PERIODICA POLYTECHNICA SER. MECH. ENG VOL. 37, NO. 3, PP. 197-213 (1993)

THERMOTECHNICAL APPROACHES TO THE INVESTIGATION OF LOCAL INJURIES CAUSED BY IONIZING RADIATION

Imre BENKŐ and György J. KÖTELES*

Department for Energy,
Technical University of Budapest
H-1521 Budapest, Hungary

*F. Joliot Curie' National Research Institute for
Radiation Biology and Radiation Hygiene
H-1775 Budapest, Hungary

Received: Oct. 22, 1993

Abstract

Skin temperature has been used as an indicator of the physiological and pathological condition of the human body for centuries. The infrared (IR) thermogrammetry (TGM)/thermography gives new vistas for the transient skin surface temperature measurements, too. IR-TGM can also be advantageously applied in radiation biology for comparative and quantitative diagnostic investigations. In Hungary, the technique was first applied in 1984, when the authors published a case study on a local radiation injury [4] and suggested that both contact and infrared thermography were useful tools in detection of the areas of radiation injury. While in 1984 a serious injury of a hand (20–30 Gy, locally) was described, later [10,15] an injury caused by a much lower dose (1–2 Gy, locally) was reported when IR-TGM could still assist the diagnosis. The measurement results obtained enabled the authors to compare the radiation burden and the temperature distribution detected at the involved skin surface.

Keywords: ionizing radiation, infrared thermogrammetry, human biology, nuclear injury.

1. Generalities

The thermal fields experienced in medical areas are more complicated than those in physical ones (*Table 1*). All of the visual methods may contribute to make a more precise diagnosis and to follow of the pathological process (*Table 2*).

The living organisms include many physical processes (mechanical, thermal, electrical, chemical, etc.). Therefore we can approach the living systems from different points of view, by various methods of different physical sciences (*Table 1*). But we always have to remember the connections of the living body with the environment.

The actual temperature and its changes can be exactly measured by the various techniques of IR-TGM irrespective of the complexity of biolog-

Table 1
Physical approaches of analysis of biological phenomena

Biophysical methods:	
- active (by using external effects)	
- passive (to detect internal conditions and processes)	
Active	**Passive**
- ionizing radiation	- thermal radiation
- ultrasound	- flow mechanics: Doppler
- microwaves	
- laser	
electrical	
- treatments,	- measurements,
- e.g. iontophoresis	e.g. measurements of biocurrents (EKG, EEG)

Table 2
Collection of thermal diagnoses (passive methods)

Based on
- the detection of thermal circumstances of the organism and
- the application of the theory of temperature field, thermodynamics heat transfer, etc.

1. **General**: thermal characterization of the human body
2. **Special**:
   - contact thermography
   - infrared thermography/thermogrammetry
   - optical thermography (Schlieren, optical/laser interferometry, etc.)

ical phenomena including regulation, which results in the appearance and distribution of temperature of a living organism (*Table 3*).

Therefore, the data provided by IR–TGM (*Table 4*) should be related to other physical, environmental, chemical, electrical and biological parameters characterising the actual state of the living body. If we neglect the registration of some important parameters of the living systems, the thermal diagnosis, cannot be valid enough.

However, quantitative measurements of the skin temperature must be made and interpreted with care, as skin temperature is affected by changes in the body's thermoregulatory state or/and environmental conditions. It is therefore difficult to derive precise physiological information from a particular skin temperature. However, preliminary observations in the laboratory have shown that if there is an inflammation beneath the skin surface,

Table 3
Applicability of thermogrammetry

1. Mapping of the local variation and surface distribution of the temperature
2. Thermal process analysis (temperature changes versus time)
3. Thermal diagnosis of thermal states (hyper- and hypothermia):
   - evaluation by pictures (PAT – picture aided thermogrammetry),
   - evaluation by data (DAT – data aided thermogrammetry, data obtained by computerized analysis)
4. Assistance to thermal typology, thermoergonomy, thermopsychology, thermobiology, etc.
5. The method of IR–TGM improves the accuracy and probability of the thermal diagnosis.
6. Perspectives: data obtained by IR–TGM (DAT).

Table 4
Step-by-step guide to quantitative analysis of IR-images

1. Determine the temperature range to be examined, so that the highest applicable resolution could be achieved (ZOOM): range and level.
2. Measure the temperature in some characteristic points with the cross-hairs (SPOT).
3. Compare the temperature distribution along different horizontal and vertical lines by using profile-thermograms (symmetries).
4. Determine the temperature distribution and its histographical parameters in a chosen area of the image. These parameters are: highest/lowest temp.(MAX/MIN); the average temp. (AVG); median (MED); standard deviation (Sdev); skewness (Skew); number of pixels (Ncal); maximum value on the ordinate (Fmax).

the rate of skin temperature changes is less dependent on thermoregulatory or/and environmental factors and potentially can give a more reliable estimate of physiological parameters.

2. Introduction

There are only a few publications in the literature on the application of IR–TGM for the diagnosis of radiation injuries [1,2,3]. Two types of the thermographic techniques can be considered for this purpose, i.e. the contact thermography, discs carrying fluid crystal layer [1] and the IR–TGM [8]. The first technique is relatively simple and is easier to apply in the routine medical practice, but its applicability has limitations like the need of tight touching by the involved body surface as well as the thermal resistance between the thermographic disc and the skin. They might influence the values of measurements. The IR–TGM does not have such limitations or even the measurement without touching the surface has advantages. The

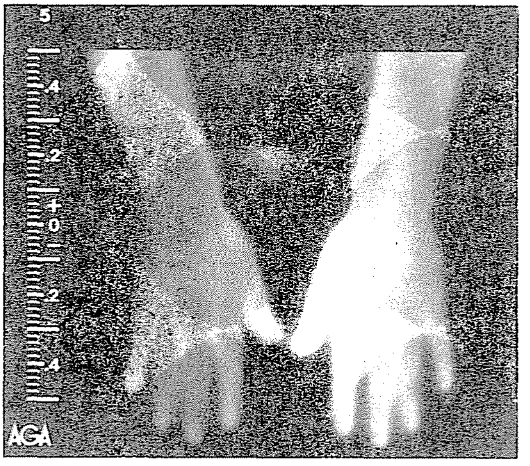

Fig. 1. Comparative IR-density images on the dorsal surfaces of the hands at the first investigation, 28 days after the serious accident

accuracy of the measurement through IR–TGM is higher than that of the contact thermography. The IR–TGM, however, is considerably expensive and the application requires higher level of expertise.

3. Biological Effects of the Ionizing Radiation

The proper diagnosis of the extent of radiation injuries is a condition of the proper medical handling. The alterations of the tissues, the appearance of clinical signs depend on the absorbed dose as well as on the time between the injury and measurement. The follow-up of the alterations is important below certain dose-levels, or before the appearance of the clinical symptoms or in the latent period. In cases of partial body irradiation of the human organisms like that of the extremities, the widely used biological indicators of radiation injuries can be hardly applied, or only on a limited basis. In such cases other diagnostic procedures have to be applied like the varieties of TGM which demonstrate the local tissue reactions through the distribution of temperature field.

4. Biological Indicators of the Radiation Effect

In the case of an injury of an extremity the amount of blood circulating through the region during irradiation is too small to contain enough lymphocytes to use them as carriers of chromosome aberrations. At the same time the local tissue reactions might the used to assess the extent and measure of injury. Out of the cells of irradiated skin and subdermal tissues the endothelial cells covering the inner, surfaces of small vessels and representing the walls of capillaries are the most radiosensitive ones. The radiation causes first the dilatation of vessels, then due to the damages of capillaries and vessels the atrophy and necrosis of the tissues. The conditions of the vessels and the consequent tissue alterations can be followed by radioisotopic scintigraphy or through image formation by thermography [3]. The latter technique has two varieties, the contact thermography and the IR–TGM. Relevant publications have been made from the Curie Institute in Paris which is the International Radiopathology Centre of the World Health Organization [3] and from the Medical Department of the former State Office for Atomic Safety and Radiation Protection in Berlin [1].

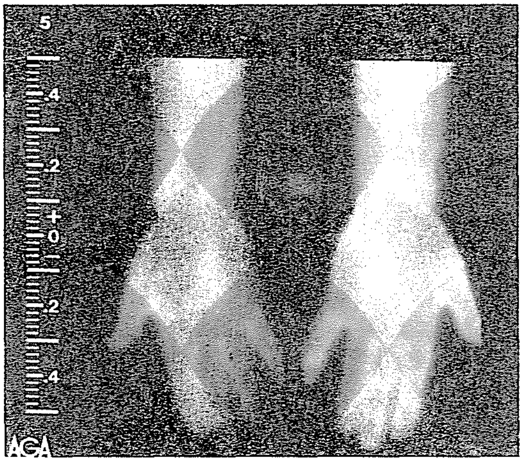

Fig. 2. Comparative IR-density images on the palmar surfaces of the hands at the first investigation, 28 days after the serious accident

5. Methods of Examination

The investigations on the hands of the radiation injured person were performed by AGA THV 780 type infrared imaging equipment on both the palmar (p) and dorsal (d) surfaces. The measurement results were stored from the different investigations, e. g. 5 days, 2 months and one and half a year after the accident by an infrared video recording which was evaluated by computerized technique [8,10 and *Table 4*].

In the first case a serious injury of hand was investigated when the local dose was appr. 20–30 Gy. The temperature differences between the injured and the not involved areas were min. 1.5 K. This difference could be well distinguished visually on the thermograms (*Figs. 1* and *2*).

In the second case the local dose assessed was only 1–2 Gy which caused an average temperature difference not more than $dt = 0.5$ K (*Table 9*). Therefore, for the evaluation of thermograms the histographic method was applied (*Fig. 5*), i.e. the parameters of the characteristic temperature distributions on the relevant areas of the hands were taken and the conclusions were drawn from the comparison of these parameters.

6. Applications of TGM in Accidental Radiation Injuries of Hands

6.1. Serious Injury of a Hand

In Hungary the technique was first applied in May of 1984 for the first time. An accident happened using 192–Iridium source for defectoscopy, the mechanism moving the radiation source has got a failure. The skilled worker dealing with the radiation source wanted to repair the spring of the equipment, therefore, he dismounted the holder of the radiation source – sharply violating radiation protection rules – and held the source in his left hand for 1–2 minutes while trying to repair the spring. The radiation source was of 1.11 TBq (30 Ci). The assessed dose to his involved fingers were between 20 and 30 Gy. This injury might lead to serious skin and tissue necrosis according to international experience, which might be treated either with skin transplantation or amputation of the involved parts.

For the sake of proper medical handling it is very important to know how far the irradiated area extends over those areas which do not show clinical signs. On the fingers of the injured person alterations characteristic of radiation injuries: erythema, oedema, development of serious blisters have appeared. Due to further human error the injured person reported only on the 22nd day to specialist. The clinical picture at that time, after the vanishing of the first phase showed only pathological alterations of the tips of two fingers. The condition of the hand was investigated by Flexitherm^R contact thermography.

It was quite obvious that the parts not showing clinical alterations were of higher temperature than the areas not involved either on the same hand or on the counterlateral one. Following the alterations it became also evident that a significant temperature distribution could be detected even after the clinical signs disappeared [5]. The list and time of clinical signs are given in *Table 5*.

Table 5
Comparison of the timing of appearances of clinical signs and time of observations with contact thermography and IR–TGM

Symptoms and investigations	Week after irradiation 1	2	3	4	5	6	7	8	9
Stiffening	+	−							
Erythema	+	+	+	+	−				
Oedema	+	+	+	+	−				
Pain	+	+	+	−					
Blisters	−	+	+	+	−				
Insensibility	−	−	+						
Desquamation							+	−	
Formation of scabs							+	+	−
Atrophic skin									+
Clinically without complaint							→		
Clinically without symptoms									→
Flexitherm (contact thermography)			positive →	→	→	→	→	→	→
AGA 780 (IR–TGM)						positive →	→	→	→

Table 6
Measurement data on the injured (left) and uninjured hands (20–30 Gy locally, 28 days after the accident)

No. of Fig [4]	Gamma irradiated area t_l, °C	Counterlateral respective area as control t_r, °C	Temperature difference $dt = t_l - t_r$, K
Palmar surface of the hands			dt_p
7.	33.70	32.15	1.55
8.	34.65	33.10	1.55
9.	34.30	32.10	2.10
10.	34.50	32.40	2.10
Dorsal surface of the hands			dt_d
11.	34.50	31.50	3.00
12.	34.00	31.40	2.60
13.	33.85	31.45	2.40
14.	33.85	31.45	2.40

6.1.1 Measurement Data in the Case of a Serious Injury

In our earlier report we have published a serious injury of hand when the local dose was appr. 20–30 Gy [4]. The temperature differences between the injured and the not involved areas were min. $dt = 1.5 - 2.4$ K (*Tables 6* and *7*). This difference could be well distinguished visually on the thermograms.

Table 7
Expectable temperature difference on the injured and uninjured hands
(20–30 Gy locally, 28 days after the accident)

Surface of the hand	Palmar	Dorsal
dt_l	$34.65 - 33.7 = 1.95$	$34.5 - 33.85 = 0.65$
dt_r	$33.1 - 32.1 = 1.0$	$31.5 - 31.4 = 0.1$
$dt = t_l - t_r$	1.55 ... 2.1	2.4 ... 3.0

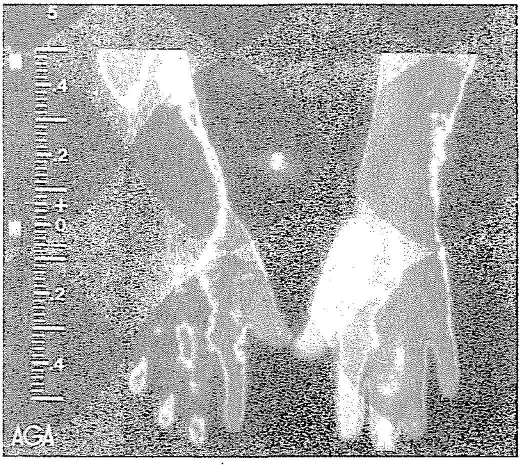

Fig. 3. Two isotherm levels on the dorsal surfaces of the seriously injured (left) and uninjured hands

The comparative IR-density pictures are shown in *Figs. 1* and *2*. In *Figs. 3* and *4* the temperature distributions of the left (injured) and right hands were labelled by two isotherm levels. The measurement data can be seen in *Tables 6* and *7*.

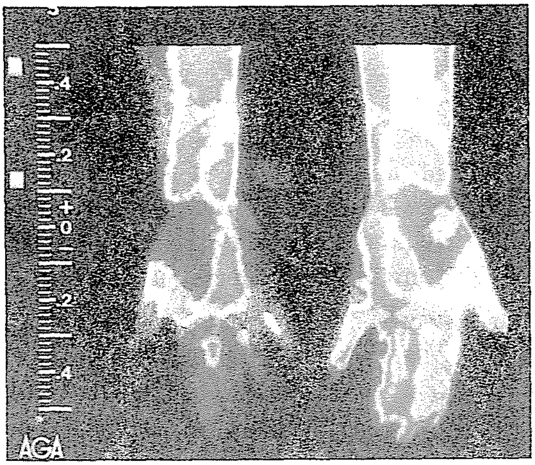

Fig. 4. Two isotherm levels on the palmar surfaces of the injured (left) and uninjured hands

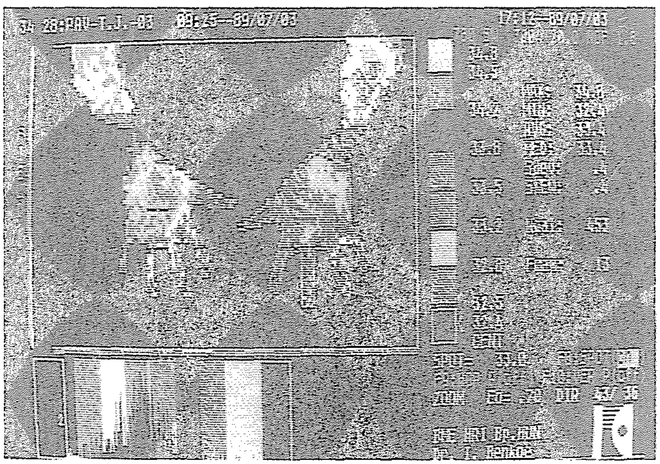

Fig. 5. IR-thermogram on dorsal surfaces of the moderately injured hands at the first investigation, 5 days after the accident

6.2. Moderate Injury of a Hand

In the second case [10] we have investigated a moderate injury when a minor radiation accident happened to a radiation worker and the IR–TGM was satisfactorily used in the diagnosis even after a rather small local dose as well as during the follow-up investigations.

A radiation worker of a nuclear power station has erroneously caught and elevated a used detector from the reactor instead of the new one which has not been irradiated yet. Due to the radioactivity of the piece held for a couple of minutes in his left hand, the person's hand has got a radiation burden from mixed gamma and neutron radiation. The personal TLD dosimeter indicated only 24.8 mGy dose and a computer estimation of the dose to the person's palms resulted in appr. 50–70 times dose, i.e. appr. 1.2–1.7 Gy. Though the indicated local dose did not seem to be dangerous for development of serious local damage, for safety reasons IR-thermogrammetric investigations were carried out five days after the accident and then 2 and 17 months later.

Table 8

Measurement data on the injured (left) and uninjured hands (1.2–1.7 Gy locally, 5 days after the accident)

Values of temperature distribution, °C						
Location	Reference spot on the other hand	Characteristics of the histograms				
		MAX	MIN	AVG	MED	Sdev K
Left dorsal	33	34.8	32.4	33.4	33.4	0.4
Right dorsal	33.5	34.7	32.5	33.2	33.2	0.3
Left palmar	34.4	35.6	32.2	34.7	34.8	0.5
Right palmar	34.8	34.9	32.6	34.2	34.3	0.5

6.2. Measurement Data in the Case of a Moderate Injury

The data of the thermograms obtained at the first investigation are shown in *Tables 8* and *9*. Due to the homogeneous and nearly identical temperature distribution of the two hands (**l**: left, **r**: right) a collection of data for comparison of histogram are presented in different phases (I.: 5 days, II.: 2 months, III.: 17 months) of the investigation (*Table 10*). The characteristic parameters for the histograms are as follows: the maximum (max.) and minimum (min.) as well as the average (avg.) temperatures, number of pixels (Ncal) within the observed areas and the median (med.) of the

Table 9
Expectable temperature difference on the uninjured and injured hands (1.2–1.7 Gy locally, 5 days after the accident)

Surface of the hand	Palmar	Dorsal
dt_l	$35.6 - 32.2 = 3.4$	$34.8 - 32.4 = 2.4$
dt_r	$34.9 - 32.6 = 2.3$	$34.7 - 32.5 = 2.2$
$dt = t_l - t_r$	avg: 0.5 at 34.4 °C	avg: 0.2 at 33.3 °C

temperature distribution. The results obtained by histographical method involved the comparisons of surface temperatures at selected sites of the counterlateral hand.

The comparative histograms of irradiated hands (palmar and dorsal surfaces) in different phases of the investigation can be seen in *Figs. 7, 8* and *9*.

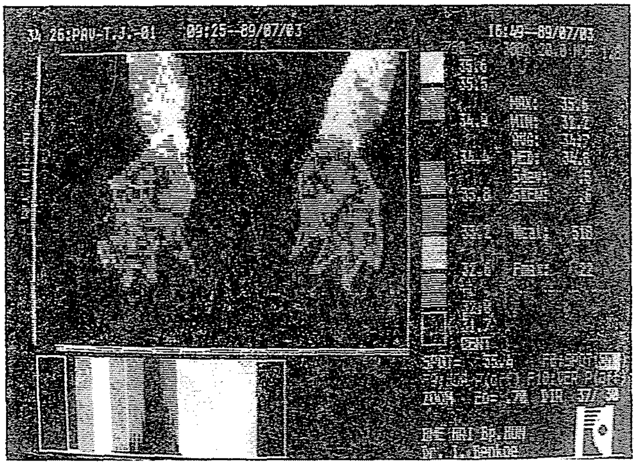

Fig. 6. IR-thermogram on palmar surfaces of the moderately injured hands at the first investigation, 5 days after the accident

Based on the results presented it can be concluded that the thermal effects of the radiation dose of 1–2 Gy 5 days after the accident was manifested in an increase of temperature, the difference proved to be $dt = 0.5$ K (*Table 11*). This considerable change has to be analyzed by other parameters of the histogram of temperature difference like the max. and min. values as well as the form of the histograms (*Figs. 7, 8* and *9*).

Table 10
Collection of data for comparison of histograms in the case of a moderate injury

No.of observation	Location	Values of temperature distribution, °C — Characteristics of the histograms				
		MAX/MIN	AVG	MED	Ncal	Fmax
I.	left palmar	35.6/32.2	34.7	34.8	518	57
	right palmar	35.6/32.5	34.6	34.7	475	26
	left dorsal	34.8/32.4	33.4	33.4	458	37
	right dorsal	34.7/32.5	33.2	33.2	405	70
II.	left dorsal	35.0/33.0	33.7	33.7	539	83
	right dorsal	34.9/32.7	33.9	33.8	507	74
	left palmar	36.2/33.5	35.5	35.5	841	119
	right palmar	36.1/33.9	35.3	35.4	781	95
III.	left dorsal	36.4/33.4	34.9	34.9	705	68
	right dorsal	36.2/33.8	35.0	35.0	686	95
	left palmar	39.9/32.8	36.1	36.2	631	71
	right palmar	37.0/34.3	36.2	36.2	682	81

7. Discussion

The results presented above give evidence for the indispensable use of infrared technique in diagnosis and follow-up of local radiation injuries (*Tables 11* and *12* and *Figs. 10* and *11*). It is quite obvious that the alterations of temperature distribution are only symptoms of the complex pathophysiological processes after radiation exposure like vasoconstrictions and vasodilatations, cell killing and scavenging the detriment, regenerative and inflammatory processes. Nevertheless, it is rather surprising that in the second case the deterministic effects of a fairly low subclinical dose (appr.1–2 Gy, locally) could be detected (*Table 11* and *Fig. 10*). The first infrared observation demonstrated higher temperature on the left hand in-

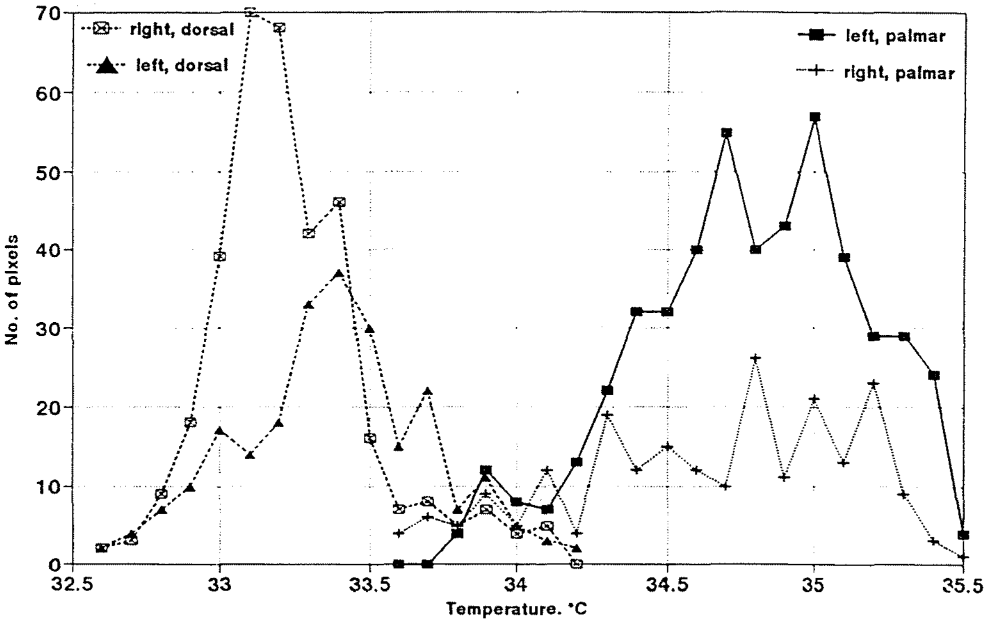

Fig. 7. Histograms of irradiated hands (palmar and dorsal surfaces), 5 days after a moderate irradiation

volved more in the accident than the right one. Two months later both the heterogeneity and the extreme values of temperature was disappeared, though the general temperature of the hands were higher than at the first investigation (*Fig. 10*). One and a half year later, the rather uniform thermal appearances of the hands show the return of normal healthy conditions (*Fig. 9*).

Table 11
Expectable temperature changes as a function of time elapsed after the accident (1.2–1.7 Gy, locally)

Surface of the hand	Estimated temperature interval, K	
	5 days	2 months
Palmar	0.5 at 34.4°C	0.2 at 35.4°C
Dorsal	0.2 at 33.3°C	0.2 at 33.8°C

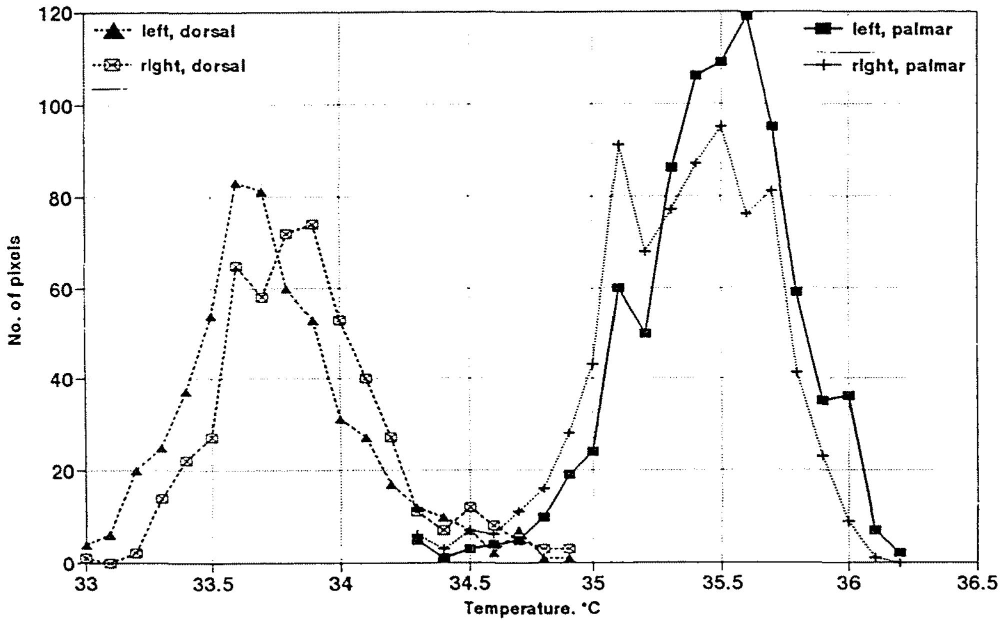

Fig. 8. Histograms of irradiated hands (palmar and dorsal surfaces), 2 months after a moderate irradiation

8. Summary

In conclusion, upon the former and present experience we suggest that thermography and thermogrammetry can be used in detection of the extent of radiation injury even at doses which do not cause clinically significant signs and symptoms. The heterogeneity of the injury within the involved area can be also observed.

Table 12
Expectable temperature changes as a function of the local dose of irradiation

Surface of the hand	Estimated temperature interval, K	
	20–30 Gy	1.2–1.7 Gy
Palmar	1.55...2.1	0.5
Dorsal	2.40...3.0	0.2

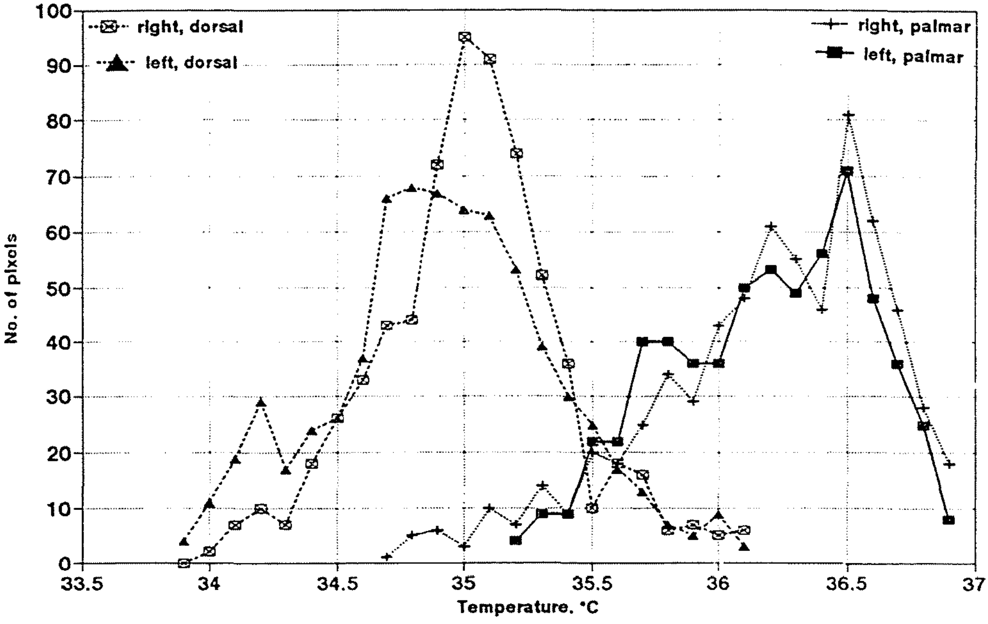

Fig. 9. Histograms of irradiated hands (palmar and dorsal surfaces), 17 months after a moderate irradiation

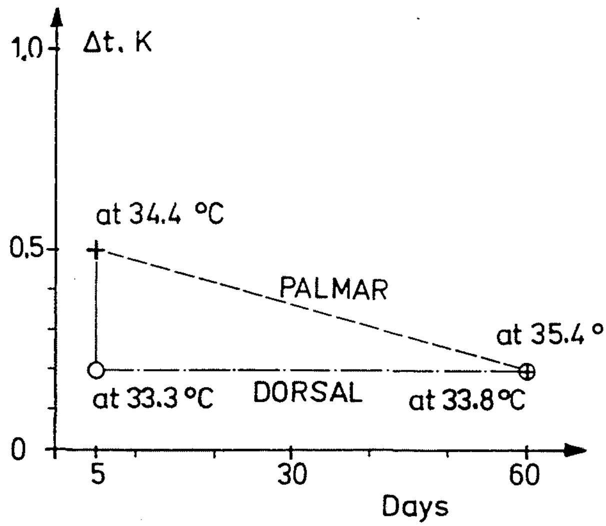

Fig. 10. Temperature changes in function of the time after the moderate accident (1.2–1.7 Gy, locally)

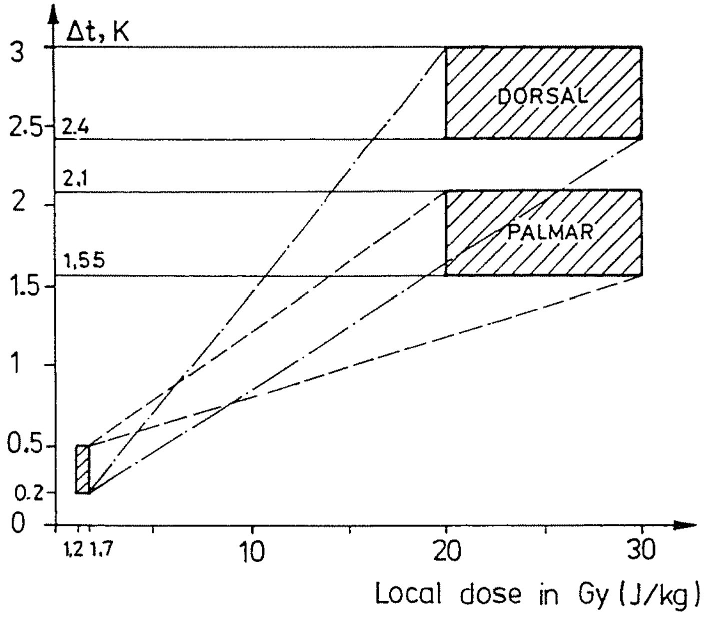

Fig. 11. Temperature changes in function of the locl dose of the irradiation

References

1. LENZ, U. – SCHMIDT, P.: Thermographie mit Flüßigkristallen in der Medizin. *Heilberufe*, Vol. 31, pp. 186-187, 1979.
2. KÖTELES, G.J. – BIANCO, A.: The Need for and Importance of Biological Indicators of Radiation Effects with Special Reference to Injuries in Radiation Accidents. International Atomic Energy Agency, *TECDOC-273*, Vienna, 7-22, 1982.
3. JAMMET, H.: Accidents Radiologiques. Conduite à tenir en cas de surexposition. Institut Curie, Commissariat à l'Energie Atomique, World Health Organization, International Collaborating Centre in Radiopathology, 1984.
4. KÖTELES, G. J. – BENKŐ, I.: Sugársérülések termikus tünetének kimutatása infravörös képalkotással (Tracing the Thermal Symptoms of Radiation Injuries by Infrared Image Forming). *Mérés és Automatika* (Measurement and Automation), Vol. 34, pp. 383-389, 1986.
5. KÖTELES, G. J. – LELIK, F. – SZTANYIK, L. B.: Thermographic Diagnosis of Radiation Injury. *Thermology*, Vol. 2, pp. 584-586, 1987.
6. KÖTELES, G. J. – KEREKES, J. – LELIK, F. – SZTANYIK, B. L.: Thermography in Diagnosis of Local Radiation Injury, in *Twenty Years Experience in Radiation Protection 13th Reg. IRPA Congr.*, Salzburg, Austria, pp. 676–680, 1988.
7. KÖTELES, G.J. – KORMOS, CS. – KEREKES, J. – SZTANYIK, B.L.: Further Approaches to Biological Indicators of Radiation Injury, in *Radiation Protection Practice*. Pergamon, Vol.3., pp. 1149–1152, 1988.
8. BENKŐ, I.: A termogrammetriai CAD energetikai és egyéb alkalmazásai (Energetical and Other Applications of the Thermogrammetric CAD). *Mérés és Automatika* (Measurement and Automation), Vol. 37, No.2, pp. 69-73, 99-102, 1989.

9. KÖTELES, G. J. – BENKŐ, I. – SZTANYIK, L.B.: Thermography in Diagnosis of Local Radiation Injury, in *Trends in Biological Dosimetry, Proceedings of International Symposium*, Lerici, Italy, Wiley-Liss Publ., New York, 1991.
10. KÖTELES, G. J. – BENKŐ, I.: New Data on Application of Thermogrammetry in Diagnosis of Local Radiation Injury. *Mérés és Automatika* (Measurement and Automation), Vol. 39, pp. 88-93, 1991.
11. BENKŐ, I.: Quantitative Analysis of Medical Infrared Pictures. *Österreich Thermologie*, 2, Sonderheft, 17, August 1992.
12. KÖTELES, G. J. –, BENKŐ, I.: Infrared Thermogrammetry as a Tool in Radiation Pathology. *Österreich Thermologie*, 2, Sonderheft, 34, August 1992.
13. BENKŐ, I.: Histographical Analysis of Infrared Images for Medical Diagnosis. *8th Int. Conf. on Thermal Engineering and Thermogrammetry,* Budapest, Hungary, pp. 307–308, 1993.
14. KÖTELES, G. J. – BENKŐ, I.: Infrared Thermogrammetry as a Tool in the Diagnosis of Ionising Radiation Caused by Local Injuries. *8th Int. Conf. on Thermal Engineering and Thermogrammetry*, Budapest, Hungary, pp. 319–320, 1993.
15. BENKŐ, I.: Possibilities of Infrared Imagery in the Field of Biology of Ionizing Radiation. *Proceedings of the Workshop on Advanced Infrared Technology and Applications.* IROE-CNR, Florence, 1993, pp. 180–196 (in printing).