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The ability of three pressure-ulcer prevention support-surfaces to maintain physiological transcutaneous gas tensions in the seated patient

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A B S T R A C T

Aims: This study evaluates the effectiveness of three seating interventions—static foam (SF), alternating pressure (AP) cushion, and lateral pressure (LP) device—in reducing pressure ulcer (PU) risk among seated individuals by maintaining tissue perfusion levels in buttocks tissue.

Methods: Eight healthy participants were seated on each intervention for 30 min, followed by a 10-min standing recovery period. Transcutaneous tissue oxygen ($TcPO_2$) and carbon dioxide ($TcPCO_2$) were measured at the right ischial tuberosity to monitor tissue perfusion. Responses were recorded as a percentage change relative to each participant's unloaded baseline gas tensions and categorised into three levels of risk. Statistical analysis included paired, one-tailed t-tests to compare the impact of each seating intervention on transcutaneous gas tensions.

Results: Both AP and LP devices revealed a lower magnitude of ischemic carbon dioxide compared to the SF cushion, with mean $TcPCO_2$ increases of 13.8 % ± 12.0 % and 14.3 % ± 12.0 %, respectively, versus 96.5 % ± 106.5 % for SF. The corresponding $TcPO_2$ decrease was significantly less for AP (−29.2 % ± 15.7 %) and LP (−28.3 % ± 32.6 %) than for SF (−67.8 % ± 29.0 %). Participants spent significantly more time in the lowest risk category on the AP (17.5 min) and LP (18.2 min) devices than on the SF (2.2 min).

Conclusion: The AP and LP devices maintained favourable buttocks tissue perfusion more effectively compared to the SF, indicating their potential benefit in reducing PU risk for seated patients. These findings support the need for further research to confirm the efficacy of interventions across large sample sizes and longer durations.

1. Background

Pressure ulcers (PUs), also known as bed sores or pressure injuries (PI), are agonizing and debilitating wounds that frequently affect individuals confined to beds or chairs [1]. PUs primarily manifest in regions with bony prominences such as the sacrum and ischial tuberosities in the buttocks [2]. Pain associated with PUs is not only persistent but often undertreated, with studies revealing that a significant proportion of patients experience severe discomfort even before ulcer formation, highlighting a critical gap in pain management [3,4]. The impact of PUs on quality of life is profound, prompting substantial investments by healthcare systems in both prevention and treatment. Notably, studies suggest that the global incidence of PUs among hospital inpatients is approximately 12 %, with some reports from the United States indicating frequencies as high as 40 % [5]. In England alone, between 1700 and 2000 patients develop at least one PU each month, with the daily cost to healthcare systems such as the UK's National Health Service (NHS) estimated at £3.8 million [6].

In 2014, the UK's National Institute for Health and Care Excellence (NICE) introduced guidelines for preventing PUs, suggesting that adults at risk of PUs should be repositioned every 4–6 hours [7]. However, several systematic reviews have found inconclusive evidence to identify clearly the optimal positions and frequency for turning patients, underscoring the ongoing debate in this field [8–10]. Interestingly, the current international guidelines do not give a set time frame for repositioning, instead encouraging healthcare professionals to use their judgement taking into account patient-specific parameters such as tissue tolerance, activity level and comfort [11]. Repositioning can be time-consuming and labour-intensive for those who lack independent mobility [12]. Accordingly, in many community settings where resources are limited, the recommended frequency and magnitude of movements are not followed [13], or delivered effectively [14]. As a result, individuals may be exposed to prolonged pressures over time, putting bony landmarks such as the sacrum at high risk of damage.

Guidelines also advocate the prescription of pressure redistributing devices, such as pressure redistributing mattresses and various seating

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and cushion options for adults in secondary care or for those at elevated risk of PUs in primary or community care [1,7]. A systematic review evaluating the effectiveness of various support surfaces used for PU prevention, with a particular focus on high-specification foam mattresses, concluded that viscoelastic foam mattresses appeared more effective than standard care in most cases, although the definition of "standard care" often lacked clarity. Furthermore, the evidence was inconclusive regarding whether viscoelastic mattresses outperformed other PU care mattresses [15]. Another systematic review found limited evidence on the efficacy of current seat cushions in preventing PUs due to a lack of research in this area [16]. The substantial investments being made in purportedly PU-prevention devices without robust supporting data on their efficacy shows the urgent requirement for both better devices and more data that demonstrate ability to reduce the risk of developing a PU.

For the seated patient, static foam cushions are common in therapeutic chairs to redistribute pressure between the seat and buttocks. Support devices being prescribed to those at high risk of PUs by healthcare services typically include more immersive materials such as air, which may have alternating pressure (AP) functions [16]. The AP cushions are made up of several inflatable air cells. Every other air cell is inflated at a given time so that only some of the buttock is loaded at any given time. The inflated cells swap in a cycle every few minutes. Recently, the concept of lateral pressure (LP) application as a method to reduce the risk of developing a PU was proposed [17,18]. The LP device uses air-filled bladders placed against the arms of a chair to force the buttocks tissue underneath the seated individual in order to increase the tissue height over the ischial tuberosities at risk of developing a PU and prevent blood vessel occlusion (Fig. 1) [17].

Although these currently prescribed support devices aim to reduce the risk to the seated patient for developing a PU, there is limited evidence of their efficacy [15,19]. Furthermore, there is evidence that interface pressure is not an accurate predictor of risk for developing a PU [20,21]. Therefore, comprehensive evidence to assess the efficacy of support devices used by the seated patient, using metrics other than interface pressure, is required.

Various techniques have been suggested to assess the health of local tissues under load [22]. For instance, transcutaneous oxygen tension ($TcPO_2$) and carbon dioxide tension ($TcPCO_2$) are considered potential indicators of tissue viability [17] and have been demonstrated to establish ischemic thresholds during progressive tissue loading [23,24]. A reduction in oxygen levels and a rise in carbon dioxide levels signal local tissue ischemia, with anaerobic cellular respiration altering tissue pH, resulting in tissue damage and the onset of PUs [25,26]. Research indicates that $TcPO_2$ decreases and $TcPCO_2$ increases when seated, compared to baseline levels recorded while standing [27–29]. These findings suggest that oximetry could serve as a proxy for predicting an ischemic response in local skin and sub-dermal tissues due to oxygen depletion and carbon dioxide accumulation, with the latter indicative of more severe ischemia in the local tissue [25].

This study aims to compare the effectiveness of three PU-prevention seating interventions to maintain baseline transcutaneous gas tensions locally in the buttocks tissue.

2. Method

Ethical approval was gained from Imperial College Research Ethics Committee, ID 6440832. Eight healthy participants were recruited for the study and gave informed consent to participate. Participants were required to be 18 years of age or older (Table 1). Exclusion criteria included any history of PUs or any period of being restricted to a bed or wheelchair in the past 12 months.

Three interventions were considered (Fig. 2): static foam, AP cushion (Aura Logic Cushion, Auto Logic 630003 Pump, ArjoHuntleigh, Sweden), and the prototype LP device. In tests with the AP cushion, the device was placed on top of the static foam seat cushion. This is in line with the prescribed use of the device. In tests with the LP device, the underbody cushion of the LP device was placed under the seat cushion, and the lateral chambers placed over the static foam seat cushion and against the arms of the chair [17]. The oximeter (TCM5 Flex, Radiometer, Denmark) was calibrated before each participant as per the User Manual.

Before arrival, participants were asked to prepare the test site by removing hair from the area of skin on their right buttock where they can feel their ischial tuberosity (IT). The testing protocol is shown

Table 1
Table of participant data.

ID	Sex	Age (years)	Weight (kg)	Height (cm)	BMI	Fat %	Muscle %
1	F	23	60.6	170	21.0	25.1	43.7
2	M	35	69.4	183	20.7	17.3	53.5
3	M	25	104.1	181	31.8	31.8	44
4	M	33	85.6	180	26.4	26.5	47.5
5	F	23	65.4	169	22.9	28.2	41.8
6	M	20	77.3	170	26.7	25.9	47.9
7	F	24	84.9	171	29.0	35.1	37.8
8	M	23	85.9	178	26.8	26.3	47.6
	Mean	26	79.1	175	25.7	27.0	45.5
	Minimum	20	60.6	169	20.7	17.3	37.8
	Maximum	35	104.1	183	31.8	35.1	53.5

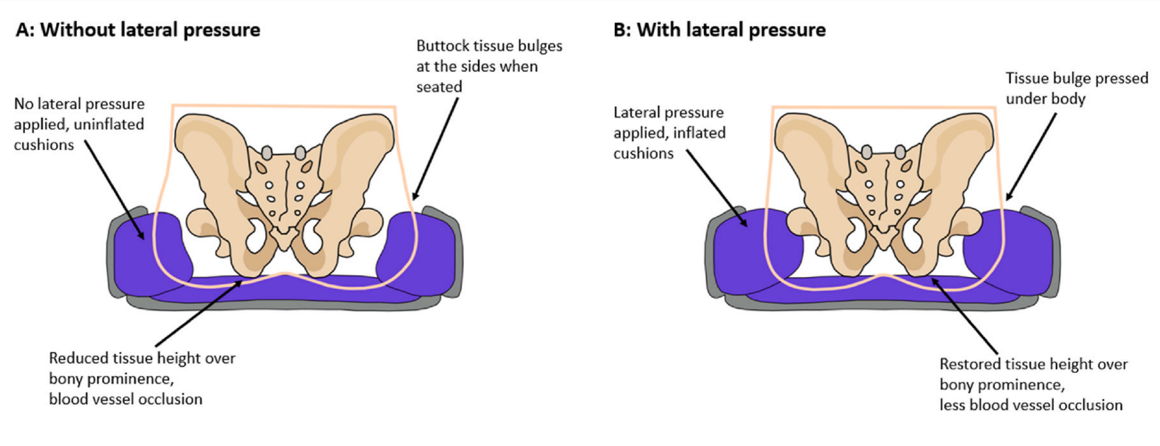

Fig. 1. Diagram summarising the effect of applying pressure laterally on the seated buttock.

Fig. 2. – Diagram of set up of three different support surfaces. From left to right: static foam (SF), alternating pressure (AP), lateral pressure (LP).

pictorially in Fig. 3. Each participant was fitted with an oximetry electrode with a fixation ring at their right IT and was asked to stand for 20 min while the skin was heated to 43 °C to allow maximum vasodilation, as per the oximeter's user manual. A baseline reading of the participant's oxygen and carbon dioxide pressures in their unloaded tissue was taken over the last 10 min of the testing period. Then the participant sat for 30 min on the following support surfaces: an armchair with static foam cushions, marketed as preventative of PUs; an AP cushion; and the LP device. The AP and LP devices were placed on the armchair with the static foam cushion, which is consistent with the intended use of each device. Each 30-min sitting period was followed by 10 min of standing (recovery) to allow for the buttocks tissue to return to baseline gas tensions. Finally, the participants stood for a further 10 min to calculate their baseline gas tensions.

The percentage change in gas tension was calculated over time relative to the baseline reading (the final 10 min of the testing protocol). Mean percentage changes in oxygen and carbon dioxide for each participant over minutes 15–25 of each seating session were calculated. Finally, oxygen and carbon dioxide percentage change for each participant at each time point was assigned a category defined by Chai and Bader as [30]:

Category 1 minimal (<25 %) changes in oxygen and carbon dioxide;

Category 2 significant change (>25 %) in oxygen but minimal changes (<25 %) in carbon dioxide;

Category 3 significant change (>25 %) in both oxygen and carbon dioxide.

Statistical analysis was conducted using GraphPad Prism (v8.4.0 for Windows, GraphPad Software, USA). The Shapiro-Wilk test was used to check for normality. Percentage change and time spent in category data were analysed using a paired, one-sided *t*-test in the case that both groups were normally distributed, and the paired, one-sided Wilcoxon tests in the case that at least one of the groups being compared was not normally distributed. The Bonferroni correction was used to account for the multiple comparisons, and hence the significance level was adjusted to $p < 0.001$.

3. Results

The gas tensions from one of the female participants on each seating intervention are shown in Fig. 4.

Fig. 5 shows the percentage change in $TcPCO_2$ and $TcPO_2$ when the eight participants sat on each of the intervention devices. The mean (± one standard deviation) increase in carbon dioxide was 96.5 % ± 106.5 % while sitting on the static foam chair. Conversely, the mean increase in carbon dioxide while sitting on the AP cushion and LP device were

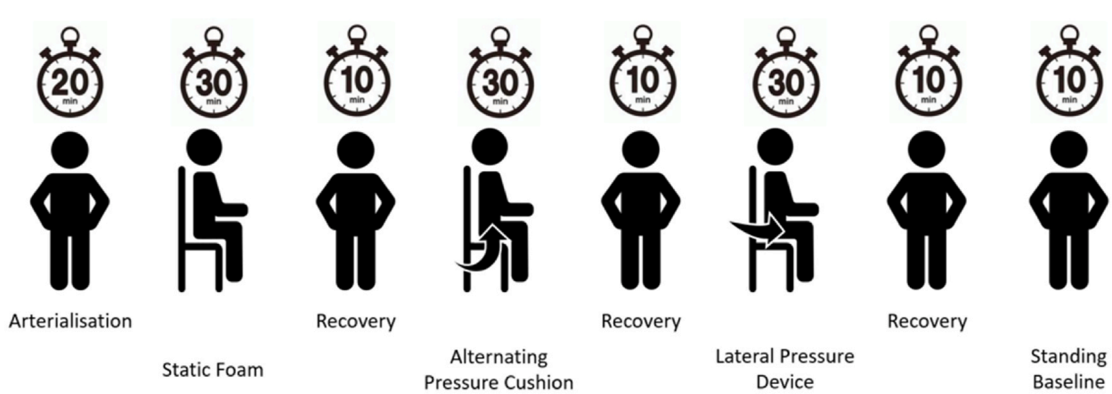

Fig. 3. Pictorial summary of testing protocol.

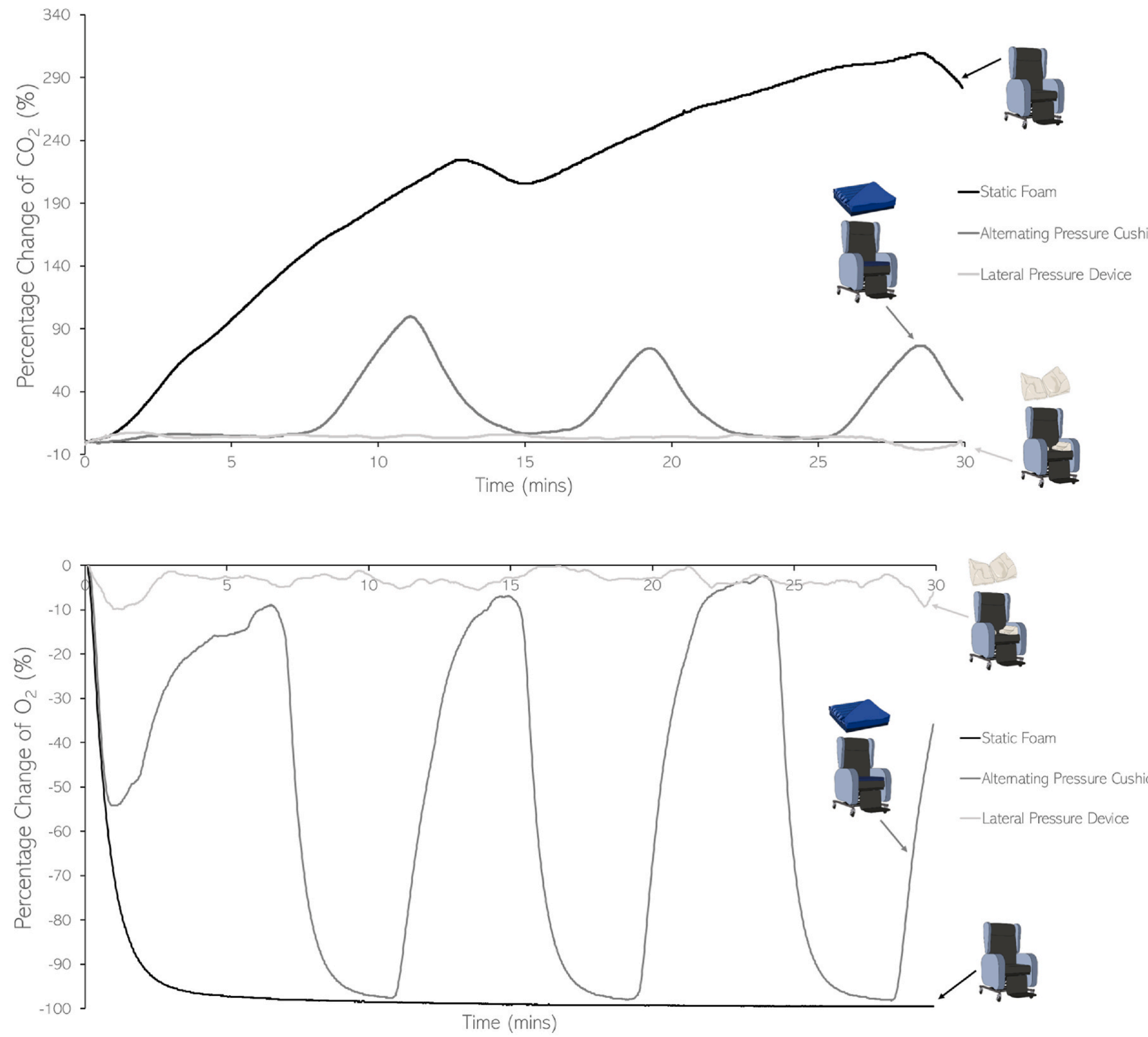

Fig. 4. Line graph showing the percentage change in transcutaneous carbon dioxide and oxygen for a single participant over time for each of the 3 seating-support devices used in this study.

13.8 % ± 12.0 % and 14.3 % ± 12.0 % respectively. This is a statistically significant decrease for both AP and LP when compared to static foam ($p < 0.0039$ for both).

The mean decrease in oxygen was −67.8 % ± 29.0 % while sitting on the static foam, but only −29.2 % ± 15.7 % and −28.3 % ± 32.6 % when sitting on the AP cushion and LP device, respectively. The AP and LP interventions did not show a statistically significant difference between them in their ability to maintain baseline oxygen levels, however, they both performed significantly better than the static foam (AP: $p < 0.0015$, LP: $p < 0.0039$).

Fig. 6 shows the amount of time participants spent in each category during the 30-min sitting period on each intervention. While sitting on the static foam, participants were in the perfused category (category 1), for an average (± one standard deviation) of 2.2 ± 2.6 min (2 min and 11 s). During sitting on the AP cushion and the LP device, time spent in category 1 increased to 17.5 ± 11.7 min and 18.2 ± 11.8 min, respectively. The AP and LP devices performed better than the static foam ($p < 0.0039$ for both) at keeping participants' tissues perfused for prolonged seated periods.

During sitting there was no statistically significant change in the amount of time spent in category 2 when participants sat on the different interventions. The mean times for the static foam, AP cushion and LP device were 10.6 ± 10.7 min, 8.5 ± 9.4 min, and 8.9 ± 7.8 min respectively. Finally, the mean time spent in the ischemic category (category 3), was 17.0 ± 12.0 min during sitting on the static foam, but only 4.0 ± 7.7 min and 2.8 ± 5.6 min when sitting on the AP and LP devices, respectively. Furthermore, six out of the eight participants experienced no time in category 3 during periods on the AP and LP interventions. Both AP and LP devices were statistically similar to one another but performed better than the static foam ($p < 0.0039$ for both) at keeping participants' tissue perfused during the seated period.

Fig. 7 shows the number of participants that were in each of the tissue-response categories during minute 20–25 of the test period on each support surface. By minute 25, there were no participants that remained in category 1 when sat on the static foam cushion and 6 out of the 8 participants were experiencing a category 3 response. In contrast, for both the AP cushion and the LP device, only 2 participants were in category 3 by minute 25 of the test. Further, 3 for the AP cushion and 6 for the LP device out of the 8 participants remained in category 1 after 25 min with each intervention, respectively.

4. Discussion

This study assessed three support surfaces that aim to reduce the risk

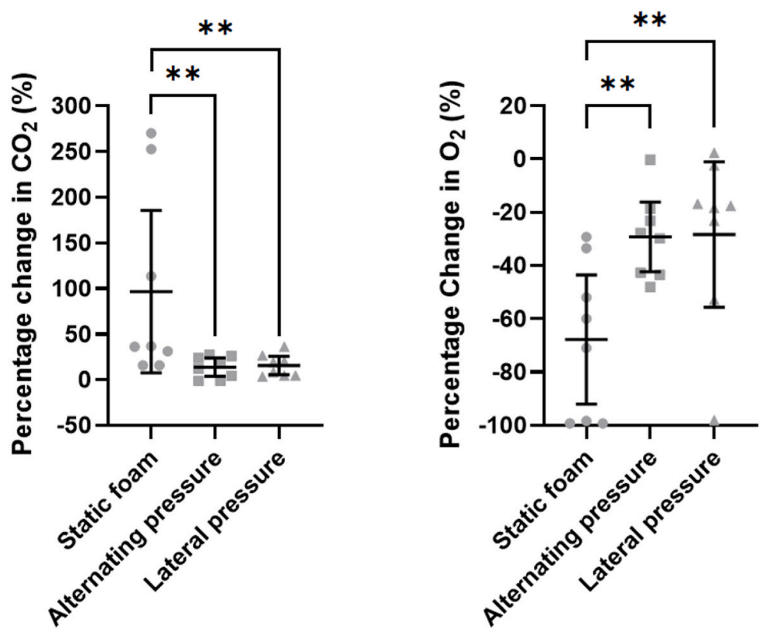

Fig. 5. Average percentage change of (left) carbon dioxide and (right) oxygen, between the three different interventions: static foam, alternating pressure device and lateral pressure device.

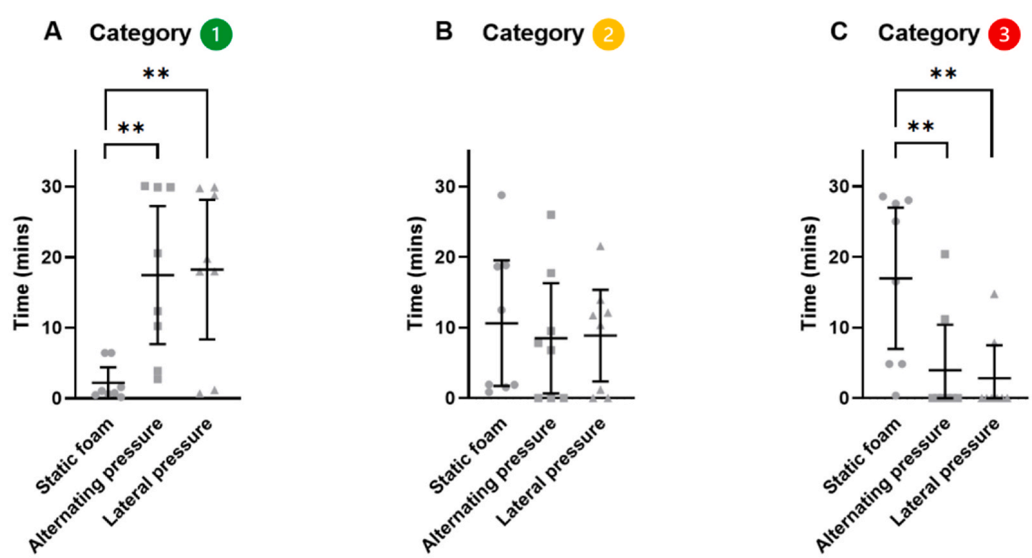

Fig. 6. Box plot showing time spent in (A) category 1 – the safest category, (B) category 2, and (C) category 3 – the most dangerous category - as defined by Chai and Bader in 2013 [30], between the different seating interventions.

of developing a PU in the seated patient. The interventions chosen were an armchair with static foam cushion, marketed as preventative of PUs, an AP cushion commonly prescribed to patients at risk in clinical settings, and a recently developed prototype LP device. The results showed that both the AP cushion and the LP device were able to maintain healthy buttocks tissue perfusion for most participants, whereas the static foam cushion had a high number of ischemic responses during 30 min of sitting. All statistically significant results have a power of at least 0.87, apart from carbon dioxide which has a power of 0.75, likely due to the large inter-subject variability.

Methods for the comparison of PU prevention devices lack standardization. Many studies use interface pressure as a surrogate marker of efficacy in preventing PUs [31–33]. However, there is significant evidence to suggest that interface pressure is a poor predictor of the risk of PUs, partly because it does not provide information about the pressure experienced deeper in the tissue, which can often be responsible for the

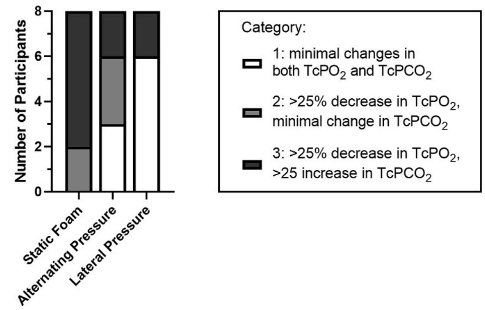

Fig. 7. – Bar graph showing the number of participants in each Chai and Bader [30] category during minutes 20–25, on different support surfaces.

formation of deep tissue injuries [18,20,21]. Instead, oximetry has been used extensively to compare PU prevention mattresses [30,34], as well as seated posture [27–29,35]. Oximetry serves as an indicator of tissue damage in several investigations involving individuals in a seated position [22,27–29,35].

Earlier studies have revealed that an elevation in $TcPCO_2$ may suggest a metabolic alteration in the nearby tissues caused by ischemia, providing an early sign of tissue damage during mechanical loading; this finding underscores the importance of avoiding a category 3 response [25,36]. The results for $TcPCO_2$ show a large degree of inter-subject variation, thus covering a large range of possible physiological responses and capturing the two distinct patterns of carbon dioxide change identified by Chai and Bader: <25 % increase for category 1 and 2 responses, and >25 % increase for a category 3 response [30].

All eight participants were in category 3 by minute-25 of sitting on the static foam cushion. The mean time it took to reach category 3 was 12 min and 42 s, however, more than half of the participants entered into category 3 within the first 5 min after sitting down, which is particularly concerning. There are no studies reporting time spent in category 3 explicitly to compare. Conversely, six out of eight participants who went into category 3 when sat on the static foam did not enter category 3 at all during the 30 min on the LP device. The two participants who did experience a category 3 response spent a mean time of 11 min and 17 s in this state. Similarly for the AP device, only two of the eight participants exhibited a category 3 response, with a mean duration of 15 min and 48 s.

Furthermore, it is thought that the irreparable damage that leads to the formation of PUs can occur in a matter of hours, highlighting the importance of maintaining a category 1 tissue response for as long as possible [37–39]. Therapeutic chairs using static foam aim at increasing the surface area in which the buttocks and the seat are in contact in order to reduce the pressure [40], however, the results imply that this only has a local effect and does not stop occlusion deeper in the tissue. This is consistent with literature that shows that altering cushion stiffness is insufficient for reducing stress deeper in the tissue at the ischial tuberosity [18,20,21].

AP cushions are a type of cushion provided to patients at risk of developing PUs [16]. The AP cushion used in the present study is one prescribed in the local NHS Healthcare Trust; it was set to operate on the default setting of a 9-min cycle, with air cells that alternately inflate and deflate to shift the load-bearing points on the buttocks. Results indicate that when the air cell under the ischial tuberosity (IT) deflates, both $TcPO_2$ and $TcPCO_2$ levels approach baseline. Although the AP device operates on this 9-min cycle, with periods of loading and unloading, the recorded results and average were taken over 10 min (minutes 15–25). During this interval, the average response observed was a category 2 response. However, this reflects time spent in both category 1 and category 3 states (Fig. 4). This observation should be considered when interpreting these findings. Future work could explore the impact of modified cycle parameters on transcutaneous oximetry. Additionally, AP cushions have limitations; there is concern that the cycles of oxygen depletion followed by reoxygenation may promote the formation of oxygen-derived free radicals during reperfusion, potentially causing cytotoxic effects on cells. This reperfusion damage is known as ischemia-reperfusion (IR) injury [26,41,42]. For instance, a 2010 study observed that rats exposed to five cycles of 2 h of loading showed more tissue damage than those subjected to a continuous 10-h load [41]. Currently, there are no specific guidelines for optimal time and pressure settings for AP cushions, so it is unclear if IR injury is a potential risk with this intervention [43]. Furthermore, anecdotal reports from tissue viability nurses suggest that some older patients experience disorientation, confusion, and balance issues during the inflating and deflating phases, which may make the cushions unsuitable for certain individuals.

The duration allocated for each seating condition in this study was limited to 30 min, significantly shorter than the NICE Guidelines' recommended maximum sitting time of 4–6 hours before repositioning [7]. This choice was informed by preliminary tests with a participant seated for 4 hours, which showed no significant change in the assumed tissue-response category beyond the initial minutes of seating, consistent with established protocols in the field [44]. Participants independently positioned the sensor over their right ischial tuberosity, introducing the potential for sensor misplacement. Time constraints prevented repeat readings, leaving possible bias from inaccurate placement unmitigated. Future research should address this by quantifying variability due to sensor placement. The small sample size of healthy, relatively young volunteers with minimal BMI variation limits generalisability, as their body composition and buttock shape may not represent individuals at risk of pressure ulcers (PUs). Notably, category 3 responses occurred in 75 % of participants after 25 min on static foam, with improvements seen upon introducing alternative interventions, consistent with prior studies showing individuals with a PU history require lower loads to alter gas tensions compared to those without PU history [23]. Future studies should involve participants whose body composition more closely mirrors patients at risk for PUs during prolonged sitting. Additionally, the oximetry probe was placed locally at the IT, meaning the results pertain to that specific tissue location. This is particularly relevant for the AP device, where benefits recorded at the IT during unloading may not extend to other buttock areas under load. Future work should evaluate the global effects of interventions by using multiple probes to monitor both loaded and unloaded tissue simultaneously, verifying if the oximetry measurements for the static foam and LP device are truly global. Furthermore, the basic configuration of the lateral chambers is not yet a commercial product and lacks optimization for consistent pressure application or accommodating diverse body shapes. Despite these limitations, the study demonstrated that the LP device is at least as effective as the AP cushion—an accepted standard of care—in maintaining transcutaneous gas levels at the buttock tissue under the ischial tuberosities.

5. Conclusion

The results of this study suggest that an AP cushion or an LP device can be beneficial interventions in reducing the risk of developing PUs in the seated patient, whereas a static foam cushion cannot. These observations were made using transcutaneous oximetry measures at the ischial tuberosity of healthy participants over relatively short sitting durations. Future research should explore tissue response across a larger area of the buttocks, a larger and more diverse participant pool, and longer timeframes of intervention and measurement. The study contributes to the understanding of the efficacy of support surfaces in preventing PUs and highlights the clear benefits of managing appropriately the overall loading environment of the buttocks.

Conflict of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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