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Sacral skin blood flow response to alternating pressure operating room overlay

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ABSTRACT

Pressure injuries resulting from long surgeries may be caused by prolonged ischemia. Operating table surfaces with alternating pressure (AP) features may reduce the risk of ischemia-induced pressure injuries by providing periodic relief of blood flow occlusions. Prior research investigated alternating loading applied with a single isolated rigid indenter and demonstrated increased perfusion. This study quantified effects of an overlay with AP on sacral skin perfusion for individuals lying supine for 60-min while blood flow was monitored. The mean normalized sacral skin blood flow was found to be greater with the AP overlay over an operating table pad compared to the operating pad alone (pad with AP mean SBF = 1.45 ± 1.16, pad without AP mean SBF = 1.03 ± 0.46, $p = 0.10$). Peak and average interface pressure at the sacrum was significantly lower during the deflation cycle of the AP surface compared to the operating pad alone ($P < 0.001$), suggesting this periodic reduction resulted in higher mean blood flow. Post-hoc regression analysis showed participant body mass index was a significant predictor of the effectiveness of the AP overlay ($p = 0.012$). The results suggest risk for pressure injuries due to prolonged ischemia might be mitigated by the addition of an alternating pressure feature on operating table pads for lower BMI patients.

1. Background

Pressure injuries are local injuries to the skin and/or underlying tissue, often found over bony prominences and caused by exposure to external pressure with or without shear [1]. Extended periods of pressure and shear induced ischemia can cause blood vessel damage and tissue necrosis, both of which can lead to pressure injuries [2]. Excessive strain has also been shown to lead to tissue damage directly, without ischemia [2]. Pressure injuries due to prolonged ischemia are especially of concern in patients undergoing long surgeries, where repositioning to relieve pressure and promote blood flow cannot be implemented. Pressure redistributing surfaces that reduce pressure over bony prominences through immersion and envelopment may be an option for avoiding ischemia [3]. Depending on other risk factors affecting perfusion, however, lying motionless on a support surface may lead to ischemia induced tissue injury[2].

Alternating pressure (AP) is a feature of a support surface that provides pressure redistribution via cyclic changes in loading and unloading [4]. The periodic pressure relief provided by AP surfaces have been reported to help maintain tissue viability as measured by gas tension recovery and tissue perfusion, thus reducing the risk for ischemia induced tissue injury [5–10]. Clinical trials on support surfaces with AP have had mixed results, with some trials showing better pressure injury outcomes compared to surfaces without AP and some showing worse or no difference in pressure injury outcomes [11]. Additional clinical studies have indicated that use of AP surfaces with regular assessments and repositioning results in low pressure injury incidence and use satisfaction in acute care, rehabilitation centers and long term care [12–15]. Studies in the operating room with AP surfaces have reported reduction in perioperative pressure injuries [16,17]. Current guidelines for prevention of surgical pressure injuries indicate effectiveness of pressure injury prevention using pressure redistributing surfaces such as alternating pressure on the operating room table during surgery, and recommend their use over standard surgical procedure surfaces for individuals at risk. The guidelines indicate the need for more research on the effectiveness of pressure redistributing surfaces for different body types [1,18,19].

Implementation of the AP feature for an operating room table may increase perfusion in tissue over bony prominences by periodically allowing otherwise occluded blood vessels to open during the unloading phase of the cycle. The effects of a full-body overlay with AP on skin perfusion over long periods of time is needed to inform clinical

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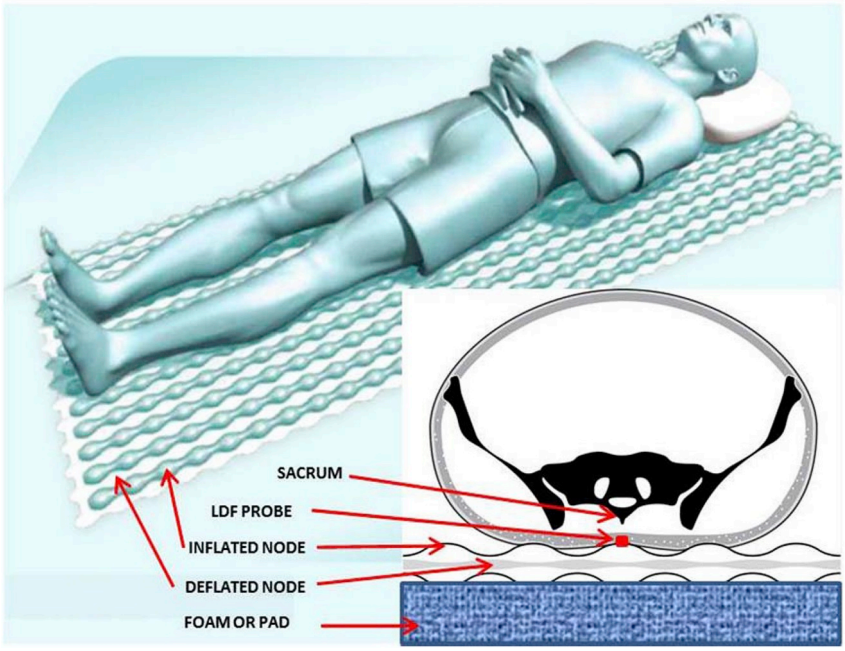

Fig. 1. Alternating pressure surgical overlay placed over a foam operating room pad. The laser Doppler flow (LDF) probe was placed on the sacrum aligned with the apex of an overlay node (shown inflated in this figure).

recommendations for individuals with increased risk of pressure injury development during long surgeries. The present study investigated the effects of AP on skin perfusion in a representative situation where individuals lay on a pneumatic AP surface for an extended period while skin blood flow (SBF) was monitored. A commercially available low-profile AP surgical overlay (less than 25 mm in height at full inflation), comprising 650 air-filled nodes arranged in offset rows and alternately inflated with air, was evaluated (Fig. 1). The AP overlay was placed over an operating room pad, and the effect on sacral SBF was quantified for participants lying supine for 60 min.

2. Methods

2.1. Participant population

Healthy participants (n = 20) from two age groups (18–40 years old (n = 10); 60 + years old (n = 10)) and body mass index (BMI) groups ($\leq$25 kg/m^2 (n = 10); $\geq$27 kg/m^2 (n = 10)) were recruited for the study. All participants were pre-screened to ensure the following inclusion criteria were met:

- no history of conditions that would make it difficult to lie supine for an extended period of time, such as a pressure injury or surgery within six months leading up to the study;
- no heart, lung or blood diseases such as high blood pressure, asthma, emphysema or a history of a heart attack;
- not currently taking medications that affect the function of the heart, lungs or blood; and
- absent of any conditions that affect movement and sensation such as diabetes or mobility limitations.

2.2. Procedure

Two support surface test conditions were evaluated during the study, a 50-mm thick operating room (OR) foam pad (STERIS Corporation, Montgomery, AL) with and without an AP overlay (DabirAIR, DABIR Surfaces, Inc., Chicago, IL). The overlay was a low-profile AP surgical overlay that is less than one inch in height at full inflation, with rows of semi-spherical nodes (25 mm base diameter) arranged in two zones that alternately inflate (Fig. 1). The overlay was set to "low" inflation pressure and "low" (10 min) cycle speed (5-min alternating inflation of the two zones) as recommended by the manufacturer. The order of surfaces tested was randomly determined for each participant to account for any potential test condition order effect.

Participants wore supplied hospital scrub pants. Self-reported age and height, as well as other demographic data were obtained. Participant weight and blood pressure were measured and recorded. A 2-mm thick, low profile laser Doppler blood flow optic probe (model VP11sc, Moor Instruments Inc., Wilmington, DE) was positioned directly over the bony prominence of the sacrum as determined by palpation, and a thermocouple temperature probe (FLUKE Inc., Everett, WA) was positioned at an offset position corresponding to the location of adjacent nodes of the AP surface. These locations on the body are illustrated in Figs. 1 and 2. Both sensors were secured to the skin with medical tape and the positions maintained throughout testing.

Baseline unloaded SBF was collected with the participant lying prone for 10 min. Loaded SBF was then collected while the participant laid supine for 60 min, followed by post-loaded SBF data collection for 10 min while the participant again laid in a prone position. For the AP overlay measurements, the sacrum was positioned so that the probe lay on the apex of one of the AP overlay node to obtain maximum inflation and deflation effect at that node (Fig. 1). All SBF data was collected at 10 Hz using LabVIEW (National Instruments, Austin, TX) software and hardware. Skin temperature was recorded manually every 5 min. Participants were instructed to remain still during the data collection period. Any movement by the participants was noted and participants were reminded to minimize body movements.

Following the post-loaded segment, sacral interface pressure was recorded at 5 Hz with the participant lying supine (XSensor Technology Corporation, Calgary, Alberta). Interface pressure was recorded for 5 min on the OR Pad alone and 10 min on the AP overlay (one full cycle with the nodes inflated and deflated for 5 min). At the end of the interface pressure recording, participants were asked to lift their pelvis to allow research staff to register the location of the optic probe over the sacrum on the pressure mat for both test conditions. This served to provide a reference point for choosing the pressure sensors in the sacral area for data analysis. A 30-min wash-out period, during which the participant stood, walked or sat with their sacrum completely

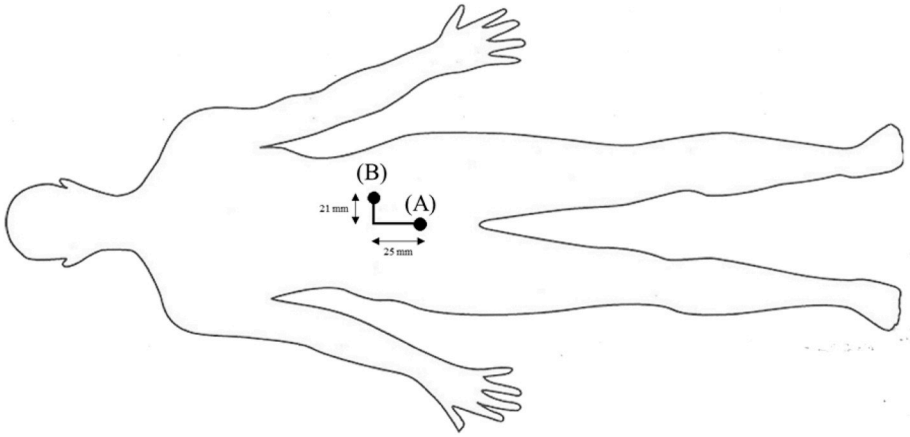

Fig. 2. Sensor placement with the participant laying prone on the test surface. The laser Doppler blood flow optic probe (A) was placed directly on the sacrum. The thermocouple temperature probe (B) was placed 25 mm superior and 21 mm lateral to (A). Both probes remained secured in position throughout testing.

unloaded, occurred between test conditions to reduce any residual effects from the first test condition.

2.3. Data reduction and analysis

2.3.1. Skin blood flow data

Raw SBF data was down-sampled to 0.5 Hz using the MATLAB (MathWorks, Natick, MA) command *decimate*, prior to being passed through a 10th order Chebyshev I low-pass filter with cutoff frequency 0.15 Hz [20]. The filtered data were then masked to remove artifacts due to noted participant movements. Filtered loaded and post-loaded SBF data were normalized to the mean baseline SBF recorded prior to each test surface.

The *mean sacral SBF* was calculated for the baseline, loaded and post-loaded conditions. For the loaded SBF calculations, the first and last 5 min of the loading period were removed to eliminate artifact from the start and stop of loading and to capture five full AP overlay cycles, resulting in 50 min of SBF data for each surface condition.

The loaded SBF was also represented as *SBF Response* (SRF_R) for each test condition, quantified as the ratio of the mean normalized SBF in the last 10 min of the 50-min data to the first 10 min (Equation (1)) to indicate whether SBF at the sacrum increased or decreased over the loading time while lying supine.

$$SBF_R = \left(\frac{\overline{SBF}_{last\ 10\ min}}{\overline{SBF}_{first\ 10\ min}} \right) * 100\% \quad (1)$$

The relative effectiveness of the AP overlay was then quantified as the difference between the SBF response on the two test surfaces (Equation (2)).

$$\Delta SBF_R = (SBF_R)_{OR\ Pad\ with\ AP\ overlay} - (SBF_R)_{OR\ Pad} \quad (2)$$

2.3.2. Sacral pressure data

For the OR Pad alone, interface pressure on the sacrum was determined by selecting a 2 × 2 (2.54 cm × 2.54 cm) sensor array in the sacral area where the laser Doppler probe was positioned and marked during data collection (Fig. 3A). The peak and mean values of these four sensors were obtained over a 60-s period (300 frames) during the second half of the 5-min recording period, to allow adequate time for the body to immerse in the OR pad. For the OR Pad with AP overlay, four sensors on the pressure map that corresponded to the AP node under the probe were used for analysis. The peak and mean values of the four sensors representing the AP node were measured over a 60-s period (300 frames) during the second half of the 5-min inflation (Fig. 3B) and deflation (Fig. 3C) cycles. The effectiveness of the OR Pad with AP overlay compared to the OR pad alone was assessed by comparing the peak and mean values during the deflation cycle of the AP overlay.

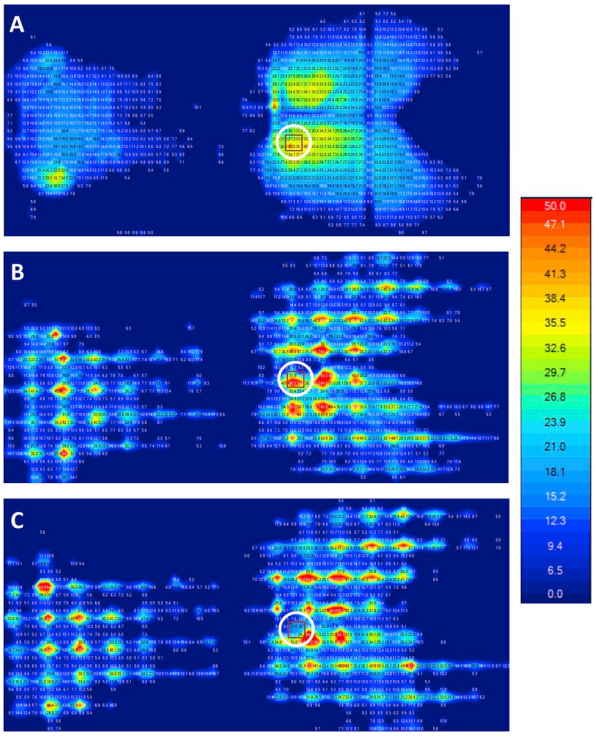

Fig. 3. XSENSOR X3 Medical V6 application showing sample pressure map of participant: (A) OR Pad alone, (B) OR Pad with AP Overlay node inflated under the probe, and (C) OR Pad with AP Overlay node deflated under the probe. The circled area with a brown square shows the four sensors in the probe location that were used to calculate sacral interface pressure. Probe location was marked on the pressure map by an investigator during data collection.

2.3.3. Analytic methods

Mean baseline, loaded and post-loaded sacral SBF were tested for significant differences between support surface conditions using two-tailed, paired t-tests. The peak and mean sacral interface pressure, and mean sacral interface temperature during the loading phase, were tested for significant differences between surfaces using paired t-tests. A post hoc multivariate linear regression analysis examined the demographic and physiologic predictors of the relative effectiveness of the overlay compared to the OR pad alone.

Table 1
Participant demographic and physiologic characteristics (standard deviation in parentheses).

Characteristic	18–40 years (n = 10)	60 + years (n = 9)	Total Population
Age (years)	27.5 (5.7)	68.4 (6.2)	46.9 (21.2)
Body Mass Index (kg/m^2)	26.8 (7.0)	25.4 (3.4)	26.1 (5.4)
Male	6	5	11
Female	4	4	8
Mean Arterial Pressure (mmHg)	91.8 (9.3)	95.4 (16.0)	93.5 (12.3)

3. Results

Healthy participants (n = 19) had a mean age of 46.9 ± 21.2 years and BMI of 26.1 ± 5.4 kg/m^2 (Table 1). One of the participants in the higher age and BMI group was excluded from all data analyses after that participant was non-compliant with the established protocol by moving excessively during the testing, which disrupted the blood flow measurements. Ambient room temperature and relative humidity were 24.2 ± 0.6 °C and 51.7 ± 11.2%, respectively, across the study trials.

Mean sacral SBF on the OR pad with the AP overlay was 40% greater than the OR pad alone during the full loading session and 76% greater during deflation at the sacrum, though not statistically significant. The baseline and normalized post-load SBF did not show much variation and were not significantly different between test surfaces (Table 2). A plot of mean SBF for one participant on the OR pad with and without the AP overlay is presented in Fig. 4.

The peak and average interface pressure on the sacrum was 39% lower on the AP overlay during the deflation cycles compared to the OR pad alone (Table 3). Peak and average interface pressure at the sacrum was significantly lower on the OR pad with AP overlay during the deflation cycles when compared to the continuous pressure observed on the OR pad ($p < 0.001$). No difference in sacral temperature was observed between the two surface conditions.

The SBF Response for each test surface (SBF_R from Equation (1)) and the relative effectiveness of the AP overlay compared to the OR pad alone (ΔSBF_R from Equation (2)) are presented in Table 4. A post-hoc multivariate linear regression analysis indicated that participant BMI was a significant predictor of the relative effectiveness of the AP overlay compared to the OR pad alone (Table 5). Age, gender and mean arterial pressure were not predictors. Fig. 5 shows the bivariate relationship between BMI and the relative effectiveness of the AP overlay (ΔSBF_R) for the total sample and for each of the two age groups.

4. Discussion

Enhanced perfusion is a possible mechanism by which support surfaces with alternating pressure features may protect loadbearing tissue from damage. This study found that skin blood flow at the sacrum averaged over an hour of lying still was higher with AP compared to the same condition without AP, though not statistically significant. The mean normalized loaded SBF during AP was approximately 40% greater than the OR pad alone for the entire loading period, and 76% greater during the deflated portion of the AP cycle. The standard

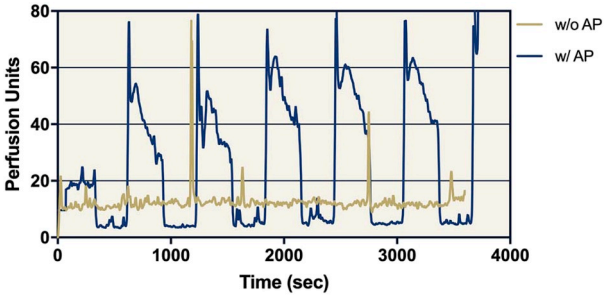

Fig. 4. Sample plot showing mean skin blood flow for participant #8 lying on the OR pad with and without the alternating pressure overlay.

Table 3
Sacral interface pressure and temperature (standard deviation in parentheses). Pressures measurements represent when the aligned overlay node was deflated.

	OR Pad	OR Pad w/AP (deflation cycle)	p value
Peak pressure (mmHg)	35.5 (10.8)	21.6 (11.7)	< 0.001
Mean pressure (mmHg)	28.7 (8.6)	17.5 (9.0)	< 0.001
Mean temperature (°C)	35.4 (0.5)	35.4 (0.7)	0.68

Table 4
Skin blood flow response (SBF_R) for participants on each surface, along with the relative effectiveness of the AP overlay (ΔSBF_R) – See Equations (1)–(2).

Participant ID	OR pad response	Overlay response	Relative response (ΔSBF_R)
01	1.08	0.74	−0.33
02	0.91	0.97	0.07
03	0.94	1.17	0.23
04	1.09	1.03	−0.05
05	1.04	1.12	0.09
06	1.25	1.15	−0.11
07	1.11	1.32	0.21
08	1.04	1.33	0.29
09	1.13	1.12	0.00
10	1.39	1.48	0.09
11	1.54	2.07	0.53
12	1.15	1.01	−0.14
13	1.20	0.95	−0.25
14	1.23	1.10	−0.13
15	0.88	1.09	0.20
16	1.30	1.20	−0.10
17	1.13	1.30	0.17
18	1.08	1.16	0.08
19	1.66	1.23	−0.42
Mean	1.17	1.19	0.02
Std Dev	0.20	0.27	0.23

Table 2
Mean sacral skin blood flow during baseline, loading and post-loading (standard deviation in parentheses). Loaded SBF measurements are deconstructed to show mean blood flow at the sacrum when the aligned overlay node was inflated and deflated.

	OR Pad	Sacral overlay node	OR Pad w/AP	p value
Mean baseline SBF (PU)	12.14 (5.95)	–	14.77 (7.43)	0.10
Mean normalized Loaded SBF	1.03 (0.46)	Full cycle	1.45 (1.16)	0.10
		Inflated	1.07 (0.74)	0.82
		Deflated	1.81 (1.77)	0.06
Mean normalized Post-load SBF	1.37 (0.81)	–	1.54 (1.89)	0.71

PU = perfusion units.

Table 5
Post-hoc multivariate regression analysis to determine factors associated with relative effectiveness of the AP overlay (ΔSBF_R) – See Equation (2).

Effect	Estimate	Standard Error	t-Ratio	Prob > |t|
Intercept	0.7946	0.3633	2.19	0.046*
Age	−8.804e-6	0.0021	0.00	0.99
Body Mass Index	−0.0256	0.0088	−2.91	0.012*
Gender [Female]	−0.0459	0.0452	−1.01	0.33
Mean Arterial Blood Pressure	−0.0012	0.0039	−0.31	0.76

deviation for SBF during AP was 2.5 times that seen in the OR pad alone indicating how SBF varies more with AP. The SBF during the AP inflation cycle will be reduced, while during the AP deflation cycle SBF will be enhanced, thus resulting in a wider variation in SBF during a full cycle of AP overlay compared to a static loading condition in the case of the OR pad alone. The results from this study support previous results by Jan et al., which demonstrated greater mean skin blood flow when pressure was periodically removed compared to constant loading with the same time-averaged magnitude [9]. Jan et al. loaded the sacrum, but surrounding tissues were not loaded. Our study investigated skin perfusion with participants in a real-world loading condition in which sacral and surrounding tissues were loaded by lying supine on an AP overlay for an extended period of time. Our study test conditions simulated the tissue loading conditions and length that occur during surgery.

The AP overlay provided periodic off-loading of the sacrum, as demonstrated by the pressure mapping data (Table 3). Peak and average interface pressures were 39% lower on the AP overlay during deflation compared to the OR pad alone. The periodic off-loading may allow restored blood flow and help prevent ischemia, thus reducing the risk of pressure injury. The overlay was set to the "low" inflation pressure setting per manufacturer recommendations. Internal pressure magnitudes of an alternating pressure mattress were demonstrated by

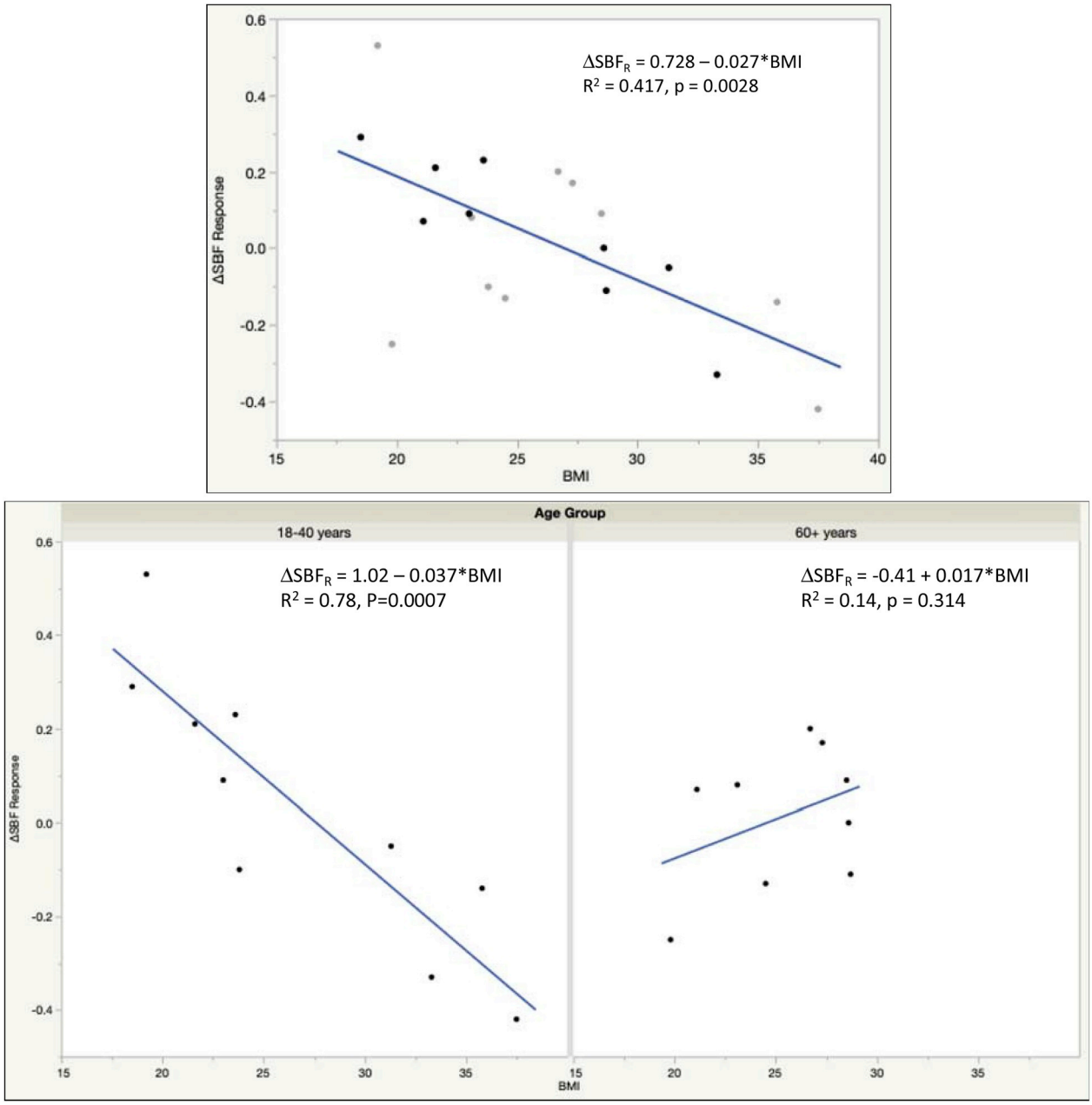

Fig. 5. Bivariate relationship between body mass index and the relative effectiveness of the AP overlay (ΔSBF_R) for the total study population (top), age group 18–40 years (bottom left) and age group 60 + years (bottom right). In top figure, light circles represent age group 18–40 years and dark represents age 60 + years.

Chai et al. to influence sacral skin viability [8].

The study was designed to investigate intrinsic factors that might affect the sacral SBF outcome, namely BMI and age. Clinical studies indicated individuals with low BMI (BMI < 19) or morbidly obese (BMI > 40) to be at higher risk for developing pressure injuries compared to normal (BMI 19–25) and obese (BMI 25–40), reporting incidence rates of 8.6% for low BMI, 5.5% for normal BMI, 2.8% for obese, 9.9% for morbidly obese [21,22]. The results of our study indicated that BMI is a predictor of the effectiveness of the AP overlay compared to not having the overlay ($p = 0.012$), and participants with lower BMI benefited more from AP compared to participants with higher BMI. We postulate that BMI is a potential factor because individuals with higher BMI are likely to have a thicker layer of adipose tissue covering their sacrum, which has the potential to alter how pressure is distributed during the high and low-pressure cycles of the AP. Additionally, these subjects with higher BMI may not exhibit dramatic changes in blood flow under constant loading. The thinner layer of adipose tissue over the sacrum in participants with lower BMI adversely affects SBF and thus the low BMI participants benefitted from the periodic release of pressure during the AP deflation cycles. Participants with higher BMI may not have needed the recovery periods afforded by the AP, and therefore showed less or no SBF benefit when compared to the OR pad only. Additional intrinsic and extrinsic factors affect pressure injury development in an individual, and further research is needed to investigate other factors including tissue composition effects. The higher BMI subjects in this study (BMI range: 27.3–37.5) were in the obese BMI category.

We were interested in the effect of age on perfusion response to AP because aging results in a loss of soft tissue tolerance, which in turn would impact how stress and strain is distributed in the tissue. If time-varying stress and strain trigger myogenic vasodilatory response, then we would expect less resilient tissue in older people to respond differently compared to more resilient tissue on younger individuals. Clinical studies on pressure injury risk confirm that age is a significant pressure injury risk factor [23–25]. Though we did see a trend toward larger differences in SBF between surface conditions for our older group, our regression results did not show age predicting relative effectiveness of the AP overlay compared to the OR pad alone. Potentially, this was due to the inclusion of older participants who were healthy and active.

The interpretation of study results is limited by our small sample size and use of participants who were not at high risk for developing pressure injuries. Subjects in the study were healthy, mostly active subjects and the 1-h data collection period may not have been adequate to cause SBF reduction consistent with surgical patients with compromised vascular status, comorbid conditions and significant immobility. Additionally, the use of a laser Doppler perfusion measurement technique to measure blood flow was limited to the superficial (1–2 mm) skin layers. Another study limitation was the lack of subjects in the underweight (BMI < 18.5) and morbidly obese (BMI > 40) BMI groups, who are reported to have high incidence of pressure injury. Future studies should look at these two vulnerable BMI groups, especially in a clinical setting.

Conflicts of interest

This research was supported by Dabir Surfaces, Inc and author Vinoth Ranganathan is Director, Clinical Research at Dabir.

Authors Karg and Brienza are faculty at the University of Pittsburgh and have no financial interest in Dabir Surfaces, Inc.

Author Michael Churilla was an undergraduate student when this research was performed and has no financial interest in Dabir Surfaces, Inc. He currently is employed as a Biomedical Engineer by Hill-Rom Services, Inc.

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