Plantar Tissue Thickness Is Related to Peak Plantar Pressure in the High-Risk Diabetic Foot

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OBJECTIVE — To investigate the relationship among plantar foot pressure, plantar subcutaneous tissue thickness, severity of neuropathy (vibration perception threshold [VPT]), callus, and BMI in a large group of neuropathic diabetic patients at risk of foot ulceration.

RESEARCH DESIGN AND METHODS — A total of 157 diabetic neuropathic patients (VPT >25 V) without either peripheral vascular or ulcer history were studied. Plantar foot pressure and plantar tissue thickness were measured at each metatarsal head (MTH) using an optical pedobarograph and an ultrasound scanning platform, respectively.

RESULTS — A significant association was observed between peak plantar pressure and plantar tissue thickness at all MTHs ($-0.26 < r < -0.61$, $P < 0.0001$), with the least pronounced association at the first MTH. In addition, the pressure time integral was significantly associated with plantar tissue thickness ($-0.24 < r < -0.57$, $P < 0.0001$). BMI was significantly related to plantar tissue thickness ($0.18 < r < 0.45$, $P < 0.05$), but not to peak forefoot pressures. Subjects with callus had significantly reduced plantar tissue thickness at all MTHs except the first MTH and increased peak pressures at all MTHs ($P < 0.001$).

CONCLUSIONS — This study confirms a strong inverse relationship between plantar tissue thickness and dynamic foot pressure measurements. Long-term follow-up of this patient population will confirm whether reduced plantar tissue thickness predicts the development of diabetic foot ulcers.

Diabetes Care 24:1270–1274, 2001

Diabetes is a common condition affecting patients in the developed and developing world. Complications affecting the lower limb are among the most common manifestations of diabetes, and those precipitated by neuropathy include ulceration, infection, and even amputation. It is estimated that foot ulceration occurs in up to 15% of diabetic patients during their lifetime and that such patients are 15–46 times more likely to have an amputation than nondiabetic patients (1). Moreover, about one in five hospitalizations among diabetic patients are directly related to foot ulceration, making this the most common reason for diabetes-related hospital admission in some regions. The costs of treating these complications accounts for ~25% of the hospital costs of diabetes care, but the indirect costs can be much more (2). Therefore, identification of patients at risk of foot ulceration can help us to focus our efforts in preventing ulcers in such patients.

A number of risk factors have been examined and found to be associated with diabetic foot ulceration, including peripheral neuropathy (3), previous ulceration, high dynamic plantar foot pressures (4), and limited joint mobility (5). Peripheral neuropathy is the most important component cause of foot ulceration, as well as foot deformity and trauma (6). The plantar surface of the foot is the most common site of neuropathic foot ulcers, especially the area under the metatarsal heads (MTHs). Peripheral neuropathy is associated with hyperextension of the metatarsophalangeal joints, clawing of the toes, and distal migration of the fibro-fatty pad on the plantar aspect of the forefoot. This process may subsequently lead to increased forefoot pressures (7). Decreased sweating and dryness of skin secondary to autonomic neuropathy results in callus building up under areas of increased pressure, which in turn further increases the pressures (8,9).

Increased pressures under the MTHs have been shown prospectively to predict ulcer development (4,10), but pressure measurement devices are costly, not always readily available, require user expertise and patient cooperation, and can be time-consuming in use. Preliminary data from diabetic and rheumatoid arthritic patients suggested that plantar foot pressures are strongly associated with reduced plantar tissue thickness under the MTHs (11), although the numbers studied in that report were small. In addition, it has been suggested that disruption in the subcutaneous tissues with the development of microhemorrhages (12) may lead to the breaking down of the overlying skin, resulting in ulcer formation. In support of this hypothesis, diabetic patients, especially those with foot ulcers, have been reported to have reduced plantar soft tissue thickness compared with nondiabetic subjects, indicating that this could be an important contributing factor in the development of foot ulceration (13,14).

It is therefore suggested that measurement of plantar subcutaneous tissue thickness could be used to predict the risk of foot ulceration. Accordingly, we aimed to confirm the relationship between plantar tissue thickness and forefoot pressure in a large group of diabetic neuropathic

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Received for publication 20 December 2000 and accepted in revised form 27 March 2001.
Abbreviations: MTH, metatarsal head; VPT, vibration perception threshold.
A table elsewhere in this issue shows conventional and Système International (SI) units and conversion factors for many substances.

Table 1—*Descriptive characteristics of patients included in the study*

Group	Total
n	157
Sex (M/F)	73/27
Type of diabetes	
Type 1	22
Type 2	78
Duration of diabetes (years)	16.4 ± 10.3
BMI	29.3 ± 5.0
VPT (V)	34.8 ± 8.7
Neuropathy disability score (maximum 10)	7.0 ± 2.3

Data are % or mean ± SD.

patients at risk of foot ulceration. The data presented here are the baseline data of a longitudinal study.

RESEARCH DESIGN AND METHODS

— A total of 157 patients with diabetes were enrolled; 73% were men, with a mean age of 61.2 ± 10.2 years. All patients had at least one palpable foot pulse and loss of protective sensation. Excluded were patients with an active or past history of foot ulcers, those with Charcot neuroarthropathy or foot surgery, as well as those who were unable to walk unaided. Patients underwent a neuropathic assessment, including the measurement of vibration perception threshold (VPT) on the tip of the hallux of both feet, using a neurothesiometer (Horwell, London) (15), and the modified neurologic disability score (16). Loss of protective sensation was defined as a VPT >25 V (3,15,17). The presence of callus was noted, and any significant buildup was debrided before any of the assessments. Only callus present under the MTHs was used for later analysis, and callus was noted as a dichotomous variable: present or absent. Dynamic plantar pressures were measured during barefoot walking using the Optical Pedobarograph (Department of Medical Physics and Clinical Engineering, Royal Hallamshire Hospital, Sheffield, U.K.) (18). The pressure plate is built into an 8-m walkway and measures at a frequency of 25 Hz and a resolution of 2 mm^2. Five steps were analyzed for each foot; any steps regarded as atypical by the investigator (e.g., subject tripping, substantially altering gait, or aiming for the pressure plate during data collection) were not saved and thus were not used for analysis. Peak pressure and pressure time integral were analyzed at each individual MTH. When addressing the area of interest for pressure analysis at each MTH, the cursor was used to select a circular MTH region; at no time was there any overlap among individual MTH pressure regions. Areas were carefully selected as previously described (19).

The plantar tissue thickness was measured under weight-bearing conditions at each MTH using the Planscan (Department of Medical Physics and Clinical Engineering, Royal Hallamshire Hospital) (20). The Planscan is a scanning platform that holds a high-resolution probe. The Toshiba SSA-240A ultrasound scanner with a 3.75-MHz curvilinear array transducer (Toshiba Medical Systems Europe) was used for the assessment. The subjects stood barefoot on the plastic barrier of the scanning platform, with the ultrasound transducer located underneath the upper surface. The MTH of interest was positioned directly above the transducer, and the distance between the most prominent part of the MTH and the skin was determined as the plantar tissue thickness. Three measurements were obtained in the longitudinal plane of the metatarsal and averaged for subsequent analysis. The Planscan device is simple to use, and we experienced no problems with patients standing on the platform. The intra-observer coefficient of variation, assessed twice at a two-weekly intervals in 11 healthy control subjects, was <8%, confirming the high degree of reproducibility.

Data are presented as means ± SD. Pearson's test was used to assess correlation between the continuous variables of peak plantar pressure under each MTH and plantar tissue thickness under the same site. Student's *t* tests were used for comparisons between the subjects with and without callus. For all calculations, we used an α of 0.05.

RESULTS

— Descriptive characteristics for this population are listed in Table 1. Average stance duration (mean ± SD) during the pressure measurements was 860 ± 127 and 865 ± 129 ms for the left and right foot, respectively. A pronounced negative correlation was observed between peak plantar pressure and plantar tissue thickness for the second, third, fourth, and fifth MTH ($-0.430 < r < -0.605$, $P < 0.0001$), whereas the correlation for the first MTH was significant but not as pronounced ($r = -0.26$, $P < 0.001$) (Table 2 and Fig. 1). In 41 patients, the tissue thickness at the sesamoid bones under the first MTH was also

Table 2—*Correlations between forefoot pressure and plantar tissue thickness by site*

Site	Peak pressure left	Peak pressure right	Pressure-time integral (left)	Pressure-time integral (right)
MTH1	$r = -0.29$, $r^2 = 0.08$ $P < 0.0001$	$r = -0.26$, $r^2 = 0.07$ $P < 0.001$	$r = -0.25$, $r^2 = 0.06$ $P < 0.01$	$r = -0.24$, $r^2 = 0.06$ $P < 0.01$
SESM	$r = -0.44$, $r^2 = 0.19$ $P < 0.005$	$r = -0.59$, $r^2 = 0.34$ $P < 0.0001$	$r = -0.28$, $r^2 = 0.08$ $P = 0.078$	$r = -0.52$, $r^2 = 0.27$ $P < 0.01$
MTH2	$r = -0.56$, $r^2 = 0.31$ $P < 0.0001$	$r = -0.61$, $r^2 = 0.37$ $P < 0.0001$	$r = -0.52$, $r^2 = 0.27$ $P < 0.0001$	$r = -0.57$, $r^2 = 0.32$ $P < 0.0001$
MTH3	$r = -0.55$, $r^2 = 0.30$ $P < 0.0001$	$r = -0.57$, $r^2 = 0.32$ $P < 0.0001$	$r = -0.51$, $r^2 = 0.26$ $P < 0.0001$	$r = -0.56$, $r^2 = 0.31$ $P < 0.0001$
MTH4	$r = -0.43$, $r^2 = 0.19$ $P < 0.0001$	$r = -0.45$, $r^2 = 0.20$ $P < 0.0001$	$r = -0.39$, $r^2 = 0.15$ $P < 0.0001$	$r = -0.43$, $r^2 = 0.18$ $P < 0.0001$
MTH5	$r = -0.49$, $r^2 = 0.24$ $P < 0.0001$	$r = -0.51$, $r^2 = 0.26$ $P < 0.0001$	$r = -0.47$, $r^2 = 0.22$ $P < 0.0001$	$r = -0.54$, $r^2 = 0.29$ $P < 0.0001$

SESM, sesamoids (average of thickness of lateral and medial sesamoid).

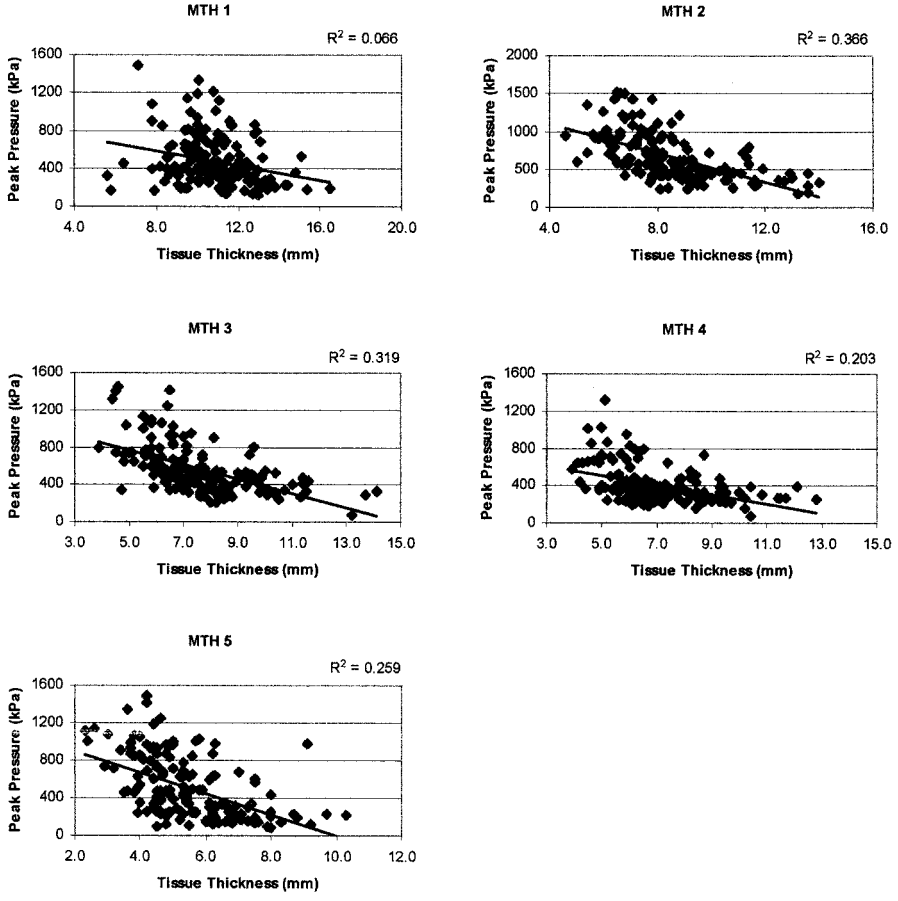

Figure 1—*Correlation between plantar pressure and tissue thickness in the forefoot.*

assessed in addition to that under the first MTH. The correlation between peak pressure at the first MTH and the average tissue thickness under the medial and lateral sesamoid bones was stronger ($r = -0.437$ and $r = -0.586$ for the left and right foot, respectively, $P < 0.005$ and $P < 0.0001$) than for the first MTH thickness itself (Table 2). The correlation between pressure time integral and plantar tissue thickness was significant for each MTH, and again the least pronounced correlation was at the first MTH (Table 2). The strength of association between plantar tissue thickness and pressure time integral was similar to the association between plantar tissue thickness and peak pressures.

BMI was significantly associated to plantar tissue thickness at all MTH sites, with correlations ranging from 0.175 to 0.428 ($P < 0.01$ for all MTH, except $P < 0.05$ for left first MTH) (Table 3). The least pronounced relationship was again observed at the first MTH, with a stronger relationship at the sesamoids. In contrast, however, no relationship was observed between BMI and peak plantar pressure at any MTH site ($-0.135 < r < 0.016$; $0.101 < P < 0.988$), except for a weak correlation at the left first MTH ($r = 0.195$, $P = 0.017$).

Subjects with callus under the forefoot (at MTH sites) had significantly reduced plantar tissue thickness at the second, third, fourth, and fifth MTH (Table 4) but not at the first MTH. Furthermore, subjects with callus under the forefoot had significantly increased peak forefoot pressure at each MTH for both feet (Table 4).

There was a significant but weak correlation between severity of neuropathy (measured as VPT) and plantar tissue thickness at only 2 of the 10 MTH sites (right third MTH $r = -0.17$, $P = 0.030$; left first MTH $r = -0.24$, $P = 0.002$). There was no correlation between VPT and peak forefoot pressure for the left and right foot.

CONCLUSIONS — In this study of a large group of diabetic patients, a significant correlation was observed between plantar tissue thickness and variables for plantar pressures (peak pressure and pressure time integral) under the MTHs, confirming and extending the results of an earlier pilot study (11). It is interesting that whereas the most common site for pressure ulcers is the first MTH, the poorest correlation occurred under the first MTH bilaterally. This weaker correlation is most likely related to the presence of two sesamoid bones under the first MTH, which are more superficial and may accept a portion of the weight load (21). Initially, the tissue thickness was only measured under the MTHs, but after an interim analysis, our current practice changed to measure the tissue thickness under the MTHs as well as the sesamoids and take the mean value of the medial and lateral sesamoids. Analysis of the first 41

Table 3—*Correlations between plantar tissue thickness and BMI by site*

Site	Left foot	Right foot
MTH1	$r = 0.18$, $r^2 = 0.03$ $P < 0.05$	$r = 0.25$, $r^2 = 0.06$ $P = < 0.005$
SESM	$r = 0.41$, $r^2 = 0.17$ $P < 0.0001$	$r = 0.39$, $r^2 = 0.15$ $P = 0.018$
MTH2	$r = 0.26$, $r^2 = 0.07$ $P < 0.005$	$r = 0.29$, $r^2 = 0.08$ $P < 0.0001$
MTH3	$r = 0.40$, $r^2 = 0.16$ $P = < 0.0001$	$r = 0.39$, $r^2 = 0.15$ $P < 0.0001$
MTH4	$r = 0.37$, $r^2 = 0.14$ $P < 0.0001$	$r = 0.43$, $r^2 = 0.19$ $P < 0.0001$
MTH5	$r = 0.32$, $r^2 = 0.10$ $P = < 0.0001$	$r = 0.31$, $r^2 = 0.10$ $P < 0.0001$

SESM, sesamoids (average of thickness of lateral and medial sesamoid).

Table 4—*Peak plantar pressure and plantar tissue thickness at each MTH for subjects with and without callus at MTH sites*

	Side	No callus	Callus
Peak pressure (kPa)			
Peak pressure forefoot (MTHs)	Left	776 ± 304‡	1001 ± 313
	Right	728 ± 269‡	1018 ± 264
MTH1	Left	469 ± 285*	592 ± 309
	Right	436 ± 247*	550 ± 290
MTH2	Left	583 ± 275‡	864 ± 360
	Right	563 ± 261‡	837 ± 306
MTH3	Left	505 ± 214‡	721 ± 287
	Right	477 ± 178‡	724 ± 303
MTH4	Left	368 ± 168*	448 ± 238
	Right	372 ± 169*	454 ± 235
MTH5	Left	438 ± 301†	598 ± 343
	Right	445 ± 296†	631 ± 356
Tissue thickness (mm)			
Sessamoids	Left	6.4 ± 1.7	5.5 ± 1.3
	Right	6.5 ± 1.7	5.5 ± 1.4
MTH1	Left	11.1 ± 1.7	10.9 ± 1.4
	Right	11.0 ± 1.8	10.6 ± 1.7
MTH2	Left	9.1 ± 1.8‡	7.9 ± 1.7
	Right	9.0 ± 2.0‡	7.7 ± 1.5
MTH3	Left	8.1 ± 1.6‡	7.0 ± 1.4
	Right	8.1 ± 1.9‡	6.8 ± 1.5
MTH4	Left	7.6 ± 1.5‡	6.7 ± 1.3
	Right	7.4 ± 1.8†	6.6 ± 1.6
MTH5	Left	5.9 ± 1.4†	5.2 ± 1.2
	Right	5.6 ± 1.5*	5.1 ± 1.3

Data are means ± SD. *$P < 0.05$; †$P < 0.01$; ‡$P < 0.0001$ callus vs. no callus.

measurements using this method showed a stronger correlation of plantar foot pressures and subcutaneous tissue thickness at the sesamoids. We believe that measuring tissue thickness under the first MTH as well as the sesamoid bones may assist in confirming or refuting this assumption.

It is, however, surprising to note that the inverse relationship between plantar tissue thickness and pressure time integral was not stronger than the correlation between plantar tissue thickness and peak pressure. Because the pressure time integral combines a measurement of time and magnitude of pressure, it was hypothesized that an early rise in pressure during stance caused by prominent MTHs would lead to an increased pressure time integral and not necessarily to an increase in peak pressure; the observed findings are therefore difficult to explain.

Because measurements of plantar pressure were made in a dynamic situation (i.e., during walking) and plantar tissue thickness was measured in a static situation (i.e., while standing), it is possible that the thickness as measured in the static situation was not the same as that measured in the dynamic situation during walking. Moreover, it may be that during walking, the plantar tissue between the MTH and the skin-floor interface was less or different from the thickness measured during standing, i.e., the MTH may move distally from the plantar tissue, although this is contrary to the established theory of plantar tissue moving distally of the MTHs in diabetic neuropathic patients with clawed toes and prominent MTHs. Indeed, a 46% reduction in plantar tissue thickness during walking has been reported, but this was only compared with non–weight-bearing and not with standing, as in our study (22).

The fact that only up to 37% of the variance of peak plantar pressure could be explained from the plantar tissue thickness could be related to this issue of walking versus standing. Tissue properties—a relatively new area of study—have been suggested to be an important contributing factor to diabetic foot ulceration and may be as important as tissue thickness (23). However, plantar pressure is related to many different factors, such as walking speed, body weight, callus, and foot structure; therefore, it is not surprising that plantar tissue thickness, unquestionably an important factor related to plantar pressure, can only explain a relatively small amount of variation. In fact, in a report by Morag and Cavanagh (24), plantar tissue thickness alone was able to explain a somewhat smaller amount of the peak pressure variation compared with multiple structural and functional factors. Nevertheless, plantar tissue thickness is to date the strongest individual predictor of peak plantar pressure to be reported in the literature.

It was interesting to observe that whereas BMI was not related to peak pressure, it was significantly associated to plantar tissue thickness. This relationship between BMI and plantar tissue thickness could explain the lack of association between BMI and peak pressure, as reported in this study and by various other authors. The results of this study suggest that individuals with a higher BMI have more subcutaneous tissue thickness and consequently lower foot pressures.

The observation of increased plantar pressure in subjects with callus in this study was expected, thereby confirming previous reports (9,25). The reported relationship between callus and reduced tissue thickness is, however, a new observation, suggesting that callus builds up at sites with reduced cushioning in order to protect the skin from breaking down.

The lack of association between VPT and peak pressure or tissue thickness is probably due to patient selection because a VPT >25 V was an inclusion criterion; thus, only a relative small range of VPT was measured in this study. Whether diabetic neuropathy could lead to loss of plantar tissue thickness is not clear from this study. However, some authors have provided preliminary evidence of reduced subcutaneous tissue thickness in diabetic neuropathic patients compared with nonneuropathic and healthy control subjects (11,13,14)

Foot ulceration remains a leading cause of morbidity in diabetic patients. Pecoraro et al. (26) identified that nonhealing foot ulcers preceded 85% of diabetic lower limb amputations. The aim set by the St. Vincent declaration was to reduce the number of amputations in Eu-

rope by 50% within 5 years (27). Although diabetic foot ulcers remain very difficult to heal and are associated with high recurrence rates, they remain potentially preventable. The first step in any prevention program involves screening diabetic patients for the presence of complications such as peripheral neuropathy. For this purpose, simple established screening tools could be used, such as VPT (15), 10-g monofilaments (28), and the presence of peripheral pulses and the ankle-brachial pressure index (29). The second step is to examine those patients with loss of protective sensation for the presence of associated and predictive risk factors for foot ulceration, such as foot deformity, limited joint mobility, presence of callus, and elevated foot pressures (4). A new potential screening technique for risk of ulceration has been presented in this report. The device used (Planscan) is relatively inexpensive, simple to use, portable, and can be made available to most diabetic clinics or radiology departments with ultrasound devices. Plantar tissue thickness was able to explain up to 37% of the variance of peak plantar pressure; although not very high, this is the strongest individual factor related to plantar pressure variables that has been reported to date. The use of the Planscan might prove to be a useful alternative tool to study and follow up the diabetic patients who are at risk of foot ulceration; however, this needs to be confirmed by prospective analysis of the patients involved in this study. Once a patient is found to have reduced plantar tissue thickness, then methods to increase tissue thickness or other methods of foot protection can be applied (19).

Acknowledgments— This study was funded by a grant from the National Health Service Executive North West/Research and Development Directorate.

We thank Dr. Ric Betts for his valuable comments about the Planscan. The Planscan can be ordered from the department of medical physics and clinical engineering, Royal Hallamshire Hospital, Sheffield, U.K.

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