Techniques of measurement in medicine 7

Medical infra-red thermography: principles and practice

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PRINCIPLES AND PRACTICE

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Preface

The preface is an important part of any book, but unfortunately is rarely read because it suffers from being considered extra to the text. In this preface I have gathered together some useful information which did not easily fit into the main text, and I also outline the objectives of the book, identifying the way in which the book has been arranged, and suggesting how readers of varying technical knowledge should use the book to their best advantage.

The object of this book is to provide readers with the information necessary to take good, consistent thermograms. I hope that the treatment will be of value, not only to those who are new to thermography, but also those who have had considerable experience yet wish to increase their understanding of the subject.

Writing for such a wide readership creates considerable difficulty because the experienced reader wants to extract relevant facts quickly, whereas inexperienced readers generally require much more explanation. This problem is compounded by an interdisciplinary subject such as thermography because some readers will be physicists and engineers with considerable technical skill but little physiological or medical knowledge, while other readers will have a medical background but little technical knowledge. I have tried to organise the book so that the conflicting irritations of having the 'obvious' spelt out, or technical concepts not explained, have been minimised. In particular, I have sought to make sure that important technical concepts mentioned in the book have been introduced from first principles, but by making extensive use of sub-sectioning I hope that the more knowledgeable readers can avoid what to them might appear to be unnecessarily trivial discussions. An introduction to the subject is provided in Chapter 1, which in addition to Appendix 1 (basic physics) should make the book reasonably self-contained for the non-technical reader. These sections can be ignored by those with the necessary background, but technically qualified readers who have not had previous experience of infra-red (IR) thermography might find it useful to skip through Chapter 1 for an introduction to basic thermographic principles and techniques.

At the suggestion of the series editors, Professors Rotblat and Watson, the text has been split into two relatively independent sections. The first half of the book introduces the subject in Chapter 1 and then discusses the clinical technique and applications. In the second half of the book, concepts introduced in Chapter 1 are treated in greater depth, and the technical aspects of IR thermography are developed.

Medical thermography is characterised by the measurement of relatively low temperatures, and by the fact that clean, healthy human skin approximates an ideal thermal solid. These somewhat simplifying features are offset by the fact that the temperature of the skin is dependent upon the physiological conditions. Thus, a thermogram of the hand will be quite different with the hand in different positions; it will be dependent upon whether the subject has just eaten a large meal, consumed alcohol, or smoked, and it will also vary with the air temperature, humidity and time of day. Control of the physiological conditions is therefore as important as control of the instrumentation.

Although the book is primarily concerned with the medical application of IR thermography, the requirements of good IR thermographic practice have a common core regardless of the application. These requirements demand a knowledge of the physics of IR radiation, together with an understanding of IR imaging systems. The emphasis in this book is therefore on creating an appreciation of 'what' is being measured and of 'how' it is being measured. Why it is being measured depends on an intimate knowledge of each particular application, the detail of which is outside the scope of this book. There is therefore little discussion of the medical interpretation of the thermograms because this can only really be done within the context of the appropriate medical speciality.

Some years ago the European Thermography Association (ETA) and its American counterpart, the American Thermography Association, were formed. These and similar organisations, such as the Japanese Society of Biomedical Thermography, have done much to foster the applications of thermography, particularly in the medical sector. They are an invaluable source of guidance for the newcomer to thermography. Industrial and civil applications are becoming increasingly important, and there is now a concerted effort to organise the industrial side of the ETA as effectively as the medical side.

Other valuable organisations within Europe are the numerous national societies that are affiliated to the ETA. I have had particular involvement with the Anglo-Dutch Thermographic Society which meets twice yearly, alternating the venue between the United Kingdom and the Netherlands. In addition, the Society has a number of specialist sub-groups which research problems relevant to their particular speciality, and keep the other members of the association informed of current developments.

The colour plates appear between pages 70 and 71.

We are indebted to AGA Infra-red Systems Ltd for a grant towards the cost of the colour illustrations.

The American Thermographic Society produces a newsletter called *Hot-Spot* which is circulated amongst its members, and the European Thermographic Society sponsors a journal called *Acta Thermographica*. The policy of *Acta Thermographica* is to publish articles on any thermographic topic, although until now the content has been overwhelmingly medically orientated. Two supplements to *Acta Thermographica* produced by the ETA might be of interest to readers of this book: a booklet explaining commonly used thermographic terminology, which takes the form of a dictionary/encyclopaedia, and a teaching booklet on medical thermography. The principal feature of the teaching book is that the various clinical applications each occupy a chapter and are written by specialists in each topic.

Other books that might be found useful are *Infrared Systems Engineering* by R. D. Hudson (1969), containing an excellent bibliography on medical thermography up to the date of publication; *Radiative Heat Transfer* by R. J. Siegel and J. R. Howell (1972), which is a treatise on IR theory that begins where Chapter 11 of this book ends; and *Thermal Imaging Systems* by J. M. Lloyd (1975), which is a fairly comprehensive discussion of the design principles involved in forward-looking IR imaging systems.

I began writing this book towards the end of 1976 and the experience has left me full of admiration for the authors of the large textbooks which I consult so regularly. There are many deficiencies of which I am aware, but my publisher has, in the nicest possible way, called *voilà tout*. My sincere thanks are extended to the many friends and colleagues who have helped me in writing this book. I am particularly indebted to my friends in the European thermographic societies, and to the IR thermographic manufacturers who so freely discussed technical details with me.

This book would never have been written without the opportunity and support given to me by Bernard Watson, nor produced without the hours of typing by Miss K. Grover and my wife, or the hard work and patience of my copy editor, Andy Colborne. I am extremely grateful to them and to Alan Winter and his colleagues at Cambridge University Press for providing the back-up necessary to produce the finished article.

Emerson said 'There is always a best way of doing everything, even if it be to boil an egg'. I hope that I have provided some useful recipes.

R. E. Woodrough May 1980

Contents

1. Important concepts

1.1. Infra-red thermography

Have you read the preface? If not, you are strongly advised to do so before reading this chapter. Non-technical readers are reminded that Appendix 1 is a guide to the basic physics taken for granted in this book, and should be consulted if an explanation is required of any unfamiliar terms.

Medical thermography is concerned with recording the temperature distribution of the human body, including temperature distributions within the body tissues. Infra-red thermography is one of the most widely used techniques of medical thermography, and is generally used to form an image of the temperature distribution over the exposed surface of the body (Figure 1.1). The majority of examinations involve the determination of temperature distribution over the skin, obtained under constant, standardised conditions. However, recent developments have led to an increasing number of examinations conducted under dynamic conditions, where changes in skin temperature are monitored following an environmental, physiological or pharmacological stress. A second important development has been the use of infra-red (IR) thermography to image the temperature distribution over the surface of body tissues other than the skin. For example, IR thermography is being successfully used to visualise coronary artery blood flow and assess myocardial perfusion during bypass surgery. The technique involves an injection of cold saline into the bypass graft connecting the aorta to the coronary artery, and monitoring its subsequent passage.

Figure 1.1. A typical monochromatic thermogram. The calibration scale at the bottom runs from cold on the left to hot on the right. In this example white areas are the hottest and black areas are the coldest.

A thermogram is the name given to the graphic record of the temperature distribution obtained by thermography, and may be a monochromatic thermogram as in Figure 1.1, or a colour thermogram (e.g. Plate 14.1). Infra-red thermograms can be produced without using a scanning mechanism, by means of special imaging detectors which convert the IR radiation emitted by the body into a visible image, or by means of infra-red cameras, which produce electrical signals corresponding to the quantity of infra-red radiation being emitted from each point in the field of view and require a scanning mechanism to produce an image. The electrical signal is then used to drive a visual display (Figure 1.2), usually a video monitor.

High contrast thermograms can only be obtained by employing some form of background subtraction because the inherent contrast in the IR image is very low. This is a severe restriction on most thermal imaging detectors, whereas background subtraction is no problem to IR cameras generating the image electronically.

The majority of IR cameras use a lens or mirror system to focus the IR radiation emitted by the body into the plane of an IR detector. Until recently the detectors most frequently used in medical IR cameras have been single element, indium antimonide detectors, requiring cooling with liquid nitrogen for successful operation. Nowadays the preferred detector is cadmium mercury telluride (HCT) which is better suited to imaging the IR radiation emitted by the human body, and can also be obtained, not just as a single element, but in 100-element arrays. Furthermore, if a degraded performance is acceptable, the HCT detector can be made to work at room temperature. Another innovation has been

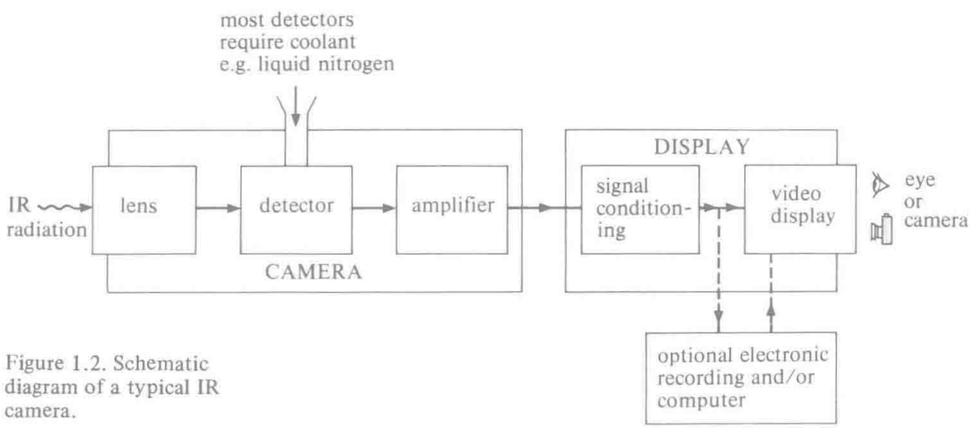


Figure 1.2. Schematic diagram of a typical IR camera.

the introduction of pyroelectric vidicon tubes capable of producing IR thermograms in a manner analogous to closed circuit television. Pyroelectric vidicon systems do not require cooling and are notable for their portability and ruggedness. Though not yet matching conventional IR cameras in performance, they are considerably cheaper and are proving sufficient for many medical applications.

Conventional IR cameras using discrete detectors require the addition of a scanning system to detect the IR radiation being emitted from each point on the surface under examination (Figure 1.3). At any instant, the quantity of IR radiation registered by a discrete detector (referred to as the instantaneous detector irradiance) is related to the temperature at a point on the emitting surface (e.g. the skin), and therefore the electrical signal produced by the detector can be used to produce an image of the temperature distribution over the surface. This is achieved by synchronising the scanning system with a display, typically a video monitor, which produces a television type of image, but represents variation in temperature rather than variation in reflected light. Incidentally, IR thermography depends

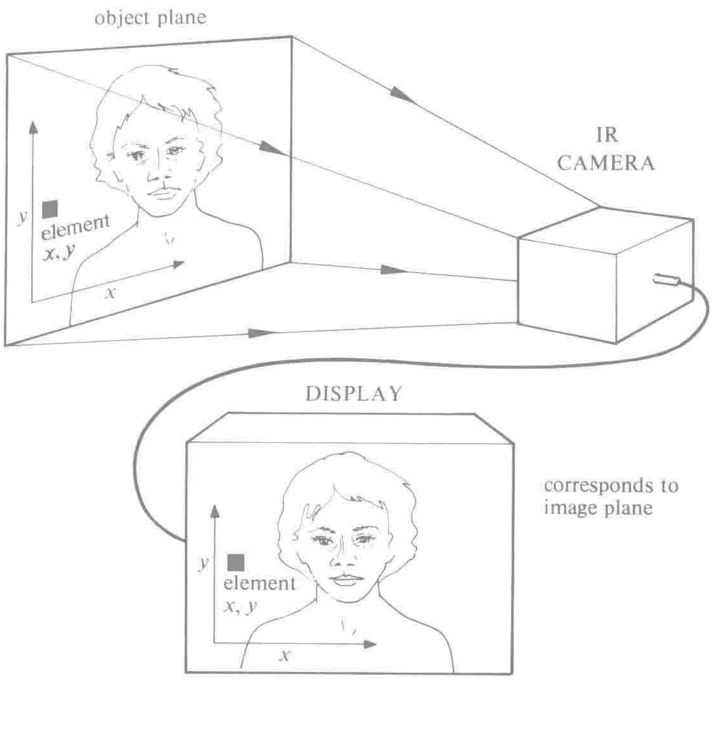


Figure 1.3. Synchronising the display with the scanning of the object field produces an image.

upon self-emitting IR radiation and must not be confused with IR photography, which depends upon reflected IR radiation of shorter wavelengths.

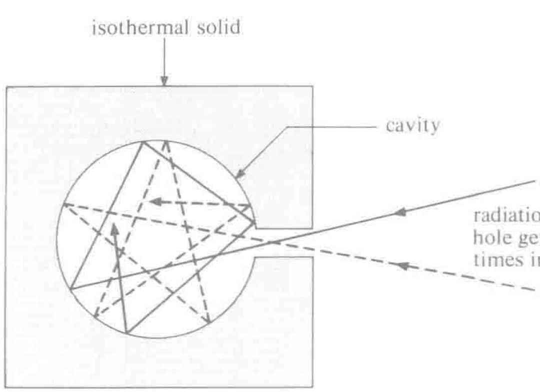
1.2. Emission of infra-red radiation

The ideal thermal solid

In solids, the electrons bonding the atoms together gain more and more energy the further the temperature of the solid is from absolute zero. A common physical model is to think of these electrons as vibrating bonds between the atoms. The warmer the solid gets, the more the bonds vibrate, and it is this oscillation which causes IR radiation to be emitted.

When discussing the emission or absorption of electromagnetic radiation, physicists make use of the concept of an *ideal thermal solid*. Such a solid has the property of absorbing all electromagnetic radiation incident upon it, irrespective of the direction from which it comes, and this property leads to a number of important radiation laws. A very close approximation to the theoretical concept of an ideal thermal solid is the *cavity radiator* (Figure 1.4) which comprises a cavity within a uniformly heated (isothermal) solid, with a very small hole connecting the cavity with the outside. The hole behaves like an ideal thermal solid, because any radiation falling upon the hole gets reflected many times within the cavity. With each reflection some energy is absorbed, so that very little energy gets reflected out of the hole. Notice that our reasoning is in no way affected by the material forming the internal surface of the cavity, or the shape of the cavity, and this fact is borne out by experiment. Since an ideal thermal solid at absolute zero would absorb all radiation incident upon it, ideal

Figure 1.4. Principle of the cavity radiator.



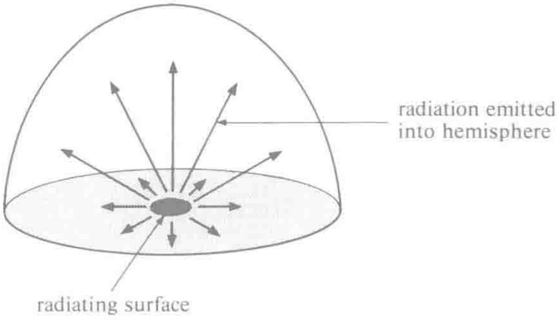
thermal solids would appear black. For this reason thermal solids are often referred to as *black bodies*, but in this book the term ideal thermal solid is preferred and the radiation emitted from such a solid at temperatures higher than absolute zero is referred to as *cavity radiation*. Ideal thermal solids are used for the calibration of IR measuring systems, full details of which are given in Chapter 15.

The total quantity of energy emitted per unit time and per unit surface area from a surface is called the *hemispherical total emissive power*. 'Hemispherical' refers to the fact that the radiation is emitted into a hemisphere because only radiation emitted into a hemisphere can escape from the surface (Figure 1.5) and 'total' refers to the fact that the energy is spread over all possible wavelengths.

Until recently there has been considerable variation and ambiguity in IR terminology, and this matter is discussed at greater length in Chapter 11, with only the most necessary terms being defined in this chapter. When describing the emission of radiation of a particular wavelength, we use the term 'spectral' rather than 'total', and refer to *spectral emissive power*. The spectral emissive power from a surface can be measured, and plotted against wavelength (Figure 1.6). Such graphs are called spectral emissive power curves. Figure 1.7 shows the spectral emissive power curves for an ideal thermal solid at various temperatures. These curves always take the same form, and can be calculated from an equation called Planck's spectral emissive power function. The theoretical description of the spectral emissive power curves from an ideal thermal solid was one of the major achievements of nineteenth century physics, and marked the beginning of the development of quantum mechanics.

Several important features of cavity radiation are immediately

Figure 1.5. Emission of IR radiation into a hemisphere.



obvious in Figure 1.7. Notice how the area under the curve increases as the temperature of the ideal thermal solid increases. The area under the spectral emissive power curve represents the total emissive power, i.e. the quantity of energy emitted by all wavelengths, and turns out to be proportional to the fourth power of the absolute temperature. A second important feature of Figure 1.7 is the way in which the wavelength, for which the spectral emissive power is a maximum, decreases as the temperature increases. The relationship is simply that the wavelength at which the spectral emissive power is a maximum multiplied by the absolute temperature is a constant.

Most surfaces do not approximate ideal thermal solids, and these surfaces emit less IR radiation than the ideal. The ratio of the emissive power emitted by a surface to the emissive power which would have been emitted by an ideal thermal solid is called the *emissivity* of the surface. Emissivity is usually wave-

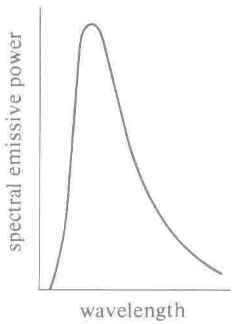


Figure 1.6. A typical spectral emissive power curve.

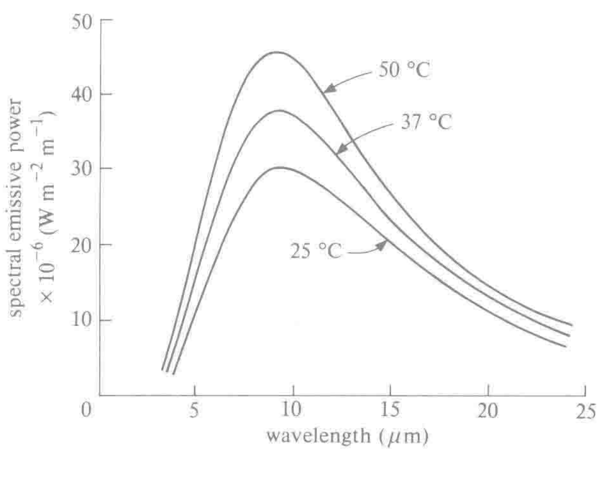


Figure 1.7. Variation of the spectral emissive power curve with temperature.

length-dependent and can vary with physical conditions. It is therefore most important to know the wavelength, or wavelength range, at which emissivity is measured, together with the physical conditions which existed when the measurement was made.

Measurements of emissivity for wavelengths in the IR have shown that some substances, such as polished metals, are very poor radiators of IR radiation but others, notably carbon black (lamp black), can approach close to the ideal. Lamp black has an emissivity of 0.95 in the IR region of the spectrum, and is often used to paint the surface of thermal radiators required to approximate ideal thermal solids.

1.3. A note on terminology

An unfortunate consequence of rigour is that definitions and terminology become long and involved. It is, for example, necessary in the technical chapters to use terms such as 'finite solid-angle band emissive power'! When confronted by such long and seemingly complicated expressions, the worst (but most common) reaction is to panic; much more sensible, is to take each word in the expression on its own. My advice to the inexperienced reader is not to get too bogged down in these definitions, because it is not necessary to understand them explicitly in order to understand the rest of the book. They have been included so that the reader is able to interpret the available data in the literature, and in order to create an awareness that, although in our everyday work we speak loosely of emissive power, emissivity, reflectivity, etc., these quantities are in fact dependent upon wavelength range, and direction. This is made clear in the terminology which always has the format: (specification of direction), (specification of wavelength range), (name of radiation property). Thus, hemispherical total emissive power specifies that we are considering all possible directions (through a hemisphere), that we are considering all possible (total) wavelengths and that the radiation property being discussed is the quantity of energy being radiated (emissive power).

1.4. Infra-red optics

Infra-red radiation obeys the same laws of reflection and refraction that we associate with visible light but some features of IR optics are worth noting.

In Chapter 11 it is shown that opaque materials, which are highly reflecting, will be poor radiators, while poor reflectors