EAT 2018-Introductory Thermography Course Syllabus

Introductory Thermography Course Structure

Date: 4th July 2018

9:00 Registration

Theory

9:10 Opening of the course (Kevin Howell)

9:15 Physical principles of heat transfer (Ricardo Vardasca)

9:45 Principles of thermal physiology/skin blood perfusion (James Mercer)

10:45 Coffee break

11:00 Standardization of thermal imaging, recording and analysis (Kurt Ammer)

12:00 Quality assurance for thermal imaging systems (Rob Simpson)

12:30 Producing a thermographic report (Kurt Ammer)

13:00 Lunch

Practical Session

13:45 Provocation tests (James Mercer and Manuel Sillero)

14:45 Image analysis (Kurt Ammer and Ricardo Vardasca)

15:15 Coffee break

15:30 Hands-on supervised practice (all course teachers)

16:30 Educational resources (Adérito Seixas)

16:45 Closing

Physical principles of heat transfer

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Thermodynamic temperature is one of seven base quantities in physics. A physical property of a system that does not depend on the system size or the amount of material in the system, is called intensive. The base quantity temperature is an intensive quantity of heat energy and represents the mean kinetic energy of atoms or molecules in a substance.

Energy can be defined as the ability to do work and is expressed by the same equation as work. It exists in many forms, such as mechanical, electrical, nuclear, and thermal. Transformation of one form of energy into another is possible, for example a thermally powered generating station can produce electricity. The transformation of all other forms of energy into heat can be total, but the contrary, i.e., the transformation of heat into one of the other forms, is never 100 percent efficient. Heat thus appears to be a special form of energy. The SI unit of energy is the Joule. For thermal energy, 1 Joule is the energy dissipated as heat when an electric current of one ampere passes through a resistance of one ohm for one second. In relation to temperature, 1 Joule is expressed as the 1/4.184 part of heat energy required to raise the temperature of a unit weight (1 g) of water from 0oC to 1oC. 4.184 Joules are equal to the traditional unit of 1 calorie [1].

In any closed system with an outer membrane (diathermal wall) permissive to energetic, but not to material exchange, energy is transferred from the high level to the low level. Thermal energy can be transferred without or with change of state of matter. Heat transfer without change of state can occur by either conduction, convection, or radiation. During heat exchange, the temperature at the high level of thermal energy falls, whilst the temperature at the low-level rises, until equilibration is achieved. [1].

In heat transfer with change of state, the temperature of the phase changing matter is constant. Since change of the state either requires or releases thermal energy, the system in which the phase change occurs gains or loses heat. Changing liquid water into vapour requires thermal energy. In a condition in which a thin film of water is evaporating from a surface, the temperature of the surface is decreasing. [1].

The minimal thermodynamic temperature is absolute zero, where the thermal motion of all fundamental particles in matter reaches a minimum. Temperature can be expressed in several scales. The International System of Units (SI) scale is the Kelvin (K), which has as its null point absolute zero, and is defined as the fraction (1?273.16) of the thermodynamic temperature of the triple point of water. The triple point of a substance is described by the temperature and pressure at which the three phases (gas, liquid, and solid) of that substance coexist in thermodynamic equilibrium. Other commonly used scales are the Celsius scale (°C), informally known as degrees centigrade and originally defined by the freezing (0°C) and boiling (100°C) points of water at a pressure of 1 atmosphere, and the Fahrenheit scale (°F), in which the null point is defined as the temperature of a solution of brine made from equal parts of ice, water and salt, and there are 180°F of separation between the freezing and boiling points of water [2-5].

In conduction, thermal energy is transmitted through a medium from one particle to another, requiring direct contact. With convection, it is transferred by fluid motion (gas or liquid), which may be caused by density differences (natural) or external mechanical forces (forced). Radiation transmits thermal energy through electromagnetic waves, the movement of heat of the charged particles inside the atoms is converted into electromagnetic radiation [3-5].

The electromagnetic spectrum describes the range of frequencies (the spectrum) of the electromagnetic radiation and their respective wavelengths and photon energies, and it can be used to characterise existing bodies and materials. This frequency range is divided into separate bands called by different names. It begins at the low frequency (long wavelength) end of the spectrum: radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and ends with gamma rays at the high-frequency region (short wavelength). The spectral range from gamma rays to high ultraviolet are classified as ionizing radiation, since their photons have enough energy to ionize atoms, causing chemical reactions which are harmful for humans. The infrared spectrum is located at the left of the visible region, ranging from 0.7 μm to 1000 μm in wavelength, and it is divided into three parts: near-infrared, medium-infrared and far-infrared [2-6].

Infrared radiation is invisible to the human eye, lower in energy than visible red light, and is naturally emitted by any object with a temperature above absolute zero. Blackbody radiation is thermal electromagnetic radiation within or surrounding a body in thermodynamic equilibrium with its environment, or emitted by a blackbody (an idealized object which absorbs all radiation falling on it at all wavelengths). It has a specific spectrum and intensity that depends only on the body's temperature, which is assumed to be uniform and constant [2-10]. The physics of radiation follow the laws of optics and thermodynamics including absorption, diffraction, emission, reflection, refraction, scattering and transmission. For measurements of infrared radiation in medicine and related health, it is recommended to acquire only emitted radiation [7, 8].

Emissivity is the ratio between the radiant emittance produced by an object to that of a blackbody at a specific temperature, being dependent of its surface fine structure. This factor affects the accuracy of a remote temperature measurement. Its value can vary between 0 and 1, with 1 being the emissivity value of a blackbody [2]. The value of the emissivity of human skin is 0.98 [11].

The thermal radiation emitted across all wavelengths by a blackbody (ideal emitter) at any temperature can be calculated by Planck's law. Planck's law expresses the spectral radiance as a function of wavelength and temperature of the blackbody. The dominant frequency interval increases proportionally with the temperature. The rate of electromagnetic radiation emitted at a given frequency is proportional to the total value absorbed by the body at the same frequency. Wien's displacement law describes the relationship between the spectrum of blackbody radiation at any two temperatures. The emission of radiation of a blackbody has a spectral distribution that depends only on temperature, and the wavelength at which maximal radiation is emitted is inversely proportional to the temperature of the blackbody. According to the Stefan-Boltzmann law, the total amount of radiation, across all frequencies increases with the fourth power of the temperature, and it is with modified versions of this law that an infrared camera can determine the temperature from a perceived radiation source, comparing with an internal calibration source [1-12].

Consequences for temperature measurements in medicine

To promote thermal equilibrium between the body and the surrounding environment there are environmental factors that must be considered such as the environment temperature and the relative humidity, and the period of acclimatization to this before performing temperature recordings [12]. The dew point is a given temperature at which air containing a specific amount of water becomes saturated (condensation). Given a constant dew point in the air, if the ambient temperature rises, relative humidity falls and vice-versa. Other factors such as air flow, incident lighting and examination room size, have also to be considered.

Equipment available to assess temperature can be chemical, electrical or mechanical in operation. Examples of mechanical devices are: mercury in glass thermometers, bimetallic thermometers and pressure spring thermometers; chemical instruments include: liquid crystal sheets; and electrical examples are: thermocouples, resistance temperature detectors, infrared pyrometers and infrared cameras. Only the last two examples allow remote temperature recording, and both are based on the principle of infrared radiation [13].

The main characteristics of an infrared camera are the type of detector (which can be cooled or uncooled), the wavelength (which normally is medium or long wavelength), the focal plane array sensor size, the noise-equivalent temperature difference and the measurement uncertainty. When performing an examination with an infrared camera it is important to know the time required to stabilize the electronics, the image uniformity and the image focus. Appropriate camera settings such as emissivity, environmental temperature, relative humidity, distance to the target and temperature range are also recommended [12, 14-16].

The infrared sensors of a camera perceive an incident thermal radiation, which is then transformed into a voltage and, depending on the thermal resolution (bits), it is then coded into a radiometric value that is recorded into the camera proprietary file format. This, along with other parameters such as the emissivity and reflected temperature, along with the Planck constants, allows through the altered Stefan-Boltzmann law the calculation of a temperature value in Kelvin, and by the translation formula to degrees Celsius [6].

References

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Principles of thermal physiology & skin blood perfusion

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Infrared Thermal imaging (IRT) in medicine is used to image (thermogram) and accurately measure the surface temperature distribution of the human skin. The temperature distribution of the skin in healthy subjects varies according to a wide range of factors that not only depend on the body part being imaged but also on a large range of intrinsic and extrinsic factors, ranging from physiological control to environmental conditions. In fact, the number of factors that can affect the skin temperature in humans is very large and the infeasibility of controlling for all of them is one of the major challenges we have in performing IRT [1]. Thus, a general knowledge of these factors is important for medical thermographers.

In addition, there are many pathological conditions that can affect skin blood perfusion and thereby skin surface temperature. Knowledge of changes in skin blood perfusion due to pathological conditions is perhaps one of the most important aspects in using IRT. These changes are often used, not only to help a medical practitioner in making a diagnosis, but also, for example, to follow the effect of a medical treatment or surgical intervention. Thus, in order to be able interpret a thermal image a thorough knowledge of thermal physiology in general and the control of skin blood flow in particular as well as some knowledge of vascular anatomy in normal healthy individuals is necessary.

In this part of the introductory course, we will start with a brief overview of the main principles of thermal physiology, including the physiological control of skin blood perfusion. We will then go into more detail on factors effecting skin blood perfusion, including an introduction to some relevant aspects of vascular anatomy. We will briefly describe the dynamic aspects of skin blood perfusion, which is important in medical thermal imaging, particularly in connection with thermal and other provocation tests. The latter topic will be covered in more detail in another section of the course. To illustrate central points a variety of thermal images and videos in normal healthy subjects will be shown. Some examples of pathological abnormalities will be also shown to further help our understanding.

It is beyond the scope of this introductory course to give a detailed instruction in thermal physiology and skin blood perfusion. These topics are well covered in the scientific literature as well as in most medical textbooks in physiology. For the interested reader I would like to recommend the following textbooks/review articles [2, 3, 4 & 5]. References [2 & 3] are book chapters that covers many points related to thermal physiology and cutaneous circulation. Both books also contain other chapters covering a wide range of relevant topics in medical thermography. Reference [4] is a user-friendly monograph designed for medical students as well as graduate students and postdoctoral trainees in medicine and other health-related sciences who need a comprehensive overview of thermoregulation. It presents the bases of the modern concepts in thermal physiology and pathophysiology, bringing together the disciplines encompassed by this highly integrative field (physiology, anatomy, biophysics, molecular and cellular biology, pharmacology, neuroscience, pathology, medicine, and others) into a clear and concise form. Reference [5] is a recent scientific review article on the physiology and function of arteriovenous anastomosis (AVA´s). AVA´s are direct short circuits between an artery and a vein and knowledge of their physiological function is important for interpreting thermal images from many body areas, especially the hands, feet and face.

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Standardization of thermal imaging, recording and analysis

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Thermal imaging is defined as imaging based on the detection of weak infrared radiation from objects. Applications include the mapping of the Earth´s surface from the air, weather mapping and medical thermography (thermal contours on the surface of the human body) [1].

A common definition of a thermogram (thermal image) is "a map of temperature distribution on the surface of the object imaged". Consequently, thermal imaging is often regarded as a technique for 2-dimensional temperature measurements [2].

Definition of a medical infrared thermal image or infrared thermogram: An infrared thermal image showing the surface temperature distribution of either the total human body or of defined body parts or anatomical regions respectively.

Important terms used in metrology will be provided such as measurement trueness, accuracy, precision, repeatability, reproducibility [3].

Standards define the minimal requirements in structure and processes which contribute to the constant quality level of a product. Following a standard protocol will lead to valid and reliable temperature measurements in medical thermal imaging. However, quality assurance procedures must not be restricted to temperature measurements, because conditions of image recordings, position and posture of the imaged subject, image composition and method of extracting temperature from thermograms affect temperature readings. Detection of temperature changes caused by physiological and pathophysiological mechanism is only possible, when all other courses of temperature alterations are very well controlled.

Most of the procedures for controlling the conditions of medical thermography have been developed by Prof Francis Ring since 1970.

They can be classified into 5 main factors [4, 5].

1. Subject or object
2. Camera Systems, Standards, and Calibration
    a. The imaging system
    b. Temperature reference
    c. Mounting the imager
    d. Camera initialisation
3. Patient Position and Image Capture
    a. Location for Thermal Imaging
    b. Ambient temperature control
    c. Pre-Imaging Equilibration
    d. Positions for Imaging - Glamorgan protocol [6].
    e. Field of View - Glamorgan protocol [6].
4. Information Protocols and Resources
    a. Patient preparation
5. Image related factors
    a. Image processing
    b. Image analysis - Glamorgan protocol [6].
    c. Image exchange
    d. Image presentation

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Quality assurance for thermal imaging systems

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This overview is an introduction to basic concepts in temperature measurement [1-3]. Its purpose is to provide background knowledge about temperature measurement, calibration and traceability. The instruments will also be considered: technical features; practical issues; application; and sources of error. Although it does not require any background in temperature measurement, it assumes that the reader has a good level of scientific knowledge.

Thermal imaging (thermography) has become widely exploited in clinical medicine, with uses ranging from general healthcare and screening, to detecting circulatory ailments and tumours. The exploitation of this qualitative imaging modality for quantitative assessment is reliant upon a robust metrology (measurement) framework, regular calibration, good measurement practice and educated users.

This is an overview that aims to introduce users to temperature measurement and take them beyond what they may have picked up in school, university or everyday life. It is hoped that, after this introduction the user will have increased measurement confidence and will expand their understanding further with the accessible literature.

We open with some background about temperature, its measurement, instrumentation calibration and traceability, and conclude with examples of some of the measurement difficulties that may be encountered in use.

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Producing a thermographic report

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A request for a thermographic investigation is the starting point and the guideline to what thermal images should be recorded. The report may vary depending on the request, and the set-up of the unit that conducts the investigation.

In the case of a clinical imaging service for physicians, the use of a referral form is recommended. In the case of studies or trials in medicine, physiology or sports science, the request is defined in the study protocol. For reporting studies in journals, books or at conferences, a checklist based on a Delphi consensus clearly defined the required content of a thermographic report [1].

For the report of an imaging service the following required information is proposed

1. Name of the referring physician

Personal information of the patient including the health problem leading to the referral. All this information is available from the referral form, which may be copied and pasted to build the first section of the report.

2. Imaging conditions

All environmental conditions such as model of the thermal imager, room temperature, time for acclimatisation, patient´s position and clothing during the acclimatisation period must be reported. Any provocation test such as exposure to a cold challenge or particular positions of imaged body parts must be described in detail.

3.Captured images

All images recorded must be displayed in the report. All images should be labelled with date, room temperature, abbreviation of body view and/or provocation test. All images must be presented together with the applied regions of interest.

4.Temperature readings

A minimal requirement is to report mean temperature ± standard deviation of each region of interest; maximum and minimum temperatures are optional. The difference in mean temperature of corresponding regions of interest must be calculated. Presentation of temperature values in a table is recommended

References

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Provocation tests

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Dynamic infrared thermography (DIRT) is based on the relationship between dermal perfusion and the rate of change of skin surface temperature (Tsk) following the application of a transient local provocation test, usually but not always, as described below, by a thermal challenge. Thus, while traditional thermography involves taking a single thermal image (thermogram), DIRT is based on the interpretation of a predetermined number of thermograms taken over a fixed period [1].

To perform DIRT, the regions of interest (ROI) being imaged are subjected to a provocation test and then single images are recorded and stored at pre-determined time intervals, for example 1 image every second. Ideally the camera position relative to the object being imaged should be kept constant. In most cases DIRT involves comparing the thermograms before, during, and at different selected time points during the recovery from the provocation (or stress), where the speed and changing thermal patterns during recovery are usually of interest [2].

In the practical part of the course this process will be examined with relation to:

1.Location of the stress

Local versus whole body)

2. Sources of stress

2.1. Heat stress [3]

2.2. Cold stress

Cold provocation tests are commonly used in order to provoke a temporary vasoconstrictor response where the rate and pattern of the spontaneous rewarming following the cold stress test is examined. A cold stress test may be invoked in several ways including cold stress provided by cold climatic chamber, water immersion, forced convection, alcohol cooling, or the cooling of a distal area (reflex cooling) [3, 4].

2.3. Pharmacological or chemical stress

For example, by caffeine ingestion, intake of nicotine, topically applied ointments or aerosol sprays [5].

2.4. Exercise stress

The effect that various forms of physical exercise has on skin temperature is commonly used, especially by those interested in thermoregulation in sports medicine [6, 7].

An introduction will be given into the effect that moderate and intense exercise during various types of sport activities has on skin temperature.

2.5. Rehabilitation techniques

The use of rehabilitation techniques such as TENS, acupuncture or pressure cuffs [8-10].

Other considerations

Age, body size, fitness level and health condition [2].

Asymmetrical differences - that is comparing left/right differences and why this is sometimes of interest and sometimes not. Also, comparisons between the dorsal and ventral aspect of a body part, for example the dorsal and palmar aspects of the hands [11].

No matter what provocation protocol one uses, it is recommended to always take normal digital photographs of the body part being imaged by the IR camera (approximately same distance and angle as the IR camera). This is done to document anomalies such as scars, skin growths such as warts and other skin injuries that may affect a thermogram

Finally, a short introduction in the uses of DIRT during surgical interventions, pre-, intra- and post-operatively will be presented.

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Image analysis

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These 2 short lectures will instruct the students in using the provided software package for image analysis.

Ricardo Vardasca will show the retrieval of thermal images, the definition of circular, rectangular and polygonal measurement areas and their positioning in the region of interest of the retrieved thermal image. He will also demonstrate the extraction of temperature values from the thermogram.

Kurt Ammer will present regions of interest on the lower extremity as defined in the Glamorgan protocol [1]. Similarity of mean temperatures of corresponding anatomical regions and comparison to reference values will be discussed [2].

References

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Hands-on supervised practice

All course teachers

Two sets of images of the calf of the same subject in the view "lower leg posterior" and in the view "total body posterior" taken by two instructors will be distributed to course students.

That results in 4 images:

Image 1 (view: lower leg posterior, Operator 1)

Image 2 (view: total body posterior, Operator 1)

Image 3 (view: lower leg posterior, Operator 2)

Image 4 (view: total body posterior, Operator 2)

On each students' computer with the analysis software installed, the students will retrieve the recorded images and practice to define a rectangular and a polygonal region of interest on Image 1. After feeling competent in defining and positioning regions of interest, the students will define the region of interest "lower leg posterior" in each of the four images. Median, minimum, maximum, mean and standard deviation of temperature and the size of the ROI in the number of pixels must be recorded.

The results must be transferred to a prepared Excel spreadsheet, which will automatically calculate the mean value of all measurements and use it as reference value. Individual errors (individual value minus reference value) will also be generated. For each image one Excel sheet will be provided. If the students already have experience with the software and manage the task quickly, the definition of regions of interest must be repeated on a set of images, free of ROIs. Another set of Excel sheets will be provided for documentation.

Such a setting allows to assess in individual students:

- the agreement of temperature readings in different views
- the agreement of temperature readings in thermal images recorded by different camera operators
- the agreement of temperature readings in repeated evaluation (when a second evaluation was performed)
- the agreement of the size of ROI in the views "lower leg posterior" and "total body posterior"
- the agreement of the size of ROI in thermal images recorded by different camera operators
- the agreement of the size of ROI in repeated evaluation (when a second evaluation was performed)

And between students:

- the agreement of the size of ROI in each view
- the agreement of the size of ROI in repeated evaluation (when a second evaluation was performed)
- the agreement of temperature readings in defined ROIs
- the agreement of temperature readings in repeated evaluation (when a second evaluation was performed)

Educational resources

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Many instructional courses have been organized under the banner of the European Association of Thermology (EAT), covering different topics and devoting different amounts of time depending on the venue of the course and available instructors [1]. The EAT decided to move from that format and after intensive and constructive discussion the Board approved an introductory course structure covering all topics required to start using thermography in daily practice or research. From basic physical and physiological principles, to imaging technique, analysis and reporting guidelines, not forgetting quality assurance for thermal imaging systems, all required topics were covered.

Thermology International is the publication organ of the European Association of Thermology (EAT) and other thermology societies. It is an international scientific journal that publishes articles related to temperature measurement in all scopes of science and is indexed in Scopus, EMBASE and Medline with full text (EBSCO), and since 2013 it is published exclusively online [2]. One of its aims is to provide a means of dissemination of knowledge in the field of thermology, acting as an educational platform for all those interested in temperature measurements, endorsing all major reporting guidelines for main study types [3] to increase transparency in the publishing process. Throughout the years many articles have been published, related to the topics covered in the course, and this is an overview of a collection of papers that were selected to be distributed among the course students.

Due to its short duration, the historical developments of thermal imaging will not be addressed in the course. However, several hallmarks should not be forgotten [4, 5]. Skin temperature has been used extensively as an outcome measure [6], but objectively assessing thermal images can be a challenging task and thermal findings must be interpreted carefully [7, 8]. Thermal images are representations in false colour scale of the temperature distribution of the surface of the imaged object, from which emissivity must be known [9], and it is important to note that false colouring may affect image resolution and distort the anatomy of the imaged body part [10]. The conversion from camera signal to temperature values is not straightforward [11].

To avoid bias in image recording, standardization is the key. The repeatability of standard views of the dorsal aspect of both hands [12], the repeatability of temperature measurements at the forehead [13] and the influence of the field of view on temperature readings of the face and upper back [14] have been studied in three papers, published with data collected during instructional courses at the University of Glamorgan. Room temperature appears to have a stronger influence on temperature readings than the number of pixels of the measurement area [15], and recently a paper was published documenting the influence of angle and distance on temperature readings of the inner-canthi [16]. Guidelines for thermographic assessment have been published [eg. 17, 18] aiming to highlight the need for a standardized technique of image recording and analysis. In 2008, Ammer [19] published the Glamorgan Protocol for recording and evaluation of thermal images of the human body, defining 24 body views and 90 regions of interest, demonstrating high reproducibility of recorded images and temperature readings.

Reporting is also a source of bias in published studies. Standardization is required, not only during image recording, but also for reporting of thermographic findings. There are clear deficits in the reporting of primary studies but also in literature reviews [20], which led to the development of a checklist - the final product of a Delphi study - that should be used by researchers planning a research study, reporting research results and/or assessing the methodological quality of thermographic studies [21].

Quality assurance of thermal imaging systems has also been a focus of publication in Thermology International [22]. Simple procedures have been described and can be used by thermographers to monitor the performance of imaging systems [23] and guidelines for specifying and testing thermal cameras for medical applications are also available [24]. It is important to understand that technical characteristics of infrared cameras influence their performance and that regular assessment of the performance of the system is required [25].

The cited references were selected from the papers published in Thermology International and are important educational resources that will be available online to download at the time of the course.

The amount of published information about thermology is constantly increasing. Ammer [26-30] has compiled reference lists of all published papers on the topic "Thermology" from 1989 to 2016 and these resources are available freely from the archives of Thermology International.

Several scientific journals can be named as examples of good sources of information. One of the most read papers in Physiological Measurement is a topical review on the use of infrared imaging in medicine [31]. Another journal - Infrared Physics & Technology - has published a similar topical review but focusing on different aspects of the applica-tion of infrared imaging in medicine [32]. The same journal has a very in-depth review about the factors that can influence the use of infrared imaging in humans [33]. The Journal of Thermal Biology recently published a Delphi study and consensus statement regarding the information that should be reported in thermographic studies [34] and the Quantitative InfraRed Thermography Journal published a very interesting review about the pioneers of infrared imaging in medicine [35]. More journals and examples of important papers could be listed but, with the increasing quality of research databases (e.g. Pubmed, Scopus, Web of Science), the access to relevant information is facilitated.

Other important sources of information are reference books. Two historical references must be mentioned: Recent advances in Medical Thermology [36] and The Thermal Image in Medicine and Biology [37]. The first was edited by Ring and Phillips and is a collection of papers presented at the 3rd International Congress of Thermology in 1982 and the second, edited by Ammer and Ring, is a collection of papers presented at two meetings, the Meeting of the Royal Photographic Society, Imaging Science & Technology Group and the 6th European Congress of Thermology in 1994. Another solid reference is the book Medical Infrared Imaging: Principles and Practices [38], edited by Diakides, Bronzino and Peterson, a comprehensive source of information covering all aspects of the use of thermal imaging, from technology and hardware to data processing and applications. Two more titles are worth mentioning, Infrared Imaging: A casebook in clinical medicine, edited by Ring, Jung and ?uber [39], and Innovative Research in Thermal Imaging for Biology and Medicine, edited by Vardasca and Mendes [40]. The first is a follow-up of the original Casebook in Clinical Medicine published twelve years earlier and evidences the advances in infrared technology and the knowledge about thermal physiology, covering theoretical and technical aspects and a wide variety of applications. The second offers an overview of recent research in biology and medicine covering the use of thermal imaging. For those particularly interested in the metrological aspects of thermal imaging, the book Infrared Thermography: Errors and Uncertainties [41] is an interesting read.

This overview is intended to provide the trainees with a list of educational references covering the topics of the course, and others, stimulating their curiosity and willingness to contribute to increase the body of knowledge in thermology.

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