Effects of Compression and Type of Bed Surface on the Microcirculation of the Heel

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Objective: To assess the effects of compression on the skin microcirculation of the heel using laser Doppler fluxmetry.

Design: Parallel groups comparing patients with control groups.

Setting: Department of Surgery, University College London Medical School, London.

Subjects and Materials: Ten patients at risk of developing pressure ulceration, 10 age- and sex-matched healthy subjects and 10 young, healthy volunteers. An acrylic indenter with a slot to accommodate a laser Doppler probe was used to apply compression to the heel region. A pressure sensor was used to measure the applied compression.

Outcome measures: The resting laser Doppler flux was measured with the subject lying supine. Compression forces were then applied in increments from 50g to 1500g and the corresponding interface pressure (IP) and laser Doppler flux (LDF) recorded. The IP and LDF were also measured from the heel while the subject was lying on a low air-loss system and then on an NHS conventional hospital bed.

Results: The resting LDF is lower in the patient group compared to the control groups (p < 0.05). Compression of the heel caused a progressive decrease in LDF in all groups. Compression greater than 30 mmHg as well as lying on an NHS bed reduced the LDF signal to a minimal value (biological zero). On the low air-loss system, the median LDF was 17% of the resting value in the age-matched control group and 32% in the patient group.

Conclusions: The results indicate that the heel microcirculation is vulnerable to compression. The low air-loss system maintained the IP sufficiently low to prevent complete cessation of the heel microcirculation.

Key Words: Microcirculation; Laser Doppler fluxmetry; Low air-loss system; Pressure ulcer of the heel.

Introduction

The effects of externally applied forces on soft tissues are complex and depend, amongst other factors, on the magnitude of the force, the duration of its application and the anatomical area to which the force is applied. Cattell reviewed the studies which investigated the effect of externally applied pressure on unicellular organisms and concluded that enormous pressure was required before signs of disruption of the cellular functions were noticed. The damaging effects of pressure in higher animals and in humans must, therefore, be related to interference with the circulatory function and the characteristics of extracellular tissues. In other words, "the death of the cells is a biological death from deprivation, rather than a mechanical death from disruption". Measurement of the microcirculatory blood flow to localised tissue areas is an essential part of the assessment of tissue viability.

In the clinical context, pressure-related tissue breakdown is commonly seen in certain susceptible anatomical areas resulting in pressure ulcers. The heel is a common site for the development of pressure ulceration. Such susceptibility may be due to the lack of soft tissue padding over the bony prominence of the heel.

The purpose of this study was to determine which levels of compression reduce the perfusion of the heel to the point where ischaemia and tissue necrosis may ensue. A specially designed laser Doppler fibre-optic system was employed to measure blood flow beneath the region of compression.

Laser Doppler Fluxmetry (LDF) is a non-invasive technique which has been widely used for assessment of the skin blood flow in various clinical conditions. We have recently used this technique to assess the effect of compression of the supramalleolar region on the skin microcirculation in patients with chronic venous insufficiency. We found that low levels of...
Table 1. Pressure ulcer risk assessment tool (Norton Scale)

<table>
<thead>
<tr>
<th>Score</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical condition</td>
<td>Good</td>
<td>Fair</td>
<td>Poor</td>
<td>Very poor</td>
</tr>
<tr>
<td>Mental state</td>
<td>Alert</td>
<td>Apathetic</td>
<td>Confused</td>
<td>Stupor</td>
</tr>
<tr>
<td>Activity</td>
<td>Ambulant</td>
<td>Walks with help</td>
<td>Chair-bound</td>
<td>Bed-fast</td>
</tr>
<tr>
<td>Mobility</td>
<td>Full</td>
<td>Slightly limited</td>
<td>Very limited</td>
<td>Immobile</td>
</tr>
<tr>
<td>Incontinence</td>
<td>Non</td>
<td>Occasionally</td>
<td>Usually</td>
<td>Doubly</td>
</tr>
</tbody>
</table>

Total score

compression, in the range normally exerted by compression stockings, increased laser Doppler flux and blood cell velocity. The effect of compression on the skin microcirculation of the heel, which is known to be at high risk of developing pressure ulceration, has not been studied.

Laser Doppler fluxmetry relies on the Doppler principle. When laser light is applied to the skin, photons reflected by moving blood cells undergo a frequency shift, whereas photons scattered in stationary tissues remain unshifted. The amount of laser light reflected back from the skin with altered frequency (Doppler-shifted light) is proportional to the volume or concentration of moving blood cells in the tissues. The mean frequency shift in the laser light is proportional to the average speed of moving blood cells or blood cell velocity. The LDF value, that is proportional to total skin blood flow in the target tissue volume, is the product of these two parameters.5

Patients and Methods

In total 30 subjects were studied. Ten old patients at risk of decubitus ulceration (3 men, 7 women), median age 64 years (interquartile range [IQR]: 54–76), these were patients at risk of decubitus ulceration and were defined as those with a score of 14 or less, according to the Norton scale (Table 1). Norton scale assesses five characteristics relating to the patient’s clinical condition: the physical condition; mental state; activity; mobility; and incontinence; each of these variables is graded from 1 to 4. The total score is the added values for the five components scored for the patient. The highest score “20” indicating the least risk, whereas the lowest score “5” indicating the highest risk. A score of 14 or less indicates susceptibility to pressure ulceration. Four of the patients have rheumatoid arthritis, two were being treated with steroids. No attempt was made to exclude the possibility of small vessel disease in these rheumatoid patients. None of the patients had open heel ulcers. The control group comprised ten sex- and age-matched, healthy volunteers, (3 men, 7 women), median age 67 years (IQR: 65–71); these were patients attending the Middlesex Hospital for treatment of minor conditions unrelated to the lower limbs. They had no symptoms or clinical evidence of lower limb vascular or other disease, and with normal mobility and conscious state. We also studied ten young, healthy volunteers: (6 men, 4 women), median age 32 years (IQR: 30–36); these were solicited from members of staff of the Department of Surgery. All subjects studied had normal ankle/brachial pressure indices (> 0.9). Patients with diabetes were excluded from the study. Informed written consent was obtained from each subject and the study was approved by the local ethics committee.

The laser Doppler measurements were made using a Perimed PF 2B laser Doppler flowmeter and a low profile laser Doppler probe (Perimed, Stockholm, Sweden). Calibration was performed using Periflux Motility Standard PF100 Solution. The measurements were made from the most prominent part of the back of the heel with the foot in a neutral position to maintain uniformity of the method throughout the study.

The tissue loading “pressure” device (Fig. 1)

For the purpose of this study we designed a special device for compression of the heel. It consisted of a stand and a pivoted arm mounted on the stand. This horizontal arm could be adjusted up and down as well as sideways. A standard 5 cm diameter pressure-applying acrylic indenter with a slot to accommodate a low profile laser Doppler probe was used to apply forces of 50–1500g to the heel region. A cantilever mechanism was used with a central pivot, so that the force could be applied to the opposite end of the arm to which the pressure indenter is attached.
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**Fig. 1.** Experimental system for compression of the heel. An acrylic indenter with a slot to accommodate a low profile laser Doppler probe is used to compress the heel. The laser Doppler fluxmeter is logged to a computer for data recording. The compression applied to the skin of the heel is measured by an interface pressure sensor.

**Interface pressure measurement**

The pressure applied to the skin of the heel (interface pressure) was measured by an interface pressure sensor (Talley Group Ltd, Romsey, Hants, U.K.). We have previously described in more detail the use of this device for interface pressure measurements. The study was carried out in an environment-controlled chamber set at a temperature of 22°C and 30 per cent relative humidity.

**Study protocol**

With the subject lying in the supine position, and following an acclimatisation period of 20 minutes, the tissue loading device described above was used to apply forces to the posterior aspect of the heel of the study limb. The weights used to apply forces were: 50, 100, 200, 400, 600, 800, 1000, 1250 and 1500g. The interface pressure and LDF corresponding to each force applied were measured using the interface pressure transducer and the laser Doppler fluxmeter, respectively. Thus, the relationship between applied force and the IP and LDF were established.

With the subject lying on a conventional NHS hospital bed (King’s Fund bed) with a standard mattress, the interface pressure and LDF over the region of the heel in contact with the bed were measured using the same IP sensor and laser Doppler probe. Finally, the subject lay on a low air-loss system known as Frameless Air Support Therapy (F.A.S.T.™) system (Cardio Systems Inc, Carrollton, Texas, U.S.A. and Humanetics Medical Ltd, Slough, U.K.). This low air-loss design incorporates a system (Micro-Adjust Pressure Profiling, MAPPT™) allowing the precise control of individual sac pressure to very low levels approaching zero mmHg. With the system chamber pressure in the heel region adjusted to 5 mmHg, the interface pressure and LDF over the region of heel in contact with the support system were assessed by the same techniques as before. The chamber pressure in the heel region of the support system was then increased to 10 mmHg and measurements repeated. Finally inflation pressures of 20 and 30 mmHg were selected for further measurements.

**Analysis of data**

The data from this study were used (1) to compare the resting laser Doppler flux in patients at high risk of pressure ulceration to healthy control groups, (2) to assess the relationship between applied force and the resultant interface pressure on the skin of the heel in the three study groups, (3) to calculate and compare the effect of compression on laser Doppler flux in each group, (4) to compare the effects of heel compression by the conventional hospital bed and the low air-loss system on the interface pressure and laser Doppler flux in each of the study groups. Statistical analyses were made using Wilcoxon matched-pairs signed rank test for paired data (for within subjects’ differences) and Mann-Whitney U test for unpaired data (for between subjects’ differences); a confidence level of < 5% was regarded as significant. The 95% confidence intervals (95% CI) were computed by Wilcoxon’s method to demonstrate the magnitude of differences. The descriptors used were median and interquartile range. Because reliable calibration in absolute perfusion units (ml/100g/min) has not been established, LDF values were expressed in arbitrary units (AU).
Statistical computation was carried out using the Statistical Package for Social Sciences (SPSS Inc. Chicago, U.S.A.) and Confidence Interval Analysis (British Medical Journal, Tavistock Square, London, U.K.).

Results

Resting laser Doppler flux in the horizontal position (Fig. 2)

The resting LDF is lower in the patient group compared to the young control group (median difference 85 AU; 95% CI: 6, 169; *p = 0.04) and the age-matched control group (median difference 163 AU; 95% CI: 13, 275; *p = 0.03). There was no significant difference in resting LDF between the young and old control groups (*p = 0.36).

The relationship between applied force and interface pressure

The relationship between interface pressure and LDF (Fig. 3)

Very low levels of compression (up to 5 mmHg interface pressure) caused no significant change in LDF in any of the three study groups (*p > 0.05). Higher levels of compression caused a progressive decrease in LDF in all groups. Compression of 50 mmHg or greater reduced the LDF signal to a minimal value (biological zero) in all the three study groups.

The effects of heel compression by the NHS conventional hospital bed and low air-loss system (Table 2)

When lying on an NHS bed, there is no significant difference in the IP between the three study groups (*p > 0.05). The LDF signal was reduced to a minimal value (biological zero) in all three study groups (5 to 7% of the resting LDF values).

When lying on the low air-loss system, there is no significant difference in the IP between the three study groups (*p > 0.05). The median LDF was 21% (young controls), 17% (old controls) and 32% (patient group) of the corresponding resting LDF values. Using low air-loss system chamber inflation pressures of 10 mmHg or higher resulted in interface pressures greater than 50 mmHg and reduced the LDF signal to...
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Figure 3. Relationship between interface pressure (mmHg) and laser Doppler flux (LDF) in arbitrary units (AU).

minimal values (biological zero) in all the three groups.

Figure 4 shows that the IP is significantly lower on lying on the low air-loss system (chamber inflation pressure 5 mmHg) compared to lying on an NHS bed in each of the three study groups. By contrast, Fig. 5 shows that the corresponding LDF values are significantly higher with the low air-loss system compared to the NHS bed.

Discussion

The use of laser Doppler fluxmetry for measuring blood flow was developed by Riva et al. in 1972. The system has since been improved and used widely in the investigation of the microcirculation. The depth of sensitivity of the laser Doppler probe depends on the geometry of the probe and the characteristics of the tissue being studied. It has, however, been estimated to be maximal at 0.6 mm; beyond that, the signal decreases exponentially with the distance from the probe. Although laser Doppler fluxmetry measures the nutritional flow in the papillary capillary loops as well as the subpapillary (thermoregulatory) shunt flow, its findings are broadly comparable to those of capillary microscopy. Tooke et al. compared the two methods and showed that the findings of the two techniques followed a similar trend – although the magnitude of change was different. Laser Doppler fluxmetry overcomes many of the problems associated with other methods for measuring microcirculatory blood flow. However, the technique has its own limitations which must be appreciated. Concern has been expressed regarding

Table 2. The effects of lying on an NHS conventional hospital bed and on the low air-loss system (heel chamber inflation pressure of 5 mmHg) on interface pressure and LDF in the three study groups

<table>
<thead>
<tr>
<th></th>
<th>Resting</th>
<th>NHS bed</th>
<th>Low air-loss system</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>LDF AU</td>
<td>LDF (%)</td>
<td>LDF (%)</td>
</tr>
<tr>
<td></td>
<td>IP (mmHg)</td>
<td>LDF (AU)</td>
<td>IP (mmHg)</td>
</tr>
<tr>
<td>Young group: M (IQR)</td>
<td>229</td>
<td>79 (59-109)</td>
<td>14 (12-17)*</td>
</tr>
<tr>
<td>Old controls: M (IQR)</td>
<td>271</td>
<td>76 (61-109)</td>
<td>15 (10-18)**</td>
</tr>
<tr>
<td>Old patients: M (IQR)</td>
<td>124</td>
<td>64 (53-89)</td>
<td>10 (5-23)**</td>
</tr>
</tbody>
</table>

AU = arbitrary units; IP, interface pressure; M (IQR) = median (interquartile range); LDF (%) = per cent of corresponding resting value; *p = 0.01, **p = 0.01, ***p = 0.02 (Mann-Whitney)
the reproducibility of the technique. It is, however, generally agreed that its reproducibility is good in a given population, but not in individual subjects.\textsuperscript{16} Significant errors are avoided when relative changes (or comparisons between groups) rather than absolute laser Doppler values are considered. It remains useful for detecting changes in blood flow after some form of stimulus such as compression, postural change, heating and post-occlusion hyperaemia. The recently introduced laser Doppler perfusion imager has, in theory, better spatial resolution as it scans a wider area. However, in a recently published study, a significant linear correlation was found between these two laser Doppler techniques.\textsuperscript{17}

Our results showed that the resting laser Doppler flux is lower in the old patient group compared to a
sex- and age-matched healthy control group and to a young healthy group. This finding was not unexpected; it may be one of the mechanisms by which such patients with poor pressure ulcer risk assessment score are susceptible to ulceration of the heel. It is interesting that the resting LDF was similar in the young and old healthy groups; this may indicate that age per se does not influence the resting LDF.

Figure 3 shows a sudden drop in LDF occurring at an interface pressure of 30 to 40 mmHg in all the three groups. At an interface pressure of 50 mmHg, the LDF signal was reduced to a minimal value. This level of compression is likely to have caused capillary occlusion and complete cessation of blood flow as higher levels of compression caused no further significant alteration in the laser Doppler signal. This signal level may represent "biological zero" which is attributable to Brownian motion of red cells and other structures in the tissues.

It was not surprising to find that the same force applied to the heel of subjects from different groups resulted in similar interface pressures. The pressures observed indicate that the force was absorbed over a small area of the heel, e.g. at 500g an interface pressure of 40 mmHg was recorded, suggesting an interface area of 28 mm in diameter. This small contact area indicates why the heel, with its small radius of curvature and little subcutaneous tissue is at such high risk of pressure ulceration. The weight of each lower limb is approximately one sixth of total body weight, so even if a small proportion of this rests on the horizontal position. The results of the present study showed that an interface pressure of the same magnitude applied to the heel region resulted in a substantial reduction of microcirculatory blood flow as measured by laser Doppler fluxmetry. This may be part of the explanation of the development of pressure ulceration of the heel in these patients.

The results showed clearly that with a conventional NHS bed very high interface pressures were observed in all the three study groups. The corresponding LDF was reduced to a minimal value (biological zero). Patients at high risk of pressure ulceration are likely to develop pressure ulcers of the heel while lying on an NHS conventional hospital bed. In our study, using the low air-loss system, with the heel chamber inflated to 5 mmHg, resulted in substantially lower interface pressures; the IP was maintained sufficiently low to prevent complete cessation of the heel microcirculation. This however was achieved only by using 5 mmHg chamber inflation pressure; inflating the heel chamber to 10 mmHg or higher resulted in much greater interface pressure and the corresponding LDF was severely reduced.

On the basis of these results we recommend that the interface pressure under the heel should be maintained as low as possible. For the low air-loss system we used in our study, the heel chamber inflation pressure should not exceed 5 mmHg, corresponding to a maximum interface pressure of 30 mmHg.

References


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