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Single Image Reconstruction in Active Dynamic Thermography: A Novel Approach

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Abstract

In the present study, a novel single thermal image reconstruction method, from the transient image series in active dynamic thermography (ADT), is proposed. ADT is performed with an external stimulation in the form of cooling, over the forearm skin tissue of a human subject, and the resulting transient images (due to thermal recovery) are captured using a non-contact Infrared (IR) thermal camera. A unique tissue activity ratio (TAR), the ratio of thermal recovery rate to excitation rate, is calculated at each pixel, and hence, a single thermal image (called TAR image) is reconstructed. Using a conventional single image reconstruction method in ADT called Tau (τ) image method, a comparative study is performed, which reveals that the blood vessel contrast produced by the TAR image is at least 1.3 times higher than the equivalent τ image. Further, using this TAR image, the diameter of the blood vessel is calculated, and the values are compared with the τ image and the earlier reported thermography results on the same subjects, which reveals that the reconstructed TAR image is an equivalent qualitative and quantitative representation of transient sequence images. The method devised can further be implemented for medical ADT procedures.

Keywords: Active Dynamic Thermography; Tissue Activity Ratio; Thermal Image Reconstruction; Image Contrast; Blood Vessel Characterization.

1. Introduction

Active dynamic thermography (ADT) involves external stimulation in the form of cold stress, heat, and pressure, that is applied over the skin tissue and the resulting transient images are captured using a non-contact Infrared (IR) thermal camera [1]–[4]. This is one of the non-invasive methods to achieve high contrast thermal images. Application of the external stimulation leads to thermal recovery of the tissue to normal condition through a transient phenomenon. The thermal images captured during this transient phase show improved target feature contrast.

Williams and Chir [5] showed the effect of ice application based stimulation over the human forearm. The authors have found that on the removal of cooling, the thermal images captured can reveal the presence of a vein, the brachial and the radial artery. Similarly, in the work of Brarnes [6], both heating and cooling stimulation are done to enhance the contrast of the superficial vein in the skin tissue. Application of heating led to the appearance of cooler veins relative to the surrounding skin. In contrast, cooling the skin tissue with a wet towel for few seconds led to the rewarming with high visibility of the superficial veins; however, the image contrast decreases as the rewarming progresses further. Subtracting the sequential images from the reference image (with no excitation) can bring additional contrast to the images as shown in the work of Ohashi and Uchida [7], wherein the potential of dynamic thermography (using electric fan for cold stimulation) in diagnosing breast cancer on 728 patients is studied. The authors have used sequential thermal images and sequentially

1 subtracted image to find the irregular hot spots as a consequence of tumor presence. This has
2 increased the diagnostic accuracy from 54% to 82%. Investigating an alternative cooling
3 method, Deng and Liu [3] examined transient images upon spraying of medical ethanol (75%
4 V/V) on the forearm of a human subject. Given the highly volatile nature of ethanol, induced
5 evaporation takes place, which leads to the cooling of the skin tissue. The authors have
6 concluded that the thermal expressions can be improved using such external stimulation.
7 Though an important stepping stone, ADT application in these studies pose only a qualitative
8 method towards visualization and a possible disease diagnosis. Moreover, selection of the
9 best contrast image from the ADT sequence is subject to the examiner's capability to
10 differentiation.

11
12 To quantify the ADT sequence, thermal recovery rate upon removal of cold
13 provocation plays an important role in determining the pathological condition of the tissue
14 under investigation. Using this principle, Dupuis [8] studied the potential of ADT in
15 diagnosing the occupational disease called vibration-induced white finger (VWF) on 317
16 subjects. The author has proposed a method to diagnose VWF based on the normal, moderate
17 and strong delay in the rewarming time of the fingers subjected to cold provocation. To
18 analyze the ADT sequence in both qualitative and quantitative manner, thermal recovery
19 time constant (called Tau time, ' τ ') is used to reconstruct a single image (Tau image) from
20 the thermal sequence data. Tau time is calculated at each pixel, which is equivalent to the
21 time to reach 63% of the temperature difference between before and at the end of thermal
22 excitation [9]. It is imperative that the Tau time for a tissue with pathological condition
23 differs from the normal one, which can be easily located in the Tau image. Using this
24 technique, Foerster et al. [10] examined 139 patients to diagnose Raynaud's phenomenon

(RP), in a retrospective study. With a critical Tau value of 6 minutes, the authors have determined the sensitivity and specificity of the method to be 95.3% and 94.6%, respectively.

Given that the thermal recovery phase is approximately exponential in nature, determination of Tau parameter can also be done by fitting an equivalent exponential curve to the experimental data. Evaluating the ADT based Tau image from the best fit curve at each pixel, Kaczmarek et al. [11] developed a diagnostic tool to monitor the open-heart surgical interventions. Artificially inducing the ischemia by clamping the left descending artery (LAD) of a pig, compared to normal heart functioning, a higher Tau value over the left ventricle is observed. Such a diagnostic tool is well suited for determination of vascularization, necrosis and other pathological conditions [12]. Taking the reciprocal of Tau parameter in the same exponential equation, Jankovic et al. [13] evaluated the rewarming rate (k) at each pixel, which produces k map of the ADT sequence. The authors have used the method to distinguish normal patient from the one suffering from vascular disorder. Exploring another important yet challenging medical diagnosis field, Renkielska et al.[14] used Tau parameter to determine the need of surgical intervention in case of burn wounds. Using ADT with Tau parameter, the authors have identified the wounds that could or could not heal within a duration of 3 weeks, along with wound depth determination. The accuracy of the devised method is found to be 83% as compared to 60.7% and 69.6% for clinical evaluation and static thermography, respectively. In the recent past, ADT parameters like ratio of temperature difference achieved during recovery and excitation, and the relative time to reach 90% and 10% of the total recovery temperature, are used to develop an early complication prediction tool in breast reconstruction procedure [15].

From the literature, it is evident that ADT is both qualitatively and quantitatively useful in medical diagnosis, however, the decision to evaluate the best contrast image, within the sequence or sequentially subtracted images, is operator dependent. Moreover, development of a single image based on various ADT parameters is still at a premature stage. Hence, in the present study, a novel method is proposed to reconstruct a single thermal image that would qualitatively and quantitatively represent the transient image sequence in ADT. This is the best contrast image as compared to the whole image sequence, that can be used to determine the quantitative characteristic like diameter of blood vessel as discussed in the following sections.

2. Materials and Methods

Three male human subjects (aged 24 ± 1 years) are recruited under ethically approved study (IRB: SHS-NTU/014/2016) [16]. In each subject, the left forearm is subjected to external cooling application (ambient: 23 ± 0.5 °C), using a cooling pad with ice water recirculation (5 ± 0.5 °C). To statistically analyze the results, in each subject, 3 repetitions are performed. For medical ADT, external heating/cooling excitation can be applied for a time duration varying from 5s to 60s [12]. In the present study, the cooling is applied for 30s and the thermal images (rows x columns: 240 x 320 pixels as shown around the vertical and horizontal axis of the images in the following sections) are captured (at a rate of 2 frames per second) for another 90s, using VarioCAM IR thermal camera by InfraTec (Fig. 1).

Fig. 1: Experimental setup: 1. IR thermal camera 2. Tripod to hold the camera 3. Human subject left forearm 4. Cooling pad

2.1 Image Reconstruction

Application of cooling led to a transient tissue rewarming phenomenon (Fig. 2). Due to blood flow in the superficial vein, the tissue just above the blood vessel is expected to rewarm faster as compared to the nearby tissue without any blood vessel. Based on this rewarming rate, within the cooling zone, a unique tissue activity ratio (TAR) is defined at each pixel. To do so, rate of rewarming and cooling is calculated at all pixels as follows:

$$\text{Rate of rewarming } (^{\circ}\text{C/s}), RR_{ij} = \frac{T_r - T_{c_{ij}}}{t_{r_{ij}}} \quad (1)$$

$$\text{Rate of cooling } (^{\circ}\text{C/s}), RC_{ij} = \frac{T_{ij} - T_{c_{ij}}}{t_c} \quad (2)$$

$$\text{Tissue activity ratio (dimensionless), } TAR_{ij} = \frac{RR_{ij}}{RC_{ij}} \quad (3)$$

where, i and j are the number of row and column, respectively, to locate the target pixel, T_r is the fixed reference rewarming temperature ($^{\circ}\text{C}$) for the whole cooling zone after removal of cooling, $T_{c_{ij}}$ is the temperature ($^{\circ}\text{C}$) of the target pixel at the end of cooling application, T_{ij} is the initial temperature ($^{\circ}\text{C}$) of the target pixel before application of the cooling, and

$t_{r_{ij}}$ and t_c are the time (s) of rewarming of the target pixel and the time (s) of application of cooling, respectively. Given the calculation of TAR is done based on final and initial temperature values during excitation and recovery phases, a lower thermal acquisition frame rate (2 frames per second) is sufficient for the present study. The selection of T_r is done on the basis that each pixel should at least reach this reference temperature, to calculate TAR value at all pixels, during the rewarming phase image acquisition. For the same rewarming duration in the rewarming phase, the temperature rise at pixels over the superficial blood vessel should be higher as compared to pixels over the skin tissue with no superficial blood vessel. Therefore, T_r is fixed by first finding the maximum value of temperature reached at each pixel (within the cooling zone) for the rewarming duration of thermal acquisition (90s for the present study), and then the minimum of these maximum temperature values at each pixel is assigned as T_r .

To compare the authenticity of the proposed TAR image method, a reference Tau (τ) image reconstruction method in ADT is used. As mentioned in Section 1, τ is the time taken by the tissue during recovery phase to reach 63% of the temperature difference created due to excitation phase ($T_{ij} - T_{c_{ij}}$). Evaluating the TAR and τ time at each pixel, a TAR and τ image can be reconstructed by replacing each pixel of the original sequence image with the calculated TAR and τ values, respectively.

Fig. 2: Cooling-Rewarming curve depicting the experiment procedure and parameters of interest

2.2 Image contrast analysis

Given the blood vessel is a feature of interest over the skin tissue as background, a quantitative contrast evaluation of the image so formed can be done using Weber's formula [17] as below:

$$W = \left| \frac{I - I_b}{I_b} \right| \quad (4)$$

where, W is the contrast, I and I_b are the image parameter over the target feature of interest (blood vessel) and the background (skin tissue), respectively.

3. Results and Discussion

3.1 Sequence to Single Image

In Fig. 3, a series of transient images after the removal of cooling (end of thermal excitation) is shown. As the cooling is removed, the thermal image obtained after 0.5s doesn't show any blood vessel, however, as the time passes, there appears a high temperature line (due to the presence of superficial blood vessel) within the cooling zone ($t=20s$) [16]. The temperature of the cooling zone keeps increasing until it resumes to normal temperature,

alike before the application of cooling, however, the rate of temperature increase over the blood vessel is higher than the rest of the skin tissue in the cooling zone; this brings contrast to the sequence images. Though rewarming at different rate as compared to rest of the skin tissue, there appears diffusion around the blood vessel, which indeed affects the image contrast. Moreover, as a practical problem, the choice of best contrast image for further analysis is another challenge. Therefore, using the rewarming rate evaluation in the form of tissue activity ratio within the cooling zone (Equation 3), a single image is reconstructed as shown in Fig. 3. Since TAR is calculated only within the cooling zone, the outside zone is given default 0 TAR value for a better visualization. Compared to the sequence images, this image has an improved contrast with quantitative sequence characteristic details such that a well segmented blood vessel is clearly visible within the cooling zone, along with the rewarming rate information (TAR parameter) in a single image. TAR image for all the subjects is given in Fig. 4.

Fig. 3: Transient image series after removal of cooling and its equivalent tissue activity ratio based single reconstructed image in Subject-1

3.2 Comparison with Tau (τ) image

As defined earlier, TAR image is based on ratio of rewarming rate and excitation rate, wherein, given the same excitation time at each pixel, the rewarming rate dominates the value

of TAR ; hence the region of skin tissue with blood vessel is marked by higher TAR value as compared to the skin tissue with no blood vessel. On the other hand, τ image is composed of a time parameter which is supposed to be less for the region of high tissue activity; resulting in less τ value for pixels above the blood vessel. Hence, unlike TAR image, the blood vessel is marked by a lower τ value in the τ image (Fig. 4); this results into opposite image characteristics in the two images. Referring to Equation 4, though the numerator ($I - I_b$) is not affected, due to $I < I_b$ for τ image and $I > I_b$ for the TAR image, the denominator (I_b) leads to an excessive lower contrast value for the case of τ image, which doesn't comply with the visual observation of the τ image; resulting into an imbalanced contrast comparison between the images obtained by the two methods. Therefore, for a balanced comparison, the original τ image is transformed into an inverted τ image (τ' image) using following formulation:

$$\tau'_{ij} = \left(\frac{1}{\tau_{ij}} \right) * \tau_{max} \quad (5)$$

where, τ'_{ij} is the transformed inverted τ value, τ_{ij} is the original τ value, and τ_{max} is the maximum τ value in the original τ image. Replacing τ'_{ij} at each pixel with τ_{ij} , the original τ image is converted into τ' image as shown in Fig. 4. This τ' image (inversely proportional to τ image) has a similar image characteristics as the TAR image, in terms of higher and lower image parameter for the skin tissue with and without blood vessel, respectively, which facilitates a balanced contrast comparison between the two methods.

Using the Weber's formula in Equation 4, the average blood vessel contrast (marked as C - C' in Fig. 6, from 3 repetitions in each subject), against the skin tissue background, is calculated. As shown in Fig. 5, the contrast value for TAR image is always higher than the

τ' image for all the subjects (with no overlapping in the Standard Deviation (SD) bar around the average values between the two methods), which is also qualitatively visible in the images (Fig. 4). The maximum and minimum difference in mean values ($\pm$ Standard Error) of contrast between the two images (TAR and τ') is found to be 0.70 ± 0.19 and 0.32 ± 0.13 , for Subject-1 and Subject-3, respectively. Moreover, the contrast improvement from τ' image to TAR image is found to be 1.65, 2.36, and 1.3 times, for Subject-1, Subject-2 and Subject-3, respectively.

Fig. 4: Reconstructed single TAR, τ , and inverted τ image (τ') from the ADT sequence of images

Fig. 5: Contrast comparison between TAR and τ' image with Standard Deviation (SD) bar

3.3 Blood Vessel Diameter

Given that the resultant TAR image provides a well segmented blood vessel, its diameter can be estimated by analyzing the change in image parameter, over a perpendicular line in the lateral direction to the blood vessel. Since both τ and τ' images are mutually related (with inverse proportionality), either of the two images can be used for diameter evaluation. In this section, diameter calculated from the original τ image is compared with the TAR image. First, the image parameter value along the lateral line is extracted and then the location of either the maximum or minimum image parameter value is marked. From the discussion in Section 3.2, it is evident that the portion of lateral lines falling over the blood vessel will have higher and lower value of image parameter than the rest of the skin tissue for TAR and τ image, respectively. Therefore, using the TAR_{max} and τ_{min} as a reference value, local difference in the image parameter from the reference value ($(TAR_{max} - TAR_{ij})$ or $(\tau_{ij} - \tau_{min})$) is respectively calculated, over the lateral line. Doing so, a reference zero is located on the line, which is by default fall within the region of blood vessel.

Fig. 6: TAR image with lateral lines marking over the blood vessel

Further, the relative change in the image parameter with respect to the reference value is plotted around the reference zero point. As shown in Fig. 6, in TAR image for Subject-1 (single experiment), 5 such lateral lines are marked at various sections of the blood vessel within the cooling zone. A similar lateral line marking is done in the τ image. For demonstration purpose, only 3 plots along 3 lateral lines, at downstream, mid and upstream (A-A', C-C' and E-E') of the blood vessel, are shown in Fig. 7. It is expected that the slope of the plot within the vessel will either remain zero or a constant value. Any sudden change in the slope of the plot marks the location of the blood vessel boundary on either side of the reference zero point [16]. Using this method, the boundary of the blood vessel on each of the lateral line is marked and the diameter is estimated.

Fig. 7: Change in image parameter along the lateral lines A-A', C-C' and E-E', in Subject-1, for (a) TAR image (b) τ image

Table 1. Diameter of the blood vessel at various sections in Subject-1, single experiment

Lateral lines	Diameter (mm)	
	TAR image	τ image
A-A'	3.35	2.73
B-B'	3.38	3.13
C-C'	3.47	3.55
D-D'	2.78	2.89
E-E'	4.16	3.85

The results for *TAR* and τ image are summarized in Table 1. It can be observed that the diameter evaluation from both cases is almost alike, with maximum and minimum deviation of 0.62 mm and 0.08 mm at section A-A' and C-C', respectively. Further, diameter ($\pm$ SD) at section C-C' for all the subjects (Fig. 6) is summarized in Table 2 (from 3 reeditions in each subject). The diameter values are compared with the previously reported values in [16], on the same subjects, which were calculated from the image resulting from noise subtraction-based sequence image manipulation. The maximum deviation ($\pm$ Standard Error) in *TAR* and τ image-based diameter from earlier reported values, in all subjects, is found to be 0.32 ± 0.06 mm and 0.35 ± 0.08 mm, respectively. Given the maximum deviation in diameter calculated from the two methods is similar, the proposed *TAR*-based single image reconstruction method is as good as the existing method (τ image), in evaluating the diameter of the blood vessel.

Table 2. Diameter of the blood vessel at section C-C' for all Subjects

Subject Studied	Vein Diameter (mm) at section C-C' $\pm$ Standard Deviation (SD)		
	TAR image	τ image	Saxena et al. [16]
Subject-1	3.48 ± 0.10	3.51 ± 0.05	3.83 ± 0.08
Subject-2	2.68 ± 0.06	2.57 ± 0.12	2.63 ± 0.04
Subject-3	2.77 ± 0.12	2.60 ± 0.26	2.76 ± 0.14

4. Conclusions

In the present study, a novel method to analyze the transient image series in active dynamic thermography is described. External cooling is used to stimulate the superficial

1 human skin tissue. A ratio, called tissue activity ratio (TAR), based on the tissue rewarming
2 and excitation rate, is defined. Using the defined ratio value, a single image is reconstructed,
3 which is the best contrast image as compared to the original image sequence. From this single
4 sequence representative image, diameter of the blood vessel is evaluated, which is in
5 agreement with the previously reported values, on same subjects, in the literature. Further,
6 to authenticate the proposed method, a conventional Tau (τ) time and its transformed
7 inverted τ -based (τ') image reconstruction method is used, and a comparative analysis is
8 done. With visual inspection, it can be concluded that the visibility of feature of interest
9 (blood vessel) is much clearer with the TAR image. Quantitatively, the contrast value of the
10 blood vessel in the TAR image, evaluated on three different subjects, is found to be minimum
11 1.3 times higher than the τ' image. Further clinical studies can be performed to test the
12 efficacy of TAR image in a medical ADT procedure.

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