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Effects of conventional and alternating cushion weight-shifting in persons with spinal cord injury

Gary A. Wu, PhD;[1] Kath M. Bogie, DPhil[1–2*]
[1]Department of Physical Medicine and Rehabilitation, MetroHealth Medical Center, Cleveland, OH; Department of Biomedical Engineering, Case Western Reserve University, Cleveland, OH; and Advanced Platform Technology Center, Louis Stokes Cleveland Department of Veterans Affairs Medical Center, Cleveland, OH; [2]Department of Orthopaedics, Case Western Reserve University, Cleveland, OH

Abstract—A repeated-measures study of 13 adult full-time wheelchair users with spinal cord injury (SCI) was carried out to determine whether alternating-pressure air cushion (APAC) use compared with independent pressure relief (IPR) provides reliable, effective pressure relief for individuals with SCI. Bilateral mean ischial interface pressure (IP), transcutaneous oxygen tension (T_cPO_2), and unilateral laser Doppler blood flow were evaluated. Blood flow component contributions were determined using short-time Fourier transform (STFT)-based spectral analysis. IPR assessment was carried out at recruitment. Study participants then used an APAC for 2 wk every 3 mo for 18 mo. IPR weight-shifting decreased mean ischial IP ($p < 0.05$) and increased mean T_cPO_2 ($p < 0.05$). All variables rapidly returned to preintervention levels following weight-shifting except for the cardiac component of blood flow. APAC-induced weight-shifting decreased mean ischial IP ($p < 0.05$). Mean T_cPO_2 increased and was higher than for IPR. STFT analysis indicated that quiet sitting following APAC-induced weight-shifting produced a higher neurogenic component of blood flow than following IPR ($p = 0.02$). Thus, IPR positively affects multiple aspects of tissue health but produces transient improvements and must be repeated regularly. APAC activation dynamically and continuously alters IP distribution with more sustained positive tissue health effects.

Key words: alternating-pressure air cushion, blood flow, independent pressure relief, interface pressure, repeated measures, spinal cord injury, tissue health, tissue oxygenation, weight-shifting, wheelchair seating.

INTRODUCTION

Many individuals with reduced mobility rely on a wheelchair system to maximize function and provide mobility, but a wheelchair system is much more than a mobility device. It is also a support system, both literally and figuratively. An essential component of any wheelchair support system is an effective cushion to maximize tissue health, prevent pressure ulcer (PU) development, and maintain a functionally appropriate posture. An

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Abbreviations: AIS = American Spinal Injury Association Impairment Scale, APAC = alternating-pressure air cushion, CMS = Centers for Medicare and Medicaid Services, Int1 = intervention phase 1, Int2 = intervention phase 2, IP = interface pressure, IPR = independent pressure relief, LDF = laser Doppler flowmetry, NIDRR = National Institute on Disability and Rehabilitation Research, PU = pressure ulcer, Q1 = quiet sitting 1 (preintervention), Q2 = quiet sitting 2 (postintervention), REDCap = Research Electronic Data Capture, ROI = region of interest, SCI = spinal cord injury, STFT = short-time Fourier transform, T_cPO_2 = transcutaneous oxygen tension.

***Address all correspondence to Kath M. Bogie, DPhil; Advanced Platform Technology Center, Louis Stokes Cleveland VA Medical Center, 10701 East Blvd, Cleveland, OH 44106; 216-368-5270; fax: 216-707-6420.**
Email: kmb3@case.edu
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effective wheelchair support system, including both a wheelchair and a seating pressure relief cushion, enables the user to achieve optimal mobility function and quality of life.

Pressure relief cushions can be classified by the materials used in their construction. This includes foam, gel, air, or combinations of each type of material. Cushion materials may be immersive and/or viscoelastic so that the cushion conforms to the loading surface, i.e., the seated individual, thus maximizing contact area and decreasing mean overall interface pressure (IP) [1]. However, this approach still relies on the user to perform regular independent pressure relief (IPR) to alter pressure distribution. Even with a pressure relief cushion, it is recommended that users perform IPR every 20 min [2–3]; however, this is rarely maintained rigorously.

Using an alternating-pressure air cushion (APAC) has the potential to augment IPR maneuvers by providing regular automatic weight-shifting in the same manner as an alternating-pressure mattress. These have long been used in hospital settings to provide pressure relief by cyclic inflation and deflation under bony prominences [4–5]. However, there were technical challenges in modifying the technology for the smaller mobile cushion application. Koo et al. reported in 1995 that an APAC had less effective pressure-relieving characteristics than a conventional cushion and that positioning of the ischial tuberosities was a critical factor [6]. Active cyclic inflation and deflation requires both a motor and pump, which can be noisy, disruptive, and in the past, prone to failure. This can be catastrophic without an appropriate fail-safe such as residual inflation.

More recently, technological developments led to an increasing number of APACs on the market. Although a Healthcare Common Procedure Coding System code exists for this class of cushion, the Centers for Medicare and Medicaid Services (CMS) has determined that medical benefit has not been demonstrated. An APAC is not considered by the CMS to be any more effective than current options and is not currently reimbursable in the United States. However, many people still use them and have been willing to pay for them out of pocket. A study by Burns and Betz found that APACs may affect regional IPs as much as conventional IPR maneuvers [7].

IP mapping is widely used in wheelchair seating clinics as the primary quantitative outcome measure to determine the most appropriate pressure relief cushion [1,8].·IP mapping provides real-time visual feedback and allows the clinician to point out high IP areas that need to be addressed to improve pressure distribution. However, PU development is multifactorial, making it hard to determine the effectiveness of an intervention or cushion by looking at just one factor [9–10]. Both pressure and time have long been known to be key factors in PU development. Local tissue oxygenation and blood flow are essential to maintain tissue viability. Higher pressure may be tolerable for short periods as long as blood flow and local tissue oxygenation is recovered before local tissue damage occurs [11]. Previous studies have found that IP mapping does not always correlate with local transcutaneous oxygenation tension (T_cPO_2), potentially because of impaired adaptation to applied pressures in persons with spinal cord injury (SCI) [12]. IP measurements concurrent with subcutaneous blood flow using laser Doppler flowmetry (LDF) can help determine local tissue microcirculation under load [13–15]. Detailed spectral analysis also reveals component contributions to blood flow [16–17]. LDF blood flow assessment combined with T_cPO_2 measurement can thus reveal tissue health information that cannot be provided by IP measurement alone [18–20].

METHODS

The goal of the current study was to determine whether APAC use provides reliable and effective pressure relief. The primary study hypothesis to be investigated was that APAC use positively affects seated tissue health in individuals with SCI compared with IPR. The secondary study hypothesis was that tissue health responses would be consistent over time.

Study Design

This was a repeated-measures study design.

Study Population

All individuals with SCI causing loss of independent ambulatory mobility were eligible for this study. The primary inclusion criteria were that, at recruitment, study participants were at least 1-yr postinjury or loss of independent walking ability and had no open skin problems or hospitalizations during the prior 3 mo. Significant active systemic disease and osteomyelitis of the pelvic region, indicated by positive pelvic inlet X-ray from routine annual urologic examination or bone scan, were also exclusion criteria for study participation.

A priori power analysis based on the Friedman test was applied to determine study cohort size for a repeated-measures study design where no assumption of normal distribution could be made. In order to determine the appropriate sample size for nonparametric testing, the asymptotic relative efficiency correction was applied [21]. We determined that repeated measures of a study cohort of eight subjects would allow differences between means to be detected with an effect size of 0.2 at a power of 0.9 and a type I error rate of 0.05. Study recruitment above this was achieved, and a total of 13 adult individuals with motor impairment caused by SCI who were full-time wheelchair users were evaluated.

Repeated Alternating-Pressure Air Cushion Use

Study participants were provided with an APAC (Airpulse PK, Aquila Corporation; Holmen, Wisconsin) for 2 wk of daily use, followed by laboratory assessment of tissue health. The APAC was provided every 3 mo over an 18 mo period, i.e., at months 0, 3, 6, 9, 12, 15, and 18. The 3-mo interval between each period of cushion use was selected empirically to achieve a balance between the time needed to achieve washout of any potential effect due to cushion use and user familiarization with cushion usage. A generic multicellular layout was employed (**Figure 1(a)**) with two series of air cells that could be independently controlled. The inflation and deflation cycle was standardized to be maintained for 3-min periods on each side, i.e., inflated under the right ischial region and deflated under the left ischial region (pattern A) with a transition period to the opposite pattern (pattern B) lasting approximately 1 min (**Figure 1(b)**). This gave a total cycle time of 7 min. The deflation time for off-loading of each ischial region was selected based on a conservative evaluation of the duration of pressure relief found by Coggrave and Rose to be necessary for recovery of local tissue oxygenation [22]. Cushion inflation pressure was adjusted based on user weight to ensure that each user was comfortable and stable when sitting on the APAC.

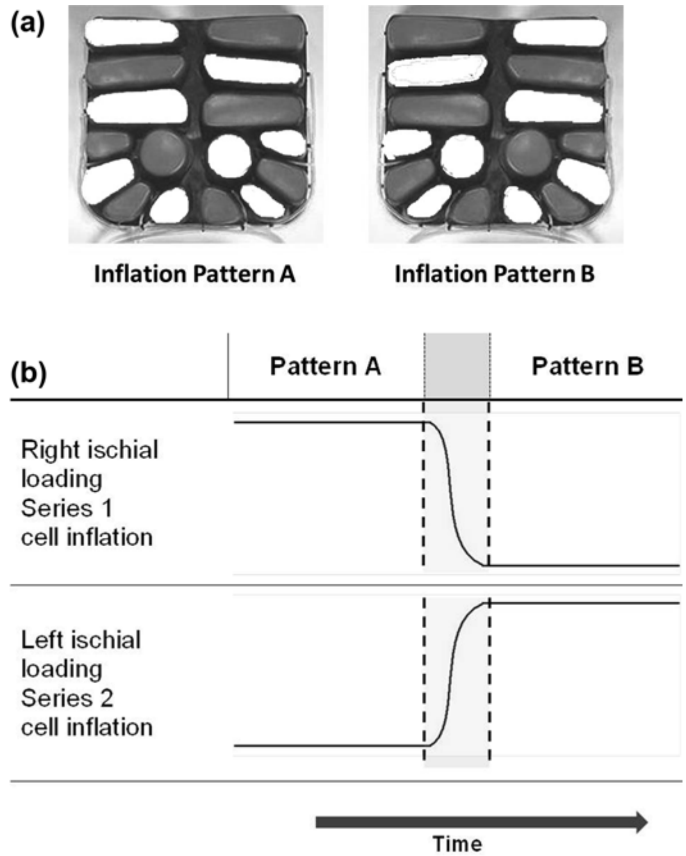

Figure 1.
Alternating-pressure air cushion (APAC) layout and cycling pattern. **(a)** APAC layout showing inflation and deflation cells. **(b)** Inflation cycling pattern.

Materials

Transcutaneous Oxygen Tension

T_cPO_2 was measured using a TCM400 monitor (Radiometer Medical; Brønshøj, Denmark). The 15 mm diameter, 11.3 mm tall sensor (model E5280–8, Radiometer Medical) was calibrated to the surrounding atmospheric air. Measurement of tissue oxygen from the deeper vascular bed was obtained by local heating to 43°C to achieve maximal local vasodilation.

Laser Doppler Flowmetry

LDF was measured using the Laserflo Blood Perfusion Monitor 2 (Väsamed Inc; Eden Prairie, Minnesota) and the Softip pencil probe (model P-435, Väsamed Inc). This system provides noninvasive measurement of skin blood flow at a depth of about 1 mm via laser and fiber optics technology using a low-power beam (2 mW) of helium-neon laser light (780 nm wavelength). The 0 to 5 V analog output is sampled at 20 Hz using a 16-bit data acquisition card (PCI-MIO-16XE, National Instruments;

Austin, Texas) to determine capillary blood flow (milliliters per minute per 100 g of tissue).

Interface Pressure Mapping

IP mapping used the CONFORMat pressure measurement system (Tekscan Inc; South Boston, Massachusetts). The CONFORMat has a 32 × 32 array of piezoresistive flexible sensors (sensels) operating at 1 to 250 mm Hg (accuracy +10%) with a 100 Hz scan rate.

Assessment Procedure

Tissue health assessments were carried out following our standard laboratory protocol [18–20], described next (**Figure 2**). These studies have shown that a 10-min assessment can reliably indicate tissue health [18]. All assessments were performed in the Tissue Health Laboratory at MetroHealth Medical Center (Cleveland, Ohio). Room temperature over the course of each assessment was maintained at 25°C ± 2°C.

The assessment commenced with an initial 20-min period of the participant side-lying on a mat with hips and knees flexed to 90°. Unloaded soft tissue over the buttocks was thus in the same position relative to the bony anatomy as in sitting. T_cPO_2 sensors were placed bilaterally over the ischial tuberosities. The CONFORMat was placed over the cushion in the participant's usual wheelchair. The participant then carefully transferred to the seated posture and the sensors were palpated to ensure they remained in the correct location before continuing with the stage 1 (IP and T_cPO_2) tissue health assessment, monitoring seated tissue health for 20 min (**Figure 2**).

The participant was then transferred back to the bed and the T_cPO_2 sensors were removed. The right ischial tuberosity was palpated and the Softip pencil probe affixed over the bony landmark. After 20 min of equilibration with the probe unloaded, the subject was carefully transferred to the seated posture. Stage 2 (IP and LDF blood flow rate) tissue health assessment was then carried out for 20 min (**Figure 2**).

In the current study, quiet sitting 1 (preintervention) (Q1) and quiet sitting 2 (postintervention) (Q2) were both assessed for 5 min and intervention phase 1 (Int1) and intervention phase 2 (Int2) were 3 min. Data from the transition phases were unstable and therefore discarded, i.e., as users either independently weight-shifted from left to right or as the APAC inflation cycled from pattern A to pattern B.

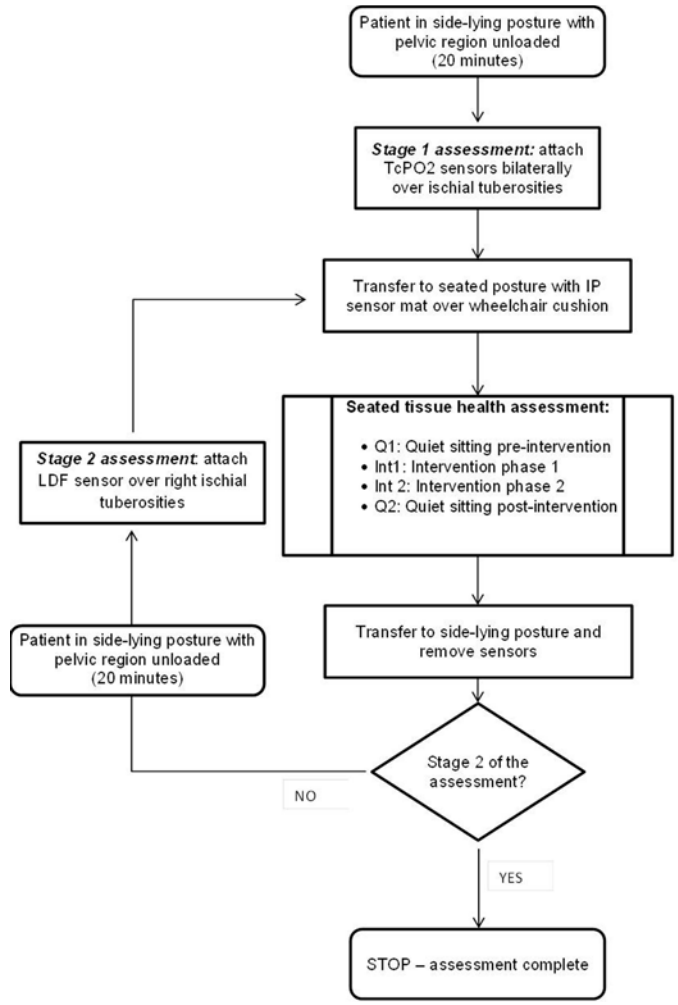

Figure 2.
Assessment procedure flowchart. IP = interface pressure, LDF = laser Doppler flowmetry, T_cPO_2 = transcutaneous oxygen tension.

IPR assessment was carried out at the initial baseline evaluation (0 mo). Each participant used his or her standard seating system and performed IPR according to his or her normal regime. All study participants had been seen by the local seating clinic and prescribed wheelchair cushions by a seating professional. For this cohort, the most commonly used (11 participants) wheelchair cushion was a Roho cushion (Belleville, Illinois). Two participants used a gel-based J2 Medical cushion (Pittsburgh, Pennsylvania). During IPR weight-shifting assessment, study participants were instructed to weight-shift first to the right (Int1) and then to the left (Int2). IPR procedures were self-selected by the study participant based on his or her normal mechanism of weight-shifting and most commonly achieved by leaning to the side, although some individuals preferred to push up and lift one buttock region. Participants were instructed to maintain their weight-shift for as long as they normally did and to repeat it on the same side as necessary for 3 min.

APAC use assessments were carried out after each 2-wk period of APAC use. Participants used an APAC of the correct size for their wheelchair constantly for 2 wk before returning to the laboratory for a tissue health assessment. Q1 with the APAC started with both series of cells evenly inflated and no cycling for 5 min. The intervention portion of each APAC use assessment started with pattern A high inflation in series 1 cells and high loading under the right ischial region (Int1), switching to pattern B high inflation in series 2 cells and high loading under the left ischial region (Int2). During the 5 min of Q2, the APAC remained on with no cycling.

Data Analysis

Tissue health data were processed as summarized next.

Transcutaneous Oxygen Tension Data

Mean ischial T_cPO_2 for each assessment phase was determined.

Laser Doppler Flowmetry Data

The total power spectral density of blood flow and the relative contributions of metabolic, neurogenic, myogenic, respiratory, and cardiac components within each assessment phase were determined by applying a standardized short-time Fourier transform (STFT)-based spectral analysis protocol [20]. It has been shown that the spectral frequency of blood flow signals arises from metabolic (0.008–0.02 Hz), neurogenic (0.02–0.05 Hz), myogenic (0.05–0.15 Hz), respiratory (0.15–0.4 Hz), and cardiac (0.4–2.0 Hz) sources [23]. Spectral density was computed using the MATLAB spectrogram function (MathWorks; Natick, Massachusetts). The frequency range was defined with a logarithmic space in order to increase the data points in the lower frequency components and allow for better visualization for the lower-frequency ranges of interest (metabolic, neurogenic, and myogenic). A 1,024-sample Hamming window was applied, and the resulting STFT was passed through a tenth-order Chebyshev I low-pass filter with a 2.0 Hz cutoff. Normalized spectral densities at the target frequency bands were obtained by computing the spectrogram based on the magnitude-square of the STFT and averaging over the duration of the phase of interest (Q1, Int1, Int2, and Q2)

Interface Pressure Data

CONFORMat pressure data were exported as numerical arrays. A MATLAB routine aligned each array, and standard analysis regions of interest (ROIs) around each ischium were defined. The ischial ROIs were bilateral 5 × 5 sensel regions, each approximately 7.5 × 7.5 cm^2. Mean contact pressures for the left and right ischial ROI were determined for each assessment phase.

Analysis of Independent Pressure Relief and Alternating-Pressure Air Cushion Use

The Wilcoxon rank test was applied to compare tissue health outcomes. Quiet sitting and pressure relief maneuvers using either IPR or APAC were compared to determine the effects of weight-shifting. Tissue health responses to IPR were compared with responses to weight-shifting caused by APAC use. Mean ischial IP was also compared with mean T_cPO_2 for each ischial region for each phase of the assessment to determine relationships between applied pressure and local tissue oxygenation.

Comparison of Repeated Alternating-Pressure Air Cushion Use

All tissue health outcomes measures were compared for each subject obtained at the six assessments using the APAC, i.e., at 3, 6, 9, 12, 15, and 18 mo. Tissue outcomes measures were compared at the same phase of the assessment for each subject, e.g., mean right ischial IP during Q1 was compared for subject 1 at the 3-, 6-, 9-, 12-, 15-, and 18-mo time points. The Friedman test was applied to compare repeated measures of tissue health outcomes for each phase of APAC use.

RESULTS

The **Table** presents subject demographics, including SCI characteristics and PU history. At study recruitment, the average age of the study participants was 42 yr old (range: 21–62 yr) and 8 yr postinjury (range: 1–24 yr). Twenty-three percent of study participants were female, which is slightly higher than in the overall population with SCI. SCI level ranged from cervical level 2 (American Spinal Injury Association Impairment Scale [AIS] A) to

Table.
Study cohort demographics.

Subject	Age* (yr)	Sex	Injury Level	AIS [35]	Time Postinjury (yr)	PU History
PT000	39	M	C6	D	3	None
PT001	50	M	T5	A	1	Yes
PT002	47	M	C5	C	6	Yes
PT004	62	M	T7	A	22	Yes
PT005	40	M	T12	A	7	Yes
PT008	42	M	C2	A	6	Yes
PT009	47	F	C6	C	24	None
PT011	55	F	T10	A	8	None
PT012	24	M	C7	C	7	Yes
PT013	21	M	T6	A	5	None
PT014	27	F	T4	A	4	None
PT015	53	M	C2	A	5	Yes
PT016	37	M	C8	A	3	Yes

*At time of initial enrollment and testing.
AIS = American Spinal Injury Association Impairment Scale, C = cervical, F = female, M = male, PU = pressure ulcer, T = thoracic.

thoracic level 12 (AIS D), and 62 percent of the study cohort had a PU history.

The Friedman test indicated nonsignificant differences between repeated assessments of APAC use for all tissue health outcomes measures, thus confirming our secondary hypothesis. Tissue health data for APAC use was thus pooled from repeated assessments.

Comparison of Weight-Shifting Using Independent Pressure Relief and Alternating-Pressure Air Cushion

Mean ischial region IP in initial quiet sitting was slightly higher (<5 mm Hg) for participants sitting on their own cushions compared with quiet sitting on the APAC (**Figure 3**). Mean ischial T_cPO_2 during initial quiet sitting was 68 percent lower under the right ischial region during Int1 and 38 percent lower under the left ischial region during Int2 for participants sitting on their own cushions compared with sitting on the APAC (**Figure 4**). Ischial T_cPO_2 was moderately asymmetric for both seating conditions.

Weight-shifting by IPR produced decreased mean ischial IP by 8 percent ($p < 0.05$) and increased mean T_cPO_2 by 11 to 23 percent ($p < 0.05$) relative to initial quiet sitting. Mean ischial IP and mean ischial T_cPO_2 returned to Q1 levels following IPR during the postintervention assessment. Blood flow components were relatively decreased at Q2, except for the cardiac component, which increased significantly ($p < 0.05$).

Mean ischial IP was significantly decreased by around 30 percent relative to quiet sitting during weight-shifting produced by the entire APAC inflation and deflation cycle ($p < 0.05$). The initial part of the inflation cycle (pattern A) had minimal effect on T_cPO_2. During the second part of the inflation cycle (pattern B), T_cPO_2 increased by 17 percent in the initially high-load right ischial region and decreased by 42 percent in the initially low-load left ischial region. This resulted in a significant decrease in T_cPO_2 in the left ischial region relative to Q1 ($p < 0.05$); however, T_cPO_2 changes over the entire inflation and deflation cycle did not reach significance following APAC-induced weight-shifting (**Figure 3(b)**). Overall, T_cPO_2 levels during APAC use were higher than for IPR, and changes over the APAC inflation and deflation cycle were less than during IPR. However, there was no significant difference at Q2 between T_cPO_2 following IPR or APAC use.

STFT analysis showed that within the APAC inflation and deflation cycle there were significant differences between patterns A and B. The LDF sensor was placed under the right ischial region; thus, regional blood flow was monitored under local cushion inflation conditions during pattern A and local cushion deflation conditions during pattern B. During weight-shifting caused by APAC use, changes in all blood flow components were less than during IPR (**Figure 5**) with the exception of the respiratory component. Quiet sitting following APAC

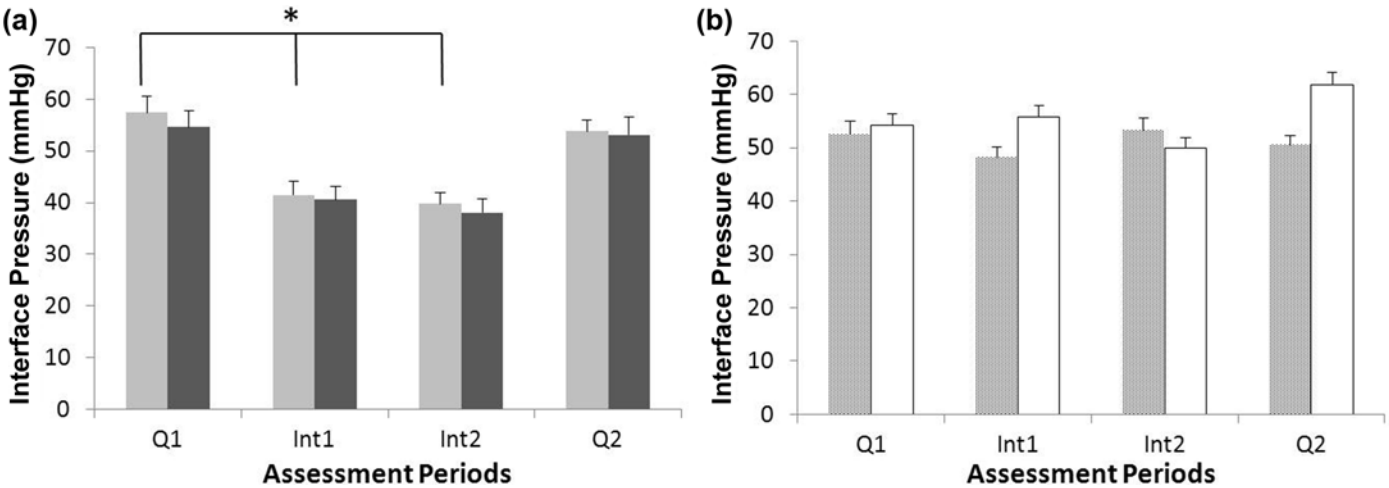

Figure 3.
Relationship between weight-shifting and mean ischial region interface pressures. **(a)** Changes with independent pressure relief. **(b)** Changes with alternating-pressure air cushion-induced weight-shifting. $^{*}p < 0.05$. Int1 = intervention phase 1, Int2 = intervention phase 2, Q1 = quiet sitting 1 (preintervention), Q2 = quiet sitting 2 (postintervention).

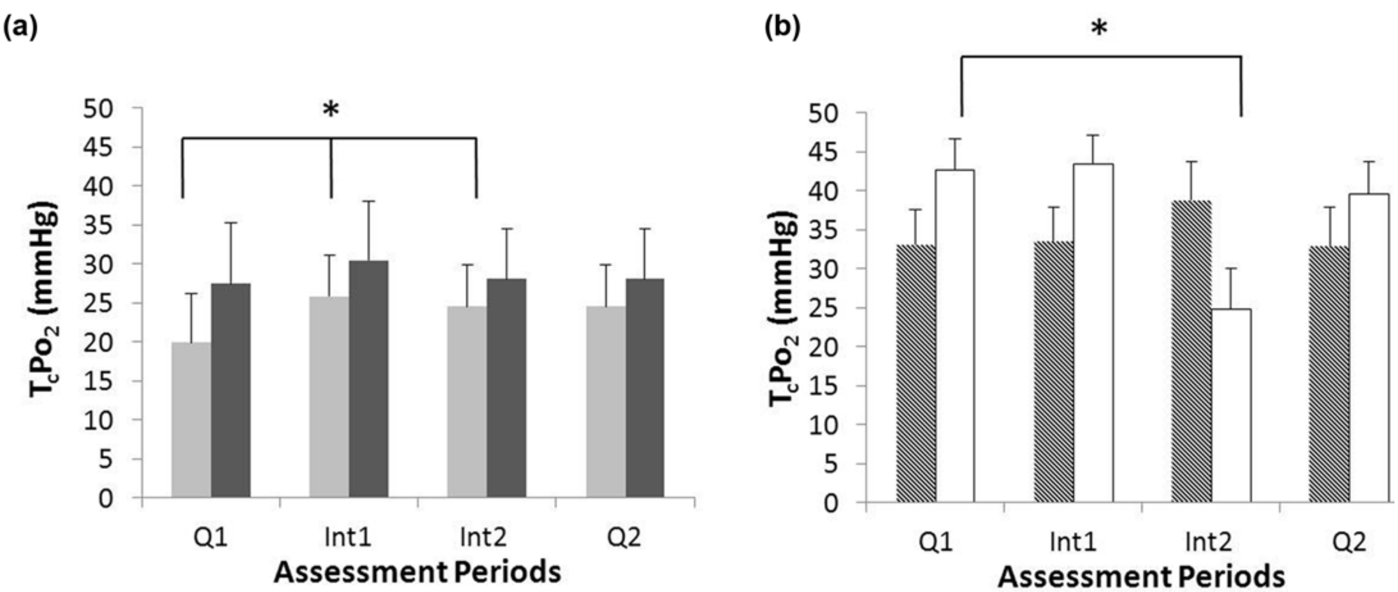

Figure 4.
Relationship between weight-shifting and ischial region tissue oxygenation. **(a)** Changes with independent pressure relief. **(b)** Changes with alternating-pressure air cushion-induced weight-shifting. $^{*}p < 0.05$. Int1 = intervention phase 1, Int2 = intervention phase 2, Q1 = quiet sitting 1 (preintervention), Q2 = quiet sitting 2 (postintervention), T_cPO_2 = transcutaneous oxygen tension.

activation produced higher neurogenic ($p < 0.05$) and respiratory ($p < 0.01$) components. It was also found that the cardiac component of blood flow was very much lower during and after weight-shifting caused by APAC use compared with IPR ($p < 0.001$).

Relationships Between Tissue Health Outcomes Measures During Pressure Relief

Only 23 percent of the study cohort exhibited a normal negative correlative response, i.e., mean ischial T_cPO_2 decreased as mean ischial IP increased. Nearly

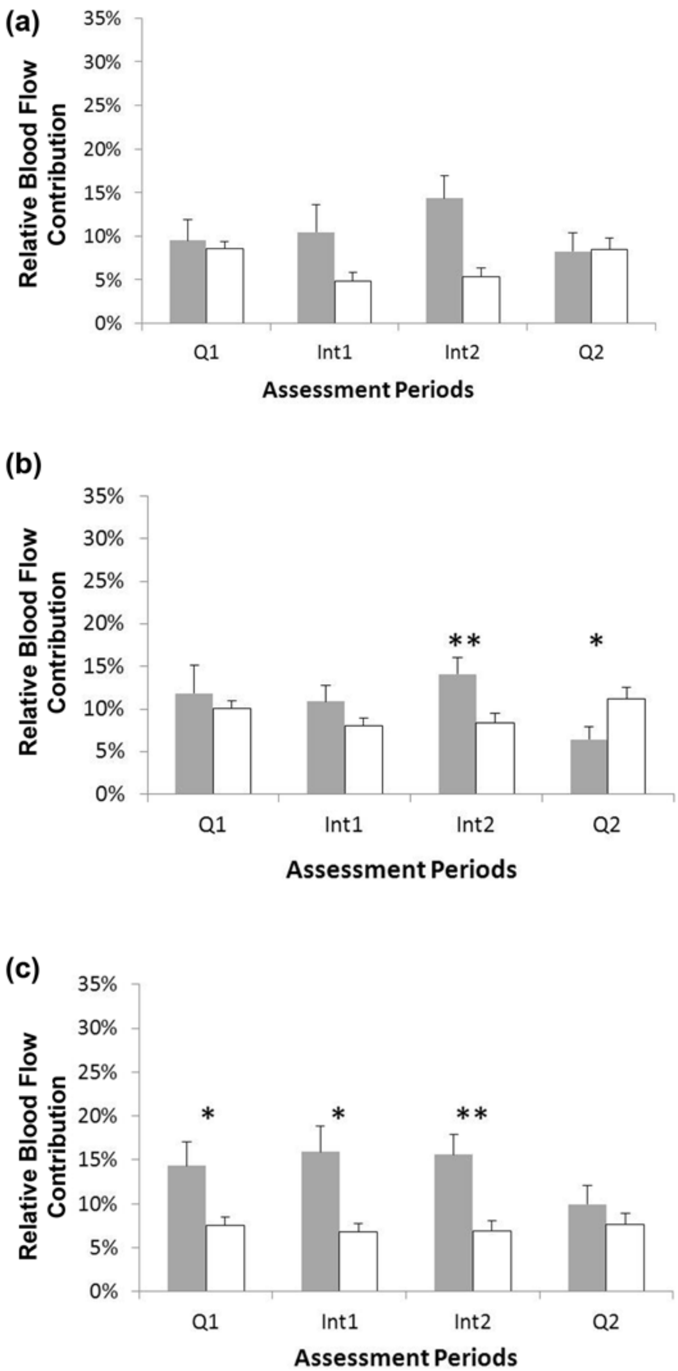

Figure 5.
Relationships between weight-shifting and relative contributions to ischial region blood flow as percentage of total power spectral density. **(a)** Metabolic component changes. **(b)** Neurogenic component changes. **(c)** Myogenic component changes. $^{*}p < 0.05$. $^{**}p < 0.01$. Int1 = intervention phase 1, Int2 = intervention phase 2, Q1 = quiet sitting 1 (preintervention), Q2 = quiet sitting 2 (postintervention).

50 percent showed no relationship between mean ischial IP and local mean T_cPO_2 during APAC use, and 31 percent exhibited a positive correlative response. However, 31 percent exhibited significant negative correlations between both metabolic and myogenic contributions to blood flow and mean IP during APAC activation. The majority of participants also showed a trend for a negative relationship between neurogenic contributions and mean ischial IP during APAC use.

DISCUSSION

The functional objectives of an effective wheelchair cushion are to prevent tissue breakdown, promote postural stability, and increase overall sitting tolerance. The current study investigated the hypothesis that APAC use has an improved effect on tissue health compared with IPR. A high-performance wheelchair cushion is a critical component in a wheelchair seating system to maximize function for individuals and decrease the risk of PU development [2,23–27]. However, all static cushions still require the user to perform regular IPR to "off load" the bony prominences, specifically the ischial tuberosities.

In the current study, we found that IPR was effective in positively affecting multiple aspects of tissue health, i.e., significantly relieving mean IP, increasing mean T_cPO_2, and increasing components of ischial region blood flow. However, all variables rapidly returned to preintervention levels following IPR, except for the cardiac component of blood flow. It was also observed that in this study cohort of individuals with chronic SCI, mean ischial T_cPO_2 values were lower than 30 mm Hg at all phases of the seated assessment during IPR, even though participants were using seating systems that had been prescribed for them by a wheelchair clinic. It has been suggested by Bogie et al. and Chai and Bader that 30 mm Hg represents a threshold above which tissue health is not considered to be compromised [28–29]. Thus, the current study findings indicate that ischial region tissue health may be compromised in these subjects if regular, effective pressure relief is not carried out, and further, that 3 min of IPR may not be sufficient to achieve this goal. The findings from applying a multifactorial methodology to assess several aspects of tissue health indicate that IPR is effective only while it is actively being performed and that the most sustained effect on tissue health is increased blood flow due to exertion.

APAC cyclic weight-shifting dynamically and continuously alters IP distribution in a programmed inflation and deflation cycle, which affected tissue health somewhat differently than IPR. The APAC used in the current study has two series of air cells that can be individually controlled (**Figure 1(a)**). At appropriate and even inflations, this may provide better pressure distribution than a standard cushion even when not active, as seen by decreased mean IP levels during Q1 (**Figure 3**). Over the complete active inflation and deflation cycle, which was standardized at 3 min on each side, mean ischial IP decreased. Mean T_cPO_2 during quiet sitting was greater with an APAC than with a conventional static cushion and varied in response to the active inflation and deflation cycle.

Following APAC activation, mean IP and mean T_cPO2 returned to preintervention levels. However, there was a sustained increase in the neurogenic component of blood flow. This component of blood flow is considered to be mediated by the metabolic and myogenic components. Thus, a slower postintervention change in the neurogenic component could be occurring in response to the changes in other components during APAC-induced weight-shifting. As suggested by Jan et al., alternating pressure appears to produce a sustained neurogenic response [30]. In this case, it appears that the regular cyclic weight-shifting produced by the APAC may promote some sustained improvement in local tissue perfusion. These findings suggest that the intrinsic smooth muscle tone of the vasculature may affect responses to external cyclic pressure-relieving stimuli. This is balanced by finding that there were no significant differences in tissue health measures over time with repeated use of the APAC. While this indicates that tissue health responses were consistent over time, there were also no sustained long-term changes in tissue health caused by using the APAC.

It is well established that prolonged applied pressure leads to decreased blood flow, tissue ischemia, and eventual tissue breakdown [31–32]. Makhsous et al. examined the effect of pressure-relief maneuvers and found differences in perfusion recovery times between individuals with SCI and control subjects [33]. Using a multifactorial tissue health assessment methodology, we found that the inverse relationships between IPs, tissue oxygenation, and blood flow were absent in many individuals in the current study cohort. This phenomenon has been observed previously in individuals with SCI, and it has been shown that some individuals with SCI show a progressive deterioration over time in the ability to maintain adequate blood flow when sitting [28]. These changes may be indicative of impaired microvascular response to applied loading. A deficient response to applied load may provide an indication of increased risk of PU development.

STUDY LIMITATIONS

The study included a statistically valid but relatively small cohort of individuals with SCI. Use of a repeated-measures study design allowed greater control of participant variables, reducing the variance of treatment-effects estimates. We also note that statistical assessment runs the risk of type I (false positive) errors and may not necessarily equate to clinical significance. Our statistical methodology included appropriate adjustments for repeated testing and provides outcomes data on multiple measures of tissue health.

The current pilot study compared repeated use of a single commercially available APAC with IPR. This provided comparison with a real-life APAC, which users might have access to, rather than a laboratory-developed prototype cushion. The overall dimensions of each APAC were fitted to the user; however, the air cell layout and inflation and deflation cycle were standardized. This provides valid information about the effect of APAC use on tissue health; however, it may affect generalization to other APACs or other cell layouts.

The current controlled study design employed APAC activation with a standardized cycle based on clinical recommendations [22]. Increasing evidence exists that pressure relief is not “one size fits all.” Detailed characterization of an individual’s tissue health characteristics and responses under physiological loading conditions may facilitate development of an effective personalized PU prevention regime, including optimization of APAC inflation and deflation cycles.

Our tissue assessment protocol has been developed based on prior studies combined with the objective of carrying out assessments in a time frame that is clinically relevant and acceptable to study participants. We have previously shown that a 10-min assessment can reliably indicate tissue health [18]. We have also found that local tissue heating recovers rapidly following a 10-min seated assessment. Any local redness disappears within 10 to 15 min. There may be subcutaneous changes that are not visible. However, it should be noted that in clinical use, T_cPO_2 assessment with local tissue heating has long been used for extended periods in high-risk groups, particularly critically ill neonates [34]. Nevertheless, the sequential design of our tissue health assessment protocol could be modified so that there is no initial tissue heating by carrying out LDF assessment in stage 1 and T_cPO_2 assessment in stage 2.

CONCLUSIONS

Some individuals appear to remain PU free following SCI, while others experience a continuous cycle of recurring PUs. Tissue breakdown and subsequent PU development is prevented by maintaining healthy viable tissue under applied loads. For the full-time wheelchair user, this means maintaining tissue health, particularly in the pelvic region, while seated. Adequate perfusion of the skin and skeletal muscle, via the local microvasculature, is essential.

The current study found that IPR produces transient improvements in tissue health and must be repeated regularly by the individual. Blood-flow analysis indicates that this may affect cardiac function.

APAC activation dynamically and continuously alters IP distribution to provide weight-shifting in a continuous programmed inflation and deflation cycle. The positive effect on tissue health appears to be more sustained than for IPR. The effect of APAC use may be affected by vascular tone. Individuals with lower vascular tone may require an extended inflation and deflation cycle.

Application of a multifactorial tissue health assessment protocol showed that individuals with SCI may exhibit a dysfunctional relationship between applied extrinsic pressure and intrinsic tissue oxygenation and blood flow. Current pressure relief regimes for individuals at risk of tissue breakdown are prescribed based on standardized thresholds for a safe duration of sustained applied pressure. However, IP measurement alone cannot fully identify those at increased risk of PU development. We suggest that a multifactorial approach be applied to develop personalized tissue health profiles.

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Study concept and design: K. M. Bogie.
Acquisition of data: G. A. Wu.
Analysis and interpretation of data: G. A. Wu, K. M. Bogie.
Drafting of manuscript: G. A. Wu.
Critical revision of manuscript for important intellectual content: K. M. Bogie.
Statistical analysis: G. A. Wu, K. M. Bogie.
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ResearcherID/ORCID: Kath M. Bogie, DPhil: N-7366-2014