Dynamic Foot Pressure and Other Studies as Diagnostic and Management Aids in Diabetic Neuropathy

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The pressures and loads under the feet during walking have been compared in three groups of 41 patients each, using a microprocessor-controlled optical system. Group A consisted of patients with diabetic neuropathy, group B of non-neuropathic diabetic patients, and group C of nondiabetic controls. Thirteen patients in group A had a history of neuropathic foot ulceration. Other investigations in the diabetic patients included motor conduction velocity (MCV) in the median and peroneal nerves, vibration perception threshold (VPT) in the great toes, the valsalva response (VR), skin resistance (SR), and the ankle pressure index (API). Fifty-one percent of neuropathic feet had abnormally high pressures underneath the metatarsal heads compared with 17% of the diabetic controls and 7% of nondiabetic subjects. All those feet with previous ulceration had abnormally high pressures at the ulcer sites. Of the other investigations, the VPT correlated most significantly with the presence of foot ulceration. In addition, a low median and peroneal nerve MCV, an abnormal VR, a high API, and the absence of sweating all correlated with the presence of foot ulceration. We therefore conclude that simple bedside investigations, such as measurement of the VPT alone, may be useful in identifying those patients at risk of foot ulceration. Foot pressure studies may then be used in such patients as a predictive and management aid by determining specific areas under the foot that are prone to ulceration.
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The long-term effects of peripheral diabetic neuropathy are thought to lead to a characteristic posture of the foot, which in turn may predispose to neuropathic ulceration.[1] Previous workers have assumed that increased pressure on the metatarsal heads during walking is an important etiologic factor for the foot ulcer,[2,3] but until recently it has not been possible to quantitate pressures underneath the foot.[4,5] The expense, both to the patients and the community, of hospital treatment for this common complication is well documented.[6] Thus, early recognition of those patients at risk of neuropathic foot ulceration is of great importance.

The recent development of an optical system, originally proposed by Chodera for static foot pressure measurement,[7] has been gaining favor as a technique for measuring pressures under the foot during walking.[8–10] This system has been successfully used in the study of a number of foot deformities, and postoperative symptomatic improvement has been equated scientifically with alterations in the pressure distribution.[11]

We chose to study dynamic foot pressures, using such a foot pressure system, in a group of patients with established diabetic neuropathy, including some with a history of foot ulceration. The results have been compared with those of matched non-neuropathic diabetic and nondiabetic control patients. Furthermore, the presence of ulcers or abnormal pressure/time curves has been correlated with other conventional investigations to determine which might be most useful in predicting feet at risk of ulceration.

PATIENTS AND METHODS

Patients

Eighty-two diabetic and 41 nondiabetic subjects took part in this study, which was approved by the hospital ethical committee. The subjects were divided into three groups.

Group A consisted of 41 diabetic patients with neuropathy. All subjects in this group satisfied the following strict criteria for selection, as assessed independently by two investigators: (1) painful symptoms in both legs (paresthesia, burning pains, cramps with symptoms more pronounced nocturnally) for at

TABLE 1
Clinical details of subjects*

Group	Number (male : female)	Mean age (yr)	Mean duration of diabetes (yr)	Mean duration of neuropathy (yr)	Mean weight (kg)
A (diabetic neuropathy)	41	52.3	12.9	4.2	74
	(29:12)	(27–69)	(2–39)	(1–13)	(47–101)
A_1 (neuropathy + ulcers)	13	57.4	15.2	6.3	79
	(10:3)	(30–69)	(3–39)	(2–13)	(69–101)
A_2 (neuropathy, no ulcers)	28	49.9	11.9	3.3	71
	(19:9)	(27–68)	(2–33)	(1.8)	(47–91)
B (diabetic control subjects)	41	52.2	12.4	—	70
	(29:12)	(24–69)	(1–38)		(47–87)
C (nondiabetic subjects)	41	51.2	—	—	70
	(29:12)	(24–71)			(45–138)

*Ranges are included in parentheses under each mean.

least 1 yr before the study, or a past history of such symptoms together with a history of neuropathic foot ulcers; (2) absent ankle jerks; and (3) no history of intermittent claudication: foot pulses palpable bilaterally. Thirteen subjects (group A_1) within group A had a history of neuropathic foot ulceration involving 22 feet. The remaining 28 subjects (group A_2) had no such history of foot ulceration.

Group B consisted of 41 diabetic subjects, who were matched for age, sex, duration, and type of diabetes. None of these patients had a history of neuropathic symptoms, peripheral vascular disease, or foot ulceration, and on examination no subject had impaired pain sensation in the peripheries. Furthermore, all those under 60 yr of age had normal ankle jerks on neurologic examination. There were 20 insulin-dependent diabetic patients (IDDM) and 21 non-insulin-dependent subjects (NIDDM) in each of groups A and B.

Group C consisted of healthy nondiabetic subjects matched for age and sex. No subject in this group had glycosuria or a family history of diabetes.

Full clinical details of the subjects are provided in Table 1.

Methods

The measurement of the distribution of pressure under the foot during standing and walking uses an optical method that has been described elsewhere.[8–11] Basically, the apparatus consists of a glass plate illuminated at two opposing edges by strip lights and covered by a thin film of soft white plastic across which the subject walks. The light rays are totally internally reflected within the glass plate, except at points where the plastic touches the glass. At these points the light rays are refracted out of the glass plate and are scattered back from the plastic film. On the microscopic scale the plastic surface is undulating in structure, and increasing pressure applied to the plastic causes these undulations to be deformed into intimate contact with the glass plate. Thus, the greater the applied pressure at a given point, the more light escapes from the glass at that point. The result is a continuous gray scale image of the sole of the foot where intensity is related to applied pressure. The image is detected by a monochrome television camera via a mirror. The subject may either stand on the plate to produce a standing pressure profile or may walk across the plate to produce a dynamic foot pressure image.

As the subject walks along a suitable walkpath, the time when the foot strikes and leaves the pressure plate is automatically detected. Every alternate frame from the television camera signal during foot/plate contact is captured by a microprocessor, digitized to 64 pressure levels, stored in the microcomputer memory, and continuously displayed on a color television monitor as a matrix of 128 × 128 pixels with 16 color levels.

The frames are superimposed on each other to form a composite foot pressure image on which areas of interest may be defined by use of a simple joystick control. The usual areas of interest are the heel, the five metatarsal heads, the great toe, and the other toes. The peak pressure/time curve for each area of interest is automatically calculated and these are then displayed on the monitor under the composite image in color-coded form. By integration of the image intensity the total load/time curve is also produced. The raw and analyzed data are recorded on a floppy disc system and plotted on a suitable printer for patient records. Previous work[10–12] on normal subjects has indicated that a reasonable threshold level for differentiating between normal and abnormal peak pressure results is 11 kg/cm^2.

Foot pressure analyses were performed on 81 feet within group A. One foot that had required a previous midtarsal amputation was not studied. Eighty-one feet were studied in group B; one was excluded because of the presence of hallux valgus, which has been shown previously to affect foot pressure studies.[11] Eighty-two feet were studied in group C.

Conventional Investigations

The following investigations were performed in all diabetic patients, after a period of rest in a warm room (23–25°C).

Vibration perception threshold (*VPT*). Vibration perception threshold was measured in each great toe using a biothesiometer (Biomedical Instrument Co., Newbury, Ohio) and the result was taken as the mean of three readings recorded at variable speeds of voltage increase.[13,14] The final VPT parameter for each patient was taken as the mean of the results from each toe. The results of VPT vary from 1 to 50: those patients who were unable to perceive any vibration sensation were assigned a score of 51 (↑ in Figure 4).

Valsalva response (VR). The valsalva response was recorded in the supine subject as described by Ewing et al.[15] A resting heart rate was measured from the electrocardiogram, after which a recording was made during 15 s of forced expiration into a sphygmomanometer sufficient to maintain the column of mercury at 40 mm Hg. The recording then continued for 30 s of complete relaxation. The VR was calculated as being:

$$\frac{\text{the longest RR interval during the relaxation period}}{\text{the shortest RR interval during forced expiration}}$$

The overall results for each patient were taken as the mean of three separate readings.

Skin resistance (SR). The presence or absence of sweating in the feet was determined using a skin resistance meter that employed a constant current source of 4 μA and a balanced potentiometer.[16] Similar methods have previously been used to study the activity of the peripheral sympathetic nervous system in diabetic individuals.[17,18] Paired electrodes were applied to the plantar surfaces of the feet with the subject at rest and a recording made. After a measurement at rest, the responsiveness of the sympathetic nervous system was tested during hyperventilation, which normally causes a fall in the SR.[17] Sweating was regarded as absent in our subjects if there was a high basal SR with no response to hyperventilation.

Motor conduction velocities (MCV). Nerve conduction velocities in the right median and peroneal nerves were estimated using a Medelec DF06 (Medelec Ltd., Woking, Surrey, England) electrophysiologic system. Recordings were made using surface electrodes over the abductor pollicis brevis and extensor digitorum brevis muscles, respectively, as previously described by Ward et al.[19] Seven patients in group A had unrecordable peroneal MCVs. They were assigned a result 1 m/s lower than the slowest MCV in this group for the purposes of statistical analysis (↓ in Figure 4).

Ankle pressure index (API). The ankle pressure index was measured using a Doppler ultrasound stethoscope. A sphygmomanometer cuff was placed just above the ankle and the systolic pressure was determined in the posterior tibial artery.

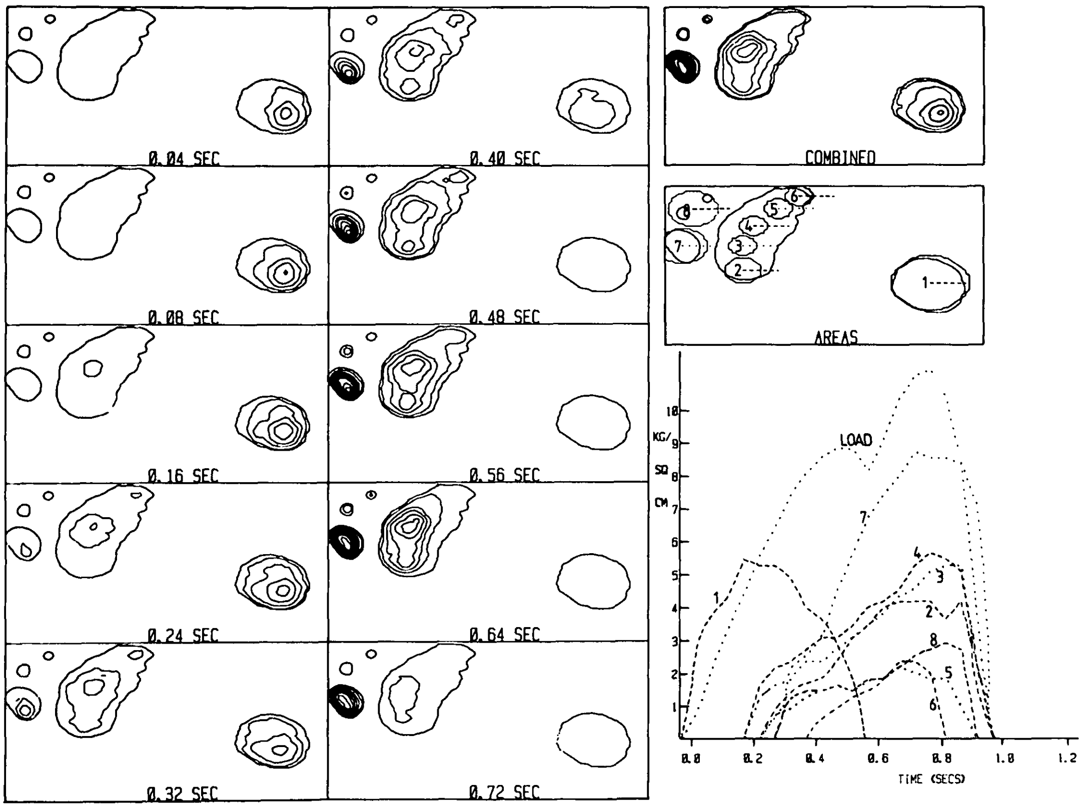

FIG. 1. The color plotter output (in black only) for a subject from group B (a diabetic patient with no neuropathy or peripheral vascular disease) showing a normal dynamic foot pressure pattern.

Similarly, the brachial systolic pressure was determined in the arm and the API was calculated according to the ratio:[20]

$$\text{API} = \frac{\text{posterior tibial artery pressure}}{\text{brachial artery pressure}}$$

The weight of all subjects was recorded at the time of study.

Statistical Methods

Mann-Whitney U and chi-squared tests were used for intergroup comparison. The results in all the tables are given as means together with standard deviations and/or ranges as indicated.

RESULTS

Figures 1, 2, and 3 show typical plotter outputs for dynamic studies. On the left are 10 sample frames from the total number recorded, where the footprint is shown with isopressure contour lines for each of the frames. On the right is shown the composite image, the areas of interest, and the peak pressure/time curves for the selected areas of interest. The isopressure contour lines, the areas of interest, and the peak pressure (load)/time graphs are normally produced in color-coded form, but for the purposes of photographic illustrations Figures 1, 2, and 3 are shown in black only and the graphs have been numbered by hand.

The results of the foot-pressure analyses are shown in Table 2. Those subjects with a history of foot ulceration had neuropathy for significantly longer periods and also were significantly heavier than those diabetic patients without ulceration ($P < 0.01$ in both cases, Table 1). In addition, all these subjects had abnormally high pressures (> 11 kg/cm^2) at the site of previous ulcers, compared with only 31% of feet with no evidence of ulceration (Table 2). Some normal nondiabetic subjects (7% of feet) did show transient high pressures, though the results in this article are only expressed in terms of maximum pressures and no temporal information is given. Table 3 contains the means and ranges of all the conventional investigations that are also represented graphically in Figure 4. There were significant differences in all these investigations between the neuropathic and non-neuropathic diabetic patients (Table 3). Furthermore, when those subjects with neuropathic ulceration (group A_1) were studied separately, there were highly significant differences in all investigations when compared with the other diabetic subjects. The VPT was the most discriminative test ($z = 5.0$, $P < 0.0001$), and further statistical analysis using this investigation showed that a VPT of greater than 35 was significantly associated with the presence of neuropathic ulceration ($\chi^2 = 11.29$,

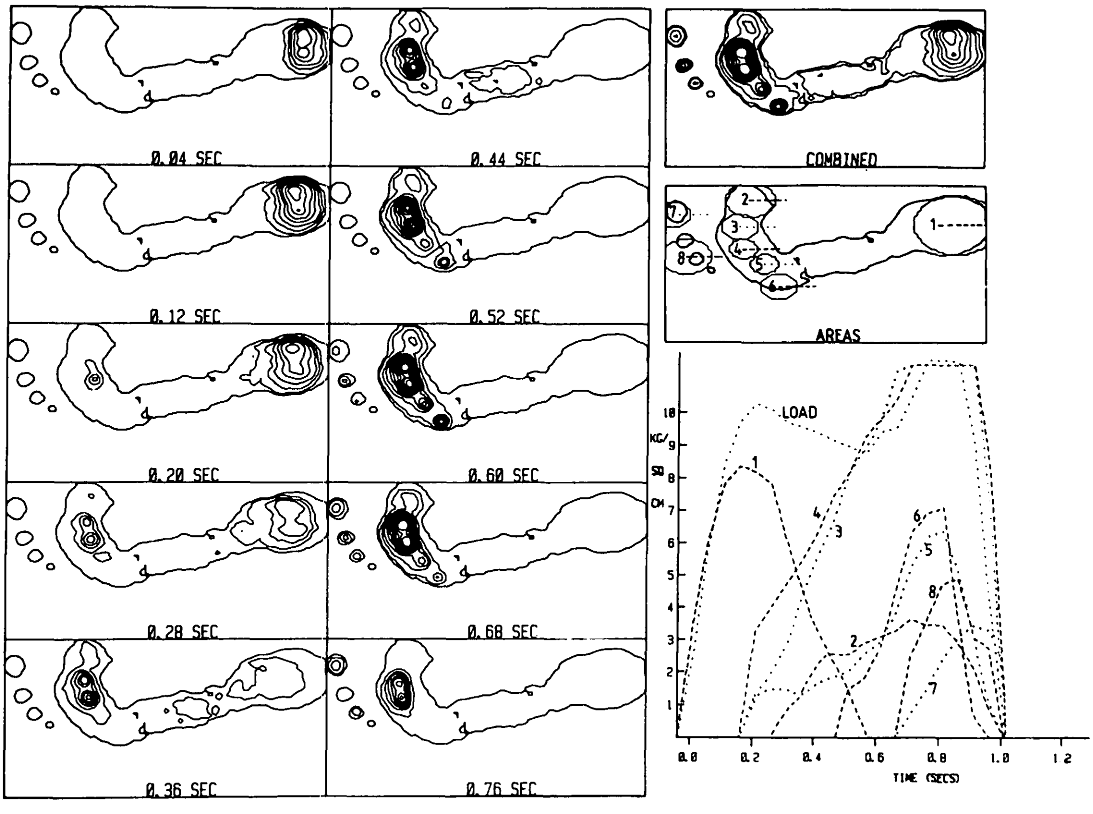

FIG. 2. The color plotter output (in black only) for a subject from group A_2 (a diabetic patient with a history of neuropathic symptoms but no ulceration) showing abnormally high pressures under the second and third metatarsal heads.

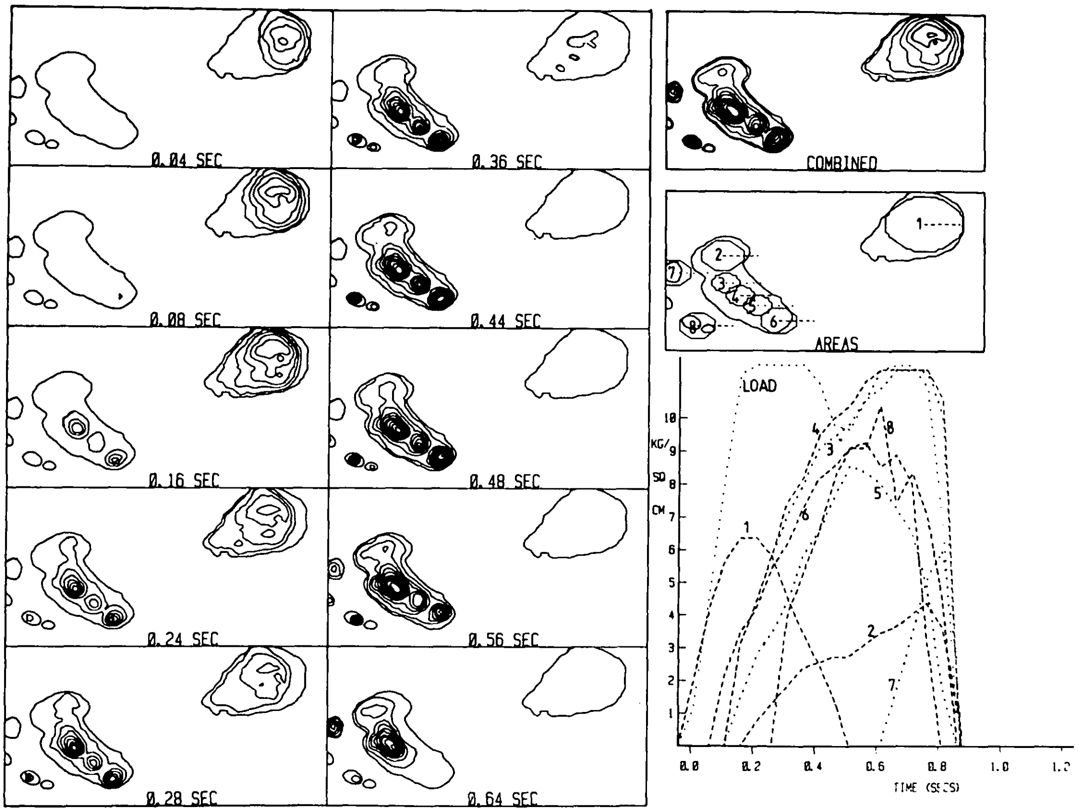

FIG. 3. *The color plotter output (in black only) for a subject from group A_1 (a diabetic patient with a history of neuropathic foot ulceration) showing abnormally high pressures under the metatarsal heads, which had been the sites of previous ulcers.*

P < 0.001). The usefulness of all these tests as predictive factors for foot ulceration is visually represented in Figure 4.

DISCUSSION

This study confirms the assumptions made by other workers in this field,[1,2] by demonstrating the association between high pressure loading and foot ulceration in every case studied. Although it was not possible to study feet with active ulceration, our results show that the abnormal loading under the metatarsal heads persists in every patient after the lesion has healed, which may explain why recurrent ulceration is frequently encountered. The long-term effects of peripheral neuropathy, with loss of pain sensation and proprioception and weakness of the intrinsic muscles of the foot, have been said to alter the weight distribution under the foot,[1,21] leading to increased loading under the metatarsal heads. Thus, the results of this study support this theory of pressure redistribution. Previous studies using a strain-gauge technique[4,5] have demonstrated similar results with ulcers occurring at the sites of maximum force. However, these techniques are more time-consuming and of lower spatial resolution than the optical system described in this study.

The method of foot pressure measurement described in this article has been used extensively in orthopedic practice, including the study of conditions such as metatarsal pain associated with hallux valgus and hallux rigidus. Isopressure contour plots may be obtained from the microprocessor-controlled printer and included in the clinical records. Changes in the pressure distribution can be clearly demonstrated by the comparison of measurements taken before and after operative correction of deformities or by the comparison of results taken repetitively over several months or years. We have now shown this system to be of clinical application to diabetic patients with neuropathy since isopressure contour plots can be obtained from both feet within a few minutes and the records filed in the patient's notes. Any "at risk" high pressure areas are immediately apparent to both the

TABLE 2
Results of dynamic foot pressure studies showing the percentages of feet with abnormally high pressures (>11 kg/cm^2) for the groups studied

Subjects	No. of feet	% Abnormal
Diabetic subjects with neuropathy and a history of foot ulceration	22	100
Diabetic subjects with neuropathy but no history of foot ulceration	59	31
Diabetic subjects with no neuropathy	81	17
Nondiabetic control subjects	82	7

TABLE 3
Results of the conventional investigations of the diabetic subjects

Group	VPT	MCV peroneal (m/s)	MCV median (m/s)	API	VR	SR % absent sweating
A						
Mean ± 1 SD	35 ± 12	31.6 ± 6.2	44.0 ± 4.8	1.30 ± 0.27	1.21 ± 0.25	
Range	12–51	20–41	33–56	1.0–2.3	0.96–2.11	71
P value*	< 0.0001	< 0.0001	< 0.0001	< 0.01	< 0.0001	
A_1						
Mean ± 1 SD	45 ± 8	27.5 ± 6.9	42.3 ± 4.9	1.44 ± 0.41	1.04 ± 0.06	
Range	28–51	20–37	35–53	1.0–2.3	0.96–1.15	100
P value†	< 0.0001	< 0.0001	< 0.01	< 0.05	< 0.0001	
A_2						
Mean ± 1 SD	30 ± 11	33.5 ± 4.7	44.8 ± 4.6	1.24 ± 0.13	1.28 ± 0.27	57
Range	12–51	20–41	33–56	1.1–1.6	1.00–2.11	
B						
Mean ± 1 SD	14 ± 6	42.7 ± 4.2	48.7 ± 3.8	1.18 ± 0.16	1.50 ± 0.37	39
Range	5–30	37–57	42–56	0.9–1.9	1.00–2.51	

*P values for group A compared with group B.
†P values for group A_1 compared with groups A_2 and B combined.

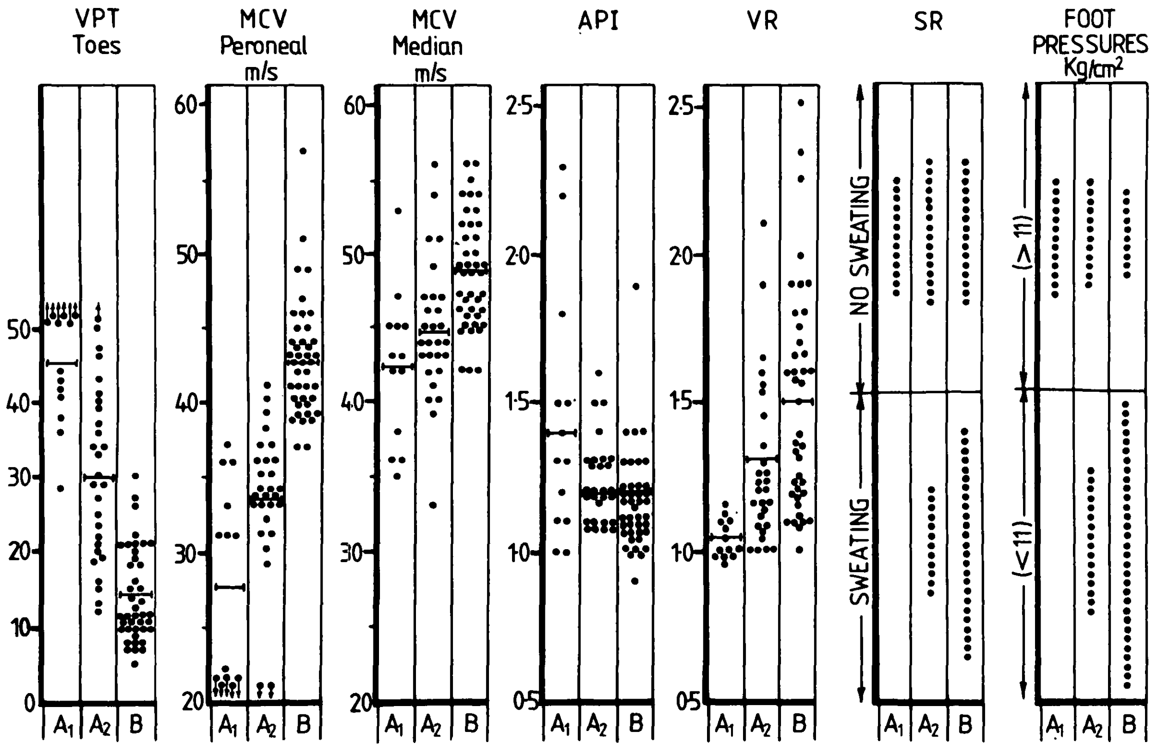

FIG. 4. Scatter diagrams showing the results of the investigations carried out on the three groups of diabetic patients (A_1, A_2, and B). The mean values for each column are indicated by a bar; the more comprehensive statistical results are shown in Table 3.

physician and the patient, and such plots may be used as visual educational aids.

There has been much interest in specialist footwear design for patients with sensorimotor neuropathy of diverse etiologies,[6,22,23] and it is current practice to provide specialist footwear for patients with neuropathic foot ulcers. The pressure distribution is currently assessed using semiquantitative methods as described by Reed, and with these results, footwear or molded insoles are designed to distribute the pressure of weight bearing evenly over the sole.[24] The application of the optical system to footwear and insole design is currently under investigation. This system should be of practical use since it provides accurate quantitative pressure plots for both feet, during walking and standing.

We chose to compare several investigations previously studied in neuropathic subjects to see which might be most useful as a predictor of those at risk of foot ulceration. Other studies have associated the absence of pain sensation and muscle weakness with diabetic foot ulcers.[1,25] Although all subjects in group A_1 had such clinical findings, these are subjective observations and are not therefore included in our results. It has previously been noted that vibration perception is usually impaired in patients with neuropathic foot ulceration,[3] and biothesiometry is a useful quantitative test of VPT.[13,14] This proved to be the most discriminative of our conventional investigations, and the results show this measurement to be associated with foot ulceration and the presence of abnormally high, localized pressure areas under the foot. Thus, this simple test, easily performed within a few minutes at the bedside, is most useful in the identification of those feet at risk of ulceration.

There have been many studies of MCVs in diabetic neuropathy,[26] and although of doubtful significance because of small numbers, Harrison and Faris demonstrated that lower MCVs were found in ulcer patients, especially in the peroneal nerve.[25] We were unable to calculate the MCV in 5 of the 13 ulcer patients, although there was a significant association between low MCV and the presence of abnormally high pressure areas or ulcers.

Both the VR and SR are tests of autonomic function that have previously been shown to be significantly associated with foot ulceration.[18] In our study, sweating was absent in all feet with ulceration, although this test and the VR were not as discriminative as the VPT. The API is a simple, noninvasive technique that can easily be performed in the clinic within a few minutes. In the nondiabetic subject it is an objective indicator of obstructive arterial disease,[27] but in the diabetic patients special problems in the interpretation of the API have been recognized as the result of medial calcinosis.[28,29] Edmonds et al. recently showed a strong association between medial arterial calcification and neuropathy,[30] although previous reports have not supported this view.[31] The correlation demonstrated in our study between the raised API and neuropathy would be compatible with arterial stiffness or calcification.[30]

We conclude that these simple, noninvasive tests may be used to identify patients at risk of ulceration. Such subjects could then be studied using the optical foot pressure measurement technique to identify specific areas under the foot that might be prone to ulceration. This technique may then prove invaluable in the long-term management of these feet.

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