Problems of cardiosurgery wound healing evaluation

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Abstract

The aim of this presentation is to analyse possibility of using the newly elaborated infrared imaging procedures called the Active Dynamic Thermography (ADT) for quantitative diagnostics and evaluation of wound healing processes in cardiosurgery. Classical thermal figures of merit as well as new descriptors are compared from the point of view of objective, quantitative estimation of wound state. Temporal properties of thermal transients are proposed for objective quantitative description of the healing process. Algorithms enabling evaluation of surgical wound healing process are discussed in terms of possible implementation of the method into clinical practice.

1. Introduction

In cardiosurgery still up to 5% of patients may be suffering postoperative complications manifested by some difficulty in healing processes. The wide review of cardiosurgery wound healing problem is described in [1]. Generally objective measures allowing proper quantitative evaluation of the state of a postoperative wound are of a high demand. Unfortunately till now in clinical practice there are not existing objective methods and tools for quantitative description and evaluation of the post surgery wound healing progress. On the other hand it is well known that increased metabolism, characteristic for properly proceeded treatment, causes local increase of temperature; high temperature can be also a sign of prolonged inflammatory processes. Similarly, local decrease of temperature, characteristic for ischaemia or process of necrosis, can be an important diagnostic symptom, too. These typically functional symptoms can be quite easily visualized in infrared IR. What is more, the same equipment (IR camera) can be used for structure determination, based on analysis of transitional thermal processes after thermal excitation. Cooling or heating, induced by outer thermal stimulations, allow for reconstruction of thermal model parameters of an examined object. In this way combination of classical thermography with **A**ctive **D**ynamic **T**hermography (ADT) [2, 3] enables elaboration of diagnostic algorithms combining the advantages of functional and structural study.

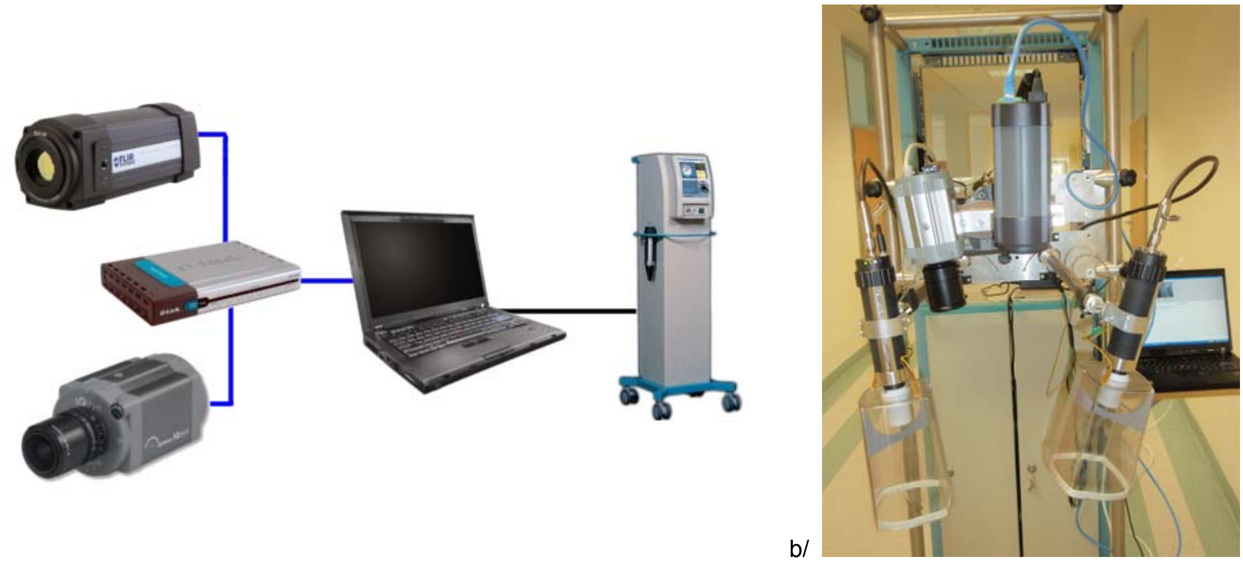
We decided to prove that thermal IR-imaging may be used for objective, quantitative evaluation of the state of a post-cardiosurgery wound. The method is safe for a patient, relatively inexpensive and what is important, it has been already used in evaluation of cardiosurgery procedures [4, 5]. Research is conducted in the interdisciplinary group of experts from Gdansk University of Technology, Department of Biomedical Engineering and from Medical University of Gdansk, the Department and Clinic of Cardiosurgery. Clinical experiments are approved by the local ethical committee.

2. Method, instrumentation and goals of the research

The problem is solved by matching diagnostic data of classical IR-thermal imaging technology with the new ADT method. In ADT infrared image sets are recorded during transitional state, after cooling of the region of interest. The analyzed region is cooled, usually to the room temperature, by temporal blow of the coolant and then it returns to the state of the thermodynamic balance. Thermal processes during the natural return to the thermal equilibrium are diagnostically essential. This procedure is judged by patients as quite pleasant and do not introduces any risk of the health hazard. This approach is an attractive diagnostic option as infrared technology is completely non-invasive. What is more, it is much cheaper comparing to CT or MRI, therefore, it can be introduced as an important tool in the clinical practice.

The research is performed based on the prototype of the ADT unit developed during previous research [3]. The main problem is proper construction of the thermal excitation unit which should provide uniform cooling of the whole region of interest (ROI). There are two types of designed ADT units: the first one utilizes carbon dioxide as the cooling factor and the other one is based on the high power air conditioning unit that provides a stream of a cold air to excite the tissue. Practically the cryotherapy unit with carbon dioxide is applied, as it is free of any bacterial contamination.

In Fig.1 main elements of the measuring set are presented. Imaging is performed by the thermal camera, as well as by the visible RGB camera, installed above the lying patient. This is, of course, a complete system that consists of computer software that realizes image acquisition and its further analysis. As an effect quantitative evaluation of examined ROI is possible. Multispectral IR analysis may be performed using IR cameras of different spectral ranges.



a/ b/

Fig. 1. The ADT set, a/ components: the data acquisition system, thermal and video cameras and a cryotherapy device for cooling excitation, b/ the laboratory stand.

The outcomes of the project and performed experiments are following:

- Elaboration of the methodology combining multimodal images, including ADT, and extraction of diagnostically important features for new criteria of surgical wounds healing process estimation.
- Elaboration of ADT data acquisition and extraction, creating a dedicated database and tools for diagnostically important features extraction.
- Definition of optimal thermal stimulation conditions and selection of the most advantageous technology of infrared images registration in the surgical wounds experiments.
- Definition of the influence of blood flow changes, mechanical stress and forced functional and morphological changes on the thermal properties of the examined tissue.
- Elaboration of the three-dimensional thermal model of the reference region and of the postsurgical wound to implement ADT technology in interpretation of wound’s healing progress.
- Elaboration of the methodology and non-invasive diagnostic procedures convenient for doctors and patients, for current estimation and differentiation of treatment progress.
- Clinical experiments using all the important technologies to assembly statistically reliable diagnostic material in correlation with classical examinations confirmation. Comparative estimation of methods.
- Checking the capabilities of using the elaborated methods and procedures in other surgical clinical applications, for example: in collop transplantation assessment in the plastic surgery. It is possible to supplement this list due to dynamic evolution of knowledge in surgery.

The outcomes of experiments will be put into clinical practice in cooperating departments of GUMed and publicized in the medical community.

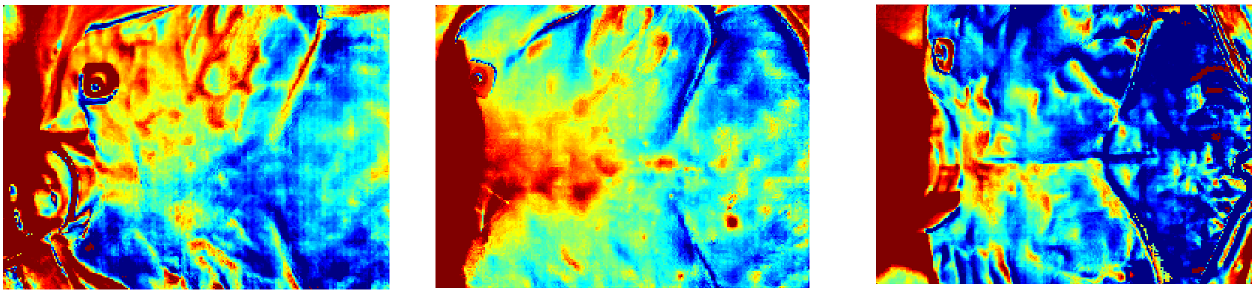
3. Diagnostic procedures

The clinical observations are carried out in 2 series of at least 200 patients each, to verify proposed procedures, to confirm value of the proposed descriptors and to validate and optimize diagnostic process. The patients are classified into following groups:
Group 0 - patients not experiencing any of the complications during wound healing process, which are mentioned below.
Group 1 - patients experiencing *complicated healing of the wound with no clinical or bacteriological characteristics of infection* also called *wound dehiscencion without symptoms of an infection*.
Group 2 – patients experiencing *superficial wound infection*.
Group 3/A – patients experiencing *acute deep wound infection and mediastinitis*.
Group 3/B – patient with *chronic deep wound infection and mediastinitis*.

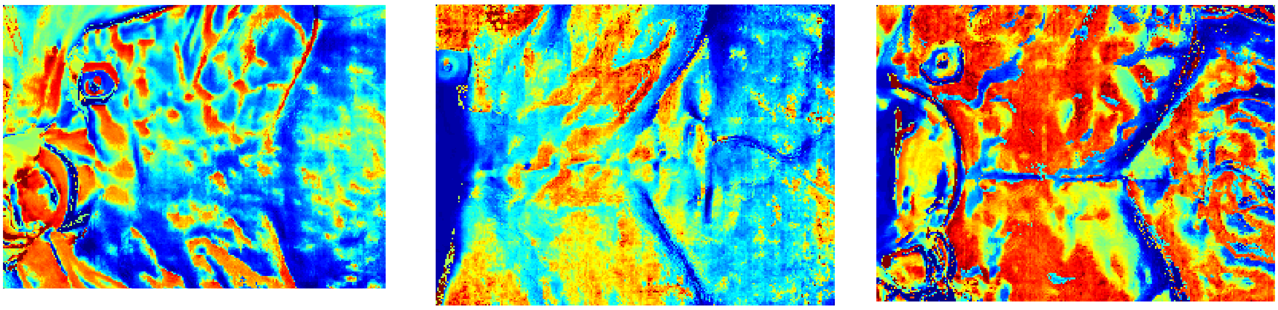
Each individual patient examination lasts about 15 minutes including dressing change, utilizing each infrared technique as well as the physical and pathology methods. The aim is to obtain a reliable statistical insight for the procedures and the method validation. The research also includes analysis of different conditions that may influence the process of wound healing. These risk factors are: age, gender, wound size, application of different healing-alternating methods (such as the therapy with oxygen), complications etc. Blood tests cover peripheral blood morphology and CRP concentration during 1st, 3rd, 5th and 7^{th} postoperative day in a case of proper healing and in a case of complicated wound healing until the wound is completely healed. In complicated healing cases, a bacteriological blood and wound exudation tests are conducted along with photographic documentation of the wound condition. An additional CT mediastinal examination is executed in diagnostically ambiguous cases.

As an example of measurements typical images of a chosen patient are presented in Fig. 2.

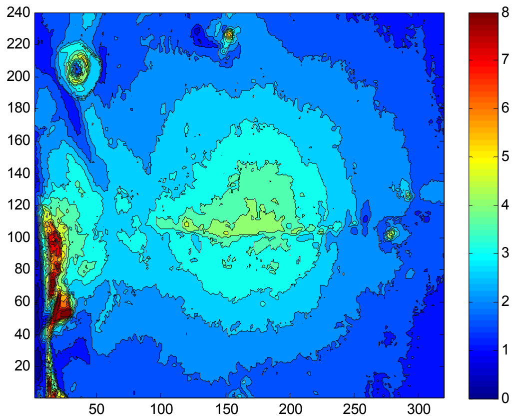
a/ Photo of a patient before, 3 days after and 5 days after operation



b/ Corresponding thermal images – temperature gradients



c/ Corresponding ADT parametric images of time constants



d/

Fig.2. Typical set of: a/ raw video; b/ thermal data of a patient in consecutive days of monitoring; c/ ADT parametric images; d/ the patient at the last day – recorded temperature differences after cooling

4. Signal processing and results

While performing ADT experiments optimized conditions of data analysis for high quality of thermographic sequence should be assured. This means that patient movements should be minimized and the tested ROI should be centered in the image with good focus.

Diagnostic information is extracted from thermal static images as well as from series of thermal transients after external excitation by further image data processing and comparison of consecutive examinations. To obtain thermal parametric images further processing of raw thermal data is needed, too. There are basic problems in terms of reliable understanding of the diagnostic content of such images. First, image corrections are necessary to allow comparison of images taken at different days, second – further displacement corrections are necessary for analysis of series of images recorded during ADT experiments. One has to correct unintentional movements of a patient caused by physiological actions of breathing, heart beating etc. Image and sequence preprocessing consists of image matching for ROI translations elimination, detection of the excitation range and time transient segmentation for determining the exact parameters of the temperature curve. One of applied methods of image matching is the FFT spectra based Direct Phase Substitution (DPS) algorithm which is very well suited for thermal images that consist of smooth temperature gradients [6]. For images with distinctive features like edges and corners more time consuming algorithms have to be applied. The typical processing diagram of thermal sequences is presented in Figure 3.

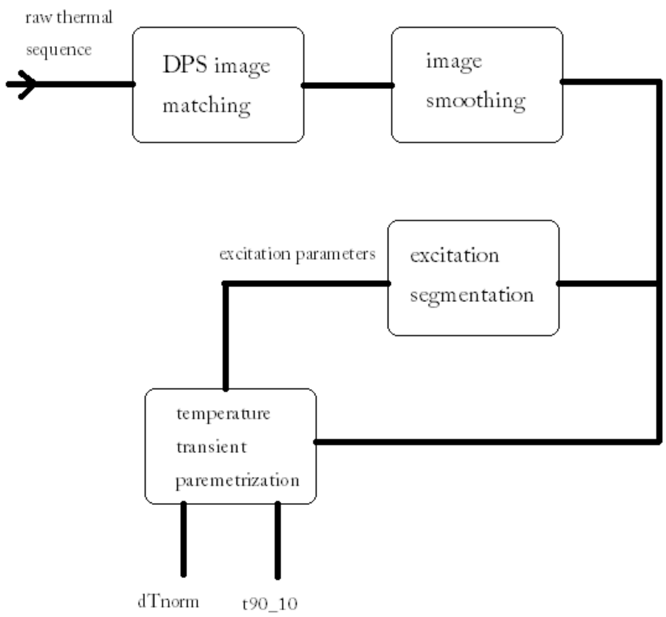


Fig. 3. Thermal sequence processing diagram using DPS algorithm; at the input there is raw thermal sequence allowing after corrections calculation of output parametric images

A typical trace of temperature in ADT experiment is shown in Fig. 4. At the first, cooling phase, ROI temperature is decreasing from T_0 till the end of excitation, followed by the phase of natural temperature return to equilibrium. In clinical practice those two phases are typically: cooling - 60s and natural return phase up to 180s, what is below of the equilibrium state temperature but allows for a significant acceleration of the measurement procedure.

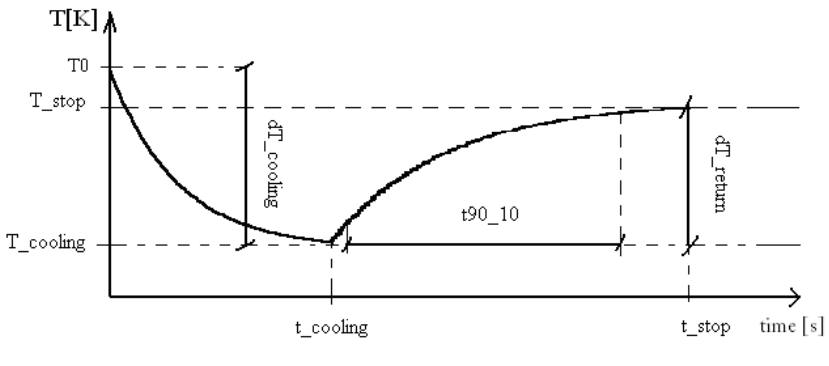


Fig. 4. Typical procedure applied in ADT experiment

The transient processes shown in Fig. 4 may be described by the following analytical models (1 – 4). One may define the descriptors dT_{norm}, and t_{90_10} (formula 1 and 2) as:

$$dT_{norm} = \frac{dT\_return}{dT\_cooling} \ , \qquad (1)$$

$$t_{90\_10} = t_{90}(T = 0{,}9 \cdot dT\_return) - t_{10}(T = 0{,}1 \cdot dT\_return) \, , \qquad (2)$$

where:
T_0 – the initial value of the temperature of the object,
$T_{\_stop}$ - the temperature value at the time of the experiment of termination,
$T_{\_cooling}$ - temperature value while the thermal excitation is switched off,
$t_{\_cooling}$ - the duration of the thermal excitation,
$t_{\_stop}$ - time moment of the end of the experiment,
$dT_{\_cooling}$ - total change of temperature value of the object while cooling,
$dT_{\_return}$ - total rise of temperature value after switching off the excitation,
t_{90_10} - a difference of time, after which the object temperature reaches 90% and 10% of the final value of dT_return.

The dT_{norm} is the magnitude parameter describing relative temperature rise in the phase of natural temperature return, on the other hand t_{90_10} is the temporal parameter that illustrates the speed of regaining the steady state temperature value by the examined object.

Tested tissue can be quantitatively assessed in a bit more advanced way using the exponential function defined in equations (3), (4) for each (x,y) pixel with thermal time constants as basic descriptors:

$$T(x,y,t) = T_s(x,y) + \sum_{j=1}^{m} \Delta T_j(x,y) \cdot e^{-\frac{t}{\tau_j(x,y)}} \qquad (3)$$

for the natural cooling phase following external heating;

$$T(x,y,t) = T_s(x,y) + \sum_{j=1}^{m} \Delta T_j(x,y) \cdot \left(- e^{-\frac{t}{\tau_j(x,y)}} \right) \qquad (4)$$

for the re-warming phase that is following external cooling. In following analysis we are using the two exponential expression, which is fully sufficient in terms of model accuracy. For this case the following descriptors are defined:

$$T(x,y) = T_s(x,y) + \Delta T_1(x,y) \cdot e^{\frac{-t}{\tau_1(x,y)}} + \Delta T_2(x,y) \cdot e^{\frac{-t}{\tau_2(x,y)}} \, , \qquad (5)$$

where: T_{mean} - mean temperature value for parameter T_s for the whole ROI; τ_{1mean} - mean value of the time constant calculated for the whole ROI.

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.

Still the choice what would be the optimal set of parametric images is discussed. To minimize execution time of applied algorithms first recorded rough images are cut to include only the ROI area. The problem is illustrated by presentation of exemplary results shown in following illustrations, Fig.5, for a chosen patient before surgery and in following days of examinations. At the left side the photographs of a tested ROI and several corresponding parametric images of chosen descriptors are shown; at the right sight is the explanation. Data are shown for the consecutive days of examination: 1– before operation – day 1; 2 - one day after operation – day 3; and 3 - 3 days later – day 6. Presented are the RGB photo and corresponding at the ROI parametric images of following thermal descriptors:

a/ RGB photo of ROI;

b/ $dT_{\_norm}$ defined by (1);

c/ t_{90_10}, defined by (2);

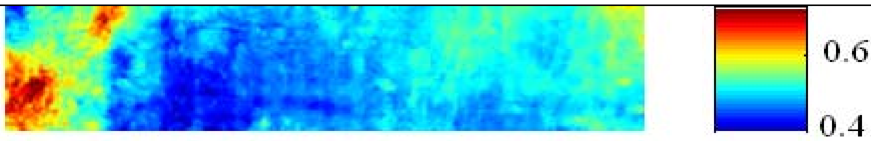
d/ $T_s - T_{mean}$ from (5);

e/ the time constant τ_1(x,y) from (5);

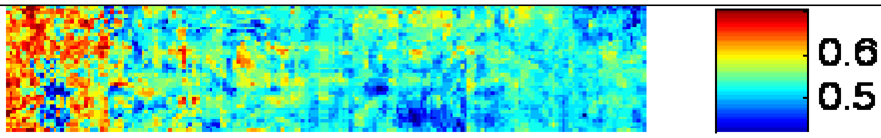
f/ τ_1(x,y) - τ_{1mean} from (5).

a1/ 

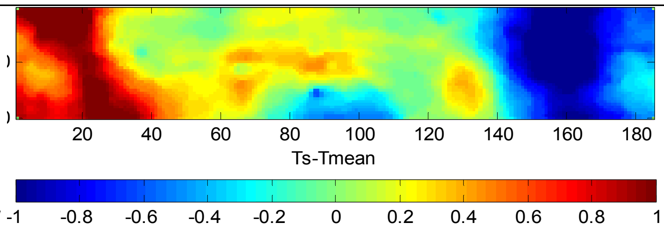
RGB photo of ROI photograph before surgery, day -1

b1/ 

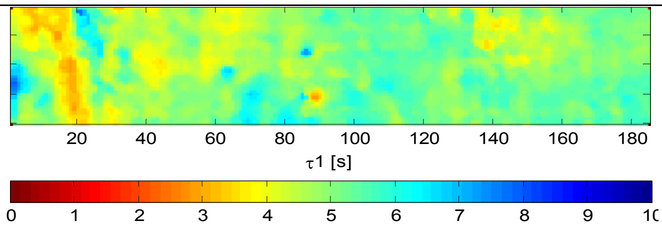
Corresponding parametric image of **dT_norm** mean value - 0.521 std: 0.047

c1/ 

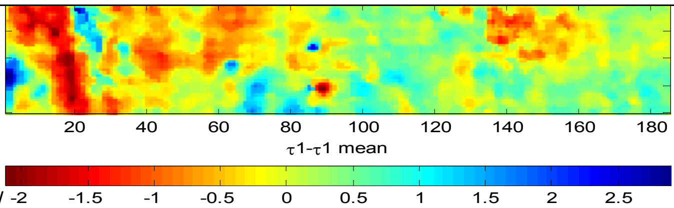
Corresponding parametric image of **t_{90-10}** mean value: 0.53 std: 0.06

d1/ 

Corresponding parametric image of the difference $T_s - T_{mean}$ T_{mean}=29,747 Std=0,1907

e1/ 

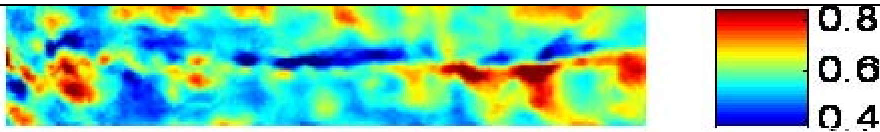
Corresponding parametric image of the time constant $\tau_1(x,y)$ τ_{1mean}= 4.949 Std=0.544

f1/ 

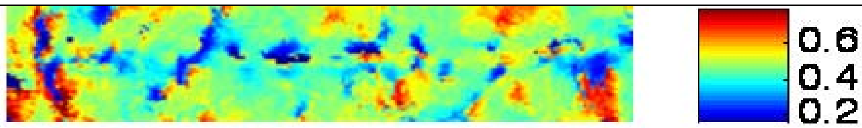
Corresponding parametric image of the difference $\tau_1(x,y)$ - τ_{1mean}

a2/ 

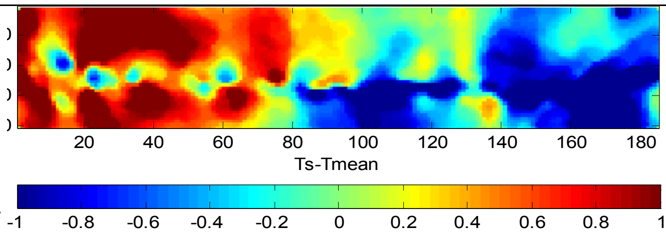
RGB photo of ROI photograph at the day after surgery, day - 3

b2/ 

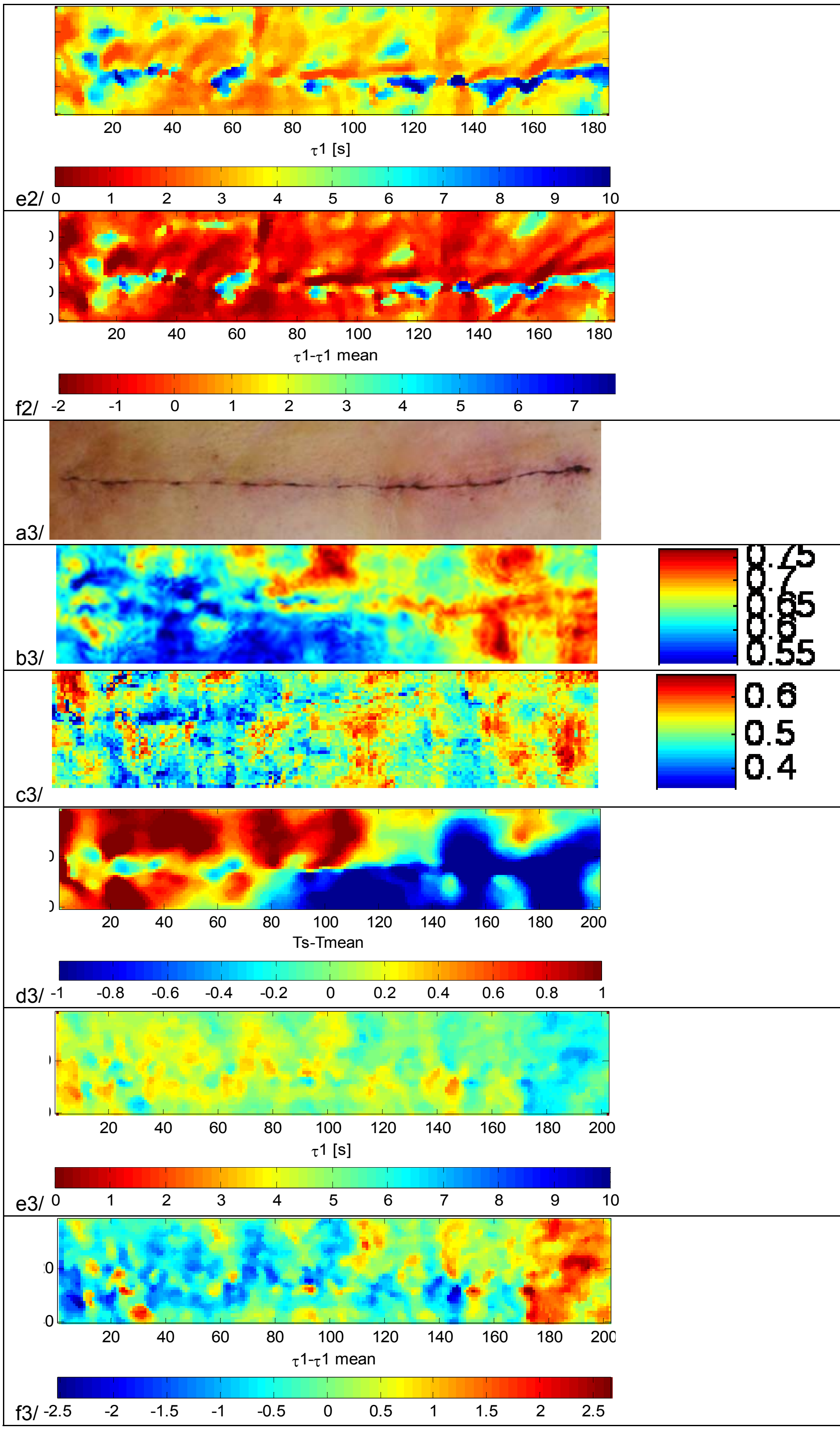
Corresponding parametric image of **dT_norm** mean value - 0.59 std: 0.09

c2/ 

Corresponding **t_{90_10}** mean value: 0.48 std: 0.1

d2/ 

Corresponding parametric image of the difference $T_s - T_{mean}$ T_{mean}=32.825 Std=0.409



e2/	Corresponding parametric image of the time constant $\tau_1(x,y)$ $\tau_{1mean}= 4.033$ Std=1.445
f2/	Corresponding parametric image of the difference $\tau_1(x,y) - \tau_{1mean}$
a3/	RGB photo of ROI photograph after next 3 days after surgery, day - 6
b3/	Corresponding **dT_norm** mean value - 0.63 std: 0.054
c3/	Corresponding **t_{90_10}** mean value: 0.51 std: 0.07
d3/	Corresponding parametric image of the difference $T_s – T_{mean}$ T_{mean}=31.703 Std=0.522
e3/	Corresponding parametric image of the time constant $\tau_1(x,y)$ $\tau_{1mean}= 4.863$ Std=0.647
f3/	Corresponding parametric image of the difference $\tau_1(x,y) - \tau_{1mean}$

Fig. 5. The ROI of a chosen patient - the RGB photograph and corresponding parametric images of thermal descriptors in consecutive days before and after operation

For further analysis of healing processes comparison of specific descriptors may be performed. Fig. 6 shows the differential images of chosen descriptors based on the following formulae

$$\Delta T_s = T_s(6day) - T_s(3day)$$
$$\Delta \tau_1 = \tau_1(6day) - \tau_1(3day) \qquad (6)$$

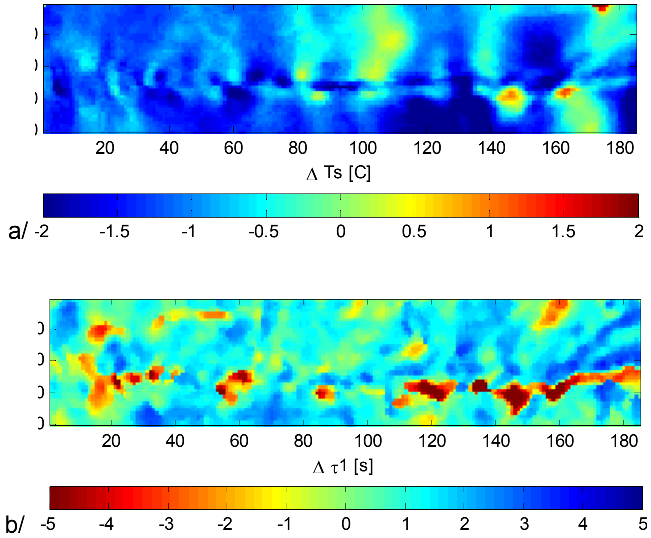


Fig. 6. Differential images of parametric data taken at the days 6 and 3, showing dynamics of healing processes; a/ differential static temperature and b/ differential time constants

Differential images allow analysis of dynamic temporal healing processes of a postoperative scar. One may observe what are the diferences in comparison to the reference data taken before operation. Evident is the conclusion that the smaller is this difference the better are the healing results. Any visible divergence in comparison with typical dynamics of healing may worn special attention of medical staff.

From Fig. 5 in consecutive days one may conclude that after operation the mean temperature in ROI ΔT_s is slightly higher comparing to the reference data while the thermal time constant is shorter in the scar. The differences are decreased with time. Such data allow for development of a model of a scar with parameters characteristic for normal healing as well as for different complications and wound infection.

5. Discussion

The research programme is not completed yet therefore statistical analysis will be presented in following publications. At the moment of sending this text the first part of the research is under completion. Generally the assumptions that IR-thermal imaging may be an effective and quantitative tool for evaluation of postoperative wound healing are fully proved. Still there are several technical problems that will be solved while realization of this project:
- Multimodal image matching and diagnostic information presentation.
- Determination of optimal conditions of thermal excitation to extract maximal diagnostic information.
- Determination the influence of blood perfusion, mechanical stress, functional and morphological changes of the examined tissue on the resulting ADT imaging.
- Elaboration of the 3D, thermal computer model of the examined structure for thermal processes simulation purposes as well as for improvement of diagnostic decisions.
- Completion of the image and sequence database for storing acquired data.
- Focusing on '*doctor's friendly'* design of the system procedures and interfaces.

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