N88-23915

Clinical Applications of Computerized Thermography

Michael Anbar

Professor and Chairman, Department of Biophysical Sciences
School of Medicine, SUNY, Buffalo, NY, 14214

Abstract

Computerized, or "digital", thermography is a new, rapidly growing diagnostic imaging modality. It has superceded contact thermography and analog imaging thermograpphy which do not allow effective quantitation. Medical applications of digital thermography can be classified in two groups -- static and dynamic imaging. They can also be classified into macro thermography (resolution>1mm) and micro thermography (resolution<100um). Both modalities allow a thermal resolution of 0.1 centigrade. The diagnostic power of images produced by any of these modalities can be augmented by the use of digital image enhancement and image recognition procedures. Computerized thermography has been applied in neurology, cardiovascular and plastic surgery, rehabilitation and sports medicine, psychiatry, dermatology, and ophthalmology. Examples of these applications will be shown and their scope and limitations will be discussed.

CLINICAL APPLICATIONS OF COMPUTERIZED THERMOGRAPHY

Michael Anbar
Department of Biophysical Sciences
School of Medicine, SUNY, Buffalo, NY, 14214

Clinical thermography is a relatively new diagnostic modality that has just recently gained acceptance by the medical community at large. In fact, the first comprehensive book on thermography appeared just a few months ago.[1] This paper presents a brief review of clinical thermography -- recording and displaying images that depict the distribution of temperature on the skin surface of patients. It describes the current status of computerized, remote sensing thermographic instrumentation, emphasizing the most recent developments. It then reviews some of the widely used clinical applications of thermology, which is the systematic interpretation of clinical thermograms, pointing out new applications currently explored. Finally, it attempts to assess the overall role and place of thermology in medicine, pointing out the need for fundamental thermological research.

INTRODUCTION

The assessment of local skin temperature as an indicator of pathology is as old as medicine and the correlation between local "hot spots" and local infections may have been discovered by the prehistorical cave men; even animals may sense the elevated temperature of local "hot spots" due to infection and then lick them. From the perspective of the written history of medicine, the associating of hot infected areas with disease appears already in Egyptian scriptures more than 2000 years before Hippocrates, who tried to classify diseases by their pyretic characteristics.[2]

Skin temperature is determined by subcutaneous blood supply, by the metabolic rate of subcutaneous tissue, by the rate of evaporation of subcutaneous moisture (including diaphoresis), and by the cooling rate of the surface. The latter may be conductive (to a touching body), convective (to the surrounding air) or radiative.

Skin temperature can be measured by contact with the measuring device (e.g, a hand, a mercury thermometer, a thermocouple, a liquid crystal layer), assuming the establishment of thermal equilibrium between the measured skin and the measuring body, and presuming that the contact does not affect the physiological behavior of the examined area. These limitations, as well as the lack of sensitivity, precision and accuracy, of measurement of the distribution of skin temperature by physical contact, made this approach unfit for meaningful clinical diagnosis.

Assessment of skin temperature through its intrinsic radiative losses (black body radiation) are much more meaningful because of the extremely fast rate of thermo-radiative equilibrium, because skin is non reflective in the wavelength range of 9 to 11 microns (the range of maximal black body emission at body temperature), and because of the negligible effect of IR sensors (since also they are non reflective black bodies) on the emisivity of the monitored surface. Since the black body radiation of the skin at body temperature peaks at about 10 microns, the assessment of skin temperature had to await the advent of an appropriate detector (photoresistive HgCdTe) coupled with a reflective optical scanner. Moreover, the quantitative measurement of skin temperature requires not only continual real-time calibration of the temperature sensor and distortion-free optics, but also the development of computerized image processing. Thus, it is not surprising that quantitative thermal mapping of the skin was achieved just a few years ago.

CURRENT STATE OF THERMOGRAPHIC INSTRUMENTATION

Today, the state of the art in clinical thermography comprises scanning cameras with high resolution (<1 milliradian, allowing surface resolution of <0.1mm at 30 cm from the camera), with a temperature resolution of <0.05C, and temperature measurement accuracy of <0.1C. A combination of rapidly rotating mirrors reflects each spot of the observed object onto the infrared thermoresistive detector, which is maintained at low temperature. The optics of most commercial machines do not permit imaging at a short distance from the camera (<15 cm), but this limitation has now been overcome by recent R&D.

The scanning speed of the best cameras used in medical diagnosis is about 30 frames per second. The time limitation is, in part, due to the relatively slow response time of the detector, and in part determined by the speed of the reflective optical scanner. The voltage across the detector is a function of its temperature, this voltage can be converted into a digital signal or stored in analog form and digitized later. The 12 bit A/D conversion currently used in clinical thermography exceeds the precision thermology requires. The resolution of the digitized image depends on the amount of memory available on the dedicated microcomputer. It has reached now 640x512 and might soon improve to 1024x1024 pixels. No single commercial machine has the combination of all the features described above (speed and resolution), but this is likely to change within the next year or two.

IMAGE PROCESSING AND DISPLAY

Image averaging and subtarction, as well as obtaining the maximal, minimal and average (absolute) temperatures of any specified area on the image, are routine in most commercial digital machines. More sophisticated image handling techniques, such as relating thermographically significant features to specific anatomic markers, as well as other pattern recognition algorithms, are currently being developed. These will enable to derive quantitative, diagnostically meaningful information, especially regarding temporal changes characteristically associated with certain pathologies or their treatment.

Thermographic diagnostic images are generally displayed on a CRT as contour maps, where each isothermal area is displayed in the same shade of grey or in the same pseudocolor. Most machines display 16 shades (on a monochrome display) or 8 to 64 colors. The baseline temperature (lowest temperature in a given image) can be selected in the range of interest (generally 20 to 40C), and one can select the temperature range (1 to 20C) to be displayed. Thus each of the 16 shades or colors can represent 0.1 to 1C. From the clinical standpoint temperature differences smaller than 1C are currently of little diagnostic value, and since the temperature range of most diagnostically interesting images is less than 10C, as few as 8 shades or psuedocolors can provide all the information necessary for the current clinical uses of thermography. The use of more shades, or colors, may reveal new, diagnostically useful, thermographic features, but their manifestation will require substantially better control of the thermal environment of the examined organ than practiced in current clinical thermography.

CLINICAL APPLICATIONS OF THERMOLOGY

Clinical thermology is essentially the science of studying local changes in skin temperature which appear on thermograms and are not due to environmental cooling or heating. As stated above, changes in local skin temperature are, generically speaking, a function of subcutaneous blood supply, and under special circumstances also of subcutaneous metabolic rate. Subcutaneous blood supply depends on (1) the patency of the arteries bringing blood into the region, (2) the rate of blood flow in these (which depends on cardiac output), (3) the extent of subcutaneous vascularization, and (4) the vasodilation or constriction of the subcutaneous arterioles. Generally, blood acts as a cutaneous heating fluid, but in cases of local hypermetabolism it may act as a coolent. The patency of arterioles is controlled by the autonomous nervous system, while that of the major arteries is primarily determined by their anatomy. In addition, thermograms may show major subcutanous veins.

Thermography reveals abnormalities in the local heating or cooling. Pathological thermological changes can, therefore, be due to (1) occlusion of arteries, (2) impaired innervation of arterioles (resulting in either excessive vasoconstriction or vasodilation, depending on the interaction between the sympathetic and parasympathetic systems and the location of the interference), (3) local interstitial fluid retention (edema) that exerts hydrostatic pressure on the arterioles and may, therefore, change both the residence time of blood in the affected region and the heat exchange with the skin, (4) a mechanically damaged capillary bed, (5) increased local vascularization, (6) local hypermetabolism or (7) local hypometabolism that are not compensated by increased circulation (cooling or heating respectively). For a review of mechanisms of local thermal aberrations from different points of view see [3].

The latter situations are accentuated by positive feedback due to the positive temperature coefficient of tissue metabolism -- inadequate cooling will result in a faster metabolism and, therefore, in an even more extensive local heat generation, while inadequate heating of a hypometabolic region might result in a local "run away" cooling effect. The situation is further complicated by the fact that inadequate temporary blood supply to a region might result in hypoxia and subseuqent glycolysis, which generates more local heat than normal aerobic metabolism.

Each of these thermographically demonsrtable pathological changes can have concrete clinical application in the diagnosis and management of different disorders. The limitations of length of this paper allow us to give just a few examples of clinical situations where the pathological changes, generically described above, are applied in different medical specialties. We will try to include references to leading recent contributions, however, for certain applications, which are currently under development, we will not be able to cite references.

1. Neurology.

Damage to the spinal cord due to osteoporotic compression or trauma may result in impaired nerve signal transmission to the arterioles in the back or the extremities, generally resulting in an assymetric temperature distribution.[4-7] Often the pattern of abnormal temperature distribution overlaps the pattern of tactile sensation or the perception of pain in the affected region.[8-10] Thermography has also been shown to be useful in the diagnosis of migraine and other types of headache.[11] The relation between temperature distribution and pain led to the popularized reference to thermography as a method to "visualize pain"; this is conceptually wrong, since pain is a mental perception and thermography measures in this case only changes in the blood flow rate through the subcutaneus capillary bed. This methodolody that indicates spinal cord lesions, is likewise applicable to any peripheral nerve that interfaces with arteriols. In certain situations the diagnosis may be confirmed by repeated thermography in the presence of electrical stimulation or drug blockage of nerves.

A different area in neurology that lends itself to thermologic diagnostic quantitation is the transient CNS stimulation of the systemic sympathetic nervous system, which results in blushing or in turning pale. Likewise, it has been shown that excessive orthostatic hypotension might be diagnosed by a transient facial blushing. Unlike the nervous system studies described above, the latter type of diagnosis calls for the interpretation of sequences of images ("dynamic thermography"). The latter findings may make thermology an interesting tool in space medicine to study remotely and continuously the behavior of the autonomous nervous system under reduced gravity.

2. Surgery.

Clinically significant occlusion of one of the carotid arteries often results in assymetrical blood supply to the upper face, particularly around the eyes.[12] Thermography might, therefore, be used as a rapid and inexpensive screening test for early detection of incipient stroke or progressive hypoxia of the brain. Other diagnostic applications in this field include the localization of occlusive venous trombosis in the legs and of impaired capillary bed circulation in the foot associated with diabetes mellitus.

A new use for real time high-resolution thermography is during open heart surgery, especially in bypass operations. Since the heart is cooled down during the procedure, the patency of the grafted vessels and the success of the anastomosis can be assessed by introduction of a slightly warmer infusate. Using short focal length high resolution thermography it might be possible to determine the success of arteioplasty and of anastomosis of different parts of the gastrointestinal tract and thus avoid the risks of injection of contrast agents to a recently traumatized region. Also plastic surgery starts to apply thermography to objectively assess healing of grafts.

3. Orthopedic surgery and physiotherapy.

One of the classical uses of thermology is the assessment of the severity of inflamation of joints. This application has been extented to include the postoperative follow up of the recovery of joints.[13] In current studies the progress of recovery following arthroscopic surgery of the knee is evaluated thermologically to determine the efficacy of postoperative physiotherapy. The control of postoperative edema of joints is studied comparing impedence plethysmography and thermography.

4. Emergency and trauma medicine

Thermography has been used and abused in legal medicine to document persistent soft tissue injuries following trauma (mainly of motor vehicle accidents). Thermology may, however, be more useful to the victims of such accidents and make a substantial contribution to emergency medicine. Correctly staging of the level of injury may be critical in such cases. A rapid themographic inspection of a traumatized patient may readily detect subcutanous hemorage and acute soft tissue injury, and reveal even injuries to deep lying blood vessels that supply blood to different regions of the skin. Also spinal injuries may be detected faster and earlier than by other means. Thermography may also help in the management of burn patients, patients with frost bites, patients with acute phlebitis or lymphatitis, patients with heat stroke, or poisoned individuals, all of whom are known to manifest pathological local or general changes in skin temperature. Essentially what would be indicative is gross assymetries in the thermographic images as well as gross deviations from the skin temperature distribution of normal subjects. An open question that may exist in such situations is whether a thermographic abnormality is related to the injury or did exist beforehand. Knowledge of normal thermophysiology combined with a repeated scan after a short while may help to differentiate between these alternatives.

5. Dermatology.

Thermological applications to dermatology have been made possible only recently with the advent of a short focal length camera. With a resolution of <0.1 mm and a thermal resolution of <0.1C the temperatures of skin lessions can be assessed and one can differentiate between vascularized or hypermetabolic lessions and hypometabolic non-vascularized ones. Research aimed at differentiating between malignant and non malignant vascularized lessions is in progress.

A special subject combining dermatology and immunology is the quantitative assessment of skin sensitivity to chemicals, by measuring the local temperature of the skin at predetermined times following a given topical exposure. This application is an extention of using themography to obtain a permanent quantitative record of allergy response following the subcutaneous injection of an antigen.

6. Oncolgy.

Thermography has gained substantial disrepute following claims that using contact area measurement methods (liquid crystals) it is an effective screening method for the detection of breast cancer.[14] The rationale was based on the fact that carcinoma of the breast is a vascularized hypermetabolic lesion, the temperature of which is proportional to its malignancy. The early success of easy detection of shallow malignant lesions was followed by the disapointing results with deeply situated malignant lumps that could be detected by other imaging modalities. It is not completely clear whether the lack of sensitivity is intrinsic in the methodology, whether it was caused by limitations of the instrumentation used in several pilot studies, or was due to lack of standardization and experience of the operators.[15] In any case, the American Cancer Society, the National Cancer Institute and the American college of Radiology have expressed serious doubts regarding claims on the efficacy of thermography as a screening technique for cancer of the breast.

On the other hand, there have been several recent reports that strongly suggest that this diagnostic method is more efficatious than is now generally believed.[15-17] It has been pointed out that using higher resolution of imaging, standardized preparation of the patients, and global pattern analysis of the images are prerequisits of an effective screening test.[15] Even contact thermography is claimed to produce reliable results if better controlled procedures are applied,[18] and the sensitivity of diagnosis improves when inflammed malignancy is assessed.[19] We must conclude that this application of thermography warrants a new and independent reevaluation.

7. Space medicine.

Thermography might offer unique information by remote monitoring of human circulation and temperature control physiology in a micro-gravity environment. Assessment of the reactions of the autonomous nervous system has been referred to above. In addition, using a light-weight telescopic IR camera, one might continuously and unobtrusively monitor the hydrostatically induced changes in cerebral blood flow during acceleration and deceleration of the space vehicle. Other uses of thermography might include the rapid detection of diaphoresis and possibly of fatigue by monitoing the faces of space travelers.

CONCLUSIONS AND PROJECTIONS

For unfortunate historical reasons, thermography became known as a technique used by lawyers and physical therapists rather than by clinicians. This and the possible oversale of thermography as a screening method for breast cancer, explain the fact that only this year has thermography been considered by the AMA for approval as an effective diagnostic procedure in neurology. This unhappy history will probably be soon forgotten with the growing number of high quality demonstration studies now in progress. Also the instrumentation that was just a few years ago marginally adequate for objective, quantitative diagnosis, has been substantially improved. New and significantly more versatile and more accurate thermographic imaging systems are being currently developed and will become part of the arsenal of clinical imaging in the next year or two.

As has been described in this brief review, computerized thermography is a new and rapidly emerging clinical technology that offers novel, objective and quantitative, diagnostic information to a growing number of medical specialties. Thermology stands out among other diagnostic imaging modalities by its completely non invasive nature which allows its repeated or continuous application with <u>no</u> side effects. Like computerized tomography, magnetic resonance imaging or digital radiography, thermography records an image (in this case a raster of the absolute temperature of each pixel of a projected plane perpendicular to the camera) that can be processed at will to later extract substantial diagnostic information. Although generically all that thermography represents is blood flow rates and the rate of local tissue metabolism, this information, which is diagnostically important in a large variety of clinical situations, is not duplicated by any other imaging modality. There is, in fact, less redundancy between thermographic diagnostic information and that of other imaging modalities, than among many of the other imaging methods.

Where does thermography fit in clinical practice? Will we train a new breed of thermological specialists, probably as a subspecialty of diagnostic imaging? Or, will thermographs become one of the many tools of the neurologist (like the EEG or EMG), or of the orthopedic or plastic surgeon (like the surgical laser)? The relatively low cost of computerized thermographic systems, the "user friendliness" of their software, and the fact that thermography is free from any side effects, will probably make this imaging technique part of the equipment arsenal of any specialty that can benefit from it; the experience with ultrasonic imaging, where for instance, sonocardiographic imaging became a routine cardiological tool while fetal imaging is routinely done in obtetrics, encourages us to make this prediction.

What is still missing is more information on the precise mechanisms of the physiological distribution and control of skin temperature on different parts of the human body. Such information will lead to a better understanding of pathological states. This information will probably be forthcoming soon with the general acceptance of thermology as an effective diagnostic method and with the advent of additional diagnostic applications.

NOTE: This review is based on a paper recently submitted by the author to the International Journal of Technology Assessment in Health Care.

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