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Thermal Imaging in Wound Healing Diagnostics

Abstract

Results of a project searching for objective, quantitative evaluation of postoperative wound healing in cardiosurgery are presented. We propose simple thermal models of the healing processes after cardiosurgery interventions as objective descriptors allowing classification of patients for extraction and following recovery at home or for prolonged treatment in a hospital. Classification of healing as the normal process or as a process with complications is possible based on temporal changes of proposed thermal descriptors.

Keywords: diagnostics, thermal model, quantitative classification, thermography, wound healing.

1. Introduction

There are clinical procedures based on observation of a patient after any cardiosurgery intervention but only general natural language description of the state of a patient is evidenced in clinical documentation and this is all one can get. The conclusion - till now any objective quantitative method for evaluation of healing processes in cardiosurgery do not exists. On the other hand the surgical procedures are matured and the number of post-cardiosurgery complications is relatively low, typically 2-3%, and generally not exceeding 5% [1]. Still, such numbers might be decreased by implementing improved procedures based on figures of merit for evaluation of all surgical interventions. This was the motivation to concentrate on a research project devoted to development of a method allowing quantitative evaluation of wound healing.

Since 2012 we are involved in a research project with the aim to develop of an objective and quantitative method for evaluation and description of the state of a post-cardiosurgery wound. The main goal of this research is to propose descriptors suitable for classification of patients to be extracted from the hospital on objective rationale supported by quantitative diagnostic data. The proposed method should be non-invasive, safe for a patient, easy in implementation and inexpensive. Novel trends in diagnostic imaging combine matching of structural and functional, metabolic data - so are thermal images captured in the infrared. Here structure of a tested object is well represented but also physiology plays important role - any changes of metabolism may be visible as hot or cold spots. Also thermal tissue properties are strongly dependent on vascularization and other existing metabolic processes. Therefore it was our intentional choice to check if transient thermal process could be applied as diagnostic descriptors in evaluation of wound healing processes [2]. In fact thermal transient processes are already widely applied in medical diagnostics (e.g. [3]) therefore probability that we are right was high.

2. Diagnostic procedure

There is a big medical background of the reported re-search [1, 2]. Around 400 regular cardiosurgery patients participated in the project. The first two year part of investigations was devoted to development of methodology, procedures, optimization of diagnostic procedures, development of reference data etc. based on at least 200 cases. The second part was mainly searching for patients with complications in wound healing as we registered only a few such cases. This allows concluding, that already all cardiosurgical procedures are well developed and safe for most of patients.

Diagnostic procedure includes already developed Active Dynamic Thermography [4] and analysis of the simplest thermal model of human tissue. Diagnostic measurements at a region of interest (ROI) are performed using the set shown in Fig.1 and Fig. 2.
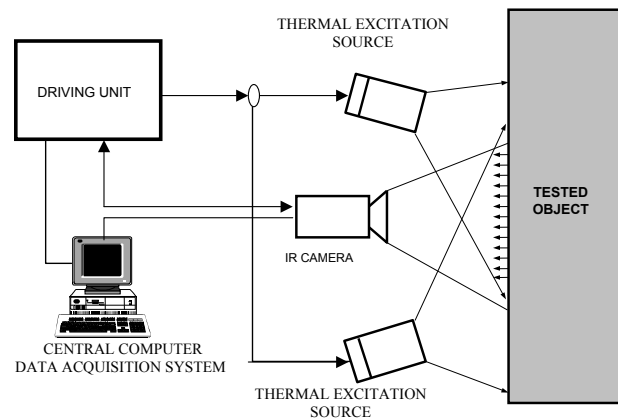

Fig. 1. The ADT diagnostic set - IR camera synchronized with the excitation source (CO_2 cryotherapy unit) allows the surface temperature in a ROI to be recorded after cooling; additionally visual camera may be applied for optical inspection

Fig. 2. A photograph of the ADT diagnostic set in clinical environment

Thermal properties of the region of interest ROI are essential for taking proper diagnostic decision - here we are making inspection within the area of the cardiosurgery wound. This field is controlled before operation, the day 1, to get reference data. Then thermal measurements are performed after operation, at the day 3 and then at the day 6. In the case of regular healing during

consecutive days one may expect slow recovery of a selected figure of merit to the initial state – before operation.

To study thermal flows in biologic structures requires solution of the heat flow in 3D space. Pennes defined „the biologic heat flow equation" [5] - equation (1), representing the general parabolic heat flow describes this problem mathematically:

$$c_p \rho \frac{\partial T(x,y,z,t)}{\partial t} = k\nabla^2 T(x,y,z,t) + q_b + q_m + q_{ex}, \qquad (1)$$

where:
$T(x,y,z,t)$ - temperature spatial distribution in K, at the moment t;
k - thermal conductivity, $Wm^{-1}K^{-1}$;
c_p - specific heat, $J \cdot g^{-1}K^{-1}$;
ρ - material (tissue) density, $g \cdot m^{-3}$;
t - time, s;
$q(P,t)$ - volumetric density of generated/dissipated power, $W \cdot m^{-3}$.
q_b - heat power density delivered/dissipated by blood;
q_m - heat power density delivered by metabolism;
q_{ex} - heat power density delivered by external sources.

Solving of this equation, including all processes influencing tissue temperature, is very complicated (analytically impossible). As an example we may refer to [6], the work related to our project and analysis of ADT procedure, using COMSOL software and FEM model. Such approach is far too complicated for any clinical use. Are there any other options?

Yes, the relationship between excitation and temperature distribution at the surface of a tested object is a measurable quantity. Results of thermal measurements and analysis show that dynamic changes of surface temperature after pulse excitation may be described by exponential functions. This leads to the simplest approach - to build equivalent models of tested tissues or organs based on such synthetic parameters as thermal resistivity R_{th} (or it's reciprocity – thermal conductivity) and thermal capacity C_{th}. The product of R_{th} and C_{th} defines τ - thermal time constant - a parameter easy measurable in ADT. For our approach we propose the two exponential model:

$$T(x,y,t) = T_s(x,y) + \Delta T_1(x,y) \cdot e^{\frac{-t}{\tau_1(x,y)}} + \Delta T_2(x,y) \cdot e^{\frac{-t}{\tau_2(x,y)}} \quad (2)$$

where:
$T(x,y,t)$ - ROI surface temperature at the moment t;
T_s - static temperature at a chosen pixel;
τ_1, and τ_2 - the time constants calculated for given pixel;
and two magnitude temperature parameters - ΔT_1 and ΔT_2.

We checked also the simplest one exponent normalized model [4].

3. Measurements and classification procedure

Active dynamic thermal IR-imaging – ADT – is based on comparison of measurement results with a simple multilayer thermal model described as above, giving a simplified description of parametric images of thermal time constants, which values are correlated with internal structure of tested objects. Recorded in time thermal transients at a given pixel are described by exponential models. Here, the two exponential models are describing the process of natural reheating, after external cooling using cryotherapy unit switched on for a limited time (usually 30 – 60 seconds). In the following figures all important descriptors we checked are shown, for consecutive days of patient diagnostics. We see as the most important the second (longer) time constant in a given pixel.

The proposed solution, as the simplest one, seems to be the most useful practically, as medical doctor usually may accept only relatively simple, still reliable description, based on synthetic parameters easy determined for such models. As an example, thermal structure of the skin may be represented by two

(according to two exponential model - eq. (2) or three equivalent layers described by the time constants defined as $R_{th(1-3)}C_{th(1-3)}$ model. Values of such simple model parameters may be relatively easy determined from experimental data using fitting procedures and are well correlated to physical phenomena, e.g. depth of wounds. This is also probably the easiest method to be applied for modern computer technology based diagnostic tools. Also correlation of model parameters coefficients is not as complicated as in the case of the FEM approach. We assumed that such approach would be also effective for the quantitative evaluation of the state of the post-cardiosurgery wound.

The best condition for proper interpretation of transient thermal results is when the surface temperature of ROI after forced cooling is equal to the ambient temperature. Then the re-warming process of the tissue mainly depends on thermal properties of the tested structure, what gives the best insight into this structure.

It should be underlined that temperatures, such as T_s and any absolute temperature differences as ΔT_1 and ΔT_2 are strongly dependent on external measurement conditions; therefore such parameters are not accurate and not reliable as figures of merit. Diagnostic information may be extracted using temporal parameters as time constants of the exponential model, which are much less dependent on external measurements conditions than magnitude parameters.

As the results of analysis in the following text two cases (patients) are compared. The first one belongs to the group of reference cases, normally healing post-cardiosurgery wound. The second one is a patient with complications. To decrease the number of presented images only static thermograms and the second thermal time constant parametric images are shown for consecutive 1, 3 and 6 days of treatment, what is described below.

Classification of patients is performed based on the differences (3):

$$\begin{aligned} \Delta T_s &= T_s(6day) - T_s(3day) \\ \Delta \tau_2 &= \tau_2(6day) - \tau_2(3day) \end{aligned} \qquad (3)$$

where:
$X(3 \, day)$, $X(6 \, day)$ - ADT model parameters obtained respectively for 3-rd and 6-th day of examination.

We choose for evaluation as a quantitative parameter the difference between day 6 and day 3 value of τ_2 parameter of the two exponential model even other parameters might be chosen, too. For $\Delta \tau_2$ classifier the classification threshold is set to:

$$\begin{aligned} \mathbf{-1} \text{ for } & \Delta \tau_2 < -10 \\ \mathbf{0} \text{ for } & -10 < \Delta \tau_2 < 1 \\ \mathbf{1} \text{ for } & \Delta \tau_2 > 10 \end{aligned} \qquad (4)$$

where on the chart:
black color (−1) - means "good (well) healing process";
gray color (0) - means "hard to say";
white color (1) - means "bad (poor) with complication healing process".

To understand the following images, Fig. 3, please refer to Fig.2. Only part of the patient chest is presented, in fact the ROI along the wound - symmetrical pixels of thermograms and related parametric images: static temperature T_s and thermal time constant τ_2. Total thermal images are composed of 320×240 pixels, while the presented ROI equals 210×80 pixels. In consecutive days presented are: static temperature, following image – the same but averaged values for 5×10 pixels; then thermal time constant τ_2 and the same averaged in sectors 5×10 pixels. These averaged sectors makes easier interpretation of images by a clinician, as general impression of pseudo-colored thermograms and parametric images may be gives excess of information. This sequence is repeated for all 3 days. The summary is given by the differential image calculated from equation (3).
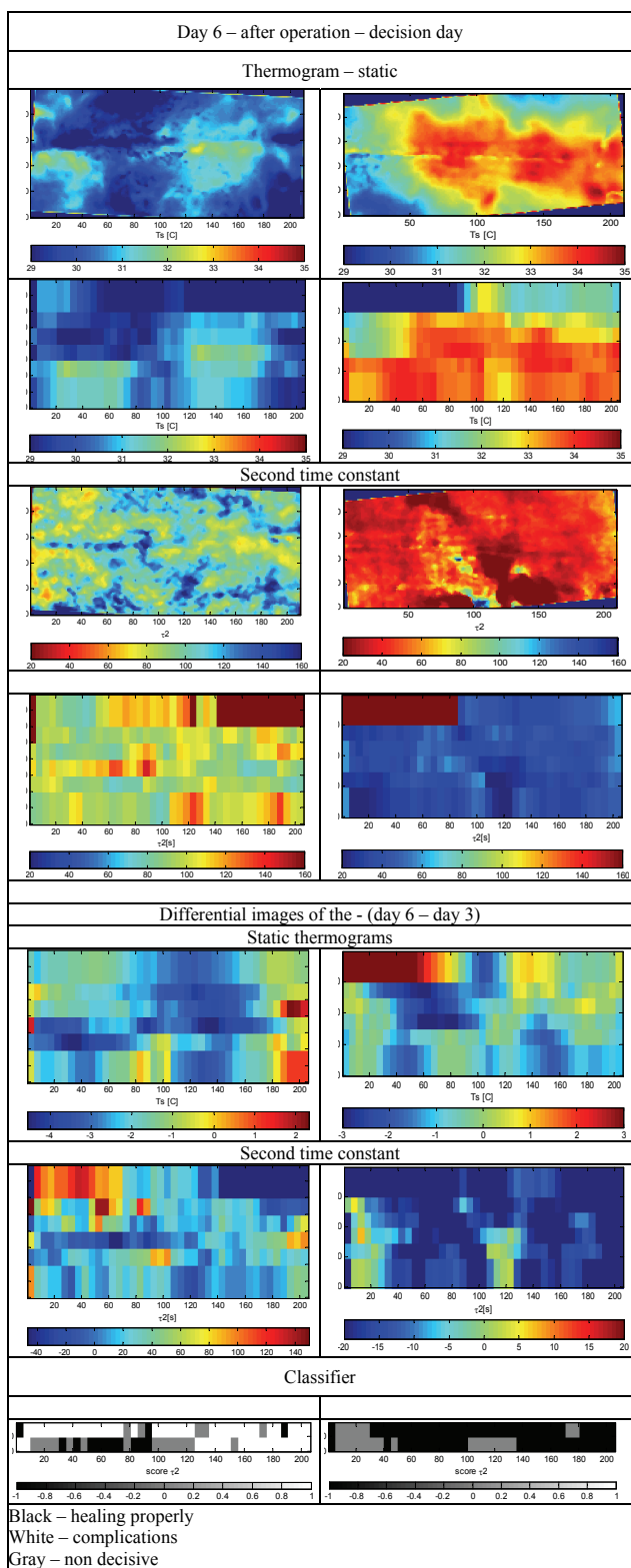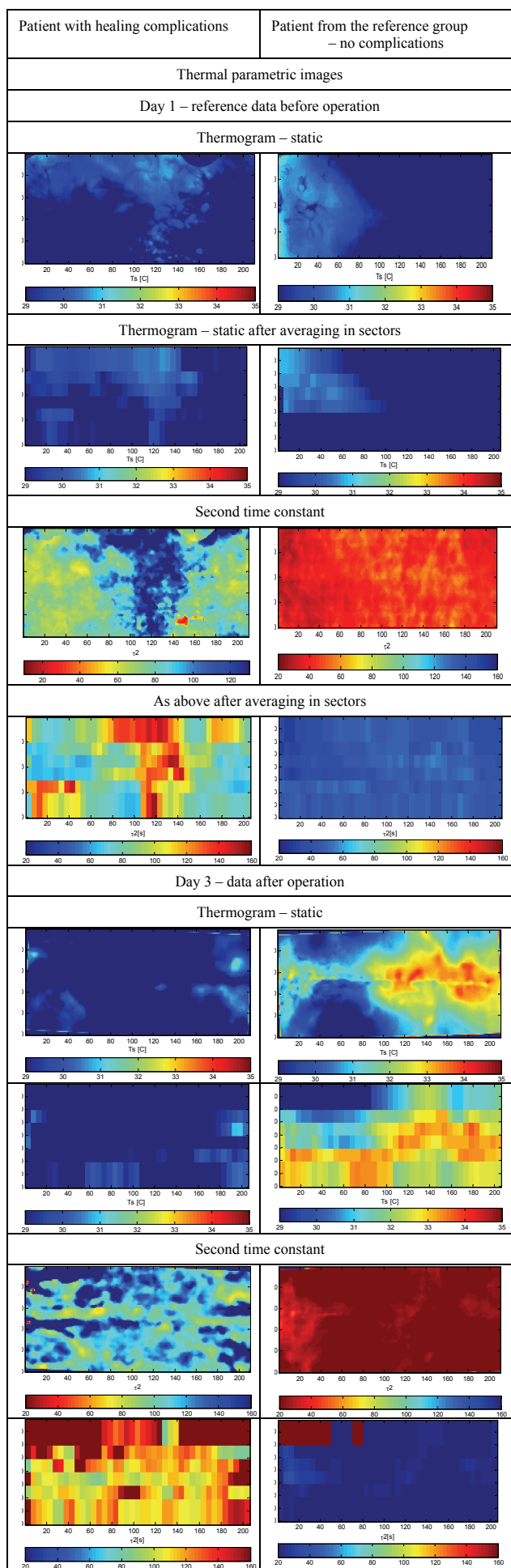
Fig. 3. Parametric images of the two patient cases: left column - complications, right column - well healing

Finally the classifier is presented. Only the pixels closest to the wound are taken into account, the region 20×210 pixels, averaged values in segments 10×5. The patient from the reference group is described by clear trend of healing – recovery of the descriptor values to the reference state, before operation. The case not healing properly is also clearly indicated by the classifier showing complications. This leads to the conclusion, that thermal diagnostics is effective in wound healing diagnostics. Presentation of thermal and RGB images is possible as in the Fig. 4. This is an additional tool to help in taking clinical decision.
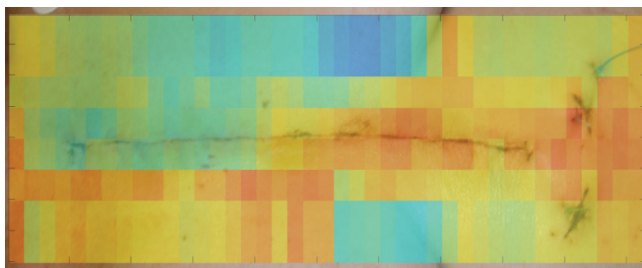
Fig. 4. Matching of RGB visual and parametric images

4. Conclusions

A new method of post cardiosurgery wound healing process is here proposed based on IR-thermal imaging. Development of IR camera technology observed in recent years makes this very attractive tool in many fields of technology and here in medicine, too. During three years of common work we found additionally that at the moment manual skills of medical staff are fantastic.

A simple thermal model, in fact the two layer physical tissue structure approximation described by the two-exponential analytical function is effective in terms of classification of patients who are treated with or without complications after cardiosurgery operations. In fact as a decisive parameter the second thermal time constant seems to be the most effective. Differences of this parameter at the days 6 and 3 applied as the classifier may be practically useful for making clinical decisions. This is the first quantitative descriptor to be applied for objective classification of patients allowing extraction and following recovery at home or the decision for prolonged treatment in a hospital.

Total number of post cardiosurgery patients taking part in the research ranges ca 400. We noticed only 5 cases of complications in wound healing. Each of 5 patients with healing complications was identified respectively to the clinical scale described in [1]. Practically each case was specific for each of patients; therefore the result gives too small number of cases to make any valuable statistics or ROC analysis.

One of important outcomes of this proposal is possibility of objective, quantitative documentation to be included into electronic patient record.

Implementation of the method into clinical diagnostic set supported by user friendly software would be an attractive offer as prices of IR-thermography instrumentation are rapidly decreasing.

5. References

[1] Siondalski P. Algorytm leczenia powikłań gojenia się ran pooperacyjnych i ropnego zapalenia śródpiersia po operacjach kardiochirurgicznych [Algorithm dealing with the treatment of healing wound complications and mediastinitis after cardiac surgeries]. Annales Academiae Medicae Gedanensis. 39:303-4135, supl. 2, 2009.

[2] Moderhak M., Nowakowski A., Kaczmarek M., Siondalski P., Jaworski Ł. Active dynamic Thermography Imaging of Wound Healing Process in Cardiosurgery, Advances in Intelligent Systems and Computing, 284, Information Technologies in Medicine, V. 197 – 202, Springer 2014.

[3] Diakides M., Bronzino J.D., Petereson D.R, Medical Infrared Imaging – Principles and Practices, CRC Press, Taylor & Francis Group, Boca Raton. 2013.

[4] Nowakowski A. Quantitative Active Dynamic Thermal IR-Imaging and Thermal Tomography in Medical Diagnostic, w Ed. M. Diakides, J.D. Bronzino, D.R Petereson, Medical Infrared Imaging – Principles and Practices, 7-1 – 7-30, CRC Press, Taylor & Francis Group, Boca Raton, 2013.

[5] Pennes H. H. Analysis of tissue and arterial blood temperatures in the resting human forearm, J. Appl. Physiol, No 1, 93 – 122, 1948.

[6] Juchniewicz T. Computer modeling and simulation of the ADT procedure in TRAM flap perfusion evaluation, MSc diploma project, Gdansk, 2015.

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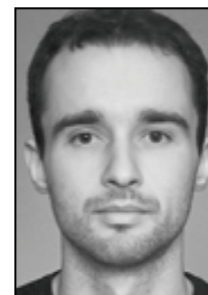
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