Assessment of Foot Complications in Diabetic Patients Using Thermography: A Review

Mahnaz Etehadtavakol and Eddie Y.K. Ng

Abstract Nowadays, there is a considerable appreciation of thermal physiology and the connection between superficial hotness and blood perfusion. Moreover, the advantages of computer-aided digital imaging and the examination modality have considerably enhanced the trustworthiness of this technique in medical fields. The advantage of this new possibility and its applicability to medical determination of peripheral perfusion and liveliness of cells are shown by studies in diabetology. Researches demonstrate that routine checking up on foot temperature could terminate the occurrence of impairment conditions including foot ulcers and lower limb amputations. Thermography is identified as one of the popular techniques in practice today. It has potential for temperature checking up on the feet and it can be employed as an adjunctive method for modern foot examinations in diabetes.

Keywords Thermography · Diabetes · Foot complications

1 Introduction

The previous infrared cameras were not as accurate or reliable as those accessible recently. However, today's modern infrared cameras support high speed and high resolution. Consequently, researches reconsidered this method. Some of the most important factors accommodated pathogenesis of the diabetic foot are represented by peripheral vascular changes, such as macroangiopathy, microangiopathy, and neuropathy-induced capillary circulation changes. These factors produce superficial temperature variations which can be identified by applying thermography. Patients' difficulties cause significant costs and life quality deprivation. Abnormal areas can

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be easily detected by thermography since temperature can be measured. Investigations indicate that routine checking up on foot hotness may terminate the occurrence of impairment conditions including foot ulcers and lower limb amputations. Many researchers comply that the thermography of the diabetic foot can be much informational to evaluate in the specified four issues: (1) the arterial circulation disorder, determination of microangiopathy and additional vascular alterations produced by diabetic neuropathy; (2) recognition of regions with great chance of ulceration or re-ulceration, determination of tissue liveliness, amputation stage, and the intra-operative skin flap activity; (3) osteomyelitis examination; (4) checking up on the reaction to medical therapy [1]. Diabetic foot wounds are in charge of more hospitalizations than any other problems of diabetes. U.S. Department of Health and Human Services stated that individuals with diabetes with some form of neuropathy are between 60 and 70% [2]. One estimate shows 16 million Americans are diabetic. Approximately 15% result a foot ulcer and for every 1000 individuals, 6–8 need amputation, correspondingly the long-term complications [1]. Indeed, in the United States, diabetes is the major producer of nontraumatic lower extremity amputations. Test of ulcer as well as the general condition of the extremity, determination of the chance of vascular inability, and determination of the chance of peripheral neuropathy are possible by different levels of physical checkup of the extremity having a diabetic ulcer. Soft tissue depth and osseous connection can identify the stage of diabetic foot wounds [3–5].

2 Considerations for Applying Thermography in Examination of the Diabetic Foot

Macroangiopathic vascular changes in the foot can be assessed using eco-Doppler and angiography. However, thermography is particularly helpful to characterize the ischemic foot and the neuropathic foot. Ischemic foot is cold while the neuropathic foot is warm. In addition, thermography has also been described to be useful in detecting areas of critical ischemia. Ischemic foot is a condition of decreased arterial perfusion. Following considerations should be reviewed for applying thermography in examination of the diabetic foot: (1) the macro-circulation pathology concentrating more often at, or below the popliteal fossa, than at the level of the aorta or iliac vessels. (2) atheromatous plaques are mono-segmental, exist in the tibial and peroneal arteries, and are generally nonexistent in the more proximal or distal (pedal) arteries. (3) changes are usually asymmetric, the tibial—peroneal triangle being the most commonly affected. (4) room temperature must be constant. (5) subject must remove their shoes, socks and seated or lay down relax up to 15–20 min.

3 Application of Thermography in Diabetic Foot Monitoring

Thermography is very useful in the detection of following cases:

3.1 Critical Ischemia Involving Small Arterial Territories

Since it involves small arterial territories it cannot be identified easily. Thermogram of a critical ischemia—hypothermic area situated above the right medial malleolus is shown in Fig. 1.

Another example is the infrared image of an ischemic foot in a patient with diabetes shown in Fig. 2. It demonstrates asymmetric heat pattern, classic for atherosclerotic lesions, caused by hypothermia on the right posterior tibialis trajectory [1].

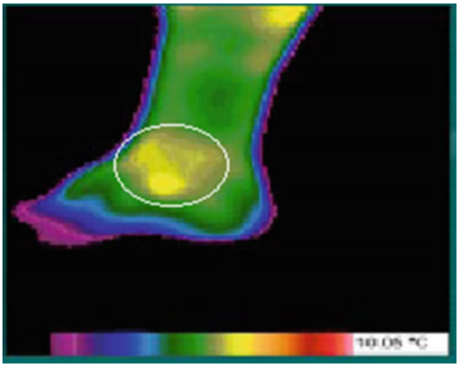

Fig. 1 Thermogram of a critical ischemia—hypothermic area situated above the right medial malleolus (hypothermic area indicated by the *white circle*) [1]

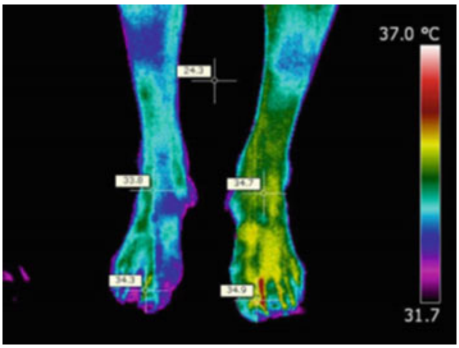

Fig. 2 An ischemic foot in a patient with diabetes (asymmetric contralateral feet and toes thermal patterns) [1]

3.2 Changes in the Cutaneous Circulation Induced by Diabetic Microangiophathy, Which Leads to Ulceration

Thermogram of a patient with symmetric decrease in infrared radiation in the distal regions of the feet is presented in Fig. 3.

3.3 Neuropathy Evaluation, Specifically Small Fiber Sensory Neuropathy

Diabetic neuropathy is a kind of nerve injury that may be developed if one individual has diabetes. High blood sugar may damage nerve fibers all over the body, however diabetic neuropathy usually harms nerves in the legs and feet. Symptoms of diabetic neuropathy may extend from pain and numbness in the extremities to complications with the blood vessels, heart, urinary tract and digestive system, based on the damaged nerves. These symptoms for some individuals are weak; for others, they can be painful, becoming physically handicapped and even death. Symptoms are varied in patients; sometimes are painful, and other times are mild or no symptoms at all. Hence careful foot examination should be mandatory to diagnose neuropathy. Two typical thermograms of patients with foot neuropathy are illustrated in Figs. 4 and 5.

Gheorghe Serbu found that average temperature of the neuropathy patients was 32.8 °C, (hyperthermia) compared to 27.9 °C in diabetic patients without neuropathy [1]. In a study, Bagavathiappan et al. [7] further confirmed that foot temperatures in subjects with diabetic neuropathy (32–35 °C) were greater than subjects without neuropathy (27–30 °C).

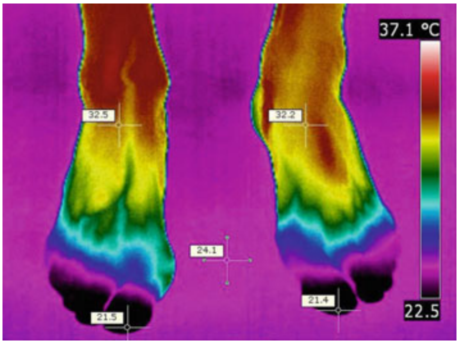

Fig. 3 Symmetric decrease in infrared radiation in the distal regions of the feet (Microangiopathy) [1]

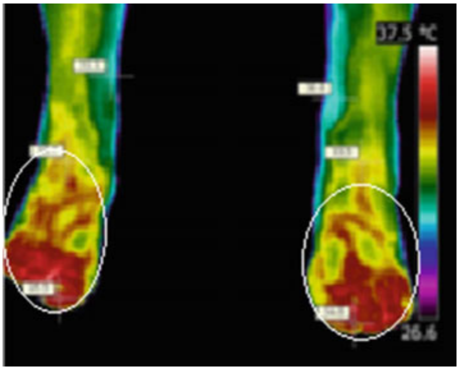

Fig. 4 A patient with neuropathy, hyperthermia of the 1/3 distal aspect of the foot and the toes (hyperthermia areas indicated by *white circles*) [1]

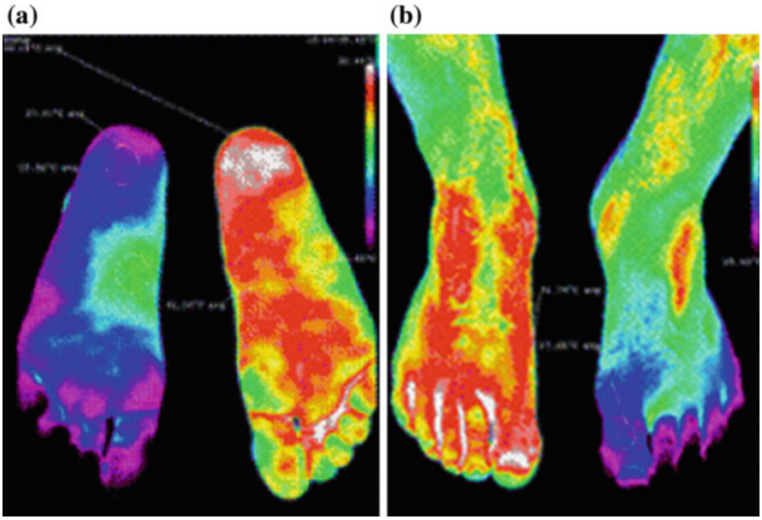

Fig. 5 A patient with foot neuropathy **a** Asymmetric contralateral feet and toes thermal patterns. **b** Asymmetric contralateral plantar thermal patterns [6]

3.4 Plantar Patterns

Skin temperature distribution of plantar in diabetic patients has been one of the valuable factors for determining feet complications in diabetic patients. Takashi Nagase et al. through a project indicated that particularized plantar thermal patterns were demonstrating larger changes in the diabetic subjects than in the healthy individuals. A new scheme of theoretical categorization of 20 contrasting classes of plantar thermal patterns in accordance with the angiosome concept of foot was

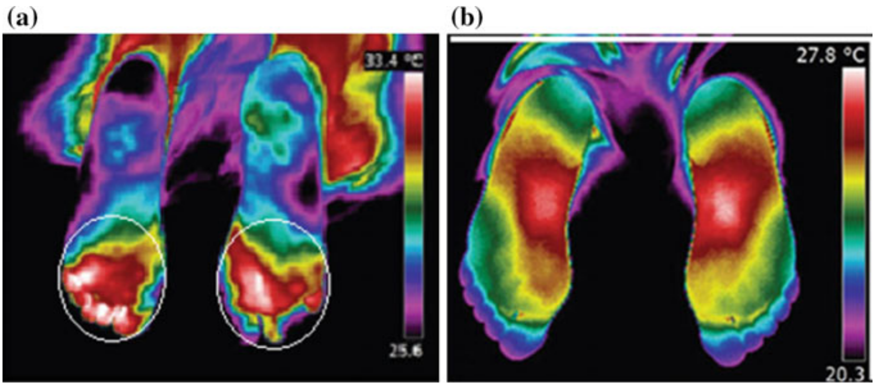

Fig. 6 **a** Plantar thermographic image in a diabetic patient (interdigital anisothermal areas indicated by *white circles*). **b** A control subject (ΔT less than 0.4 °C) [9]

introduced. In their work for the healthy category, greater than 65% of thermal patterns of feet were assigned to the two usual classes, containing the "butterfly pattern" in the whole 20 classes, considering 225 ft (87.2%) of the diabetic groups were differently assigned to 18 out of the 20 classes [8].

An image segmentation method was employed by Mori et al. to propose a novel plantar forepart thermal patterns classification system. They observed larger changes of the plantar forepart thermal patterns in the subjects with diabetes mellitus comparing with those in the control subjects [9]. In addition, Balbinot et al. employed cardiac tests (heart rate variability) as a reference standard since autonomic small fibers are damaged first by this disease for evaluating plantar thermography sensitivity and specificity to diagnose diabetic polyneuropathy. In Fig. 6, a plantar thermal image in a diabetic patient, interdigital anisothermal (ΔT less than 0.4 °C) as well as a control subject (ΔT less than 0.4 °C) are presented with Fig. 6b. They observed that plantar thermography is helpful in early diagnosing diabetic neuropathy and also, the interdigital anisothermal method alone did better performance in diabetic patients comparing the thermal recovery index alone, accompanying an improved sensitivity (81.3%) and specificity (46.2%) [10].

3.5 Detecting area at High Risk for Ulceration or Pre-ulceration and Monitoring Ulcer Healing

In diabetic patient, the ulcer is the most detecting problem and their early detection is crucial. Weak circulation, high blood sugar or hyperglycemia, nerve injury, and irritated or injured feet are mostly responsible for diabetic ulcers. Poor blood circulation can be described as a model of vascular disease in which blood cannot flow to the feet adequately [11]. In addition, poor circulation makes healing of ulcers more difficult. A long-term effect of diabetes is nerve damage which can lead to a failure of feeling in the feet which named neuropathy. In onset of harmed nerves conditions individuals may feel stimulated and hurtful. In the long term, sensitivity to foot pain is reduced and painless wounds which have ability to cause ulcers are formed [12]. All individuals with diabetic foot ulcers must be evaluated so as to investigate the urgency for revisional surgery, debridement, vascular reconstruction, bony construction, or soft tissue coverage.

Liu et al. [13] in a study, discussed different imaging techniques applied to identify presigns of ulceration. Four different imaging techniques are as follows: photographic imaging, foot sole scanning, thermal imaging, and hyperspectral imaging. However foot sole scanning demands individuals to squeeze the foot against the scanner, which will generate some undesired force on the foot sole. Consequently, they deduced that a noninteractive foot scanner is preferable to acquire a superior view of the foot skin [13]. Some of presigns of ulceration are local skin temperature increasing, redness, callus formation, blisters and fissures that let a therapist to identify the location of risk sites. By early identification, the first appearance of diabetic foot ulcers may be halted and following treatment can be started. Nonetheless, early identification depends on repeated risk evaluation, which is not consistently manageable. Self-examination is almost not possible and regular examination by specialists is also priceless and not achievable. Liu et al. [13] focused on the basic analysis on the collected thermal images with their setup to show the ability of employing thermal imaging to identify the local temperature rising [13]. The final goal of their research was to establish an intelligent telemedicine monitoring system that can be utilized at the patients' home surroundings for repeated test of the patients' feet, to identify presigns of ulceration in an appropriate approach.

In a study, Lavery et al. [14] discovered that Infrared temperature home monitoring has potential to defeat these restrictions, to identify the early warning signs automatically, and it is non-invasive, non-contact and effortless using. It should be supported and put into action in diabetic foot care [14]. Researches indicate that there is a connection between rising temperature and foot problems in diabetes [15–17]. A week before a foot ulcer is developed; a raised temperature may be happened [15, 18]. Patients hardly experience pain in this initial stage of the disease as a consequence of neuropathic sensory loss. It shows that raised temperature can be a helpful indicative sign of foot ulceration and subclinical inflammation of the feet.

Besides, 3D surface reconstruction is also important to identify the presigns. It has potential to acknowledge the local 3D deformity of the skin superficial and present proper information about the surface textures. Geometrical changes of the surface such as fissures, papillary lines, and heavy callus as well as radiometric changes can cause these textures. Colantonio et al. [19] presented a model to reconstruct, visualize, and manage data of three-dimensional infrared volumes especially for diabetic foot disease. One example of their work is shown in Fig. 7.

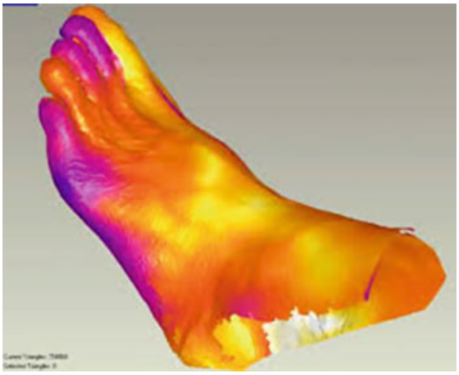

Fig. 7 3D image of the diabetic foot [19]

4 Asymmetry Analysis

Since symmetry generally shows healthy subjects [20], the rise of asymmetry development of paired structures could be a sign of abnormality. Many studies have been accomplished by applying asymmetry analysis in order to investigate breast abnormalities [21–28]. Temperature variations between corresponding areas on contralateral feet indicate inflammatory development. Investigations indicate that elevated temperatures may be identified at a level where a capable diabetic foot problem is still reversible. Temperatures of corresponding areas on contralateral feet do not generally alter of greater than 1 °C and a temperature alteration of greater than 2.2 °C (4 °F) is treated abnormal [29–31]. In a study, Liu et al. [32] showed that thermography is a hopeful technique for early identification of diabetic foot complications. The temperature differences between corresponding sites of the right and left foot are the clinically important features. Their outcome was 97.8% ± 1.1% sensitivity and 98.4% ± 0.5% specificity over 76 high-risk diabetic subjects with manual comments as a Ref. [32].

van Netten et al. [33] found that mean temperatures >1.5 °C between the ipsilateral and the contralateral foot in subjects without complications were not differentiated. In subjects with local complications, mean temperatures of the ipsilateral and the contralateral foot were identical, while temperature at the ROI was >2 °C greater contrasting with the matching area in the contralateral foot and to the mean of the whole ipsilateral foot. In addition, Netten et al. observed the mean temperature differences of >3 °C between ipsilateral and contralateral foot in patients with diffuse complications.

A methodology was presented by Peregrina-Barreto et al. [34] to provide assessable information about atypical temperature variations in symmetric sites between feet and inside of the same foot [34]. The methodology took into account the temperature differences, their distribution, and their area. Differences between symmetric areas in both feet were studied in their first analysis while studying temperatures inside the angiosomes in order to detect the existence of small abnormal areas (hot spots) was performed in their second project. In order to accomplish asymmetry analysis, 140 thermal images were collected by Rathod et al. [35]. They concluded that the overlapping technique works well only when the feet projections sizes and shapes are the same, the scalable scanning technique works well for all types of feet projections.

Mendes et al. [36] in a work showed that thermography is able to quantify small temperature asymmetries in order to monitor some physiological conditions for recognition of subjects at risk for diabetic foot [36]. Although diabetic foot clinical examination involves a 10-g Semmes–Weinstein monofilament test, palpation of peripheral arterial pulses, subjective evaluation of skin temperature, besides the observation of structural and dermatological characteristics of the feet. Kaabouch et al. [37] established an asymmetry investigation to observe the thermal pattern of the feet for the sake of identifying inflammation that leads to foot ulceration. Extraction of higher order statistical parameters helps them to raise the performance of their introduced method. The experimental findings indicate that their method is trustworthy and have potential detecting foot inflammation.

5 Conclusion

This review article gives the reliability and availability of thermography for foot temperature monitoring as a method of early identification of foot complications in diabetes. The objective here is describing and summarizing experiences from experimental use. Researches indicate that routine checking up on foot temperature may terminate the occurrence of impairment conditions including foot ulcers and lower limb amputations.

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