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Research Paper

The physiological response of skin tissues to alternating support pressures in able-bodied subjects

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ABSTRACT

Prolonged mechanical loading can lead to breakdown of skin and underlying tissues which can, in turn, develop into a pressure ulcer. The benefits of pressure relief and/or redistribution to minimise risk have been well documented and these strategies can be provided by employing support mattresses in which internal air pressures can be alternated to minimise the risk of pressure ulcers in patients during prolonged periods of bed-rest. The paper describes the performance of a prototype alternating pressure air mattress (APAM), in terms of its ability to maintain skin viability in a group of healthy volunteers lying in a supine position. In particular, the mattress includes a sacral section supported with alternating low pressure (ALP), with values adjusted to subject morphology, using an in-built pressure sensor. The mattress was supported at four different head of bed (HOB) angles ranging from 0 to 60°. Internal mattress pressures and transcutaneous gas (T_cPO_2/T_cPCO_2) tensions at the sacrum and a control site, the scapula, were monitored. Interface pressures were also measured. The sensor was found to be sensitive to the BMI values of the 12 healthy volunteers. In the majority of test conditions the internal support produced sacral T_cPO_2 values, which either remained similar to those at the scapula or fluctuated at levels providing adequate viability. However in a few cases, associated with a raised HOB angle (≥45°), there was compromise to the skin viability at the sacrum, as reflected in depressed T_cPO_2 levels associated with an elevation of T_cPCO_2 levels above the normal range. In all cases, interface pressures at the sacrum rarely exceeded 60 mmHg. Although such studies need to be extended to involve bed-bound individuals, the results offer the potential for the development of intelligent APAM systems, whose characteristics can be adjusted to an individual morphology. Such preventive strategies to maintain skin viability at loaded sites will be designed for subjects deemed to be at high risk of developing pressure ulcers.

1. Introduction

Prolonged mechanical loading of skin and underlying tissues will lead to a reduction of supply of perfusion and vital nutrients to local cells, which affects tissue remodelling and can result in the development of pressure ulcers (Gawlitta et al., 2007). This condition, which has a significant impact on Quality of Life, particularly affects immobile and insensate individuals who are

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bed or chair-bound for much of their day. The benefits of some form of pressure relief and/or redistribution have been well established for many subject groups deemed to be at high risk of developing pressure ulcers. It can be provided by a number of management strategies ranging from regular turning of the patient, which is labour intensive, to active support surfaces including a number of commercial alternating pressure air mattresses (APAMs). The use of APAMs is based on the premise that such systems, which are used in both hospital and community settings, reduce the effects of prolonged load-induced ischaemia on soft tissues overlying bony prominences, such as the sacrum and heels. For financial reasons, they are generally reserved for use with subjects deemed to be at high risk of developing pressure ulcers.

A large cohort study indicated that fewer patients developed heel pressure ulcers on a commercial APAM compared to a control group supported on a viscoelastic foam mattress (Vanderwee et al., 2005). However, there have been relatively few scientific studies examining the effectiveness of APAMs in maintaining the health and/or viability of skin and underlying soft tissues. As a consequence, the design and manufacture of APAMs have been influenced by practical issues, such as characteristics of the incorporated pumps that provide air flow to the mattress, as opposed to considerations related to tissue viability. Of the few relevant studies, Rithalia and Gonsalkorale (2000) examined the effects of a 2-cell low-pressure profile APAM system on the skin response of healthy volunteers by measuring transcutaneous oxygen levels (T_cPO_2), which represents an objective parameter of local skin viability (Bader, 1990; Colin et al., 1996; Coggrave and Rose, 2003; Kim et al., 2012). They reported T_cPO_2 values at the sacrum to be similar to unloaded basal values, associated with interface pressures which were generally maintained below 30 mmHg. In addition, the transcutaneous carbon dioxide tensions (T_cPCO_2) were maintained in the normal range of 35—45 mmHg (4.7—6.0 kPa) throughout the mattress cycle (Bogie et al., 1995; Knight et al., 2001). In a separate study, the effects of pressure relief were evaluated by monitoring skin blood perfusion in the heel supported by an air cell of an experimental mattress (Mayrovitz and Sims, 2002). Their findings revealed that with healthy subjects the degree of pressure relief often determined the level of skin perfusion. The authors did suggest, however, that the impact of pressure relief may be critical in subjects with diminished hyperaemic reserve. A further study (Rithalia, 2004) determined the effects of pressure relief as provided by two commercial APAM systems, using both transcutaneous gas tensions and Laser Doppler Flowmetry. The author reported that during the deflation phase of the pressure profile, interface pressures at the heel were significantly lower on the APAM system despite the fact that the inflation pressure was significantly higher. Thus low alternating pressures are not necessarily associated with reduced interface pressures. Subsequently, Goossens and Rithalia (2007) investigated the performance of three APAMs for normal subjects with a range of Body Mass Index (BMI) values. Their findings indicate differences with respect to physiological responses, associated with gas tension recovery and tissue perfusion, but no statistical differences in maximum interface pressures between the three APAMs. In a recent study, it was suggested that the characteristic non-linear properties of blood flow oscillations in skin as measured by LDF may provide a useful index for assessing risk of pressure-induced damage (Liao et al., 2010). Indeed some decrease in these oscillations at the sacrum was detected in elderly subjects with well established vascular impairment. Jan et al. (2011) also examined sacral skin perfusion under alternating or constant pressures profiles in subjects with Spinal Cord Injury (SCI). Their results showed that the pressure profiles affected skin perfusion responses in weight-bearing tissues. In particular, there was an increase in skin perfusion with alternating pressures when compared with SCI subjects supported at constant support pressures. Additionally there was no overall difference in the skin perfusion responses of the SCI as compared with non-SCI subjects. This finding supports the concept of using alternating pressure technology to enhance perfusion and maintain skin viability and thus minimise the risk of developing pressure ulcers.

The present study examines the performance of a prototype mattress, incorporating an inbuilt force-sensitive sensor. This is achieved by assessing the interface conditions with volunteer subjects of various morphologies supported in a supine position on an articulated bed at a range of backrest angles. In particular, the study is designed to evaluate whether the prototype mattress can maintain skin viability, as determined by the well-established monitoring of transcutaneous gas tensions (T_cPO_2 and T_cPCO_2).

2. Material and methods

2.1. *Description of support mattress*

The prototype support mattress (PAM, Hill-Rom, Montpellier, France), hereafter referred to as the mattress, was divided into four sections. Three sections incorporated rows of air cells, two of which were at continuous low pressures (CP), supporting the lower limb using 3 rows, and supporting the upper torso using 9 rows. Between these two sections a sacral section, as seen in Fig. 1, incorporates 8 rows of air cells with an alternating low pressure (AP) signature (internal peak pressures and cycle time), adjusted by subject morphology, using a self adjusting low pressure sensor (SAALP™) (Hill-Rom). The technical description of the principle and operation of the SAALP™ sensor is detailed in two patents (Caminade et al., 2009a, 2009b). To review briefly, a resistive force-detector cell sandwiched between two protective plates was designed to support a range of pressures (equivalent to subject weights of between 40 kg and 200 kg) applied to the APAM prototype. For each subject the body weight, morphology and subject position were analysed and the sensor computed an internal pressure profile in the mattress. The resulting conditioned signals activate a pair of solenoid valves either connected to a pump or to the atmosphere. The pump stops when the defined internal pressure in the mattress is attained. The cycle time is thus dependent on the characteristics of the pump in attaining the defined internal air pressures during the inflated phase of the AP cycle. The heel section was made from carved foam. The mattress was placed on an articulated hospital bed (AVG800 frame, Hill-Rom), with a Head of Bed (HOB) adjustment.

2.2. Subject cohort

The study was approved by the local ethics committee of Queen Mary University of London (QMUL Ref no. QMREC 2009/43), and informed consent was obtained from each subject prior to testing. Exclusion criteria involved any subject with a history of skin-related conditions. The study recruited 12 volunteer subjects, with their details summarised in Table 1. All tests were performed in a side room off the Biomechanical Performance Laboratory at QMUL, which was maintained at a temperature of 26±2 °C.

2.3. Test protocols

The two separate transcutaneous gas electrodes (Model 841, Radiometer, Denmark) were set at a temperature of 44 °C, to ensure maximum vasodilatation (Bogie et al., 1995), during both the calibration and subsequent testing phases. Each was attached to either the mid-region of the sacrum or the right scapular, the latter representing a control site, while the subject adopted a sitting position. During an acclimatisation period of 15—20 min, in which the transcutaneous gas values attained unloaded basal values, the mattress was activated with the HOB set at 0° i.e. in the horizontal position.

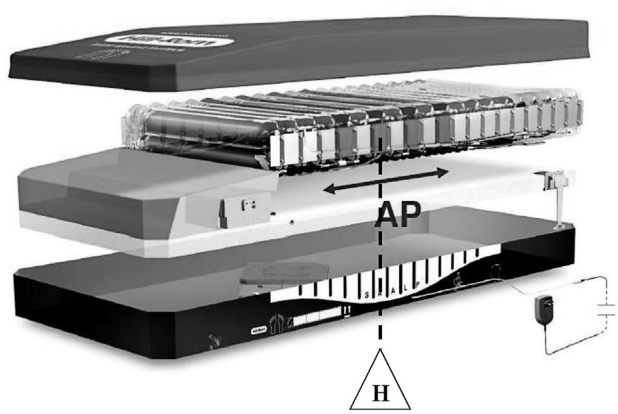

Fig. 1 – Schematic of the prototype support mattress. The central mattress section incorporates 20 rows, 8 of which are subjected to alternating pressure (AP), as indicated by the arrow. The location of the hinge, as indicated by the triangular icon, is important when the head of bed angle is altered.

After the set-up period, each volunteer was then carefully positioned on the prototype mattress in a comfortable, supine position, with their hips aligned with the triangle of the bed frame (Fig. 1). Each subject made contact with a thin sheet incorporating a 96 cell array positioned on the top surface of the mattress and attached to an interface pressure monitoring system (Mark III, Talley Medical Group, Romsey, UK). The output of the internal pressures within the mattress was monitored to ensure that the cycle performance of the mattress had attained a steady state condition. This was demonstrated by repeatable levels of intermittent pressures in the sacral section of the mattress, which was generally achieved between 3 and 12 min after the subject was positioned on the mattress. The control site was supported by continuous low pressures.

The interface pressures were recorded before and after each test period, which lasted a minimum period of 30 min. A maximum value for interface pressure was recorded across the 96 cell array sampled for three complete cycles (total duration of approximately 4 min) for skin areas adjacent to the sacrum and the right scapular. The internal pressures within the prototype mattress were recorded continuously throughout the test period for both the AP and CP sections of the mattress. For the AP section, the maximum and minimum internal pressures were recorded and a cycle time was estimated. The transcutaneous gas tensions (T_cPO_2/T_cPCO_2) were measured continuously throughout the test period. All outputs were processed using appropriate software associated with a PC. For the three subsequent measurement sessions, each subject was tested at HOB angles of 30, 45 and 60°, to simulate typical bed positions adopted in clinical practice.

2.4. Statistics

Linear regression models were used to examine the relationship between estimated maximum internal pressures and the

Table 1 – Summary of volunteer characteristics.

Subject	Age	Sex	Height (m)	Weight (kg)	BMI (kg/m^2)
A	28	M	1.76	80	25.8
B	27	F	1.64	53	19.7
C	27	M	1.74	70	23.1
D	28	M	1.92	105	28.5
E	27	M	1.70	75	26.0
F	26	M	1.83	71	21.2
G	27	F	1.64	60	22.3
H	26	F	1.68	65	23.0
I	30	F	1.64	76	28.3
J	26	F	1.65	52	19.1
K	24	M	1.92	115	31.2
L	33	M	2.00	170	42.5
Range	**24—33**		**1.64—2.00**	**52—170**	**19.1—42.5**

BMI of the volunteers. To examine the effects of the HOB angles on the internal pressures as determined for each subject, an ANOVA was performed. A level of 5% was considered statistically significant (*$p \leq 0.05$).

3. Results

3.1. *Internal characteristics of the mattress*

The internal state of the mattress achieved a steady state for the majority of the test conditions. In these cases, the maximum and minimum pressures in the AP section and continuous pressures recorded in the CP sections were constantly maintained by the SAALP™ sensor. When the maximum internal pressures in the sacral section were examined for all subjects, as illustrated in Fig. 2, their values clearly depended on the BMI of the individual. Indeed when the data was subjected to analysis, the four linear models corresponding to each of the HOB angles were statistically significant at the 1% level. Analysis of the effects of HOB angles, revealed that the differences in internal pressures for the subject groups were statistical significant ($p < 0.001$). Thus the mean values were lowest in the horizontal position (HOB=0°) and highest for subjects positioned at a HOB angle of 60°. The corresponding values for all subjects at the minimum pressures of the AP cycles ranged from 1.9 to 3.9 mmHg (0.25—0.52 kPa) with no evident trends with respect to individual BMI values.

The corresponding cycle time of the AP cycle in the sacral section for each of the test conditions is presented in Fig. 3. In all but one condition where the stabilisation of the mattress had been attained, the cycle times were between 7 and 14 min for each of the HOB angles. There was no trend evident with respect to BMI values. It should be noted, however, that the sensor was not able to stabilise the pressure cycle in 10% of all conditions within a 14 min period, most notably for the two subjects with the highest BMI when supported at a HOB angle of 60° (Figs. 2 and 3).

3.2. *Monitoring parameters of tissue viability*

In the sacral region, simultaneous measurements of transcutaneous oxygen and carbon dioxide (T_cPO_2 and T_cPCO_2) tensions were performed, whereas at the scapular only T_cPO_2 values were recorded. Close examination of the data enabled the categorisation of a number of characteristic responses to a representative number of mattress cycles at the two skin sites.

Category 1. For about 50% of test conditions, the T_cPO_2 levels at the sacrum were of similar magnitude to those at the scapula, for all four HOB angles. Such a skin response to applied loading is illustrated in Fig. 4.

Category 2. Alternatively for about 35% of test conditions, the skin response at the sacrum revealed distinct perturbations in the T_cPO_2 levels, which were associated with the AP profile within the mattress. This mechanism generally ensured that the T_cPO_2 levels remained relatively high for a significant proportion of the test period. Such a characteristic response is illustrated in one subject supported at HOB angles of 0, 30 and 45° (Fig. 5(a—c)). However, the skin response of the same subject when supine at the HOB angle of 60° revealed periods in which the T_cPO_2 levels were compromised (Fig. 5d).

For both Categories 1 and 2, the corresponding maximum interface pressures did not exceed 66 mmHg (8.7 kPa). In addition for both categories, there was minimal change in T_cPCO_2 throughout the monitoring period (Figs. 4 and 5), regardless of the levels in T_cPO_2 at the sacrum. Indeed the T_cPCO_2 values were within the normal range of between 35 and 45 mmHg (4.7—6.0 kPa).

Category 3. By contrast, in a few cases there was a distinct elevation of T_cPCO_2 values, when the measurement was performed at a HOB angle of 60°. An example of this alternative response is illustrated for two subjects in Fig. 6. This skin response occurred when the T_cPO_2 values were severely compromised during the monitoring period.

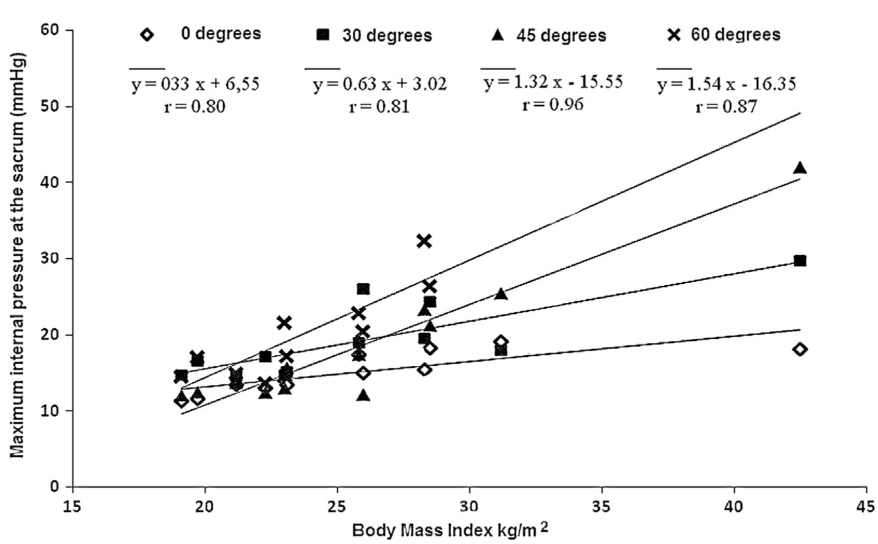

Fig. 2 – The relationship between maximum internal pressures in the AP section of the mattress and Body Mass Index (BMI) for each of the four Head of Bed angles. Statistical analysis of each linear model also indicated.

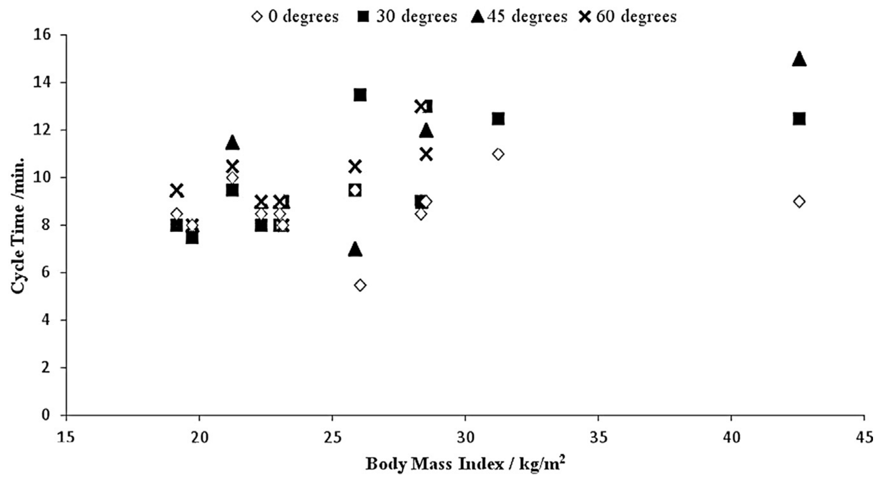

Fig. 3 – The relationship between cycle time in the AP section of the mattress and BMI for each of the four Head of Bed angles. A threshold cycle time of 15 min is indicated.

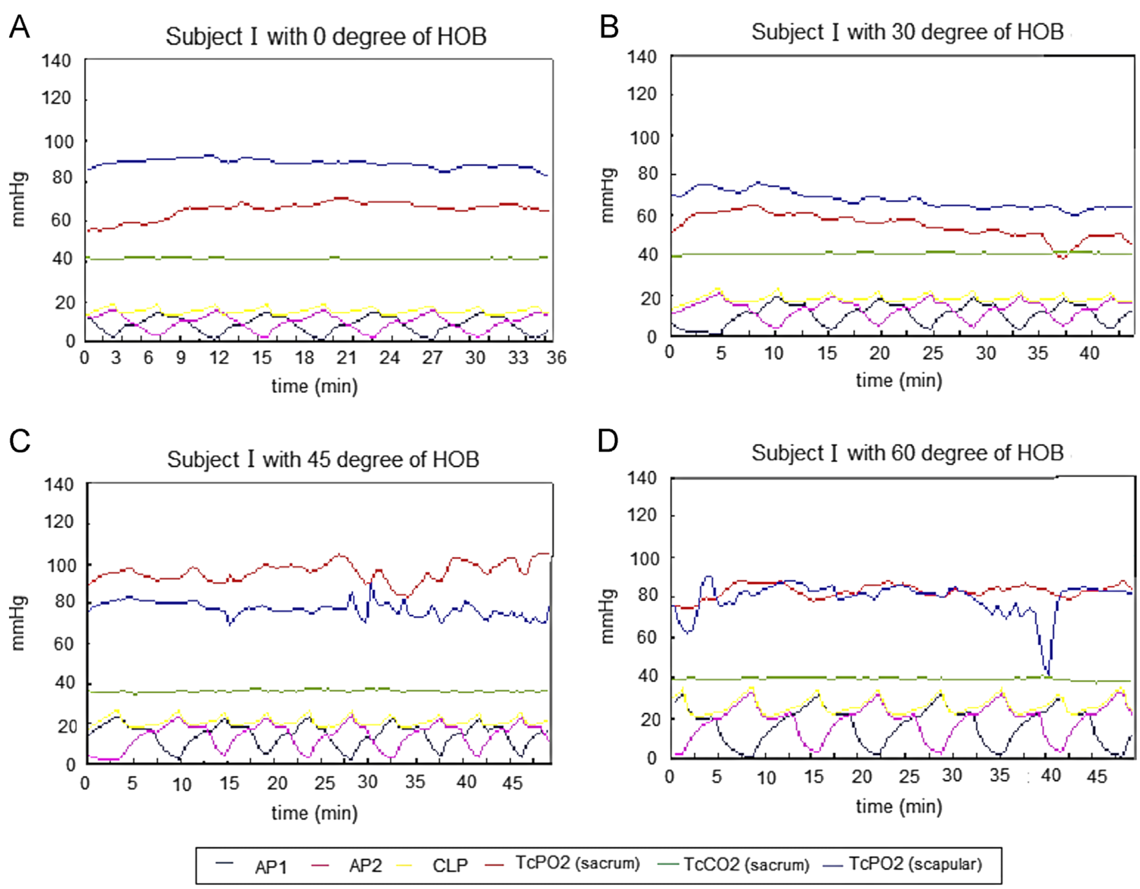

Fig. 4 – A complete set of data for each of the four Head of Bed angles tested with subject I lying on the prototype mattress. AP1 and AP2 indicate individual air internal pressures within the sacral section and CLP indicated the corresponding internal pressure within the continuous low pressures sections. The T_cPO_2 levels are indicated for both sacral and scapular sites over the monitoring period, whereas the T_cPCO_2 response is only recorded from the sacral site.

4. Discussion

This study examined the response of normal healthy subjects at two skin sites when positioned supine on a prototype mattress supported on an articulated bed frame at a range of Head of Bed angles up to 60°. A particular feature of the mattress was the incorporated Self Adjusting Low Pressure sensor (SAALP™), which adjusted the internal state of the

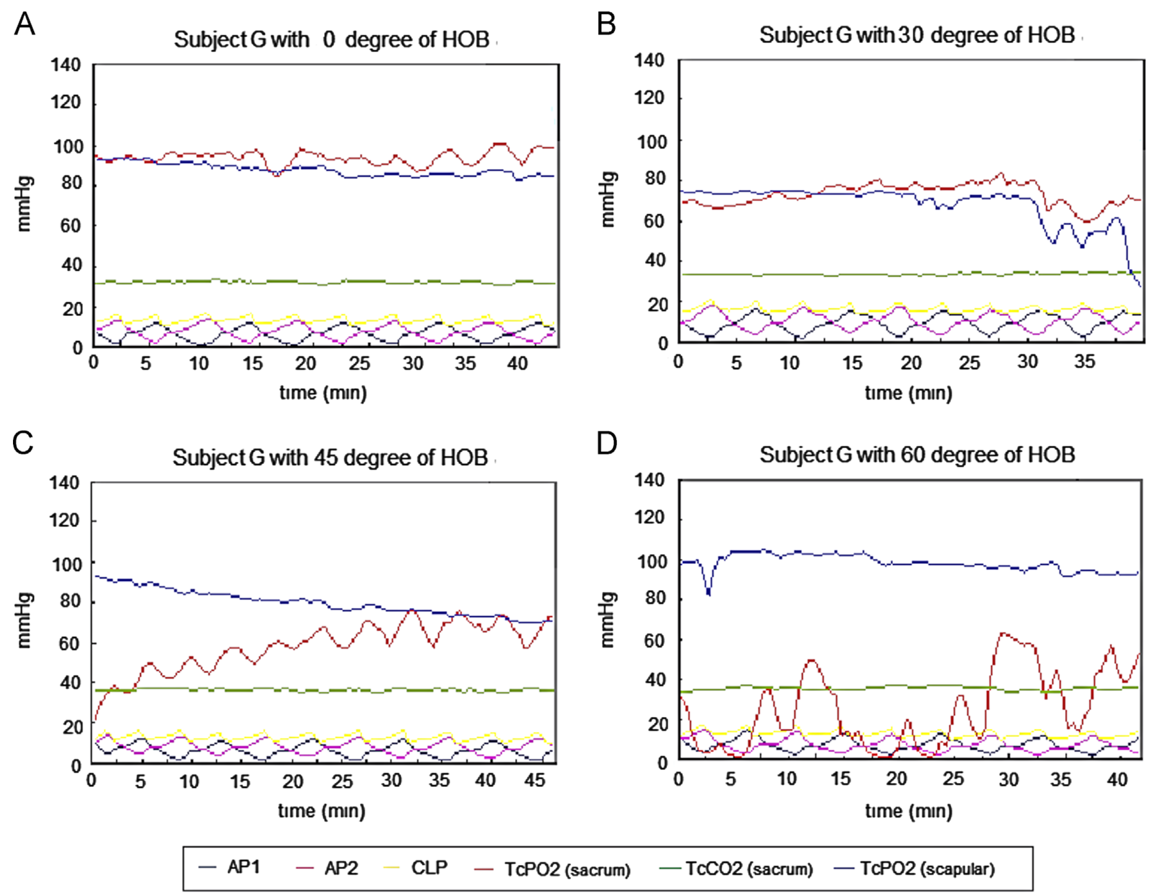

Fig. 5 – A complete set of data for each of the four Head of Bed angles tested with subject G lying on the prototype mattress. AP1 and AP2 indicate individual air internal pressures within the sacral section and CLP indicated the corresponding internal pressure within the continuous low pressures sections. The T_cPO_2 levels are indicated for both sacral and scapular sites over the monitoring period, whereas the T_cPCO_2 response is only recorded from the sacral site.

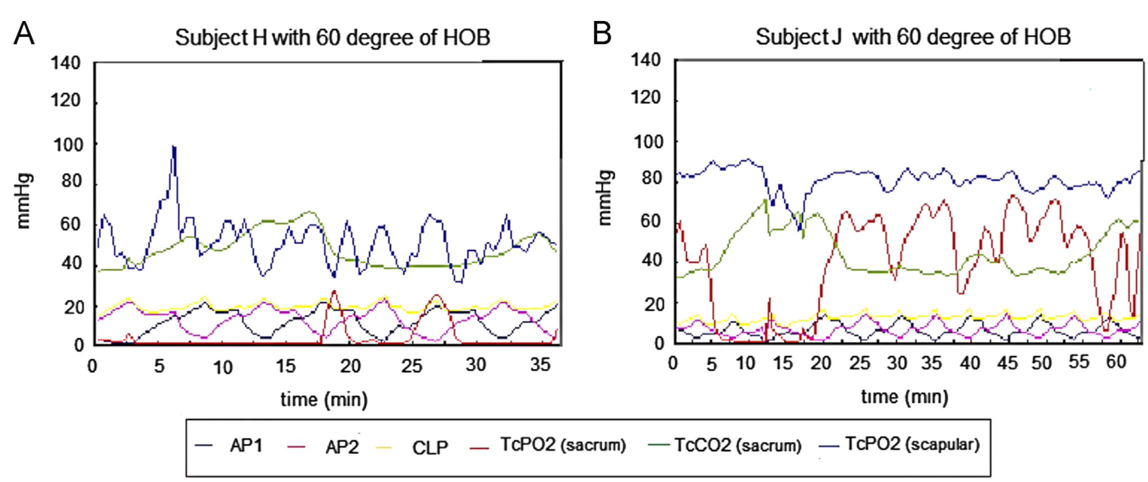

Fig. 6 – The response of two subjects (H and J) supported at a Head of Bed Angle of 60°. AP1 and AP2 indicate individual air internal pressures within the sacral section and CLP indicated the corresponding internal pressure within the continuous low pressures sections. The T_cPO_2 levels are indicated for both sacral and scapular sites over the monitoring period, whereas the T_cPCO_2 response is only recorded from the sacral site. In all cases there was an increase in T_cPCO_2 levels, associated periodic low values of T_cPO_2 levels.

mattress according to the morphology and positioning of the individual subject (Caminade et al., 2009a, 2009b). In the majority of conditions the alternating pressure signature was stabilized and the system accommodated both higher BMI values and increased HOB angles, by increasing the internal pressure (Fig. 2). Similar trends were also recorded for the internal pressures in the CP sections of the mattress which supported areas such as the scapular (data not shown).

The developed methodology provides a well-established system of assessing the tissue viability and internal/interface conditions for volunteer subjects supported on a prototype air mattress system with one section providing alternating pressure support in between sections providing low pressure support. In particular, transcutaneous gas levels and interface pressures were measured at both the sacrum and the scapular. The sacrum contains a higher density of capillary loops, a reduced density of elastin fibres (Hagisawa et al., 2001) and a higher level of perfusion than many other tissue sites (Kanno et al., 2007). These factors, allied to the degree of subcutaneous soft tissue at the sacrum, makes the site particularly susceptible to tissue breakdown when the blood flow is impaired by prolonged mechanical loading (Mayrovitz et al., 2002). It is evident that for many subjects, both the sacral T_cPO_2 and T_cPCO_2 were maintained at approximately basal levels for the monitoring period of over 30 min. This Category 1 type response is illustrated in Fig. 4 for a subject I (BMI of 28.3 kg/m^2), in which the maximum internal pressures (AP) ranged from 15.6—32.4 mmHg over the range of HOB angles. By contrast, Category 2 cases revealed clear perturbations in the T_cPO_2 during the monitoring period, associated with the alternating pressure signature. As indicated in Fig. 5(a—c), the T_cPO_2 levels were generally maintained well above 30 mmHg, a threshold value above which tissue viability is not considered to be compromised (Bogie et al., 1995). Alternatively, in a few cases, the perturbations in T_cPO_2 consistently fell below this threshold value (Figs. 5d and 6). These cases were often associated with enhanced levels of T_cPCO_2 (Fig. 6) and occurred with the subjects supported at a HOB angle of 60°. In these cases, the pressure signature was clearly inadequate in maintaining sacral tissue viability during the monitoring period. A schematic indicating these three distinct categories of skin response to alternating support pressures is provided in Fig. 7. It is evident that the prototype mattress does not ensure maintenance of skin viability if a Category 3 response is observed.

The relationship between transcutaneous gas tensions and sweat metabolites, each reflecting different aspects of tissue ischaemia, has been demonstrated in a previous study (Knight et al., 2001). For example, in severe conditions of ischaemia, as evidenced by a significant reduction in T_cPO_2 compared to unloaded basal levels, both T_cPCO_2 and sweat lactate levels were elevated. It has also been reported that carbon dioxide levels can control vascular tone in acute spinal cord injured subjects, a group prone to pressure ulcer development (Bogie et al., 1995). Furthermore, a theoretical model describing the effects of reactive hyperaemia on tissue recovery following ischaemia, indicated that the time required for removal of lactate from tissues was greater than that needed for re-oxygenation (Hyman and Artigue, 1977). Thus it could be speculated that species, such as carbon dioxide and lactate, may be critical in tissue recovery and in the control of related physiological responses, particularly when skin tissues are exposed to alternating pressures. This approach clearly requires further investigation if a simple screening method is to be ultimately developed to identify subjects at high risk of developing pressure ulcers.

Two subjects (K and L) were included in the study whose BMI could be classified as obese (American Obesity Society, 2008). The sensor adjusted the internal pressures in the mattress accordingly with values in excess of 25 and 42 mmHg at the HOB angle of 45° (Fig. 2). The resulting response was similar to that presented in Fig. 5, with adequate skin viability over the monitoring period. However for both subjects supported at a HOB angle of 60°, the sensor was not able to attain a steady state pressure signature in the AP section within a cycle period of 14 min (Fig. 3). These findings highlight the importance of stabilizing the AP signature for each subject if the mattress is to provide adequate support for each subject.

Certain questions were not addressed in the present study. For example, we did not examine whether for some subjects, the support offered by CLP might have proven sufficient to maintain tissue viability with no additional need for alternating air pressure support in the sacral region. In addition, the study only included young healthy subjects. Thus the effectiveness of this prototype mattress for

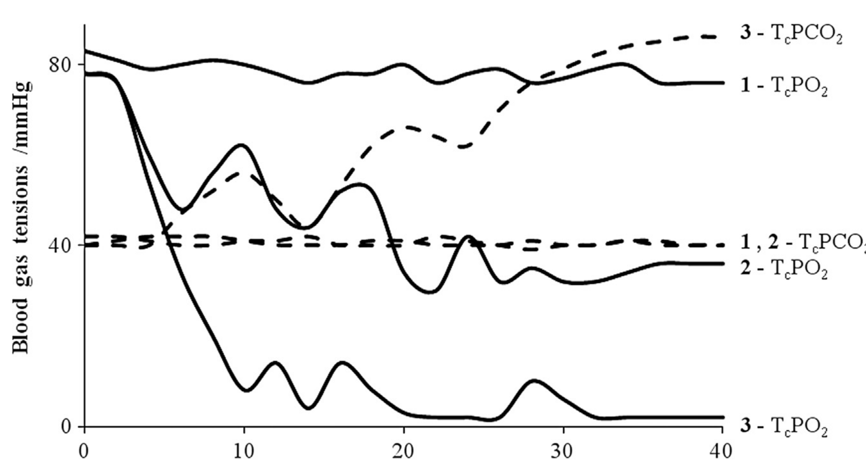

Fig. 7 – Schematic representation of three distinct categories (1,2,3) of skin response at the sacrum when subjected to alternating pressures provided by a support mattress. Continuous lines represent T_cPO_2 responses and dashed lines represent T_cPCO_2 responses.

Table 2 – The interface pressures for both sites corresponding to the subjects in Figs. 4 and 5.

Head of Bed angle	Maximum interface pressures (mmHg) Sacrum		Maximum interface pressures (mmHg) Scapular	
	First scan	Second scan	First scan	Second scan
Subject I (Fig. 4)				
0°	37	34	23	22
30°	39	38	32	29
45°	46	36	34	25
60°	51	51	34	34
Subject G (Fig. 5)				
0°	43	40	23	25
30°	53	50	23	26
45°	61	51	33	40
60°	66	50	26	23

bed-bound subjects, who may be particularly susceptible to skin breakdown, needs to be investigated. This would elucidate whether the intermittent form of pressure relief, at an internal alternating pressure signature as determined by the mattress, is sufficient to maintain viability of skin tissues compromised by intrinsic factors.

It is evident that values of interface pressures, which rarely exceeded 60 mmHg at the sacrum (Table 2), were not related to the specific tissue response and therefore revealed little about the effectiveness of the pressure signatory within the mattress. Such findings reinforce the proposition that it is not the interface pressures per se, but their prolonged effects on tissue viability, which are critical in assessing individual risk of tissue compromise (Knight et al., 2001; Goossens and Rithalia, 2007; Bader, 1990; Colin et al., 1996; Sakai et al. 2008). The findings also question the common use of pressure distribution data in commercial literature describing the effectiveness of APAM systems. It is evident that existing mattresses incorporating a single pressure signatory do not accommodate the inter-subject variability with respect to morphology, BMI and other intrinsic factors The present results offer the potential for an intelligent support surface whose characteristics can be adjusted according to the needs of an individual morphology to maintain skin health during prolonged periods of bed-rest.

In conclusion, the SAALP™ sensor incorporated in the prototype support mattress was found to be sensitive to changes in BMI values of individual subjects (Fig. 2). The alternating pressure mode in the section incorporating the sacral region provides optimal support in maintaining tissue viability for many of the test subjects (Figs. 4 and 5(a—c)). In some subjects, however, when the HOB is raised there is compromise to the tissue viability at the sacrum, in terms of depressed T_cPO_2 levels and elevated T_cPCO_2 levels (e.g. Fig. 6). The present approach needs to be employed with bed-bound and/or wheelchair-bound individuals, who are at risk of developing pressure ulcers.

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