Medical Thermography

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30.1 Definition

Thermography is a technique that allows visualizing and accurately measuring the temperature of bodies, without the need of physical contact since it captures infrared radiation they emit. Medically, it allows registering the cold and hot areas of a patient's body thanks to the energy radiated by their skin, with a precision that can reach up to one hundredth of a degree centigrade [1] (Fig. 30.1).

30.2 Spectral Regions

As is well known, the human eye can detect a small portion of the electromagnetic spectrum, whose wavelength is between violet 400 nm and deepest red 700 nm (0.4–0.7 μm). Beyond this dark red, there is a vast spectral region called infrared that ends at 1000 nm the point where the microwave region begins [1].

From a practical point of view, the infrared region can be subdivided into two large regions: (a) the *near infrared* or *NIR* region (0.7–1.4 μm), capable of being captured by any CCD or CMOS photographic sensor prepared for infrared, and

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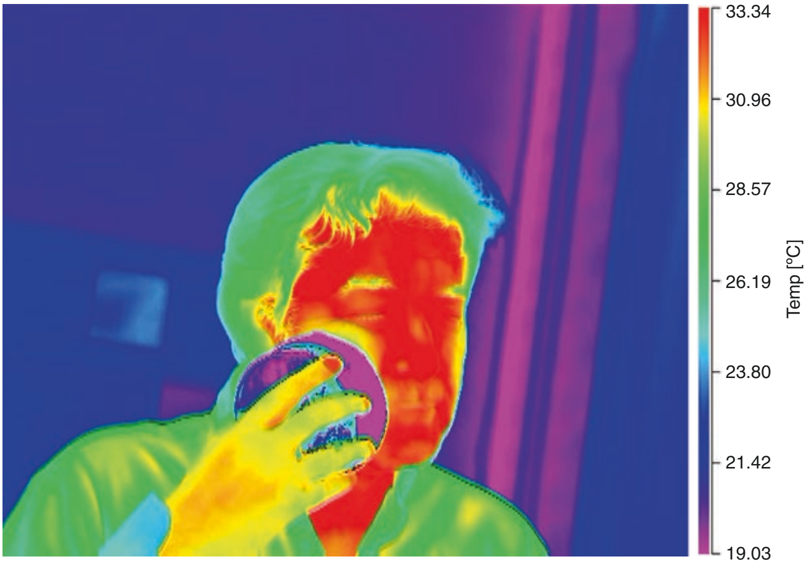

Fig. 30.1 Thermographic image of the face of one of the authors after rubbing his cheek with a can of frozen film

Table 30.1 Infrared spectrum regions

Name		Abbreviation	λ, µm	Band frequency, THz	Characteristics
Near infrared		NIR, IR-A	0.7–1.4	400–214	Photographic region (CCD and CMOS)
IR thermographic region	Short-wavelength infrared	SWIR IR-B	1.4–3	214–100	Cooled cameras
	Mid-wavelength infrared	MWIR IR-C	3–6	100–37	Cooled cameras
			6–8		Not useful Opaque atmosphere
	Long-wavelength infrared	LWIR IR-C	8–15	37–20	Non-cooled microbolometers (8–12 µm also cooled)
	Far infrared	FIR	15–1000	20–0.3	Interferences with atmosphere

(b) the *far infrared* or *IR thermographic region* (1.4–1000 µm), which is susceptible to partial registry through the use of thermal imaging cameras with special sensors. This chapter will mostly deal with this region as it is the one with the greatest medical applications.

The thermographic region is subdivided into two subsets: (a) *medium infrared*, which is the one that interests us and comprises the *short wave* region or SWIR (1.4–3 µm), *medium* or *MWIR* (3–8 µm), and *long* or *LWIR* (8–15 µm), and (b) the *far infrared FIR* (15–1000 µm) has scarce practical use [2] (Table 30.1).

Cameras capture the body's *reflected radiation* which belongs to the closer infrared regions (NIR and SWIR); the middle regions (MWIR and LWIR) are captured by *radiation* emitted from the body, since any object above of zero degrees Kelvin (−273.15 °C) is capable of emitting infrared radiation.

Atmosphere, water vapor, carbon monoxide, nitrogen, ozone, and even the heat emitted by the Earth itself create a series of barriers and interferences that allow only certain regions to be of thermographic utility for medical applications. These regions are called *infra-*

red windows, and they mostly belong to the MWIR and LWIR bands.

30.3 Thermographic Camera

A thermal camera consists of the following components:

- *Lenses*: the lenses for thermography are manufactured with materials permeable to the entire infrared spectral band and have a characteristic opacity. The most common materials are germanium, silicon, and zinc selenide (Fig. 30.2).
- *Detectors*: are matrixes of sensors placed in the focal plane of the lens. The distance between the center of two adjacent sensors is called pixel pitch (also referred to as "dot pitch") and is measured in millimeters (written in the form of p(mm)). Together with the number of sensors pixel's pitch is what determines the resolution of the detector, which usually has between 60,000 and 1,000,000 sensors.

Depending on whether the detectors have an inner cooling system or not, there are two types of cameras and detectors [3, 4] (Fig. 30.3).

- *Uncooled microbolometers*: consist of a matrix of microbolometers that, in essence, are plates of vanadium oxide or amorphous silicon attached to the base by two small legs that work as insulators. The infrared image (in the spectral band between 8 and 13 µm) once projected on each microbolometer heats proportionally the plate modifying their electrical resistance, which translates into a greater or lesser signal intensity in each pixel. These cameras are affordable, their startup is instantaneous, their energy consumption is lower (they do not have refrigeration), and they are more robust (Figs. 30.4 and 30.5).

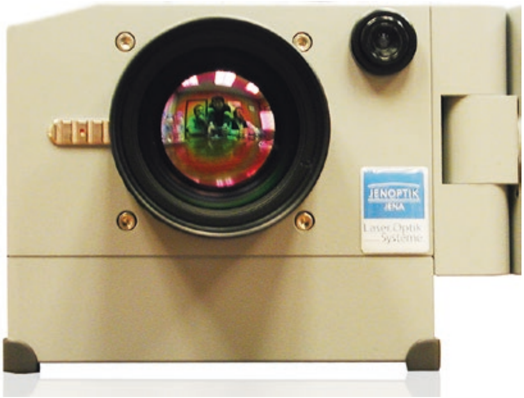

Fig. 30.2 Germanium lens for thermal imaging cameras

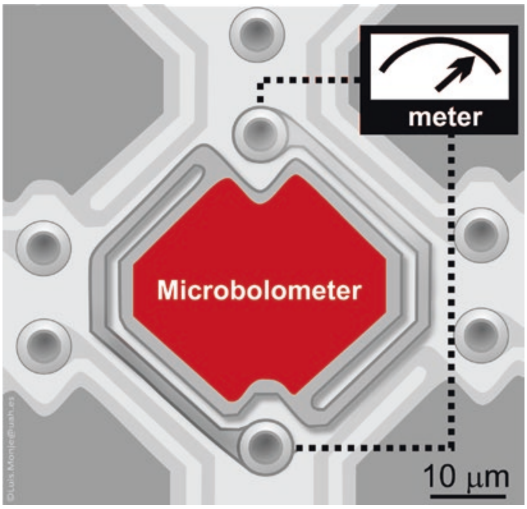

Fig. 30.3 Top view of a plate of romboidal microbolometers. Note the long isolation pins (Original image by Luis Monje)

- *Cryo-cooled solid-state detectors*: They are based on the photoelectric effect similar to photographic sensors. They consist of a matrix of cells, each with two closed layers of doped semiconductors connected to each other by a measurement circuit. The valence layer has an electronic imbalance, and when infrared radiation hits it, it frees up electrons to the conduction layer. These electrons return to the valence shell by a circuit that measures the generated electrical current, delivering the signal of each pixel. Most detectors are composed of indium antimonide (InSb), indium gallium arsenide (InGaAs), platinum silicide (PtSi), mercury and cadmium telluride (MCT), vanadium

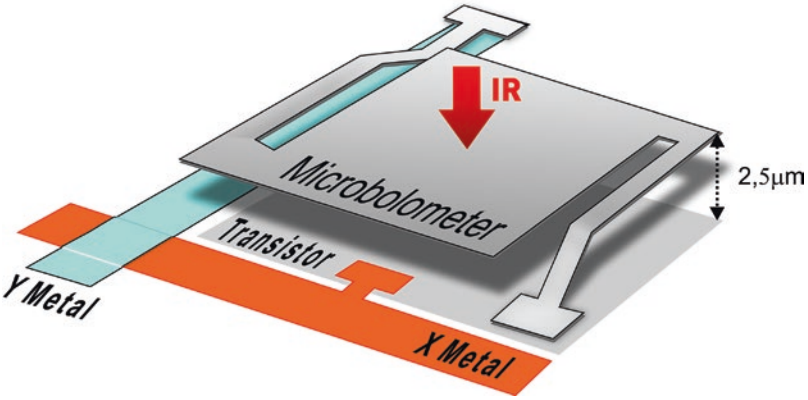

Fig. 30.4 Perspective view of a rectangular microbolometer (Original image by Luis Monje)

Fig. 30.5 High-end thermographic camera from InfraTec with microbolometer detector model VarioCAM® HD research 900, equipped with a sensor with a resolution of 1024 × 768 pixels that by an opto-mechanical scan can go up to 2048 × 1024 pixels. Its partial image speed is 240 Hz, and it has an integrated 5.6″ TFT monitor and viewfinder (Image courtesy of InfraTec GmbH (www.infratec.de))

oxide (VOx), or amorphous silicon. The material chosen determines the spectral segment to work with, since none of them is capable of capturing the entire infrared region. CO2, N^2, and O3 molecules found in water vapor in the atmosphere are opaque to infrared and act as a filter, retaining most of the infrared spectral band except in certain permeable segments called *windows*. Thanks to this, in thermography we can use IR windows of 1.4–3 µm (SWIR), 2–5.6 µm (MWIR), and 8–14 µm, corresponding to the LWIR. The detector is usually attached to a Dewar vessel (double-walled vessel containing liquid nitrogen at −200 °C) or to other types of simpler coolers based on the Peltier and Stirling effect. The reason for cooling the detector is to prevent air from the camera itself and its circuits interfering with the capture by the sensor, thus achieving greater accuracy and thermal resolution. The thermal accuracy can be ten times that of cameras with uncooled detectors and represents approximately 0.01 °C compared to the average accuracy of 0.85 °C of microbolometers (not refrigerated). Its spectral range varies between 1.5 and 5.1 μm. The cameras with cooled detector are much more expensive to manufacture and need a minimum startup time of about 7 min, although their sensitivity and resolution are much higher as their cells are much smaller and carry refrigeration. In addition, the device is larger, more delicate, and with a higher power consumption. When the subject undergoes sudden changes in temperature, the microbolometers take some time to warm up and show the effect, while in the cooled detectors, the change is almost instantaneous (1 μs), which makes them ideal for thermal analysis of subjects in movement [5] (Figs. 30.6 and 30.7).

30.4 Uses of Thermography

Due to its intrinsic characteristics, thermography is very useful for remote temperature measurements like evaluation of buildings' insulation, location of hot zones in motors and electric circuits, detection of thermal bridges, imaging people and animals in total darkness, night maritime rescue operations, gas leaks, surveillance tasks, defense and security, meteorology, and health sciences.

30.5 Medical Applications of Thermography

Thermography has been used for quite some time for the functional and clinical assessment of the human body. It has been part of a complementary evaluation system that based his diagnostic imaging potential in the detection of multiple patholo-

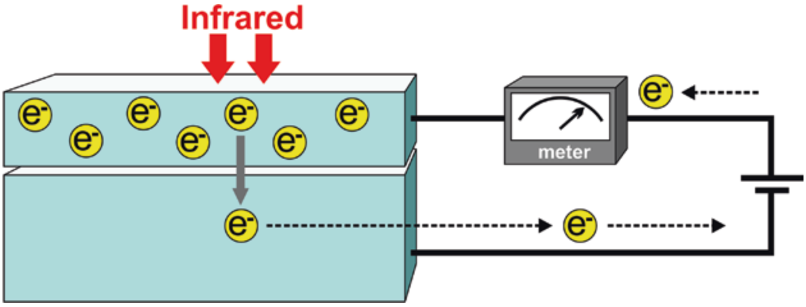

Fig. 30.6 Schematic drawing showing principle of operation for a solid-state detector

Fig. 30.7 High-end thermographic camera by Telops with solid-state detector, model HDR M100hd. It has a sensor of 1280 × 1024 pixels at 105 ips, with partial image speed of 240 Hz and a spectral range between 3 and 5 μm. Its price exceeds 190,000 USD (Image courtesy of Telops®)

gies [6]. Hyperemia (an excess of blood in the vessels supplying an organ or other part of the body) is caused by vasodilatation, and it is a sign present in multiple conditions. It causes a temperature increase, in many cases at a superficial level and from a direct or reflex effect on the vessels. It is currently being used [7] as a tool for the detection of pathologies with trophic symptomatology of thermal origin, since it is a very precise system for measuring the superficial temperature in the human body.

Recently it has been used a complementary non-invasive imaging technique to evaluate pathologies linked to breast cancer [8], such as mastitis, with the understanding that it cannot be used yet as a screening system, let alone unique, for mammary oncological pathologies [9]. For this reason, its use as an initial assessment system has been abandoned when tumor alterations are suspected, although it is still an adequate tool to control the evolution of other pathologies that may present thermal superficial alterations.

With the incorporation of new precision systems and the reduction of costs of equipment, different research works and case reviews are being carried out to incorporate thermography and evaluate its effectiveness in the management of pathologies from different medical specialties [10]. Currently, thermal image capturing has different clinical applications due to its interesting uses [11, 12] in the complementary diagnosis and evolution of the patient.

The human body has different mechanisms of thermoregulation; trophic changes are generated by physiological and physio-pathological processes that result in the loss, increase, or modification of body heat. This is linked to the vascular, neurovegetative, and musculoskeletal system. The visualization of all these changes of temperature by means of thermographic cameras is becoming increasingly accessible and can be a valuable element for detecting problems/alterations related to the physiopathology of certain injuries. Registering the succession of thermal changes over time would provide added value to the knowledge of the evolution of certain lesions, helping to select the appropriate therapy and monitoring the response to treatment. Thermal changes after the application of paraffin on the skin (Fig. 30.8), ultrasound (Fig. 30.9), infrared and hot pack (Fig. 30.10), and radial shock waves (Fig. 30.11) can be assessed by thermography [13]. In the application of therapies like short wave, microwave, or other thermotherapy equipment, there are already bioengineering investigations which incorporate thermographic technology as an adequate control system to modulate the intensity of application of these physical therapies. Having an automatic system that allows regulating the power of application by means of measuring skin and subcutaneous tissues temperature can avoid injuring tissue due to burns. This technology will surely be incorporated in future equipment in the very near future, and thermography will postulate itself as an excellent control system (Fig. 30.12).

Fig. 30.8 Thermographic application to evaluate the effect and temperature after the application of infrared thermotherapy [1]

Another use of thermography has been in the textile industry for the development of new technical fabrics. Thermal body images are used to assess body heat losses before, during, and after exercise, as well as under adverse weather conditions.

In these cases, the measurements are not related to the diagnosis and physiopathology of the body but are intended to study how the organism interacts with the environment. Detecting

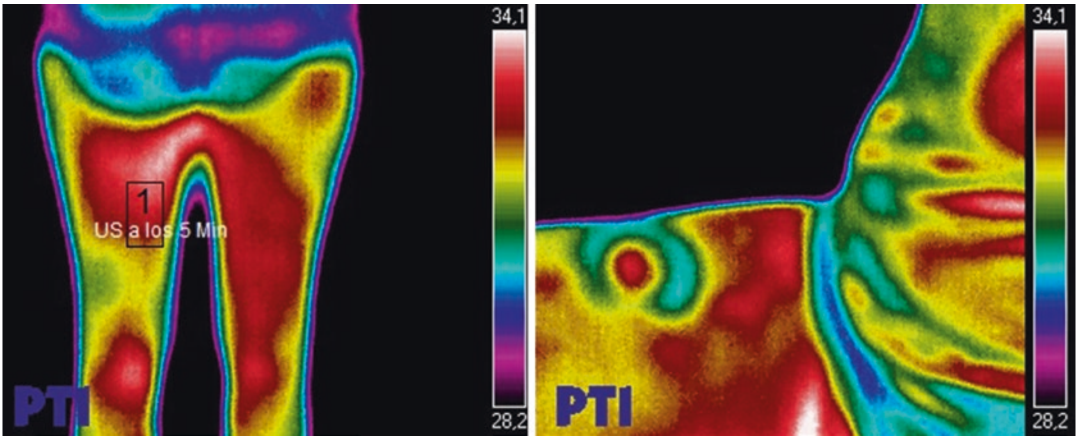

Fig. 30.9 Using thermography to measure the temperature and evaluate the effect of ultrasound

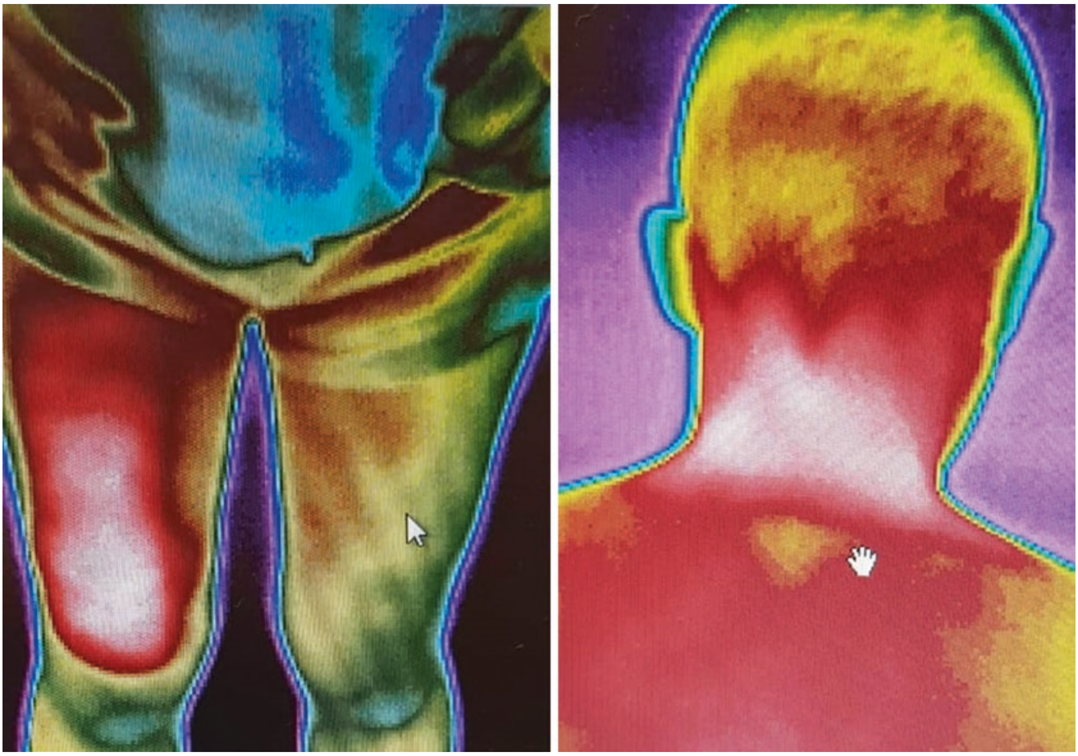

Fig. 30.10 Thermographic application to evaluate the effect and temperature after hot pack

heat leaks or checking if these could alter the mechanisms of human thermoregulation is relevant for the effectiveness and efficiency of the technical material. Multiple brands of clothing and footwear have presented studies with this tool to support the new design of materials or introduce improvements to their models.

A proper knowledge on the mechanisms involved in the physiology of the corporal thermal production and its alterations is a requirement for adequately interpreting thermal images [14]. Its complexity exceeds the purpose of this chapter. Knowing these processes is as essential as mastering the camera and its software.

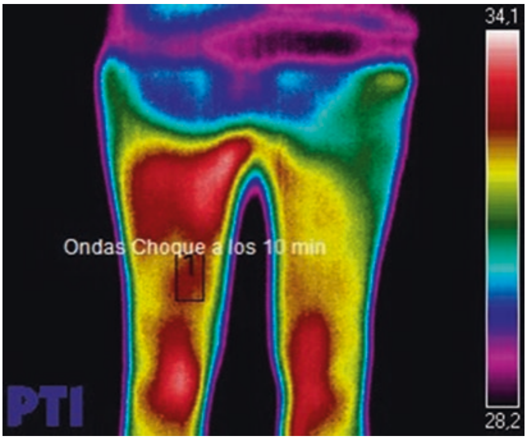

Fig. 30.11 Thermographic application to evaluate the effect and temperature after the shock waves

Fig. 30.12 Thermographic camera donated by the Clinical Research Unit in Biomechanics and Physiotherapy, San Juan de Dios School of Nursing and Physiotherapy, Comillas Pontifical University, Spain. The thermographic system www.Enraf.es, is a device equipped with a latest technology detector of vanadium oxide microbolometers with the capacity to generate thermal images of 320 × 240 pixels in the spectral range of 7.5–13.0 μm. The system makes visible differences of temperature of 50 mK and provides data of 16 bits with up to 50 frames per second with complete resolution of box of 640 × 480 thanks to its connection Gigabit Ethernet. It has a high-speed window system function that increases the frequency of output images up to 200 Hz in a window of 640 × 120 pixels

30.6 Current Studies of Thermography in Medicine and Health Sciences

As previously mentioned, there is a large number of medical pathologies were vascular changes are present, both as hypertrophic or ischemia. Thermal changes in the skin can be visualized and quantified by thermography. One of the clearest problems for which the diagnostic use of thermography has not become extended is probably because within the same medical specialty, (a) multiple pathologies with different symptoms do not present peripheral vascular changes, and (b) different pathologies can present similar vascular changes. This reduces the discriminatory potential of thermography to differentiate pathologies. One possible use, however, could be to monitor changes of a lesion over time or after treatment.

Thermography can be an excellent tool to analyze the evolution of the injury. The clearest examples are seen in the fields of physiotherapy [15], physical medicine and rehabilitation [16], traumatology [17], sport medicine [18], endocrinology [19], dermatology [20], and rheumatology, where symptomatic peripheral vascular components are present at the time of diagnosing and at follow-up.

The specialty of neurology, both in its phase of motility and in the processes of immobility, can be benefited by the use of this technique as trophic changes or vascular alterations can be present in certain conditions for certain pathologies. Thermography is a low cost, no invasive technique with no contraindications that allows obtaining information very quickly and easily. In a recent paper, Hegedus et al. [21] showed the effectiveness of using thermography as a tool for monitoring patients who had stokes (cerebrovascular accidents) by recording the trophic changes in motor or sensory areas that have suffered brain damage. The clinical incorporation of thermography would allow to know improvements obtained during the rehabilitation, such as increase in Range of Movement (ROM) that produce vascular and therefore thermal changes, as well as other mobility aspects (speed, strength, motor control) that also evolve with easily recordable trophic variations and without contraindications for patients.

The first thermographic cameras appear in the twentieth century as assessment tools in traumatic pathologies. In 1977 the use of thermal imaging as an assessment system for fractures and infections was published [22], emphasizing its importance not for the initial diagnosis or screening but as a system of assessment in the evolution of the pathology. It was also during this period that thermal therapy was used [23] to monitor patients with alterations in the locomotor system. It helped objectify clinical changes. Research with this non-invasive clinical tool in the area of fractures continues today [24] as it provides [25] an assessment and objectification of clinical changes in the injured area. In children with traumatisms, evidences have been found [26] of its usefulness as a predictive system as it can be used to rule out the existence of fractures, which suggest that it could be a promising system to incorporate in clinics.

Regarding the area of traumatology and physiotherapy [27], its use could be suitable to assess the evolution of tendinopathies of various kinds, although it is not a valid initial diagnostic system as it does not differentiate among them. However, muscular conditions like active trigger points can be diagnosed with thermography [28] as well as observe changes caused by physiotherapy. This could be an excellent tool to analyze the evolution and effectiveness of such therapies. It remains to be studied whether in latent or non-active myofascial trigger points it could be a potential diagnostic tool.

The number of articles on thermography in medicine is not high when compared to other non-invasive imaging technologies; however, there are qualitative trials on the possible professional utility that this tool can provide in clinical use with interesting results. The *Journal of Thermal Biology* published in 2017 [29] an interesting Delphi study on the interest of health professionals in this system as a potential tool for clinical assessment; further studies should be done to understand what data is important, how to standardize procedures, and how to analyze the results obtained so far. In 2018, Ginart et al. [30] compared the use of thermography with other diagnostic imaging systems in patients with cervical lesions. Again and as seen in other clinical specialties (neurology, traumatology, physiotherapy, etc.), it is a useful technique for monitoring but not to make an initial diagnosis or screening system. However, there are already investigations that are being done in the opposite direction: they have shown that thermography could be useful as an initial diagnostic tool in lumbar injuries, helping in deciding the possible physiotherapy scheme (osteopathy) [31]. On the other hand, a research work has also been published [32] (2015) using thermography to differentiate between two physiotherapy treatments for lumbar injuries. As indicated by these works, its use is highly interesting but remembering that its strength is in monitoring rather than screening and diagnosing.

Thermographic technology can also be used to analyze the resistance of orthotic material, as it can be a good system to know the stresses and fatigue of the material [33]. It could be an adequate tool to evaluate orthoses and fatigue of materials used in rehabilitation, physiotherapy, and traumatology. This field is enormous as there are currently multiple studies and research works in the development of new products, materials for orthotic systems. The use of this non-invasive technique to understand how these materials are worn out by mechanical stress could be of great help.

30.7 Final Considerations

As final considerations of the publications of recent years and as a trend in the clinical area, we could summarize that thermography:

- It's an excellent system for analyzing the evolution of lesions, especially in those pathologies that with inflammation or ischemic areas, thermal modifications easily recordable by thermographic systems.
- These systems have proven effective in recording surface temperature variations without contact with the patient. They are non-invasive systems without any contraindication for the patient as they just collect the emission of the temperature radiated by the patient's body.
- They are not an initial screening or diagnosis system capable of detecting relevant clinical aspects for their differentiation from other pathologies. The fact that thermography does not detect deep aspects can be limiting, but it can guide in monitoring and symptom assessment.
- Numerous medical specialties as well as other branches of health science have publications that provide evidence of their usefulness in evolution of conditions with trophic changes. These investigations are becoming more numerous as cost of equipment is decreasing. The use of thermography is yet not new, as it has been used since last century.
- The study of thermography in other health fields should continue in order to understand its possible clinical application and determine in which pathologies it could add value to use. There is growing evidence recently of its high interest as a non-invasive system that has no contraindications and is increasingly more accessible.

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