Title: A modified evaluation of spacer fabric and airflow technologies for controlling microclimate at the loaded support interface.

Short Title: The Effects of Spacer Fabric on Microclimate Management.

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Abstract

The microclimate between an individual and their support surface can have a significant effect on skin health. Recently, healthcare companies have developed mattress systems designed to regulate the temperature and humidity at the individual-support surface interface, which include spacer fabric materials and active airflow systems. However, to date, there has been little formal evaluation of their performance. The aim of this study was to evaluate mattress systems using an established lab-based approach.

A physical model tank was applied to each support surface, filled with 20 L of water maintained at 37°C. A continuous network of perforated plastic tubing deposited water equivalent to a sweat rate of 1.5 mL/min for 25 minutes. Humidity and temperature sensors, stitched onto the thin cotton sheet, monitored the interface conditions for a total of 24 hours. Tests were conducted using a range of support surfaces incorporating spacer fabrics, with and without active airflow and ventilated covers.

The results from this study revealed that spacer fabric appears to dissipate heat more effectively than viscoelastic foam (Heat Flux 33.6W/m^2 vs. 10.4 W/m^2). With no active airflow the viscoelastic foam and spacer fabric exhibited a limited reduction in relative humidity at the interface. However, with active airflow, the spacer fabric had the ability to reduce relative humidity over time to basal levels through moisture vapour transfer (MVTR) capability. This represented a change from saturation (99% RH) to ambient humidity (40%) over a 24 hour period (water vapour transfer rate = 0.9 g/m^2;hr).

Further parametric testing is required to evaluate the optimal combinations of spacer fabric material and active airflow systems.

Keywords: Microclimate, spacer fabric, airflow, skin health, pressure ulcers.

Introduction

There are many situations both in the hospital and community settings where individuals will be supported by interfaces such as cushions or mattresses for prolonged periods. When vulnerable individuals cannot reposition themselves, pressure and shear forces can cause damage to the underlying skin and soft tissues, resulting in chronic wounds termed pressure ulcers. A pressure ulcer (PU) is defined as a localized injury to skin and/or underlying tissue usually over a prominence as a result of pressure or pressure in combination with shear. [1] Pressure ulcers vary in severity depending on the depth of the lesion; from non-blanching erythema (category 1) to full thickness wound down to bone (category 4). [1] In spite of efforts to prevent pressure ulcers, the incidence rate remains high worldwide, especially in hospitals and nursing homes [2, 3], with a mean incidence in the acute care setting of 17.6% (range 1.4-49%) and in the long stay setting of 6.6% (range 3.1–8.4%).[3] Recent evidence has shown the cost of treating wounds in the UK is £5 billion, with pressure ulcers accounting for 7% of this total.

In addition, thermodynamic conditions within and around skin tissues, commonly termed microclimate, strongly influence the risk of soft tissue breakdown and the development of pressure ulcers. Indeed, it is well established that both heat and moisture decrease the resiliency of the epidermis and hence increase its susceptibility to damage at the skin-support interface in load-bearing regions of the body. [4-6] Moisture has also been shown to increase the interfacial frictional forces, which can prove damaging to the skin surface. [7] Traditionally, most active support surfaces designed to minimize the risk of PUs have focused on providing pressure relief and/or redistribution, particularly for those individuals with impaired mobility and sensation. However, there has been a recent interest among manufacturers to design mattresses and cushions, which regulate the microclimate. A number of manufacturers have introduced novel fabric technologies and active air flow e.g. Skin IQ™ MCM Technology (Arjo-Huntleigh) at the patient-support surface interface, which are designed to facilitate the transport of moisture away from the loaded body sites. In addition, technological advances in woven manufacturing techniques have given rise to new 3D spacer fabrics, which can be incorporated as overlays within mattress systems e.g AeroSpacer (Medstrom, UK). These spacer fabrics are composed of co-planar knitted structures that are joined together by yarns of known rigidity to provide a well-defined and pressure-tolerant inter-space between the different knitted layers. These fabrics are designed to exhibit superior cyclic compression–recovery properties. [8] In addition, due to the highly porous structure and the open apertures in the surfaces, 3D knitted spacer fabrics usually exhibit high air permeability and low thermal resistance. [9]

Relatively few studies have reported validated tests to examine the effectiveness of support surfaces in the management of microclimate. Of the few laboratory-based model studies, Nicholson *et al* (1999) described a performance test, based on textile industry protocols, to measure the moisture vapour and heat transport capability from the controlled environment into a mattress cover. [10] A microenvironment of controlled humidity and temperature was established above a sample of fabric of a low-air-loss (LAL) cover to simulate the steady state of moisture diffusion through the fabric at physiological conditions. However, this approach did not incorporate patient body weight on the mattress and hence their findings reflect vapour transmissibility of the mattress cover, as opposed to a simulation of its performance in-situ. Reger *et al* (2001) examined mattress performance by using a water-saturated patient analogue resting on a LAL mattress system to provide moisture and energy inputs. The mattress performance was inferred from measurements of the temperature beneath the analogue, reflecting the removal of latent energy for up to 90 minutes. [11] This approach, however, only offered a qualitative analysis of moisture transport as the measurements are difficult to interpret. Several studies have been performed on automotive support surfaces, using ISO standards for air permeability (ISO9237),[12] measures of transient and steady-state thermo-physical properties and water vapour permeability.[13] However, these do not simulate the clinical scenario of a patient lying in bed or sitting in a chair. In addition, the clinical scenario will typically involved bed sheets covering the support surface and garments on patients which can influence the efficacy of the microclimate management at the skin surface.

Based on transport conservation principles, Figloila (2003) developed a reproducible test methodology to measure and control the moisture transported into, through, and out of a LAL mattress system. The system incorporated a test rig comprising of a load, water bladder and moisture reservoir to simulate the human body at its normal temperature and rates of perspiration. The entire system was incorporated within a controlled environment. The input and output airflow was quantified in terms of temperature, mass flow rate and relative humidity, to provide an accurate indicator of the performance of mattress systems in dissipating heat and moisture. It yielded characteristic temporal profiles of the estimated moisture transport, which described the effectiveness of different support surfaces. [14] It further indicates that temperature and, in particular, moisture, can be monitored at the microenvironment interface using airflow techniques. This work provides the motivation of the present study, which was designed to evaluate the relative performance of support surfaces incorporating spacer fabrics with varying airflow parameters on the management of microclimate at a hot and humid interface.

Materials and Methods

A lab-based model was developed, based on a previous description (Figloila, 2003), which enabled an assessment of various support surfaces in terms of their ability to control microclimate. The human analogue model involved a medium density polyethylene tank (surface area 0.3 m^2) filled with 20L of water maintained at 37 ± 1°C. The equivalent pressure under the tank was approximately 20 mmHg (2.7kPa). At the base of the tank, there was a continuous network of plastic tubing (Tygon® laboratory tubing of outer diameter 3.2mm and inner diameter: 1.6mm) through which water was pumped via a peristaltic pump **(**Masterflex C/L**,** Cole-Parmer, UK**)**. Small holes regularly located along the tubing enabled water release under the tank. This is in contrast to the moisture-bearing patient moisture reservoir (PMR), made from a non-woven fabric towel used by Figloila and colleagues. The tank was placed on a cotton sheet which itself was placed on the support surface (Fig. 1).

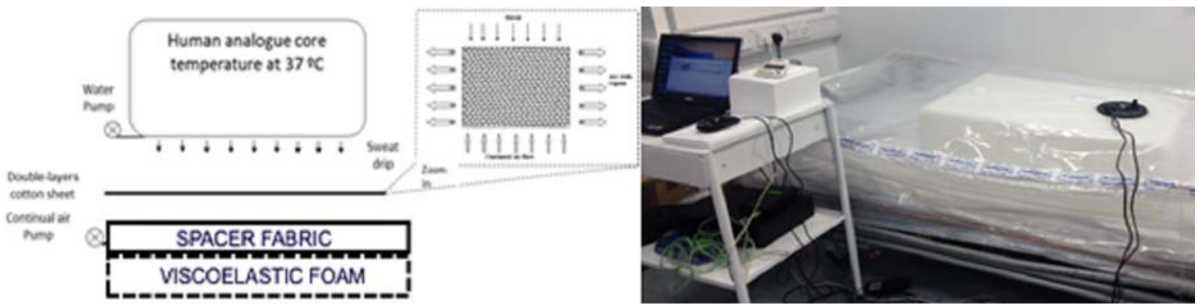

Figure 1. Schematic (left) and image (right) of the lab-based model used to monitor microclimate.

Humidity and temperature sensors, stitched onto a thin cotton sheet, were designed to monitor the interface conditions, acquiring data at 0.5Hz during and after the simulated sweating phase using a data logger (Model SHT75, Sensiron AG). Two additional sensors were placed away from the analogue to monitor ambient conditions. The sensors have an accuracy of ~ ±0.5°C and ±1.8% RH, with their dimension being 19.5 x 5.08 x 3.1mm. The complete arrangement was located within a test chamber made of a copper frame surrounded by polyethylene sheeting, with a removable and re-sealable upper layer of polyethylene creating a sealed environment (Fig. 1 right).

Test Protocols

The tests, lasting a total of 24 hours, utilised a range of support surface combinations, incorporating spacer fabric (Medstrom Ltd, UK), active airflow and ventilated covers (Figure 2). The support surface comprised of three distinct layers of spacer fabric to create a functional gradient of immersion. Each layer was made of 100% polyester with the following properties:

- Layer 1 (superficial); Low Dtex Monofilament with a material density of 25-70kg.m3, depth 15mm and weight 500-700g.m2.
- Layer 2 (middle); Medium Dtex Monofilament with a material density of 37-77kg.m3, depth 20mm and weight 900-1150g.m2.
- Layer 3 (deep); High Dtex Monofilament with material density of 32-67kg.m3, depth 20mm and weight 800-1000g.m2.

Four separate mattress combinations were examined and compared to a standard viscoelastic foam design. At the start of each test water was released through the tubing under the tank at rates equivalent to normal physiological sweating of 1.5 or 3.0 mL/min, for a total period of 25 min. These sweat values were chosen to represent the range measured from collection of human sweat at the sacrum in both loaded and unloaded states. [15] Temperature and humidity data were then recorded for the subsequent period up to 24 hours.

Test Condition	Material	Cover	Active Fan
1	Viscoelastic Foam	Polyurethane	No
2	3D spacer fabric	Polyurethane	No
3	3D spacer fabric	Polyurethane	Yes – cut into corner of device
4	3D spacer fabric	Polyurethane – with side vents	No
5	3D spacer fabric	Polyurethane – with side vents	Yes – fully integrated fan device

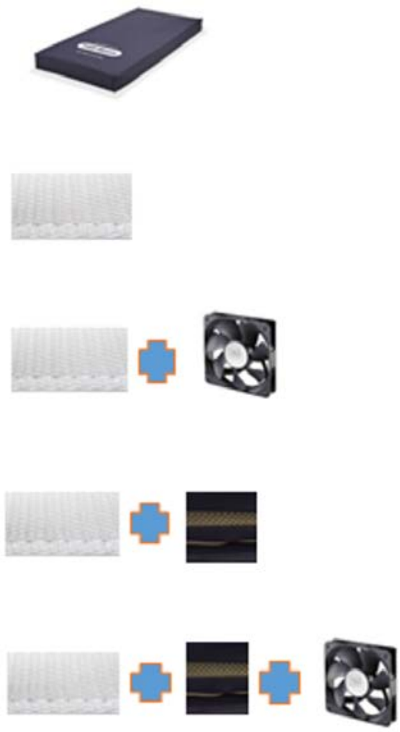

Figure 2: Five test combinations of support surfaces incorporating spacer fabrics, with and without active airflow, with a standard viscoelastic foam mattress.

Temporal profiles of temperature and humidity were evaluated over the 24hr test period, with specific metrics estimated (Figure 3). The primary outcomes measures included ;

1. The peak temperature (°C) at the patient support interface
2. The peak relative humidity (% RH) at the patient support interface
3. The overall moisture vapour transfer (MVTR) capability (g/m².hr) of the support surface, i.e. its total evaporative capacity

4. The heat flux (W/m^2) at the patient support interface, i.e. the total heat withdrawal including dry flux and wet flux
5. The area under the curve for the time spent above and below ambient conditions was estimated (Fig 3c)

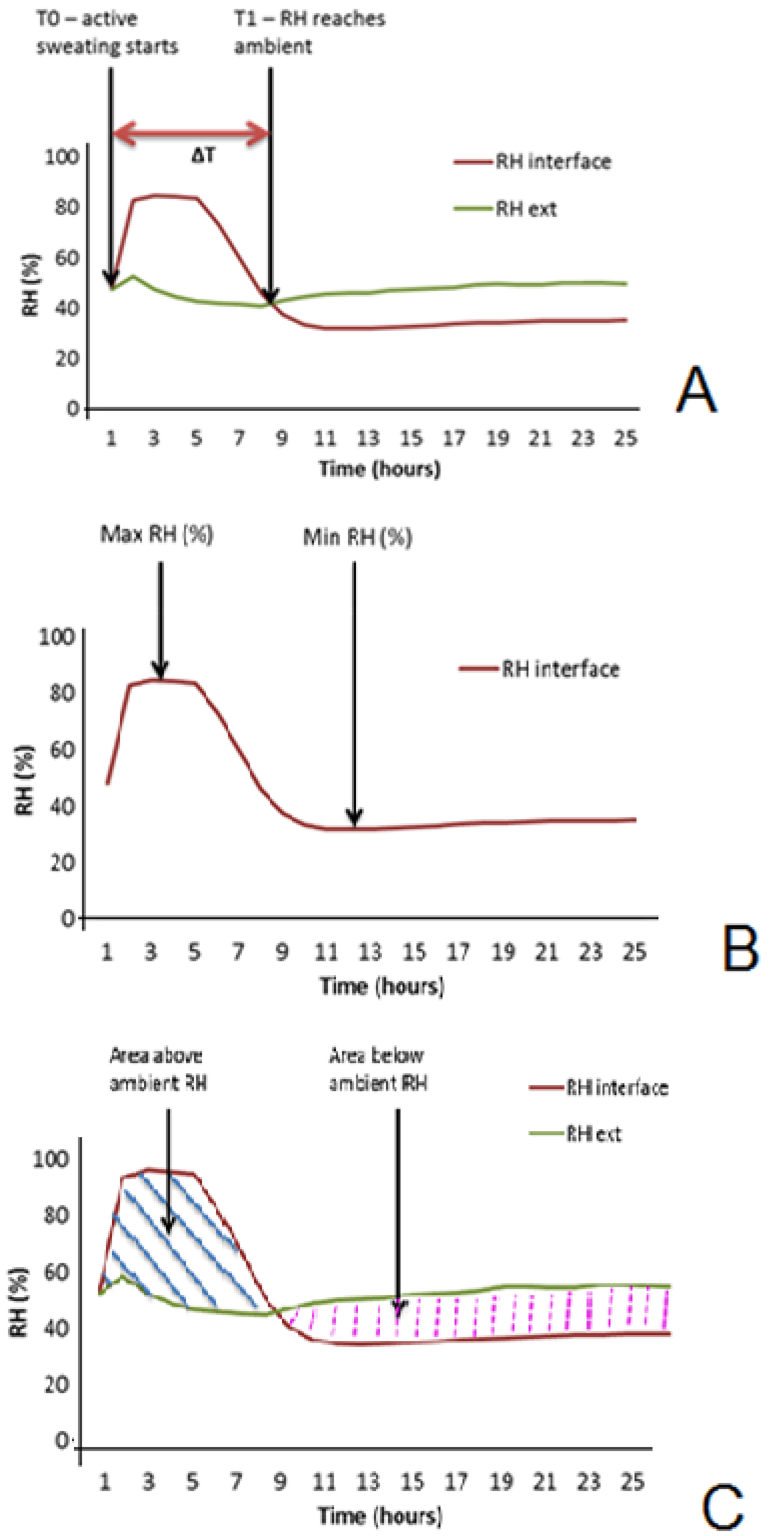

Figure 3. Selected output parameters from temporal profiles of RH (a) time taken to reach ambient (b) max and min temperatures. (c) Estimation of the area above and below the ambient conditions for RH.

Statistics

Descriptive statistics were used to present the data from the repeat trials. Mean changes in temperature and humidity were estimated for each test condition and trends were observed between the data sets. Data was analyzed across the test period, with discrete values presented at seven key time points, namely t1 representing baseline values with no phantom and no sweat, t2 and t3 representing 15 and 25 minutes of sweating under the phantom, respectively, and t4, t5, t6 and t7, represent 4, 8 12 and 24 hours post-sweating under the phantom.

Results

Twenty trials comprising 4 repeats of the 5 test conditions, were completed on the support surfaces.

Temperature

Results from the temperature readings showed that interface temperatures increased sharply from baseline (t1) following the application of the human analogue, reaching 33-37 degrees for all test conditions (Table 1). These elevated temperatures were maintained throughout the sweating period (t2 -t3). During the subsequent period there was a sharp decrease in temperature over the first 4 hours (t4) followed by a more gradual decrease over the remaining period (t4 to t7), such that at the end of the test period a mean decrease of 6.5°C from the peak temperature was recorded for all conditions with a spacer fabric (Figure 4). The addition of airflow or cover ventilators had a negligible effect on temperature values. The corresponding decrease in the viscoelastic foam was 4°.

Table 1. Temporal profiles of temperature from the five test conditions over 24 hours. Mean ± standard deviation from the three test repeats.

Test Condition	Sensor location	t1 (°C)	t2 (°C)	t3 (°C)	t4 (°C)	t5 (°C)	t6 (°C)	t7 (°C)	Heat Flux (W/m^2)
1	Interface	28 ±0.8	37 ±0.6	37 ±0.5	37 ±0.5	36 ±0.6	33 ±0.4	33 ±0.3	10.4 ±0.9
	ambient	23	23	23	24	23	23	23	
2	Interface	25 ±1.0	35 ±1.2	35 ±0.8	31 ±1.2	31 ±0.6	30 ±0.5	31 ±0.4	19.2 ±2.3
	ambient	22	22	23	22	22	21	21	
3	Interface	26 ±1.1	33 ±0.8	37 ±0.8	32 ±0.9	31 ±0.8	31 ±0.9	31 ±0.4	28.8 ±2.6
	ambient	22	22	22	23	22	22	22	
4	Interface	29 ±1.4	35 ±1.2	37 ±1.2	32 ±0.9	31 ±1.1	31 ±0.6	30 ±0.6	33.6 ±3.3
	ambient	22	22	23	23	22	22	22	
5	Interface	29 ±1.3	36 ±1.0	37 ±0.9	32 ±1.2	30 ±0.8	30 ±0.5	30 ±0.5	33.6 ±4.7
	ambient	22	22	22	22	22	21	21	

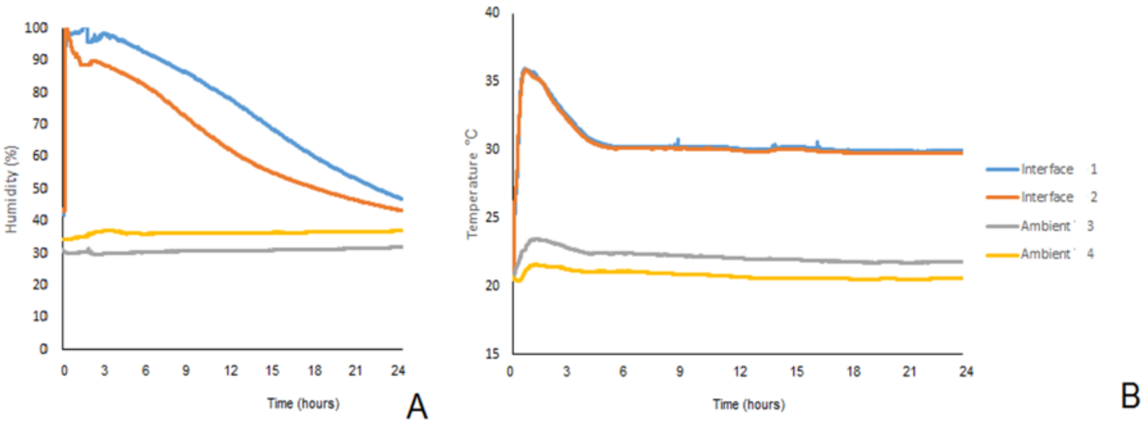

Figure 4. Temperature profiles over test period for the spacer fabric with active airflow (Test Condition 2).

Ambient temperatures remained relatively constant throughout the test period. The temperature changes over the 24hr period resulting in a heat flux of 0.10 W/cm^2 for the viscoelastic foam, compared to a heat flux ranging between 1.9-3.4W/cm^2 for the test combinations including the spacer fabric (Table 2).

Humidity

The corresponding changes in relative humidity (RH) are presented in Table 3. Values at the support surface-phantom interface rose steadily during the application of sweat at the loaded interface, attaining a maximum value of between 78% and 99% RH after the 25 minute period (t3). The viscoelastic foam subsequently retained high RH values for the entire test period. This result was also observed for the spacer fabric test conditions with an inactive fan (test conditions 2 and 4). By contrast, there was an observed reduction in RH when the fan was active (test conditions 3 and 5), particularly involving the spacer fabric model with vents (test condition 5), where RH values increased to 79% RH after sweating, but returned to basal levels of 43% RH during the 24hr test period (Table 2, Figure 4a).

Figure 5a shows a typical temporal profile in RH with the test condition 5. It is evident that there is a sharp increase in RH levels following the sweating period, but these values gradually decline at a constant rate over the 24hr period. This resulted in a moisture vapour transfer (MVTR) capability of 0.9g/m^{2}hr, in the spacer fabric with active air flow. When the mattress was tested with the fan inactive, there was no effect on the RH levels throughout the test period (Figure 5b). As the other test conditions remained saturated at the support surface interface, it can be assumed that MVTR was negligible. In both cases, the ambient RH values remained constant within a range ± 5% during the entire test period.

Table 2. Temporal profiles of Relative humidity from the five test conditions (see Table 1) over 24 hours. Mean ± standard deviation from the three test repeats.

Test Condition	**Sensor location**	**t1 (%RH)**	**t2 (%RH)**	**t3 (%RH)**	**t4 (%RH)**	**t5 (%RH)**	**t6 (%RH)**	**t7 (%RH)**
1	Interface	51 ±10	56 ±7	99 ±3	100 ±3	100 ±2	100 ±2	100 ±2
	ambient	41	41	41	49	47	45	44
2	Interface	48 ±9	49 ±9	98 ±4	100 ±2	100 ±3	100 ±2	81 ±2
	ambient	45	45	44	46	44	44	48
3	Interface	55 ±7	58 ±8	78 ±11	86 ±9	86 ±8	82 ±8	72 ±11
	ambient	43	43	43	54	53	50	49
4	Interface	48 ±11	49 ±12	85 ±12	85 ±10	84 ±8	86 ±9	81 ±11
	ambient	45	46	46	50	46	45	42
5	Interface	43 ±8	55 ±10	79 ±12	78 ±9	70 ±11	61 ±13	43 ±10
	ambient	39	39	39	43	40	40	39

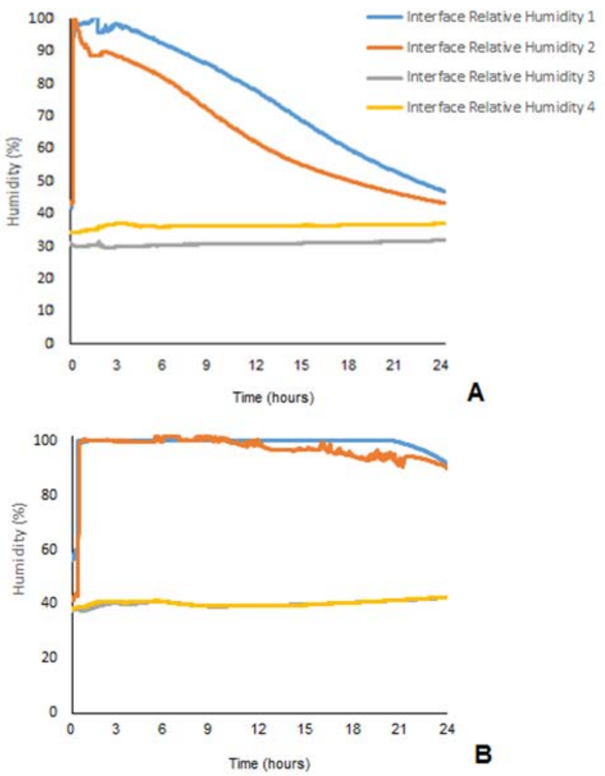

Figure 5. Relative humidity values from 3D spacer fabric with (a) blue vented polyurethane cover with active fan (condition 5) and (b) without fan (condition 4)

A summary of the output parameters reflecting the microclimate at the model-support interface is indicated in Table 3. It confirms considerable differences between the performances of the test combinations. In particular, the combinations involving the active air flow are considerably more effective in controlling the microclimate with, for example, a nine-fold increase in moisture vapour transfer rate compared with the combinations incorporating the spacer fabric alone.

Table 3: Summary of selected parameters for humidity and temperature from the physical model testing of five test support combinations (average from three repeat tests).

Sweat Rate	Test Condition				
Test parameter	1	2	3	4	5
Max interface RH (%)	99	99	86	85	78
Min interface RH (%)	99	81	72	81	47
Time to ambient RH (min)	NA	NA	NA	NA	1440
Area above ambient RH (%RH.hr^2)	1890	1369	679	1253	387
Area under ambient RH (%RH.hr^2)	0	0	0	0	0
Mean ambient RH (%)	49	45	48	47	45
Moisture Vapour Transfer Rate (g/m^2;hr)	0	0.1	0.1	0.1	0.9
Max Interface Temp (°C)	37	36	37	37	37
Min Interface Temp (°C)	33	31	31	30	30
Change in Interface Temp (°C)	4	5	6	7	7
Mean Ambient (°C)	23	22	22	22	22
Time to equilibrium (mins)	820	420	300	480	240

Discussion

The aims of the study were to evaluate the relative performance of support surfaces incorporating spacer fabrics with varying airflow parameters on the management of microclimate at a hot and humid interface. The design of the human physical analogue model proved ideal to deposit moisture uniformly at its interface with the loaded support surface. This resulted in an increase in both temperature and humidity values over the 25 minute period of simulated sweating when compared with ambient conditions. The addition of 3D knitted spacer fabric produced a significant effect on moisture transfer at the interface when an active fan pumped air through the material. This effect was not observed when the fan was inactive.

Using the current methodology further work can be carried out to investigate, for example, the performance of different covers on different foams, gels and spacer fabric mattress or cushions, and to determine the effect of bed clothing. A parametric evaluation of interface materials porosity under load and varying airflow distributions would add significant values to your understanding of microclimate management systems. The present methodology provides opportunities over previous systems [10] in that it can be adapted to provide varying interface conditions (temperature and pressure) as well as sweating rates over a realistic surface area. It is of note, however, that the physical model is limited in terms of the static nature of the assessment. Research has shown postural changes significantly affect the microclimate at the patient-support surface interface, [16] with lateral lying postures used to relieve vulnerable skin sites such as the sacrum. The physical model distributed moisture in a pattern associated with the orientation of the perforated tygon tubing. Thus, sweat was deposited in the corner closest to the moisture inlet and then dispersed across the area of the physical model over time. Further technical developments to employ even dispersion over the simulated sweating period would improve the assessment of support surface performance.

The temperature changes over the 24hr period resulted in a heat flux of 10.4 W/m2 for the viscoelastic foam, compared to a heat flux ranging between 19 and 34 W/m^2 for the spacer fabrics. These flux values are comparable to previous studies investigating the conductive heat exchange with a gel-coated circulating water mattress, [17] hospital contract mattresses and other microclimate management systems. [10] A previous study has revealed that spacer fabric in mattresses generated a thermally comfortable fabric that regulated the human body temperature during sleep. The study also revealed that fabric design, fabric tightness, and fiber composition were found to be significant on almost all thermal behavior, apart from thermal diffusion. [18] The combination of spacer fabric, vented cover and active airflow was able to demonstrate wicking away of moisture over the 24 hour test period, resulting in a water vapour transfer rate of $0.9g/m^2.hr$. Although the initial results of reducing humidity appear to be beneficial to skin health, some caution must be noted to avoid excessive drying. Indeed, excessive dryness of the skin also causes challenges for tissue integrity. Dry skin presents with reduced lipid levels, water content, tensile strength, flexibility, and junctional integrity between the dermis and the epidermis. [19] However, the values observed in the present study showed that RH reduced to 40% RH, suggesting adequate moisture to maintain skin health.

It is important that advances in support surface construction for pressure ulcer prevention and management improve the thermodynamic and moisture dissipating properties without limiting the pressure reducing properties. Indeed, the mechanical properties of support surfaces can be altered by heat and moisture. The present study has shown the thermal and moisture transport benefits of 3D spacer fabrics, in particular when air is forced through the 3D matrix. Spacer fabrics offer superior cyclic compression–recovery properties, [8] delamination resistance and fracture toughness characteristics offer advantages in support surface design compared to traditional materials. The spacer fabrics can also be tailored in terms of fabric orientation and density.[20] The present study used a new support surface with no prior conditioning, which may have influenced the efficacy of its microclimate control. Further longitudinal studies are required to assess the pressure redistribution qualities of spacer fabrics, with simulated mechanical loading to investigate wear characteristics.

In order to support the maintenance of microclimate it is important to regularly reposition immobile patient is to allow cooling and moisture dissipation from the body/support interface,[16] especially when there is excessive heat and sweat production. More research is needed to optimize support surface design to effectively manage both pressure redistribution and microclimate. Standardized test methods, such as the physical model described in the present study will provide the mean to provide relative performance statistics on support surfaces. This information will need to be translated into a clinical relevant and user friendly decision tool for clinicians and managers to use during procurement processes. The present study did have some limitations, for example we only assessed the spacer fabric within a mattress. In clinical practice there are many situations where an individual can be sat in a leisure chair or hospital chair in excess of eight hours, [21] making the interface with the buttocks highly vulnerable. In addition, we limited the test to standard viscoelastic foam and spacer fabrics, future testing should consider a wide range of material properties for support surfaces including, foams, gels and spacer fabrics in addition to the material properties of covers to distinguish the related performance of designs. Future research employing computational modelling techniques could also offer significant insight into the design of support surfaces with respect to microclimate management. [22] Although the deviation in microclimate values within test conditions was low (Tables 1&2), further formal evaluation of repeatability would allow for confidence intervals to be estimated. The validity of the test protocol was provided through the standardized use of representative temperatures, interface pressures and sweat rates delivered through the physical model to simulate a sweating patient scenario.[15]

Conclusion

This paper reports a modification of a laboratory method used for the simultaneous measurement of the heat and water vapour dissipating properties of hospital mattress systems. The results revealed that foam mattresses with standard polyurethane covers have limited capacity to remove heat and moisture away from a loaded interface. The addition of spacer fabrics without active airflow provided limited benefits to moisture vapour transfer. However, with the addition of active airflow, dissipation of heat and moisture vapour transfer were observed. This was revealed by temporal changes in microclimate conditions at the support surface interface over a 24 hour period. Further parametric studies are required to establish optimal composites of support surface materials with active airflow technologies to maintain the microclimate adjacent to the skin and promote tissue health.

Acknowledgements:

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