ACTIVE DYNAMIC THERMOGRAPHY AS A DIAGNOSTIC TOOL IN BURNS TREATMENT

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Abstract: Measurements of temperature distribution synchronised with external light excitation allow registration of dynamic changes of local temperature dependent on heat exchange conditions. Preliminary results of active thermography applications in medicine are discussed. For skin and under-skin tissues an equivalent thermal model may be determined. Results of some medical cases as well as reference data of in vivo study on animals are presented. We see the proposed new in medical applications technique as a promising diagnostic tool. It is a fully non-invasive, clean, handy, fast and affordable method giving not only qualitative view of investigated surfaces but also an objective quantitative measurement result, accurate enough for many applications including fast screening of affected tissues.

Introduction

Infrared thermography is a fully non-invasive diagnostic and inspection method. It is know in medical diagnostics for more then 40 years. It is non-contact, therefore aseptic and safe, gives no interaction with tissues, it is fast and easy in use, storage of data is simple as well as presentation of surface temperature is very attractive. Recently one may observe a great progress of this technology, what makes it extremely attractive again. Systems with the temperature resolution up to 0.01^0C, and with high time & spatial resolution (respectively more than 1000 frames/second and 1 million pixels) are already available. Adding advances in computer technology, data processing and visualization one may claim this is a real technological revolution in IR thermal imaging.

Broad bibliography of classical thermography in medicine is available in Glamorgan University [1] and as conference proceedings [2, 3].

The goal of the presented research was to apply dedicated data processing and external thermal excitations to get objective, quantitative thermal data of tested tissues [3]. It allows validation of active dynamic thermography (ADT) in medical diagnostics and development of new diagnostic procedure. Our studies in that field are concentrated on applications to diagnostics of burns, skin transplants, cancer visualization and open heart surgery evaluation [4, 5, 7, 8].

One of the possible fields of active thermography applications is determination of the state of skin burns, for objective diagnostics of injury and state of the healing processes. This seems to be a serious medical problem as the only fully accepted objective method for evaluation of skin burns is basing on biopsies and histopathologic observation [9, 10]. However, this investigation is expensive, invasive and time consuming. The extensive experience of medical staff is not always sufficient for proper reaction and determination of the optimal treatment procedure. This concerns especially evaluation if the degree of a burn is of the II-d or the III-rd order, what has an important meaning from the point of view of the action to be applied. Therefore, the use of an objective, non-invasive method would be strongly appreciated, especially if the procedure could be easy and not expensive what might be the case of active thermography.

Materials and Methods

The methods most frequently used in active dynamic thermography are illustrated in Figures 1 and 2. In the ADT thermography a target object is thermally excited for a given time period. Different methods of excitation can be applied [6]. Here we use optical heating and air fan cooling.

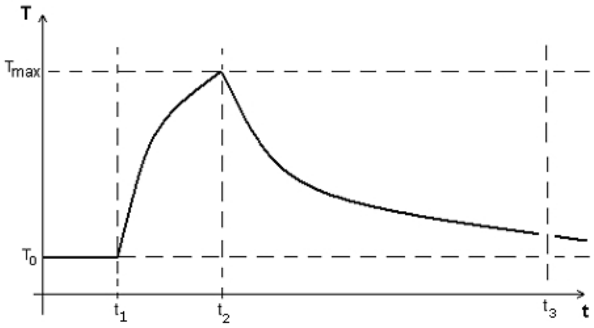

Figure 1: ADT procedure for heating excitation

Theoretically both phases: external heating $|t_2 - t_1|$ and recovery time $|t_3 - t_2|$ are suitable for thermal sequence recording and further analysing. In practical case for halogen heating the heating phase is no useful for further image processing due to high reflection from the surface of the tested tissue. Only recovery phase is

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used to reconstruction of the thermal model coefficients. There is no interaction between air fan cooling system and thermal camera so both phases are used for estimating thermal parameters of tested tissue in this procedure.

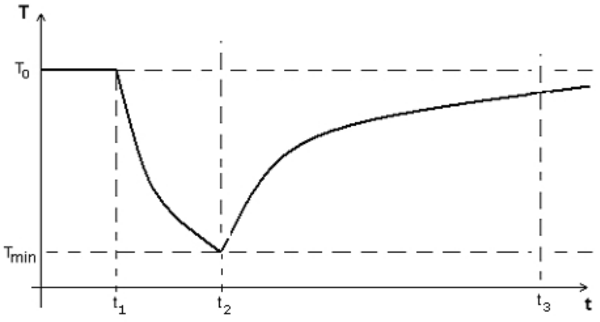

Figure 2: ADT procedure for cooling excitation

As a result of external excitation the recorded surface temperature varies in time according to thermal properties of an object. The basic information is given in dynamic parameters as thermal time constants, which are dependent on tissue properties.

The main assumption for biological (medical) applications of NDE-DT is the different temporal behavior of locally heated or cooled tissues comparing to other physiological mechanisms responsible for thermoregulation processes in the human body.

Thermal transients are described by exponential functions. For one directional heat flow the simplest description of surface temperature changes may be given for the point (x,y) for cooling phase (as shown in Figs.1 i 2) by:

$$T(t,x,y)=T_0(x,y)+\Delta T(x,y)\cdot\exp\left(-\frac{t}{\tau(x,y)}\right), \quad (1)$$

and for natural heating phase:

$$T(t,x,y)=T_0(x,y)-\Delta T(x,y)\cdot\exp\left(-\frac{t}{\tau(x,y)}\right), \quad (2)$$

where T(t,x,y) is the pixel (x,y) temperature T in time t; T_0 is the temperature before excitation; ΔT is the temperature rise or down due to excitation. So, corresponding to Figure 1 - the maximum temperature after heating: $T_{max} = T_0 + \Delta T$; and Figure 2 – the minimum temperature after air cooling: $T_{min} = T_0 - \Delta T$.

The value of the thermal time constant τ depends on different existing mechanisms of heat flow and is strongly correlated to the physical structure of the burns. Calculated time constant represents dynamic change of the measured temperature on a skin surface and depends on tissue properties - τ is mainly function of a thermal diffusivity:

$$\tau[s]=f\left(\frac{\rho\cdot c}{k};other\ \ factors\right) \quad (3)$$

where: ρ – material density, c – specific heat, k – thermal conductivity, other factors – eg. blood flow intensity.

Basing on thermographic transient temperature processes measurement and applying proper data fitting algorithm (Levenberg-Marquardt) we obtained 3 parametric pictures described by thermal model as equations 1 and 2 according to physical state of the skin.

For in vivo experiments on animals (performed according to all legal regulations and permission of the Local Ethics Commission for Experimentation on Animals at the Medical University of Gdansk, Poland) the pigs have been studied due to the closest to human physiological and anatomical structure of the skin. Burn experiments are based on the research of Singer at al (2000) [9] and his methodology on standardised burn model. Following his experiment 8 paired sets of burns were inflicted on the back skin of four young domestic anaesthetised pigs using aluminium bars preheated in water in the range from 60^oC to 90^oC. Each pair was representing different conditions of injury giving a set of controlled burn depths. Additionally each of measuring points was controlled by full-thickness skin biopsies and followed by histopathologic analysis of burn depth – Figure 3. The results of skin burn degree are in good accordance to the data given by Singer. This resulted in burn wounds of the following depths, expressed as the relative thickness of the skin, a percentage of the dermis thickness at the measurement site (dtms):

1; 5 – of 11.92 ± 2. 98% dtms;
2; 6 – of 21.58 ± 3.22% dtms;
3; 7 – of 47.8 ± 18.16% dtms;
4; 8 – of 67.3 ± 14.65% dtms.

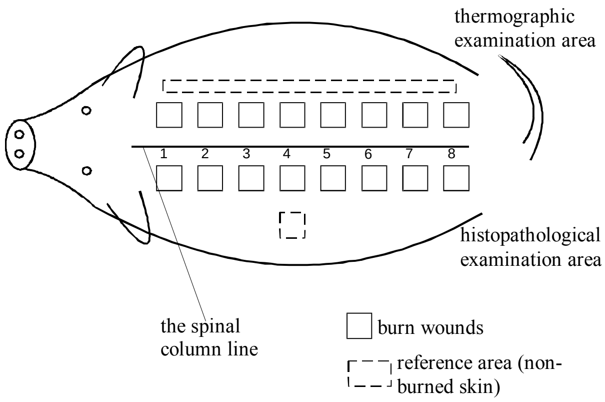

Figure 3: Positioning of the burned areas on the back of a pig. Symmetrical wounds for reference histopathological examination and for thermographic observation are indicated

The pigs were maintained under a surgical plane of anaesthesia in conditioned environment of 24 ^{0}C. The back skin was clipped before creation of burns. The total body surface area of the burns in each pig was approximately 4 %. The animals were observed and treated against pain or discomfort.

The examination was conducted over the 3 consecutive days following infliction of the burn wound. A thermographic IR-camera AGEMA THV-900 SW/TE of 0.1˚C resolution was used for recording thermal images. This was placed at a distance of 0.75 m from the pig's back in the plane perpendicular to it. The parameters applied for burn wound depth evaluation with a view to the choice of treatment, namely static thermography – ΔT_s and Active Dynamic Thermography - τ, were calculated for the 3 consecutive post-burn days. The observation area, depending on the camera field of view (FOV), was typically 20cm x 15cm.

The ADT experiment was performed with pulse optical excitation lasting 15 seconds and resulting in a surface temperature rise of ~2.5˚C, followed by a 30-second recording of the self-cooling phase. The excitation was performed using a set of halogen lamps of ~1000W and equipped with a mechanical shutter for prompt switching on and off of the power pulse. The second kind of investigation was performed using air fan cooling device designed for cryotherapy. An air cooling lasting 30 seconds and resulting in a surface temperature falls of about 6˚C followed by a 90 second recovery (self heating) phase.

One exponent approximation (model of the thermal equivalent structure – equations 1 and 2) was applied to determine the time constant τ. The full diagnosis takes several minutes using automatic calculation procedures. The same recording procedure was applied in the clinical cases to illustrate the application of the method in hospital practice.

Results

The final results of the research are based on comparison of the value of applied thermographic methods and illustrated also by practical cases in clinics.

The two sets of data was obtained on experiments in vivo on pigs: static thermograms and ADT parametric pictures. The results for static thermograph is shown on Figure 4.

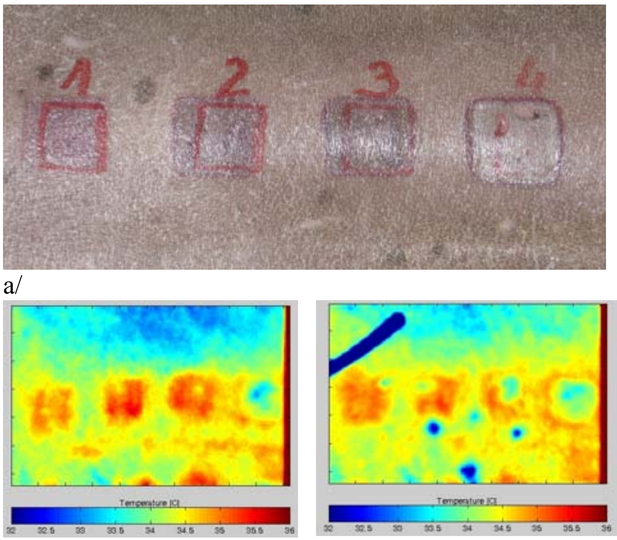

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Figure 4: Burn investigation: a/ photo of burns, and static thermogram of burns in b/ first day c/ second day after burn infliction

For static thermography ΔT_s is defined as the difference between the mean values of skin area temperature for the burn wound area and the unaffected reference skin area. For deeper burns the surface temperature is lower than for healthy skin when for surface burns is higher. It can be easy seen that destroying processes are still active even in second day – temperature of field 3 and 4 is lower then one day before.

In the current study mean ΔT_s values on the second day after burn infliction for superficial partial skin thickness burns II˚a, deep partial skin thickness burns II˚b and full skin thickness burns III˚ were ΔT_s=0.96±0.54˚C, ΔT_s=0.77±0.73˚C and ΔT_s=-0.44±0.70˚C, respectively. Thus deep dermal burn wounds had positive ΔT_s, similarly to the superficial partial skin thickness burns. According to the clinical method, differences between the relevant values for groups II˚a and II˚b were not statistically significant. In this study, therefore, ΔT_s, when correlated with the wound depth classification according to the clinical method (ΔT_s + clinical method), did not constitute an objective criterion for differentiating between the two groups of burns. This sharply contradicts the clinical reports of other authors, where distinct ranges are quoted for the temperature difference values for particular burn wound depths, including the II˚a superficial dermal burn group and the II˚b group of deep dermal burns. In 1974, Hackett [10] proposed some ranges for burn wounds of the following depths: II˚a – (>-1.5˚C); II˚b – (-1.5˚C – -2.5˚C), III˚ - (<-2.5˚C). The fact that all these values were negative was probably a result of cooling of the wounds as a result of evaporation water loss. According to Cole et al. [4], II˚a burns had ΔT_s of 1.19 ±0.97˚C, II˚b burns ΔT_s of –1.40 ±1.17˚C, while the respective value for III˚ wounds was ΔT_s=-2.21 ±1.16˚C.

In the search for the optimal choice of treatment, an attempt was made to find the most useful correlation between ΔT_s and the burn wounds under study, which led to the conclusion that it should be a correlation with a classification which groups burns into those that did heal spontaneously within 3 weeks following the wound infliction (the referential average ΔT_s from all the healed cases) and into those that did not heal spontaneously in this period (the referential average ΔT_s from all the unhealed cases). The differences in the average temperature ΔT_s for the healed burns and for the unhealed ones are statistically highly significant ($p<0.001$). The value ΔT_s=0.3˚C, which marks off healed from unhealed burns, was assumed to be of sufficient classificatory power to group all the burns investigated and thus of the highest importance for choosing the method of treatment. However, the value ΔT_s=0.3˚C has been obtained by animal experiment and should not be regarded as a specific threshold for human treatment procedures.

Active Dynamic Thermography procedure after applying proper fitting algorithm produce set of tree parametric pictures. The high importance has the "tau" picture as it was explained in Materials and Methods section. The set of ADT parametric images gives rather structural information of the tested tissue. Properties of tissue are dependent on blood flow and physical processes of burn. Figures 5-8 shows sets of parametric pictures for different method of excitations: halogen heating and air fan cooling respectively.

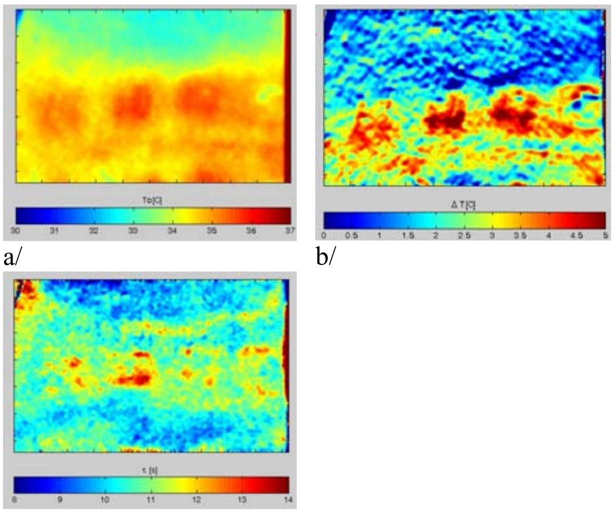

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Figure 5: ADT parametric pictures for halogen heating method, first day investigation: a/ T_0 [^{0}C], b/ ΔT [^{0}C], c/ τ[s]

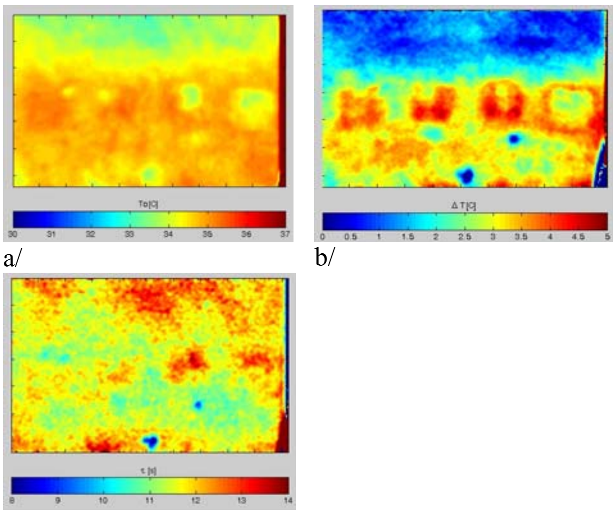

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Figure 6: ADT parametric pictures for halogen heating method, second day investigation: a/ T_0 [^{0}C], b/ ΔT [^{0}C], c/ τ[s]

For ADT the mean value of the thermal time constant for burns shallower than 60% of the dtms (those healing within 3 weeks) was τ=12.08±1.94s, and for deeper ones ("non-healing") it was τ=9.07±0.68s. The difference was at the statistically significant level, ($p<0.05$). We found that parameter τ had a higher value (was longer) for wounds which self-healed within 3 weeks than for the unaffected skin, while τ had a lower value (was shorter) for deeper burns that failed to heal within this period. The discrimination threshold was calculated as τ=10.125s (Fig.11). Using this value for burn discrimination, the accuracy, sensitivity, and specificity were all 100%.

In our experiment with the air fan cooling method only recovery phase (natural heating) carry diagnostic information – Figure 7. In the excitation phase the cooling source was so strong that there is no useful information in parametric pictures. Whole investigated surface cooling down in this same way – Figure 8.

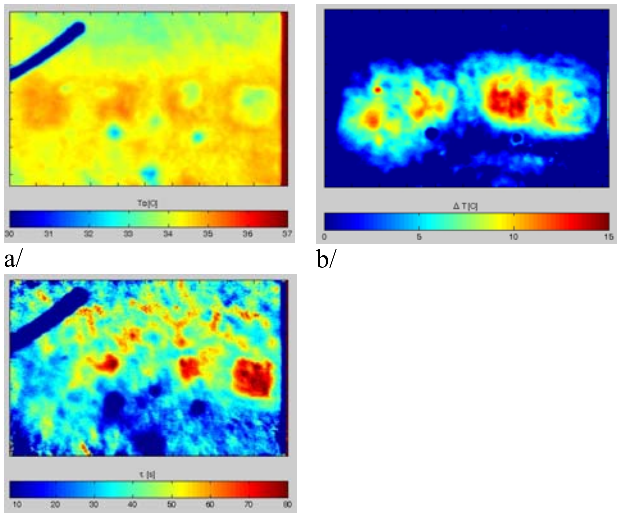

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Figure 7: ADT parametric pictures for air fan cooling method, second day investigation, recovery phase: a/ T_0 [^{0}C], b/ ΔT [^{0}C], c/ τ[s]

For air fan cooling method time constant τ of temperature profile for recovery phase is longer then for halogen method. For deep burns the τ is about 75-80 second when for superficial dermal burn is about 45 second. This difference is mainly due to difference in blood flow in both kinds of burn.

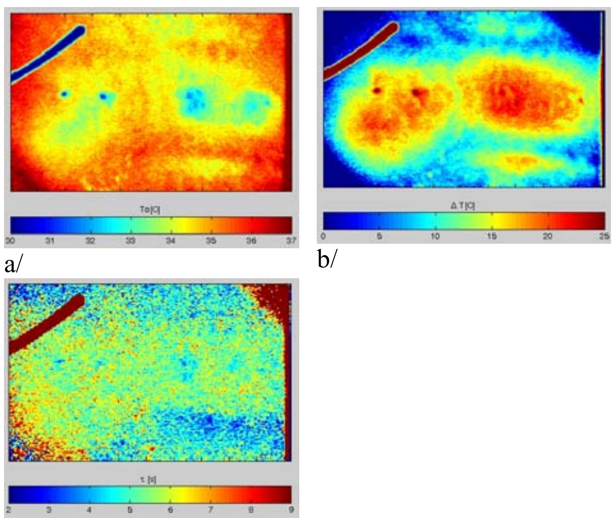

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Figure 8: ADT parametric pictures for air fan cooling method, first day investigation, cooling phase, sequence this same as on previous figures

The ADT method has already been adopted for clinical use. As an example, a burn wound on the right thigh of one patient is shown in Figure 9 and burns on both thighs and buttocks of another patient are shown in Figure 10.

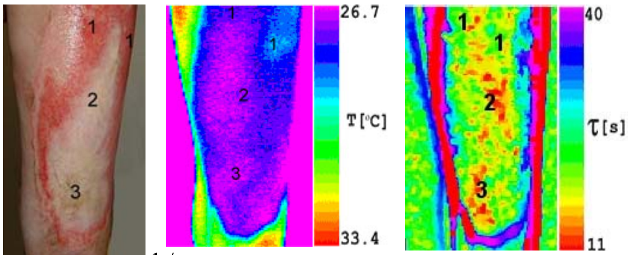

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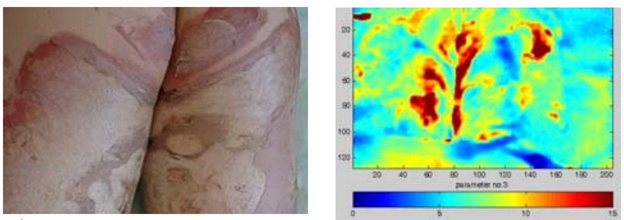
Figure 9: Photographic and corresponding thermographic images of a burn wound to the posterior surface of the right thigh of a 49-year-old patient:
a/ Clinical burn depth evaluation of the area marked:
1 - II˚a - superficial dermal,
2 - II˚a - superficial dermal and, more centrally, II˚b - deep dermal
3 - II˚b - deep dermal and, in the lower part, III˚ - full thickness
b/ Static thermography (the extremity is slightly medially rotated in comparison to the photograph). Areas 2 and 3 are the coldest and are without marked internal differentiation.
c/ Active Dynamic Thermography parametric image (rotation of the extremity as above). The areas with short thermal time constants τ and which qualified for surgery are well defined. These areas are markedly smaller when compared with areas 2 and 3 in the photograph and in the static thermogram.

The measurement was taken on third day following an accident – Figure 10. As an excitation source set of halogen lamps of 1000W was used, excitation time – 15s and observation time of natural cooling phase was 30 seconds. Recorded data was fitted to one-layer model and parametric images calculated.



a/ b/

Figure 10: a/ Photo of burn, b/ parametric image due to mathematical model, visualisation of time constant - τ

We found that parameter τ was longer (yellow and red colour on fig. 10b) for wounds self-healing within 3 weeks than for the unaffected skin, while τ was shorter (blue colour on figures xx**c**) for deeper burns that failed to heal within this period.

Examination of the clinical cases reveals that ADT discrimination of the area needed for surgery would be possible in both cases, although more experience is necessary to define the values of the thermal time constants for humans in order to evaluate human skin burns objectively and quantitatively and to make an automatic classification of the region for surgery. The patients were, therefore, treated on the basis of clinical prognoses. In both cases, however, (especially that presented in Fig.10) prognoses based on the ADT criterion valid for animals indicate that the decision concerning treatment should be modified and surgery markedly limited.

Discussion

The analysis performed shows that information gained from active dynamic thermography measurements allows direct inspection of the state of the tissue. It provides contrast enhancement between healthy and pathological tissues. In our studies the discrimination threshold was calculated as τ=10.125s (Fig.11) for halogen heating method. Using this value for burn discrimination, the accuracy, sensitivity, and specificity were all 100%.

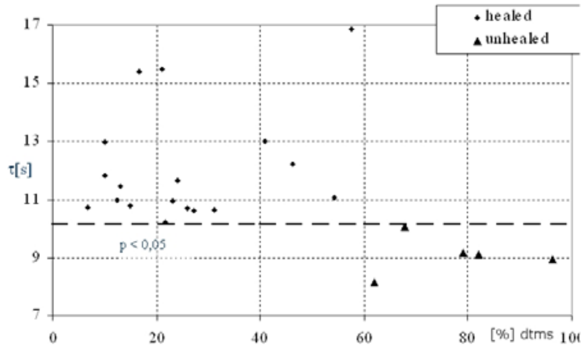


Figure 11: Results of in vivo experiments for τ parameter; dashed line mark the threshold between healed and unhealed bourns

Necrosis or intensive healing processes may be easy differentiated. For burn depth estimation most important from therapeutic point of view are measurements done up to tree days following an accident. Active thermography seems to be a powerful, non-invasive and easy to use for medical staff diagnostic modality.

The main limitations of all thermographic methods is that only surfaces accessible for observation may be inspected and that during investigation an object should stay immovable.

Conclusions

Correlation of the figure of merit ΔT_s with the classification according to the clinical method does not allow for a satisfactory choice of burn wound treatment.

The results obtained in this work for the ADT method by evaluating the thermal time constants lead us to conclude that this may be declared a new effective method for burn wound discrimination and, therefore, for early burn treatment planning. The results of the ADT and histopathological evaluations are fully in agreement. This should not be regarded as the general rule, as the evaluation of the method was made ex post and in reality the classification threshold could be slightly shifted up or down, decreasing the score. The specific threshold of the τ value as a predictor of burn healing could also be established for human burn wounds.

Generally, ADT examination is simple, non-contact and short. The instrumentation to be applied is based on the IR-cameras already used in hospitals and now available at reduced prices. The procedure is not as sensitive to external conditions as static thermography. The result is quantitative, enabling burns to be objectively evaluated and treatment clearly documented. One image may be used to visualize wounds covering an extensive area. As has already been illustrated by Figures 9 and 10, it is a method that could easily be applied in clinical practice.

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