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Enhancement of heat and mass transfer between human body and hospital mattress to reduce pressure ulcer formation

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A pressure relieving mattress has been developed along with multilayered functional bed cover to reduce the magnitude, direction and/or duration of pressure and temperature, thereby avoiding excessive tissue distortion on vulnerable parts of the body. The interface pressure and temperature between body and mattress are measured and analyzed using the parameters, such as deformation index and pressure gradient. The pressure relieving mattress developed reduces the interface pressure by 30-60%, and reduces the heat generated by ~ 3° C. Hence, the new mattress developed along with the cover sheet reduces the chance for pressure ulcer formation and improves the comfort of the patients.

Keywords: Hospital mattress, Interface pressure, Interface temperature, Pressure ulcer, Pressure relieving mattress, Pressure distribution

1 Introduction

Most of the hospitals in India are using tough mattresses, covered with a water proof coated fabric, over which a simple single layered cotton bedspread is used, which makes the patient highly uncomfortable due to the strain and heat generated on the contact areas. When the pressure on any part of the body increases beyond 33 mm mercury level, blood circulation is arrested which leads to bedsore development. There is also compelling evidence that factors in addition to pressure, also contribute to the damage and hence must also be considered when attempting to fully understand the pressure-sore phenomenon. Studies have included factors such as shear stress[1], impact loading of tissue[2], elevated temperature and humidity[3], age, nutritional status, general health, activity level[4], deformity, posture and postural change[5,6] body stature[7], and psychological deficits. Few causative factors in pressure ulcer development[8] are pressure, temperature, shearing, friction, and moisture.

Bedsores are formed at the places, where the weight of the person's body presses the skin against the firm surface of the bed. Pressure of less than 25% (the pressure of a normal mattress) can lead to bedsores. Complete muscle necrosis was observed at 100 mmHg for 6 h, the pressures of 70 mmHg for 2 h results in pathological changes within the muscle and the lower pressure of 35 mmHg for 4 h results in no change[9]. The metabolic heat generated by the body must be transferred through the bed linen; the failure of which leads to an increase in interface temperature between the body and the mattress. Elevated body temperature raises the metabolic activity of tissues by 10% for every 1^0C of temperature increase. It has been shown in animal studies that pressure induced tissue injury accelerates with increasing the body temperature[10]. Shearing and friction causes the skin to stretch and blood vessels to kink, which can impair blood circulation in the skin. For a person confined to bed, shearing and friction can occur when the person is dragged or slides across the bed sheets. The wetness from perspiration, urine or faeces can make the skin too soft and more likely to be injured by pressure. Research studies show a prevalence of pressure ulcers in 11% of the hospitalized population and in 20% of nursing home residents at any given time[11]. For patients in nursing homes[12], the prevalence of pressure sores ranges from 7% to 35%, resulting in a four-fold increase in mortality[13]. In spinal cord injured patients, pressure ulcer incidence is as high as 42 – 85% in some centers[14]. In the past the principal approach to the challenge of maintaining healthy skin and avoiding breakdown has been its prevention.

An attempt to reduce pressure on a bony prominence is based on two concepts, viz. (i) area in contact with the support surface can be increased, and

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(ii) contact can be temporarily removed or shifted to other areas. In the first case, immersion and envelopment are the phenomena that produce reduction under pressure at a bony prominence. In the second case, the change in areas of contact over time is the therapeutic consideration. To be effective, support surfaces must mould around the body to maximise contact, and then redistribute the patient's weight as uniformly as possible. They are designed to work on the principle of Pascal's law, which states that the weight of the body floating in a fluid system is evenly distributed over the entire surface; as the pressure is increasingly distributed over more body surface area, the intensity of pressure decreases over all body areas. Support surfaces also use the principle of deformation, meaning they must be capable of deforming enough to permit prominent areas of the body to sink into the support. The surfaces also must be able to transmit pressure forces from one body area to another[15-17].

To overcome the problems faced by the patients and to fulfil the basic comfort requirements of an immobile patient, an attempt has been made to develop a pressure relieving mattress with air circulation device and a multilayered bed cover sheet which is engineered for the required elongation, breathability and moisture management properties, so that it supplements the performance of the mattress.

2 Materials and Methods

The basic concept used in the design of pressure relieving support surfaces is to increase the immersion and envelope of the support surface so that the pressure is distributed to more area. Polyurethane foam, hollow polyester fibre and lyocell fibre were selected for the mattress development based on their high resiliency and flexibility.

2.1 Development of Mattress with Air Circulation Device

A mattress was developed using soft polyurethane foam with a thickness of 10 cm, provided with horizontal and vertical drill holes connected to an air circulation device to give enough air circulation through the mattress. Vertical and horizontal holes were drilled to enhance air circulation inside the foam mattress. Slots were cut on the surface of the foam to accommodate a continuous air tube and the air tube was provided with small drill holes on its surface, through which mild air circulation was maintained throughout the length and width of the mattress. Both the ends of air tubes were connected to an air circulating device which had two outlets, one for air outlet and another for air suction. This foam part of the mattress acted as the firm bottom support for the mattress, over which a needle punched nonwoven fibre web made of hollow polyester fibre was laid one over the other for a thickness of about 20 cm. The foam and fibre filled mattresses were covered by means of a knitted fabric cover, made of lyocell fibre and micro encapsulated with phase changing material.

2.2 Design features of Mattress Cover Material

The design features of the cover material warrants sufficient elastic property which plays an important role in the ability of the mattress to deform and envelope around the body. For example, a fluid filled support surface, such as a waterbed, would not envelop as water does, because the membrane cover containing the water does not have enough elastic properties. A mattress cover under high tension (over stretched or very tight bed covers) may cause locally high peak pressures. Hence, the mattress cover material is an important element of the support surface, which affects the loading in the plane of the skin and the microclimate at the interface between subject and mattress. The choice of cover material significantly influences these factors. Relatively inelastic covers tend to produce high interface stresses at the skin surface.

Primarily, the weight of the body is taken by both deformation of the support structure, e.g. foam top surface and the elastic stretching of the cover material. If the cover material is relatively in elastic, then more of the load is taken by cover material in the plane of the skin, and this tends to have a shearing effect on the skin. This form of loading can significantly contribute to the development of pressure ulcers. Cover material with relatively homogeneous elastic properties, e.g. two-way stretch can be used to minimize the stretching effect. Hence, Lyocell knitted fabric which is capable of stretching in both length and width wise directions is selected as the cover material for the mattress.

2.3 Development of Surface Finishing of Mattress Cover using Microencapsulated Phase Changing Material

Effective thermoregulation of the patient's body is ensured by designing the cover material so as to absorb the heat developed in the interface between the body and the multilayered mattress by coating microencapsulated phase-changing material on the knitted fabric cover. The PCM was dissolved in hot water and after 24 h incubation; 0.5 mL of the liquor was transferred to micro centrifuge tubes followed by centrifugation. The pellets obtained were treated with phosphate buffer (*p*H 7.0, 0.3 M), fixed with glutaraldehyde (1%) for 1 h at 4°C and further treated with 10% absolute alcohol in a sequential manner to obtain the microcapsule. Fabric samples were prepared, weighed, washed and rinsed with water. The required amount of microencapsulated PCM was mixed with one litre of water. The fabric samples were rinsed in water, soaked in the prepared finish solutions for 30 min and then sent through padding mangle for uniform application of finish after which it was dried at 120°C and cured at 150°C without applying pressure. Finally, the samples were analyzed for its thermo-regulating property. Knitted fabric was selected as the base fabric to apply PCM, because of its ability to elongate and match with the body contour. The specifications of the phase changing material used for microencapsulation were carbon number: C (18); name: *n*-Octadecane ($C_{18}H_{38}$); concentration: 35-50 gpl; boiling point: 316°C and material-to-liquor ratio: 1:2.

2.4 Testing Procedure

The performance of mattress with knitted cover sheet was analyzed for the interface pressure, temperature and comfort characteristics by subjective and objective analysis. The distribution of pressure and shear forces were determined by a number of physical properties including stiffness and elasticity of the cover material.

2.4.1 Measurement of Interface Pressure between Body and Mattress

A new pressure measurement system with self-inflatable balloon, Kikuhime, (TT Medi Trade, Soleddet 15, DK 4180 Soro) was used to measure the interface pressure between body and mattress. The instrument was composed of two self inflatable air filled balloons, a connecting tube and a measuring unit (Fig. 1).

The small, flexible, air-filled pressure bladder has a dimension of 30 × 38 mm and thickness of about 3 mm when calibrated to zero, and the other one has the dimension of 120 ×100 mm. The outer membrane of the balloons was made of polyurethane membrane of the thickness of about 200 µm for normal size, and 100 µm for smaller size. Inside the balloon also a polyurethane foam sheet (3 mm) was built. Normal size balloon was found suitable for measuring a pressure at sacrum area, and so on. The smaller one was found good for pressure measurement at a limited area like a bone prominent area as the heel. The instrument is capable of measuring pressure up to 200 mmHg.

2.4.2 Measurement of Body Temperature Using LM35

The LM35 series are precision integrated-circuit temperature sensors by Texas Instruments, Texas, with an output voltage linearly proportional to the Centigrade temperature. Thus, the LM35 has an advantage over linear temperature sensors calibrated in Kelvin, as the user is required to subtract a large constant voltage from the output to obtain convenient centigrade scaling. The LM35 does not require any external calibration or trimming to provide typical accuracies of ±¼°C at room temperature and ±¾°C over a full temperature range from −55°C to 150°C. The LM35 with low output impedance; linear output and precise inherent calibration make interfacing to readout or control circuitry especially easy. It can be used with single power supply.

3 Results and Discussion

The performance of the pressure relieving mattress and the cover material developed was analyzed by measuring the interface pressure, temperature, pressure gradient and deformation index. The cover material coated with phase changing material was analyzed using a scanning electron microscope and a differential scanning calorimetry. Figure 2 shows the

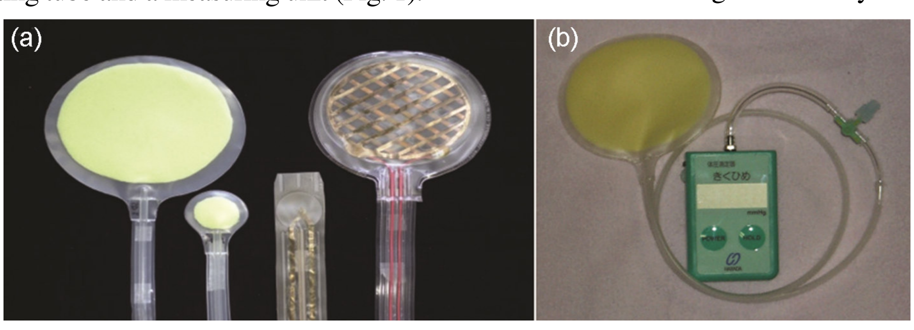

Fig. 1— (a) Inflatable balloons for pressure measurement and (b) pressure measuring device

Fig. 2— SEM images of PCM coated fabric with magnification levels of (a) × 500, (b) × 1000, (c) × 2000

scanning electron microscopic image of the phase changing material coated knitted fabric. The PCM capsule size is about 10 microns. SEM photograph shows deposition of PCM on the fabric surface.

3.1 DSC Analysis of Microencapsulated PCM

DSC test results show that the PCM coated knitted fabric is capable of absorbing heat in the body temperature range (Fig. 3). The heat flow value remains constant up to a temperature around 26º C. It is observed that the shoulder of the peak becomes wider when comparing this microencapsulated *n*-octadecane with normal *n*-octadecane PCM. The phase transition of microencapsulated PCM occurs between (endothermic peak) 26º C and 40º C. This phenomenon indicates that the melting peak temperatures of the microcapsules are higher than that of normal n-octadecane, which may be attributed to low thermal conductivity of the shell materials.[18]

In the same way, cooling (exothermic peak) appears from 36 ° C to 25 ° C. The onset temperature of both endothermic and exothermic peaks varies from the original DSC curves of n-octadecane because of the shell material. The thermal conductivity of the shell materials affects the heat transfer rate from the outside to the PCM inside the shells, which, in turn, increases the phase change temperatures (latent heat) of the microcapsules[19].

3.2 Interface Temperature between Body and Mattress

The interface temperature between body and mattress was measured using the temperature measuring instrument developed. The LM35 series are precision integrated-circuit temperature true sensor whose output voltage is linearly proportional to the Celsius temperature.

When a patient lies for a long duration on the bed, unbearable heat is generated in the contact areas. This excessive heat creates restlessness in patients. The

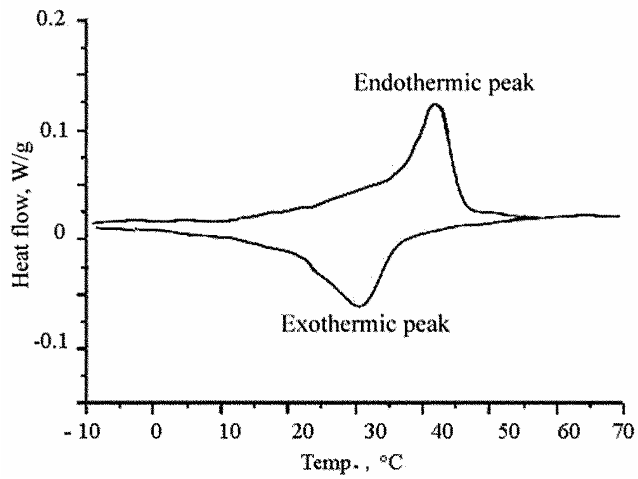

Fig. 3— DSC analysis of PCM

Table 1– Interface temperature between body and mattress

Mattress	Interface temperature, ° C				
	Initial temperature ° C	After 10 min	After 20 min	After 30 min	After 40 min
Hospital mattress	32.5	33.7	34.0	35.2	35.6
Without air circulation device	32.3	32.6	32.8	33.0	33.2
With air circulation device	32.1	32.0	32.0	31.9	31.8

increase in temperature is measured on the patient body while lying on normal hospital bed and on the mattress developed. The room temperature was 31º C and the initial body temperature was 32.5º C. The body temperature measured after every 10 min is given in Table 1.

Temperature is also measured with and without air circulation system. The result shows that there is a considerable reduction in the raise in temperature when compared to the normal hospital bed. The pressure reducing mattress with air circulation system reduces the heat generated in between the body and the top surface of the mattress. The air circulation device pumps air in through one nozzle and the air is sucked out through the other nozzle. Air leaks out through the small drill holes and ensures mild air circulation throughout the mattress, which reduces the heat generated by the body. The presence of dead air acts as thermal insulator and causes raise in temperature, whereas moving air assists in conducting the heat away through the circulated air. Hence, the mattress developed reduces the interface temperature and confirms the efficiency of the mattress in ensuring comfort to the patient.

3.3 Interface Pressure between Body and Mattress

One method of evaluating the weight of the body being transferred to the mattress surface is through the use of interface pressure (IP) measurements with pressure sensors. IP is a measure of the sum of forces being transmitted between the body and the mattress over the area of the pressure sensor. The pressure exerted on the body parts due to its own weight is measured using a Kikhume pressure sensor. When the pressure on any part of the body increases beyond 33 mm mercury level, blood circulation is arrested which leads to bed sore development. To avoid excessive pressure, the area of contact of the body with the bed has to be increased. An increase in the contact area between any two objects will result in lowering peak pressure. This objective is achieved by developing a super soft polyurethane bed with hollow fibre filled mattress. The larger area of contact by the soft bed is also complemented by using knitted fabric in the top layer. The knitted fabric ensures good elongation, confirmation to body contour and reduced shear on the body. The interface pressure developed between body and mattress is measured for people of different weight range (Table 2) for both standard hospital mattress and newly developed pressure reducing mattress.

From the interface pressure measurement on the hospital mattress and the novel mattress developed, it can be observed that pressure developed on the body in hospital mattress is more than 33 mm Hg in certain areas of the body, like head, mid-back, hip, buttocks and heel. As the body weight increases, the interface pressure also increases proportionately. The interface pressure is reduced drastically in the case of novel mattress. The reduction in pressure ranges from 30% to 66%. This reduction in pressure is due to the highly soft nature of the hollow fibre filled part of the mattress which deforms to fit the shape of the body, thereby increasing the area of contact between the body and the mattress, leading to pressure distribution to more area. The terminologies used to explain these phenomena are ‘Immersion’ and ‘Envelopment’. Immersion allows pressure concentrated beneath a bone to spread over the surrounding tissue. By increasing immersion, the potential for pressure reduction increases as the body weight is shifted to areas around other bony prominences. Envelopment describes a support surface ability to deform around irregularities on the surface, without causing a substantial increase in pressure. Due to higher envelopment and immersion of the soft mattress, body weight is distributed to more area and the interface pressure is reduced to a great extent.

3.4 Measurement of Deformation Index

Unevenly distributed weight rather than peak interface pressure is the main causative factor for pressure development. This concept is also supported by the experience of sea divers, who do not suffer

Table 2−Interface pressure between body and mattress

Body part	Pressure developed, mmHg														
	45 kg			52 kg			60 kg			71 kg			91 kg		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Head	65	32	51	63	31	51	50	27	46	69	33	52	62	30	54
Top shoulder	16	11	31	17	11	35	11	11	0	20	12	40	16	11	31
Shoulder blade	15	12	20	21	16	33	24	16	33	32	18	44	37	17	54
Mid back	23	13	43	25	17	32	10	9	10	27	16	41	36	20	44
Hip	40	17	58	22	16	28	20	18	10	18	12	33	29	20	31
Buttocks	27	22	19	28	21	33	34	20	41	27	18	33	35	20	43
Thigh	6	5	17	11	9	18	10	5	50	9	8	11	13	11	15
Knee	10	5	50	8	5	38	7	5	29	7	5	29	5	3	40
Calf	20	12	40	12	8	33	32	11	66	11	9	18	16	8	50
Heel	40	25	38	53	28	47	63	30	32	65	26	60	63	33	38
Elbow	6	2	67	7	3	57	29	18	38	8	6	25	12	9	25

The values 45,52,60,71 and 91 kg are the body weight.
A− Hospital mattress; B− Developed mattress; C− % Reduction in pressure.

Table 3– Deformation index of body

Body weight	Total pressure, mm Hg		Average pressure, mm Hg		Peak pressure, mm Hg		Deformation index	
Kg	Hospital mattress	Developed mattress	Hospital mattress	Developed mattress	Hospital mattress	Developed mattress	Hospital mattress	Developed mattress
45	268	152	24.36	14	65	32	1.66	1.28
52	267	165	24.27	15	63	31	1.59	1.06
60	290	170	26.36	15.45	63	30	1.39	0.94
71	293	163	26.64	14.81	69	33	1.59	1.23
91	324	186	29.45	16.90	63	33	1.14	0.95

from tissue damage because the higher hydrostatic pressure is applied evenly all over the body. Therefore, use of an index for pressure differentials or tissue deformation across the skin contact area may be a better guideline for support surface selection, particularly as this criterion is related to patient's comfort. The deformation index can be estimated by comparing peak to average pressure, as shown below:

$$\text{Deformation index} = \frac{\text{Peak pressure - Average pressure}}{\text{Average pressure}} \quad \ldots (1)$$

The deformation index, for the above-mentioned five different weight ranges are given in Table 3. Total pressure is the sum of pressure measured on the eleven contact points of the body parts, and the average pressure is calculated by dividing the total pressure by the number of contact points; the peak pressure is found to be the maximum pressure measured among the eleven points. These parameters are calculated for the hospital mattress and the pressure relieving mattress developed separately for all the body weight ranges and then the deformation index is calculated and compared.

Lower deformation index value implies that the strain on the body is minimum whereas, higher deformation index shows more strain on the body parts. The deviation of peak pressure from average pressure for the hospital mattress is high and the deformation index is around 1.6 which shows that the peak pressure is 2 -3 times more than that of average pressure. However, in the pressure relieving mattress developed, the deformation index ranges from 0.95 to 1.28 which is much lower than that of the hospital mattress. From the reduction in the deformation index, it can be ascertained that the strain on the body and skin is reduced considerably in the mattress developed. The mattress developed gives an appreciable reduction of 23- 33% in the deformation index.

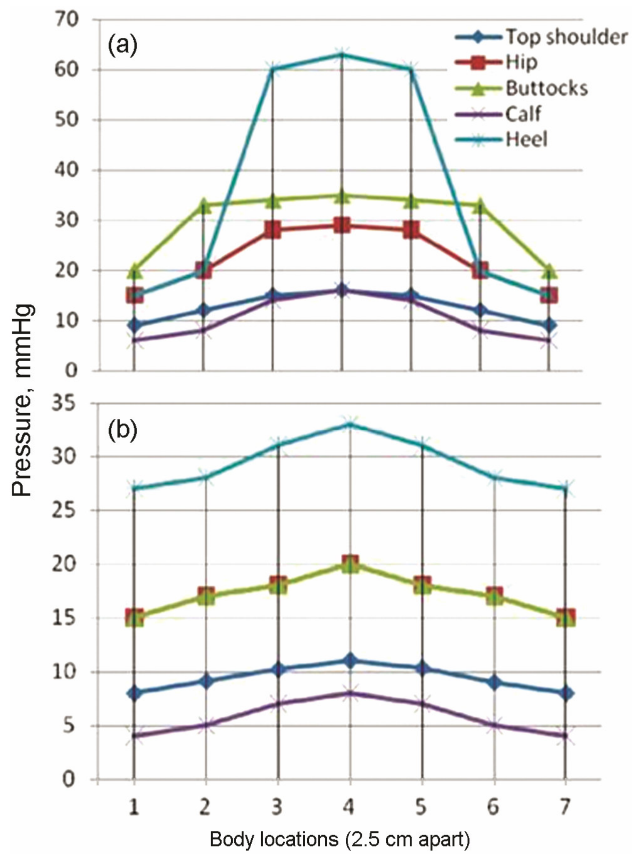

Fig. 4— Pressure gradients (a) hospital mattress and (b) developed mattress

3.5 Measurement of Pressure Gradient

Pressure gradient measurement describes the amount of change in the pressure over a distance (generally over a short distance of less than one inch) from one section of the support surface to another. However, in general, pressure gradients represent a continuum of values over the distance measured. If the pressure across a surface is plotted, the pressure gradient would be the slope of the curve. Figure 4 shows the pressure gradient curve on the areas which are prone to skin damage measured on the hospital mattress and the novel pressure relieving mattress.

Steep gradients between applied pressures over adjacent areas of soft tissue increases the shearing force, which damages the skin tissues. Measurement of change in pressure over 2.5 cm gap in novel mattress shows that the change in pressure is very gradual with the difference ranging from 1 mmHg to 3 mmHg, whereas in hospital mattress, the change in pressure is more than 10 mmHg which causes more shear force on the skin. The pressure gradient curve also indicates the amount of shear force experienced by the skin. The immersion created in the pressure relieving mattress and the knitted cover fabric leads to a gradual reduction in pressure and hence the shear force on the skin is reduced.

4 Conclusion

A pressure relieving mattress was developed along with multilayered functional bed cover to reduce the magnitude, direction and/or duration of pressure, thereby avoiding excessive tissue distortion on vulnerable parts of the body. From the interface pressure measurement on the hospital mattress and the novel mattress developed, it can be observed that the reduction in pressure ranges from 30% to more than 60%. This reduction in pressure is due to the highly soft nature of the hollow fibre filled part of the mattress which deforms to fit to the shape of the body, thereby increasing the area of contact between the body and mattress, leading to pressure distribution in more area. The pressure relieving mattress with air circulation system reduces the heat generated between the body and the top surface of the mattress by around 3° C and keeps the body comfortable. The deformation index, which is a measure of the difference between the peak and average pressure, is reduced by 23 - 33% in the mattress as compared to the hospital mattress. Hence, the new mattress developed along with the cover sheet may provide comfort to the patients.

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