Use of High-Resolution, High-Frequency Diagnostic Ultrasound to Investigate the Pathogenesis of Pressure Ulcer Development

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ABSTRACT

OBJECTIVES: To investigate the pathogenesis of pressure ulcers utilizing high-resolution ultrasound and to explore the utility of this technology for the detection of incipient pressure ulcers prior to visual clinical signs.

DESIGN: An observational prospective study comparing high-resolution ultrasound images obtained from 119 long-term-care facility residents determined to be at risk for pressure ulcer development (Braden Scale score of 18 or less) with images obtained from 15 healthy volunteers (medical students and medical residents). Common pressure ulcer sites were scanned, including the heels, sacrum, and ischial tuberosity.

SETTING: A medical center and a long-term-care facility.

INTERVENTION: Anatomic sites universally accepted as at risk for pressure ulcer development were scanned using high-resolution ultrasound; the sites did not have visual evidence of skin breakdown. The images obtained from the long-term-care facility residents were compared with images considered normal that were obtained from healthy volunteers. In addition, documentation of the clinical assessment finding for erythema was reviewed, recorded, and compared with the high-resolution ultrasound finding for each specific site.

MEASUREMENTS: The images obtained were classified as not readable, normal, or abnormal. The images classified as abnormal were further classified by depth of abnormal finding: pattern 1 (deep) or pattern 2 (superficial). The images classified with the abnormal finding pattern 1 (deep) were further classified and subdivided by anatomic location of abnormal finding(s): subgroup 1, abnormal findings in the subdermal area only; subgroup 2, subdermal and dermal abnormal findings; and subgroup 3, subdermal, dermal, and subepidermal edema. Pattern 2 (superficial) included images with abnormal findings limited to the dermal/epidermal junction.

RESULTS: 630 (55.3%) of the images obtained from the long-term-care residents were different from the images obtained from the healthy volunteers. The healthy volunteers' images classified as normal had the expected ultrasound findings for homogeneous pattern of ultrasound reflections, allowing for visualization of various skin layers (epidermis, superficial papillary dermis, deep reticular dermis, and hypodermis) and subcutaneous tissue (subdermal). However, many images (55.3%) obtained from the residents at risk for pressure ulcer development had patterns where areas within the various skin layers were not visible, interrupted by areas indicative of fluid or edema. Moreover, most images (79.7%) with abnormal ultrasound patterns did not have documentation of erythema.

CONCLUSION: High-resolution ultrasound is an effective tool for the investigation of skin and soft tissue changes consistent with the documented pathogenesis of pressure ulcers. A progressive process for pressure ulcer development from deep subdermal layers to superficial dermal then epidermal layers can be inferred. Dermal edema was only present with subdermal edema. In other words, there was never evidence of dermal edema in the absence of subdermal edema. A better understanding of the pathogenesis of pressure ulcers through the use of high-resolution ultrasound to detect soft tissue damage and edema before visible clinical signs could lead to earlier and more focused pressure ulcer prevention programs, resulting in reduced pain and suffering for improved patient quality of life and wound care cost savings.

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Pressure ulcers (PrUs) are a major health problem in the United States. Incidence rates vary greatly within and among health care sectors: from 0.4% to 38.0% in hospitals, from 2.2% to 23.9% in long-term-care facilities, and from 0% to 17% in home health care agencies.[1] The prevalence rate for PrUs in long-term-care facilities is approximately 8.9%.[1]

In 1992, the average cost of treating a PrU reportedly ranged from $500 to $70,000 per ulcer episode, depending on severity,

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with the annual cost in the United States conservatively estimated at $1.3 billion.[2] The cost of preventing PrUs varies greatly, depending on the variables included in the equation. Studies in long-term care have shown that the cost of using pressure-relief modalities to prevent a single ulcer can range from a monthly mean cost of $100 to $242 for a one-time charge for a support surface.[3,4] Although not quantifiable, quality of life and the reduction of pain and suffering must also be considered. Therefore, from humane and financial perspectives, the prevention of PrUs is of paramount importance.

Tissue necrosis will occur if the pressure applied to soft tissue is sufficient to stop capillary blood flow for a specific time, resulting in PrU development.[2] However, the amount of pressure and duration of time required to induce a PrU is unknown. Moreover, it is also unknown whether the pressure and time duration varies between anatomic sites and/or the health status of the individual.[5] When a PrU develops, it is classified as being of a particular stage, based on depth and tissue layer involvement. The National Pressure Ulcer Advisory Panel's staging system is widely used.[6] In this system, PrUs are classified from Stage I to Stage IV—where Stage I describes a superficial ulceration, having an intact epidermis, with persistent redness in lightly pigmented skin or persistent red, blue, or purple hues in darker skin tones, and Stage IV describes the most severe ulceration, with loss of full-thickness skin, involving underlying superficial and deep fascia, ligaments, and bone.

These stages refer solely to the depth of the ulcer and, therefore, to some extent, its severity. They do not necessarily describe sequential stages in the development of ulcers caused by pressure. The question of the pathogenesis of PrUs has remained unanswered. Do such ulcers begin superficially and progress to deeper tissue if pressure is not relieved, or do they start close to the bone and progress to the epidermal layer? Are there 2 types of PrUs, some superficial and others deep in origin? In 1996, Maklebust and Sieggreen[7] suggested that Stage I and Stage II PrUs are superficial in origin and are the result of friction and shear.

The purpose of the present study was to explore and describe the pathogenesis of PrUs with the aid of high-resolution ultrasound (HRUS) in an attempt to answer these questions. The study was also intended to explore the utility of this technology for the detection of incipient PrUs before clinical signs appear.

DIAGNOSTIC ULTRASOUND

Ultrasound has been used to aid the diagnosis and assessment of human pathologies since the 1950s. It has been shown to be a safe, cost-effective modality for the assessment and diagnosis of soft tissue injury.[8-13] Ultrasound (ultrasonography) utilizes the echoes of sound waves to create images of soft tissue anatomy. A probe transmits sound waves into the body. When these sound waves hit a boundary between acoustically different tissue, such as fluid or soft tissue, a proportion of the energy, depending on the degree of acoustic mismatch, is reflected back (echoes). The ultrasound machine then calculates the distance and intensity of these reflections and displays a 2-dimensional image, incorporating the reflection intensities and distances the sound wave has traveled. B-mode scanning occurs when the transducer automatically moves tangentially over the object and a series of ultrasound pulses are depicted and electronically processed to form a 2-dimensional image.

Recent developments in ultrasound technology have allowed for the increase in ultrasound frequency used for B-mode imaging. Frequencies of 15 megahertz (MHz) and higher have led to the ability to image tissue at a higher resolution than had been possible before. Although higher frequencies enable greater resolution, the depth of penetration of the sound waves is reduced. Therefore, HRUS, often referred to as high-frequency ultrasound (HFUS) and ultrasound biomicroscopy, is ideal for imaging near-surface pathology. High-resolution ultrasound has been compared with nuclear magnetic resonance spectroscopy, in that both can be used to demonstrate the fluid content of tissue.[8] Greater fluid content in tissue results in a decrease in echogenicity readily detectable by HRUS.[8-13] High-resolution ultrasound images have shown a strong correlation with features detected by histologic examination.[14]

The use of HRUS has been shown to be effective in measuring skin thickness and can be used to assess dermal burn depth and chronic wounds.[15-23] Moreover, HRUS can be used to determine dermal edema and the architectural structure of skin.[8,14] It provides a detailed microscopic image of the skin and subcutaneous structures akin to a biopsy, but without tissue damage. The layers of the epidermis, the dermis, and the subcutaneous tissue can be distinguished.[14] The interface between bone and soft tissue can be identified by a strong reflection.

Advances in computer technology have led to ultrasound units becoming less expensive and more portable. This allows for greater utilization of diagnostic ultrasound and greater convenience because the HRUS unit can be brought to the patient's bedside. High-resolution ultrasound examination has, therefore, become a safe, noninvasive, convenient modality to assess the skin and superficial tissue of patients at risk for PrUs in a variety of settings.

METHODS

Instrument

The Longport Digital Scanner (EPISCAN I-200; Glen Mills, PA) was used for this study. The EPISCAN I-200 is a portable

20-MHz frequency system specifically developed to examine the skin and underlying soft tissue with 65-micron resolution. The EPISCAN I-200 consists of 4 main elements: an ultrasound probe, a custom-designed proprietary ultrasound analogue-to-digital converter board, a portable computer, and operating software. The system displays the information obtained in the form of a B-scan as either a color or gray-scale image. The procedure for scanning and capturing images consists of placing the probe and ultrasound gel over the site of interest and capturing an image at prescribed settings.

The EPISCAN I-200 was specifically chosen for its degree of resolution, or image clarity, in concert with its depth of penetration. Twenty megahertz ultrasound will produce images with high resolution to a depth of 2 cm. Anatomic sites predisposed to PrU development are located over bony prominences and are therefore visible with this system.

Participants

In this study, images were first obtained from common PrU sites, including scans of the heels (3 sites on each heel), the sacrum (2 scans), and the ischial tuberosity (2 scans) of 15 healthy volunteers (medical students and medical residents) to provide standardization of the system settings. The ultrasound gain (amplification), depth, and time/gain compensation were standardized for each anatomic site to ensure consistent results. Standardizing the system settings was important because of their influence on image clarity and quality and their contribution to reliability. These images served as the controls, which were used for comparison with images from the study group, and confirmed the EPISCAN I-200 as an appropriate tool with consideration to penetration depth. The average distance from the top reflection of the epidermis to the reflection from bone was 10 mm in the anatomic sites examined.

The study group included 119 residents newly admitted to a long-term-care facility. These residents had Braden Scale[24] scores of 18 or less, which indicated that they were at risk for the development of PrUs. Similar to the control group, images were obtained from the heels, the sacrum, and the ischial tuberosity of subjects in the study group. The number of scans per patient varied according to the nurses' assessment. Anatomic sites assessed as being at risk were scanned and ultrasound images were captures. The anatomic site, clinical assessment findings, as well as the date and time the image was obtained were recorded.

All patient identification information that constituted protected health information was removed prior to the review and interpretation of the images to ensure confidentiality and compliance with the Health Insurance Portability and Accountability Act.

Protocol

Protocols for scanning were established to ensure consistent images. The protocols specified probe placement, patient position, and ultrasound settings. The anatomic site, the date and time of the scan, and any outward clinical signs were recorded. Four registered nurses who were certified wound specialists were trained to perform the scanning and obtain images. Reliability was enhanced through posttraining observation of individual scanning technique on the control group and initial study group participants.

Interrater reliability for image interpretation was assessed to be 97%. The assessment was done using 3 individuals' independent interpretation of the same images. Image interpretation focused on the identification of differences between the images obtained from the control group and the study group. The nurses were trained to differentiate ultrasound findings consistent with normal skin and underlying soft tissue from soft tissue edema and edema possibly indicative of tissue breakdown. The scans were reviewed and interpreted by the prinicipal investigator after coding so that they could be assessed in blind fashion.

The images were classified in 5 categories:

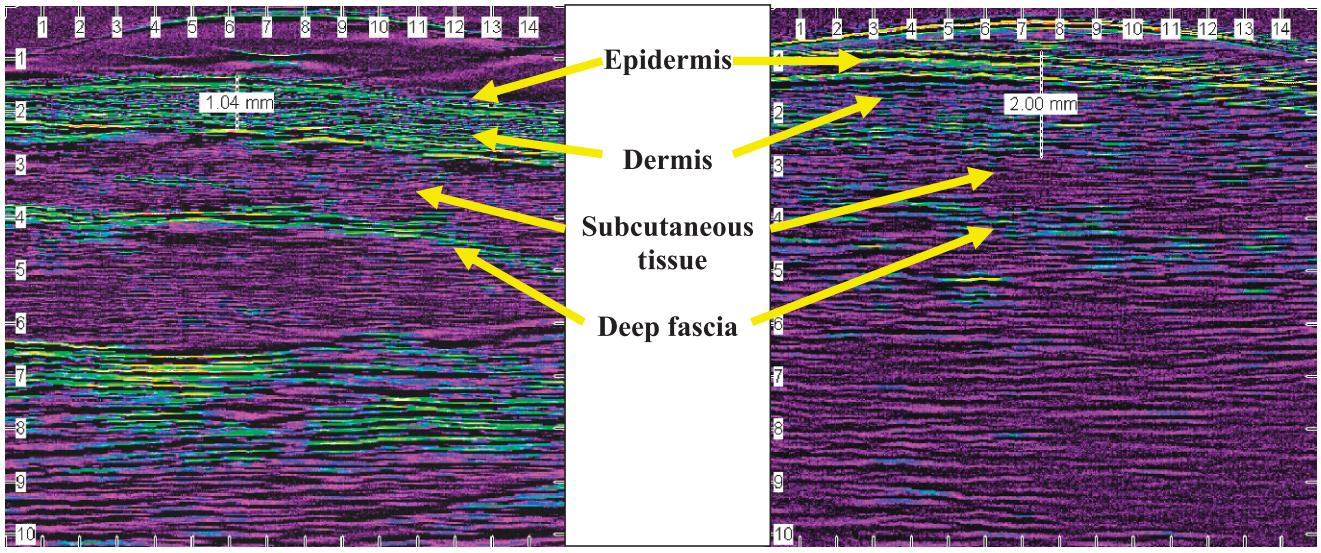
- normal, no evidence of edema
- subdermal pockets of edema
- subdermal and dermal fluid (edema)
- subdermal and dermal edema, with pooling of fluid immediately under an intact epidermis (ie, subepidermal edema)
- subepidermal edema in the absence of dermal and subdermal edema.

RESULTS

Two hundred readable images were obtained from 15 healthy volunteers; 1139 readable images were obtained from 119 long-term-care residents. Not all subjects in the study group had the same number of images captured; images were captured on the basis of the nurses' assessment, and some images were excluded from the study as not readable. The images obtained from the control group showed a homogeneous pattern of ultrasound reflections with clear demarcations between the epidermis and dermis, the dermis and the subdermal tissue, and the soft tissue and the bone (Figures 1a and 1b). The images obtained from the study group differed in that many did not always have a homogeneous pattern of reflections, but instead had areas of low reflections. The 1139 readable images obtained from the 119 residents were interpreted without consideration for Braden Scale score and clinical assessment findings (Table 1).

Most of the images (630, 55.3%) were found to have ultrasound patterns consistent with abnormal skin and soft tissue. There were 509 (44.7%) images that demonstrated a

Figure 1.
EXAMPLES OF THICK AND THIN SKIN



1A. Thin skin, iliac crest. Note sharp border between the dermis and the subcutaneous tissue.

1B. Thick skin, lateral heel. Note thicker epidermis and dermis and the nondistinct border between the dermis and subcutaneous tissue.

pattern consistent with normal skin and soft tissue. Images with abnormal skin and soft tissue demonstrated 2 distinct abnormal ultrasound patterns (Figures 2a and 2b):

• *Pattern 1.* Deep areas of weak reflection that appear to progress from a deep subdermal area to a superficial dermal area (541 images, 47.5%).

• *Pattern 2.* A superficial layer of weak reflection directly below the intact epidermis (89 images, 7.8%).

As previously noted, weak reflective patterns in HRUS images indicate increased fluid content or edema in the tissue.[16-19]

Table 1.

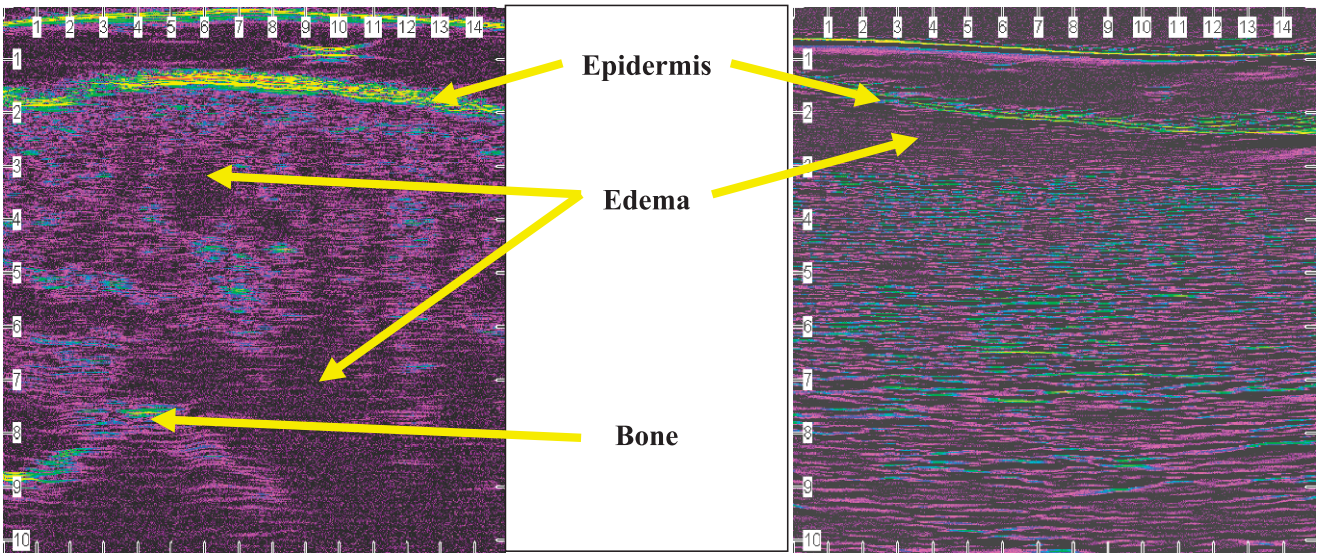
ULTRASOUND FINDINGS OF 119 LONG-TERM-CARE FACILITY RESIDENTS

	Total number of images	Normal images	Pattern 1: Images with deep areas of edema	Pattern 2: Images with edema directly under the epidermis without deep edema
Number of images	1139	509	541	89
Percentage of images (%)	100	44.6	47.5	7.8

The data from the present study suggested different etiologies for ulcer formation; therefore, the authors chose to include preulcerative changes induced in a healthy volunteer to aid in the understanding of ulcer etiology. One area was subjected to friction by rubbing a gauze pad over a site for a period of 7 minutes. A second area was subjected to prolonged pressure by lying on a hard object placed on the skin covering the coccyx for 1 hour. Both sites were scanned prior to intervention and scanned at intervals following the applied friction or pressure. The postfriction images showed edema directly under the epidermis with no changes in deep tissue. These findings were consistent with the images of superficial edema obtained from the study group. (Figure 2b). The postpressure images exhibited pockets of deep edema with no superficial changes, consistent with the pattern 1 images of deep edema obtained from the study group (Figure 2a).

The images obtained from the study group that demonstrated deeper areas of weak reflection were divided into 3 subgroups based on the extent and location of the weak reflective pattern. The first subgroup (91 images, 16.8%) demonstrated pockets of weak reflections in the tissue between the bone and the dermal layer (Figure 3a). The ultrasound pattern for this was normal in the dermal layer, the subepidermal layer, and the intact epidermis. The second

Figure 2.
HIGH-RESOLUTION ULTRASOUND IMAGES OF DEEP EDEMA VERSUS SUPERFICIAL EDEMA

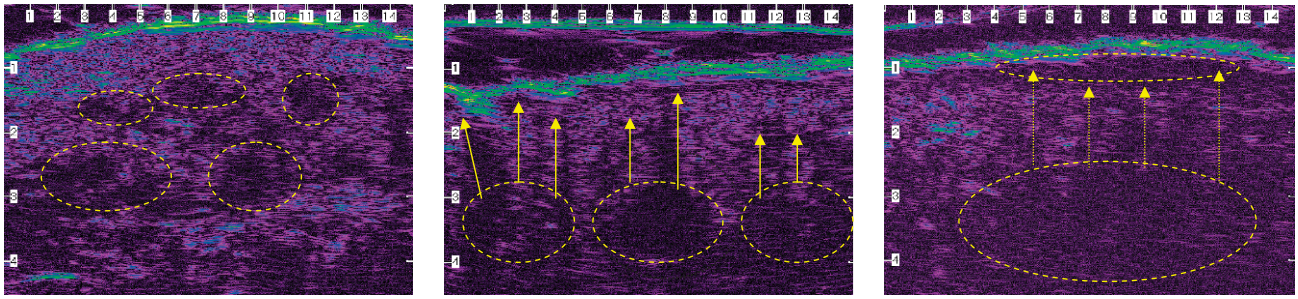


2A. Pattern 1. Example of deep edema extending from the bone and extending upward, most likely caused by pressure.

2B. Pattern 2. Example of superficial edema, most likely caused by friction or incontinence.

subgroup (177 images, 32.7%) showed more areas of weak reflection in the subdermal tissue, with progression into the dermal layer (Figure 3b). In this group, strips of weak reflections extended outward from the pockets of weak reflection into the more superficial tissue. The third subgroup (273 images, 50.5%) showed significantly decreasing reflections in the subdermal and dermal layers and a distinct layer of weak reflection directly under the intact epidermis (Figure 3c).

Figure 3.
HIGH-RESOLUTION ULTRASOUND IMAGES DEMONSTRATING THE 3 PHASES OF PRESSURE ULCER DEVELOPMENT



3A. Subgroup 1. Pressure ulcer development with pockets of edema in the subcutaneous tissue but with no dermal involvement.

3B. Subgroup 2. Pressure ulcer development with edema extending from the subcutaneous tissue into the dermis.

3C. Subgroup 3. Pressure ulcer development with edema extending from the subcutaneous tissue via the dermis to the dermal/epidermal junction where it has pooled.

In the third subgroup, there also was the consistent presence of a very weak reflective pattern in the deep tissue, possibly suggesting that the dermal and subepidermal changes occurred only after there was overt change in the subdermal tissue (Figure 3c).

The ultrasound findings were compared with the documented visual clinical signs for erythema, which is the current standard of care for skin assessment and predicting PrU risk.

Of those documented as having a visual clinical sign for erythema, 2 (less than 1%) of the 509 normal images showed erythema; however, 74 (11.7%) of the images with abnormal ultrasound findings had documented visual clinical signs for erythema. Of these, 17 (23.0%) had ultrasound findings in subgroups 1 and 2; whereas, 57 (77.0%) had subgroup 3 changes. This indicates that many PrUs are forming prior to observable erythema, and the further the progression of the ulcer, the more likely it is that erythema will be observed (Table 2).

For the images reflecting pattern 2, superficial (subepidermal only) edema, the clinical sign of erythema was often documented. In fact, 60.0% (53) of the images that showed superficial ultrasound changes also had erythema documented for that anatomic site. Because these ulcers begin in the epidermis, it is to be expected that clinical signs would become visible at an earlier stage.

DISCUSSION

The findings of this study support the hypothesis that PrUs originate in the deeper tissue and progress in an outward direction, whereas friction ulcers originate within and/or directly beneath the epidermis. These findings correspond to animal studies[25-30] showing that deeper tissue is affected before the skin in pressure-induced ulcers. Studies of the effect of pressure on tissue suggest that the deeper subcutaneous tissue and muscle are more susceptible to pressure necrosis than skin.[25-30] It has been found that where bone is close to the surface, such as the heel, the tissue damage will be full-thickness from the beginning.[26] A study conducted by Daniel et al[25] utilizing computer-controlled electromechanical pressure on the greater femoral trochanter of swine demonstrated 3 groups of statistically significant pathologic changes at the site of the induced wounds: muscle damage only, muscle and deep dermal damage, and full-thickness damage extending from bone to skin. Another study in rats found necrosis in the muscle and adipose layer before skin changes were seen.[30] These findings suggest that PrUs begin in the deeper tissue and progress outward to the skin.

Table 2.

PERCENTAGE OF PATTERN 1 IMAGES DEMONSTRATING ERYTHEMA

	Phase 1	Phase 2	Phase 3	Total
Total images	91	177	273	541
Number with erythema	7	15	88	110
Percentage with erythema (%)	7.7	8.5	32.2	20.3

The findings from the present study indicate that there is a distinct progression in PrU formation illustrated sequentially by subgroups 1, 2, and 3 of the pattern 1 images. Pressure ulcers appear to begin in the subdermal tissue between the skin and bone, progressing by direct extension in the dermal tissue. This is illustrated by pockets of edema, indicated ultrasonically by areas of weak reflection. The strips of weak reflection suggest that the edema takes the path of least resistance along anatomic channels. The weak reflective pattern in the dermis suggests greater fluid content in the dermis and the weak reflective area directly beneath the epidermis indicates edema pooling. Because the epidermal tissue is denser than the dermal tissue, it is to be expected that edema would collect beneath the epidermis before breaking through. All of the images that demonstrated dermal edema also showed edema in the deeper subdermal tissue. Dermal edema was not seen in the absence of deeper subdermal edema, suggesting that PrUs begin deep and work toward the surface. The pathogenesis of PrU development suggested by the ultrasound findings can be described in 3 phases:

- *Phase 1:* the formation of pockets of edema in the tissue between the bone and the dermis, such as in the subdermal tissue (pattern 1, subgroup 1 findings)
- *Phase 2:* the spread of the edema by direct extension into the dermis (pattern 1, subgroup 2 findings)
- *Phase 3:* increased subdermal edema with frank dermal edema and subepidermal edema or pooling of fluid. (pattern 1, subgroup 3 findings)

Further examination of the images classified as pattern 1, subgroup 3 (phase 3) showed the consistent lack of ultrasound reflections, indicating a considerable amount of edema from the bone to the dermal/epidermal interface. This may indicate that by the time the epidermis is broken, there is already considerable deep tissue injury/damage that could result in a deep ulcer. This could explain why so many deep ulcers seem to appear overnight.

A layer of edema was observed directly beneath the epidermis in 89 images obtained from residents of a long-term-care facility. There was a clear boundary between the edema and the underlying dermal tissue. None of these images showed any evidence of subdermal edema; however, some of the images showed streaks of weak reflection extending downward from the edema layer with some dermal edema.

These findings suggest that friction ulcers begin at the surface and progress from superficial to deep tissue. Because friction and/or increased surface moisture would be expected to cause more damage to superficial tissue than to deeper tissue, it is suggested that these ulcers are caused primarily by friction and/or incontinence rather than pressure.

CONCLUSIONS

High-resolution ultrasound is an effective aid in the investigation of the pathogenesis of PrUs. It provides a noninvasive, economical way of detecting early changes in the subdermal tissue and skin. Examination of anatomic sites at risk for PrU development suggests that HRUS can be a valuable tool in PrU prevention or management.

High-resolution ultrasound can detect early signs of PrU development independent of clinical signs. The ultrasound findings in the present study demonstrated edema in the subdermal tissue and skin before clinical signs were apparent; 79.3% of the anatomic images had tissue changes in the absence of erythema. Therefore, HRUS provides a method for detecting damage earlier than the current methods that rely on visual assessment of clinical signs.

The literature often does not distinguish between PrUs and friction ulcers. It has been well documented that friction, moisture, and pressure can create ulceration.[25] Although there is rarely only one cause or mechanism of PrU development, treatments are implemented to address the primary causative mechanism. Therefore, it is important to distinguish between ulcer types. High-resolution ultrasound can distinguish the primary causative mechanism, such as pressure versus pressure and friction, allowing for focused intervention. This should lead to more effective treatments and quicker resolution.

Many authors have suggested that PrUs develop in the deeper tissue and progress outward toward the skin surface.[25-29] In the present study, HRUS showed edema in the deep tissue between the bone and skin before clinical signs were seen, supporting this assertion. Three distinct patterns of abnormal ultrasound findings were visualized, possibly suggesting progressive edema beginning with subdermal pockets, followed by channeling into the dermis, and finally, edema pooling directly beneath the epidermis. Identification of these abnormal ultrasound findings for classification of tissue injury phases could provide caregivers with information regarding the severity of tissue injury and, therefore, risk of skin breakdown, enabling appropriate corrective measures to be taken before clinical signs appear.

In the subgroup 3 findings of pattern 1, 273 (50%) of the 541 images that demonstrated diffuse edema throughout the subdermal tissue and pooling under the epidermis. These images indicate damaged tissue between the skin, muscle, and bone. This may help to explain why many deep ulcers, such as Stage III and IV ulcers, present immediately after epidermal breakthrough.

In conclusion, this study supports the use of HRUS for early detection of tissue injury associated with pressure and friction. Future studies should further explore the different ultrasound patterns within the context of time and risk. More study is also needed to address the use of ultrasound to monitor the effectiveness of particular interventions as well as to address the utility and cost-effectiveness of HRUS in the detection of PrUs. Although this study supports the use of HRUS for the detection of tissue damage associated with pressure and friction, further study is necessary to determine whether the use of HRUS could lead to reductions in the incidence of PrU formation in health care settings. Proactive approaches for early intervention and PrU prevention require clinical diligence. High-resolution ultrasound is a potential tool to help clinicians achieve this goal. ●

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