The Historical Development of Thermometry and Thermal Imaging in Medicine

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Fever was the most frequently observed condition in early medical observation. From the early days of Hippocrates, when it is said that wet mud was used on the skin to observe fast drying over a tumoural swelling, physicians have recognised the importance of a raised temperature. For centuries, this remained as a subjective skill, and the concept of measuring temperature was not developed until the 16th Century.

Galilleo made his famous thermoscope from a glass tube, which functioned as an unsealed thermometer. It was subject to atmospheric pressure as a result.

In modern terms we now describe heat transfer by three main modes. The first is conduction, requiring contact between the object and the sensor. The second mode of heat transfer is convection, and the third radiation. Both of the latter had led to remote detection methods.

Thermometry

Thermometry developed slowly from Galilleo's experiments. Florentine and Venetian glassblowers in Italy made complex sealed glass containers of various shapes, to be tied onto the body surface. Temperature was assessed by the rising or falling of small beads or seeds within the fluid inside the container. Huygens, Roemer and Fahrenheit all proposed the need for a calibrated scale in the late 17th and early 18th century. Celsius did propose a centigrade scale based on ice and boiling water. He strangely suggested that boiling water should be zero, and melting ice 100 on his scale. It was the Danish biologist Linnaeus in 1750 who proposed the reversal of this scale, as it is known today. Although International Standards have given the term Celsius to the 0-100 scale today, strictly speaking it would be historically accurate to refer to degrees Linnaeus or Centigrade [1].

The Clinical thermometer, which has been universally used in medicine for over 130 years was developed by Carl Wunderlich in 1868. This is essentially a maximum thermometer with a limited scale around the normal internal body temperature of 37^{0}C or 98.4^{0}F. Wunderlich's treatise on body temperature in health and disease is a master-piece of painstaking work over many years. He charted the progress of all his patients daily, and sometimes two or three times during the day. His thesis, was written in German for Leipzig University and has also been translated into English in the late 19th century [2].

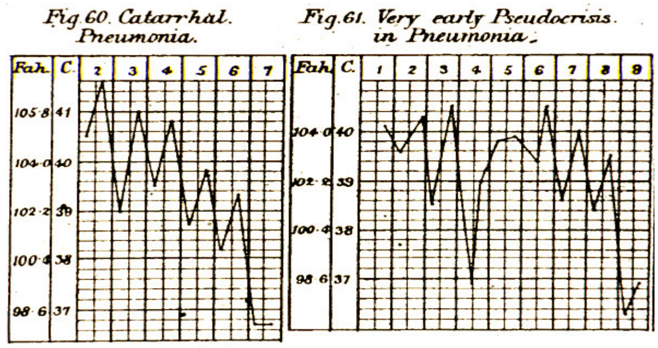

figure 1 Two of Wunderlich's early temperature graphs.

Today, there has been a move away from glass thermometers in many countries, giving rise to more disposable thermocouple systems for routine clinical use.

Contact thermography

Liquid crystal sensors for temperature became available in usable form in the 1960's. Originally they were painted on the skin which had previously been coated with black paint. Three of four colours became visible if the paint was at the critical temperature range for the subject. Micro-encapsulation of these substances that are primarily cholesteric esters, resulted in plastic sheet detectors. Later these sheets were mounted on a soft latex base to mould to the skin under air pressure using a cushion with a rigid clear window. Polaroid photography was then used to record the colour pattern while the sensor remained in contact. The system was re-usable and inexpensive. However, sensitivity declined over 1-2 years from manufacture, and many different pictures were required to obtain a subjective pattern of skin temperature[3].

Radiation based methods

Convection currents of heat emitted by the human body have been imaged by a technique called Schlieren Photography. The change in refractive index with density in the air around the body is made visible by special illumination. This method has been used to monitor heat loss in experimental subjects, especially in the design of protective clothing for people working in extreme physical environments.

Heat transfer by radiation is of great value in medicine. The human body surface requires variable degrees of heat exchange with the environment as part of the normal thermo-regulatory process. Most of this heat transfer occurs in the infra red, which can be imaged by electronic thermal imaging. Infra red radiation was undefined before 1800 when Sir William Herschel performed his famous experiment to measure heat beyond the visible spectrum[4]. Nearly 200 years before Italian observers had noted the presence of reflected heat. John Della Porta in 1698 observed that when a candle was lit and placed before a large silver bowl in church, that he could sense the heat on his face. When he altered the positions of the candle, bowl and his face, the heat was no longer experienced.

Reflect heat, cold, and the voice too, by a Concave-Glass.

If a man put a Candle in a place, where the visible Object is to be set, the Candle will come to your very eyes, and will offend them with its heat and light. But this is more wonderful, that as heat, so cold, should be reflected: if you put snow in that place, if it come to the eye, because it is sensible, it will presently feel the cold. But there is a greater wonder yet in it; for it will not onely reverberate heat and cold, but the voice too, and make an Eccho; for the voice is more rightly reflected by a polite and smooth superficies of the Glass, and more compleatly than by any wall.

Figure 2. Quotation from an account by Della Porta.

William Herschel, in a series of careful experiments showed that not only was there a “dark heat” present, but that heat itself behaved like light, it could be reflected and refracted under the right conditions. William’s only son John Herschel repeated some experiments after his father’s death, and successfully made an image using solar radiation. This he called a “thermogram” a term still in use today to describe an image made by thermal radiation. John Herschel’s thermogram was made by focussing solar radiation with a lens onto to a suspension of carbon particles in alcohol. This process is known as evaporography [5].

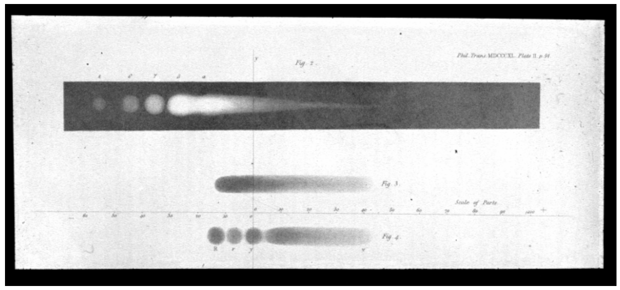

Figure 3. A solar evaporagram named *Thermogram* by Sir John Herschel in 1840.

A major development came in the early 1940's with the first electronic sensor for infra red radiation. This was made from indium antimonide, and was mounted at the base of a small Dewar vessel to allow cooling with liquid nitrogen. The first medical images taken with a British prototype system the "Pyroscan" were made at The Middlesex Hospital in London, and The Royal National Hospital for Rheumatic Diseases in Bath in 1959-1961. By modern standards these thermograms were very crude. A mark 2 Pyroscan was made for medical use in 1962, with improved images. However, the mechanical scanning was slow and each image needed from 2-5 mins. to record. The final picture was written line by line on electro-sensitive paper. During this time the potential for thermal imaging in medicine was being explored in an increasing number of centres. Earlier work by the American physiologist J Hardy had shown that the human skin regardless of colour is a highly efficient radiatior with an emissivity close to that of a perfect black body – 0.98. Cancer detection was a high priority subject, and with hopes that this new technique would be a tool for screening breast cancer many centres across Europe the USA and Japan became involved. In the UK K.Lloyd Williams showed that many tumours are hot, and the hotter the tumour the worse the prognosis. By this time the images were displayed on a cathode ray screen in black and white. Image processing by computer had not arrived, so much discussion was given to schemes to subjectively score the images, and to look for hot spots and asymmetry of temperature in the breast. This was confounded by changes in the breast through the menstrual cycle in younger women. The use of false colour thermograms was only possible by photography at this time. A series of bright isotherms were manually ranged across the temperature span of the image, each being exposed through a different colour filter, and superimposed on a single frame of film.

By the mid 1970's the first computer systems had arrived. In Bath, a special system for nuclear medicine made in Sweden was adapted for thermal imaging. A colour screen was provided to display the digitised image. The processor was a PDP8, and the programme was loaded every day from paper-tape. With computerisation many problems began to be resolved. The images were archived in digital form, standard regions of interest could be selected, and temperature measurements obtained from the images. Manufacturers of thermal imaging equipment slowly adapted to the call for quantification and some sold thermal radiation calibration sources to there customers to aid the standardisation of technique. Workshops which had started in the late 1960's became a regular feature, and the European Thermographic Association was formed with a major conference in Amsterdam in 1974. Apart from a range of physiological and medical applications groups were formed to formulate guidelines for good practice. The included the requirements for patient preparation, conditions for thermal imaging and criteria for the use of thermal imaging in medicine and pharmacology [6,7] .

A thermal index was devised in Bath to provide a simplified measure of inflammation for clinicians. A normal range of values was established for ankle elbows hands and knees, with raised values obtained in osteoarthritic joints and higher values in Rheumatoid Arthritis.

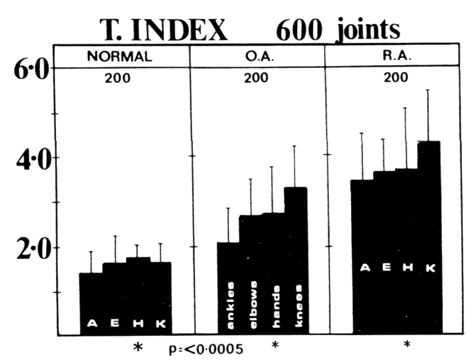

Fig. 4 Thermal Index calculated from standard regions of interest over the peripheral joints of control subjects, a group with Osteoarthritis and a group of Rheumatoid arthritis patients (on alalgesic treatment only).

A series of clinical trials with non-steroid anti-inflammatory oral drugs and steroid analogues for joint injection were published using the index to document the course of treatment [8].

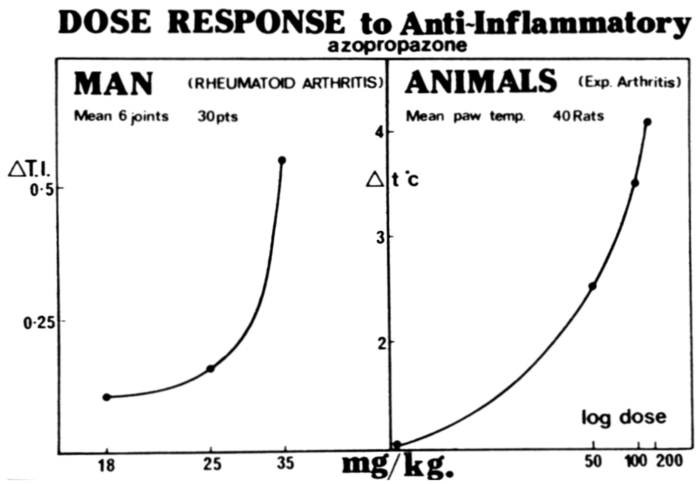

Figure 5. Thermal index, dose response curve of the drug Azopropazone applied to both man and animals in clinical trials.

Thermal Imaging Systems

Improvements in thermal imaging cameras have had a major impact, both on image quality and speed of image capture. Early single element detectors were dependant on optical mechanical scanning. Image resolution, spatial and thermal were inversely dependant on scanning speed. The Bofors and some American imagers scanned at 1-4 frames per second. AGA cameras were faster at 16 frames per second, and used interlacing to smooth the image. Multi element arrays were developed in the UK and were employed in cameras made by EMI and Rank. Alignment of the elements was critical, and a poorly aligned array produced characteristic banding in the image. The first significant detector for faster high resolution images was produced by Prof. Elliott, this subsequently became known as the Sprite detector, representing Signal Processing In The Element. The detector was used in the Rank Taylor Hobson High Resolution system called Talytherm. This camera also had a high specification Infra red zoom lens, with a macro attachment. Superb images of sweat pore function, eyes with contact lenses, and skin pathology were recorded with this system. (figure 6).

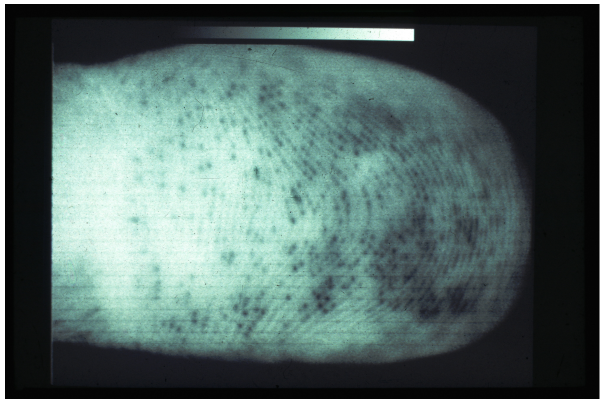

Figure 6 High resolution thermogram showing sweat distribution on a finger.

From the multi element arrays, came the first focal plane array detectors, with increasing numbers of pixel/elements, yielding high resolution at video frame rates. Un-cooled bolometer arrays have also been shown to be adequate for many medical applications. Without the need for electronic cooling systems these cameras are almost maintenance free. Good software with enhancement and analysis is now expected in thermal imaging. Many commercial systems use general imaging software, which is primarily designed for industrial users of the technique. A few dedicated medical software packages have been produced, which can even enhance the images from the older cameras. CTHERM is one such package which is a robust and almost universally usable programme for medical thermography (Univ. of Glamorgan www.medimaging.org).

As standardisation of image capture and analysis become more widely accepted, the ability to manage the images, and if necessary transmit them over an intranet or internet for communication become paramount. Future developments will enable the operator of thermal imaging to use reference images and reference data as a diagnostic aid. This however depends on the level of standardisation that can be provided by the manufacturers, and by the operators themselves in the performance of their technique [9].

Modern thermal imaging is already digital and quantifiable, and ready for the integration into anticipated hospital and clinical computer networks.

Paper given at the conference on Thermal imaging In Medicine, The Royal Free Hospital, London May 2002.

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