The recovery characteristics of soft tissues following repeated loading

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Abstract—Pressure relief at the patient support interface is important to avoid tissue breakdown by ischemia, particularly with debilitated subjects. However, there are still few guidelines to indicate the level of relief required for specific tissue areas. This paper examines the nature of the tissue recovery to repeated loading in compression. Loading was produced by (1) external application using an experimental system attached to the sacrum and (2) ischial support on a dynamic cushion. In both cases, the interface pressures applied for a prescribed time were related to changes in transcutaneous gas tension, the latter being an index of tissue viability. Results indicate two distinct responses to repeated loading. The normal response provides rapid and complete tissue recovery to unloaded values of transcutaneous oxygen tension. This was observed with all normal subjects and some of the debilitated subjects. There was also a group of debilitated subjects who demonstrated impaired and delayed tissue recovery. It is proposed that they are at most risk of developing tissue breakdown.

Key Words: *cushion, interface pressure, ischemia, pressure sore, tissue breakdown, transcutaneous gas tension.*

INTRODUCTION

Compression is the predominant form of loading in situations in which the body interfaces externally with load-carrying devices. For example, it is relevant in the provision of support surfaces for wheelchair-bound individuals and in the design of prosthetic sockets. The resulting

interface pressures are supported by the intervening soft tissues and stress and strain fields are established within the interstitium. This mechanical environment may be sufficient to impair the integrity of the local blood supply and lymphatic circulation. If the interface conditions are prolonged, cell necrosis will follow, leading to possible tissue breakdown and development of pressure sores.

In the clinical setting, patients are encouraged to move regularly to reduce the periods of persistent interface pressures. Pressure relief can be performed by regular turning and lift-off from the support surface for all individuals, particularly those who are insensitive. Active pressure relief provided by external power is also possible with various support surfaces, including ripple cushions and mattresses. These dynamic devices are in regular clinical use and provide continual transfer of the body weight across support areas.

The compression characteristics of the soft tissues will undoubtedly influence their susceptibility to the breakdown process. Areas at particular risk will have a minimal soft tissue covering over bony prominences. These present an inherent high compressive stiffness to deforming loads. The overall properties of the skin/soft tissue composite in compression have received relatively little attention. One of the few such *in vivo* studies (2) determined the estimated values of compressive stiffness derived from tissue recovery that were on average 25 percent higher than those derived from tissue indentation. This was evident for subjects of different ages and for tissue from differing sites.

The nature of the recovery is determined by the resilience of the specific tissues and the tissue structures, including the blood and lymph vessels. The soft tissues

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exhibit viscoelastic behavior (7) and thus the nature of the recovery will depend on the rate and time of loading as well as its magnitude. Short term loading generally produces elastic recovery, while long term loading results in the creep phenomenon and requires a longer time for complete tissue recovery.

It has been well established that tissue damage is often apparent following prolonged loading even at relatively low level pressure intensities (11). Any significant period of loading will result in vascular occlusion. On load removal, there will be a period of increased blood flow through the tissues which had been ischemic. This phenomenon, termed reactive hyperemia, is a consequence of a local regulatory mechanism where the arterioles are dilated and the resistance to blood flow is reduced. The identity of the vasodilator agents remains unclear, although there are many possible candidates for the role, such as histamine and prostaglandin-like substances. It has been shown that the nature of their release will be affected by the time period of ischemia (12).

RELATED STUDIES

The Oxford Pressure Monitor provides an accurate measure of the pressure distribution at the patient support interface (5). However, the measurement of interface pressure alone is not sufficient to alert the clinician of potential areas of tissue breakdown. Some measure of tissue viability is required for this, which is dependent on an adequate supply of nutrients as supplied by the blood.

Transcutaneous gas monitoring has proved an accurate and repeatable method to investigate the effects of loads on tissue viability (10). This work was extended to investigate the effects of prolonged loading at the sacrum on tissue viability on a mixed group of debilitated subjects, who were considered to be particularly prone to the development of pressure sores (3,4). Results indicated a wide range of integrated pressure and time that the soft tissues will tolerate. For example, the applied pressures to produce a 50 percent reduction in the unloaded resting value of transcutaneous oxygen tension (T_cPO_2) ranged from 3.0 kPa (22 mmHg) to 12.2 kPa (92 mmHg). This emphasized the individual nature of the tissue response which should be determined before clinical guidelines of safe pressure levels can be established. In these tests, the T_cPO_2 levels were allowed to recover following removal of the load. Recovery to unloaded values before the test generally occurred within 1 minute, although in some cases complete recovery took considerably longer.

This paper describes two separate investigations of recovery characteristics of soft tissues subjected to externally applied cyclic loads. In the first, the effects of repeated loading on the tissue viability at the sacrum were determined. The second study involved monitoring subjects who were supported on a dynamic cushion which produced repeated loading at the ischial tuberosity. Both studies included young healthy subjects and debilitated subjects who may be considered to be at risk of developing pressure sores.

METHODS AND MATERIALS

The T_cPO_2 was measured using a Radiometer TCM1 TC Oxygen Monitor connected to a chart recorder. The electrode (Radiometer E5243) was calibrated to a zero level of oxygen in a bisulphite buffer solution and to atmospheric oxygen pressure. In the later tests, this system was superseded by a Radiometer TCM3 Monitor with a combined oxygen and carbon dioxide electrode (Radiometer D841). The temperature control system of both monitors was set to 44.5 degrees Celsius. This temperature ensured that local arterialization or maximal vasodilation was achieved in the cutaneous tissue underneath the electrode. The variation in room temperature over the course of the investigation was 24 ± 2 degrees Celsius.

Repeated loading of sacral tissues

The experimental system to provide loading of the soft tissues consisted of a balanced beam with a moveable weight at one end counterbalancing a loading pan directly above a rigid indenter (**Figure 1**). The transcutaneous gas electrode was incorporated into the indenter. As illustrated in **Figure 2**, the 38 mm indenter was curved along its edges to minimize the effects of high stresses at the periphery of the indenter/soft tissue contact area (10, 14). The indenter was attached to the cleaned skin using a double-sided adhesive ring. Careful alignment of the experimental system ensured that the loading was perpendicular to the skin surface, thus avoiding significant shear forces.

Stable thermal vasodilation was obtained after about 15 minutes. The tissues were loaded for 10 to 15 minutes and then unloaded for 2 to 5 minutes. The load was then reapplied and the cycle repeated on at least two more occasions. The pressure at the interface between the indenter and sacrum was measured for each applied load using one cell of the Oxford Pressure Monitor. A moderate interface pressure of about 4 kPa (30 mmHg) was employed; this pressure level was observed to produce a

Figure 1.
Experimental system to provide repeated loading at the sacrum.

significant initial reduction in T_cPO_2 levels without providing complete occlusion. The pressure was measured before and after the main test procedure. A maximum pressure variation of 0.40 kPa (3 mmHg) was estimated from the actual interface value during the indentation test (4).

These tests were performed at the sacral area, a common site of tissue breakdown. This relatively flat area permitted the indenter to make total contact with the skin surface. The subjects were required to remain in a relaxed prone position on a standard hospital mattress during a maximum 1-hour period of the test. The thickness of the experimental tissue site was measured with skin-fold calipers. Blood pressures were recorded for each subject.

Measurements were made on eight normal healthy subjects and six debilitated subjects; the latter had no recent

history of sacral pressure sores. The debilitated subjects, including four with multiple sclerosis, had been admitted to the Mary Marlborough Lodge Disabled Living Research Unit in Oxford for a 1- to 2-week assessment.

Tissue relief with a dynamic support cushion

The cushion is comprised of 48 individual, cylindrical shaped, soft inflatable bellows arranged in eight rows of six (Talley Group Ltd, UK). Each row of bellows may be in an inflated or deflated state as dictated by the control unit. Individual bellows are instrumented with one pneumatic cell that is connected to the Oxford Pressure Monitor (5). The instrumented cushion and the control unit, which permitted alteration of cycle time, are illustrated in **Figure 3**.

The combined transcutaneous electrode was attached

over one ischial tuberosity for each subject. The subject was then positioned carefully on the instrumented cushion that was supported by a plywood base in a standard wheelchair. The single bellows of the cushion which supported the ischial tuberosity was noted.

The pressure distribution across six rows of the cushion was monitored sequentially throughout the test. At the same time, the transcutaneous gas tension levels were continuously recorded. The test continued for a minimum of 20 minutes to allow at least three complete cycles of the cushion. The position of a subject is illustrated in **Figure 4**.

Tests have been performed on six normal healthy subjects and on an increasing number of debilitated subjects. Twenty-two subjects with an age range of 24 to 78 years have been tested and include six with spinal cord injury,

three with an amputation, two with cerebral palsy, and two with Guillain-Barre' syndrome.

RESULTS

Repeated loading of sacral tissues

The tissue response from a group of young healthy subjects has revealed a consistent pattern, as typified in **Figure 5**. On load application, there was a significant reduction in T_cPO_2 levels which partially recovered during the loading period. Following load removal, tissue recovery to unloaded T_cPO_2 levels was achieved rapidly. The apparent effect of the applied load diminished with successive cycles.

By comparison, some of the debilitated subjects produced a response clearly differing from the normal (**Figure**

Figure 2.

Close-up of transcutaneous gas electrode mounted at the center of a rigid indenter. It is attached to the skin surface using a double-sided adhesive ring.

Figure 3.

Dynamic support cushion and associated control unit. Individual cushion bellows are instrumented with single pneumatic cells connected to the pressure monitoring system (not shown).

6). In these cases, there was no recovery during the loading period; following load removal, recovery was not fully achieved within the 2-minute period. Subsequent loading had a cumulative effect on the diminution of T_cPO_2 levels.

Tissue relief with a dynamic support cushion

Initial studies with healthy male subjects indicated that if half the total number of bellows were deflated simultaneously, localized interface pressures over the other half of the cushion could reach values in excess of 110 mmHg (1). This was considered to be unacceptable and so the control circuit was modified to provide only one deflated row of bellows at any one time of the cycle. In addition, the automatic inflation and deflation were restricted to the posterior four rows of bellows. This produced pressure relief corresponding to those sensitive areas such as the ischial tuberosities where pressure sores are most likely to occur, while providing permanent support under the thighs. This arrangement ensured that maximum interface

pressures were reduced, generally to below 70 mmHg. The bellows were enclosed in a soft foam core to improve lateral stability, which is particularly useful for patients with uncontrollable movements. The cycle time was set within narrow limits of 5 ± 1 minutes.

The response of a healthy male subject is indicated in **Figure 7**. When the subject initially sat down on the cushion with full support under the ischial tuberosity there was a dramatic reduction in T_cPO_2 levels. These levels recovered partially as the support pressure fell on the first deflation cycle. On subsequent cycles the effect of support pressures diminished, while the deflation phase of the cycle became increasingly effective. At the end of the test, with the cushion cycle switched off and deflated support under the ischium, the tissue oxygen recovered to unloaded values.

Figure 8 illustrates the response of a debilitated subject with syringomyelia. In this subject, a significant reduction in the T_cPO_2 level was followed by recovery on successive deflation phases of the cushion cycle. **Figure 9**

Figure 4.

Equipment used to monitor a subject positioned on a dynamic support cushion in a standard wheelchair. Note the Oxford Pressure Monitor (foreground) and the transcutaneous gas monitoring system.

shows the response of a spinal cord injured subject. The ischial pressures in this subject were consistently low and associated with small changes in T_cPO_2 levels over the prolonged sitting period. In both cases, the T_cPCO_2 levels increased as the subjects sat down, but thereafter remained constant at about 5.3 kPa (40 mmHg).

By comparison, another patient with a spinal cord lesion exhibited a significant reduction in tissue oxygen level that was unaffected by changes in the cushion cycle (**Figure 10**). Thus, after 8 minutes of constant support by the cushion involving about 1.5 complete cycles, there was no evidence of tissue recovery. At this time, the subject required maximal lift-off from the cushion (about 90 seconds) to restore T_cPO_2 levels, although these did not regain unloaded values during the first lift-off. During the second lift-off, the unloaded value was attained but was followed by diminution of T_cPO_2 levels to below 1.3 kPa (10 mmHg) as the subject was resupported on the cushion. The T_cPCO_2 levels followed a mirror-image pattern of the oxygen levels reaching a maximum value close to 13.3 kPa

(100 mmHg) prior to initial subject lift-off. It is worthy of note that, on examination, the ischial tuberosities of this subject displayed erythema following the sitting period. Four of the 22 debilitated subjects tested (18 percent) demonstrated these features.

DISCUSSION

This paper describes a series of studies which use the measurement technique for transcutaneous gas tension to assess the recovery characteristics of soft tissues following repeated loading. These measurements were performed with heated sensors: the absolute values of T_cPO_2 and T_cPCO_2 at physiological temperatures are small and any changes would have to be interpreted with caution. It is accepted that, at the elevated temperatures, normal blood flow regulation was abolished and the perfusion under the electrode was mainly determined by the arterial blood pressure. Although the absolute

Figure 5.

Changes in skin oxygen levels as a result of repetitive loading at the sacrum of a normal healthy female aged 22 years. ($\downarrow$ indicates application of load; $\uparrow$ indicates removal of load.)

Figure 6.

Changes in skin oxygen levels as a result of repetitive loading at the sacrum of a 42-year-old male with multiple sclerosis.

Figure 7.

Skin surface oxygen levels at the ischium of a healthy normal 29-year-old male. The subject is seated on the dynamic support cushion.

Figure 8.

Skin surface oxygen levels at the ischium of a 70-year-old female with syringomyelia. The subject is seated on the dynamic support cushion.

Figure 9.

Skin surface oxygen levels at the ischium of a 30-year-old male with a spinal cord injury. The subject is seated on the dynamic support cushion.

Figure 10.

Skin surface oxygen levels at the ischium of a 22-year-old male with a spinal cord injury. The subject is seated on the dynamic support cushion. (↑ indicates subject lift-off during the test.)

T_cPO_2 levels measured were undoubtedly elevated for normal healthy subjects and debilitated subjects, it was the relative changes which were of interest.

The tissue response of all subjects to cyclic loading at the sacrum could be characterized into one of two distinct forms, both having physiological implications. The response shown in **Figure 5**, in terms of loading and recovery characteristics, suggests a normal physiological reaction, as typified by reactive hyperemia. Similar responses were also observed at the ischial tuberosity, where subjects were supported on the pressure relieving support cushion (**Figures 7, 8, and 9**). In these cases involving a normal healthy subject and two debilitated subjects, there is clearly an active vasomotor response mechanism which produces a diminished effect on subsequent loading cycles. If the cycles were continued the reduction in T_cPO_2 levels would presumably reach an asymptotic level, which would be a function of interface pressure. This normal response may be a direct result of the mechanical stresses that can transduce the release of biochemicals such as histamine and prostaglandins, which are known vasodilators (13). The normal response may also be partly due to the anoxic state of the tissue during the loading phase. The fact that there is partial recovery during the loading period may also be explained in terms of a viscoelastic material exhibiting stress relaxation with time under constant deformation.

By comparison, the alternative response, apparent at the sacrum (**Figure 6**) and ischial tuberosity (**Figure 10**), suggests an impaired control mechanism. The time (2 minutes) permitted for tissue recovery was inadequate and would inevitably lead to diminished oxygen levels on repeated loading and eventual tissue ischemia.

Using a theoretical model, effects of reactive hyperemia on tissue recovery following ischemia have been discussed (8). The presence of reactive hyperemia shortened the time intervals for the initial return of tissue oxygen levels and for the washout of accumulated lactic acid. Additionally, it was noted that the time required for removal of lactic acid from the tissues was much greater than that necessary for reoxygenation. Therefore, oxygen may not be the only key species involved in tissue recovery and in the control of related physiological responses.

In the present study, the degree of anaerobic respiration is represented by the T_cPCO_2 levels and illustrated only in **Figure 8** and **Figure 9**. For all subjects displaying a normal response, these levels stabilized between 5.0 kPa (38 mmHg) and 6.7 kPa (50 mmHg) throughout the sitting period, as illustrated in **Figure 8** and **Figure 9**. However, the abnormal response showed a considerable build-up of

T_cPCO_2 levels to values well in excess of 6.7 kPa (50 mmHg) when the subject was supported for more than a few minutes (**Figure 10**). It may be this biochemical marker which determines the susceptibility to tissue breakdown.

Previous studies by the author showed little correlation between tissue response and the nature of the clinical condition (4). This has also been suggested in the present study of subjects with the same clinical condition such as multiple sclerosis or spinal cord injury: they demonstrated either one or the other distinct response to repeated loading. It is well established in the clinical setting that some spinal cord injured subjects may sit every day for many years without any tissue damage while others are at high risk of developing pressure sores soon after injury. This emphasizes the importance of intrinsic factors in determining susceptible subgroups of patients.

Clearly, the group with the impaired mechanical response requires adequate tissue relief not provided by the dynamic support systems. Manual lift-off provided some relief, although the required frequency of every 5 to 7 minutes would be prohibitive even for the most active. Certain prophylactic measures may be attempted, particularly with those subjects with less active capabilities. For example, rebuilding tissue bulk using electrical stimulation techniques may prove successful for spinal cord injured subjects (9). This should also improve the tissue blood flow, which is reduced in this patient group (6).

CONCLUSIONS

The experimental approach of this study to monitor the viability of tissues subjected to repeated loading regimes provides a means to identify potential areas of tissue breakdown. A specific tissue response has been observed that is suggestive of an impaired physiological control mechanism. Subjects demonstrating this response are at particular risk and require extensive nursing care and adequate pressure relief mechanisms. Results from this study can also establish the intervals of pressure relief necessary to avoid tissue compromise to the individual subject.

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