

**The application of medical thermography to discriminate neuroischaemic
toe ulceration in the diabetic foot**

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Abstract

This study aimed to determine whether thermal imaging can detect temperature differences between healthy feet, non-ulcerated neuroischaemic feet and neuroischaemic feet with toe ulcers in patients with type 2 diabetes (T2DM). Participants were prospectively divided into 3 groups: T2DM without foot problems, a healthy, non-ulcerated neuroischaemic and an ulcerated neuroischaemic group. Thermal images of the feet were obtained with automated segmentation of regions of interest. Thermographic images from 43 neuroischaemic feet, 21 healthy feet and 12 feet neuroischaemic feet with active ulcer in one of the toes were analyzed. There was a significant difference in toe temperatures between the 3 groups ($p=0.001$) ie. non-ulcerated neuroischaemic ($n=181$; mean temp $27.7^{\circ}\text{C} \pm 2.16$ SD) vs. neuroischaemic ulcerated ($n=12$; mean temp $28.7^{\circ}\text{C} (\pm 3.23$ SD)) and healthy T2DM group ($n=104$; mean temp $24.9^{\circ}\text{C} (\pm 5.04$ SD). A post hoc analysis showed a significant difference in toe temperatures between neuroischaemic non-ulcerated and healthy T2DM groups ($p=0.001$), neuroischaemic ulcerated and healthy groups ($p=0.001$). However no significant differences in toe temperatures were identified between the ulcerated neuroischaemic and non-ulcerated neuroischaemic groups ($p=0.626$). There were no significant differences between the ulcerated toes ($n=12$) and the non-ulcerated toes ($n=57$) of the same foot in the ulcerated neuroischaemic group ($p=.331$). Toe temperatures were significantly higher in neuroischaemic feet with or without ulceration compared to healthy feet in patients with T2DM. There were no significant differences in temperatures of ulcerated toes and the non-ulcerated toes of the same foot, implying that all the toes of the same foot could potentially be at risk of developing complications, which can be potentially detected by infrared thermography.

Keywords: diabetes mellitus; medical thermography; neuroischaemic; ulceration.

Type 2 diabetes mellitus (T2DM) is a medical condition that has reached pandemic proportions, causing a worldwide health crisis according to the International Diabetes Federation. It has long been established that this condition may give rise to several serious complications in the foot, including neuropathy and peripheral arterial disease (PAD) which may also co-exist as neuroischaemia¹. The latter are very vulnerable to injury, both from minor and major trauma, and may develop ulcerations, or even amputations.² Accordingly, the risk of amputations is very high,²⁻⁴ calling for early identification of at-risk feet.^{2,5,6}

The need to improve foot screening to improve outcomes remains. In this context, medical infrared imaging, or thermography, has been widely recognised as a non-invasive, potential tool for detecting temperature difference in patients with diabetes in order to detect vascular and neuropathic changes.⁷ Normal thermographic patterns have been established for healthy, normal DM, neuropathic and neuroischaemic feet.^{8,9} However, we lack data on the utility of thermography in the assessment of neuroischaemic ulcers. Should the presence of ulceration provide a distinctive thermal image pattern, this might prove useful as a screening tool of incipient lesions, enabling early intervention before ulceration occurs.

Thus, the aim of this study was to determine whether thermal imaging in patients with T2DM can detect differences in temperature between healthy feet, neuroischaemic feet without ulceration and neuroischaemic feet with ulcers.

Patients and Methods

This study included consecutive T2DM patients from a vascular clinic in a general hospital. Overall, 88 patients presenting with an ulcer of any aetiology were initially identified. Of these, 12 were finally included. The study was approved by the institutional ethics

committee (University Research Ethics Committee), and patients gave their informed consent, in accordance with the Helsinki Declaration of Human Rights.¹⁰

Exclusion criteria were: wounds other than neuroischaemic; post-surgical wounds; significant co-morbidities that could affect thermal characteristics including Raynaud's phenomenon, rheumatoid arthritis, venous insufficiency, deep vein thrombosis; oedema; recent foot surgery.

For each patient, we obtained detailed medical history and clinical examination. Neuropathic deficits in the feet were evaluated by the Semmes Weinstein 10 g monofilament. The arterial circulation was evaluated by the Ankle Brachial index (ABI) and spectral waveform Doppler analysis (SWDA).^{6,8} The diagnosis of neuroischaemic feet was based on abnormal monofilament plus ABI <0.9 and biphasic or monophasic Doppler waveforms. Patients were divided into 3 groups: T2DM with healthy feet; T2DM patients with neuroischaemic feet without ulcers; T2DM patients with neuroischaemic ulcerated feet.

Thermal imaging was captured utilising a FLIR SC7200 camera according to standard protocols.⁸ Following a 15 minute acclimatisation period, with the patient lying supine in a clinic with temperature controlled at 23°C, both visual and thermal images were taken, with both thermal and digital cameras placed 1.5 m equidistant from the foot. Only one image was taken from each foot, and the FLIR Research software extracted the mean temperature of the region of interest. Visual images were used for reference purposes only. Thermal data for the toes and forefoot were extracted by a purposely-designed algorithm¹¹ and input in a Microsoft Excel sheet. Since vascular and neuropathic status can vary between feet of the same participant, these were examined and categorised separately.

Statistical analysis was carried out by Statistical Package for Social Sciences version 25 (SPSS, Chicago, IL). Data distribution was determined by the Shapiro-Wilks normality test. Differences in temperatures between the groups were examined by the independent sample t-

test and one-way ANOVA. Significance was defined at the 5% level (two tailed p-value < 0.05).

Results

Thermographic images from 43 non-ulcerated neuroischaemic feet (from 30 subjects), 21 healthy feet (15 subjects) and 12 feet (12 subjects) with an ulcer in one of the toes were analyzed. Demographics are shown in Table 1. There was no difference ($p=0.331$) in temperatures between ulcerated and non-ulcerated toes of the same foot.

In the comparison of mean temperature differences between non-ulcerated neuroischaemic toes ($n=181$; mean temperature 27.7°C $2\pm.16$ SD) vs. neuroischaemic ulcerated toes ($n=12$; mean temperature 28.7°C ± 3.23 SD) and toes of participants with T2DM and no complications ($n=104$; mean temperature 24.9°C ± 5.04 SD) (Figure 1), there was a significant difference between the 3 groups ($p=0.001$). In a post-hoc analysis, a significant difference was shown between neuroischaemic non-ulcerated and healthy toes ($p=0.001$), neuroischaemic ulcerated toes and healthy ($p=0.001$). However, no significant differences in temperatures were noted between the neuroischaemic ulcerated and non-ulcerated neuroischaemic toes ($p=0.626$).

Discussion

This study is, to our knowledge, the first to examine thermographic patterns relating to toe temperatures of patients with neuroischaemic ulceration, as compared with neuroischaemic non-ulcerated and with healthy feet in T2DM. It was found that temperatures in healthy feet are significantly lower than neuroischaemic ulcerated and neuroischaemic non-ulcerated toes. Furthermore, there were no significant differences between toes of patients with non-ulcerated toes and those with neuroischaemic ulcerated toes of the same foot.

Previous studies have reported temperature differences between the toes of healthy adults, otherwise healthy patients with diabetes mellitus, ischaemic, neuroischaemic and neuropathic subjects.^{9,12} They have shown no significant difference between toes of healthy adults and healthy patients with diabetes mellitus (group 1); no significant difference between neuropathic, neuroischaemic and ischaemic toes (group 2); a significant difference between these two groups.

Importantly, we have also shown no difference in temperatures between an ulcerated toe and the adjacent toes of the same foot (Figure 2). The meaning of this finding may be that these remaining toes also carry an increased risk of developing ulceration, and this risk is manifested in the similarity of toe temperatures. In practice, the adjacent toes warrant careful attention by healthcare providers and patients to prevent further complications. This increased attention will have to be a part of the improved comprehensive multidisciplinary footcare,^{13,14} including surgical interventions¹⁵ and emergency treatment.¹⁶ Additional data would be required to confirm this assumption and to clarify the exact contribution of thermography to the clarification as to which toes of the same foot carry a high risk of ulceration and how, perhaps, serial thermographic images may help as warning signs for the clinician.

The strengths of this study are the new comparisons between ulcerated neuroischaemic, neuroischaemic and healthy DM toes and the use of modern thermographic imaging. The limitations are as follows. First, the patient population was very small. Secondly, no prospective follow-up data were available, but this was beyond the scope of the study.

In conclusion, in T2DM this study has reported a significant difference between toe temperatures of non-ulcerated neuroischaemic and ulcerated neuroischaemic toes when compared with those of healthy feet. Furthermore, no significant differences between temperatures of ulcerated toes and the non-ulcerated toes of the same foot, suggesting that all the toes of the same foot could potentially be at risk of developing complications. These data

add to the growing appreciation of thermography as a new modality of foot assessment in T2DM.

Conflicts of Interest: The authors declare no conflict of interest.

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Group	N	Gender	Age(SD)	Weight (SD)	Height (SD)	Duration of DM(SD)	Type of Treatment	HbA _{1c}
		M/F	years	kg	cm	years	Diet/OHA/INS/Mix	
Neuroischaemic	30	19/11	66.76(6.2)	84.72(14.13)	162.25(10.55)	19.07(10.53)	0/10/13/7	9.49

T2DM Healthy	15	9/6	64(9.13)	89.8(15.7)	164(10.7)	11.71(9.27)	0/12/1/2	7.1
Neuroischaemic ulcerated	12	6/6	68.42(12)	80.61(12.8)	162.25(3.85)	14.08(12.32)	2/5/4/1	7.6

Table 1. Demographics of study subjects.

Type of treatment: Diet = diet only; OHA = Oral Hypoglycaemic Agents; Ins=Insulin;

Mix=OHA+INS

Figure Legends:

Figure 1: Mean temperatures between groups.

Figure 2. Adjacent toes demonstrating similar thermal characteristics to the ulcerated toe (ulcer is on medial-plantar aspect of hallux).