Infrared Thermography for Detection of Diabetic Neuropathy and Vascular Disorder

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Abstract Body temperature is a significant indicator of illness and hence is a useful parameter for clinical diagnosis. Among various techniques available for accurate and reliable measurement of subject temperature, infrared thermography is a relatively new methodology. However, it has become popular because of its noncontact, noninvasive, and real-time temperature measurement capability. During the last few decades, numerous applications of infrared thermography are reported in the field of medical sciences, which are rapidly growing. Diabetes is a metabolic disorder associated with high blood sugar levels over prolonged duration. One in every 11 adult population of the world is affected by diabetes and for every 6 s, one person dies from diabetes-induced complications. Therefore, a worldwide dedicated effort to prevent diabetic complications by early detection is important. Studies so far reveal that infrared thermography is capable of detecting subtle changes in skin temperature distribution in diabetic-at-risk foot and is capable of early detection diabetic-related peripheral neuropathy and vascular disorders. This chapter attempts to highlight the applications of infrared thermography in the early detection of diabetic neuropathy and vascular disorder. The basics of infrared thermography, classification of medical thermography techniques, details of infrared camera, ideal experimental conditions, data analysis, etc. along with typical case studies are discussed in detail.

Keywords Diabetic neuropathy · Vascular disorder · Classification · Experimental conditions · Data analysis

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1 Introduction

Temperature has been considered as a very good indicator of health and has been used as a parameter for clinical diagnosis since 400 BC [1–3]. Although thermometers were developed around seventeenth century [2], only in 1868, Wunderlich [4] first systematically studied the temperature of human subjects suffering from fever and compared the same with normal subjects and established the physiological and clinical importance of temperature. Till then, temperature has been considered as one of the most significant indicators of illness. Among various techniques being used for accurate and reliable measurement of subject temperature, infrared thermography is a comparatively new methodology that has become popular because of its noncontact, noninvasive, and real-time temperature measurement capability [5, 6]. Although infrared thermography is routinely used for nondestructive evaluation and condition monitoring studies [5–9], its application in the bio-medical field is huge and rapidly growing [10–16]. Numerous applications of infrared thermography in the medical sciences have been reported in the last few decades.

Some of the reviews highlighting the application of infrared thermography in medical science are by Jones [12], Ammer and Ring [13, 17], Jung et al. [18], Yang and Yang [19], Fauci et al. [20], Jiang et al. [21], Ring et al. [22], Lahiri et al. [10], and Faust et al. [23]. Infrared thermography has been extensively used in various fields of bio-medical sciences, viz., fever screening [24–31], breast cancer detection [32–37], brain imaging (thermoencephaloscopy) [38], dentistry and dermatology [39–42], muscular pain and shoulder impingement syndrome detection [43], dry eye syndrome detection [44, 45], diagnosis of rheumatologic diseases [46–49], evaluation of skin sympathetic dysfunction in Parkinson's disease [50], thermoregulation [14, 15, 51–53], detection and treatment of parasitic and metastatic liver diseases [54, 55], bowel ischemia [56], diagnosis of tuberculosis [57], renal transplantation [58, 59], gynecology [60–62], acupuncture [63], forensic medicine [64, 65], heart treatment [66], quantification of bacterial concentration [16, 67], and diagnosis and early detection of diabetic neuropathy and vascular disorder [68–77]. The developments in the field of medical thermography between 1989 and 2003 are reviewed by Ammer [78, 79]. An internet search in popular bibliometry service "Pubmed" [80] with the keywords, "Medical" and "Thermography" in all fields, yields in total 932 publications spanned over 1964–2016. Figure 1 shows the number of publication in the field of medical thermography as a function of publication year. It can be seen that in recent years (especially from 2000 onward), the number of publications per year clearly increased indicating a rapid growth in the use of infrared thermography in medical sciences. Figure 2a shows the year-wise number of publications on infrared thermography-based studies on diabetes, which was obtained from the "Pubmed" [80] database which clearly shows a surge of interest in infrared thermography-based detection of diabetes-related complications. Figure 2b shows the percentage of diabetes-related publication with respect to total

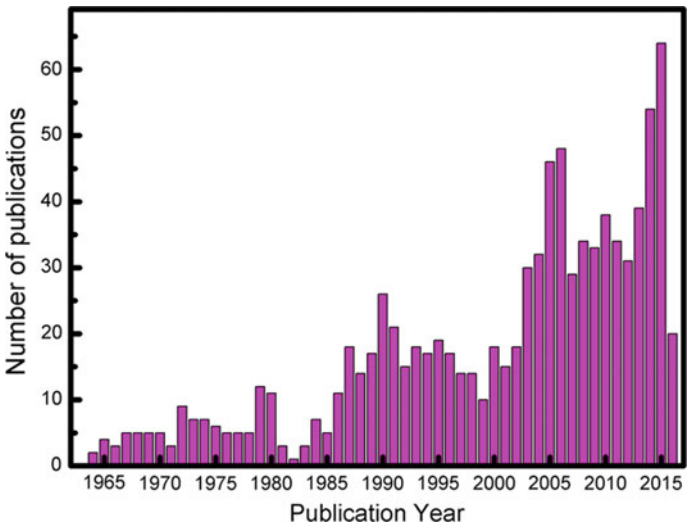

Fig. 1 Histogram distribution showing the number of publications in the field of medical thermography as a function of the year of publication. The data was obtained from "Pubmed" database [80] using the keywords: "Medical" and "Thermography" in all fields

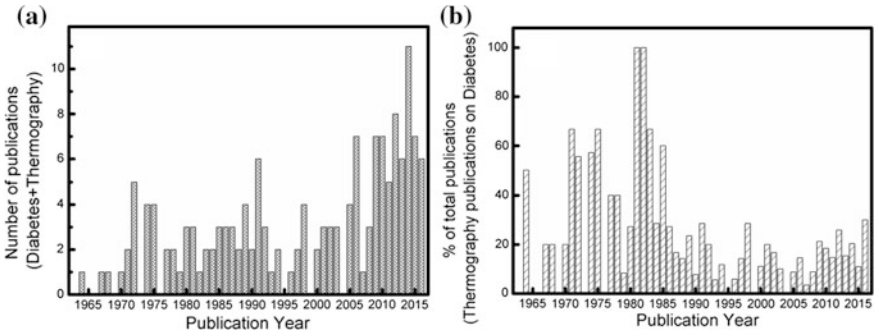

Fig. 2 **a** Histogram distribution showing the number of publications on application of thermography in diabetes. The data was obtained from "Pubmed" database [80] using the keywords "Diabetes" and "Thermography" in all fields. **b** Histogram showing the percentage of publications on application of thermography in diabetes with respect to the total number of publication in the field of medical thermography

number of year-wise publications in medical thermography which indicates diversified applications of infrared thermography in other medical fields, like breast cancer detection, fever screening, diagnosis of rheumatologic diseases, etc.

Diabetes is a metabolic disorder associated with high blood sugar levels over prolonged duration. 415 million cases of diabetes have been reported up to 2015 and the number is expected to rise to 642 million by 2040 [81]. One in every 11 adult population of the world is affected by diabetes and for every 6 s a person dies

from diabetes-induced complications [81]. It has also been reported that 1 in every 7 birth is associated with gestational diabetes [81]. Hence, a worldwide dedicated effort has been witnessed toward diagnosis, prevention, and early detection of diabetes. Bharara et al. [70, 82] reported that the incidence of diabetic foot diseases is growing worldwide leading to an increased socio-economic burden on health care systems of different countries. Diabetic foot with higher temperature patterns is indicative of early onset of diabetic neuropathy and subsequent ulceration, if not treated. Moreover, peripheral small fiber damages are often undetected using clinical and nerve conduction studies resulting in delayed diagnosis and detection of neuropathic symptoms. Infrared thermography is capable of detecting subtle changes in skin temperature distribution in diabetic-at-risk foot and hence, early detection is feasible using this technique which resulted in a renewed interest in application of infrared thermography in diagnosis of peripheral neuropathy and vascular disorder in diabetic subjects.

This chapter attempts to highlight the applications of infrared thermography in diabetic neuropathy and vascular disorder. For non-specialists, the basics of infrared thermography and classification of medical thermography techniques are discussed in detail, followed by a brief discussion on infrared camera, experimental conditions, and data analysis techniques. In the subsequent section, the physiological relationship of temperature with diabetic complications is discussed along with relevant literature survey. Finally, a few case studies on infrared thermography-based detection of diabetic neuropathy and vascular disorder are briefly presented.

2 Infrared Thermography

2.1 Basics of Infrared Thermography

Infrared thermography is a noncontact temperature measurement methodology where the electromagnetic radiation emitted by the surface of an object under observation is detected using a suitable infrared detector and surface temperature of the object is obtained from the intensity of the recorded radiation. The infrared radiation (wavelength ranging from 0.75 to 1000 μm) lies in between the microwave and visible regions of the electromagnetic spectrum. This vast range is further subdivided into three categories, viz., far infrared or FIR (wavelength range: 5.6–1000 μm), medium infrared or MIR (wavelength range: 1.5–5.6 μm), and near infrared or NIR (wavelength range: 0.75–1.5 μm). Although the theoretical understanding about infrared thermography was available from 1800, it took nearly 150–200 years for the technique to be available for routine use, due to lack of proper equipments and technical knowhow. The origin and theory of infrared thermography can be found elsewhere [5, 6].

Blackbody is a hypothetical object which absorbs all radiation incident on it and emits a continuous spectrum characteristic of its temperature and this continuous spectrum is governed by the well-known Planck's law [5]:

$$L_\lambda = \frac{C_1}{\lambda^5\left[\exp\left(\frac{C_2}{\lambda T}\right) - 1\right]}, \tag{1}$$

where λ is the wavelength (μm), L_λ is the power radiated by the blackbody per unit surface and per unit solid angle (W m^{-2} μm^{-1} sr^{-1}), T is the temperature of the blackbody in absolute scale (K), and C_1 and C_2 are the first and second radiation constants, respectively. Integrating Planck's law over all wavelength leads to the Stefan–Boltzmann's law which shows that the radiative power emitted per unit area is directly proportional to T^4, as described below [5]:

$$\frac{q}{A} = \sigma T^4, \tag{2}$$

where q is the rate of energy emission (W), A is the area of the emitting surface (m^2), and σ is the Stefan–Boltzmann's constant ($\sigma = 5.676 \times 10^{-8}$ W m^{-2} K^{-4}). For a real object the Stefan–Boltzmann's law is modified as $\frac{q}{A} = \varepsilon\sigma T^4$, where the parameter ε is known as emissivity which is defined as the ratio of spectral power radiated by a real surface at a particular temperature to that of a hypothetical blackbody maintained at the same temperature. For a hypothetical blackbody $\varepsilon = 1$ and for real surfaces $\varepsilon < 1$ [5]. It has been reported that the emissivity of human skin is $\sim 0.98 \pm 0.01$ in the wavelength range of 2–14 μm [83]. The skin emissivity does not vary with the color or texture of the skin or the nature of experiments, i.e., in vivo or in vitro [83]. On the other hand, studies show that the application of cosmetics or surface curvature may lead to a change in skin emissivity [84, 85]. Watmough et al. [86] have shown that the errors associated with surface temperature measurement are insignificant for viewing angles up to 45° which essentially rules out the variation of emissivity with skin curvature for medical thermography studies except for the cases of female breast imaging where silver, copper, or aluminized mylar mirrors have been used as reflectors with suitable correction factors [84].

The temperature of an object is measured using infrared camera using the following radiometric equation [5]:

$$M_{\text{cam}} = \tau\varepsilon M_{\text{obj}} + \tau(1-\varepsilon)M_{\text{env}} + (1-\tau)M_{\text{atm}}, \tag{3}$$

where M_{cam} is the radiance received by the infrared camera, M_{obj}, M_{env}, and M_{atm} are the radiance emitted by the surface of the object under investigation, surrounding environment and atmosphere, respectively. ε and τ are the surface emissivity of the object under investigation and atmospheric transmittance, respectively. Considering atmospheric transmittance to be nearly equal to unity for indoor experiments, Eq. 3 can be simplified to $M_{\text{cam}} = \varepsilon M_{\text{obj}} + (1-\varepsilon)M_{\text{env}}$.

Radiance received by the infrared camera is converted into an electrical signal by the infrared detector housed inside the camera casing and surface temperature of the object under investigation is obtained using suitable calibration curves [5].

Modern-day infrared cameras show the surface temperature distribution as visual images often pseudo-color coded where each pseudo-color indicates a range of temperature which aides in online visualization and fast analysis. Specifications of a typical infrared camera (FLIR SC5000) are shown in Table 1 [87].

2.2 Classification of Medical Thermography Techniques

On the basis of temperature measurement methodology, medical thermography can be primarily classified into four categories, viz., cutaneous temperature discrimination, electrical contact thermometry, liquid crystal thermography, and infrared

Table 1 Specifications of a typical high-end cooled type infrared camera (FLIR SC 5200)

Parameters	Values
Detector	Indium Antimonide (InSb)
Spectral range	3–5 μm (Detector response is from 2.5 to 5.1 μm)
Resolution	320 × 256 pixels
Pixel pitch	30 × 30 μm
Temperature range	5–300 °C (standard) −20 to 300 °C (very low temperature: additional) 5–1500 °C (high temperature: additional) 5–2500 °C (very high temperature: additional) 5–3000 °C (ultra high temperature: additional)
Accuracy	±1 °C or ± 1%
Noise equivalent temperature difference (NETD)	<25 mk (20 mK typical) @ 25 °C
Sensor cooling	Stirling closed cycle cooler
f/#	f/3.0
Power	12 V (DC)
Integration	Snapshot type
Integration time (electronic shutter speed)	3 μs–20 ms
Read-out mode	Asynchronous integrate then read
Dynamic range	14 bit
Full frame rate	Programmable 1–170 Hz
Sub-windowing	160 × 128/64 × 120/64 × 8 (minimum)
Well capacity	7.1 M electrons
Operability	99.5%
Dimension (L × W × H) (mm)	320 × 141 × 159
Weight (kg)	3.8

thermography [69]. Bertelsmann et al. have shown that cutaneous temperature discrimination threshold, which is a measure of small nerve fiber function, can be used for early diagnosis of diabetic subjects [88]. One of the most widely used instruments for the cutaneous temperature discrimination is the TipTherm (Axon GmBh, Germany) which is pen-like device without any external power supply and consist of two flat surfaces, one of them is metallic and the other one is synthetic [69]. Viswanathan et al. [89] used TipTherm for studying distal symmetrical polyneuropathy. In another study, Liniger et al. [90] used a thermo-resistance-based device, Thermocross (Medical School, Geneva, Switzerland) for thermal sensitivity in subjects with diabetic neuropathy. In electrical contact thermometry, individual or arrays of suitable transducers (thermistors or semiconductor sensors) are used for measuring skin temperature in contact mode [69]. A temperature difference of ± 1.5 °C was proposed as a limit of agreement between thermistor-based electrical contact thermometry and localized infrared thermometer [91]. Although the major drawback of electrical contact thermometry is due to fluctuation of skin temperature due to excessive contact pressure and lack of uniform contact with skin surface, small local arrangement of sensors in the size and shape of human foot to measure temperature of the plantar surface of the foot in diabetic neuropathy subjects is immensely beneficial [69]. In liquid crystal thermography, temperature-sensitive cholesteric liquid crystals are arranged in several layers between two flexible and heat sensitive rubber sheets for proper contact with skin surface [41, 69]. The liquid crystals change their color according to the temperature and the resultant pattern is a representation of skin surface temperature distribution. The major drawbacks of liquid crystal thermography are poor spatial resolution (>5 mm), low thermal sensitivity ($\sim$0.3–1.0 °C), slow response time (>60 s), and contact-based subjective temperature measurement [41, 92]. Two liquid crystal thermography-based commercial products, namely Spectrasole Pro 1000 (Sweden) [93] and Tempstat^{TM} (USA) [94], are available since 2004. Although Spectrasole is more focused on preventive diagnostics and monitoring of healing, Tempstat is a personal homecare product along with regular professional expertise. Taiwan-based Thermoscale is also a personal care device with integrated temperature-sensitive thermistors (electrical contact thermometry) for each foot, along with body weighing scale and fat measurement function. Piotr et al. [95] reported the development of a temperature measurement system for continuous monitoring of feet temperature using a data logger and wireless communication.

Infrared thermography, on the other hand, is a completely contactless temperature measurement technique where the infrared rays emitted by the skin surface are remotely detected in a noninvasive way. It is fast and can monitor temperature variations over a comparatively larger area. Modern infrared cameras are capable of real-time skin temperature measurement, with onboard image processing, which enables fast online data interpretations. The representation of skin surface temperature distribution in terms of pseudo-color-coded visual images also aides in data interpretation. Moreover, infrared thermography records naturally emitted radiations and no harmful radiation effects are present which makes this technique

perfectly suitable for prolonged and repeated use. In general, for medical applications, passive infrared thermography technique is used without the presence of external heat sources. An object at 27 °C emits a wavelength in the range of 2–20 μm with a peak around 10 μm. A narrow wavelength band of 8–12 μm is in general used for medical applications, which is also termed as body infrared rays. With the advent of newer generation infrared cameras near and mid-infrared bands are also used for medical thermography [68, 96]. Several commercial infrared cameras are available in the market as subsequently discussed.

3 Experimental Methods

3.1 Infrared Camera

The major requirements for medical thermography experiments are an infrared camera, a tripod, an image display, and processing unit. With advent of sophisticated computers, on-chip image processing is very common and most modern infrared cameras are equipped with inbuilt visual display and primary image analysis options. Personal computers equipped with necessary hardware and software configurations are the most widely used alternatives for detailed image processing and data analyses. Ring [74] stressed the need of a parallax-free mounting stand (not a common tripod) for medical infrared imaging for ensuring that reproducible camera positioning and reduced angular errors in the field of view between the infrared camera and the subject under investigation.

Development and detailed working principle of various infrared cameras and detectors have been described elsewhere [5, 97, 98]. Infrared cameras have undergone three major generations of advancements. The first-generation cameras were equipped with a single detector and two scanning mirrors for image production. These cameras were very slow and they suffered from saturation and calibration errors. Time delay integration was enabled in the second-generation cameras which improved image production. They were equipped with a small 2-D array or a large linear array of detectors along with two scanning mirrors. Third-generation cameras were free of any scanning mirrors and a focal plane array detector produced an image of the entire field of view in one snap. Modern-day infrared cameras are improved version of third-generation cameras with better and faster backplane electronics, sharpness controlled autofocus, on-chip image processing, variable integration time, and frame rate for image acquisition which make them suitable for real-time temperature measurement enabling online monitoring of dynamic temperature variation. Modern infrared detectors can be classified into two major categories, viz., cooled and uncooled. Traditionally cooled cameras are more stable and provide better spatial and temperature resolution but they are heavy and costly. On the other hand, uncooled cameras are light weight, portable, and cheap compared to the cooled cameras and with advancement of solid-state electronics,

the thermal sensitivity of uncooled cameras has reached ~0.05 °C, which is more than sufficient for majority of applications and mass manufacturing of such detector is possible using silicon wafer technologies [99]. It has been reported that infrared cameras equipped with focal plane arrays have spatial resolution of ~2 mm over a range of working distances and fields of view (e.g., 200 × 200 mm to 500 × 500 mm at a distance of 1 m) [100]. To provide a guideline for nonspecialist for selecting infrared cameras from various models available in the market, a few infrared cameras used for diabetes-related thermal imaging are tabulated in Table 2.

3.2 Experimental Conditions

Infrared radiation emitted from skin surface depends on several environmental factors like airflow, surrounding temperature, humidity, and the physiological condition of subjects. Hence, it is essential to perform medical thermography experiments in a controlled environment, especially when the main objective is to detect subtle temperature changes. The importance of a standard data acquisition protocol was stressed by Clark et al. [115] and Ring and Ammer [116] for reproducible and reliable results. According to their studies, the basic standards for examination room, subject information processing, imaging system, data acquisition, and data processing were very important for medical thermography. International Organization for Standardization (ISO) guidelines on human temperature screening [117, 118] were also found to provide additional useful information on test requirement and implementation guidelines for a proper and accurate medical thermography experiments.

Amalu et al. [32] reported that the temperature and humidity of the examination room must be selected in such a way that the physiology of the subjects is not "stressed into a condition of shivering or perspiring." A comfortable room temperature ensures mild thermal stress-induced vasoconstriction aided cooling of skin rendering the hot spots due to the underlying abnormalities to be clearly discernible [12]. A thermal acclimatization time is useful for the subjects to adjust with the environmental temperature and the duration of thermal acclimatization time is essential as it affects skin temperature profile. This thermal acclimatization procedure can be either nude or with normal dressing, depending on the requirements. For infrared thermography experiments on the lower or upper extremities, in most of the cases, disrobing is not required. Literature shows a wide variation in thermal acclimatization time adopted by various researchers, viz., nil duration [119], 1–5 min [68, 105, 120], 15–20 min [101, 107, 109, 111], and up to 30 min [104]. 15 min of thermal acclimatization time is more than sufficient in maximum cases as this is approximately 50% higher than the recommended duration for stabilization of infrared thermography images of human subject at rest [121]. Experimental conditions followed by a few research groups are highlighted in Table 3.

Table 2 List of infrared cameras used by various study groups (UCM indicates uncooled micro-bolometer type detectors) and their important features

Sl. No	Reference	Year	Camera make/Model	Spectral range/Temperature range	Thermal sensitivity	Detector type
1	Branemark et al. [101]	1967	AGEMA 780	3–5.6 μm	0.1 °C	Cooled
2	Cheng et al. [102]	2002	Thermo Tracer, Th2100 (NEC Co.)	8–13 μm	0.02 °C	UCM
3	Sun et al. [103]	2006	Spectrum 9000 MB	7–14 μm	0.05–0.08 °C	UCM
4	Bagavathiappan et al. [68]	2008	AGEMA THV550	3.6–5 μm	<0.1 °C	Cooled
5	Anburajan et al. [104]	2011	Thermacam T400	7.5–13 μm	<45 mK at 30 °C	UCM
6	Huang et al. [105]	2011	Spectrum 9000-MB	7–14 μm	0.05–0.08 °C	UCM
7	Szentkuti et al. [106]	2011	HEXIUM's MIDS (Medirlab Infra-diagnostic System)	8–14 μm	30 mK at 30 °C	FPA-UCM
8	Balbinot et al. [107]	2012	4010 IRYSIS, and T400 Flir	7–12 and 8–14 μm	0.08 and 0.01 °C	UCM
9	Bharara et al. [70]	2012	IRISYS- Model IRI 4010, UK	8–14 μm/(−10 to 250 °C)	0.15 °C at 21 °C ambient	160 × 120 pixels (UCM)
10	Balbinot et al. [108]	2013	IRISYS- Model IRI 4010, UK	8–14 μm/(−10 to 250 °C)	0.15 °C at 21 °C ambient	160 × 120 pixels (UCM)
11	Mori et al. [109]	2013	TH5108ME,	0–70 °C	0.08 °C at 30 °C	UCM
12	Netten et al. [110]	2013	FLIR SC305	7.5–13 μm	<0.05 °C at 30 °C	UCM
13	Oe et al. [111]	2013	Thermo-Shot F30S	8–14 μm	0.1 °C at 30 °C	UCM
14	Bandyopadhyay et al. [112]	2014	FLIR SC325	7.5–13 μm	<0.05 °C at 30 °C	UCM
15	Yavuz et al. [113]	2014	TiR2FT, Fluke Corporation	8–14 μm (−20 to 100 °C)	≤0.07 °C at 30 °C	160 × 120 FPA Vanadium oxide (UCM)
16	Alfred Gatt et al. [114]	2015	FLIR SC 7000	7.7–9.3 μm	<25 mK	Cooled

Table 3 Experimental parameters followed by a few research groups

Serial no.	Researcher	Year	Experimental conditions	
			Ambient room temperature (°C)	Acclimatization time (min.)
1	Branemark et al. [101]	1967	18–20	15–20
2	Armstrong et al. [71]	1997	21 ± 2	15
3	Hosaki et al. [75]	2002	20	15
4	Sun et al. [103]	2006	21 ± 1	15–20
5	Bagavathiappan et al. [68]	2010	25	5

Additionally, the examination room must be free from secondary sources of infrared radiation like incandescent lamps and direct sunlight to reduce the scattering and background temperature fluctuations. Moreover, the subjects should be advised to refrain from the use of cosmetics, deodrants, and antiperspirants. The ambient temperature of the experiment room can be varied between approximately 26–33 °C, i.e., within the limit of classical thermoneutral zone [122]. The physiological conditions of the subjects (like drugs, medications, alcohol, nicotine, exercise, etc.) may alter the skin temperature and hence, proper protocol must be followed in subject selection. Infrared thermography results are to be compared with clinical and medical data to establish possible correlations.

3.3 Data Analysis and Image Processing

Data analysis and image processing are important in medical thermography applications. Temperature data obtained from the acquired thermal images are in general presented as mean ± standard deviation (S.D.). The fluctuations in experimental conditions lead to such deviations and hence, statistical analysis is important obtaining reliable measurement of skin temperature distribution. The common statistical tools are hypothesis testing (Student's t test, Fischer's test), correlation analysis, χ^2 test, and analysis of variance (ANOVA) [71, 103, 123]. Selection of optimal statistical tool is very important as it varies with experimental protocol, data size, and primary objective of the study and design of experiments. Personal computer-based statistical software packages like IBM-SPSS, SAS/STAT statistical analysis software, R, Origin, and Microsoft Excel are in general used for statistical analysis.

Thermal waves attenuate exponentially in a medium and hence, skin surface thermal signatures, which represent underlying anomalies, are of comparatively low signal-to-noise ratio (SNR) [124]. Hence, image processing is fundamental to medical thermography and its importance in medical thermography was rightly

pointed out by Jones and Plassmann [11]. Nowadays, the image obtained from the infrared camera is directly fed into a personal computer where different filters, in time and frequency domains, for minimizing noise, preservation of edges, reducing blurring and for enhancing image quality, are used [112]. Soft computing techniques like artificial neural network (ANN), fuzzy logic, image fusion, etc. have significantly contributed to the development of the semi-automatic processing of medical thermography images [37, 112, 125]. Bandyopadhyay et al. [112] used histogram and Hough transform-based image processing algorithm for screening and monitoring of diabetic status from acquired infrared images of the subjects. Content-based automatic target localization and pattern matching has also been implemented in a few studies [126, 127]. Liu et al. [128] used asymmetric analyses for automatic detection of diabetic foot complications. They developed a robust algorithm for avoiding foot segmentation error using color images and used non-rigid landmark-based registration along with B-splines to circumvent contralateral differences arising out of shape or amputation. Hernandez-Contreras et al. [129] used 3D morphological pattern spectrum for automatic classification of thermal patterns in diabetic foot. Standardization of image capture by means of software masks have been reported by Ring [74]. These masks were designed for infrared imaging of subjects with diabetic neuropathy and vascular disorder where the masks fit the dorsal and plantar surfaces of the feet and hands along with other body parts. Recently, the concept of angiosome, which is defined as the "composite unit of skin and underlying deep tissue supplied by a source artery" [130], has emerged in thermographic monitoring of diabetic foot. Attinger et al. [131] have proposed four angiosomes in the plantar surface of foot, viz., the medial plantar artery angiosome, lateral plantar artery angiosome, medial calcaneal artery angiosome, and the lateral calcaneal artery angiosome. The concept of angiosome along with the aid of software mask will be immensely helpful for accurate monitoring and reliable measurement of temperature patterns in diabetic foot. Plassmann, Ring and Murawski [132, 133] have developed a modern PC-based software called CTHERM which is capable to acquire, store, and manipulate infrared images from both modern and older generation cameras. Modern software packages like Matlab, Labview, Altair, Thermacam-Researcher, etc. have multitude of options for image acquisition and image processing to suit the requirements of medical thermography researchers. The need for a digital database for medical thermography images was felt long ago and substantial work has been done in this direction [134–137]. Colantonio et al. [138] integrated infrared thermography data with 3D shapes to present a 3D image of diabetic foot. Netten et al. [110] have developed and implemented an automatic algorithm for differentiating between local and diffuse diabetic foot complications which was based on parameters captured by an infrared camera and was also capable of detecting absence of diabetic foot complications in healthy subjects. Nevertheless as of now, there is no dedicated database of medical thermography images for diabetic neuropathy and vascular disorder.

4 Infrared Thermography for Detection of Diabetic Neuropathy and Vascular Disorder

The term "diabetic foot" indicates physiological and clinical condition of lower extremities of human subject resulting from diabetes or its long-term complications [139]. The major issues of diabetic foot can be categorized into four types of complications, viz., peripheral neuropathy, peripheral arterial disease or vascular disorder, secondary infection, and soft tissue or bone deformity [140]. Mayfield et al. [141] discussed in detail the various complications of diabetes and preventive foot care methodologies.

Peripheral neuropathy in the lower extremity is one of the most common complications in diabetes subjects and approximately 60% diabetic subjects suffer from peripheral neuropathy [10, 68, 140, 142–144]. It has also been reported to be the most significant cause of pain in diabetic foot with burning or tingling sensation in the foot, which is often accompanied with radiating pain in the plantar regions [140]. In general, it has been observed that the severity of peripheral neuropathy increases with subject's age or duration of diabetes. Diabetic neuropathy affects large and small fibers affecting temperature discrimination and sensory functions [69, 70, 88, 103]. Sympathetic dysfunction in lower limbs often results in reduced sweating and dry skin leading to cracks, fissures, and thermoregulatory sweating abnormalities [103, 145, 146]. Cyclic and repetitive pressure, shear force during weight-bearing exercise or walking, etc. leads to an increased plantar pressure on diabetic foot leading to callus formation and skin breakdown [140]. Diabetic foot motor neuropathy is often associated with the imbalance of flexor and extensor muscles, which results in foot deformation along with prominent metatarsal heads, dry skin, and clawing of claws [140]. If left untreated, foot deformity may progress to joint deformity requiring conservative off loading or surgical intervention [140]. Charcot's neuropathy is a limb threatening advanced stage of joint neuropathy which involves small fiber neuropathy and the two major mechanistic processes involved in the pathogenesis are neurovascular theory and neurotraumatic theory which may ultimately lead to dislocation, disorganization, and changes in bone density [71, 140]. Sympathetic skin response is in general mediated through post-junctional unmyelinated small fibers via pseudo-motor pathways, which is anatomically distinct from vasomotor pathway, whereas skin temperature is regulated by vasomotor as well as pseudo-motor pathways [103, 147]. The elevated skin temperature in neuropathic foot is due to arteriovenous shunt flow [103, 148, 149]. Although the peripheral neuropathy affects somatic and sympathetic neural components in diabetic subjects, clinical and nerve conduction studies investigate only the somatic functions of large myelinated fiber [103, 150]. It has been reported that diabetic neuropathy can be identified in the early stage through detection of damage to unmyelinated small fibers [151] which is associated with change in skin temperature [103]. Studies show that infrared thermography can be reliably applied for early diagnosis of diabetic neuropathy and feet with elevated skin temperature in

diabetic subject is considered as an indication of early diabetic neuropathy [68, 69, 71, 103, 140, 145, 149]. Harding et al. [152] used infrared thermography for early detection of foot ulceration in diabetic neuropathic foot and observed that compared to radiation or isotope-based methods, infrared thermography is beneficial due to radiation protection, logistic, and cost reasons. Bharara et al. [69] reported that in early stages of diabetic neuropathy the skin temperature appears elevated, whereas in later stages the affected areas present lower skin temperature distribution due to significant vascular damage.

Branemark et al. [101] applied infrared thermography to study 16 (12 females and 4 males) diabetic subjects with an average history of 13 years and found that all of them presented abnormal temperature distribution in the feet and hands, like reduced temperature over the toes, fingers, and metatarsal regions. This is one of the first thermography-based studies on diabetic subjects and their studies indicated no variation in the temperature pattern over the dorsal aspect of the foot and tibia in the subjects. Bharara et al. [69] presented an excellent review on diabetes-induced complication in foot and the role of infrared thermography in diagnosis of diabetic foot. Sun et al. [103] used infrared thermography for studying the relationship between plantar skin temperature and sympathetic dysfunction in diabetic-at-risk foot in 29 diabetic subjects and compared the findings with temperature pattern of 25 control subjects. Their studies indicated that diabetes-at-risk subjects have significantly higher mean foot temperature (30.2 $\pm$ 1.3 °C) compared to the normal subjects (26.8 $\pm$ 1.8 °C). Mean foot temperature was obtained by averaging of the foot temperature over six regions, viz., hallux, lesser toes, forefoot, arch, lateral sole, and heel. Armstrong et al. [71] carried out comparative studies on the skin temperature of subjects affected with asymptomatic peripheral neuropathy (78 subjects), neuropathic ulcers (44 subjects), and Charcot's anthropathy (21 subjects) where contralateral limb was used as control. Their studies revealed significant contralateral temperature difference in the cases of neuropathic ulcers (5.6 °F) and Charcot's anthropathy (8.3 °F) whereas, no such temperature difference was observed in the cases of asymptomatic peripheral neuropathy. Vinik et al. [153] reported large temperature variation in extremities of diabetic subjects which was found to depend on several factors like environmental temperature and activity of the neurovegetative sympathetic nervous system. Papanas et al. [154] and Vinik et al. [155] studied the association of pseudo-motor dysfunction with foot temperature and dermal neurovascular dysfunction in diabetic subjects, respectively. Sivanandam et al. [156] studied 62 diabetic subjects using infrared thermography along with other clinical examinations and reported that infrared thermography was very successful in examining the extremities of the subjects and early diagnosis of foot ulceration was possible. This study also indicates a better sensitivity, accuracy, and specificity of infrared thermography-based diagnosis compared to conventional HBA1c-based measurements. Chan et al. [157] reported that diabetic subjects with painful peripheral neuropathy have higher forefoot temperature compared to normal subjects. Benbow et al. [73] and Stess et al. [158] reported that higher foot temperature in diabetic subjects was indicative of foot ulceration and temperature measurement aids in early diagnosis. Roback et al. [93] studied the feasibility of

thermography technique for early detection of foot complications in diabetic subjects. Fujiwara et al. [159] also used thermography for skin temperature measurement in diabetic subjects. Nishide et al. [160] applied thermography and ultrasonography for studying latent inflammation in diabetic foot callus. Recently, Kanazawa et al. [161] used a smartphone attached infrared thermography system (FLIR one) for assessment of pressure ulcer induced inflammation and diabetic foot monitoring and their results suggest that such ultra-lightweight alternative thermography systems can be reliably used for diabetic foot monitoring. Hazenberg et al. [162] combined digital photography and infrared thermography for assessment of foot infection in diabetic subjects and obtained high specificity (>79%) and high sensitivity (>60%) from the combined technique which was not possible to achieve with an individual technique alone. A typical case study [68] carried out in author's laboratory is described below. The infrared images were acquired using AGEMA Thermovision 550 infrared camera which is equipped with a focal plane array of platinum silicide (PtSi) detector elements cooled using an internal Stirling cycle. The spectral range was 3.6–5 μm and thermal sensitivity of the camera was better than 0.1 °C. Experiments were performed under controlled environment with an ambient temperature of 25 °C and 5 min of thermal acclimatization time during which the subjects were requested to remove their foot wears and socks and lie supine on a couch.

Randomly chosen 112 subjects suffering from type 2 diabetes were studied using infrared thermography. Anthropometric measurements like weight, height, waist, and hip sizes were carried out along with clinical measurements of vibratory perception threshold (VPT) using biothesiometry and pathological measurement of glycated hemoglobin (HBA1c). Mean foot temperature (MFT) was obtained from the infrared images of the plantar surface of the subjects by averaging the temperature over various locations, viz., hallux, lesser toes, arch, lateral sole ,and forefoot regions. It was also observed that neuropathic subjects (VPT > 20) have higher MFT compared to non-neuropathic subjects and the MFT showed a positive correlation with right and left great toes VPT values [68]. Figure 3 shows the variation of MFT values as a function of VPT values and it can be seen that 28 subjects with VPT values less than 20 (non-neuropathic) showed MFT values within the temperature range of 27–30 °C. On the other hand, 33 subjects were found with VPT values higher than 20 (neuropathic) and MFT values varying between 30 and 37 °C. Figure 4a, b shows the infrared images of the lower extremities of a 44-year-old neuropathic male diabetic (HbA1c value = 9.6%) and a 67-year-old non-neuropathic female diabetic (HbA1c value = 6.6%) subjects, respectively. The mean foot temperatures over the encircled regions were found to be 34.1 and 29.1 °C, respectively. It can be clearly seen that neuropathic subjects were associated with a higher mean foot temperature. The elevated skin temperature in neuropathic foot is attributed to arteriovenous shunt flow [103, 148, 149].

Diabetes often leads to peripheral arterial diseases (PAD) or vascular disorder which mainly affects the small and large blood vessels in the extremities, more commonly in the lower arteries resulting in varicose veins with inadequate

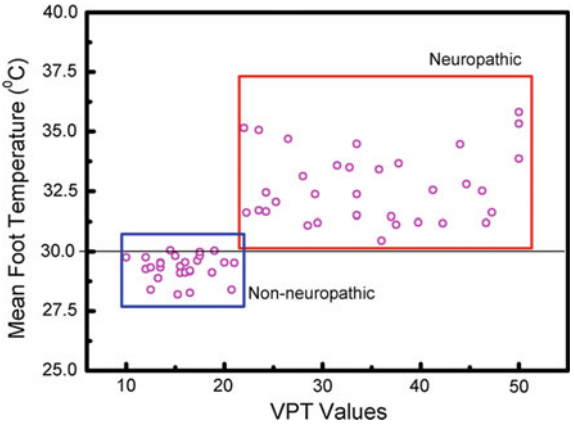

Fig. 3 Mean foot temperature (MFT) of diabetic subjects as a function of their vibratory perception threshold (VPT) values [68]. For non-neuropathic subjects (indicated by the *blue rectangle*) with VPT values less than 20, MFT values were distributed within 27–30 °C, whereas for neuropathic subjects (indicated by the *red rectangle*) with VPT values greater than 20, MFT values were within a range of 30–37 °C

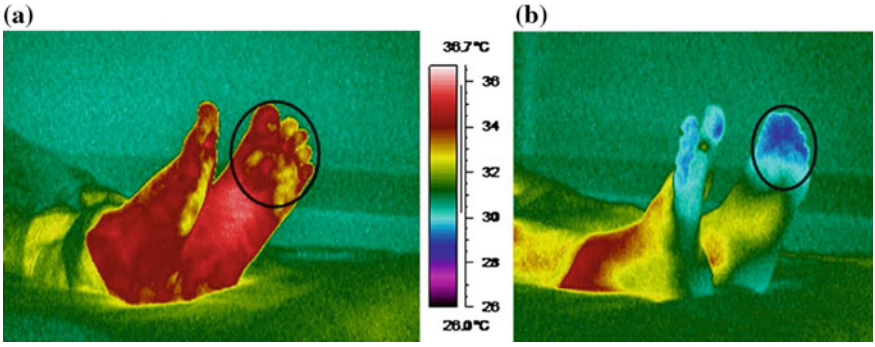

Fig. 4 Typical pseudo-color-coded infrared images of the plantar regions for two diabetic subjects [68]. **a** A 44-year-old neuropathic male subject and **b** A 67-year-old non-neuropathic female subject. The average temperature over the encircled regions were found to be 34.1 and 29.1 °C, for the neuropathic and non-neuropathic subjects, respectively

drainage. The major arteries that deliver blood to the lower extremities are posterior tibial, anterior tibial, and peroneal arteries and with progressing diabetes-induced vascular disorder these arteries may be affected [140]. It has been reported that progressing PAD primarily affect anterior tibial and peroneal arteries, whereas dorsalis pedis, posterior tibial, and plantar arteries are less affected resulting in normal pulsating responses in these arteries [76, 140]. Further complications of vascular disorder result in micro-arterial dysfunction, limited capillary capacity, increased arteriovenous shunting, and decreased neurogenic regulation, mild to

severe pain due to lack of oxygen and nutrient. Varicose veins are often associated with mild inflammation which can be detected using infrared thermography from the abnormally higher skin temperature over the affected regions [76]. Moreover, toe temperature at the distal positions appears to be lower in diabetic subjects suffering from vascular disorder due to inadequate drainage [76, 77] which can be reliably detected using infrared thermography. Historically, infrared thermography had been used for studying peripheral vascular disorder from mid-sixties. Probably, the first two studies on the application of infrared thermography in peripheral vascular disorder was reported by Skversky et al. [163] and Winsor and Bendezu [164] in 1964. In 1970, Robins and Bernstein [165] applied digital plethysmography and infrared thermography on subjects with peripheral vascular diseases and compared the efficacy of both the techniques. Application of infrared thermography for vascular disorder was also studied by Langer et al. [166] in 1972. Soulen et al. [167] compared angiography, ultrasonography, and thermography in the evaluation of peripheral vascular diseases in 166 subjects with suspected thrombophlebitis and 300 other subjects with peripheral arterial diseases and found that thermography aided in recognition of phlebitis and in assessment of post-operative vascular disorder. Holm et al. [168] reported the use of thermography in vascular surgery based on results obtained from 12 case studies. Henderson and Hackett [169] described thermography as a reliable, noninvasive and rapid methodology for investigating subjects with peripheral vascular disorders. Hosaki et al. [75] applied infrared thermography to quantitatively study peripheral vascular circulation in 27 diabetic subjects in which 14 were males and the rest were females. They observed temperature gradients, indicating abnormal blood flow in the affected regions which were found to be correlated with other clinical findings. This study also indicated that recovery ratio calculated from the infrared images were correlated with blood flow measured using laser Doppler flowmetry and it was suggested that infrared thermography can be used as a potential tool for early detection of arteriosclerosis obliterans (ASO) in diabetic subjects. Hitoi and Matsuoka [170] stressed the usefulness of infrared thermography-based monitoring of peripheral circulation in diabetic subjects. Balbinot et al. [108] applied IRT to diabetic subjects and found that rewarming index after cold stress presented good repeatability. The study also revealed that temperature difference (ΔT) measured using infrared thermography was clinically more relevant. Fushimi et al. [171] studied the abnormal vaso-reaction of peripheral arteries to cold stimulation in both hands of diabetic subjects. Huang et al. [105] applied infrared thermography for evaluating subjects with higher risk of lower extremity peripheral arterial disease (PAD) and observed that temperature changes in the soles of PAD versus non-PAD subjects were −1.25 versus −0.15 ($p < 0.001$). Mitchell et al. [172] applied thermography for studying skin blood flow and limited joint mobility in 32 insulin-dependent subject and 13 healthy control subjects at room temperature and after immersing in warm and cold water. They reported a predominantly distal rewarming pattern after withdrawal of cold stress with higher mean index finger temperature in the insulin-dependent subjects compared to the controls which was experimentally confirmed using

thermography. Toutouzas et al. [173] used an infrared thermography-based procedure for evaluating subjects with diabetes mellitus and coronary artery disease and reported that such subjects suffer from higher carotid inflammation. Uchikawa et al. [174] studied the effects of cilostazol (anti-platelet agent) on peripheral vascular disorder in diabetic subjects and reported that infrared thermography is beneficial in planning individual dose and monitor the effects of cilostazol and subject compliance during long-term drug administration. The effect of cilostazol in peripheral arterial occlusion was also studied by Ohashi et al. [175] using thermography techniques. Staffa et al. [176] applied infrared thermography for long-term monitoring of foot temperature in diabetic subjects. Three case studies, carried out by Bagavathiappan et al. [76, 77], on application on infrared thermography in detection of peripheral vascular disorder are described below. AGEMA Thermovision 550 infrared camera was used for acquiring the infrared images. Experiments were performed under controlled environment after 15 min of thermal acclimatization time.

Case: 1

First is a 48-year-old male subject reported recurring pain in the left calf muscle for past two years with the severity of pain continuously increasing over the last half a year. The pain was found to increase on walking or prolonged standing and presented symptoms of relief on comfortable seating posture. Clinical examinations revealed normal pulses in the left and right upper and lower limbs, normal dorsalis pedis and posterior tibial pulse in the right lower limb, and low volume of dorsalis pedis and posterior tibial pulse in the left lower limb. A non-healing ulcerous 8-month-old injury in the left great toe was observed with the presence of gangrenous tissue. The subject was occasional user of alcohol and nicotine. The respiratory system (RS), cardiovascular system (CS), central nervous system (CNS), and abdominal examinations were also found to be normal for this subject. Thermal imaging was carried out on the left leg of the subject.

Figure 5a shows the pseudo-color-coded infrared image of the medial view of the left leg of the subject along with the temperature scale. Figure 5b shows a horizontal line scan (as indicated in Fig. 5a) along the calf muscle which indicates a region of higher temperature at the middle portion which is also visually discernible from the thermal image [76, 77]. Such abnormal higher temperature regions were not present in healthy subjects used as control. This region of higher temperature was attributed to the presence of thrombosis which is an arterial obstruction to blood flow causing blood clotting within blood vessels. Such thrombosis may turn potentially life threatening if the dislodgement of the thrombus results in pulmonary embolism. This region of higher temperature was found to be associated with mild to severe inflammation and was coincident with the region of pain. Infrared thermography enabled noncontact detection of the region of pain and associated thrombosis. It was concluded that this may be due to thromboangiitis obliterans (or Buerger's disease) due to arterial insufficiency.

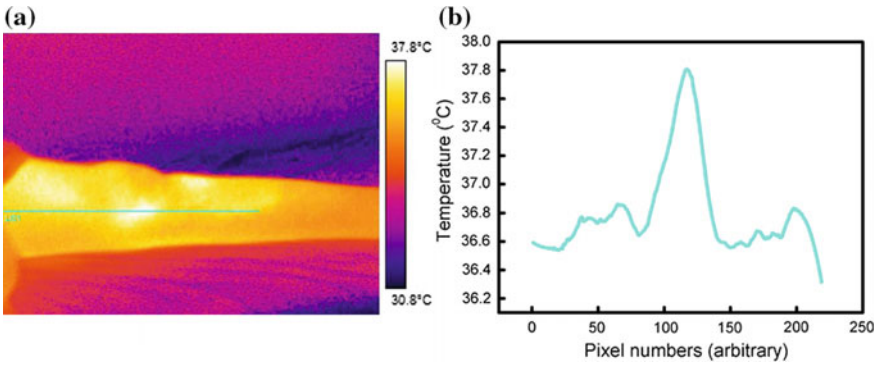

Fig. 5 **a** Pseudo-color-coded infrared image of the dorsal profile of the left leg of a 48-year-old male subject suffering from vascular disorder [77]. **b** Temperature profile along the horizontal line shown in the infrared image which indicated the presence of a higher temperature region that was attributed to the presence of thrombosis

Case: 2

A 31-year-old male subject with a long history (approximately five years) of swelling in both lower limbs on prolonged standing reported recurrent ulceration on the left lateral malleolus associated with pain and discharge of pus even after undergoing treatment and surgery (four years earlier). The RS, CVS, CNS, abdominal examination, and palpable arterial pulse were found to be normal for the subject. The subject was suffering from systematic hypertension and was under medication for the same for 6 months. Clinical examinations of the left lower limb revealed tortuous dilated veins and recurrent healing ulcers on the left lateral malleolus which were covered with slough and pus discharge. Thermal imaging was carried out on the left leg of the subject.

Figure 6 shows the pseudo-color-coded thermal image of the dorsal view of the left leg of the subject. It can be seen from the infrared image that clinically detected areas with varicosity presented an elevated temperature distribution (encircled by the black-dotted line) which was attributed to the varicosity-induced mild inflammation and slow passage of warm blood through the tortuous veins compared to normal veins. It was observed that the higher temperature regions (containing varicose veins) were presented in the lateral side of the left leg and not in the medial side of the leg (most commonly observed locations of varicose veins). It can be further seen from the infrared image that distal regions in the vicinity of the toes were at a significantly lower temperature (indicated by the white arrow) which was due to vascular disorder resulting in poor perfusion of blood [76, 77].

Case: 3

A 28-year-old male subject was suffering from a pain in the left lower limb which increased on prolonged standing. RS, CVS, CNS, abdominal examination, radial pulse, carotid pulse, dorsalis pedis, and posterior tibial pulse were found to be

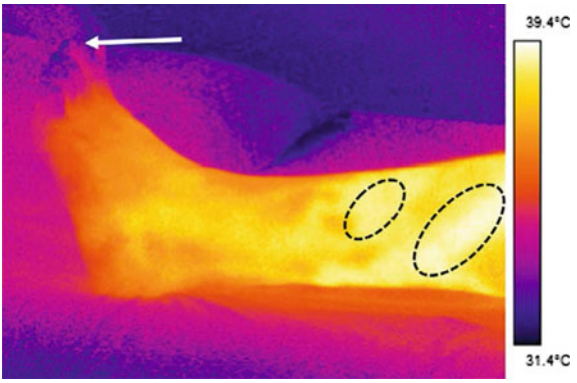

Fig. 6 Typical infrared image of the dorsal profile of the left leg of a 31-year-old male subject suffering from vascular disorder [76, 77]. Clinically diagnosed areas of varicosity were found to coincide with the regions of higher temperature (encircled by the *black-dotted lines*). The distal region was found to be at a lower temperature (indicated by the *white arrow*) due to inadequate blood flow

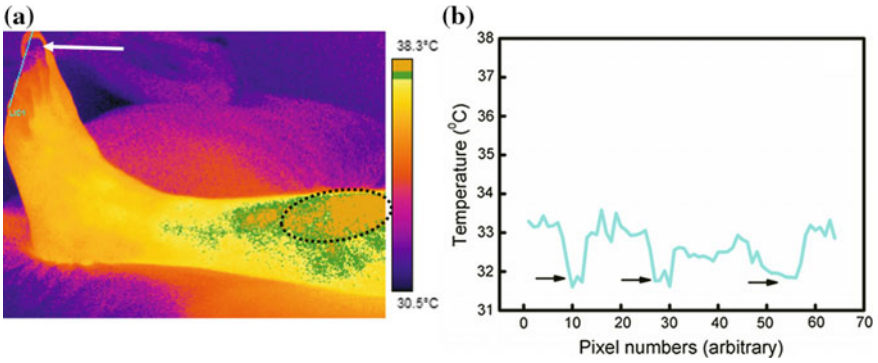

Fig. 7 **a** Typical infrared image of the left leg of a 28-year-old male subject suffering from vascular disorder. The image is shown in pseudo-color-coded isotherm scale and the region of higher temperature (encircled by the *black-dotted line*) corresponded to the mild inflammation of the varicose veins. The distal regions (indicated by a *white arrow*) presented a lower temperature due to inadequate blood perfusion. **b** Temperature profile along the line indicated in the infrared image. The periodic lower temperature confirmed slow blood perfusion in the distal regions (toes)

normal for the subject. Clinical examinations revealed varicosity of the long saphenous system of the left lower limb and the varicosity-related complications were predominant for the past one year. Thermal imaging was carried out over the left leg of the subject.

Figure 7a shows the pseudo-color-coded infrared image of the left leg of the subject. The line profile over the toe tips is shown in Fig. 7b. It can be clearly seen that distal position (indicated by the white arrow in the thermal image) had a

comparatively lower temperature, which was attributed to varicosity-induced inadequate venous drainage. Higher temperature regions (encircled by the black-dotted line) were observed over the left leg of the subject, which were found to be coincident with the varicosity-affected regions. It was observed that the temperature was 0.7–1.0 °C higher in these regions compared to the surrounding skin temperature. The affected regions presented an elevated temperature distribution due to varicosity-induced mild inflammation which was otherwise not detected during routine clinical examination.

Foot damages resulting from diabetic neuropathy, vascular disorder, or ischemia very often causes infection, which ultimately results in foot ulceration. Infection can be active (bacterial or fungal) or passive (biofilms). Most common species causing infection in diabetic foot are aerobic gram-positive cocci (*Staphylococcus aureus*), gram-negative bacilli (*Escherichia coli*), and anaerobic *Bacteroides* sp. and *Peptostreptococcus* sp. [140, 177]. Infrared thermography is successfully used for monitoring wound healing in the cases of foot ulcerations [178]. Apart from peripheral neuropathy and vascular disorder, infrared thermography has also been applied to diabetic retinopathy. Sodi et al. [179] performed a comparative study of the ocular surface temperature (OST) in 51 subjects with nonproliferative diabetic retinopathy (NPDR) and in 53 age and gender matched healthy subjects. They found that in diabetic subjects OST was significantly lower than the normal subjects. Although majority of the infrared thermography-based studies were conducted on subjects with type 2 diabetes, a few recent studies [180, 181] report the applicability of infrared thermography on type 1 diabetic subjects. Sejling et al. [180, 182] studied the changes in skin temperature during hypoglycemia in type 1 diabetic subjects and reported that skin temperature decreased during hypoglycemia over the nose and glabella regions. They indicated the suitability of infrared thermography to study the hypoglycemia-induced decrease in skin temperature which was observed to be higher in subjects with hypoglycemia awareness. Zotter et al. [181] applied infrared thermography to assess the abnormalities in skin blood flow before and after cold challenge on lower leg of 25 adolescent asymptomatic subjects with type 1 diabetes. Their studies revealed that adolescent type 1 diabetic subjects show abnormalities in skin blood flow over the tips of first and fifth toes and inner ankles after cold challenge which was successfully mapped using infrared thermography. Schindl et al. [183, 184] applied infrared thermography for monitoring low-intensity laser-induced improvement in peripheral circulation in subjects with diabetic microangiopathy.

The above case studies and literature survey clearly indicate that diabetic foot complications are associated with significant changes in skin temperature with definite patterns (e.g., lower temperature distribution in the distal position of the toes in the cases of vascular disorders and elevated foot temperature for the diabetic neuropathic subjects), which facilitates early diagnosis of diabetic complications using infrared thermography-based skin temperature monitoring. Therefore, periodic monitoring of skin temperature reduces the risk of foot ulceration [185]. Further, identifying individuals at high risk and treating for lower extremity

complications may reduce the number of amputations by 85% [186]. Pafili and Papanas [187] suggested that a 5-year use of infrared thermography or liquid crystal thermography for daily self-examination among high-risk group of subjects may significantly lower further complications in diabetic foot.

5 Conclusions

Among various techniques available for accurate and reliable measurement of subject temperature, infrared thermography is a relatively new methodology that has become popular because of its noncontact, noninvasive, and real-time temperature measurement capability. During the last few decades, numerous applications of infrared thermography are reported in the field of medical sciences. Considering the huge increase in diabetics cases worldwide, a dedicated effort for early detection of diabetes is essential. Studies reveal that infrared thermography is capable of the early detection of diabetic peripheral neuropathy and vascular disorders. This book chapter highlights the studies on diabetic neuropathy and vascular disorder using infrared thermography technique. The basics of infrared thermography, classification of medical thermography techniques, details of various infrared cameras available, ideal experimental conditions, data analysis, etc. along with typical case studies on the above two subjects are discussed. To become IRT as routine techniques for diagnosis of diabetic neuropathy and vascular disorder, more systematic case studies in large number of subjects from various continents and correlating the IRT results with clinical findings are a prerequisite. Further, refinements in the experimental protocols, automation, rapid, and reliable data analysis approaches are to be developed. One of the impeding issues in the use of this technique in the past was the higher cost of infrared camera but it has now surmounted because of the availability of infrared cameras at affordable rates.

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References

1. Houdas, Y., Ring, E.F.J.: Human Body Temperature. Plenum, New York (1982)
2. Ring, E.F.J.: The historical development of temperature measurement in medicine. Infrared Phys. Technol. **49**, 297–301 (2007)
3. Tan, J.H., Ng, E.Y.K., Acharya, U.R., Chee, C.: Study of normal ocular thermogram using textural parameters Infrared Phys. Technol. **53**, 120–126 (2010)
4. Wunderlich, C., Woodman, W.: On the Temperature in Diseases, A Manual of Medical Thermometry, vol. 71 The New Sydenham Society, London, England (1871)
5. Maldague, X.: Theory and Practice of Infrared Technology for Nondestructive Testing, 1st edn. Wiley, New York (2001)

6. Meola, C.: Infrared Thermography: Recent Advances and Future Trends. Bentham eBooks (2012)
7. Bagavathiappan, S., Lahiri, B.B., Saravanan, T., Philip, J., Jayakumar, T.: Infrared thermography for condition monitoring—A review. Infrared Phys. Technol. **60**, 35–55 (2013)
8. Lahiri, B.B., Bagavathiappan, S., Soumya, C., Mahendran, V., Pillai, V.P.M., Philip, J., Jayakumar, T.: Infrared thermography based defect detection in ferromagnetic specimens using a low frequency alternating magnetic field. Infrared Phys. Technol. **64**, 125–133 (2014)
9. Lahiri, B.B., Haneef, T.K., Bagavathiappan, S., Kulasegaran, N., Mukhopadhyay, C.K., Jayakumar, T., Philip, J.: Infrared thermography-based studies on hydrotesting of stainless steel pressure vessels. Insight **57**, 406–413 (2015)
10. Lahiri, B.B., Bagavathiappan, S., Jayakumar, T., Philip, J.: Medical applications of infrared thermography: a review. Infrared Phys. Technol. **55**, 221–235 (2012)
11. Jones, B., Plassmann, P.: Digital infrared thermal imaging of human skin. IEEE Eng. Med. Biol. Mag. **21**, 41–48 (2002)
12. Jones, B.F.: A reappraisal of the use of infrared thermal image analysis in medicine. IEEE Trans. Med. Imaging **17**, 1019–1027 (1998)
13. Ammer, K., Ring, E.F.J.: The Thermal Image in Medicine and Biology. Uhlen-Verlag, Vienna (1995)
14. Lahiri, B.B., Bagavathiappan, S., Nishanthi, K., Mohanalakshmi, K., Veni, L., Yacin, S.M., Philip, J.: Infrared thermography based studies on the effect of age on localized cold stress induced thermoregulation in human. Infrared Phys. Technol. **76**, 592–602 (2016)
15. Lahiri, B.B., Bagavathiappan, S., Soumya, C., Jayakumar, T., Philip, J.: Infrared thermography based studies on mobile phone induced heating. Infrared Phys. Technol. **71**, 242–251 (2015)
16. Lahiri, B.B., Divya, M.P., Bagavathiappan, S., Thomas, S., Philip, J.: Detection of pathogenic gram negative bacteria using infrared thermography. Infrared Phys. Technol. **55**, 485–490 (2012)
17. Ring, E.F.J., Ammer, K.: Infrared thermal imaging in medicine. Physiol. Meas. **33**, R33–R46 (2012)
18. Jung, A., Zuber, J., Ring, F.: A Case Book of Infrared Imaging in Clinical Medicine. MedPress, Warszawa (2003)
19. Yang, W.J., Yang, P.P.: Literature survey on biomedical applications of thermography. Biomed. Mater. Eng. **2**, 7–18 (1992)
20. Fauci, M.A., Breiter, R., Cabanski, W., Fick, W., Koch, R., Ziegler, J., Gunapala, S.D.: Medical infrared imaging-differentiating facts from friction, and the impact of high precision quantum well infrared photodetector camera systems, and other factors, in its reemergence. Infrared Phys. Technol. **42**, 334–344 (2001)
21. Jiang, L.J., Ng, E.Y., Yeo, A.C., Wu, S., Pan, F., Yau, W.Y., Chen, J.H., Yang, Y.: A perspective on medical infrared imaging. J. Med. Eng. Technol. **29**, 257–267 (2005)
22. Ring, E.F.J., Jung, A., Zuber, J.: New opportunities for infrared thermography in medicine. Acta Bio-Opt. Inf. Med. **15**, 28–30 (2009)
23. Faust, O., Acharya, U.R., Ng, E.Y.K., Hong, T.J., Yu, W.: Application of infrared thermography in computer aided diagnosis. Infrared Phys. Technol. **66**, 160–175 (2014)
24. Bitar, D., Goubar, A., Desenclos, J.C.: International travels and fever screening during epidemics: a literature review on the effectiveness and potential use of non-contact infrared thermometers. Eurosurveillance **14**, 1–5 (2009)
25. Mercer, J.B., Ring, E.F.J.: Fever Screening and infrared thermal imaging: concerns and guidelines. Thermol. Int. **19**, 67–69 (2009)
26. Ng, E., Kaw, G.: IR images and fever monitoring devices: physics, physiology, and clinical accuracy. In: Medical Devices and Systems, Biomedical Engineering Handbook. CRC Press, Boca Ranton (FL) (2006)

27. Ng, E.Y.K.: Is thermal scanner losing its bite in mass screening of fever due to SARS? Med. Phys. **32**, 93–97 (2005)
28. Ng, E.Y.K., Kaw, G., Chang, W.M.: Analysis of IR thermal imager for mass blind fever screening. Microvasc. Res. **68**, 104–109 (2004)
29. Ring, E.F.J., Jung, A., Zuber, J., Rutowski, P., Kalicki, B., Bajwa, U.: Detecting fever in Polish children by infrared thermography. In: 9th International Conference on Quantitative Infrared Thermography, Krakow, Poland (2008)
30. Ring, F.: Pandemic: thermography for fever screening of airport passengers. Thermol. Int. **17**, 67 (2007)
31. Ring, F., Mercer, J.: Thermal imaging for fever screening, pp. 33–35, ISO Focus, February (2007)
32. Amalu, W.C., Hobbins, W.B., Head, J.F., Elliot, R.L.L: Infrared imaging of the breast—an overview. In: Bronzino, J.D. (ed.) Biomedical Engineering Handbook, Medical Devices and Systems, 3rd edn, pp. 20. CRC Press (2006)
33. Louis, J.W.K., Gautherie, M.: Long term assessment of breast cancer risk by thermal imaging. Biomed. Thermol., 279–301 (1982)
34. Kennedy, D., Lee, T., Seely, D.: A comparative review of thermography as a breast screening technique. Integr. Cancer. Ther. **8**, 9–16 (2009)
35. Ng, E.Y.K.: A review of thermography as promising non-invasive detection modality for breast tumor. Int. J. Therm. Sci. **48**, 849–859 (2009)
36. Ng, E.Y.K., Kee, E.C.: Advanced integrated technique in breast cancer thermography. J. Med. Eng. Technol. **32**, 103–114 (2008)
37. Tan, T.Z., Quek, C., Ng, G.S., Ng, E.Y.K.: A novel cognitive interpretation of breast cancer thermography with complementary learning fuzzy neural memory structure. Expert Syst. Appl. **33**, 652–666 (2007)
38. Shevelev, I.A.: Functional imaging of the brain by infrared radiation (thermoencephaloscopy). Prog. Neurobiol. **56**, 269–305 (1998)
39. Fikackova, H., Ekberg, E.: Can infrared thermography be a diagnostic tool for arthralgia of the temporomandibular joint? Oral Surg. Oral Med. Oral Pathol. Oral Radiol. Endod. **98**, 643–650 (2004)
40. Carlo, A.D.: Thermography and the possibilities for its applications in clinical and experimental dermatology. Clin. Dermatol. **13**, 329–336 (1995)
41. Anbar, M., Gratt, B., Hong, D.: Thermology and facial telethermography. Part I: History and technical review. Dentomaxillofac. Radiol. **27**, 61–67 (1998)
42. Gratt, B., Anbar, M.: Thermology and facial telethermography: Part II. Current and future clinical applications in dentistry. Dentomaxillofac. Radiol. **27**, 68–74 (1998)
43. Park, J., Hyun, J.K., Seo, J.: The effectiveness of digital infrared thermographic imaging in patients with shoulder impingement syndrome. J. Shoulder Elbow Surg. **16**, 548–554 (2007)
44. Zelichowska, B., Rozycki, R., Tlustochowicz, M., Kujawa, A., Kalicki, B., Murawski, P.: The usefulness of the thermography in the dry eye syndrome. Klin. Oczna **107**, 483–487 (2005)
45. Tan, J.H., Ng, E.Y.K., Acharya, U.R., Chee, C.: Infrared thermography on ocular surface temperature: a review. Infrared Phys. Technol. **52**, 97–108 (2009)
46. Cosh, J.A., Ring, E.F.J.: Thermography and rheumatology. Rheumatology **10**, 342–348 (1970)
47. Jacobsson, H., Vesterskold, L.: The thermographic pattern of the lower back with special reference to the sacro-iliac joints in health and inflammation. Clin. Rheumatol. **4**, 426–432 (1985)
48. Vecchio, P.C., Adebajo, A.O., Chard, M.D., Thomas, P.P., Hazleman, B.L.: Thermography of frozen shoulder and rotator cuff tendinitis. Clin. Rheumatol. **11**, 382–384 (1992)
49. Will, R.K., Ring, E.F.J., Clarke, A.K., Maddison, P.I.: Infrared thermography, what is its place in rheumatology in the 1990s. Br. J. Rheumatol. **31**, 337–344 (1992)

50. Antonio-Rubio, I., Madrid-Navarro, C.J., Salazar-Lopez, E., Perez-Navarro, M.J., Saez-Zea, C., Gomez-Milan, E., Mínguez-Castellanos, A., Escamilla-Sevilla, F.: Abnormal thermography in Parkinson's disease. Parkinsonism Rel. Disord. **21**, 852–857 (2015)
51. Costello, J.T., McInerney, C.D., Bleakley, C.M., Selfe, J., Donnelly, A.E.: The use of thermal imaging in assessing skin temperature following cryotherapy: a review. J. Therm. Biol **37**, 103–110 (2012)
52. Bouzida, N., Bendada, A., Maldague, X.P.: Visualization of body thermoregulation by infrared imaging. J. Therm. Biol **34**, 120–126 (2009)
53. Tanda, G.: Skin temperature measurements by infrared thermography during running exercise. Exp. Therm. Fluid Sci. **71**, 103–113 (2016)
54. Milonov, O.B., Lebedeva, O.D., Pomelova, L.A.: The use of echography and thermography in patients with parasitic liver diseases. Sovet. Med. **4**, 62–67 (1980)
55. Mansfield, C.M., Farrell, C., Asbell, S.O.: The use of Thermography in the detection of metastatic liver disease. Radiology **95**, 696–698 (1970)
56. Brooks, J.P., Perry, W.B., Putnam, A.T., Karulf, R.E.: Thermal imaging in the detection of bowel ischemia. Dis. Colon Rectum **43**, 1319–1321 (2000)
57. Fiz, J.A., Lozano, M., Monte-Morenoc, E., Gonzalez-Martinez, A., Faundez-Zanuy, M., Becker, C., Pons-Rodriguez, L., Manzanoa, J.R.: Tuberculine reaction measured by infrared thermography. Comput. Methods Programs Biomed. **122**, 199–206 (2015)
58. Kopsa, H., Czech, W., Schmidt, P., Zazgornik, J., Pils, P., Balcke, P.: Diagnostic relevance of contact thermography in renal transplantation (author's translation). Med. Klin. **74**, 1067–1070 (1979)
59. Kopsa, H., Czech, W., Schmidt, P., Zazgornik, J., Pils, P., Balcke, P.: Use of thermography in kidney transplantation: two year follow up study in 75 cases. Proc. Eur Dial Transplant Assoc. **16**, 383–387 (1979)
60. Loriaux, C.: Role of thermography in gynecology. J. Radiol. Electrol. Med. Nucl., 56 (suppl.), 57–58 (1975)
61. Birnbaum, S.J., Kliot, D.: Thermography-obstetrical applications. Ann. N. Y. Acad. Sci. **121**, 209–222 (1964)
62. Topalidou, A., Downe, S.: Investigation of the use of thermography for research and clinical applications in pregnant women. Infrared Phys. Technol. **75**, 59–64 (2016)
63. Ernst, M., Lee, M.H.M.: Sympathetic vasomotor changes induced by manual and electrical acupuncture of the hoku point visualized by thermography. Pain **21**, 25–33 (1985)
64. Cattaneo, C., Giancamillo, A.D., Campari, O., Martrille, L., Jouineau, C.: Infrared tympanic thermography as a substitute for a probe in the evaluation of ear temperature for post-mortem interval determination: a pilot study. J. Forensic Leg. Med. **16**, 215–217 (2009)
65. Al-Alousi, L.M., Anderson, R.A., Worster, D.M., Land, D.D.: Multiple-probe thermography for estimating the postmortem interval: I. Continuous monitoring and data analysis of brain, liver, rectal and environmental temperatures in 117 forensic cases. J. Forensic. Sci. **46,** 317–322 (2001)
66. Manginas, A., Andreanides, E., Leontiadis, E., Sfyrakis, P., Maounis, T., Degiannis, D., Alivizatos, P., Cokkinos, D.: Right Ventricular endocardial thermography in transplanted and coronary artery disease patients: first human application. J. Invasive Cardiol. **22**, 400–404 (2010)
67. Salaimeh, A.A., Campion, J.J., Gharaibeh, B.Y., Evans, M.E., Saito, K.: Real-time quantification of viable bacteria in liquid medium using infrared thermography. Infrared Phys. Technol. **54**, 517–524 (2011)
68. Bagavathiappan, S., Philip, J., Jayakumar, T., Raj, B., Rao, P.N.S., Varalakshmi, M., Mohan, V.: Correlation between plantar foot temperature and diabetic neuropathy by using an infrared thermal imaging technique. J. Diab. Sci. Technol. **4**, 1386–1392 (2010)
69. Bharara, M., Cobb, J.E., Claremont, D.J.: Thermography and thermometry in the assessment of diabetic neuropathic foot: a case for furthering the role of thermal techniques. Int. J. Low. Extrem. Wounds **5**, 250–260 (2006)

70. Bharara, M., Schoess, J., Armstrong, D.G.: Coming events cast their shadows before: detecting inflammation in the acute diabetic foot and the foot in remission. Diabetes Metab. Res. Rev. **28**(Suppl 1), 15–20 (2012)
71. Armstrong, D.G., Lavery, L.A., Liswood, P.J., Todd, W.F., Tredwell, J.A.: Infrared dermal thermometry for the high-risk diabetic foot. Phys. Ther. **77**, 169–175 (1997)
72. Lavery, L.A., Higgins, K.R., Lanctot, D.R., Constantinides, G.P., Zamorano, R.G., Athanasiou, K.A., Armstrong, D.G., Agrawal, C.M.: Preventing diabetic foot ulcer recurrence in high-risk patients. Diabetes Care **30**, 14–20 (2007)
73. Benbow, S.J., Chan, A.W., Bowsher, D.R., Williams, G., Macfarlane, I.A.: The prediction of diabetic neuropathic plantar foot ulceration by liquid-crystal contact thermography. Diabetes Care **17**, 835–839 (1994)
74. Ring, F.: Thermal imaging today and its relevance to diabetes. J. Diab. Sci. Technol. **4**, 857–862 (2010)
75. Hosaki, Y., Mitsunobu, F., Ashida, K., Tsugeno, H., Okamoto, M., Nishida, N., Takata, S., Yokoi, T., Tanizaki, Y., Ochi, K., Tsuji, T.: Non-invasive study for peripheral circulation in patients with diabetes mellitus. In: Annual reports of Misasa Medical Branch, Okayama University Medical School, Tottori Japan, vol. 72, pp. 31–37 (2002)
76. Bagavathiappan, S., Saravanan, T., Philip, J., Jayakumar, T., Raj, B., Karunanithi, R., Panicker, T., Korath, M.P., Jagadeesan, K.: Infrared thermal imaging for detection of peripheral vascular disorders. J. Med. Phys. **34**, 43–47 (2009)
77. Bagavathiappan, S., Saravanan, T., Philip, J., Jayakumar, T., Raj, B., Karunanithi, R., Panicker, T.M., Korath, P., Jagadeesan, K.: Investigation of peripheral vascular disorders using thermal imaging. Br. J. Diabetes Vasc. Dis. **8**, 102–104 (2008)
78. Ammer, K.: Published papers on thermology or temperature measurement between 1989 and 2003. http://www.lla.if.sc.usp.br/art/public1989-2003.pdf
79. Ammer, K.: Thermology on the internet—An update. Thermol. Int. **19**, 15–28 (2009)
80. http://www.ncbi.nlm.nih.gov/pubmed.in
81. International Diabetes Federation: IDF diabetes atlas, 7th edn (2016). http://www.diabetesatlas.org/. Accessed on 24/05/2016
82. Reiber, G.E., Lipsky, B.A., Gibbons, G.W.: The burden of diabetic foot ulcers. Am. J. Surg. **176**, 5S–10S (1998)
83. Steketee, J.: Spectral emissivity of the skin and pericardium. Phys. Med. Biol. **18**, 686–694 (1973)
84. Webb, S.: The Physics of Medical Imaging, 1st edn. Institute of Physics Publishing, Bristol (1988)
85. Clark, J.A.: Effects of surface emissivity and viewing angle on errors in thermography. Acta Thermogr. **1**, 138–141 (1976)
86. Watmough, D.J., Fowler, P.W., Oliver, R.: The thermal scanning of a curved isothermal surface. Phys. Med. Biol. **15**, 1–8 (1970)
87. FLIR: FLIR Silver SC5000 MWIR (2009). http://www.flir.com/assets/e9d4e1d5563e4a54a7f220d7904e232e.pdf. Accessed on 6/6/2016
88. Bertelsmann, F.W., Heismann, J.J., Weber, E.J., van der Veen, E.A., Schouten, J.A.: Thermal discrimination thresholds in normal subjects and in patients with diabetic neuropathy. J. Neurol. Neurosurg. Psychiatr. **48**, 686–690 (1985)
89. Viswanathan, V., Snehalata, C., Seena, R., Ramachandran, A.: Early recognition of diabetic neuropathy: evaluation of a simple outpatient procedure using thermal perception. Postgrad. Med. J. **78**, 541–542 (2002)
90. Liniger, C., Albeanu, A., Moody, J., Richez, J., Bloise, D., Assal, J.: The Thermocross: a simple tool for rapid assessment of thermal sensation thresholds. Diabetes Res. Clin. Pract. **12**, 25–34 (1991)
91. Kelechi, T., Michel, Y., Wiseman, J.: Are infrared and thermistor thermometers interchangeable for measuring localized skin temperature? J. Nurs. Meas. **14**, 19–30 (2006)
92. Anbar, M.: Clinical thermal imaging today. IEEE Eng. Med. Biol. Mag. **17**, 25–33 (1998)

93. Roback, K., Johansson, M., Starkhammar, A.: Feasibility of a thermographic method for early detection of foot disorders in diabetes. Diabetes Technol. Ther. **11**, 663–667 (2009)
94. Frykberg, R.G., Tallis, A., Tierney, E.: Diabetic foot self examination with the Tempstat™ as an integral component of a comprehensive prevention program. J. Diab. Foot Complicat. **1**, 13–18 (2009)
95. Piotr, F., Piotr, L., Jan M.W., Martin, B., Julius, G., Karolina, M.-M., Maria, M., Stanislawa, S., Anna, C.: Continuous monitoring of feet temperature using a data logger with wireless communication. Biocybern. Biomed. Eng. **32**, 59–64 (2012)
96. Mansfield, J.R., Sowa, M.G., Payette, J.R., Abdulrauf, B., Stranc, M.F., Mantsch, H.H.: Tissue viability by multispectral near infrared imaging: a fuzzy C-means clustering analysis. IEEE Trans. On Med. Imaging **17**, 1011–1018 (1998)
97. Jones, D.P.: Biomedical Sensors. Momentum Press, New York (2010)
98. Zhang, Z.M., Tsai, B.K., Machin, G.: Radiometric Temperature Measurements. Academic Press, Oxford (2010)
99. Diakides, N.A.: New developments in low cost infrared imaging system. Eur. J. Thermol **7**, 213–215 (1997)
100. Ring, E.F.J.: High resolution infrared imaging. Eur. J. Thermol. **8**, 121 (1998)
101. Branemark, P.I., Fagerberg, S., Langer, L., Soderbergh, J.S.: Infrared thermography in diabetes mellitus. Diabetologia **3**, 529–532 (1967)
102. ISO/TR 13154:2009, http://www.iso.org/iso/catalogue_detail?csnumber=51236
103. Sun, P., Lin, H., Jao, S.E., Ku, Y., Chan, R., Cheng, C.: Relationship of skin temperature to sympathetic dysfunction in diabetic at-risk feet. Diabetes Res. Clin. Pract. **73**, 41–46 (2006)
104. Anburajan, M., Sivanandam, S., Bidyarasmi, S., Venkatraman, B., Menaka, M., Raj, B.: Changes of skin temperature of parts of the body and serum asymmetric dimethylarginine (ADMA) in type-2 diabetes mellitus Indian patients. In: 33rd Annual International Conference of the IEEE EMBS, Boston, Massachusetts, USA, pp. 6254–6259 (2011)
105. Huang, C.-L., Wu, Y.-W., Hwang, C.-L., Jong, Y.-S., Chao, C.-L., Chen, W.-J., Wu, Y.-T., Yang, W.-S.: The application of infrared thermography in evaluation of patients at high risk for lower extremity peripheral arterial disease. J. Vasc. Surg. **54**, 1074–1080 (2011)
106. Szentkuti, A., Kavanagh, H.S., Grazio, S.: Infrared thermography and image analysis for biomedical use. Period. Biol. **113**, 385–392 (2011)
107. Balbinot, L.F., Canani, L.H., Robinson, C.C., Achaval, M., Zaro, M.A.: Plantar thermography is useful in the early diagnosis of diabetic neuropathy. Clinics **67**, 1419–1425 (2012)
108. Balbinot, L.F., Robinson, C.C., Achaval, M., Zaro, M.A., Brioschi, M.L.: Repeatability of infrared plantar thermography in diabetes patients: a pilot study. J. Diab. Sci. Technol. **7**, 1130–1137 (2013)
109. Mori, T., Nagase, T., Takehara, K., Oe, M., Ohashi, Y., Amemiya, A., Noguchi, H., Ueki, K., Kadowaki, T., Sanada, H.: Morphological pattern classification system for plantar thermography of patients with diabetes. J. Diab. Sci. Technol. **7**, 1102–1112 (2013)
110. van Netten, J.J., van Baal, J.G., Liu, C., van der Heijden, F., Bus, S.A.: Infrared thermal imaging for automated detection of diabetic foot complications. J. Diab. Sci. Technol. **7**, 1122–1129 (2013)
111. Oe, M., Yotsu, R.R., Sanada, H., Nagase, T., Tamaki, T.: Screening for osteomyelitis using thermography in patients with diabetic foot. Ulcers, **2013** (2013)
112. Bandyopadhyay, A., Mondal, H.S., Chaudhuri, A.: Thermal imaging based diabetes screening using medical image processing techniques. Int. J. Eng. Res. Technol. **3**, 1298–1302 (2014)
113. Yavuz, M., Brem, R.W., Davis, B.L., Patel, J., Osbourne, A., Matassinie, M.R., Wood, D.A., Nwokolo, I.O.: Temperature as a predictive tool for plantar triaxial loading. J. Biomech. **47**, 3767–3770 (2014)
114. Gatt, A., Formosa, C., Cassar, K., Camilleri, K.P., Raffaele, C.D., Mizzi, A., Azzopardi, C., Mizzi, S., Falzon, O., Cristina, S., Chockalingam, N.: Thermographic patterns of the upper and lower limbs: baseline data. Int. J. Vasc. Med., **2015** (2015)

115. Clark, R.P., de Calcina-Goff, M.L.: International standardization in medical thermography. In: 18th International Conference of the IEEE Engineering in Medicine and Biology Society, Amsterdam, the Netherlands (1996)
116. Ring, E.F.J., Ammer, K.: The technique of infra red imaging in medicine. Thermol. Int. **10**, 7–14 (2000)
117. Standards Technical Reference for Thermal Imagers for Human Temperature Screening Part 1: Requirements and Test Methods, TR 15–1, Spring Singapore (2003)
118. Standards Technical Reference for Thermal Imagers for Human Temperature Screening Part 2: Users' implementation guidelines, TR 15–2, Spring Singapore (2004)
119. Boyko, E.J., Ahroni, J.H., Stensel, V.L.: Skin temperature in the neuropathic diabetic foot. J. Diabetes Complications **15**, 260–264 (2001)
120. Cheng, K.-S., Yang, J.-S., Wang, M.-S., Pan, S.-C.: The application of thermal image analysis to diabetic foot diagnosis. J. Med. Biol. Eng. **22**, 75–82 (2002)
121. Marins, J.C.B., Moreira, D.G., Cano, S.P., Quintana, M.S., Soares, D.D., da Fernandes, A.A., dos Silva, F.S., Costa, C.M.A., dos Amorim, P.R.S.: Time required to stabilize thermographic images at rest. Infrared Phys. Technol. **65**, 30–35 (2014)
122. Kingma, B.R., Frijns, A.J., Schellen, L., van Lichtenbelt, W.D.M.: Beyond the classic thermoneutral zone. Temperature, **1**, 10–17 (2014)
123. Pagano, M., Gauvreau, K.: Principles of Biostatistics, 3rd edn. Duxbury Press (1994)
124. Rajic, N.: Principal component thermography for flaw contrast enhancement and flaw depth characterisation in composite structures. Compos. Struct. **58**, 521–528 (2002)
125. Brioschi, M.L., Colman, D., Neto, H.M.: Fusing IR and magnetic resonance (MR) image. J. Korean Med. Thermol. **2**, 57–58 (2002)
126. Paul, J.L., Lupo, J.C.: From tanks to tumors. IEEE Eng. Med. Biol. Mag. **21**, 34–35 (2002)
127. Irvine, J.M.: Targeting breast cancer detection with military technology. IEEE Eng. Med. Biol. Mag. **21**, 36–40 (2002)
128. Liu, C., van Netten, J.J., van Baal, J.G., Bus, J.G., van der Heijden, F.: Automatic detection of diabetic foot complications with infrared thermography by asymmetric analysis. J. Biomed. Opt. **20**, 26003 (2015)
129. Hernandez-Contreras, D., Peregrina-Barreto, H., Rangel-Magdaleno, J., Ramirez-Cortes, J., Renero-Carrillo, F.: Automatic classification of thermal patterns in diabetic foot based on morphological pattern spectrum. Infrared Phys. Technol. **73**, 149–157 (2015)
130. Taylor, G.I., Palmer, J.H.: The vascular territories (angiosomes) of the body: experimental study and clinical applications. Br. J. Plast. Surg. **40**, 113–141 (1987)
131. Attinger, C.E., Evans, K.K., Bulan, E., Blume, P., Cooper, P.: Angiosomes of the foot and ankle and clinical implications of limb salvage: reconstruction, incisions, and revascularization. Plast. Reconstr. Surg. **117**, 261S–293S (2006)
132. Plassmann, P., Ring, E.F.J.: An open system for the acquisition and evaluation of medical thermological images. Eur. J. Thermol. **7**, 216–220 (1997)
133. Plassmann, P., Murawski, P.: CTHERM for standardized thermography. In: 9th European Congress of Medical Thermology, Krakow, Poland (2003)
134. Jones, C., Ring, E., Plassmann, P., Ammer, K., Wiecek, B.: Standardization of infrared imaging: a reference atlas for clinical thermography-initial results. Thermol. Int. **15**, 157 (2005)
135. Ring, E.F.J., Ammer, K., Wiecek, B., Plassmann, P.: Technical challenges for the construction of a medical IR digital image database. In: Chatard, J.P., Dennis, P.N.J. (Eds.) Proceedings of SPIE, Detectors and Associated Signal Processing II, pp. 191–198 (2005)
136. Fujimasa, I., Saito, I., Chinzei, T.: Far infrared medical image database on the world wide web. In: Proceedings of 19th International Conference IEEE/EMBS, Chicago, IL, pp. 652–653 (1997)
137. Ring, E.F.J., Ammer, K., Jung, A., Murawski, P., Wiecek, P., Zuber, J., Plassmann, P., Jones, C.D.: Standardization of thermal imaging. The Anglo-Polish reference database. In: 10th Congress of the European Association of Thermology, Zakopane, Poland (2006)

138. Colantonio, S., Pieri, G., Salvetti, O., Benvenuti, M., Barone, S., Carassale, L.: A method to integrate thermographic data and 3D shapes for diabetic foot disease. In: Proceedings of the 8th International Conference on Quantitative Infrared Thermography (QIRT 2006) ITC-CNR, Padova, Italy (2006)
139. Boulton, A.J.: The diabetic foot. Medicine **43**, 33–37 (2014)
140. Ahmad, J.: The diabetic foot. Diabetes Metab. Syndr. Clin. Res. Rev. **10**, 48–60 (2016)
141. Mayfield, J.A., Reiber, G.E., Sanders, L.J., Janisse, D., Pogach, L.M.: Preventive foot care in people with diabetes. Diabetes Care **21**, 2161–2177 (1998)
142. Zubair, M., Malik, A., Ahmad, J.: Clinico-microbial study and anti-microbial drug resistance profile of diabetic foot infections in North India. Foot **21**, 6–14 (2011)
143. Young, M.J., Boulton, A.J., MacLeod, A.F., Williams, D.R., Sonksen, P.H.: A multicentric study of the prevalence of diabetic peripheral neuropathy in the United Kingdom hospital clinic population. Diabetelogia **36**, 150–154 (1993)
144. Zubair, M., Malik, A., Ahmad, J.: Study of plasmid-mediated extended-spectrum β-lactamase-producing strains of enterobacteriaceae, isolated from diabetic foot infections in a North Indian tertiary-care hospital. Diabetes Technol. Ther. **14**, 315–324 (2012)
145. Watkins, P.J.: The diabetic foot. Br. Med. J. **326**, 977–979 (2003)
146. Springett, K., White, R.J.: Skin changes in the at risk foot and their treatment. Br. J. Community Nurs. **12**, 25–32 (2002)
147. Shahani, B.T., Halperin, J.J., Boulu, P., Cohen, J.: Sympathetic skin response—A method of assessing unmyelinated axon dysfunction in peripheral neuropathis. J. Neurol. Neusurg. Psychiatry **47**, 536–542 (1984)
148. Uccioli, L., Mancini, L., Giordano, A., Solini, A., Magnani, P., Manto, A., Controneo, P., Greco, A.V., Ghirlanda, G.: Lower limb arterio-venus shunts, autonomic neuropathy and diabetic foot. Diabetes Res. Clin. Pract. **16**, 123–130 (1992)
149. Flynn, M.D., Tooke, J.E.: Diabetic neuropathy and micro-circulation. Diabet. Med. **12**, 298–301 (1995)
150. Kimura, J.: Principles and variation of nerve conduction studies. In: Electrodiagnosis in Diseases of Nerve and Muscle: Principles and Practice, pp. 91–129. Oxford University Press, New York (2001)
151. Tack, C.J. ,van Gurp, P.J., Holmes, C., Goldstein, D.S.: Local sympathetic denervation in painful diabetic neuropathy. Diabetes, **51**: 3545–3553 (2002)
152. Harding, J.R., Wertheim, D.F., Williams, R.J., Melhuish, J.M., Banerjee, D., Harding, K.G.: Infrared imaging in diabetic foot ulceration. In: Proceedings of the 20th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (Volume: 2) Hong Kong, pp. 916–918 (1998)
153. Vinik, A.I., Erbas, T., Park, T.S., Pierce, K.K., Stansberry, K.B.: Methods for evaluation of peripheral neurovascular dysfunction. Diabetes Technol. Ther. **3**, 29–50 (2001)
154. Papanas, N., Papatheodorou, K., Papazoglou, D., Kotsiou, S., Maltezos, E.: Association between foot temperature and sudomotor dysfunction in type 2 diabetes. J. Diab. Sci. Technol. **4**, 803–807 (2010)
155. Vinik, A.I., Erbas, T., Park, T.S., Stansberry, K.B., Scanelli, J.A., Pittenger, G.L.: Dermal neurovascular dysfunction in type 2 diabetes. Diabetes Care **24**, 1468–1475 (2001)
156. Sivanandam, S., Anburajan, M., Venkatraman, B., Menaka, M., Sharath, D.: Medical thermography: a diagnostic approach for type 2 diabetes based on non-contact infrared thermal imaging. Endocrine **42**, 343–351 (2012)
157. Chan, A.W., Macfarlane, I.A., Bowsher, D.R.: Contact thermography of painful diabetic neuropathic foot. Diabetes Care **14**, 918–922 (1991)
158. Stess, R.M., Sisney, P.C., Moss, K.M., Graf, P.M., Louie, K.S., Gooding, G.A., Grunfeld, C.: Use of liquid crystal thermography in the evaluation of the diabetic foot. Diabetes Care **9**, 267–272 (1986)
159. Fujiwara, Y., Inukai, T., Aso, Y., Takemura, Y.: Thermographic measurement of skin temperature recovery tim of extremities in patients with type 2 diabetes mellitus. Exp. Clin. Endocrinol. Diabetes **108**, 463–469 (2000)

160. Nishide, K., Nagase, T., Oba, M., Oe, M., Ohashi, Y., Iizaka, S., Nakagami, G., Kadowaki, T., Sanada, H.: Ultrasonographic and thermographic screening for latent inflammation in diabetic foot callus. Diabetes Res. Clin. Pract. **85**, 304–309 (2009)
161. Kanazawa, T., Nakagami, G., Goto, T., Noguchi, H., Oe, M., Miyagaki, T., Hayashi, A., Sasaki, S., Sanada, H.: Use of smartphone attached mobile thermography assessing subclinical inflammation: a pilot study. J. Wound Care **25**, 177–182 (2016)
162. Hazenberg, C.E.V.B., van Netten, J.J., van Baal, S.G., Bus, S.A.: Assessment of signs of foot infection in diabetes patients using photographic foot imaging and infrared thermography. Diabetes Technol. Ther. **16**: 370–377 (2014)
163. Skversky, N.J., Herring, A.B., Baron, R.C.: Thermography in peripheral vascular diseases. Ann. N. Y. Acad. Sci. **121**, 118–134 (1964)
164. Winsor, T., Bendezu, J.: Thermography and the peripheral circulation. Ann. N. Y. Acad. Sci. **121**, 135–156 (1964)
165. Robins, B., Bernstein, A.: Comparative studies of digital plethysmography and infrared thermography in peripheral vascular disease. Angiology **21**, 349–354 (1970)
166. Langer, L., Fagerberg, S.E., Johnsen, C.: Peripheral circulation in diabetes mellitus—a study with infrared thermography. Acta Med. Scand. **191**, 17–20 (1972)
167. Soulen, R.L., Lapayowker, M.S., Tyson, R.R., Korangy, A.A.: Angiography, ultrasound, and thermography in the study of peripheral vascular disease. Radiology **105** (1972)
168. Holm, J., Johnsen, C., Schersten, T.: Thermography in vascular surgery. A preliminary report based on a study in 12 cases. Acta Chir. Scand. **140**, 445–448 (1974)
169. Henderson, H.P., Hackett, M.E.J.: The value of thermography in peripheral vascular disease. Angiology **29**, 65–75 (1978)
170. Hitoi, A., Matsuoka, A.: patho-physiological analysis on peripheral circulation using thermography as an example of functional body imaging japan. J. Clinical Pathology **38**, 1119–1125 (1990)
171. Fushimi, H., Inoue, T., Yamada, Y., Matsuyama, Y., Kubo, M., Kameyama, M.: Abnormal vaso reaction of peripheral arteries to cold stimulus of both hands in diabetics. Diabetes Res. Clin. Pract. **32**, 55–59 (1996)
172. Mitchell, W.S., Winocour, P.H., Gush, R.J., Taylor, L.J., Baker, R.D., Anderson, D.C., Jayson, M.I.: Skin blood flow and limited joint mobility in insulin-dependent diabetes mellitus. Br. J. Rheumatol. **28**, 195–200 (1989)
173. Toutouzas, K., Benetos, G., Drakopoulou, M., Bounas, P., Tsekoura, D., Stathogiannis, K., Koutagiar, I., Aggeli, C., Karanasos, A., Panagiotakos, D., Siores, E., Stefanadis, C.: Insights from a thermography-based method suggesting higher carotid inflammation in patients with diabetes mellitus and coronary artery disease. Diabetes Metab. **40**, 431–438 (2014)
174. Uchikawa, T., Murakami, T., Furukawa, H.: Effects of the anti-platelet agent cilostazol on peripheral vascular disease in patients with diabetes mellitus. Arzneimittelforschung **42**, 322–324 (1992)
175. Ohashi, S., Iwatani, M., Hyakuna, Y., Morioka, Y.: Thermographic evaluation of the hemodynamic effect of the antithrombotic drug cilostazol in peripheral arterial occlusion. Arzneimittelforschung **35**, 1203–1208 (1985)
176. Staffa, E., Bernard, V., Kubicek, L., Vlachovsky, R., Vlk, D., Mornstein, V., Staffa, R.: Using noncontact infrared thermography for long-term monitoring of foot temperatures in a patient with diabetes mellitus. Ostomy Wound Manag. **62**, 54–61 (2016)
177. Sommer, T.C., Lee, T.H.: Charcot foot: the diagnostic dilemma. Am. Fam. Physician **64**, 1591–1598 (2001)
178. Mercer, J.B., Nielsen, S.P., Hoffmann, G.: Improvement of wound healing by water-filtered infrared-A (wIRA) in patients with chronic venous stasis ulcers of the lower legs including evaluation using infrared thermography. Ger. Med. Sci. **6**, 1–26 (2008)
179. Sodi, A., Giambene, B., Miranda, P., Falaschi, G., Corvi, A., Menchini, U.: Ocular surface temperature in diabetic retinopathy: a pilot study by infrared thermography. Eur. J. Ophthalmol. **19**, 1004–1008 (2009)

180. Sejling, A.S., Lange, K.H., Frandsen, C.S., Diemar, S.S., Tarnow, L., Faber, J., Holst, J.J., Hartmann, B., Hilsted, L., Kjaer, T.W., Juhl, C.B., Thorsteinsson, B., Pedersen-Bjergaard, U.: Infrared thermographic assessment of changes in skin temperature during hypoglycaemia in patients with type 1 diabetes. Diabetologia **58**, 1898–1906 (2015)
181. Zotter, H., Kerbl, R., Gallistl, S., Nitsche, H., Borkenstein, M.: Rewarming index of the lower leg assessed by infrared thermography in adolescents with type 1 diabetes mellitus. J. Pediatr. Endocrinol. Metab. **16**, 1257–1262 (2003)
182. Sejling, A.S., Lange, K.H.W., Frandsen, C.S.S., Diemar, S.S., Tarnow, L., Faber, J., Kjaer, T.W., Juhl, C.B., Thorsteinsson, B., Pedersen-Bjergaard, U.: Facial skin temperature measured by infrared thermography during hypoglycaemia in patients with longstanding type 1 diabetes. Diabetologia **57**, S260–S260 (2014)
183. Schindl, A., Heinze, G., Schindl, M., Pernerstorfer-Schon, H., Schindl, L.: Systematic effects of low-intensity laser irradiation on skin microcirculation in patients with diabetic microangiopathy. Microvasc. Res. **64**, 240–246 (2002)
184. Schindl, A., Schindl, M., Schon, H., Knobler, R., Havelec, L., Schindl, L.: Low-intensity laser irradiation improves skin circulation in patients with diabetic microangiopathy. Diabetes Care **21**, 580–584 (1998)
185. Armstrong, D.G., Holtz-Neiderer, K., Wendel, C., Mohler, M.J., Kimbriel, H.R., Lavery, L.A.: Skin temperature monitoring reduces the risk for diabetic foot ulceration in high-risk patients. Am. J. Med. **120**, 1042–1046 (2007)
186. Bharara, M., Fitzgerald, R., Rilo, H.R., Armstrong, D.G.: Practical thermal monitoring solutions: empowering diabetic foot care teams for prevention of lower extremity complications. Can. J. Diabetes **33**, 217–218 (2009)
187. Pafili, K., Papanas, N.: Thermographyin the follow up of the diabetic foot: best to weigh the enemy more mighty than he seems. Expert Rev. Med. Devices **12**, 131–133 (2015)