Skin Thermal Imaging

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Keywords
Skin temperature • Thermal imaging • Raynaud's phenomenon • Fever detection

1 Principle

The human body is endothermic. Human skin functions as an interface between the body core stable temperature (around 37 °C) and the variable environment temperature. Except in extreme cases such as strong sun-heat exposure, the skin surface is cooler than the blood. Therefore it should be possible to measure the variation of the skin blood perfusion by those of the skin surface temperature.

In normal conditions the latter depends on the outside temperature, the heat coming from the blood (variable with its location in the skin and transfer ability), and the heat generated by the skin (mostly the epidermis and appendages) metabolic activity. When inflammation or a high metabolic rate tumor develops within the skin or close deeper tissue, a heat conductive transfer is added. Practically the production of metabolic heat by healthy skin (0.16 cal min^{-1} cm^{-2}) (Houdas and Ring 1982) or even psoriatic skin (0.27 cal min^{-1} cm^{-2}) is too low to interfere.

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1.1 Contact Measurements: Thermometry

When a thermometer is applied on the skin, its temperature and the skin temperature are both modified at the point of contact (Stüttgen et al. 1989; Ring 1995). For the temperature at equilibrium to be very near the initial skin temperature, it is essential to comply with the following items: small contact area, low thermal sensor inertia, and moderate initial difference between temperatures. Furthermore, the skin heat being in continuous production induces its accumulation as soon as there is an occlusion of the skin surface. Contact skin temperature measurements must therefore be brief as possible.

1.2 Point Measurement

Thermometers use a variety of physical principles: thermocouples, electric resistance, thermistors, and semiconductors.

Thermocouples are an application of the thermal-electric effect. In a circuit made of two different metals (e.g., copper-constantan), a voltage is produced if the junctions are at different temperatures. This type of thermometer consists in a small applicator located at one of the junctions, the other being maintained at a stable temperature (reference temperature). A galvanometer records the generated voltage. The result is immediately displayed.

Metal resistance thermometers have an electric circuit consisting of a generator and a resistance (in nickel or platinum) which varies with temperature. The resistance is in the applicator which consequently has a large application area. However it is possible to find Pt sensors with a small contact area (less than 1 mm^2). The results are also displayed instantaneously.

Thermistors are also resistance thermometers, but provided with complex linearization electronics. Unfortunately they do not age well and it is necessary to recalibrate them regularly. Disposable probes are now available thus eliminating the need of cleansing and disinfection.

Semiconductors are based on a similar principle: the resistivity of the sensor varies with temperature. They are more durable and stable than thermistors and do not require frequent recalibration.

During application of contact thermometers, pressure must be avoided: this alters the blood flow, and the recorded temperature can be more like the interior of the skin, while the purpose of the measurement is to record the skin surface temperature.

For a point measurement, application should be made for 1 or 2 s only to prevent a disturbance of the temperature from occlusion or pressure. Metallic resistance and thermistor thermometers can have a preheated sensor, which may slightly modify the skin temperature. As a consequence they are preferably used for temperature monitoring over time, such as in intensive care.

The skin temperature in resting and neutral thermal conditions (i.e., the subject is naked, in resting position; in a room where the air and the walls are at the same temperature, close to 30 °C, the relative humidity is below 50 %, and the movement of the air is low (0.1 m to 0.2 m/s)) varies with body sites (Table 1), because each of them has its own vasculature pattern due to its anatomy and reactivity and has a specific thermal environment. Such diversity explains why the assessment of mean or average skin temperature requires measurements in numerous places. Modern infrared cameras can now image a whole body anterior and posterior from which total body mean temperatures can be readily calculated. Table 1 shows firstly the forehead as a relatively stable temperature and the large variability of the temperature in the extremities and then the homogenization of the temperatures in hot conditions and, in the opposite situation, great topographical diversity in cold conditions.

Skin temperature has a considerable inertia when compared to the variations in the arterial supply it depends on. For example, for a blood flow increase over 4 min followed by a plateau, the skin temperature rise may be seen only 6 min later and may plateau in 7 min.

Table 1 Current temperature on various body sites in an adult subject naked and lying supine in various environmental temperatures (Houdas and Ring 1982)

Body site	Cool (20 °C)	Thermal neutrality	Warm (40 °C)
Forehead	32.0	34.8	36.1
Palm	24.0	32.9	36.6
Volar forearm	27.7	33.6	36.7
Arm, anterior aspect	28.0	33.4	37.3
Chest, anterior	31.9	34.5	36.8
Close to umbilicus	31.3	34.4	36.2
Iliac fossa	30.7	34.7	36.1
Thigh anterior aspect	27.9	33.4	36.3
Leg, anterior aspect	25.8	32.7	36.4
Dorsum foot	20.0	31.1	37.0

1.3 Bidimensional Measurements (Mapping)

1.3.1 Noncontact Measurement: Thermography

Any warm surface emits an electromagnetic radiation whose energy is a function of the fourth power of its absolute temperature, according to the equation $E = \sigma\varepsilon T^4$ where σ is the Stefan-Boltzmann radiation constant and ε the surface emissivity. Between 32 °C and 36 °C (305–309 K), the skin surface emission is mainly at 10.5 μm, in the infrared (IR). It is therefore possible to measure, at a distance, the skin surface temperature by its IR radiation. Since water absorbs IR, the detected radiation is emitted by the stratum corneum, not by the underlying living tissues which are in a water environment. Like contact thermometry, thermography measures the skin superficial temperature. It provides the absolute temperature, but is mainly used to reveal topographical differences and follow variations on a quantitative image. Mapping of temperature distribution, absence of contact, and possibility of sustained observation provide many advantages over the contact methods. In recent years there has been a dramatic rise in the use of tympanic membrane radiometry, which has in many hospitals and clinics become more commonly used than contact thermometers for routine temperature assessment.

1.3.2 Thermal Imaging Cameras

IR cameras are of different types, depending on the IR detector, the image capture mode, and its processing (Ring et al. 2009). Cameras with cooled indium antimonide (AGA system) mainly detect 2–5.5 μm IR, which are wavelengths outside the absorbing zones of water. Mercury cadmium telluride IR cameras mainly detect 7–12.5 μm IR.

There are now a number of infrared cameras that use a focal plane array detector that can operate over a broader spectral band. Most of these do not need the cooling required for earlier detectors. There are continuous improvements and increasing numbers of detector elements. As a result modern systems are much easier to use in medicine. Excellent images can be obtained from 640 × 480 focal plane arrays. Compared to the earlier single-element scanners, they provide high resolution at high speed (real time). These improvements, together with a range of IR-transmitting lenses, also result in smaller compact cameras. In most cases now, a digital output signal can be directly fed to a small computer (earlier systems required the signal to pass through an analogue to digital converter, which increased the risk of calibration drift). With decreasing costs and improved reliability, thermal imaging is more available to clinicians who wish to use the technique. It is still recommended that the user purchases a blackbody temperature

reference source, which is needed to make regular checks on calibration of temperature, especially with the uncooled cameras. The thermographic signal is normally examined by computer image analysis.

1.3.3 Thermographic Image

The ranges of grays or colors indicate the difference of temperature (maximal thermal resolution 0.2 °C) in relation to a reference temperature selected by the operator. The larger the thermal resolution, the smaller the displayed temperature range. To obtain a good topographic discrimination, it is therefore necessary to choose the appropriate range, based on a reference temperature close to the average temperature of the zone investigated.

Finding both the temperature difference among body sites and especially hot or cold areas is easier in cool environmental conditions (Table 1), hence the choice of 22–23 °C as a usual examination room temperature.

For a selected ambient temperature, the skin temperature distribution is remarkably constant in the same individual. The fingertips are normally colder than the dorsal hands except in reactive hyperemia (Fig. 1a), but if the difference is over 2 °C, it indicates a vascular disease of the extremities (Fig. 1b). The warmest area is the head and the coldest the toes, and the difference is 4 °C in neutral thermal conditions, exceeding 10 °C in cold environmental conditions.

Reactive hyperemia, systemic or local cold test, heat test, and various pharmacological tests can be followed by thermography in real time with image registration at regular intervals or at some important times. For example, to measure the degree of a Raynaud syndrome and follow up the treatment, the generally used procedure is (Ring 1995):

- The patient remains seated in the examination room for 15 min, in neutral thermal conditions (in a room where the air and the walls are at the same temperature, close to 30 °C, the relative humidity is below 50 %, and the movement of the air is low (0.1 m to 0.2 m/s); in practice, the subject is neither cold nor too hot and does not feel any hot or cold air flow) with his forearms undressed.
- Thermogram of the dorsal side of both hands.
- The hands, in thin and transparent plastic gloves, are immersed up to the wrists in a 20 °C water bath for 1 min.
- Thermogram 10 min after removing the hands from the bath.

1.3.4 Interpretation

The thermograph image indicates an excessive or deficient heat supply to the skin surface. It may be due to a variation (increase or decrease) of the skin perfusion by the warm blood coming from the deeper parts or of a thermal transmission from underlying tissues.

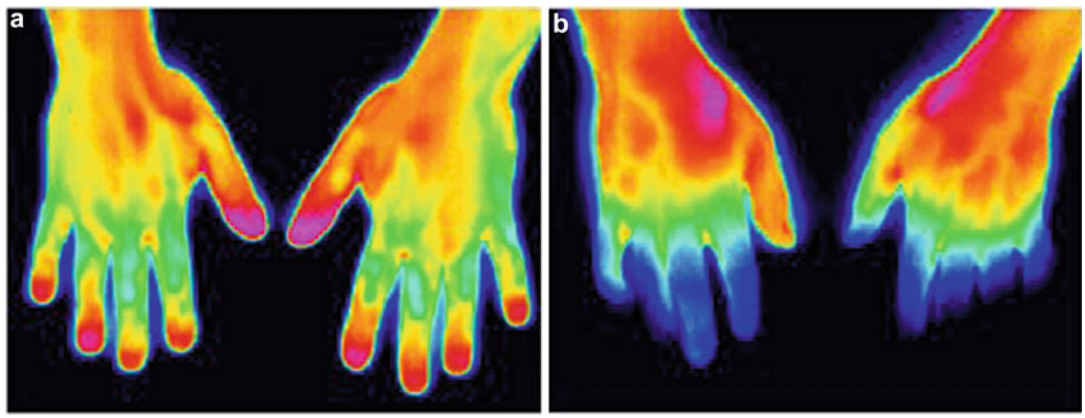

Fig. 1 (**a**) Reactive hyperemia in normal hands post-cooling by 1 min 20 °C water (hand protected by thin plastic gloves). (**b**) Thermogram of hands of a Raynaud's phenomenon patient after same water immersion as above

The first case applies to active (i.e., arteriolar) vasodilatation: opening of the "skin radiator" valve. A passive vasodilatation, for example, by increase of the venous pressure only (standing up from lying), remains invisible. The "skin radiator" is the subepidermal vascular plexus; therefore, any active erythema has a thermographic version. But the skin can be normally perfused and warm without erythema, and thermography can then show the topography of this invisible active vasodilatation. In inflammation, thermography is a means of assessing the extent of the process and its intensity (by the degree of thermal increase).

In the second case, a deeper source of heat, without involvement of the subepidermal plexus, is shown by thermography. The skin is warmer along the subcutaneous normal veins and varicose veins. The warm thermographic image of actively growing tumors depends on their intense angiogenesis, which usually connected with their proliferating activity.

Thermography detects the transmission to the skin surface of heat produced in deeper tissues. Any disruption in this transfer, such as edema or thickened tissues, impairs the image. A typical example is the papular urticaria. Accordingly a hyperthermia in an edematous zone would be most likely related to active vasodilatation of the subepidermal plexus.

These principles have resulted in some of the most interesting uses of thermography:

- Detection and delineation of invisible cutaneous, subcutaneous, or deeper tissue inflammation, since without erythema: for example, the persistent peri-lesion vasodilatation after healing in psoriasis, the lymph or blood drainage path of a tumor, and the degree of inflammation of a joint.
- Invisible vasoconstriction detection (Stüttgen and Flesch 1985) (e.g., in healed psoriasis lesions) or analysis (the blanched area induced by topical corticosteroids spreads beyond the area of hypothermia, which would indicate a preferential effect of the drug on capillaries rather than arterioles).
- Investigation of angiodysplasias in order to discern hyperperfused (warm), stagnant (cold), and normally perfused zones and to follow them up during treatment.
- Assessment of malignant tumor growth (generally associated with hyperthermia).
- The dermatological use of thermography is well developed and illustrated in the work of Stüttgen and Flesch (1985).

2 Good Practice

2.1 Examination Room

- An air lock is an ideal way to reduce temperature changes and drafts occurring on entrance or exit. This air lock may also be used as a cubicle for the patient to undress (Ammer and Ring 2013).
- The volume of the room must include air conditioning. Surface: 8–12 m^2. Maximal height 2.5 m in order to reduce temperature differences between the floor and the ceiling, which are reproduced between the patient's feet and head in standing position.
- Thermal insulation of the walls of the room can improve thermal stability.
- Air conditioning is essential, preferably set at 22–23 °C, so that the skin temperature differences are clearly revealed but allowing the undressed patient to feel comfortable. It is most efficient if left to operate day and night continuously. The relative humidity must not exceed 50 % since the stratum corneum hydration alters its emissivity.
- To reduce thermal currents to the minimum, it is recommended to block up the windows because they let the cold and the sun in.
- Avoid reflecting materials (aluminum, steel) or paint any reflecting surfaces. Walls should also be covered in nonreflecting paint.
- Room lighting should be operated by cold light or fluorescent tubes providing indirect lighting.

The central heating radiators should be placed as far as possible from the examination table, in any case not less than 2 m.

2.2 Method

- The subject should stay at least 15 min at room temperature before the examination takes place.
- Clothes strongly modify the thermal environment of the skin. The subject must therefore be undressed 15 min before the test.
- Alcohol or spicy food must be avoided 2 h prior to the examination to avoid the risk of facial, thorax, or extremity flush, in spite of the absence of erythema.
- The skin must be dry as humidity absorbs IR. Wet skin looks cold. A wound can appear to be 2 °C below its actual temperature.
- The subject must be placed at least 15 cm from the nearest wall, to avoid heat reflection, and 2 m from any source of heat.
- There should be no entrance or exit from the room during the examination.

2.3 Commercial Equipment

Most modern infrared cameras today are better equipped with faster detectors than the earlier systems of more than 30 years ago. Focal plane arrays are fast and efficient, providing images at real-time video speeds. There is now a wider range of cameras that operate successfully for medical applications without the need for detector cooling (Ring et al. 2009). However, it is always recommended that such systems should be used with an external blackbody reference temperature source. Time to reach stability can vary, and it is necessary to take a series of images for measurement from a known stable temperature reference source to verify when an individual camera is ready for image capture and temperature measurement. Modern systems also generate a digital thermal image, so that connection to a computer can be by fire wire or by wireless transmission. In many cases, a storage provision within the camera itself can be used, allowing the operator to download to the computer at a later time for detailed image analysis. In recent years the image and temperature resolution has increased. Currently many systems provide thermal images at 320 × 240 pixels, with 640 × 480 and upward becoming readily available at higher cost. Manufacturers and agencies exist now in many countries around the world. A large company that has integrated several well-known manufacturers is based in Sweden and the USA with a wide range of systems for many different applications in medicine science and industry. Whatever the choice of camera system selected for medical studies, it is important that regular maintenance by the company be undertaken. A thermal camera may perform to the manufacturer's specification for a period of time from leaving the factory, but is subject to offset drift, and multielement detectors can be affected by individual pixel and detector loss, which the manufacturer needs to deal with on a regular basis.

Reproducible results with thermal imaging depend on rigorous technique by the operator. Standardized procedures are now commonly adopted and can be found in the literature.

3 Clinical Applications

A number of modern reviews indicate that some applications have become more widely accepted in clinical medicine than others (Ring and Ammer 2012; Lahiri et al. 2012). Inflammatory lesions such as those found in the arthritides, rheumatoid arthritis, osteoarthritis, gout, psoriatic arthropathies, scleroderma, etc. can be effectively monitored by thermal imaging. The effect of anti-inflammatory treatments can be objectively monitored and has been documented in controlled clinical trials. Topical agents applied to the skin may be observed as a dynamic process (Fig. 2). In peripheral vascular diseases, skin temperature monitored by thermal imaging can be efficiently studied, particularly where a thermal or pharmacological challenge has been applied. Raynaud's phenomenon and vibration injury (hand-arm vibration syndrome) and complex regional pain syndrome are examples.

Due to the international concerns of pandemic influenza and the massive increase in air travel, attention has been focused on the use of thermal imaging in fever screening. The International

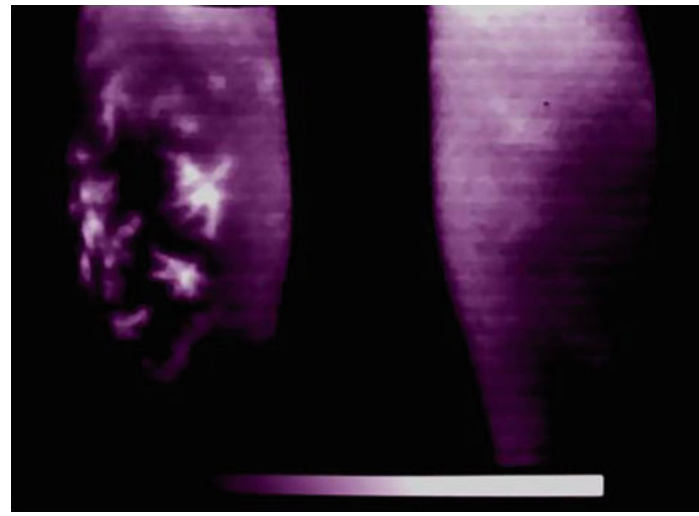

Fig. 2 Response to nicotinic acid spray to the calf

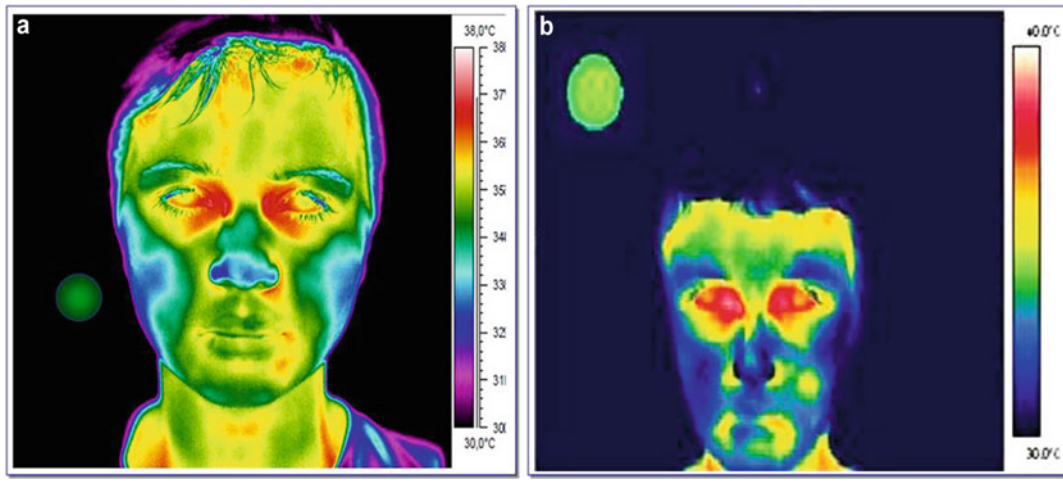

Fig. 3 (**a**) Thermogram of the face of a young male without fever. The checks and nose are the coolest areas. (**b**) Thermogram of the face of a young male with fever. The forehead checks and nose are cooler due to sweating. There is increased heat at the inner canthi of the eyes

Standards Organization has published two documents that specify the minimum technical requirements for this and also the required procedure to capture meaningful information from a close-up thermal image of the face. It is now shown that from such a close-up image, the temperature measured at the inner canthus of the eye can provide discriminatory evidence of systemic fever in children and adults compared to nonfebrile subjects (Fig. 3a, b) (Ring et al. 2013).

4 Conclusion

The technical performance of thermal imaging cameras, together with the power of computing and image processing, has transformed this technique in recent years. As a result the physiological knowledge of skin temperature in health and disease has also improved. From noninvasive monitoring of treatments to studies

in high-performance sport science, infrared thermal imaging has matured and when correctly performed can be a valuable and reliable objective imaging procedure in certain aspects of clinical medicine. The very high costs of the past have fallen, and performance has risen, making this technique more accessible than in the former years of its development.

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