Temperature-Modulated Pressure Ulcers: A Porcine Model

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ABSTRACT. Kokate JY, Leland KJ, Held AM, Hansen GL, Kveen GL, Johnson BA, et al. Temperature-modulated pressure ulcers: a porcine model. Arch Phys Med Rehabil 1995;76:666-73.

• *Objective:* A reliable porcine model was developed to facilitate investigations of pressure ulcer formation, healing, and prevention. In the present study, it was specifically used to study the relationship between applied temperature, applied pressure, and time of application in the formation of cutaneous and deep tissue injuries. *Design:* An apparatus and procedure were created to simultaneously apply 12 metal discs (each with a diameter of 51mm) on the dorsal aspect of the swine, all at an equal pressure of 100mmHg, for a 5-hour period, while servo-controlling disc temperatures at either 25, 35, 40, or 45 degrees C. *Results:* The severity of the resultant tissue injuries correlated with an increase in applied temperature. No damage was observed in the superficial or deep tissues underlying the sites of the 25°C pressure applicators. In general, only deep tissue damage resulted from the application of a 35°C temperature, whereas the application of higher temperatures caused both cutaneous and subdermal damage (the extent of necrosis being greater at the 45 degrees C sites). There was a high degree of reproducibility of these results among a large population of sites per temperature (n = 64) and number of animals investigated (n = 16). Furthermore, subsequent healing (monitored up to 4 weeks) was uniform for the degree of induced damage. Insights into pressure ulcer formation were also sought via systematic examination of histological sides and postmortem visual assessment over the 4-week period. *Conclusion:* It was concluded that this animal model of temperature-modulated pressure ulcers has the potential for significant use in all major areas of this field, ie, wound formation, healing, and prevention.

The occurrence of pressure ulcers have an extensive impact on patients and health care providers. The decreased quality of life, the loss of productivity, and the high cost of treatment are among the major impacts. Chronic ulcers are estimated to have a prevalence of 0.3 per 1,000 persons in the United States,[1] and annual costs are estimated to be 3.5 to 7 billion dollars.[2] This prevalence is believed to be 3% to 10% of all hospitalized patients and to be as high as 20% to 32% among the hospitalized elderly and patients with long-term disabilities.[1]

Although there is extensive literature about pressure ulcers, no clear consensus is apparent for the cause of such wounds.[3-7] To illustrate the prevailing uncertainties, animal studies have shown that the spatial progression of a pressure ulcer may occur in either direction, ie, from muscle upwards[6] and from upper dermis downwards.[7] The application of elevated pressure over time on bony prominences is believed to be the primary causative factor of these ulcers.[1] Other ancillary factors include the magnitude of shear, presence of friction, and/or moisture.[5] It has been shown, however, that pressure thresholds for wound causation (defined by other models) are routinely surpassed clinically without apparent damage to tissue, eg, in paraplegic patients without other complications as reported by Patterson and Fisher.[8] Other patients may experience tissue damage before such thesholds are reached; hence, supplementary physiological factors that warrant consideration include age, nutrition, psychologic abnormalities, sensory loss, mobility, and/or temperature.[1]

The role of temperature in the causation of pressure ulcers has been the least explored. Nonetheless, the following suggests a strong link between higher temperatures and pressure wound causation. Higher temperature causes an increase in tissue metabolism and oxygen consumption (about 10% for 1 degree C).[9] The heightened need for nutrients and oxygen cannot be fulfilled, however, because of tissue compression and resulting ischemia. Studies indicating an increase in local skin temperature caused by both pressure application[10] and insulating effect of cushions/mattresses[11] appear to affirm temperature as a significant factor in pressure ulcers. The role of temperature either in the causation or prevention of pressure ulcers must be determined.

The main focus of the present study was to develop a reliable porcine model for the creation and assessment of temperature-modulated acute pressure ulcers. Protocols, instrumentation, and methodologies for creating reproducible wounds are established as an essential part of this model. The reproducibility and consistency of the thus-created wounds were established by histological evaluation of the application sites and by postmortem visual inspection of each tissue layer beneath the applicator site. The use of a swine model was motivated by the similarities in skin properties, in physiological structure and function, and in susceptibility to conditions such as diabetes, paraplegia, and hypo/hyperthermia. Concurrent with the model development, information was accumulated concerning the cause of cutaneous and/or deep tissue damage and about the relative severity

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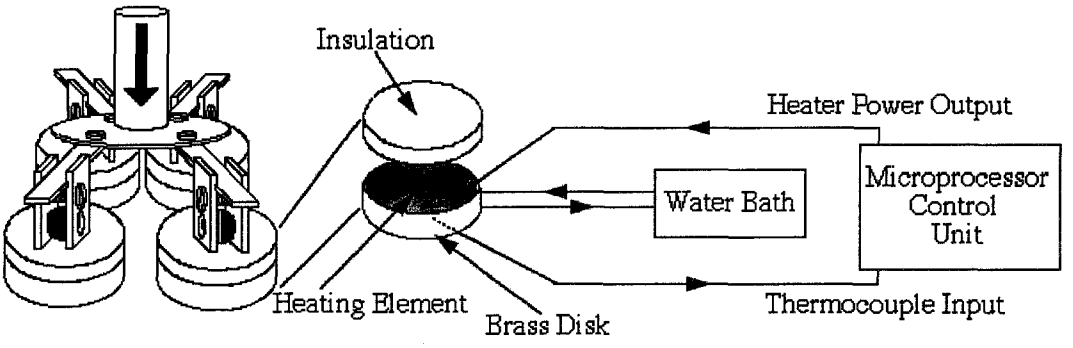

Fig 1—At the left is pictured a cluster of four disks whose function is to apply pressure and temperature to preselected wound sites. The temperature modulation was obtained using a microprocessor-controlled unit. Cooling was provided by a water bath and heating by electrical resistance wire, and temperatures were maintained within ±0.5°C.

of wounding at different levels of surface temperature modulation.

MATERIALS AND METHODS

Pressure-Temperature Applicator

A device capable of applying uniform and controlled pressure and temperature to preselected cutaneous sites was developed. A set of four pressure-temperature applicators was mounted on a support fixture that allowed for independent positioning of each applicator to adapt to the contour of the animal (fig 1). Twelve pressure-temperature applicators were used in each experiment (ie, three independent support fixtures). Each pressure-temperature applicator consisted of a brass disk, 51mm in diameter and 10mm thick, a Kapton-encased heating element, and an 8-mm thick disk of polystyrene that thermally guarded the heater. To facilitate arbitrary modulation of the applied temperature at levels both below and above normal skin temperature, passages were machined into each brass disk to accommodate inflow and outflow of cooling water. As seen in figure 1, the four applicators of a given set are connected to a platform that accommodated deadweights (not shown), the magnitude of which could be selected to attain a desired loading (ie, pressure) at the downfacing surfaces of the brass disks. The deadweights were centered and held in place by a shaft attached to the platform. For the duration of each experiment, the temperature of each applicator was held constant by a microprocessor control unit. Among the 12 applicators, applied temperatures of 25, 35, 40, and 45 degrees C were employed in each experiment (normal skin temperatures are in the range of 35 degrees C, whereas 45 degrees C is a commonly accepted upper bound for thermal therapies applied to the skin {eg, water beds}). In each experiment, there were three 25 degrees C applicators, three 35 degrees C applicators, and so forth. When applied to the porcine surface, the temperature at each location of application could be selected randomly from the aforementioned four values.

For this study, the weights were chosen to yield an applied pressure of 100mmHg in order to simulate those pressures that may cause pressure ulcers in patients bedridden for extended periods.[12] In a supplementary experiment, a pressure transducer was mounted on the side of one of the disks to verify the deadweight loading used to achieve the applied pressure of 100mmHg. In all the trials, the recorded transducer pressures were within 5mmHg of the target surface pressure, independent of the location of the specially instrumented disk.

Preoperative Protocol

The Animal Care Committee at the university approved the use of 3- to 4-month-old mongrel swine in a 28-day experimental protocol. Animals weighing 30 to 40kg were used and provided a sufficiently large and flat upfacing back surface area to enable the attainment of uniform pressure at each of the 12 applicator sites. On arrival, the animals were housed in an area with appropriate facilities and staff for administering a regimen of prescribed diet and care. After two days to allow for acclimatization, the swine were fasted overnight and then anesthetized using intramuscular Telazol[a] (12 to 15mg/kg) to facilitate placement of a cannula in an ear vein. With the cannula in place, lactated Ringer's solution and thiopental (2 to 3mg/kg) were administered enabling the placement of an indwelling catheter in the external jugular vein for the administration of antibiotics, analgesics, and anesthetics.[6] The next day, the animal was initially anesthetized using intravenous thiopental (2 to 3mg/kg), given atropine (0.03mg/kg), and intubated. The lungs were mechanically ventilated at a rate of 10 to 15 breaths per minute with an inspired oxygen fraction of 0.5 and 1.5% to 2% isoflurane. Tidal volume[b] was adjusted to maintain an end-tidal partial arterial pressure of carbon dioxide between 35 and 45mmHg. Ringer's solution was administered for fluid maintenance at 10mL/kg/hr.

Operative Protocol

The pressure-temperature applicators were then installed anterior to posterior along the prone swine's back (thoracic, lumbar, and coccygeal and sacral vertebrae, respectively) as shown in figure 2. The applied pressure and temperature

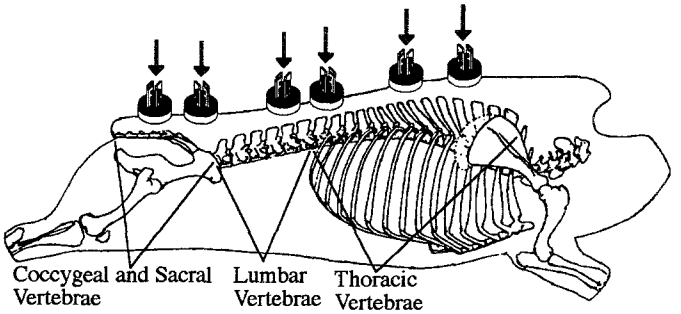

Fig 2—Disc application and subsequent assessment sites.

were maintained constant for 5 hours. Core temperature was monitored using a rectal probe[c] and adjusted to and maintained at either 38 or 35 degrees C (ie, two groups of animals) using convective air warming/cooling.[d] Heart rate was monitored continuously,[e] and blood pressure was determined every 5 minutes using an automated blood pressure cuff.[f]

Postoperative Protocol

At the end of the application period, the anesthesia was discontinued, and the mechanical ventilation was stopped. Once the animals were spontaneously breathing, they were transported to a postsurgical care area where they were given intravenous injections (via the aforementioned indwelling jugular catheter) ie, for analgesia, buprenorphine hydrochloride (0.001 to 0.002mL/kg) was provided, and in case of infection, antibiotics were administered as needed. Beginning with the first day after the removal of the applicators and every 3 days thereafter for a 4-week period, wound characterization measurements were made at all applicator sites and at relevant control areas. Blood pressure, heart rate, and core temperature also were monitored at these times. Thiopental was administered by a constant infusion to minimize error in measurements caused by fluctuations in depth of anesthesia.

A qualitative ranking of erythema and edema was performed by qualified blinded observers. A ranking scale of 0 to 4 was used in both categories, with 0 indicating no visible manifestation and 4 denoting the most severe condition.

Local subsurface tissue perfusion was recorded at the central location and at the periphery (closest to the spine) of each applicator site and each control site with a laser Doppler blood perfusion monitor.[g] The probe's sensor was positioned at the surface of the skin and measured blood perfusion data to a depth of 1mm beneath the surface. The blood perfusion monitor provides blood flow in units of mL/min/100g of tissue. A moving average of 10 seconds was sampled and recorded for all locations.

Local wound temperatures were sensed optically by an infrared microscanner.[h] The microscanner was calibrated and checked against an ASTM-certified thermometer accurate to 0.1 degrees F. Skin surface temperature measurements were made at the same locations as were the blood flow measurements.

Histological samples extending through the subcutaneous fat into the underlying muscle and postmortem visual inspection provided the basis for assessing the reproducibility of the status of the tissue under each pressure applicator. The samples were removed using a double-bladed scalpel with an interblade separation of 2 to 3mm. The samples were taken from approximately 10 to 12mm of tissue outside the pressure applicator site to 10 to 12mm within the applicator region. The average depth of the extracted samples was 25mm, which thus extended into the underlying skeletal muscle. After total excision, the specimens were fixed in formalin and routinely embedded in paraffin using an automated tissue-processing unit; 5-μm sections were stained with hematoxylin and eosin. After the animal was killed, incisions were made to a depth of 8 to 10cm below the applicator sites extending down to the bone. Damage to deep tissue was visually assessed and recorded and compared with the histological samples.

Statistical Analysis

Perfusion and temperature data obtained postoperatively were normalized to reduce variability between animals and to allow each swine to function as its own control. A control site was centered within each group of four applicator sites. Perfusion and temperature data for all 25 degrees C sites were compared with those for all 35 degrees C sites, using the Bonferroni multiple comparison test. To facilitate this, the normalized temperature and blood perfusion data at all 25°C sites were averaged and similarly for the respective 35, 40, and 45 degrees C sites.

To characterize core temperature, heart rate, and end-tidal CO_2 during the 5-hour operative period, the respective quantities were measured every half hour and averaged. For the postoperative period, the every-third-day measurements of core temperature, heart rate, and mean arterial pressure were respectively averaged. The average values of the measured physiologic variables over the 5-hour application period and the 4-week postoperative period were respectively pooled either for each animal group or for the total population, and the standard deviation was calculated. The histological samples were classified by qualified blinded observers with respect to the degree of injury to the epidermis (tissue necrosis), dermis (color, hair follicle damage, apocrine gland damage, vascular damage, nerve/muscle damage, and inflammatory cells), subcutaneous tissue (infiltrate, vessel damage, and compression), and underlying muscle (visible damage).

RESULTS

Physiological Status

The physiologic status of the animals was maintained well within desired limits during the imposed pressure-temperature application portion of the study (table 1) ie, core temperature (rectal), heart rates, and end-tidal CO_2 varied only slightly. Similarly, the animals' physiologic condition monitored over the 28-day protocol also showed acceptably small variability (table 2). However, in some animals, an elevation in core temperature was observed for several days after the application protocol. It should be noted that such elevation was observed in only a few animals at different timepoints; hence, they are not discernible on pooling the data from all animals investigated (see table 2). These responses could either be caused by a visually undetected infection (although antibiotics were provided) or to stress induced by the experimental protocol. For example, in two animals included in the study group, hind-quarter recumbency was observed in the postpressure application period, which spontaneously disappeared within a couple of days.

Resultant Tissue Injuries

Based on histological samples obtained at 7 days postapplication, table 3 exhibits the generalized effects of an applied pressure of 100mmHg for 5 hours at either 25, 35, 40, or 45 degrees C. It is especially noteworthy that the imposition of a 25 degrees C temperature appeared to protect all tissue layers, whereas application at normal skin temperature

Table 1: Changes in Systemic Variables During Imposition of Pressure-Temperature Applicators in Each Group of Animals

	Normothermic (n = 8)			Hypothermic (n = 4)		
Hours	Rectal Temp. (C°)	Heart Rate	End-Tidal CO_2	Rectal Temp. (C°)	Heart Rate	End-Tidal CO_2
0	37.6 ± 0.7	86 ± 15	41.5 ± 14	35.8 ± 1.0	102 ± 13.1	30.0 ± 2.0
1	37.5 ± 0.9	100 ± 21	44.2 ± 16	34.4 ± 1.4	117 ± 22.6	34.0 ± 4.4
2	37.7 ± 0.7	121 ± 25	48.2 ± 16	34.6 ± 0.3	124 ± 22.7	36.3 ± 5.7
3	37.8 ± 0.5	122 ± 23	42.2 ± 7.2	35.1 ± 1.4	136 ± 27.3	35.7 ± 4.0
4	37.9 ± 0.4	131 ± 24	41.2 ± 5.4	35.3 ± 0.9	140 ± 32.2	38.0 ± 5.3
5	38.1 ± 0.4	135 ± 27	44.7 ± 7.1	35.6 ± 1.1	139 ± 31.0	38.3 ± 4.2

NOTE. Values represent means ± standard deviations.

(~35 degrees C) resulted in muscle necrosis only (fig 3). Postmortem visual assessment of each tissue level at each application site concurred with the assessments of the histological sections. It was determined both from this study and from another set of animal studies performed in the laboratory (unpublished data) that the optimal time for detecting any potential change from control tissue in histology samples was approximately 7 days (ie, including all tissue layers: epidermis, dermis, subcutaneous fat, and skeletal muscle). It should be noted that before this date, muscle damage was not consistently detectable within the histological sections obtained from the 35 and 40 degrees C applicator sites. This latter observation is supported by the visual analysis of the histological sections shown in figure 4.

Reproducibility of Induced Injuries

In general, the occurrence of damage induced by the application of a pressure of 100mmHg for 5 hours at a given temperature was virtually independent of the location of the applicator on the dorsal surface of the animal. This conclusion is based primarily on postmortem visual assessment of each tissue layer beneath each application site. It was also consistent with the results of noninvasive measurements made at the application sites over the duration of this study (to be described shortly). However, for the application sites at 35 degrees C, the spatial distribution of the damage within the muscle layer was nonuniform. Thus, the relative degree of tissue damage observed histologically, at application temperatures of 35 and occasionally 40 degrees C, provided a somewhat lower correlation of the relative occurrence or the degree of tissue damage for the three sites at a given temperature for selected animals. Specifically, the histological sampling was from randomized regions of the total application site (ie, 2 to 3mm wide slices of tissues), which resulted in some discrepancy in the tabulated histological analysis (fig 4). This spatial variability may have been related to the presence or absence of underlying skeleton (fig 2).

Detection of the relative changes in postoperative cutaneous blood flow over time resulted in fairly consistent patterns corresponding to each applied temperature. At application temperatures of 25 and 35 degrees C, there was little or no difference in postapplication surface temperature and cutaneous blood flow from control. For the 40 degrees C sites, blood flow increased above that of noninjured skin for several days postapplication; whereas at all 45°C sites, blood flow was absent in the central regions of the application area for the whole 28-day period of study (fig 5). A comparison of normalized temperature measurements between applicator sites showed marginal significance for the third day but were insignificant for the rest of the 28-day protocol.

Table 2: Changes in Systemic Variables During the 4-Week Postapplication Period: Data for All Animals Were Pooled

Days	Rectal Temp. (C°)	Heart Rate	Mean Arterial Pressure
1	38.4 ± 1.6	124 ± 19	100 ± 21
3	39.4 ± 0.6	142 ± 21	109 ± 17
6	39.3 ± 0.8	137 ± 27	115 ± 25
9	38.9 ± 0.9	150 ± 9	112 ± 18
12	38.8 ± 1.4	139 ± 23	99 ± 19
15	39.3 ± 0.7	140 ± 18	127 ± 20
18	39.5 ± 0.7	142 ± 22	108 ± 21
21	38.8 ± 0.9	127 ± 20	104 ± 18
24	39.3 ± 0.6	135 ± 22	100 ± 28
27	38.7 ± 1.0	129 ± 21	113 ± 10

NOTE. Values represent means ± standard deviations.

Temporal Changes at Each Application Site for the 28-Day Period

Visually observed changes at each applicator site were noted over the 28-day study period and provided a basis for comparison with histological data. The 25 degrees C sites were remarkable in showing no visible damage at any of the applicator sites for all participating animals. No reddening or swelling was apparent either immediately after pressure-temperature applicator removal or in the subsequent 28-day period. Histologically, biopsies from the 25 degrees C sites were distinguished by total absence of tissue damage except for one site in one pig, which showed a focal superficial erosion. Furthermore, laser Doppler blood flow measurements (fig 5) and skin surface temperature readings taken at these sites showed no significant differences from those of control sites.

For the 35 degrees C applicator sites, visible damage was

Table 3: Summary of Tissue Status After the Application of 100mmHg for 5 Hours at 25, 35, 40, or 45 Degrees C

25 degrees C sites:	All tissue layers normal.
35 degrees C sites:	Moderate muscle damage.
40 degrees C sites:	Partial epidermal necrosis (regional), moderate muscle damage.
45 degrees C sites:	Full epidermal necrosis, moderate dermal and subdermal damage, and severe muscle damage.

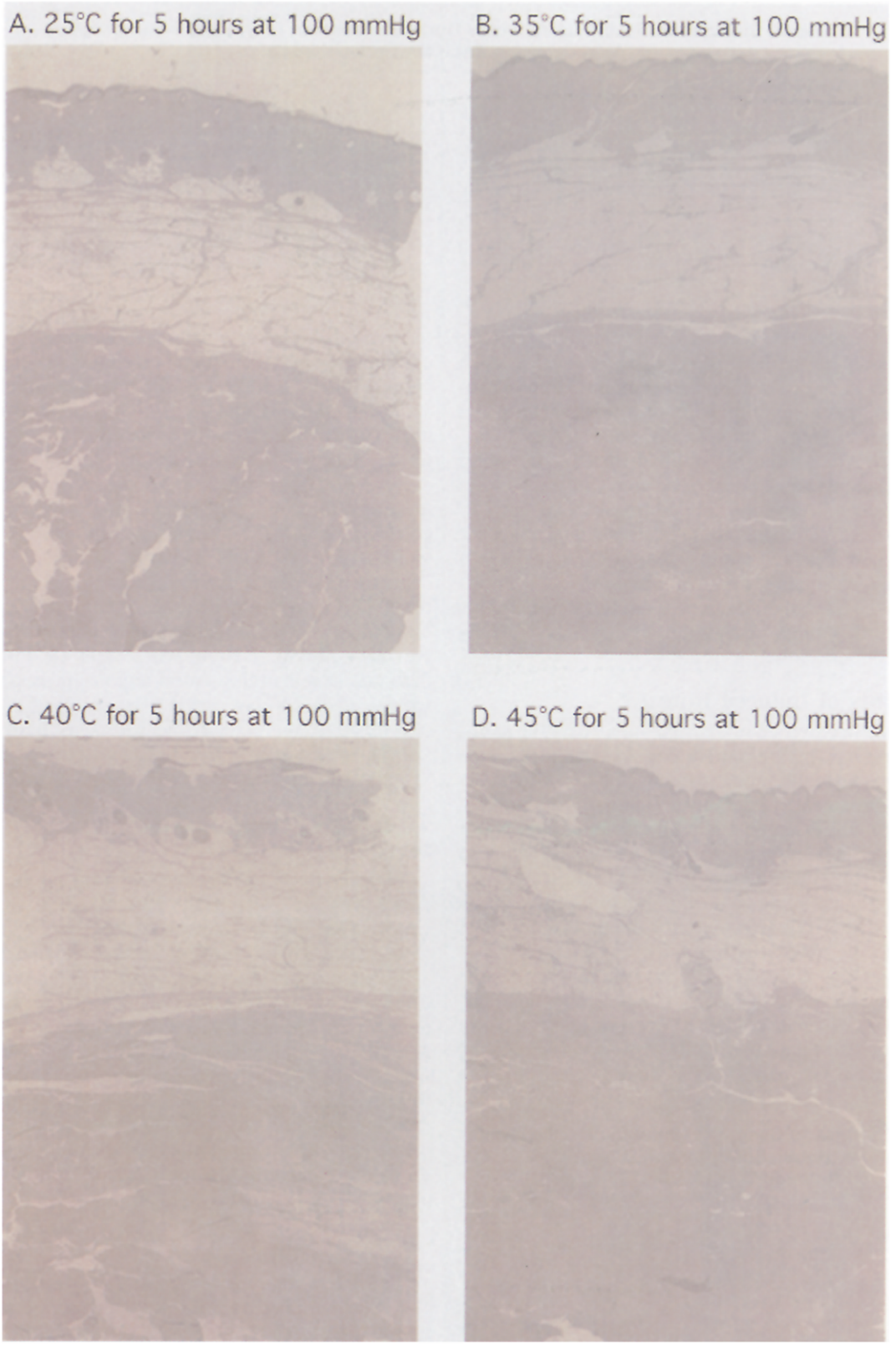

Fig 3—Histological sections of cutaneous and subdermal tissues after the application of pressure disks (100mmHg) for 5 hours at temperatures of either 25, 35, 40, and 45 degrees C at day 7.

#	Day	25 °C				35 °C				40 °C				45 °C			
		Epid	Derm	Subc	Musc	Epid	Derm	Subc	Musc	Epid	Derm	Subc	Musc	Epid	Derm	Subc	Musc
1	0	N	N	N	N	N	N	N	N	+	N	N	N	++	++	N	N
1†		N	N	N	N	N	N	N	N	N	N	N	N	++ ++	++ ++	++ ++	* *
2‡		N	N	N	N	N	N	N	N	N	N	N	N	++	++	N	*
3		N	N	N	N	N	N	N	N	N	N	N	N	+	+	N	N
4		N	N	N	N	N	+	N	N	+	+	N	N	+	+	N	N
1‡	1	N	N	N	N	N	N	N	N	+	++	+	N	++	+	+	N
1	2	N	N	N	N	N	N	N	N	N	+	+	N	++	++	++	++
2‡		N	N	N	N	N	N	N	N	N	+	N	*	++	++	N	*
1‡	3	N	N	N	N	N	N	N	N	N	N	N	N	++	++	+	*
1‡	6	N	N	N	N	N	N	+	N	N	N	N	N	++	++	++	N
1	7									N	N	++	++	++	++	++	++
2										N	N	+	N	*	*	*	*
3		N	N	N	N	N	N	N	++	N N	N N	+ +	+ +	+	+	++	++
4		N	N	N	N	N	N	N	N	*	*	+	++	+	+	+	N
1‡	9	N	N	N	N	N	N	N	N	+	N	N	N	++	++	++	++
1‡	15	N	N	N	N	N	N	N	N	+	+	N	N	++	++	++	+
1	21	N	N	N	N	N	N	N	N	N	N	N	+	++	++	++	+
														++	++	++	++

Fig 4—Histological evaluation: the presence or absence of temperature-modulated pressure ulcers at an applied disk pressure of 100mmHg for a 5-hour duration. Epid, epidermis; derm, dermis; subc, subcutaneous fat; musc, muscle; N, normal tissue characteristics; +, partial necrosis; ++, full necrosis; *, information not available; †, 12 hours postapplication; ††, biopsies were performed at multiple times from different sites on this animal.

evident at specific sites situated over bony prominences but disappeared within a couple of days. Biopsies at the 35 degrees C sites showed no obvious epidermal or dermal damage. In one biopsy site 6 days after applicator removal, a mild lobular chronic inflammatory infiltrate of the subcutaneous tissue was noted, suggestive of deep injury; but there was no significant epidermal or dermal involvement. Deep tissue dissection performed on two animals at 7 days indicated deep muscle damage. Laser Doppler and skin surface temperature measurements did not provide any evidence for this underlying muscle damage.

The observed responses at the 40 degrees C applicator sites were remarkable in that almost all sites showed blanchable erythema on removal of the pressure applicators and subsequently for up to 8 to 10 days depending on the applicator site. Histological changes at the 40 degrees C sites (relative to the control sites) were inconsistent and varied with pig and site. Epidermal necrosis was patchy and sometimes involved only the superficial layers of the epidermis. Underneath these foci, vessels were congested and a mild neutrophilic infiltrate was observed early on (day 1), but the infiltrate was confined to the more superficial dermis, and no significant chronic inflammation ensued and no dermal coagulative necrosis occurred. Laser Doppler measurements indicated a uniform increase in perfusion for the first few days, but there were no significant differences (relative to the control) for the rest of the protocol period; skin temperature measurements were inconsistent.

The 45 degrees C applicator sites were the most remarkable and consistent, with visible erythema and edema present from the moment of the applicator removal. These symptoms progressed and eventually led to a uniform eschar formation at all sites on all the animals. The loss of dermal and epidermal layers was reflected in the null measurements taken by the laser Doppler fluxmeter (fig 5). Histologically, changes were noted immediately after removing the applicators. Within the epidermis, there was full thickness eosinophilic glassy alteration of the keratinocyte cytoplasm accompanied by nuclear pyknosis. Focally, at the dermal-epidermal junction, there was clefting and separation, with the space filled with homogenous eosinophilic fluid or frank hemorrhage. Similar changes were inconsistently observed in the follicular epithelium. The appendegeal glandular structures showed eosinophilic alteration of the cytoplasm and acantholysis. The dermal and subcutaneous vessels were congested with patchy areas of hemorrhage. Within 12 hours after removal of the applicators, neutrophils started infiltrating both the dermis and subcutaneous fat. By 2 days at some sites, there was amphophilic homogenization of the upper dermis, with karyorrhexis of nuclei and erythrocyte breakdown. At 7 days,

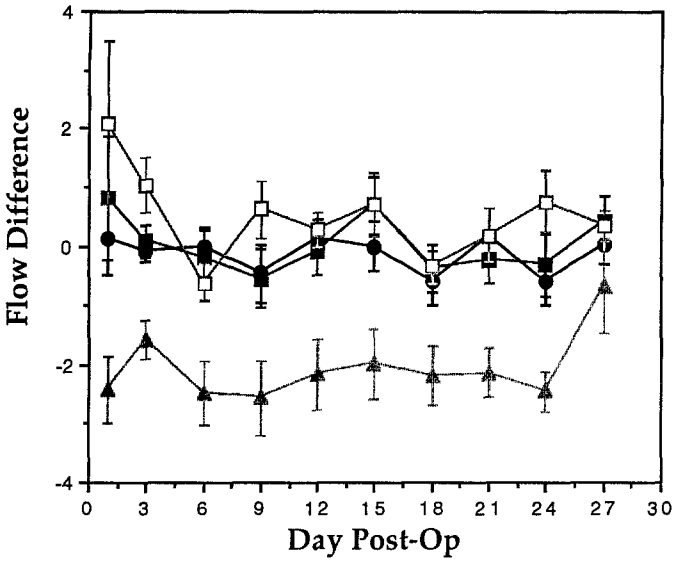

Fig 5—Normalized flow at the wound sites show a marked difference in the higher temperature sites as compared with the lower sites. The 25 degrees C sites were almost normal, whereas, the 40 degrees C sites show increased flow in the initial stages of wounding. -●-, 25 ave; -■-, 35 ave; -□-, 40 ave; -▲-, 45 ave.

there was a significant acute and chronic inflammatory infiltrate that involved the dermis, subcutaneous fat, and focally extended into the skeletal muscle. By 2 weeks, obvious full thickness epidermal and dermal coagulative necrosis was present, and the inflammatory infiltrate was predominantly chronic, with dystrophic calcification observed in the deep tissues along with multinucleate giant cells.

Visual assessment ranking correlated well with histology in superficial wounds. Instances of deeper muscle and fascia damage not identified in visual rankings were apparent in deep biopsy samples. Visual assessment of deep incisions taken at the wound sites also showed extensive damage to deep tissue not detectable either by any of the noninvasive techniques or even by histology immediately after removal of the applicators (ie, day 0, see fig 4).

DISCUSSION

The use of swine as a model for pressure ulcer research has long been accepted by reason of the similarities in skin properties and comparable cardiovascular systems with those of humans. The possibility of inducing conditions such as radiation impairment, paraplegia, and diabetes, in both domestic and miniature swine has allowed for modulation of these parameters to mimic clinical situations in humans. Miniature pigs have been extensively used in wounding studies[13] and allow the study of susceptibility to pressure ulcers in mature animals. In the present study, 3-to-4-month-old mongrel swine weighing 40 to 45kg were employed to allow for large surface areas and ease of handling.

The rational bases for the design of the pressure application system and the experimental protocol were numerous. The animal size was such that the applicators could swivel to follow the contour of the animals so that the interface angle of each disk was nearly perpendicular to the vector of force applied by the dead weights. The use of 12 applicator disks on the dorsal surface of each animal allowed for several applications of the same temperature-pressure condition for a given animal; hence, one could investigate potential regional variability of the susceptibility for tissue damage. In ongoing studies, the affect of different durations (ie, the three sets of four applicators are randomly removed after 2, 5, or 10 hours) or different application pressures (eg, application pressures of 10, 50, and 100mmHg at the respective sets) are being studied. Furthermore, by using paired applicators placed symmetrical to either side of the spine of the animal, experimental protocols could be designed in which one applicator of each pair would serve as a site for active intervention while the other of each pair would serve as a control. Six such pairs would be available.

Examination of histological data and visual assessment of incisions below wound sites indicate that the application of a temperature of 35 degrees C caused deep tissue injury, specifically over bony prominences. On the other hand, no such damage was apparent under any of the 25 degrees C sites. This finding motivates the conjecture that lower applied temperatures could be protective: information that is clinically significant for prevention of pressure sores. In this regard, studies at higher pressures and longer durations are ongoing in this laboratory in which the benefits of lower temperature are being further explored (unpublished data). For example, whereas the avowed rationale for many commercially available mattresses and beds is the redistribution of pressure as a means for preventing pressure ulcers, the operating temperature for a number of such devices is in the 28 to 35 degrees C range.[14] These temperatures may actually accelerate pressure sore formation. Concurrent studies to define the critical range of temperatures that are most protective are envisioned.

The effect of hypothermia in the causation of these wounds was considered, but a comparison of the wounds from hypothermic animals with those from normothermic animals showed no significant differences. This information is relevant because it implies that it is not hypothermia but the application of a lower temperature that is protective.

The lack of sensitive methods to quantitate the status and progression of wounds is often cited as one of the primary factors limiting progress in wound-healing research.[15] In the present study, laser Doppler fluxmetry was deemed more successful than either local skin temperature measurement or visual ranking for the assessment of wounds. It was found that the indicated perfusion was highly responsive to fluctuations in depth of anesthesia, and concurrently, to variations in blood pressure and heart rate. Induction of pentothal by infusion rather than as boluses reduced the variability in blood pressure and heart rate. However, laser Doppler fluxmetry did not allow for detection of deep tissue injury. Debrided wounds could provide a better platform than undebrided wounds for testing fluxmetry as an assessment tool.

In the present study, it was observed that even when the postoperative, applicator-site temperature measurements were normalized, no definitive trends were observed that correlated with other assessments of degree of tissue damage. Ischemia is known to occur at applied pressures exceeding capillary pressure. Thus, blood flow at wound sites

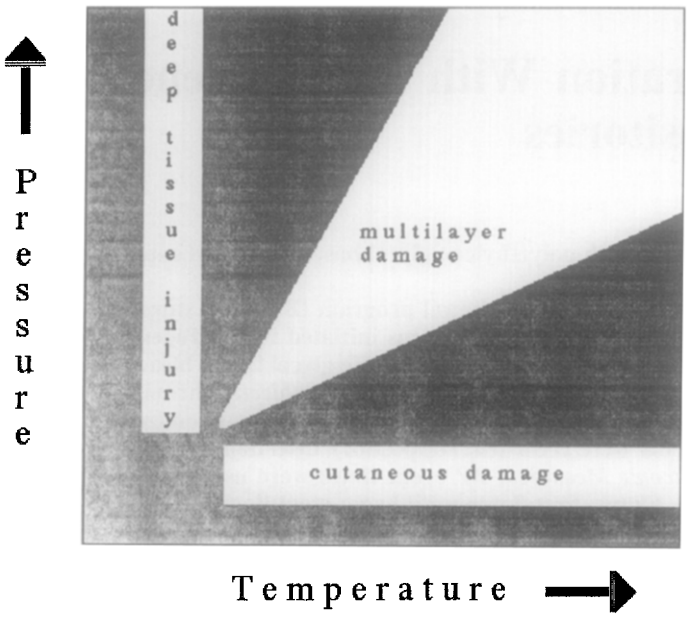

Fig 6—A conceptual schema of the areas that are damaged is shown in fig. Extensive deep tissue injury is observed for high pressures over long durations, whereas cutaneous damage is observed for temperature application over similar durations. The effect of temperature and pressure probably causes damage at both ends.

varies over time as reactive hyperemia, and then tissue necrosis, occur. This should manifest itself as a change in perfusion and a corresponding change in temperature. Thermography has been successfully used as a predictor of pressure sore formation,[16] and a mathematical model[17] suggests that dynamic temperature measurement (timeswise/spatial) could be a more accurate descriptor than localized, intermittent temperature measurement at the wound site. The ease of using temperature scanners warrants further exploration of temperature as a sensitive tool for assessing wound damage, although present results are not encouraging.

One of the goals of the present study at the time of its inception was to gain insights into wound etiology. A systematic evaluation of the histological data (fig 4) and postmortem visual assessment indicates that the first signs of corresponding to pressure application at normal skin temperature (35 degrees C) occurs in the deep muscle. Dermal and epidermal damage was evident at higher temperatures (40 and 45 degrees C), and muscle damage was observed to potentiate with an increase in applicator temperature. It has been suggested that pressure ulcers could start at both dermal and muscle layers.[18] It could be conjectured that shear, friction, moisture, temperature, and aging (loss of collagen) cause dermal damage, whereas higher pressures cause deep injury (caused by ischemia and damage to lymphatics[19]). A conceptual scheme for temperature-modulated pressure injuries induced in this study is illustrated in figure 6. It is hoped that this design will allow the generation of wounds with specific layer damage.

CONCLUSIONS

A reliable swine model for the development and assessment of temperature-modulated, pressure-induced tissue damage was successfully established. The model allows for easy, independent modulation of pressure, temperature, and duration to allow for creation of specific classes of wounds. These techniques can be used to induce injuries classically defined as pressure ulcers, and also those considered as burns. The local application of 100mmHg for 5 hours at 35 degrees C caused deep tissue damage, at 40 degrees C caused dermal and deep tissue damage, and at 45 degrees C caused full thickness cutaneous and deep tissue injury. In contrast, the application of disks at 25 degrees C resulted in the absence of damage; hence, injuries were deemed preventable by temperature modulation.

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Suppliers

a. Telazol; Aveco Co., Inc., Fort Dodge, IA.
b. SARAcap A.G.; PPG Biomedical Systems, Lenexa, KS.
c. Monatherm model 6510; Mallinckrodt Medical Inc., St. Louis, MO.
d. Bair Hugger Therapy; Augustine Medical Inc., Eden Prairie, MN.
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