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ORIGINAL ARTICLES

Correlation between Plantar Foot Temperature and Diabetic Neuropathy: A Case Study by Using an Infrared Thermal Imaging Technique

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Abstract

Background:

Diabetic neuropathy consists of multiple clinical manifestations of which loss of sensation is most prominent. High temperatures under the foot coupled with reduced or complete loss of sensation can predispose the patient to foot ulceration. The aim of this study was to look at the correlation between plantar foot temperature and diabetic neuropathy using a noninvasive infrared thermal imaging technique.

Methods:

Infrared thermal imaging, a remote and noncontact experimental tool, was used to study the plantar foot temperatures of 112 subjects with type 2 diabetes selected from a tertiary diabetes centre in South India.

Results:

Patients with diabetic neuropathy (defined as vibration perception threshold (VPT) values on biothesiometry greater than 20 V) had a higher foot temperature (32–35 °C) compared to patients without neuropathy (27–30 °C). Diabetic subjects with neuropathy also had higher mean foot temperature (MFT) (p = .001) compared to non-neuropathic subjects. MFT also showed a positive correlation with right great toe (r = 0.301, p = .001) and left great toe VPT values (r = 0.292, p = .002). However, there was no correlation between glycated hemoglobin and MFT.

Conclusion:

Infrared thermal imaging may be used as an additional tool for evaluation of high risk diabetic feet.

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Abbreviations: (CPT) current perception threshold, (HbA1c) glycated hemoglobin, (IR) infrared, (IRT) infrared thermography, (MFT) mean foot temperature, (NCV) nerve conduction velocity, (NIR) near-infrared, (PC) personal computer, (SD) standard deviation, (VPT) vibration perception threshold

Keywords: diabetic neuropathy, infrared thermal imaging, mean foot temperature, serum cholesterol, type 2 diabetes

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Introduction

The prevalence of type 2 diabetes is rising rapidly worldwide. It has been recognized that the main causes of ulceration are diabetic neuropathy and vascular disease of both the macro- and microcirculation.[1] Uncontrolled diabetes leads to various complications affecting the eyes, kidneys, heart, nerves, and feet. Indeed, foot complications are one of the most frequent problems of diabetes mellitus and key contributors to medical costs, as 50% of all inpatient admissions due to diabetes are due to foot complications.[2,3] The two main causes of diabetic complications are decreased blood supply and loss of sensation in the feet (neuropathy). Currently, there are equipment to measure these two parameters, namely nerve conduction velocity (NCV) measurements and alternating current perception threshold (CPT). For confirming the presence or absence of diabetic neuropathy, NCV measurements and alternating CPT are used as the standard methods. The latter is used to assess the quantitative level of severity of diabetic sensory neuropathy.[4] Handheld dermal thermometers and liquid crystal thermography are being used for home temperature monitoring, e.g., warmth or coldness of feet. High temperatures under the foot coupled with reduced or complete loss of sensation can predispose the patient to foot ulceration.[3,5] Thermography has emerged as a potential tool for diagnostics as it enables remote and noncontact mapping of thermal patterns.[6–9] Infrared thermography (IRT) has been used to determine the temperature variations of the plantar surface of feet. Previously, we have shown the usefulness of IRT for diagnosing peripheral vascular disorders.[10] In addition, IRT has been used to study young diabetes subjects with or without vascular complications.[11] The purpose of the present study was to examine the correlation between foot temperature and neuropathy in subjects with type 2 diabetes.

Materials and Methods

Infrared thermography is a noncontact tool that maps the surface temperature of an object in a noncontact and remote manner. Medical infrared thermal imaging has been used to study the flow of blood, detection of breast cancer, and muscular performance of the human body.[6,7] Thermal images have been used to quantify sensitive changes in skin temperature in relation to certain diseases. Infrared (IR) radiation covers wavelengths that range from 0.75 to 1000 μm. Human body emissions that are traditionally measured for diagnostic purposes occupy a narrow band of wavelengths ranging from 8 to 12 μm.[12] This region is referred to as the long-wave infrared or body infrared rays. The image generated by IR radiation is referred to as a thermogram. The near-infrared (NIR) region occupies wavelengths between 0.75 and 1.4 μm. Although the NIR and mid-wave infrared regions are not traditionally used in human body screening, the new generation detectors enable the use of multispectral imaging in medicine, in which these regions are observed in different diagnostic cases. Medical IR diagnostics uses the fact that many pathological processes in the human organs manifest themselves as local changes in heat production and also as changes in blood flow pattern of affected organs or tissues. In clinical diagnostics, IR imaging is used as a physiological test that measures the subtle physiological changes that might have been caused by many conditions such as contusions, fractures, burns, carcinomas, lymphomas, melanomas, prostate cancer, dermatological diseases, rheumatoid arthritis, diabetes mellitus and associated pathology, deep vein thrombosis, liver disease, and bacterial infections.[8]

In the case of foot temperature imaging by IR radiation, the important parameters such as mean foot temperature (MFT), temperature difference (ΔT), and normalized temperature (T_N), are calculated using **Equations 1**, **2**, and **3**, respectively.

$$\text{MFT} = \frac{T_a + T_b + T_c + T_d + T_e + T_f}{8} \ (^{o}\text{C}) \quad (1)$$

$$\Delta T = T_R - \text{MFT} \ (^{o}\text{C}) \quad (2)$$

$$T_N = \frac{\Delta T}{T_R} \quad (3)$$

Where T_a is the Hallux temperature, T_b is the lesser toes temperature, T_c is the arch temperature, T_d is the lateral sole temperature, T_e is the forefoot temperature, and T_f is the heel temperature. In our experiment, where T_R is the reference temperature, it is the average hand temperature (shown in **Figure 2A**).

Study Subjects and Study Methods

Study subjects (n = 112) were randomly selected from those attending Dr. Mohan's Diabetes Specialities Centre, a tertiary diabetes centre in Chennai in southern India. The criteria for selection were absence of any diabetic

foot problems such as ulcers, infections, or amputations. From the list of patients attending the clinic every day, about 8–10 patients were randomly selected using random numbers. The study was approved by the ethics committee of the Madras Diabetes Research Foundation. A total of 112 type 2 diabetes subjects underwent thermal imaging using the IR thermal system.

Anthropometric measurements including weight, height, waist, and hip measurements were obtained using standardized techniques according to the Anthropometric Standardization Reference Manual.[13] Blood pressure was recorded twice (5 minutes apart) in the sitting position in the right arm to the nearest 2 mm Hg with a mercury sphygmomanometer (Diamond Deluxe Industrial Electronic and Products, Electronic Co-op Estate, Pune, India) and the mean was taken as the final reading.

Glycated hemoglobin (HbA1c) was estimated by high-pressure liquid chromatography using the Variant machine (Bio-Rad Laboratories Inc., Hercules, CA). The intra- and interassay coefficient of variation of HbA1c was <10%.

Subjects were requested to remove their shoes and socks and lie supine on a couch for at least 5 minutes before the measurements were made. The foot was kept warm during the measurement and as the room was air conditioned, the temperature of the room was about 25 °C and the humidity was also maintained. Neuropathy was assessed using a biothesiometer (Biomedical Instrument Co., Newbury, OH). The vibratory perception threshold (VPT) of the great toes was measured in a standardized manner by a single observer, as reported previously.[14,15] Vascular sufficiency was assessed using Doppler studies as detailed previously[16] and the ankle/brachial index was normal in all subjects studied. The biothesiometer factor, which vibrates at 100 Hz with an amplitude proportional to the square of the applied voltage, was applied perpendicular to the test side with a constant and firm pressure. Subjects were initially familiarized with the sensation by holding the tactor against the distal palmar surface. The VPT was then measured at the distal plantar surface of the great toe. The voltage was slowly increased at the rate of 1 V/s and the VPT was defined as the moment when the subject indicated he/she first felt the vibration. The voltage at which this occurred was recorded. Three further cycles of readings at each site were performed and recorded. The mean value of three measurements of both legs was used for analysis. The mean plus 2 standard deviations (SDs) was used to derive the upper limit of normal for the non-diabetic study population aged 20–45 years, which was 19.7 V. Hence, the cutoff point was derived as VPT ≥20 V.[15] This method was adopted from Shaw *et al.*[17] in 1998 and defined neuropathy as levels of VPT exceeding the mean + 2 SDs among Mauritian non-diabetic subjects, as the Mauritian and Indian population are of similar ethnic origin. The VPT is largely meant to diagnose high risk patients for diabetic ulcers. However, several epidemiological studies have been done using VPT as a cutoff point because it is the simplest parameter of assessing neuropathy. Vibration perception threshold is recognized as a simple screening tool for epidemiological studies.[15]

Investigators were masked to the VPT results when thermal imaging was done. The skin temperatures of both feet and hands were imaged using an IR thermal imaging system. Thermal imaging of the patients was carried out using the AGEMA Thermovision 550 system (Danderyd, Sweden), a compact, lightweight, focal plane array-based system with a temperature resolution of 0.1 K. A high-resolution color image is provided in real time, which can be viewed on the miniature screen provided with the system or using an external monitor. The image is captured and stored in the removable personal computer (PC) card. The surface temperature profiles of the patients were recorded and later analyzed using IRWIN software (Danderyd, Sweden).

Statistical Analysis

Data were expressed as mean ± SD. Pearson correlation analysis was used to determine the relation between MFT and other risk variables. All analyses were done using the Windows-based SPSS statistical package, Version 10.0 (SPSS Inc., Chicago, IL). $p \leq .05$ was considered as significant, where p is a significant coefficient.

Results

A total of 112 individuals with type 2 diabetes were included in the analysis. **Table 1** shows the clinical and biochemical characteristics of the study subjects classified as those with and without neuropathy. Diabetic subjects with neuropathy were older ($p < .001$), had longer duration of diabetes ($p < .001$), and had higher MFT ($p = .001$) compared to non-neuropathic subjects. Of the 112 subjects, 73 were on statins, 70 were on antihypertensive drugs, and 30 were on antiplatelet drugs. None of the patients had any vascular insufficiency, ulcers, or other diabetic foot problems.

Table 2 shows the Pearson correlation between MFT, HbA1c, and mean VPT of the right and left great toes in all study subjects. Mean foot temperature showed a

positive correlation with right great toe VPT (r = 0.301, p = .001) and left great toe VPT (r = 0.292, p = .002), where r is a correlation factor.

Figures 1A and **1B** show typical thermal images of the foot. In **Figure 1A**, the plantar thermal image was divided into six regions of interest. Sufficient care was taken for thermal equilibrium and the planar view of the plantar foot was taken in most of the specimens. The MFT was calculated from these six regions, i.e., (a) hallux (big toe), (b) lesser toes, (c) arch, (d) lateral sole, (e) forefoot, and (f) heel. In **Figure 1B**, cold regions in the toe regions are encircled. The patient of **Figure 1A** is a 44-year-old non-neuropathic male with a history of diabetes for 7 years and a HbA1c value of 9.6%. **Figure 1B** is of a 61-year-old non-neuropathic female with a history of diabetes for 31.7 years and a HbA1c value of 6.6%. In **Figure 1B**, the average foot temperature in the circled region is 29.3 °C.

Figure 2A shows a typical thermal image of the dorsal view of the hands, and the marked area on the hand image corresponds to the reference temperature (T_R) [average temperature in the marked area (°C)]. **Figure 2B** shows a thermal image of a patient with cold spots in both hands (encircled region). The patient in **Figure 2A** is a 38-year-old non-neuropathic male with a history of diabetes for 6 years and a HbA1c value of 6.2%. The average temperature of the marked area in **Figure 2A** is 36.8 °C. The patient in **Figure 2B** is a 26-year-old non-neuropathic female with a diabetes history of 3.8 years and a

Table 1.
Clinical and Biochemical Parameters of the Study Subjects.

Parameters	Non-neuropathic subjects (n = 79)	Neuropathic subjects (n = 33)	p value
Male, n (%)	41 (51.9%)	20 (60.6%)	.485
Age (year)	50.3 ± 10.2	62.3 ± 12.0	<.001
Duration of diabetes (year)	8.7 ± 6.6	15.2 ± 10.1	<.001
Body mass index (kg/m^2)	26.7 ± 5.2	26.6 ± 4.2	.905
HbA1c (%)	8.3 ± 2.1	8.6 ± 2.4	.478
Mean VPT			
Right great toe	15 ± 3	35 ± 9	<.001
Left great toe	15 ± 3	36 ± 10	<.001
MFT (°C)	31.4 ± 1.92	32.73 ± 1.48	.001

Table 2.
Pearson Correlation of MFT in the Study Groups.

Parameters	r value	p value
Age (year)	0.161	.089
Duration of diabetes (year)	0.096	.317
Body mass index (kg/m^2)	0.017	.220
HbA1c (%)	-0.060	.531
Right great toe VPT	0.301	.001
Left great toe VPT	0.292	.002

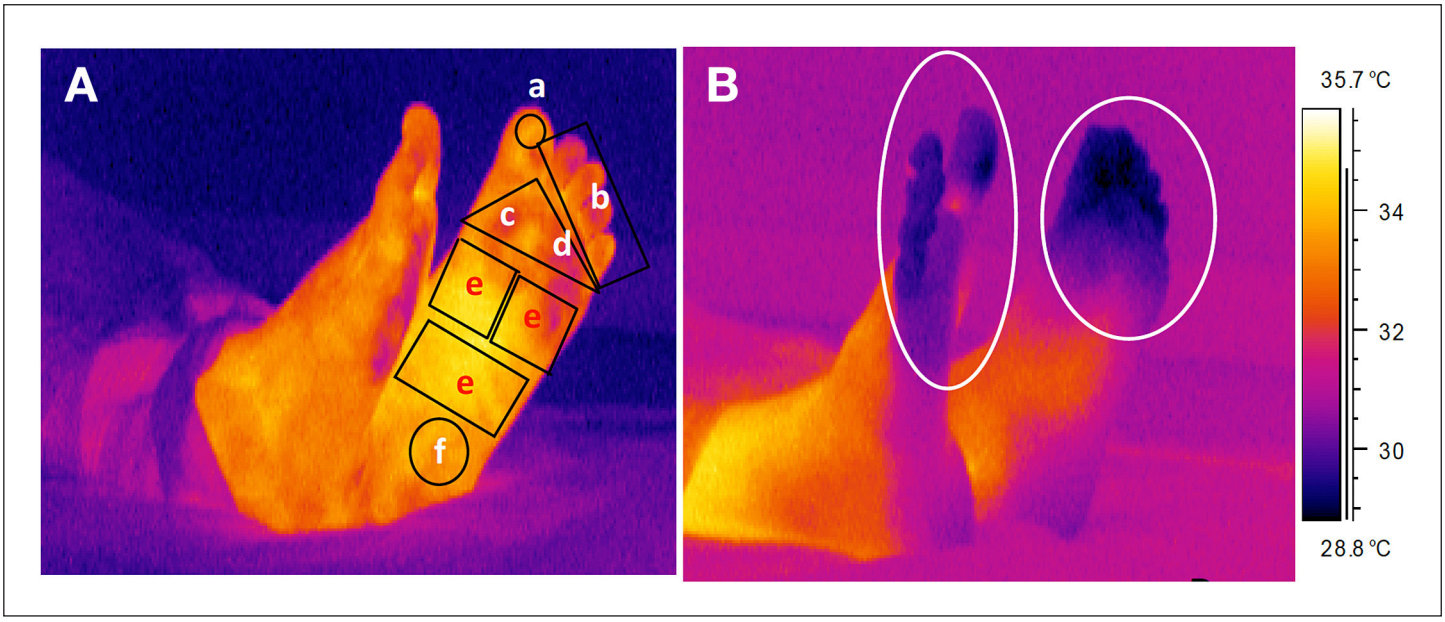

Figure 1. Typical thermal image of the foot with **(A)** hot and **(B)** cold regions.

HbA1c value of 11.2%. In **Figure 2B**, the average finger temperature in the circled region is 30.1 ºC.

Figure 3 shows the MFT values as a function of mean VPT values. The MFT values were higher for the patients with neuropathy. There were 28 patients with VPT values less than 20 at the great toe; they had foot temperature values within the band of 27–30 ºC. In contrast, there were 33 patients with diabetes neuropathy (VPT values greater than 20); they showed higher foot temperatures in the range of 30–37 ºC.

Figure 4 shows the great toe temperature as a function of biothesiometry. The results are very similar to the great toe temperature values. Also, the patients with VPT <20 had lower MFT values compared to those with VPT >20.

Similar trends were observed for the arch, lateral sole, forefoot, and heel regions (data not shown).

Figure 5 shows the HbA1c levels plotted against the MFT values among the diabetes patients. There was no correlation between the HbA1c and MFT values.

Discussion

The novel part of this study is the original findings on the correlation between VPT and MFT values, which was done using an advanced noninvasive technique in patients with diabetic neuropathy. This work is the first of its kind and the results are novel. Moreover, it has potential applications for diagnosing patients with diabetic neuropathy. Our study shows that patients with VPT values on biothesiometry greater than 20 show a higher foot temperature band compared to patients without neuropathy. Diabetes subjects with neuropathy had higher MFT values compared to non-neuropathic subjects. The MFT values also showed a positive correlation with right great toe and left great toe VPT values.

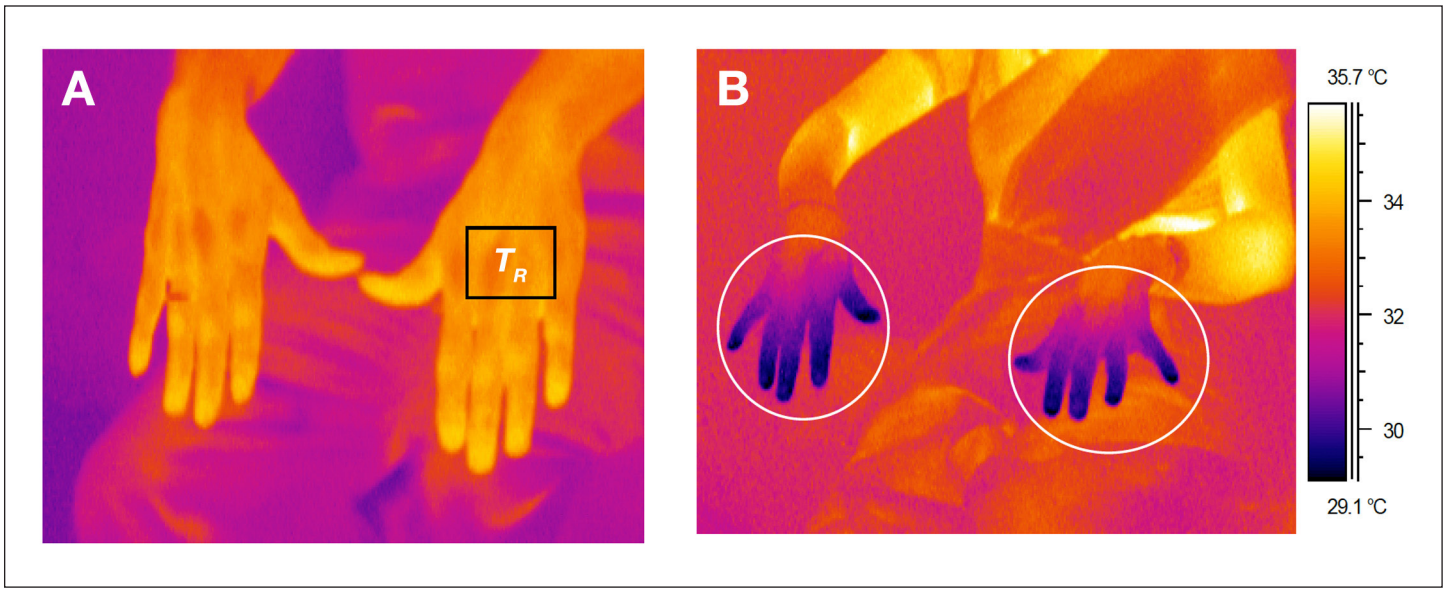

Figure 2. (A) Typical thermal image of dorsal view of hands of patients and **(B)** thermal image of patient with cold spots in both hands.

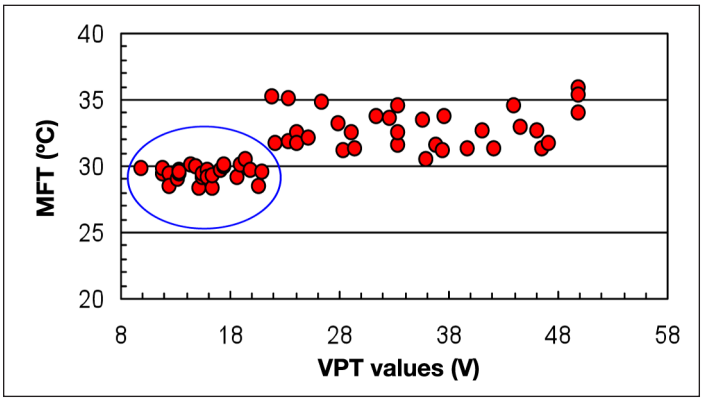

Figure 3. MFT as a function of VPT values measured by biothesiometry.

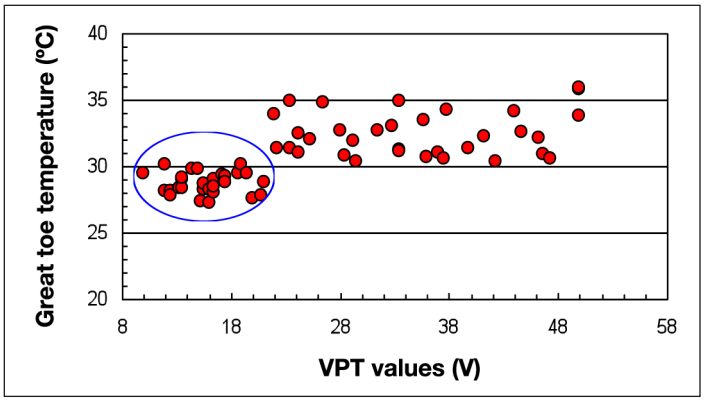

Figure 4. Great toe temperature as a function of VPT values measured by biothesiometry.

Hile *et al.*[1] reviewed thermal measurement techniques specific to the diabetic foot such as electrical contact thermometry, cutaneous thermal discrimination thresholds, IRT, and liquid crystal thermography. David Armstrong and colleagues[5] compared skin temperatures of patients with asymptomatic peripheral sensory neuropathy, neuropathic ulcers, and Charcot's arthropathy using the contralateral limb as a control. Their study concluded that monitoring of the corresponding contralateral foot site can provide clinical information before other clinical signs of injury can be identified.

Deng and colleagues[18] proposed a novel approach to effectively enhance the skin thermal expression of a tumor by induced evaporation on the skin surface. Systematic studies on home temperature monitoring of foot ulcers in high-risk patients with diabetes revealed that high temperature gradients between feet can predict the onset of neuropathic ulceration and reduce the risk of ulceration.[19] Some studies indicate that thermoregulatory disturbance and sweating abnormality is an early indicator of sympathetic damage in diabetic feet.[20] The importance of temperature monitoring to reduce the incidence of foot ulcers in individuals with high risk diabetes has been stressed.[21]

The diabetic neuropathic foot is considered as warm with palpable pulses and distended veins, indicating increased blood flow in the affected limb. It has been reported that microcirculation is stable or even reduced due to sluggish blood flow to the foot.[22] The ability to increase blood flow depends on the existence of normal neurogenic vascular response. Due to impaired neuro-vascular response in diabetic neuropathy subjects, a significant reduction of blood flow under conditions of injury or infection is observed.[23] A systematic study shows that the nerve-axon-related vasodilatory response to iontophoresis of acetylcholine was significantly reduced in diabetes patients when compared with healthy subjects or diabetes patients without complications.[24] In all these studies, only relative and not absolute temperatures are significant and the relative temperatures have to be measured at many points on the skin; in this sense, the IR sensing device has many advantages over conventional devices.[9] The accuracy in the temperature measurement using our camera was 0.1 K. One of the disadvantages for widespread adaptation of IR technology as a diagnostic tool is its higher cost compared to other temperature monitoring devices. However, IR thermal imaging has the advantages of being a remote and noncontact technique. Further, it can map the temperature of relatively large areas and objects in a single shot.

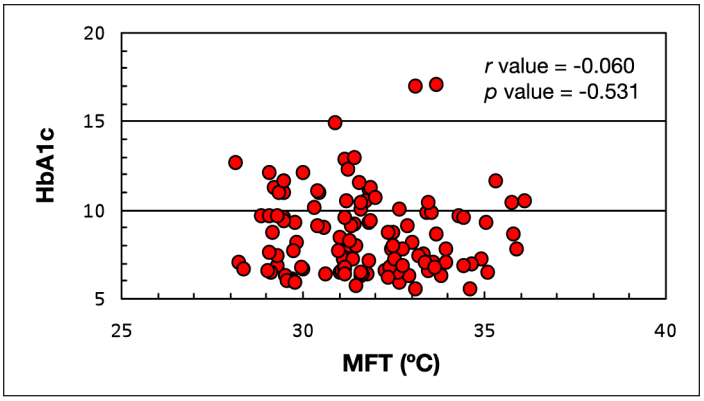

Figure 5. HbA1c levels as a function of MFT values among diabetes patients.

Findings of the present study offer the possibility of using IR thermal imaging for detection of diabetes neuropathy. Further, our results show no direct correlation between HbA1c and MFT or diabetes neuropathy.

The strengths of IR thermal imaging are that it is a fast, safe, noninvasive, and nonionizing imaging technique without any side effects upon repeated use. It can map the temperature of relatively large areas (entire human body) in a single shot and hence a single thermogram could provide indications on diseases like detection of breast cancer, vascular disorder, chronic pain, skin cancer, breast cancer, and muscular performance of the human body, etc.

One of the limitations of IR imaging is that the IR camera is more expensive than other contact thermometers. However, the sensitivity of the IR camera is much better than that of contact thermometers. Another limitation of this study is that it was clinic-based and hence there could have been some referral bias in the selection of the subjects. Finally, the sample size was relatively small. However, even with these limitations, the results suggest that thermal imaging can be a useful additional tool in a diabetes clinic.

References:

1. Hile C, Veves A. Diabetic neuropathy and microcirculation. Curr Diab Rep. 2003;3(6):446-51.
2. Sims DS, Cavanagh PR, Ulbrecht JS. Risk factors in the diabetic foot. Recognition and management. Phys Ther. 1988;68(12):1887-902.
3. Bharara M, Cobb JE, Claremont DJ. Thermography and thermometry in the assessment of diabetic neuropathic foot: a case for furthering the role of thermal techniques. Int J Low Extrem Wounds. 2006;5(4):250-60.
4. Hyllienmark L, Jonsson B, Ekberg K, Lindström P. Abnormal cold perception in the lower limbs: a sensitive indicator for detection of polyneuropathy in patients with type 1 diabetes mellitus. Diabetes Res Clin Pract. 2009;85(3):298-303.
5. Armstrong DG, Lavery LA, Liswood PJ, Todd WF, Tredwell JA. Infrared dermal thermometry for the high-risk diabetic foot. Phys Ther. 1997;77(2):169-75.
6. Ring F. Thermal imaging today and its relevance to diabetes. J Diabetes Sci Technol. 2010;4(4):857-62.
7. Bouzida N, Bendada A, Maldague XP. Visualization of body thermoregulation by infrared imaging. J Therm Biol. 2009;34(3):120-6.
8. Jiang LJ, Ng EY, Yeo AC, Wu S, Pan F, Yau WY, Chen JH, Yang Y. A perspective on medical infrared imaging. J Med Eng Technol. 2005;29(6):257-67.
9. Vainer BG. FPA-based infrared thermography as applied to the study of cutaneous perspiration and stimulated vascular response in humans. Phys Med Biol. 2005;50(23):R63-94.
10. Bagavathiappan S, Saravanan T, Philip J, Jayakumar T, Raj B, Karunanithi R, Panicker TMR, Korath MP, Jagadeesan K. Investigation of peripheral vascular disorders using thermal imaging. Br J Diabetes Vasc Dis. 2008;8(2):102-4.
11. Brånemark PI, Fagerberg SE, Langer L, Save-Söderbergh J. Infrared thermography in diabetes mellitus. A preliminary study. Diabetologia. 1967;3(6):529-32.
12. Maldague XP. Nondestructive evaluation of materials by infrared thermography. London: Springer-Verlag; 1993.
13. Harrison GG, Buskirk ER, Lindsay Carter JE, Johnston FE, Lohman TG, Pollock ML, Roche AF, Wilmore J. Skinfold thickness and measurement technique. In: Lohman TG, Roche AF, Martorell R, editors. Anthropometric standardization reference manual. Champaign, Illinois: Human Kinetics Books; 1988. p. 55-70.
14. Ashok S, Ramu M, Deepa R, Mohan V. Prevalence of neuropathy in type 2 diabetic patients attending a diabetes centre in South India. J Assoc Physicians India. 2002;50:546-50.
15. Pradeepa R, Rema M, Vignesh J, Deepa M, Deepa R, Mohan V. Prevalence and risk factors for diabetic neuropathy in an urban south Indian population: the Chennai Urban Rural Epidemiology Study (CURES-55). Diabet Med. 2008;25(4):407-12.
16. Premalatha G, Shanthirani S, Deepa R, Markovitz J, Mohan V. Prevalence and risk factors of peripheral vascular disease in a selected South Indian population: the Chennai Urban Population Study. Diabetes Care. 2000;23(9):1295-300.
17. Shaw JE, Hodge AM, de Courten M, Dowse GK, Gareeboo H, Tuomilehto J, Alberti KG, Zimmet PZ. Diabetic neuropathy in Mauritius: prevalence and risk factors. Diabetes Res Clin Prac. 1998;42(2):131-9.
18. Deng Z, Liu J. Enhancement of thermal diagnostics on tumors underneath the skin by induced evaporation. Conf Proc IEEE Med Biol Soc. 2005;7:7525-8.
19. Armstrong DG, Holtz-Neiderer K, Wendel C, Mohler MJ, Kimbriel HR, Lavery LA. Skin temperature monitoring reduces the risk for diabetic foot ulceration in high-risk patients. Am J Med. 2007;120(12):1042-6.
20. Sun PC, Lin HD, Jao SH, Ku YC, Chan RC, Cheng CK. Relationship of skin temperature to sympathetic dysfunction in diabetic at-risk feet. Diabetes Res Clin Pract. 2006;73(1);41-6.
21. Lavery LA, Higgins KR, Lanctot DR, Constantinides GP, Zamorano RG, Athanasiou KA, Armstrong DG, Agrawal CM. Preventing diabetic foot ulcer recurrence in high-risk patients: use of temperature monitoring as a self-assessment tool. Diabetes Care. 2007;30(1):14-20.
22. Murray HJ, Boulton AJ. The pathophysiology of diabetic foot ulceration. Clin Podiatr Med Surg. 1995;12(1):1-17.
23. Jörneskog G, Brismar K, Fagrell B. Skin capillary circulation severely impaired in toes of patients with IDDM, with and without late diabetic complications. Diabetologia. 1995;38(4):474-80.
24. Arora S, Smakowski P, Frykberg RG, Simeone LR, Freeman R, LoGerfo FW, Veves A. Differences in foot and forearm skin microcirculation in diabetic patients with and without neuropathy. Diabetes Care. 1998;21(8):1339-44.