Does Pressure Cause Pressure Ulcers? An Inquiry Into the Etiology of Pressure Ulcers

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Pressure ulcers remain problematic across health care settings, with prevalence and incidence changing little over the past 2 decades. Because external pressure is viewed as the chief factor in the development of pressure ulcers, considerable research has focused on pressure relief. Because relief of external pressure is possible, and would hypothetically eliminate all pressure ulcers, the development of a pressure ulcer is often regarded as a failure of the care system. This logic conveys the notion that sustained pressure is the only factor in the development of pressure ulcers and disregards additional factors in the pathogenesis of pressure ulcers intrinsic to the patient. Patient-specific factors leading to derangement in tissue perfusion may account for an observed development of a pressure ulcer, despite the provision of common prevention measures that include pressure reduction. A more comprehensive understanding of unique individual intrinsic factors may lead to more effective interventions. **(J Am Med Dir Assoc 2010; 11: 397–405)**

Keywords: Pressure ulcers; tissue perfusion; pressure reduction; tissue compression loading

A pressure ulcer is the visible evidence of a pathological interruption in blood supply to the dermal tissues.[1] The cause is frequently attributed to unrelieved pressure, usually focused over a body prominence, and is part of the definition of a pressure ulcer by some experts. In this view, external pressure is viewed as the chief cause in the development of a pressure ulcer. Although it is recognized that other contributing or confounding factors are associated with development of a pressure ulcer, these factors are often downplayed or disregarded.

Pressure ulcers remain problematic across health care settings. The prevalence and incidence of pressure ulcers have changed little over the past 2 decades.[2] In a state-wide survey in acute hospital settings, the incidence of pressure ulcers varied from 7.0 to 8.3 per 100,000 population, but did not change from 1987 to 2000.[3] In a voluntary, convenience sample among acute hospital patients, the pressure ulcer incidence remained stable from 1999 to 2004 (8%versus7%,respectively).[4]

In another acute hospital setting, the point prevalence of stage 2 or higher pressure ulcers was 33% in 2002 and 28% in 2004. The point prevalence decreased in surgical care units (by 27% to 17%), but increased in medical care units (24% to 27%), despite documented increases in prevention measures.[5] In a large study of pressure ulcers in a hospital setting, the point-prevalence of pressure ulcers was 24% in 2002 and 23% in 2006, despite shorter lengths of stay in 2006. When Grade 1 pressure ulcers were excluded, the prevalence rates increased from 8% in 2002 to 12% in 2006. This occurred despite finding that patients with a pressure ulcer received turning and repositioning and a pressure-reducing device more frequently than patients without pressure ulcers (25% in 2002 versus 41% in 2006).[6]

In the National Spinal Cord Injury Database, pressure ulcers were 1.4 times more common from 1994 to 2002 than from 1986 to 1993, which could not be explained by the effects of age, duration of injury, demographics, and other clinical factors.[7]

This observed stability in the incidence and prevalence of pressure ulcers has occurred in the context of considerable research into the etiology and prevention of pressure ulcers. A number of randomized, controlled trials have suggested that the incidence and severity of pressure ulcers can be reduced by various interventions in orthopedic patients,[8,9] in surgical and oncology patients,[10] in intensive care units,[11,12] and in acute hospital patients.[13] The data are mixed, however. Other trials have not shown this reduction in acute care[14–16] or long-term care.[17,18]

The highest incidence of pressure ulcers is found in acute hospital settings, particularly among surgical patients, intensive care admissions, and spinal cord injury patients. Attention has been focused on pressure ulcers in acute hospitals because of this higher incidence and changes in hospital reimbursement for pressure ulcers. This acute care population is useful for examining factors in the development of a pressure ulcer, as patients are usually screened for ability to tolerate a surgical procedure, and a particular surgical procedure is usually standardized across differing patients.

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PRESSURE ULCERS IN SURGICAL PATIENTS

Tissue damage secondary to unmet cellular demands (eg, need for oxygen and nutrients) has been reported in numerous operating room quality assurance studies.[19–21] Intraoperatively acquired pressure ulcers range from as low as 12% to as high as 66%.[16,22,23] Pressure ulcers are commonly observed in an intensive care setting, with prevalence rates ranging from 33% to 56%.[24,25] Pressure ulcers also occur frequently at the end of life.

A small descriptive study of 281 general surgical patients showed a 3.5% incidence of a pressure ulcer within 7 days of operation. Two thirds of observed pressure ulcers developed by the fourth postoperative day. Cardiac, orthopedic, general, and vascular surgeries were the most common procedures in this patient sample, and two thirds of pressure ulcers were stage 3 or higher. These pressure ulcers developed despite use of foam or gel padding during surgery.[26]

Cardiovascular surgery is associated with a particularly high incidence of pressure ulcers, ranging from 5.0%[27] to 29.5%[28,29](Table 1). Reduced hemoglobin, high creatinine, altered level of consciousness, frequency of repositioning, and number of vasoactive infusions were significantly associated with pressure ulcer development at different time points in the first 3 days after a surgical procedure.[33]

During the acute hospital stay, 15% of patients undergoing hip surgery developed a pressure ulcer. The cumulative incidence at 32 days after initial hospital admission was 36%. The adjusted pressure ulcer incidence rate was highest during the initial acute hospital stay (relative risk [RR] = 2.2, 95% confidence interval [CI] = 1.3–3.7) and during readmission to the acute hospital (RR = 2.2, 95% CI = 1.1–4.2).[34]

In intensive care units (ICU), the incidence of pressure ulcers varies as follows: 8% in a general ICU,[35] 12% in a neurological ICU,[36] and up to 30% in cardiovascular ICU[28] (Table 2). The postoperative incidence of pressure ulcers in an ICU was 53%, and 40% of these were stage 2 or higher. Half of these subjects developed an ulcer within the first 48 hours after ICU admission. A significant difference in length of stay in the ICU among patients with and without pressure ulcers was observed. In this study, no significant differences were found among patients who underwent cardiothoracic surgery, length of surgery, length of stay at the nursing ward, and length of total hospital stay.[32]

Patients who develop a pressure ulcer have a higher mortality (45% versus 17%), a longer duration in the ICU (24 versus 5 days), and were more likely to be men (66% versus 54%), compared with patients who did not develop a pressure ulcer. In the ICU, subjects who developed a pressure ulcer had higher body temperature, tachycardia or bradycardia, hyperkalemia, acidosis, elevated creatinine, elevated glucose, and a higher C-reactive protein. The severity of illness was higher in subjects who developed a pressure ulcer, including use of parenteral nutrition, sepsis, hemodynamic instability, mechanical ventilation, vasopressor use, sedation, and insulin therapy. Subjects with a pressure ulcer did not differ in age, body mass index, or treatment days in the hospital before ICU treatment. Notably, the Waterlow scale to predict development of a pressure ulcer had low value, explaining only 59% of the variance.[38]

Pressure ulcers are nearly twice as common in patients with stool or urinary incontinence (26% versus 10%). Other factors include an albumin level of or below 35 g/L (21% versus 8%), multiple diagnoses (42% in 3 days), and being underweight (50% versus 6% in overweight patients). No significant relation was found between pressure ulcer incidence and age or gender, length of stay, and Braden score.[33] Mechanical ventilation in the ICU is a risk factor, with 20% of ventilated individuals developing a pressure ulcer in the ICU.[43]

End-stage skin failure also occurs when the hypoperfusion occurs at the end of life.[44] Mortality rates range from 21% within 30 days of detection to 73% at 1 year after onset. Deep tissue destruction over pressure points and dependent areas can appear in just a matter of hours.[45] The prevalence of pressure ulcers is estimated at 11% to 18% in palliative care patients. This type of skin failure can result in large and unusual presentations of skin failure.[46,47]

INTERVENTIONS FOR PRESSURE RELIEF

Because immobility is viewed as the chief factor in the development of pressure ulcers, considerable research has focused on pressure relief.

In a national sample of hospitalized persons who developed pressure ulcers, persons who were documented at risk for pressure ulcers, or who received a pressure-reducing device within 48 hours of arrival to the hospital, or who were turned every 2 hours had a higher incidence of pressure ulcer development.[48,49] In a community hospital, 25% of patients with limited mobility developed a new pressure ulcer. Ninety-six percent of the patients who developed an ulcer did so while on various pressure-reducing devices.[50]

An observational study in hospitalized patients across the European Union found that hospital locations varied considerably (from 19% to 52%) in having a plan of care for turning and repositioning. Across all sites, 68% had no turning schedule. Most hospitals that had a plan for turning and repositioning used a 2-hour frequency. Among the patients, 23% of subjects without turning schedule and 24% with turning schedule had a pressure ulcer at discharge. The lack of turning schedule in relation to the incidence of a pressure ulcer was not different between groups.[51]

DeFloor and colleagues[52] observed the effect of different turning schedules on the development of a pressure ulcer in 838 patients in long-term care settings. In their study, the lowest incidence occurred in patients who were turned every 4 hours while on a pressure-reducing mattress. No additional benefit was seen in patients turned every 2 or every 3 hours while on a pressure-reducing bed.

In a trial of regular turning and positioning while on a pressure-reducing device, subjects were randomized to receive an intensive intervention as soon as they were recognized as at risk by the Braden scale or after they developed a stage 1 pressure ulcer. Overall, 17% of the population developed an incident pressure ulcer. Among subjects who had a Braden score less than 17, but did not have a stage 1 pressure ulcer, 13% of

subjects developed a higher grade pressure ulcer. Among the subjects who had a higher Braden score and a stage 1 pressure ulcer, almost half developed a higher-grade pressure ulcer (stages 2–4). Pressure ulcers deteriorated from stage 2 to stages 3/4 in 18% of the experimental group and in 19% of the control group, despite pressure reduction in both groups. The data suggest that intervention in this trial is not sufficient to prevent pressure ulcers from occurring or deteriorating in large numbers of persons.[53] Other trials have found similarly a high incidence despite various interventions.[50–56]

In a study of repositioning in subjects who had nonblanchable erythema (a stage 1 pressure ulcer), assignment to either of 2 groups was evaluated. In the experimental group, patients were repositioned for 2 hours in a lateral position, alternating with 4 hours in a supine position. In the control group, patients were repositioned every 4 hours. Both groups received a pressure-reducing mattress. Sitting up in a chair was identical in both groups. Sixteen percent of subjects in the experimental group and 21% of subjects in the control group ($P = .40$) developed an incident stage 2 to 4 pressure ulcer. Neither the severity nor location nor time to development of the pressure ulcers differed between groups. The authors concluded that more frequent repositioning on a pressure-reducing mattress does not necessarily lead to fewer pressure ulcer lesions and consequently cannot be considered as a more effective preventive measure.[53]

According to the pressure-dependent hypothesis, relief of external pressure at the skin surface before the onset of tissue damage should eliminate pressure ulcers. Because relief of pressure is possible, and would eliminate all pressure ulcers, the development of a pressure ulcer is a failure of the care system.[57] This logic conveys the notion that sustained pressure is the only factor in the development of pressure ulcers and disregards additional factors intrinsic to the patient in the pathogenesis of pressure ulcers.[58] An alternate hypothesis is that healthy people, including those with reduced mobility, do not normally develop a pressure ulcer, but that those same patients may become acutely vulnerable following the onset of an intercurrent illness or trauma.[59]

Despite common sense approaches to turning, positioning, and improving passive activity, no published data support the view that pressure ulcers can be prevented by passive positioning.[60]

RISK FACTORS FOR DEVELOPMENT OF A PRESSURE ULCER IN SURGICAL PATIENTS

A number of studies have attempted to define risk factors for the development of pressure ulcers in surgical patients. In patients undergoing cardiovascular surgery, risk of developing a pressure ulcer increased with vascular compromise; vascular surgery; supine positioning on the operating room table; age older than 50 years; medical diagnosis of hypertension, diabetes, or congestive pulmonary disease; transfer from another facility; and low pressure ulcer risk using a skin risk assessment tool.[29,61] Only 2 studies show that time in the operating room is a risk factor. Most studies report the use of a pressure-reducing device during surgery. Most studies show that the preoperative risk of developing a pressure ulcer was low, which may result from selection of good surgical candidates. This suggests that these scales are not appropriate in the surgical/ICU setting and that factors that increase risk are not captured by the variables (Table 1).

Anesthetic agents used in surgery interrupt protective muscular mechanisms by creating alterations in the vascular status that affect blood pressure, tissue perfusion, response to pressure and pain, and the exchange of oxygen and carbon dioxide.[62] General anesthesia increases the risk of development of a pressure ulcer compared with regional anesthesia.[63] A diastolic blood pressure less than 60 mm Hg has been associated with the development of pressure ulcers in surgical patients.[19,30,64] Also, the number of hypotensive events that occur during surgery has been shown to be a factor in the development of a pressure ulcer in the postoperative period.[33] Medication given to reverse hypotension causes further injury secondary to increasing oxygenation, resulting in an overproduction of toxic free-radicals, particularly in the elderly. Hypnotics and sedatives used for their anesthetic effect have been implicated in decreasing blood pressure, thereby causing peripheral hypoperfusion.[65]

Experimental[65] and descriptive[20] studies have reported an increase in postoperative pressure ulcers when a warming blanket is placed beneath patients during surgical procedures. The body experiences a 10% increase in tissue metabolism with each 1 degree Centigrade rise in skin temperature.[21] Tissue damage increases significantly as skin temperature increases, even when pressure and time remain constant.[66]

Hip Fracture

In hip fracture patients, time to surgery was a factor in long-term mortality and morbidity in unadjusted analyses. However, after adjustment for demographic characteristics and underlying medical problems, the effect of time to surgery was no longer statistically significant, suggesting that time to surgery is a marker of comorbidity. Delaying surgery up to 72 hours after admission did not increase mortality or morbidity, but was associated with a higher risk of pressure ulcer incidence.[67] Fourteen percent of patients undergoing hip fracture surgery in another study developed a pressure ulcer. Delay of surgery of more than 48 hours was associated with a 2-fold higher risk of pressure ulcer incidence.[68] The chief reason for delay in surgery is likely to be comorbid conditions, or a higher severity of illness.

Heel pressure ulcers are common after hip fracture surgery, and the second most common site for pressure ulcers overall. Measurements of heel transcutaneous oxygen tension in patients after surgical repair of the hip demonstrated that heel oxygen tension decreased after placing the heels on the bed surface for 15 minutes. However, the decrease in heel oxygen tension continued after the heels were removed from the bed surface, and the anticipated hyperemic response to relief of pressure did not occur. Moreover, the heels of both the nonoperative and operative leg had lower oxygen tension in response to external pressure, and it was not until the third postoperative day that the oxygen tension on the nonoperative heel was higher than that of the operative leg. This suggests that physiological factors rather than simple pressure

Table 1. *Risk Factors in Cardiovascular Surgery Associated with Incidence of Pressure Ulcers*

Study	Incidence, %	Associated Variables	Not Associated
Kemp et al (1990)[30]	12.0 (stage 2 or higher)	Age, time on operating room table, and extracorporeal circulation	Braden score
Papantonio et al (1994)[29]	27.2 (stage 1 or higher; 15% stage 2 or higher)	Age, preexisting respiratory disease, diabetes mellitus, reduced hematocrit, albumin less than 3.6 g/dL, ecchymosis, and operating room time	Race, sex, weight, height, body mass index, hospital days, location presurgery, preexisting medical conditions, smoking history, type of surgical procedure, and on bypass or cross-clamp, lowest perfusion pressure, position on operating room table, vasoactive drugs, temperatures, cautery pad location, prep. solution on bullocks rewarming blanket and temperature, vasoactive drugs, vascular assist devices
Jesurum et al (1996)[16]	25.0 (stage 1 or higher)	Age, history of cerebrovascular disease, renal insufficiency, high APACHE and patient identification for rotation scores, and a reduced Braden score on the first postoperative day. Reduced hemoglobin, high creatinine, altered level of consciousness, frequency of repositioning, and the number of vasoactive infusions	Gender, ethnic group, preoperative albumin, ejection fraction, preoperative/ intraoperative cardiopulmonary resuscitation, intra-aortic balloon pump days, number of comorbidities, low air loss bed therapy, length of stay
Lewicki et al (1997)[19]	4.7 (stage 1 or higher; 2.6% stage 2 or higher)	Reduced hemoglobin, hematocrit, and albumin levels, the presence of a postoperative intra-aortic balloon pump, a low preoperative Braden risk score, diabetes mellitus, comorbidity, rapid return to preoperative body temperature, and turning less often	Age, gender, preoperative days in ICU (preop variables to calculate comorbidity index), skin assessment, use of leg positioner, time on operating room bed, time on extracorporeal circulation, operating time with diastolic less than 60 mm Hg, full body skin assessment after the surgical procedure, 4-stage scale, equipment that reduces mobility, vasoactive medication, sedatives, corticosteroid, anesthetics, patients response to discomfort or pain
Stordeur et al (1998)[28]	29.5 (stage 2 or higher)	Preoperative Braden score, hemoglobin at admission, and postoperative steroid therapy	Age, sex, height, weight, fever, diarrhea, heart failure, peripheral arteritis, neurologic deficit (hemiplegia, paraplegia), blood pressure, use of antihypertensive medications, use of morphine analgesia, use of vasoconstrictive medications, diabetes mellitus, characteristics of pressure scores (stage, sites, evolution), surgical intervention (type and duration of intervention, duration of anesthesia, type and duration of extracorporeal circulation, unexpected readmission to ICU, nosocomial infection, unplanned or additional surgical reintervention, length of stay in various wards
Pokorny et al (2003)[31]	7.0 (stage 1 or higher)	Age, sex (female), heart failure, Braden score day 2 to 5 after surgery, and time from admission to surgery and from admission to hospital discharge	Body mass index, hypertension, diabetes, cholesterol level, previous myocardial infarction, chronic obstructive pulmonary disease, previous vascular surgery
Schuurman et al (2009)[32]	53.0 (21% stage 2 or higher)	Length of intensive care stay	Length of stay at the nursing ward, length of surgery and length of total hospital stay

Selected studies of incidence in patients admitted to a cardiovascular intensive care unit. Methodology and inclusion criteria differed among studies. Factors associated and not associated with an incident pressure ulcer are tabulated.

APACHE, Acute Physiology and Chronic Health Evaluation; ICU, intensive care unit.

Table 2. *Risk Factors for Incident Pressure Ulcer in a Surgical ICU*

Study	Incidence, %	Associated Variables	Not Associated
Frankel et al (2007)[37]	3 (stage 2 or greater)	Age >60 years, history of diabetes, spinal cord injury, renal insufficiency during an ICU admission	Gender, APACHE II score (>25 versus <25), vascular service admission, and vasopressor requirement during the ICU admission, universal use of specialty beds and early nutrition
Compton et al (2008)[38]	17 (stage 2 or higher)	Male gender, ICU mortality, duration of stay in ICU, Waterlow score at admission, body temperature, maximum heart rate, higher creatinine, acidosis, higher glucose, and C-reactive protein, sepsis, mechanical ventilation, vasopressors, Glasgow score	Age, weight, body mass index, days in hospital before ICU admission, enteral nutrition
Baumgarten et al (2008)[39]	6 (stage 1 and higher)	ICU admission	Any immobilizing medication in the ED, ED stay >8 h, any immobilizing procedure in the ED, any surgical, radiological, or cardiological invasive procedure, any restraining, immobilizing, or compression device, any immobilizing medications inpatient
Suriadi et al (2008)[40]	27–32 (stage 1 and higher)	Interface pressure, body temperature, and cigarette smoking	
Terekeci et al (2009)[41]	8 (stage 2 and higher)	Age, low Norton score, higher hospitalization days, high APACHE II score, hypotension, higher nutrition risk score, hypoalbuminemia	Body mass index and hemoglobin
Nijs et al (2009)[42]	20 (stage 2 and higher)	Medical history of vascular disease, use of dopamine > 5 μg/kg/min, intermittent hemodialysis or continuous veno-venous hemofiltration, mechanical ventilation, adequate prevention, turning, floating heels, frequency of turning >6 times a day or the use of an alternating mattress	Use of sedatives and body temperature >38.5 °C, sitting in chair

Selected studies of incidence in patients admitted to an intensive care unit. Methodology and inclusion criteria differed among studies. Factors associated and not associated with an incident pressure ulcer are tabulated.

APACHE, Acute Physiology and Chronic Health Evaluation; ED, emergency department; ICU, intensive care unit.

post operative loading affect the heel oxygen tension in surgical repair of hip fracture.[69]

Risk factors for development of a pressure ulcer in hip fracture patients include age, diabetes mellitus, a lower mental test score, a lower mobility score, a higher American Society of Anesthesiologists risk score, lower admission hemoglobin, and an intraoperative drop in blood pressure. Care-related factors, such as traction, thickness of gurney padding, time to surgery and duration of surgery, spinal anesthesia, and perioperative warming were of minor importance for development of a pressure ulcer.[70]

Intraoperatively acquired pressure ulcers typically start as burnlike lesions.[71] Changes in skin integrity may appear typically within 72 hours following surgery. The affected area becomes ecchymotic and may blister. Necrosis occurs within 2 to 6 days; patients with vascular compromise and subsequent altered skin integrity may present with an area of skin that has a mottled irregular pattern that may resolve or result in a full-thickness wound.[72] In many patients, compromised vascular disease in the pelvis and lower extremities may be undetected, and only suggested by the diagnosis of diabetes mellitus, coronary artery disease, or peripheral arterial disease.

Spinal Cord Injury

Persons with a spinal cord injury have severe alterations in physiological functions. This has been compared with the mythological creature Pan, who is half human, half animal. Although the skin both above and below the level of injury appears the same, they are very different physiologically.[73] An estimated 50% to 80% of patients with spinal cord injuries develop pressure ulcers at least once in their lives.[74]

Intensive Care Unit

Interventions to reduce the incidence of skin failure in an intensive care setting can be quite challenging. Sedation and immobilization are often required to keep the person breathing regularly and effectively and to prevent inadvertent self-harm. Vasopressors are required to maintain adequate core internal organ perfusion. The simple act of repositioning from side to side can significantly impact hemodynamic stability, as well as blood pressure and ventilator management. The use of pressure-redistributing mattresses can lower the interface pressure between the bed surface and the tissue, but an individual in such a critical condition may not have sufficient blood pressure and adequately nourished blood to maintain viability of the stressed tissue, despite the most advanced surfaces.[75]

A recent study in general surgical ICU subjects demonstrated a comparatively lower 3% incidence of pressure ulcers. The risk of developing a pressure ulcer was almost 3-fold higher in diabetic patients, patients older than 60 years, and patients with a creatinine greater than 3 mg/dL. Patients with a spinal cord injury have a nearly 17-fold higher risk of developing a pressure ulcer. These data suggest that factors that impair skin perfusion—diabetes, paraplegia, and renal insufficiency—are more important in developing a pressure ulcer than Acute Physiology and Chronic Health Evaluation II (APACHE II) score or ICU length of stay. Pressure ulcers occurred in this setting where specialty beds and early nutrition were universally applied.[37]

THE SKIN AS AN ORGAN

The skin is the largest organ in the body, accounting for about 16% of body weight. Skin blood flow accounts for 5% to10% of cardiac output. Only muscle tissue receives a higher proportionate amount of blood flow. Skin blood flow is highly variable, and may decrease in the presence of cold environmental temperature or increase up to 8 liters per minute in the presence of heat stress, thus fulfilling the skin's major role in thermoregulation.

Skin blood flow is controlled by the sympathetic system in response to changes in body temperature. Skin blood flow is also dependent on cardiac output. Perfusion may be reduced in diseases such as congestive heart failure, peripheral vascular disease, sepsis, and with hypotension.

Normal dermal capillary closing pressure is approximately 32 mm Hg. As external surface pressure modestly increases up to about 50 mm Hg, skin blood perfusion increases.[76] Regional blood pressure also increases as the external surface pressure increases. Skin blood flow ceases when the external surface pressure exceeds the rise in systolic arteriolar pressure.[77]

In animal models, zero blood flow occurs at an average external surface pressure of approximately 58 mm Hg.[78] The duration of the external surface pressure necessary to produce histological changes in the underlying tissue is not known, but has required 2 to 6 hours in animal models. Relief of external surface pressure is followed by reactive hyperemia and vasodilation during a recovery period of 15 to 30 minutes.

The 4 most commonly hypothesized pathophysiological explanations for the development of pressure ulcers include (1) localized ischemia caused by capillary occlusion attributable to pressure load[79,80]; (2) reperfusion injury, that is, injury resulting from the accumulation of substances associated with the inflammatory response to ischemia as blood is reintroduced into an ischemic region[81]; (3) impaired lymphatic function that causes metabolic waste products, proteins, and enzymes to accumulate[82]; and (4) prolonged mechanical deformation of tissue cells.[83]

Historically, the effect of pressure and duration has been expressed as a critical pressure/time product (interface pressure times time).[84] In this model, higher pressure for shorter times, or lower pressures for longer duration, produce pressure ulcers. However, this relationship has been shown to be inaccurate at the extremes of short and long durations of pressure. For example, the pressure-time curve indicates that the individual could be injured at pressure levels lower than 25 mm Hg (300 mm Hg per hour for 12 hours). Currently available operating table pressure devices produce peak interface pressures that are substantially higher.[85] If this view is correct, avoiding pressure ulcers during prolonged surgery would be impossible. Yet, observational trials show that only a minority of patients undergoing prolonged surgery develop pressure ulcers and most do not.

The pressure/time model has been evaluated in rat models. With pressure exposure less than 1 hour, the magnitude of

pressure is the important factor for causing cell death and the duration has little or no effect. Even relatively short exposures (15 minutes to 1 hour) to pressures greater than 240 mm Hg will cause cell death in rat muscle tissue. For exposures of 2 hours or greater, the magnitude of pressure is the important factor for causing cell death. Pressures greater than 67 mm Hg applied for more than 2 hours consistently cause muscle cell death. For the intermediate exposures (between 1 and 2 hours), the magnitude of cell-death–causing pressure strongly depends on the time of exposure, with critical pressure levels dropping from 240 mm Hg to 67 mm Hg.[86] Although these data cannot be directly applied to humans, it does suggest that pressure ulcers could be prevented by a reduction in tissue interface pressures below 67 mm Hg if pressure/time is the only cause. This level of pressure reduction is achievable using various pressure-reducing devices. In patients with a hip fracture, use of a pressure-reducing support resulted in trochanteric pressure below 20 mm Hg in 80% of subjects, and sacral pressures lower than 60 mm Hg in 70% of subjects.[87]

In a pig model, muscle damage occurs with high pressure–short duration (500 mm Hg for 4 hours), whereas skin destruction requires a higher pressure–longer duration (800 mm Hg, 8 hours). Skin breakdown did not occur with a pressure of 200 mm Hg for 15 hours, thus contradicting previous assumptions that pressure exceeding 35 mm Hg for 2 hours would cause ischemia resulting in a pressure ulcer. It appears that normal tissue is far more resistant to pressure-induced ischemia than previously hypothesized.[88] This resistance suggests that development of a pressure ulcer may require abnormalities in the soft tissues such as paraplegia, infection, repeated trauma, or other factors.

The differential effect of pressure on the tissue layers suggests that injury occurs first in muscle before changes are observed in the skin, the so-called deep tissue injury. Pressure ulcers are classified in stages defined by the visible layers of tissue damaged from the surface toward the bone. Current research clearly demonstrates that a bottom-to-top pathogenesis is commonplace. In many cases, the changes visible at the surface of the tissue are minor compared with the damage seen at the deepest layers of tissue. This differential tissue susceptibility suggests that a number of factors are involved in the development of pressure ulcers, including the type of pressure load and biochemical changes in the tissue because of reperfusion injury or tissue compression. It is apparent from both in vitro and in vivo studies that further studies evaluating the changes occurring in deeper layers of the tissue in humans in response to loading are necessary to better understand the effects of pressure on tissue and the development of pressure ulcers.

Ischemia-reperfusion injury is known to produce a complex cascade of molecular and cellular events leading to tissue damage. This effect has been demonstrated in organ transplantation,[89] myocardial infarction,[90] stroke,[91] and vascular surgery.[92] Ischemia-reperfusion injury has been suggested as an etiologic factor in the development of pressure ulcers.[93,94] In animal models, tissue injury increased with an increasing number of total ischemia-reperfusion cycles, duration of ischemia, and frequency of ischemia-reperfusion cycles.[95]

Tissue compressive loading acts in conjunction with ischemic injury, but the effect of compressive loading appears to be more important than localized ischemia in animal models. A 2-hour period of compressive loading leads to irreversible damage to rat muscle tissue, whereas ischemic loading results only in reversible tissue changes.[96]

Provocative research into human skin blood flow may shed some light on the development of pressure ulcers. Skin blood flow before and during surgery was monitored in subjects selected because of lengthy abdominal or spine surgical procedures.[97] Pressure ulcers developed in 36% of these subjects. Contrary to the hypothesis that prolonged pressure reduces skin blood flow, an increase in skin blood flow was observed in most subjects during surgery. However, in the persons who developed a pressure ulcer, the skin blood flow decreased to half of the preoperative levels, whereas skin blood flow in persons who did not develop a pressure ulcer increased to 500% of maximum baseline value. These data suggest that individual tissue response is more important than externally applied pressure.

Other studies have suggested that sacral skin blood flow is higher than blood flow over the gluteus maximus,[98] and that a decrease in skin blood flow may be more serious in the sacral area than in other areas. Sacral pressure ulcers are common, but gluteal pressure ulcers are rare.

The neural response to cold stimulation produces differences in skin blood flow among older subjects who do or do not develop pressure ulcers. There was a positive correlation between the blood flow response time over the greater trochanter and the development of pressure ulcers.[99] The measure of skin blood flow is technically difficult, with a high degree of variability. However, these data suggest that individual factors may act in concert with external pressure in the development of pressure ulcers.

IMPLICATIONS

Pressure ulcers represent a serious and frequent injury, particularly in older persons. The hypothesis that pressure relief would eliminate the chief cause of pressure ulcers has not been confirmed in prospective trials, suggesting that individual factors play an important role in etiology.

1. Despite progress in understanding the etiology of pressure ulcers, the stability of pressure ulcer incidence over time suggests that current interventions have not been sufficient to prevent all pressure ulcers.
2. External pressure or shear force is a necessary but insufficient cause for pressure ulcers. Sufficiently high pressure for a sufficiently long time will invariably cause pressure ulcers. How high the pressure must be and how long it must be maintained to cause tissue damage depends on an individual's tissue tolerance, which varies among persons. In surgical patients exposed to the same pressure load and duration of surgery, individual intrinsic factors appear to play a larger role in development of a pressure ulcer than the tissue interface pressure. Intrinsic factors leading to derangement in tissue perfusion may account for observed development of a pressure ulcer, despite the

provision of common prevention measures that include pressure reduction. These factors are beginning to be identified but more research is needed.

3. Although progress has been made in reducing pressure loads, further progress may require addressing unique individual intrinsic factors. From observational trials, many of these intrinsic patient factors may not be amenable to interventions.

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