Thermographic Diabetic Foot Assessment in Podiatric Practice

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Introduction

In a typical UK podiatrist practice 10% of patients in the age group between 40 and 49 are living with diabetes. This figure rises to almost 20% in the group between 50 and 59 and to over 25% in those older than 60 years old[1].

Podiatrists and vascular specialists are aware that this significant patient cohort is at risk of developing a range of foot complications which, when left untreated, can result in foot ulcers (in the UK 70,000 to 90,000 patients at any moment in time) and amputations (8,793 in 2018)[2]. 40% of diabetic foot ulcer patients die within 5 years and 50% of amputees survive only 2 years[3].

Figure 1 below summarises the diabetic foot problems seen in podiatric practice and outlines those conditions where thermography can be deployed.

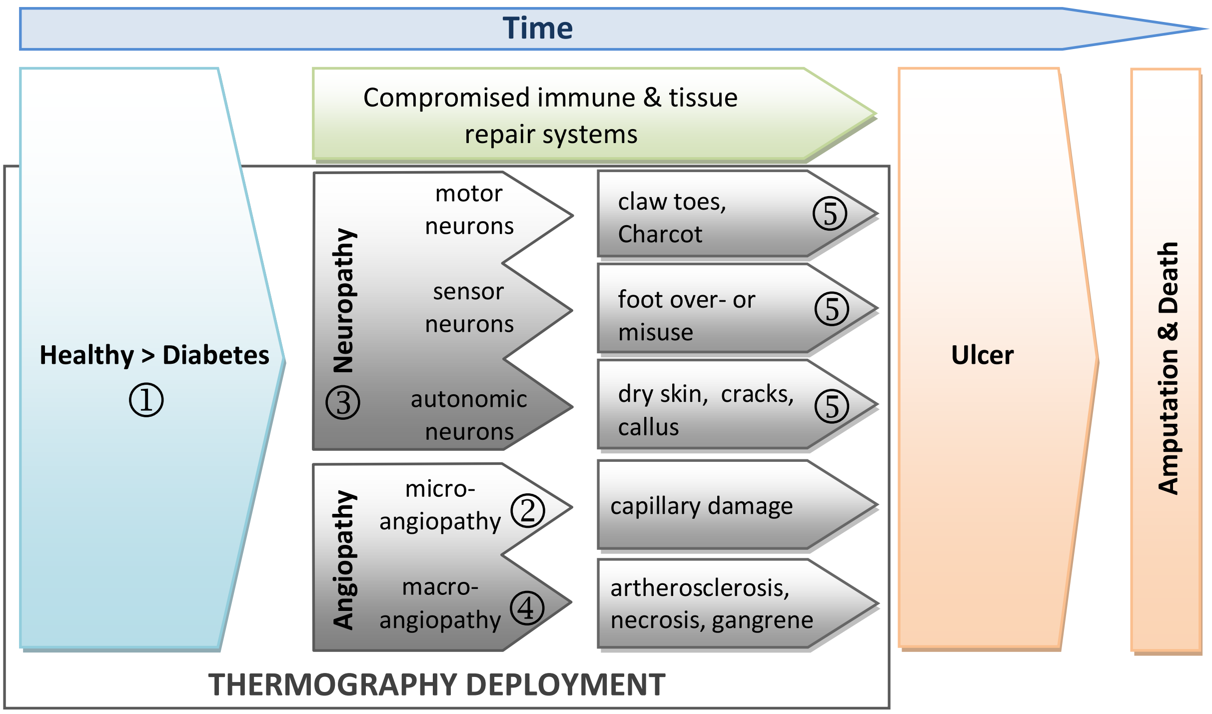


Figure 1: Simplified diagram of diabetic foot problems and those aspects where thermographic assessment may be beneficial. Numbers in circles (① to⑤) refer to the sections in this document where further information is provided.

Using thermography or thermal mapping of the foot can help the podiatrist in several ways:

Educating patients. Thermography is a simple yet immediately intuitive and powerful visual tool for explaining diabetic foot conditions to patients. Better understanding of their own condition may enhance patient compliance and encourage improved and informed self care.

Detecting foot conditions. Thermography can help to detect the onset of particular conditions at an early stage by visualising suspicious temperature distributions that hint at pathological processes.

Preventing. The earlier a particular problem is detected the higher the chances that further deterioration can be avoided. A suspicious temperature distribution may hint early towards a pathological process, which can then be confirmed by established methods of proven diagnostic accuracy.

Aiding treatment decisions. Thermography can be a useful adjunct to locate a problem area and to indicate the direction of further assessment.

Monitoring. The effect of interventions can be visualised to provide an additional indication if a treatment approach is successful.

Undertaking R&D. Thermography of the foot is an emerging area and in order to exploit its full potential more research is needed, generating publication and differentiation opportunities for practitioners.

Using thermography in this way can improve patient care and treatment outcomes. This in turn makes it more likely that patients will remain in primary care without the need for referral to secondary care.

Limitations of Thermography

With all the advantages of Thermography outlined above the professional user should be aware of two limitations:

1 Thermography on its own is not a diagnostic tool

The technique must not be used on its own to arrive at a diagnosis or treatment decision. The reason is that the temperature values and patterns are an indicator predominantly of blood flow but are not specific to a particular disease or condition. As an example, a hot hallux detected by thermography may be caused by an ingrown toenail, a bone micro-fracture, an embedded foreign body, pressure from ill-fitting shoes or simply by temporary over-use. Thermography can only suggest that there is a problem and it is then up the training, knowledge and experience of the podiatrist to establish the exact cause and treatment.

2 The medical value of absolute temperatures is limited

The professional user must question and interpret the apparent accurate readouts of any thermographic device. This has 3 reasons:

i. The equipment itself is, as any measurement tool such as rulers, voltmeters or normal thermometers, subject to accuracy limitations. The vast majority of thermal cameras have an accuracy of $\pm 2^\circ C$ (that is more than 20% of the human skin temperature range) and this is only directly after calibration and following an approximately 10 minute settling time after switching on and at a fixed environmental temperature. Thermo-chromic liquid crystal based devices tend to perform better but are still subject to inaccuracies between $\pm 0.5^\circ C$ (Podium Pro) and $\pm 1^\circ C$ (Podium home).

i. The human foot is subject to the body's natural thermal regulation system and naturally fluctuates within a wide temperature range. A healthy toe may be only 15°C one moment and, following exercise, over 30°C half an hour later.
ii. The user will also have to consider environmental factors (room temperature, humidity, time to acclimatise to room), clothing and the use of drugs (alcohol widens, nicotine constricts capillaries) prior to thermographic examination into account when considering absolute temperature readouts.

Relative temperature differences and patterns are, in contrast, more reliable. If, for example, a thermographic device has an offset of +2°C then it will usually affect all points in the thermographic image in approximately the same way, meaning that the temperature differences are broadly correct.

In conclusion, the user must be aware that a "high-tech looking thermal image" is not diagnostic on its own and that the temperature readouts are subject to many influencing factors. A well thought out measurement protocol[4] that defines the environment, patient preparation, equipment setup, timing and other factors can be helpful.

Section ① The Healthy Foot

In order to understand how thermography can inform the assessment of feet in people living with diabetes, it is important to realise that the temperature pattern of any part of skin, consequently also the foot, is determined primarily by width of the vascular beds directly underneath the skin resulting in variations of blood flow. More blood flow or dilated blood vessels create warmer skin and vice versa. However, skin temperature does not represent blood temperature which is in terminal cutaneous vessels closer to skin temperature than to core temperature. In turn, skin temperature is mainly dependent on ambient temperature. Due to equilibration of temperature across all tissue components of the skin, thermal imaging sees a rather uniform and homogenous temperature area, and not a network of vessels. The latter appear only after the equilibration was disturbed, for example by convective cooling or in the recovering phase following exercise.

The distribution of nutrients and oxygen transported by the blood is the primary function of the vascular control, but thermoregulatory responses come next.

Figure 2 below shows the microvascular network underneath the skin. In the context of the diabetic foot arterio-venous anastomoses (AVAs) are of particular importance for thermoregulatory responses.

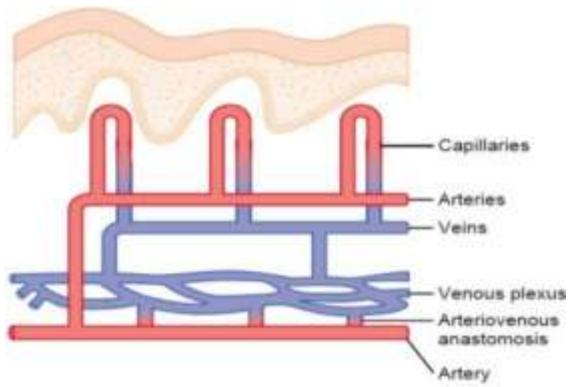


Figure 2: Vascular microcirculation network of skin and subcutaneous tissue[5]

AVAs are direct connections (shunts) between the small arteries and veins in subcutaneous tissue. They are concentrated in the glabrous (hairless) skin of the hands and feet, in particular fingers and toes. As shown in figure 2 the AVAs are short vessel segments with a large inner diameter[6].

They are surrounded by muscles which are controlled by the sympathetic nervous system. When the muscles are relaxed the AVAs open and shunt blood directly from the arteries into the venous plexuses which are, in contrast to the much narrower nutritional capillaries, in effect heat radiators for the body.

Consequently the AVAs are important effectors in human thermoregulation, i.e. keeping the body core temperature stable. Simplistically speaking[7], when core temperature becomes too low the temperature control centre in the hypothalamus sends signals via the sympathetic noradrenic nerves to the AVA muscles, causing them to contract and thus closing the shunts. This reduces the blood flow through the subcutaneous tissue, preserving body heat. The skin cools down. Conversely, when core temperature is too high, the signals of the sympathetic nerves reduce or stop completely[8]. The AVA muscles relax, the shunts open, blood flow increases and the skin warms up radiating heat away from the body.

In healthy individuals most of the blood goes through the nutritional skin capillaries. Even under conditions where the body core temperature increases and the shunts open sufficient blood supply through the capillaries is maintained. At a room temperature of 22°C the naked foot of a lightly dressed person acclimatised to the room for 10 minutes will show little shunting and as a result the thermal pattern will appear as shown in the left picture of figure 3.

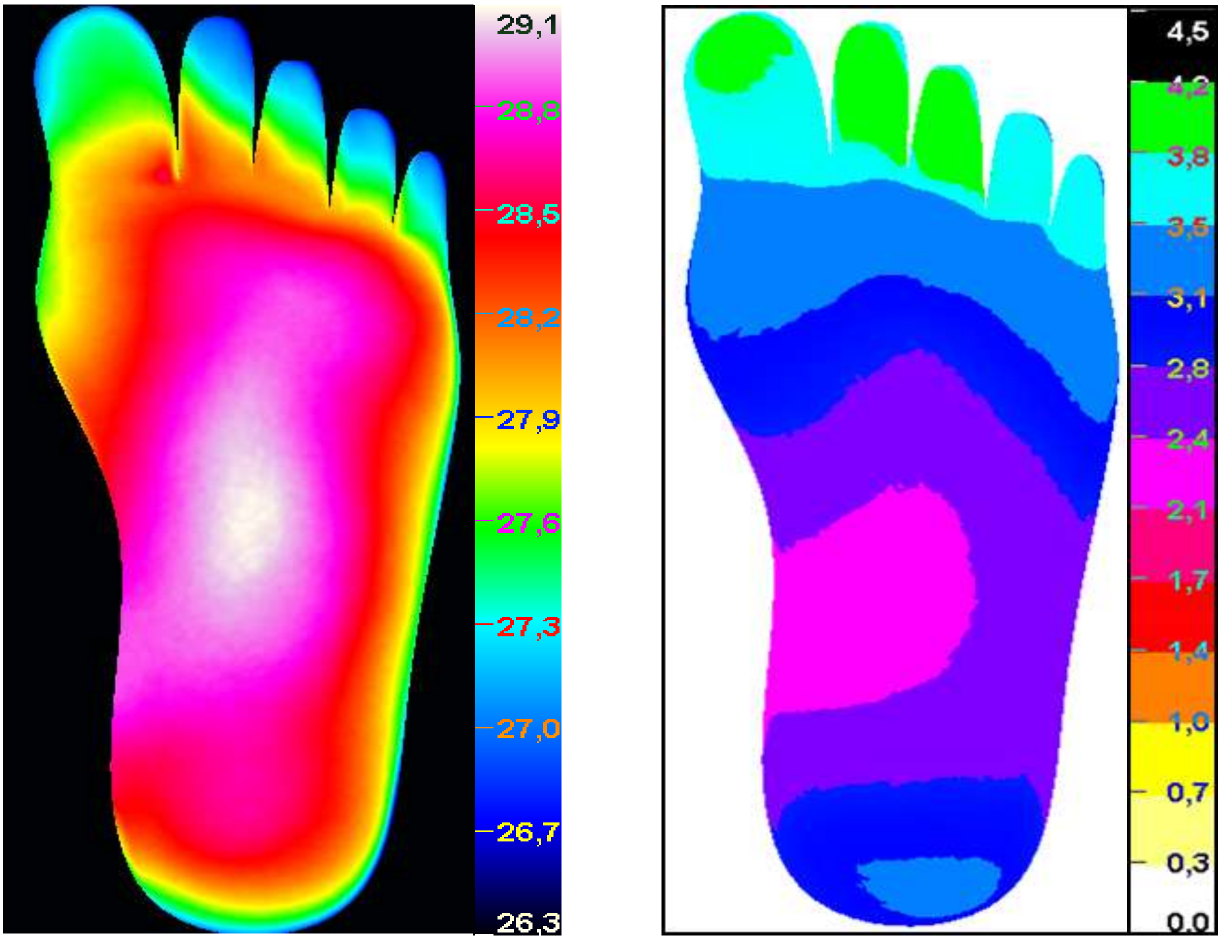


Figure3: Average plantar foot temperature (left) of 103 healthy subjects, resting at 22°C, 10 minutes after taking socks off. Variation of temperature (right) between the 103 subjects, 1 standard deviation[9].

As shown in the left picture of figure 3 the temperature gradient between the toes and the medial arch area is under these environmental conditions typically slightly less than 3°C (26.3°C to 29.1°C) but this could be up to ca. 4°C more (1 standard deviation, i.e. a 68% confidence interval) as indicated by the variation image at the right of figure 3.

A second thermal characteristic of healthy feet is that the temperature pattern is highly symmetrical between left and right foot.

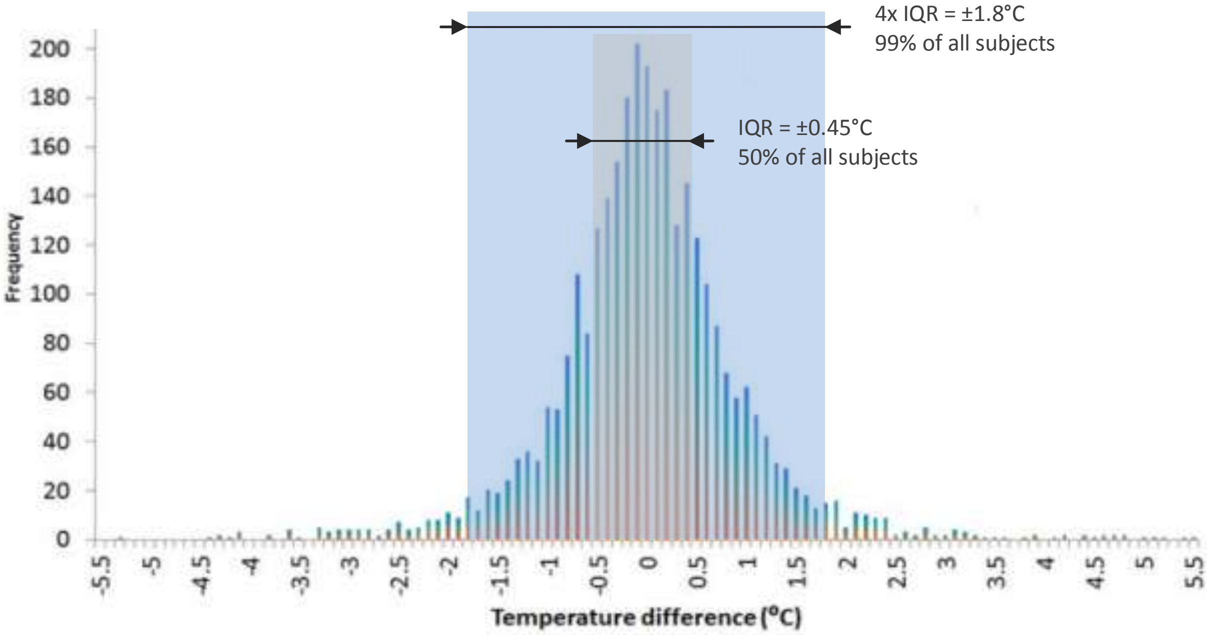


Figure 4: Feet are thermally highly symmetrical. The figure shows a histogram of the left – right differences at 33 distinct points in the feet of 103 healthy subjects (resulting in 3,399 data points). The width of the interquartile range (IQR) is 0.9°C, i.e. 50% of all aspects in one foot differ by less than 0.45°C from those of the other foot, 99% less than 1.8°C. Reproduced from[10].

Figure 5 shows the three most frequent and clearly distinct symmetrical patterns[11].

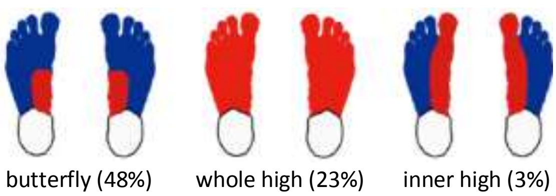


Figure 5: Frequent plantar temperature distribution patterns

The most common "symmetric bilateral butterfly pattern"[12] is illustrated in figure 6.

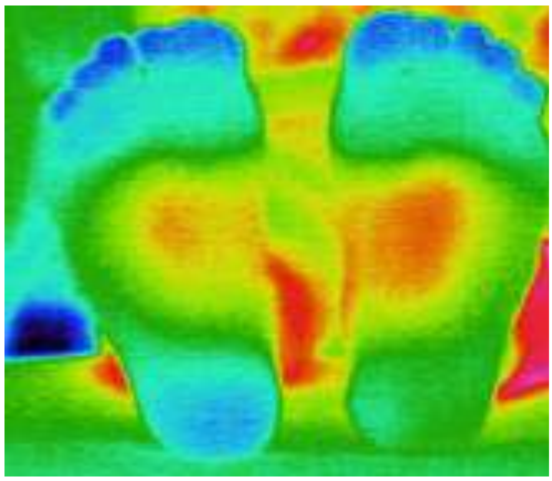


Figure 6: Thermal image of healthy feet showing the Butterfly pattern

Importantly, in all these patterns, the temperature of the small toes is almost always lower or at most equal to that of the medial arch; never higher.

Overall, the thermal characteristics of a healthy foot can be summarised as shown in the table 1.

TABLE 1 HEALTHY FOOT CHARACTERISTICS
Temperature gradient from medial arch to toe/heel is 0°C to 7°C
Left-Right (contralateral) temperature mirror-symmetry < 1.8°C
2^{nd} to 5^{th} toe approx. the same temperature
No hot spots
Average foot temperature 26°C (toes) to 29°C (arch)

Example Podium Images of Healthy Feet

Figure 7a below shows the thermal image created by a Podium scan. On the right is a histogram of the right image, i.e. a graphical representation of the amount of discrete temperature values in the left image.

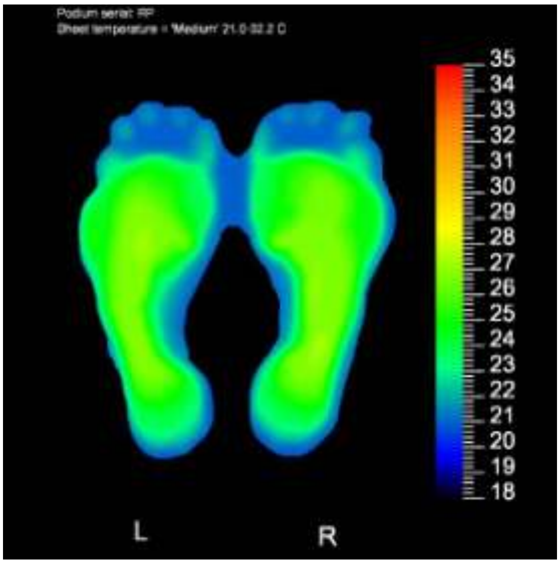


Figure 7a: Example thermogram of healthy feet

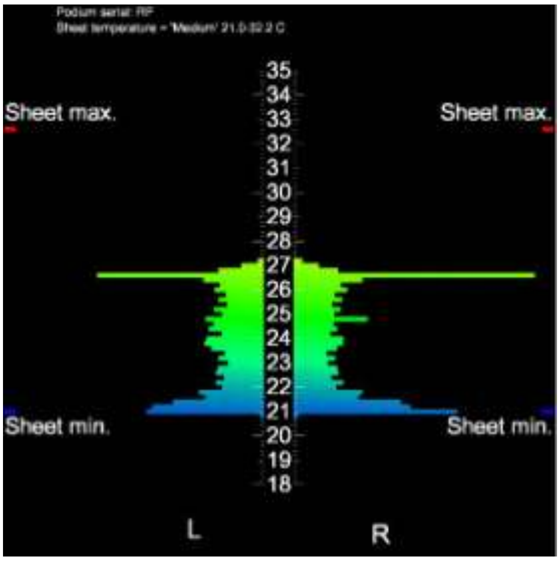


Figure 7b: Histogram associated with figure 7a

The example Podium output images can be assessed using the typical characteristics listed in table 1:

- **Arch to toe/heel gradient 0°C to 7°C**
It is immediately obvious from the thermal image on the left that the medial arch is significantly warmer than the toes and slightly warmer than the heels.

- **Left-Right (contralateral) temperature mirror-symmetry < 1.8°C**
The histogram shows an approximately symmetrical temperature distribution in the left and the right foot.

- **2^{nd} to 5^{th} toe capprox. same temperature**
This is again obvious from the htemrogram on the left

- **No hot spots**
No hot spots are visible in either the thermogram or the histogram.

- **Average foot temperature 26°C (toes) to 29°C (arch)**
The histogram shows a temperature range from approximately 23°C (the toe "prints", ignore the blue area in-between toes) to 27°C (arch). This is within the single standard deviation range (see figure 3, right image).

Section ②:
Diabetic Microangiopathy

Long-term high glucose levels in people living with diabetes cause, via a cascade of biochemical changes a thickening of the basement membrane in the capillary wall[13]. These changes may lead to occlusive angiopathy and to tissue hypoxia and damage[14] (the minimal blood flow for supporting cutaneous tissue is 0.8ml /100ml tissue /min).

According to[15]: "*The ensuing complications depend on the nature of the surrounding tissue, ranging from reduction of functional reserve, as seen in skeletal muscle, to the devastating functional consequences observed in organs with endarterial circulation such as the kidney and retina.*" In the foot the blockage reduces or completely blocks the flow of blood through the capillaries. This is particularly apparent in the toes where capillary concentration is highest. They appear significantly colder than normal in a thermogram as shown in figure 8[16].

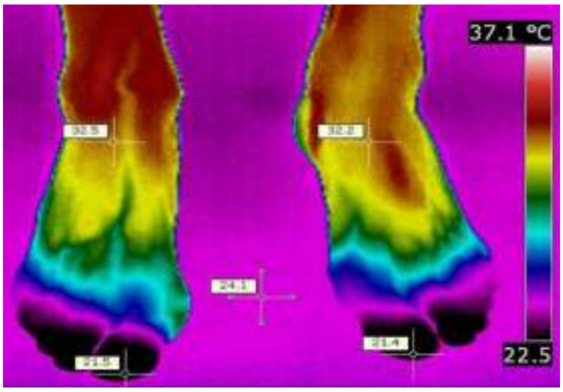


Figure 8: Cold toes, a characteristic marker of suspected microangiopathy

A high temperature gradient as shown in the figure is on its own not a proof of microangiopathy but one of the markers consistent with the condition.

The cold toes in figure 8 could be mistakenly interpreted as the effect of normal thermoregulation. However, frequently up to three characteristic aspects can be observed that distinguish the angiopathic from a simply cold foot. Figure 9 shows all three of them[17]:

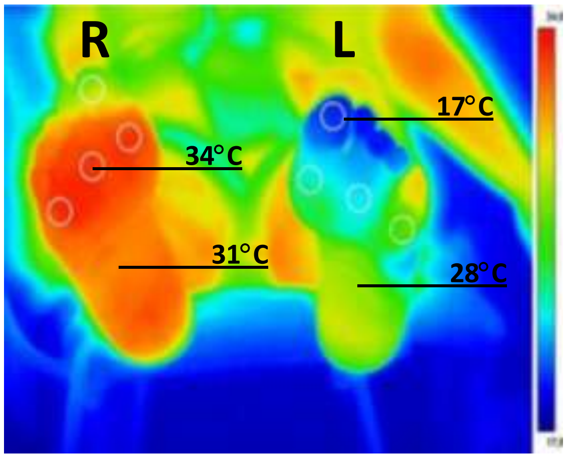


Figure 9: Characteristic marker of microangiopathy in left foot (L). Thermal signatures consistent with neuropathy in the right (see next section).

- **Firstly**, there is a large temperature gradient of 11°C between toes and ankle area. Normal would be up to 3°C (up to ca. 7°C max., see figure 3).
- **Secondly**, and in stark contrast to normal thermoregulation, the effect of microangiopathy tends to be contralaterally asymmetric (i.e. different in left and right foot).
- **Thirdly**, in normal thermoregulation it would be normal that all toes of a foot are affected in approximately the same way, with perhaps the big toe being slightly warmer than the little one. Figure 8 shows the opposite with the little toe almost unaffected and warmer than the big one.

Note that the right foot in figure 9 is more than 5°C warmer than the average healthy foot (compare figure 3) and shows an inverted temperature gradient between medial arch and the metatarsal area and heel. This indicates that the right foot may be neuropathic[18].

Table 2 below summarises the typical thermal characteristics of the angiopathic plantar foot. They are visualised in the images in figure 10.

TABLE 2 PLANTAR FOOT - THERMAL CHARACTERISTICS	
HEALTHY	**SUSPECT OF MICROANGIOPATHY**
Temperature gradient from Medial arch to toe/heel is 0°C to 7°C	Temperature gradient from Medial arch to toe/heel is more than 7°C
Left-Right (contralateral) mirror-symmetry < 1.8°C	Broken contralateral symmetry
2nd to 5th toe approx. the same temperature	Occasional different temperatures in toes 2 to 5
No hot spots	
Average foot temperature 26°C (toes) to 29°C (arch)	Average foot temperature significantly below 26°C (toes) but still 29°C (arch)

Example Podium Images of Suspected Microangiopathic Foot

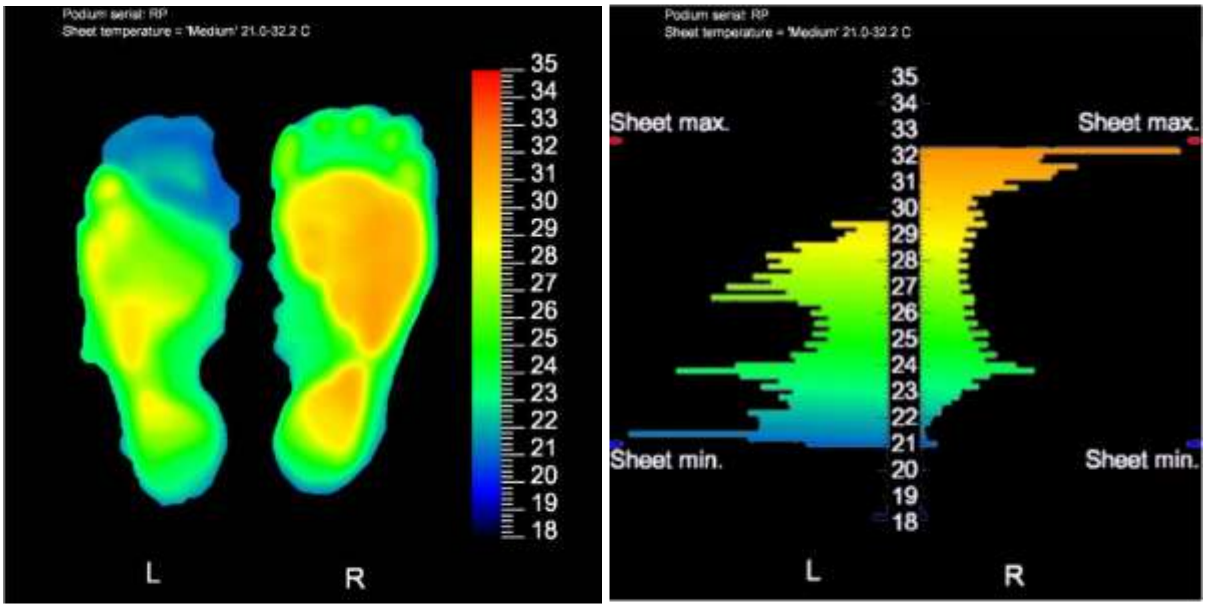


Figure 10: Thermogram (left) and histogram (right) of suspected microangiopathy in the left foot

Section ③: Diabetic Neuropathy

As a result of microangiopathy, tissues surrounding the affected capillaries are damaged, for example, in the retina (diabetic retinopathy) or the kidney (diabetic nephropathy). In the foot microangiopathy is one of the contributing factors to nerve damage (neuropathy). **Sensory** neuropathy causes the patient at first to notice numbness, "pins and needles", tingling sensations, hypersensitivity to touch and sometimes a burning sensation.

Approximately 50 percent of people with type 2 diabetes and 20% of those with type 1 diabetes develop this kind of nerve damage. Apart from microangiopathic effects other factors are contributors. Several studies quoted by[19] identify again high glucose levels, poor diabetes control, high total cholesterol (increasing risk of neuropathy by 67%), high triglycerides (doubles risk), high blood pressure (increases risk by 65%), obesity (doubles risk) and smoking (increasing risk by 42%)[20].

The increasing damage to the nerves may eventually lead, as a worst case scenario, to a total loss of function and sensation. Diabetic (poly)neuropathy is fully established[21]. Amongst the affected nerves are those of the somatic system (over which temperature information is transmitted) and the sympathetic fibres that control the thermoregulatory blood flow as outlined in section ① above. The lack of stimulus signals from the impaired nerves causes the muscles of the arteriovenous anastomoses (AVAs, see figure 2) to remain permanently relaxed and the AVAs thus being open. This can override the cooling associated with microangiopathy. The wide open shunts direct the majority of arterial blood straight into the venous plexus, warming the toe area as shown in figure 11 (image from[22]).

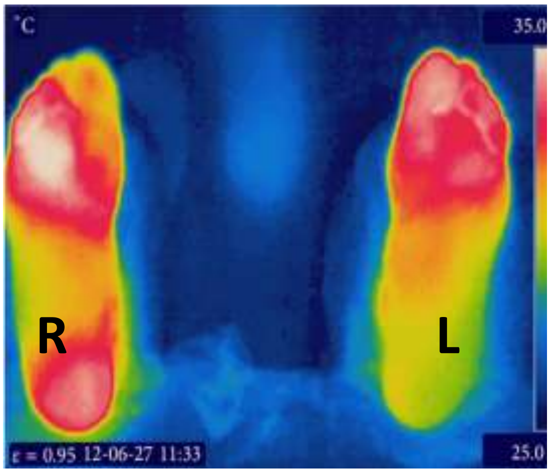


Figure 11: Diabetic neuropathy causing hyperaemia of toes and right heel with associated significant warming. Note the inversion of the normal medial arch-toe temperature gradient and the asymmetry between left and right foot compared to the healthy foot in figure 3.

Lack of sympathetic nerve signals to the sweat glands also means that the skin cannot sweat. Absence of sweat and also reduced passive transdermal skin wetting through the epidermis in diabetics contribute further to the higher temperature of the neuropathic foot and makes the skin brittle, increasingly susceptible to fissures, frequently with subsequent development of infection which will then show up as hot spots in a thermogram.

Cold stress tests of the kind often employed in assessing neural damage in hands (vibration white finger syndrome, some forms of Raynauds's) are reported to be helpful showing "good repeatability"[23] and it was found[24,25] that parameters such as mean foot temperature, temperature difference (ΔT), and recovery index after cold stress testing can be used for neuropathy screening to distinguish between the normal and neuropathic foot.

The table on the next page summarises and contrasts the typical characteristics of the neuropathic plantar foot.

TABLE 3	PLANTAR FOOT - THERMAL CHARACTERISTICS	
HEALTHY	**SUSPECT OF MICROANGIOPATHY**	**SUSPECT OF NEUROPATHY**
Temp. gradient from Medial arch to toe/heel is 0°C to 7°C	Temperature gradient from Medial arch to toe/heel is more than 7°C	Medial arch to toe/heel gradient is inverted
Left-Right (contralateral) mirror-symmetry < 1.8°C	Lack of contralateral symmetry	
2nd to 5th toe approx. the same temperature	Occasional different temperatures in little toes	
No hot spots		Extended hot areas
Average foot temperature 26°C (toes) to 29°C (arch)[26]	Average foot temperatures ignificantly below 26°C (toes) but still 29°C (arch)	Average foot temperature 35°C (toes) to 32°C (arch)[27,28]

Example Podium Images of Suspected Neuropathic Feet

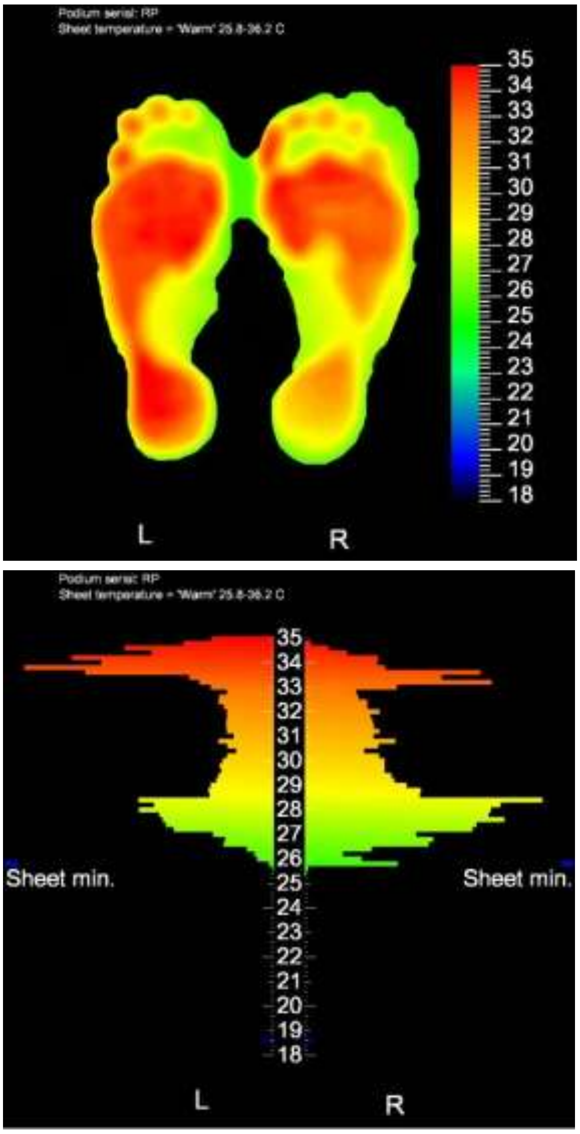


Figure 12: Thermogram (top) and histogram (bottom) of suspected neuropathy in both feet

The characteristic features of suspected neuropathy are visualised in the Podium images in figure 12. According to table 3 these are:

• **Medial arch -> toe/heel gradient inverted**
In the thermogram of the right foot this is obvious, in the left foot it is not quite so clear but the usually expected gradient between medial arch and toes/heel of is certainly very low.

• **Lack of contralateral symmetry**
The histogram shows the asymmetrix distribution of temperatures between feet

• **Occasional temperature differences in toes**
Compare the the differences between the left and the right first (big) toe

• **Extended hot areas**
These are visible both in the thermogram on the left and the large area of high tempertures in the histogram on the right.

• **Average foot temperature 35°C (toes) to 32°C (arch)**
The histogram shows this typical elevated temperature range, significantly higher than the healthy range between 26°C (toes) and 29°C (arch).

Section ④: Diabetic Macro-Angiopathy

Macro-angiopathy (atherosclerosis) in patients with diabetes is similar to that of non-diabetics. However, it occurs earlier in life, progresses faster and in the diabetic foot manifests itself with similar effects as non-diabetic peripheral vascular disease (PVD).

Non-diabetic PVD is found at all levels of the arterial tree supplying the foot but atheroma (plaques) appear predominantly at certain locations, in particular at bifurcations and bends in the artery. For lower limb PVD the responsible sites are the abdominal aorta, supplying the superficial femoral artery and subsequently the more distal vessels below the trifurcation such as the peroneal, anterior, and posterior tibial arteries shown in figure 13[29]. Surprisingly, foot vessels such as the dorsalis pedis are often spared[30].

The plantar foot areas are supplied by particular arteries (angiosomes) shown in figure 14.

Figure 14: Arterial supply areas (angiosomes) of the plantar foot[31]

The MPA (medial plantar artery) LPA (lateral plantar artery) and MCA (medial calcaneal artery) angiosomes are supplied by the posterior tibial artery, the LCA (lateral calcaneal artery) one is supplied by the peroneal artery.

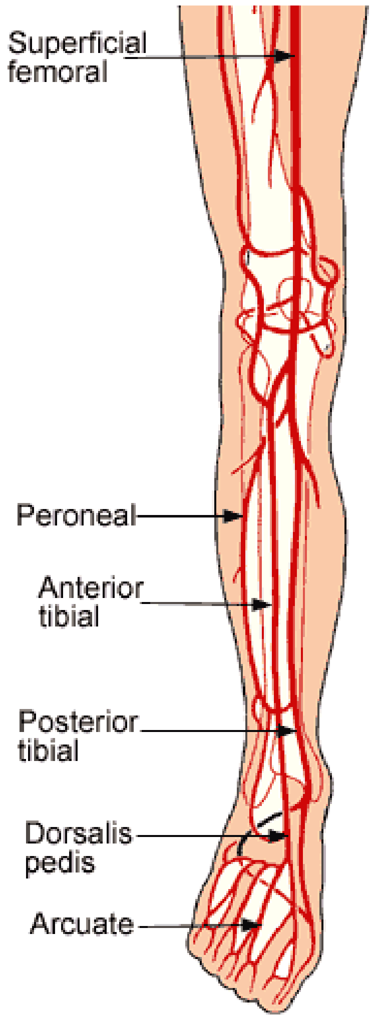


Figure 13: Major arteries of the lower limb

Sclerotic occlusion of arteries causes the supplied tissue to become ischemic. The lack of perfusion leads to cooling of the affected areas which can be detected in a thermal image as shown in figure 15 (after[32]).

TABLE 4 DIABETIC FOOT CLASSIFICATION[33]	
Classification	Prevalence
neuropathic	54%
neuro-ischemic	34%
ischemic	10%
other	2%

Ischemia reduces tissue perfusion, ulceration on foot margins, digital necrosis, and gangrene. If neuropathy is present pain may not be felt by the patient.

Figure 15: Examples thermal image of ischemic foot (L) and neuropathic foot (R) with inverted medial arch -> heel temperature gradient

<table>
<tr><th>TABLE 5</th><th colspan="3">PLANTAR FOOT - THERMAL CHARACTERISTICS</th></tr>
<tr><th rowspan="2">HEALTHY</th><th colspan="3">SUSPECT OF</th></tr>
<tr><th>MICROANGIOPATHY</th><th>NEUROPATHY</th><th>MACROANGIOPATHY</th></tr>
<tr><td>Temperature gradient from Medial arch to toe/heel is 0°C to 7°C</td><td>Temperature gradient from Medial arch to toe/heel is more than 7°C</td><td>Medial arch to toe/heel gradient is inverted</td><td>Random gradients</td></tr>
<tr><td>Left-Right (contralateral) mirror-symmetry < 1.8°C</td><td colspan="3">Lack of contralateral symmetry with differences exceeding 1.3°C [34]</td></tr>
<tr><td>2nd to 5th toe approx. the same temperature</td><td colspan="2">Occasional different temperatures in toes 2-5</td><td>Random</td></tr>
<tr><td colspan="2">No hot spots</td><td>Extended hot areas</td><td>Extended cold (ischemic) areas</td></tr>
<tr><td>Average foot temperature 26°C (toes) to 29°C (arch)</td><td>Average foot temperature significantly below 26°C (toes) but still 29°C (arch)</td><td>Average foot temperature 35°C (toes) to 32°C (arch)</td><td>Significantly below healthy average in affected areas</td></tr>
</table>

Example Podium Images of Suspected Macroangiopathic Foot

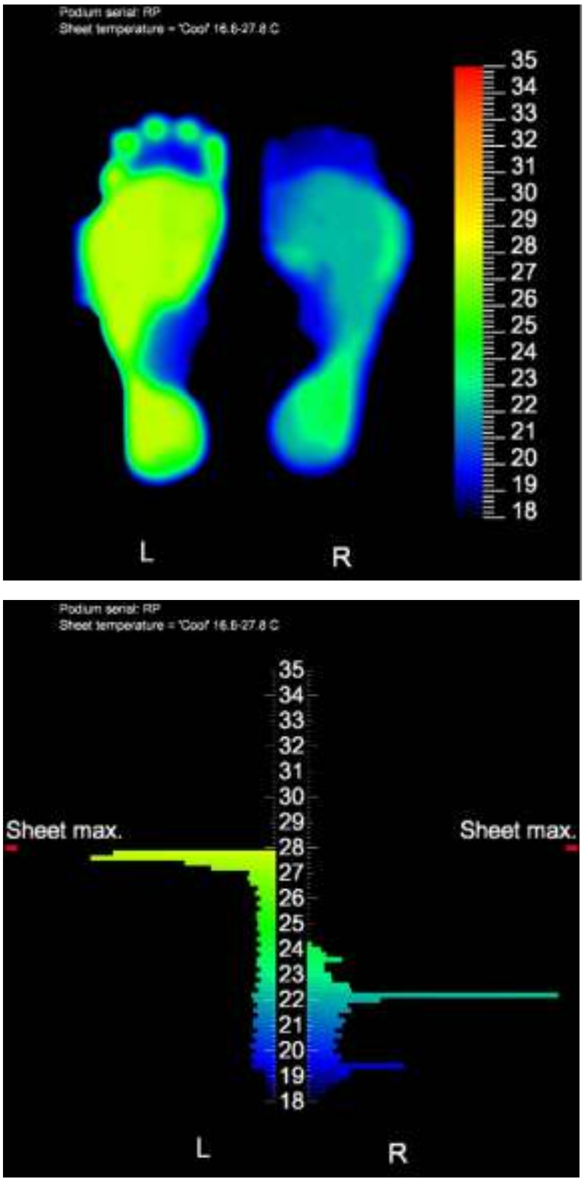


Figure 16: Thermogram (top) and histogram (bottom) of suspected macroangiopathy in the right foot

The characteristic features of suspected neuropathy are visualised in the Podium images in figure 16. According to table 5 these are:

• Random gradients

The medial arch to toe/heel gradients are significantly different between the left and the right foot. In the left foot there is only a very small gradient which could indicate neuropathy. In the thermogram of the right foot this is obvious, in the left foot it is not quite so clear but the usually expected gradient between medial arch and toes/heel of is certainly very low.

• Lack of contralateral symmetry

The histogram shows the asymmetrix distribution of temperatures between feet

• Random temperatures in toes

Compare the the differences between the left and the toes

• Extended cold areas

These are visible both in the thermogram and the large amount of low temperature values in the histogram.

• Average foot temperature significantly below average in affected areas

The histogram shows that parts of the right foot are significantly below the healthy average range between 26°C (toes) and 29°C (arch).

Section ⑤: Post-Neuropathic Complications

5.1 Effects caused by Motor Neuropathy

Motor neuropathy affects the patient's ability to co-ordinate walking movements. This can lead to a form of foot deformities, in particular hammer toes. A further example of foot deformity as a consequence of diabetic neuropathy is the Charcot foot, a foot and joint complication.

Due to a lack of nerve control, muscles of the foot weaken. The associated loss of co-ordination leads to unbalanced pressure being exerted on the foot, in particular the ankle when walking. Due to the sensory neuropathy that progresses in parallel to motor neuropathy patients are unaware to any tissue and bone damage that is caused by the pressure overload. Consequences are:

- sprains (stretching or tearing of ligaments)
- bone dislocation and fractures, including micro-fractures
- bone deformation of the foot (Charcot foot, see figure 17[35])
- excessive callus formation under bony prominences, further increasing pressure

All of these damages are associated with an inflammatory response of the surrounding tissue which can be picked up by thermographic assessment (unless the tissue in question is severely ischemic). In the affected Charcot foot a difference over 2°C to the corresponding contra-lateral site on the other foot is indicative of an active period[36].

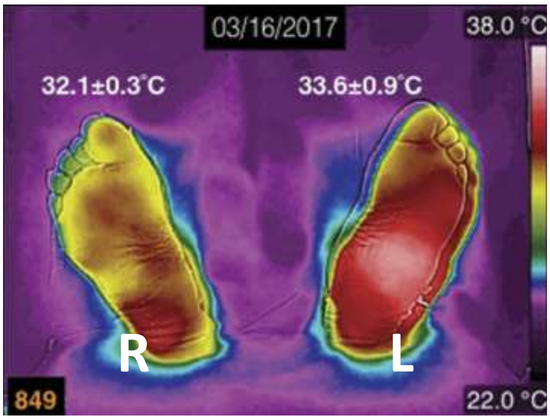


Figure 17: Thermographic appearance of a Charcot foot (L).
Neuropathy, as indicated by inverted middle arch to heel temperature gradient observable in the other Foot (R). Temperature values (white) are the average foot temperatures, both feet significantly increased with respect to healthy status (26-29). Note that in patients with neuropathy it may be difficult to distinguish between hyperthermia due to neuropathy and hyperthermia caused by an inflammatory period of Charcot deformity.

The most commonly affected areas are the tarsal, tarsometatarsal, and ankle joints. Clinical findings include swelling, deformity, and instability of one or more joints.

Success of podiatric interventions (immobilisation, orthotic offloading, rest) can be assessed and verified by continuous thermal monitoring.

It is interesting to note that thermography of the plantar foot can be used to visualise inflammatory reactions that are located elsewhere. In Figure 18 the medial and plantar thermal images of a Charcot episode in the left ankle are shown[37].

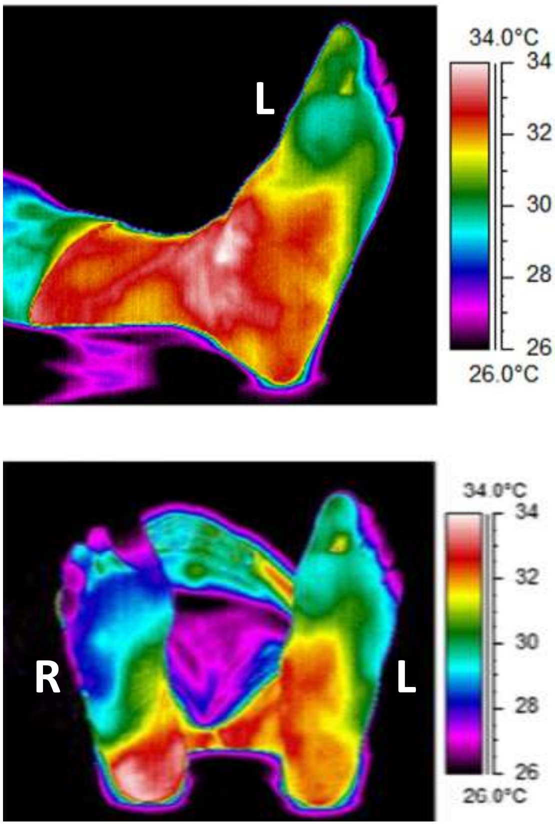


Figure 18: Thermogram of a patient with known Charcot in the left ankle (top image). The local heating is also visible in the plantar foot image (bottom image).

In the plantar image there are also warm areas at the right heel area and extending into the medial ankle aspect but according to the author *"this was attributed on clinical assessment to very dry skin and associated inflammation. Care is therefore needed when contrasting bilateral temperature differences and with image interpretation when multiple pathologies might be present."*

Example Podium Images of Charcot Foot

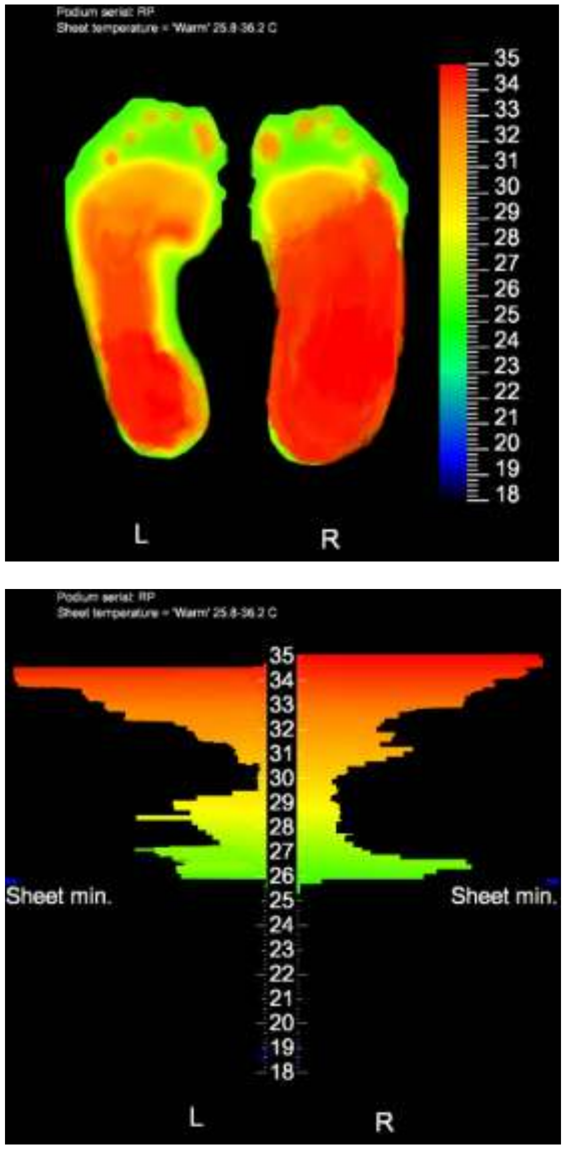


Figure 19: Thermogram (top) and histogram (bottom) of Charcot condition in the right foot.

5.2 Effects caused by Autonomous Neuropathy

Neuropathy of sensory fibres may cause "plus" and "minus" symptoms. "Plus" symptoms are pins and needles, paraesthesia, pain, particularly allodynia. "Minus" symptoms include hypoaesthesia, hypoalgesia, analgesia, loss of discrimination, loss of position sense, loss of information from tension sensors in tendons and muscles. Both symptoms may exist simultaneously.

In the context of thermography, denervation of autonomous dermal structures leads to decreased sweating. The lack of sweat means that there is no evaporative cooling, further amplifying the increase in foot temperature caused by arterio-venous anastomoses (shunting) as already explained in section 3.

The dry skin (Xerosis) encourages fissure formation, which predispose the skin to infection. These will show up on the thermogram as isolated hot spots.

5.3 Sensory Neuropathy

Once patients reach the neuropathic stage no discomfort, pain or other warning signals can be noticed by the patient any more. The natural feedback loop from the feet to the brain is broken. This encourages unwise behaviour ("no pain = no problem"). However, the loop can be partially closed by two replacements:

1. Regular foot examinations and/or thermal scans at home
2. Education, leading to behavioural change – facilitated in part by visually intuitive thermal foot imagery

5.4 Where to look for pre-ulcers

The table below shows where the podiatrist can expect ulceration to occur. By paying particular attention to these regions it is claimed that, under ideal care conditions, "up to 75% of all ulcers are preventable"[38].

In people with diabetes ulceration is particularly likely to occur at the toes (69% - see table 7). Due to the small volume of toes and the joint vascular supply of dorsal and plantar side the inflammatory response of a dorsal toe pre-ulcer is is also detectable on the plantar aspect.

Following in frequency are the plantar aspect of the metatarsal heads (22%) and the heel (9%) where the associated pre-ulcer inflammation can also be picked up by plantar thermography.

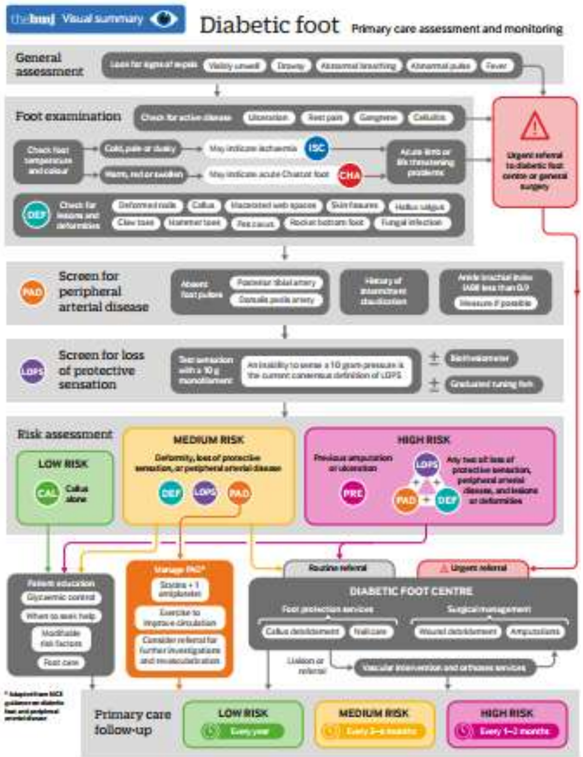
TABLE 7 LOCATION AND DEVELOPMENT OF FOOT ULCERS (191 patients, after[39])

Location	healing	minor amputation	major amputation	turn chronic	TOTAL
Toes	9%	43%	8%	10%	**69%**
Metatarsal heads	7%	9%	2%	4%	**22%**
Heel	3%	0%	3%	3%	**9%**
Total	**19%**	**51%**	**12%**	**17%**	**100%**

If a patient previously had an ulcer that is now in remission, re-ulceration occurs on the same foot in 84% and at the same site in a third of all cases[40]. The majority of these can be expected to be on the plantar aspect of the foot with a general distribution as shown in the 'Total' column of table 7.

5.5 Diabetic Foot Risk Assessment

Readers are encouraged to download the risk assessment chart shown on the right, produced by the British Medical Journal, BMJ[41]



References and Notes

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[8] The bulk of evidence strongly indicates that that thermally mediated thermodilation in the hands and the foot is mediated entirely by withdrawal of vasoconstrictor tone whereas in other parts of the body vasodilator

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