cooling) in Subject-3

Ten seconds after the start of the experiment, the cooling is applied with a total cooling application time of 60 seconds. It can be observed that the temperature evaluation at the first set of markers over the blood vessel and the second set of markers over the skin with no blood vessel is differed in a specific pattern. While temperature drop is observed for all the markers, a sudden drop in temperature is obvious for the first set of markers (marker-1 and 2) due to the

presence of cold blood flow beneath it. Assuming no presence of blood vessel, the temperature drop trend at all the four markers is supposed to be similar. With the presence of blood vessel, however, the corresponding temperature progression between marker-1 and marker-3, and marker-2 and marker-4 is same for first few seconds after the application of cooling, due to uniform heat diffusion effect from the skin to the cooling pad and then, there is a temperature drop at marker-1 and marker-2 with a time lag. Since the cold blood first reaches marker-1, its temperature drops first, followed by marker-2. This delay in time (Δt) is equivalent to the time required for the cold blood to move from marker-1 to marker-2. Knowing the distance between the two markers (d), velocity of the blood flow (v_b) can be calculated using Eq. (4).

$$v_b = \frac{\text{distance between the two markers over the blood vessel } (d)}{\text{time delay for the blood to reach marker-2 from marker-1 } (\Delta t)} \quad (4)$$

For Subject – 1, 2 and 3, the mean velocity ($\pm$ SD) of blood flow is found to be 3.59 ± 0.22 mm/sec, 3.51 ± 0.26 mm/sec and 3.72 ± 0.08 mm/sec, respectively.

4. Conclusions

In the present study, an active thermographic method is used to characterize the blood flow in the superficial vein. In the form of external thermal excitation, continuous cooling method is used, and the thermal images are captured after the removal of the cooling. The thermal images acquisition can correctly characterize the location of blood vessel in the forearm. Temperature data is extracted at certain data points from the images to mathematically quantify the presence of blood vessel. A method is described to evaluate the direction of blood flow and diameter of the blood vessel from the thermal image. Finally, a transit time based

- 1 method is devised to estimate the velocity of blood flow in the target vein during the
- 2 application of cooling. Successful characterization of the superficial venous blood flow
- 3 presented in this work could help in developing an external cooling excitation based active
- 4 thermographic diagnosis tool for skin blood flow diseases.

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