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Patient repositioning and pressure ulcer risk—Monitoring interface pressures of at-risk patients

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Abstract—Repositioning patients regularly to prevent pressure ulcers and reduce interface pressures is the standard of care, yet prior work has found that standard repositioning does not relieve all areas of at-risk tissue in nondisabled subjects. To determine whether this holds true for high-risk patients, we assessed the effectiveness of routine repositioning in relieving at-risk tissue of the perisacral area using interface pressure mapping. Bedridden patients at risk for pressure ulcer formation (n = 23, Braden score <18) had their perisacral skin-bed interface pressures recorded every 30 s while they received routine repositioning care for 4–6 h. All participants had specific skin areas (206 +/– 182 cm^2) that exceeded elevated pressure thresholds for >95% of the observation period. Thirteen participants were observed in three distinct positions (supine, turned left, turned right), and all had specific skin areas (166 +/– 184 cm^2) that exceeded pressure thresholds for >95% of the observation period. At-risk patients have skin areas that are likely always at risk throughout their hospital stay despite repositioning. Healthcare providers are unaware of the actual tissue-relieving effectiveness (or lack thereof) of their repositioning interventions, which may partially explain why pressure ulcer mitigation strategies are not always successful. Relieving at-risk tissue is a necessary part of pressure ulcer prevention, but the repositioning practice itself needs improvement.

Key words: decubitus ulcer, interface pressure, patient repositioning, pressure, pressure sore, pressure ulcer, pressure ulcer risk, prevention, standard of care, triple-jeopardy area.

INTRODUCTION

Pressure ulcers are a high-risk, high-volume, and high-cost problem for hospitalized and bedridden patients. Overall pressure ulcer prevalence rates have been reported at 12.3 percent across all facilities, with prevalence being highest in long-term acute care facilities (22%), and facility-acquired prevalence being highest in adult intensive care units (8.8%–10.3%) [1]. Preventing pressure ulcers and reducing their incidence is an ongoing challenge because they are associated with increased cost, length of stay, morbidity, and mortality. Managing one full-thickness ulcer can cost up to $70,000 [2], and over $17 billion is spent on pressure ulcer treatments annually in the United States [3].

Note: The authors would like to dedicate this article to the memory of their colleague Dr. Schwab.

Abbreviations: BMI = body mass index, HOB = head of bed, NPUAP = National Pressure Ulcer Advisory Panel, q2h = every 2 h, SLR = supine-left-right.

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A pressure ulcer, as defined by the National Pressure Ulcer Advisory Panel (NPUAP), is a "localized injury to the skin and/or underlying tissue usually over a bony prominence, as a result of pressure, or pressure in combination with shear and/or friction" [4]. It is widely accepted that this mechanical loading is the main cause of pressure ulcer formation; however, the pathophysiological responses to this loading are less agreed upon [5]. Theories include localized ischemia [6], reperfusion injury [7], impaired interstitial fluid flow [8], and sustained cell deformation [9]. Tissue-loading models have been developed to study pressure ulcer formation, and results have shown that acute stresses and strains in the deep tissue (fat, muscle), which is more susceptible to damage than the skin, present themselves before they are apparent in the superficial tissue [5,10–11]. However, tissue pressures greater than capillary pressure can be endured for some time before ischemia results [12].

Pressure ulcers result when increased pressure on the skin and subcutaneous tissues exceeds the local capillary pressure, which compromises blood flow and results in ischemia and decreased oxygen delivery [13]. Healthy capillary pressures typically range from 10 to 30 mm Hg [14]; however, capillary pressures may be lower for individuals in poor health [15–16]. Studies on blood flow in response to loading vary in the amount of pressure required to stop or reduce blood flow and oxygen delivery as well as by anatomical location or tissue type [17–21]. Therefore, no widely accepted value exists that will ultimately lead to pressure ulceration [5,22]. When pressures exceed capillary pressure, tissue hypoperfusion, accumulation of metabolites, and impairment of tissue reperfusion may occur, all of which can damage the tissue [23–25]. It is well established in animal and human studies that not only is the magnitude of pressure a factor for tissue damage but the duration is important as well—the greater the pressure, the less time it takes until damage occurs [6,22,26–29]. Over time, prolonged high pressure applied to a tissue area will inevitably cause damage. Interface pressure is the perpendicular force per unit area between the support surface and the body. Interface pressures are greatest around the sacrum, coccyx, and ischial tuberosities, so it is not surprising that the majority of pressure ulcers develop near these locations [30–31]. However, note that tissue interface pressures do not directly measure internal tissue and capillary pressures [22].

The Centers for Medicare and Medicaid Services recently designated pressure ulcers as a quality measure, and consequently, they will not reimburse additional patient expenses resulting from a reasonably preventable condition that occurs while providing care [32–33]. Thus, pressure ulcers have become a liability for hospitals, long-term care facilities, and other healthcare providers [34–35]. However, disagreement persists about the presumed inherent preventability of all pressure ulcers [36–37]. To address this issue, the NPUAP hosted a multidisciplinary consensus conference in 2010 and redefined what is generally considered avoidable and unavoidable. The group unanimously agreed that most, but not all, pressure ulcers are avoidable [37]. Consensus was reached that "unavoidable pressure ulcers may develop in patients who are hemodynamically unstable, terminally ill, have certain medical devices in place, and are nonadherent with artificial nutrition or repositioning" [37].

PATIENT REPOSITIONING

Repositioning patients regularly—every 2 h (q2h)—to prevent sustained high pressures on any particular tissue area is the standard of care [2,16,37–40]. However, several recent studies in which repositioning was used as the primary intervention strategy failed to reduce the incidence of pressure ulcer formation [39–41]. Additionally, the NPUAP conference could not reach a consensus that q2h repositioning should be the standard of care. However, they did agree that q2h repositioning should be the "guideline for care" when clinically appropriate [37]. It was also unanimously agreed that pressure-redistributing surfaces cannot replace patient repositioning care [37].

Our prior work found that standard, lateral turning by experienced nurses does not reliably relieve all areas of high skin-bed interface pressures in the perisacral region of nondisabled adult subjects [42], i.e., the collective tissue area around the sacrum, coccyx, and ischial tuberosities. Even though subjects are repositioned and the perisacral area is no longer touching the mattress, this perisacral skin area remains exposed to significant levels of interface pressure between the pillow or wedge that is supporting the laterally turned position. Furthermore, specific skin areas remain at risk even after being placed in all three positions: supine, turned left, and turned right. These specific skin regions are termed "triple-jeopardy areas" because the same tissue remains at risk while in any of the three different positions [42]. This may help explain why pressure ulcers still develop despite implementation of standard preventive measures, including scheduled patient repositioning. To determine whether this is the case for at-risk patients, this study examined the effect of routine repositioning over an extended time period on the interface pressures of the perisacral skin area of bedridden patients at risk for pressure ulcer formation using interface pressure mapping.

METHODS

Study Design

We performed a descriptive, observational study, collecting data at a tertiary care, university-affiliated hospital with 170 intensive and intermediate care beds from 2007 to 2009. Subjects were invited to enroll in the study during regular care by their physician. We hypothesized that bedridden patients undergoing q2h repositioning would demonstrate a triple-jeopardy area (i.e., triple-jeopardy area is not zero). To achieve a power of 80 percent, a one-tailed test with an effect size of 0.8, and an error probability of 5 percent required a minimum sample size of 12. The effect size, though seemingly large, is conservative based on results from our previous study with nondisabled subjects [42] and, since a negative area does not exist, a one-tailed test is appropriate. We enrolled participants in the study until we monitored at least 12 in all three distinct positions: supine, turned left, and turned right. To compute the power, we used G*Power 3.0 (Institut für Experimentelle Psychologie, Heinrich Heine Universität Düsseldorf; Düsseldorf, Germany).

Subjects

We enrolled 23 participants in the study from a convenience sampling of intensive care (n = 20) and intermediate care (n = 3) unit patients. We obtained written informed consent from the patient or his or her proxy. The patient inclusion criteria were bedridden, residing in intensive care or intermediate care unit, at risk for pressure ulcer formation determined by a Braden score of ≤18 (at time of consent), and receiving lateral repositioning as part of routine care. Not all patients were intubated or sedated, but none was able to reposition themselves in bed. **Table 1** shows the demographics of the study cohort (sex, age, height, weight, and body mass index [BMI]) and Braden scores (on date of data collection). The subgroup of patients that we observed in all three positions will be referred to as the supine-left-right (SLR) group (n = 13).

Instrumentation

We obtained interface pressure measurements using a pressure mapping system (XSENSOR Technology Corporation; Calgary, Canada). The pressure sensor is a flexible, thin pad with 48 × 48 half-inch sensors forming a 24 × 24 in.^{2} array. The 2,304 independent sensors use proprietary capacitive technology to discretely measure the pressures applied to the sensor array. The interface box relays individual pressure information from each sensor to a computer for real-time visualization and recording. We calibrated the sensor array according to the manufacturer's recommendations to measure pressures from 10 to 200 mm Hg, with a reported accuracy of ±10 percent, placing the sensor array between two air bladders held together in a metal frame and inflated to specific pressures. During calibration, sensor readings were all within ±10 percent of the measured value across the calibrated range. We used the same calibration file for all subjects. Before use in the clinical environment, we wrapped the sensor array in very thin (0.0254 mm) plastic sheeting to protect it from contamination and placed it beneath the patient's underpads (thin, towel-like incontinence pads). We disinfected the sensor array after each use. We used a modern hospital bed with low air-loss technology for all measurements (Total Care or Total Care SpO2RT, Hill-Rom; Batesville, Indiana). The bed's built-in ball-bearing indicator located in the side rail of the bed indicated the head of bed (HOB) elevation.

Protocol

We placed the sensor array beneath the patient, spanning from the lower back to mid-thigh to ensure data collection of the perisacral area. Placing the sensor array required the nurses to roll the patient to one side and then the other so that the array could be positioned, without wrinkles, beneath the patient.

We recorded interface pressure measurements every 30 s as the patient lay in bed and received routine care, which included lateral turning by his or her nurse. The lateral turning methods included the use of pillows and/or wedges placed behind the back and thighs. The repositioning technique was not prescribed by the study, and the nursing technique was unconstrained so that the results would reflect current clinical practice. Any pillows or wedges that were used to maintain a laterally

Table 1.
Patient demographics and Braden score data. These data represent mean ± standard deviation for demographic and Braden score data for study cohort and for supine-left-right (SLR) group.

Patient	Sex	Age (yr)	Height (m)	Weight (kg)	BMI	Braden Score	SLR Group
1	M	65	1.78	111	35.0	13	—
2	F	73	1.65	75	27.5	—	—
3	M	69	1.83	80	23.9	16	—
4	F	84	1.57	64	25.8	10	√
5	M	70	1.78	86	27.3	15	—
6	M	69	1.78	110	34.8	11	√
7	M	60	1.65	91	33.4	10	√
8	F	53	1.68	70	24.9	12	—
9	M	58	1.73	120	40.1	15	—
10	M	71	1.80	65	20.1	16	—
11	F	61	1.63	77	29.0	17	√
12	M	54	1.82	120	36.2	16	√
13	M	43	1.85	125	36.3	11	√
14	M	76	1.75	79	25.7	11	—
15	F	74	1.60	71	27.7	15	—
16	F	67	1.40	55	28.2	12	—
17	F	69	1.60	80	31.3	10	√
18	F	47	1.63	62	23.3	11	√
19	F	80	1.65	64	23.4	12	√
20	M	46	1.70	110	38.0	10	√
21	M	64	1.75	80	26.1	17	√
22	M	72	1.73	68	22.7	19	√
23	M	32	1.83	114	34.0	13	√
Total	14 M, 9 F	63.3 ± 12.7	1.70 ± 0.11	85.9 ± 21.9	29.3 ± 5.6	13.3 ± 2.8	—
SLR Group	8 M, 5 F	60.1 ± 15.2	1.71 ± 0.09	89.6 ± 23.2	30.3 ± 5.5	12.8 ± 3.2	√

√ = included in SLR group, BMI = body mass index, F = female, M = male.

turned position were placed beneath the sensor array to allow continuous measurement of interface pressures between the patient and the supporting device. The sensor array was inspected after each turn to confirm that the patient's perisacral area was recorded. If the sensor array got bunched up or if the patient's perisacral area moved off the array, adjustments were made only when the patient was already in the process of being repositioned to avoid interfering with patient care.

We monitored patients for 4 to 6 h. We chose this time frame to allow for observation of the three distinct positions (supine, turned left, and turned right) during the q2h repositioning protocol. The same investigator (M.P.) recorded the general positioning of the patient (direction of turn and HOB elevation) for all of the data collection periods for all patients. We obtained demographic information from the patients' charts.

Data Variables

Definitions of four data variables of interest and how we calculated them include—

- At-risk areas (centimeters squared) for pressure ulcer formation are the skin areas exposed to various interface pressure thresholds (32 mm Hg—a historical and contested value [5,16,20,22]—used for statistical analyses, 40 mm Hg, and 50 mm Hg). We calculated at-risk areas for every position experienced by each patient, as well as for how long these particular skin areas were at risk. At-risk areas could be located over any load-bearing tissue, such as the greater trochanter while laterally turned.

- Always-at-risk areas (centimeters squared) are the skin areas at risk for >95 percent of the total observation period, regardless of the number of positions experienced. We used >95 percent of the patient's monitoring time rather than 100 percent to provide a more realistic representation of what the patients actually experienced. For example, if a patient momentarily rolled to one side and then back during a recording, the pressure profile could indicate that specific tissue areas were relieved, though just briefly.
- Triple-jeopardy areas (centimeters squared) refer to the same always-at-risk areas of skin that coincide in all three positions. This term only applies to the patients observed in all three distinct positions and to areas in the perisacral region.
- Peak pressure over time (millimeters of mercury) was calculated by averaging the peak interface pressure measurement of each pressure profile obtained over the duration of each position (supine, turned left, or turned right). This value demonstrates the constancy of the maximal pressures experienced, rather than just a one-time value experienced for 30 s of a 2 h time period.

Data Analysis

We used MATLAB (MathWorks; Natick, Massachusetts) and Excel (Microsoft; Redmond, Washington) to image, align, analyze, compile, plot, and compare the interface pressure data. Each pressure profile provided the interface pressure (millimeters of mercury) at each of the 2,304 discrete sensors. We determined peak interface pressures and confined them to the tissues surrounding the perisacral area, buttocks, and greater trochanters. We also calculated the skin areas that were subjected to various pressure thresholds over time. In addition to the 32 mm Hg threshold, we also analyzed the data using more stringent at-risk area interface pressure thresholds of 40 and 50 mm Hg, an increase of 25 and 56 percent, respectively.

We used the pressure profiles of the various positions obtained for each patient to determine how repositioning affected the patients' interface pressures. We anatomically aligned the pressure profile images by maximizing normalized two-dimensional cross-correlation, as conducted in previous work [42], and then adjusted them further, if necessary, by visual inspection to ensure that skin areas from one position were compared with the same skin areas of another position. We used a one-sample Wilcoxon signed rank test to test the hypothesis that the triple-jeopardy area was not zero. Wilcoxon rank sum and signed rank tests were used, as appropriate, to compare interface pressures, at-risk areas, and triple-jeopardy areas between positions. We also compared these at-risk patients with the nondisabled subject findings from Peterson et al. [42] using similar statistical techniques; we considered $p < 0.05$ significant.

RESULTS

Pressure Profiles and Patient Positioning

We recorded a total of 15,784 pressure profiles from more than 131 h of patient monitoring; each patient was monitored an average of 5.7 ± 1.0 h. We could not analyze some of the pressure profiles (<8%) because data were recorded during patient repositioning or because the perisacral area had moved off the sensor array. After removing these profiles, we analyzed 14,527 pressure profiles from 121 h of monitoring. The SLR group consisted of 8,028 profiles from 66.9 h of monitoring time.

Table 2 shows the specific positions observed for each patient. We recorded the HOB elevations for each of the positions periodically throughout the study. For the supine position, the average HOB elevation was 30° (range: 15°–65°); for the turned-left position, the average HOB elevation was 26° (range: 18°–40°); and for the turned-right position, the average HOB elevation was also 26° (range: 15°–45°).

Interface Pressures and At-Risk Areas

The peak interface pressures, peak pressures over time, and at-risk areas did not differ significantly by position (**Table 3**). However, on an individual basis, the peak interface pressures and specific areas of at-risk skin were susceptible to significant changes upon patient repositioning. For example, the peak interface pressures for one patient upon being turned to the left from a supine position increased nearly threefold due to shifting of the patient's body weight directly over the greater trochanter (**Figure 1**).

Always-at-Risk and Triple-Jeopardy Areas

All 23 patients demonstrated always-at-risk areas, with a mean always-at-risk area of 206 ± 182 cm^2 (**Table 2**).

Table 2.
At-risk patient positions observed and corresponding always-at-risk and/or triple-jeopardy areas.

Patient	Positions	No. of Positions	Always-at-Risk Area (cm^2)	Triple-Jeopardy Area (cm^2)
1	R, L, R, L	4	297	—
2	R, L	2	5	—
3	S, L	2	469	—
4	S, L, R, L	4	8	8
5	S, L, S	3	73	—
6	S, R, S, L	4	108	108
7	S, L, R	3	119	119
8	S, L	2	169	—
9	S	1	261	—
10	R	1	247	—
11	S, R, L, R	4	110	110
12	R, S, L	3	456	456
13	S, R, L	3	613	613
14	S, Sit, S, R	4	516	—
15	S, L	2	427	—
16	R, L, R, L	4	105	—
17	S, L, S, R	4	76	76
18	R, S, L	3	15	15
19	R, L, R, S	4	195	195
20	S, L, R	3	248	248
21	S, R, L	3	2	2
22	S, L, R	3	15	15
23	S, L, R	3	194	194
Mean ± SD	—	3.00 ± 0.95	206 ± 182	166 ± 184

Note: In "Sit" position, head of bed was 65°.
L = left, R = right, S = supine, SD = standard deviation.

Accordingly, all 13 patients in the SLR group demonstrated triple-jeopardy areas as well and had a mean triple-jeopardy area of 166 ± 184 cm^2 (**Table 2**). These unambiguous results support our hypothesis that bedridden, at-risk patients do demonstrate a triple-jeopardy area (SLR group, $p < 0.001$) or always-at-risk area (all patients, $p < 0.001$). To view the areas of skin that were always-at-risk and for how long, we compiled the at-risk areas from every pressure profile from each patient's entire monitoring period. **Figure 2** illustrates the typical interface pressure profiles for the three different positions and how the at-risk skin areas were affected over time.

We also analyzed the data with more stringent interface pressure thresholds. At 40 mm Hg, 18 of 23 patients (9 of 13 in SLR group) had always-at-risk areas, and at 50 mm Hg, 10 of 23 patients (3 of 13 in SLR group) still had always-at-risk areas. Since the at-risk patients differed in age, Braden score, and body type, we also analyzed the data to see whether any of these factors affected the results. However, no trend emerged upon analyzing always-at-risk or triple-jeopardy areas with respect to age, height, weight, BMI, or Braden score.

DISCUSSION

Regular q2h repositioning of patients is the standard of care that is routinely implemented to reduce the risk of pressure ulcer formation. Our results clearly demonstrate that bedridden, at-risk patients have substantial areas of

Table 3.
Comparison of interface pressure (mm Hg), at-risk areas (cm^2), triple-jeopardy areas (cm^2), and always at-risk areas (cm^2) between patients at risk for pressure ulcer formation and nondisabled subjects. Data presented as mean ± standard deviation, and all measurements were taken on same brand of modern hospital bed. Nondisabled subject data from Peterson et al. [42].

Peak Interface Pressures (mm Hg)	Position		
	Supine	Left	Right
At-Risk Patients with HOB Elevation			
Peak Pressures*†	122.5 ± 45.1	134.2 ± 43.7	119.8 ± 33.8
Peak Pressures Over Time*	99.1 ± 34.3	99.5 ± 30.0	88.9 ± 17.1
Nondisabled Subjects	—	69.2 ± 12.8	64.8 ± 9.1
Supine Measurement Prior to Turning to Left Side	68.6 ± 19.5	—	—
Supine Measurement Prior to Turning to Right Side	65.8 ± 11.7	—	—
Turned with 30° HOB Elevation	—	84.5 ± 17.5	80.4 ± 11.4
At-Risk Areas (cm^2)	**Position**		
	Supine	**Left**	**Right**
At-Risk Patients with HOB Elevation‡	716 ± 290	742 ± 304	744 ± 287
Nondisabled Subjects	—	468 ± 151	434 ± 147
Supine Measurement Prior to Turning to Left Side	470 ± 170	—	—
Supine Measurement Prior to Turning to Right Side	480 ± 170	—	—
Turned with 30° HOB Elevation	—	569 ± 192	558 ± 159
Triple-Jeopardy and Always-at-Risk Areas (cm^2)	**Triple-Jeopardy Area**	**Always-at-Risk Area**	
At-Risk Patients	166 ± 184	206 ± 182§	
Nondisabled Subjects	60 ± 54	—	

*At-risk patient values were significantly larger than nondisabled subjects for corresponding supine and laterally turned positions ($p < 0.001$).
†At-risk patient values were significantly larger than nondisabled subjects for corresponding turned with HOB elevation positions ($p < 0.001$).
‡At-risk patient values were significantly larger than nondisabled subjects for corresponding supine and laterally turned positions ($p < 0.003$).
§At-risk patient values were significantly larger than nondisabled subjects ($p < 0.006$).
HOB = head of bed.

skin that do not get relieved and remain at risk despite repositioning by experienced nurses. This observation was not isolated to only a few patients—all 23 patients monitored in this study demonstrated always-at-risk areas. We monitored patients for approximately 6 h consecutively, and they had specific skin areas that remained at risk during the entire observation period. Based on these results, we can reasonably assume that these skin areas are at risk for the majority of time a patient is bedridden. These results mirror those of the nondisabled subject study that first described the triple-jeopardy area phenomenon [42] and confirm that at-risk patients also have substantial always-at-risk skin areas despite routine repositioning.

Since there is no widely accepted value for an interface pressure threshold for tissue risk or damage, we also used more stringent interface pressure thresholds. Upon evaluation with greater interface pressure thresholds, the results revealed that always-at-risk areas and triple-jeopardy areas still continued to exist in a significant subset of at-risk patients, which suggests that the current standard of care is not sufficient. However, of the patients that demonstrated an always-at-risk area, the fraction of those patients that were from the SLR group decreased as the interface pressure thresholds increased. Furthermore, the mean always-at-risk area was less for the SLR group (triple-jeopardy area) than for the overall study population as a whole. These results provide objective support that routine patient repositioning, when done properly, reduces always-at-risk areas, which should, in turn, reduce pressure ulcer risk. Accordingly, future studies are needed to assess whether patients with always-at-risk

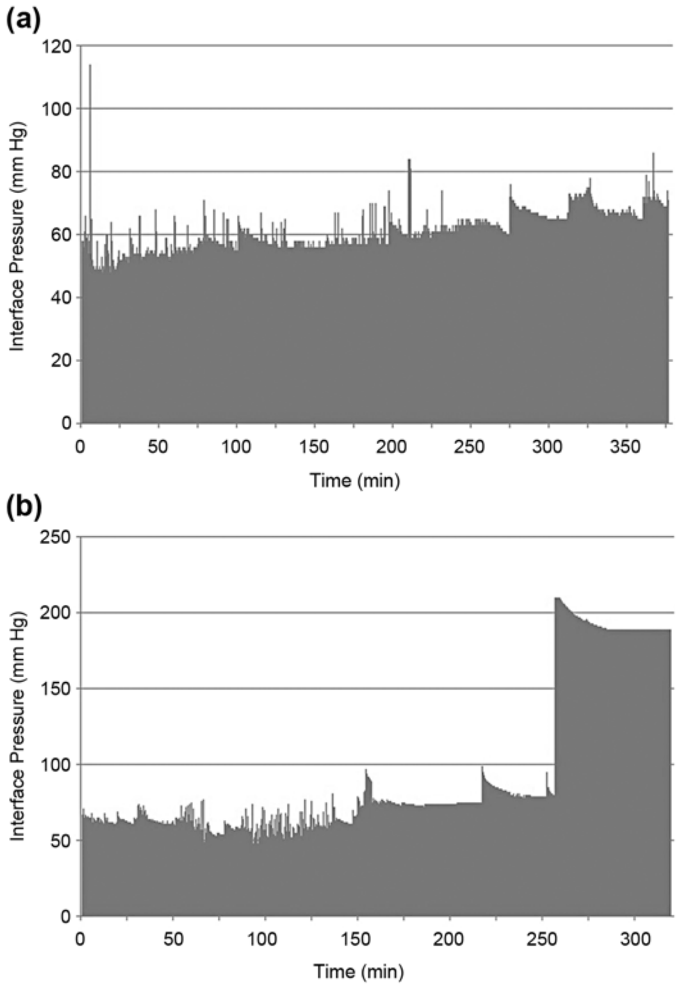

Figure 1.
Interface pressure changes by position. Peak interface pressures over time are displayed for two different patients. Peak pressures were located around perisacral area and greater trochanters. Repositioning at times resulted in large sustained changes in peak pressures (bottom graph) but not always (top graph). (**a**) Peak interface pressures for patient 6 initially in supine position, turned right at minute 7, supine at minute 210, and turned left at minute 325. (**b**) Peak interface pressure for patient 18 initially turned right, supine at minute 147, and turned left at minute 268.

areas are more likely to develop (1) pressure ulcers, (2) more severe pressure ulcers, and/or (3) pressure ulcers at these specific tissue locations.

Despite the standard of care (q2h), repositioning intervals varied between patients (**Table 2**, "Positions") and none was effective in relieving all at-risk tissue areas. For example, two patients were not repositioned during the entire monitoring period. It was not clear why the repositioning procedures were different, but we believe our observations mirror typical interoperator repositioning technique differences. All the same, it may not matter exactly how repositioning is accomplished, but rather that the at-risk tissue gets relieved regularly from pressure. To put our observations in perspective, the average always-at-risk area was over 200 cm^2; therefore, an area one-third the size of an 8.5 × 11 in. sheet of paper is not getting relieved and remains at risk for pressure ulcer formation. Hence, future research is needed to establish how pressure mapping, implemented as a patient monitoring device or as a means to educate caregivers to improve their repositioning techniques, can further reduce or eliminate high skin-bed interface pressures, at-risk areas, and always-at-risk areas (including triple-jeopardy areas) in at-risk patients to reduce pressure ulcer risk.

We are not aware of any prior work examining the interface pressures of a cohort of patients during an interval of care that covers the spectrum of positions experienced by patients who typically have the highest prevalence of pressure ulcer formation. Comparing the at-risk patients of this study with nondisabled subjects [42] (for values and statistical significance, see **Table 3**), we found the peak interface pressures were 49 to 59 percent and 85 to 94 percent higher for the at-risk patients than for nondisabled subjects, with and without HOB elevation, respectively. The peak pressures over time of at-risk patients were 11 to 18 percent and 37 to 51 percent greater than the peak pressures of nondisabled subjects, with and without HOB elevation, respectively. The at-risk areas were 30 to 33 percent and 52 to 71 percent larger for the at-risk patients than nondisabled subjects in the supine and laterally turned positions, with and without HOB elevation, respectively. The triple-jeopardy and always-at-risk areas were also considerably larger for the at-risk patients than for nondisabled subjects, 277 and 343 percent, respectively. Perhaps due to pain, frailty, medical condition, or the reservation of nurses to not disturb the patient too much, bedridden at-risk patients experience higher interface pressures and larger at-risk and always-at-risk areas (including triple-jeopardy areas) than nondisabled subjects. These results that demonstrate at-risk patients have higher interface pressures than nondisabled subjects are consistent with data reported by Berjian et al. [43].

Our study had a few limitations. First, tissue interface pressures do not directly measure internal tissue and capillary pressures. We are not implying that an at-risk area

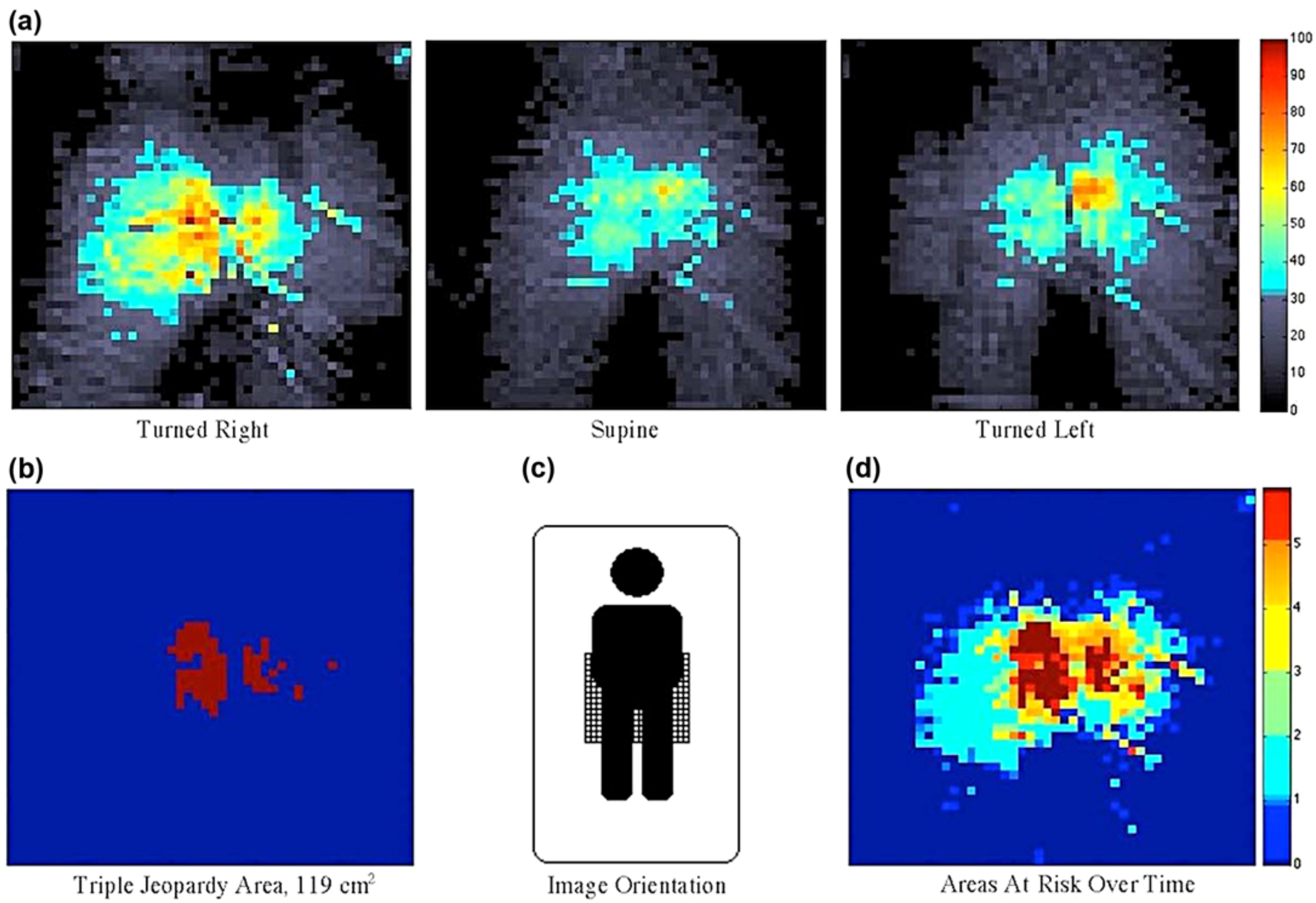

Figure 2.
Interface pressure profiles by position and triple-jeopardy areas. (**a**) Typical perisacral interface pressure profiles from one intensive care unit patient; color bar is in millimeters of mercury with color denoting at-risk areas. (**b**) Total amount of triple-jeopardy (always-at-risk) area. (**c**) Schematic of patient lying in bed on pressure sensor. Pressure profiles should be viewed as if you are facing patient. (**d**) Amounts of time specific areas of skin were at risk across all positions experienced by patient. Color bar indicates time (in hours) that specific skin areas were at risk. Areas at risk for maximal amount of time (dark red) were always at risk and never relieved.

is ischemic, but we feel these areas are at-risk due to elevated interface pressures. Moreover, interface pressure mapping is currently the best noninvasive method to measure pressures applied to the skin. The use of peak interface pressures has been reported to be unreliable for test-retest scenarios [44], but this did not affect our always-at-risk and triple-jeopardy results. Second, patient shifting and/or raising the HOB could result in a patient moving off the sensor array, generating unusable pressure profiles (<8% of total data collected). However, active movements (absent shear) are likely beneficial because they redistribute the patient's weight similar to nondisabled people, for example, when shifting weight while sitting in a chair. Third, we anatomically aligned patient interface pressure profiles when necessary to ascertain that specific areas of skin were correctly tracked over time. We needed alignment for half of the patients we observed. This adjustment, or any patient movement, could have led to minor errors in tracking specific skin areas, but we found no significant difference in triple-jeopardy or always-at-risk areas between patients who had their pressure profiles aligned compared with those who did not. Last, we placed the sensor array beneath the patient's underpads to protect it from the patient and additional contaminants and so that it would not be used in place of the underpads to help lift and reposition the patient. The underpads may aid in slight pressure relief, thus resulting in lower measured pressures.

CONCLUSIONS

Bedridden patients at risk for pressure ulcer formation exhibit high skin-bed interface pressures and specific skin areas that are likely always at risk (i.e., triple-jeopardy and always-at-risk areas) for the vast majority of the time patients are in bed despite routine repositioning care. Healthcare providers are unaware of the actual tissue-relieving effectiveness (or lack thereof) of their repositioning interventions, which may partially explain why pressure ulcer mitigation strategies are not always successful. Relieving at-risk tissue is a necessary part of pressure ulcer prevention, but the repositioning practice itself needs improvement. Further research is needed to determine how pressure mapping can be used to develop better patient repositioning techniques and improve at-risk tissue pressure relief to help prevent pressure ulcer formation.

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