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Published in:
Pain Medicine

DOI (link to publication from Publisher):
10.1093/pm/pnv063

Publication date:
2016

Document Version
Accepted author manuscript, peer reviewed version

INTERFACE PRESSURE BEHAVIOR DURING PAINFUL CUFF ALGOMETRY

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Original paper for: Pain Medicine

Running head: *Cuff algometry and interface pressure*

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There is no conflict of interest related to this study.

Abstract

Objective: Cuff algometry is used for psychophysical assessment of deep-tissue pain sensitivity. The cuff pressure homogeneity may affect the pain sensitivity assessment and potentially be improved by alternative cuff designs optimizing the pressure distribution. The aim of this study was to investigate the relationship between pain sensitivity, inflation pressure and distribution of interface pressure between the skin and cuff during stimulation with a conventional air tourniquet and a novel tourniquet including a water tube interfacing the air cuff with the skin.

Methods: Air and water cuff stimulations were applied separately on the right lower leg of twelve subjects until the tolerance pain threshold. The inflation pressure was controlled and recorded by a computer-control program while the interface pressure distribution was measured by a flexible pressure sensor mat located between the cuff and skin.

Results: The mean interface pressure across the entire stimulation surface was not significantly different from inflating pressure during air-cuff algometry. For the water-cuff there was a significant reduction in the mean interface pressure compared with inflating pressure at both the detection and tolerance pain levels, respectively ($P<0.002$). The interface pressure distribution of the water-cuff around the limb was significantly more homogeneous compared with the air-cuff ($P<0.03$). This homogeneity showed a significant correlation with pain sensitivity ($P<0.008$).

Conclusion: Cuff systems with a liquid medium optimize the homogeneity of interface pressure distribution. However, the deviation of interface pressure from inflating pressure is crucial as it counteracts the influences of pressure homogeneity on pain sensitivity in water-cuff algometry.

Keywords: Cuff algometry, water cuff, air cuff, interface pressure, variability, homogeneity

INTRODUCTION

Pressure algometry is widely used as an appropriate procedure for assessing deep tissue pain sensitivity in healthy volunteers and in patients with musculoskeletal pain (1,2). Single-point algometry is traditionally used to apply a concentrated pressure by a small probe on a restricted area (3) while cuff algometry is used to stimulate more musculoskeletal structures simultaneously (4). In both methods the external pressure is transmitted to the deep tissue nociceptors via the superficial layers (5). Previous studies demonstrated inhomogeneous tissue deformations below an air-cuff inflated to provoke pain (6). This spatial inhomogeneity in the delivered stimulus may affect the reliability of the pain sensitivity assessment. So far the cuff pressure inhomogeneity has not been assessed and potentially improved by alternative cuff designs optimizing the homogeneity of the delivered pressure distribution. Moreover, it is unknown if the distribution of interface pressure between the cuff and limb can affect the pain response and hence the reliability of the pain assessment. Generally, the magnitude of interface pressure and its spatial distribution are two external factors which play an important role in provoking the deep tissues and determine the reliability of the pain response during the cuff stimulation. A detailed understanding of the spatial pattern of the pressure distribution on the tissue may lead to an improvement in the reliability of cuff algometry to provide meaningful clinical data.

The biomechanical features of the pneumatic tourniquet have been investigated from a theoretical perspective (7) and three-dimensional pressure propagation in superficial and deep tissues has been studied during painful cuff algometry (6). Based on magnetic resonance imaging during painful air-cuff pressure stimulations it was found that the tissue indentations were highly variable and inhomogeneously distributed (8) around the extremity which influence the transmission of pressure to the deeper structures (6) and as such the deep tissue pain response. It has been shown that the highest pressure for an air-cuff is manifested under the midpoint of the cuff and the lowest pressure is under the cuff edges (9). The results have suggested that the pressure gradient may cause shear forces inside the limb (9). It may be that changing the interface media from e.g. air to water would change this unfortunate shear force characteristics.

Human tissues are inhomogeneous and anisotropic (10,11) and their mechanical properties are dependent on the location (12). These factors as well as the irregular geometry of the limb may affect the uniformity of pressure distribution during the cuff inflation. Using an interface media between the cuff and limb might moderate the biomechanical interaction between the cuff and tissues during cuff pressure algometry. Water is incompressible compared with air and one way to make the pressure distribution more homogeneous may be the use of a liquid interface between the skin and air-cuff.

The purpose of this study was to investigate cuff algometry performed with the air-cuff and water-cuff and compare the (1) pain sensitivity assessments, (2) relationship between the pressure inside the cuff chamber and the pressure in the cuff-limb interface, and (3) spatial distribution of interface pressure around the limb.

MATERIALS AND METHODS

Subjects

Twelve healthy subjects (age range: 23-33 years; mean age: 29; lower leg circumference: 31-36 cm; six females; BMI: 18.8-25.5) participated in the study. The subjects had no acute or chronic pain conditions and none of them took medication one day prior to the study. They had no previous injuries that could interfere with the results. Written informed consent was obtained from each subject prior to inclusion in the study. The study was conducted in accordance with the Declaration of Helsinki and the human experimental data was a part of a larger study approved by the local ethics committee (N-20140002)

Cuff pressure algometry

Pressure stimulation was applied by a computer-controlled cuff algometer (Nocitech and Aalborg University, Denmark). Two different kinds of tourniquet cuffs were used in the study. A 6-cm wide air-cuff (VBM, Germany) and also a 5-cm water-filled cuff (Nocitech, Denmark) were separately wrapped around the right leg of each subject just below the heads of the gastrocnemius muscle, with the cuff centered at the level with the maximum leg circumference. After mounting the water-cuff and before the inflation, it was adequately tightened based on the leg circumference of each subject but caution was taken to prevent the excessive passive pressure which may result in inconvenience of the subjects and affect the painful pressure intensities. The air-cuff was a conventional tourniquet whereas the water-cuff was based on an inner cylindrical cuff filled with water and an outer cuff inflated with air. The air which was pumped into the air chamber of the water-cuff did not mix with water. Figure 1 is the schematic representation of water-cuff inflation. The cuffs were inflated by 1 kPa/s and the pressure limit was 100 kPa provided by a computer-controlled air compressor. The participants used an electronic Visual Analogue Scale (VAS) to rate their pressure-induced pain intensity and pressed a bottom when the pressure tolerance level was reached. The electronic VAS was sampled at 10 Hz. Zero and 10 cm extremes on the VAS were defined as “no pain” and as “maximal pain”, respectively. The first time VAS exceeded 1 cm the cuff pressure defined the pain detection thresholds (PDT) and the pressure when subjects stopped the stimulation defined the pressure tolerance threshold (PTT). The PDT and PTT values were measured three times with a 2 min resting interval between two successive times and the mean of pressure values were used to define the final values of PDT and PTT for each subject. The experiment was separately conducted using the air-cuff and water-cuff with the same procedure.

Measurement of interface pressure

A pressure sensor mat type S2119 (novel GmbH, Munich, Germany) was used to record the interface pressure. The system consists of a flexible and elastic measuring mat with 32×16 pressure sensors, a pliance multi-channel analyzer, and software for control and monitoring. The size of each sensor in the mat was 10×10 mm^2 and was able to measure the pressure values up to 400 kPa. The pressure mat was placed between the cuff and the limb surface. Interface pressures were recorded at 32×16 coordinates inside and outside the cuff area. The interface pressure values were sampled at 35 Hz during the ramp inflation of 1 kPa/s until the previously recorded PTT level. This measurement was done one time for each subject and with each cuff. For those subjects where the pressure mat did not completely cover the limb circumferentially, the measurement was performed in two stages. At first, the non-recorded area was marked and then the mat was moved to cover the non-recorded area and the data recording was repeated. The pressure matrix data of two recordings were concatenated and interpolated to produce the pressure values at 100 circumferential and 60 axial points. The pressure distribution frames representing the pattern of interface pressure at different cuff stimulation intensities and also at PDT and PTT conditions were extracted for further analysis. The system showed a minor interface pressure (< 4 kPa for both the air and water cuff) after wrapping the cuff around the limb and before the inflation. This passive pressure was calibrated to zero and then the interface pressure was recorded during the inflation.

Characterization of interface pressure distribution

Based on the width of the cuffs and sensor resolution of the pressure mat (1 sensor per cm^2) the rectangular area under the cuff was defined in the software and mean interface pressure was calculated in this area. In order to evaluate the ability of cuffs in terms of the size of the stimulated area, the standard deviation of the interface pressure distribution was calculated for non-zero pressure cells (i.e. excluding the effect of areas outside the cuff position). Low standard deviation shows the reduced variability of pressure distribution meaning that the cuff is able to stimulate larger areas on the limb surface with the pressure values near the mean interface pressure.

To assess the pressure homogeneity an entropy-based test was performed on the map of interface pressure distribution. The entropy is a non-negative scalar value which is the measure of uniformity of a distribution X and is defined by the following formula (13):

$$H(X) = \sum_{i} p_i * \log(1/p_i)$$

where p_i are the probability values composing the distribution X and lower amount of entropy illustrates the more uniformity of that distribution. In this study the histogram of the non-zero cells of the matrix of interface pressure representing the cuff area was extracted for each subject at the specified cuff pressure values. Using this histogram roughly estimating the probability density function of interface pressure distribution the p_i values were obtained and the entropy of the interface distribution was calculated for all the subjects.

All calculations of standard deviation, and entropy of interface pressure were performed at four consecutively different intensities of cuff pressure (10, 20, 30, 40 kPa) for evaluation of the trend of these parameters during the cuff algometry. Moreover, the entropy values were extracted at pain detection and pain tolerance thresholds for assessment of the correlation between the uniformity of pressure distribution and painful pressure values.

Statistics

The data are presented as means and standard deviation (SD). All statistical analysis was conducted using SPSS 22 (IBM, USA). The Kolmogorov-Smirnov test was used to test for normality of the interface and cuff pressure, standard deviation, and entropy values. Since the assumption of normality was violated, the interface and cuff pressure at PDT and PTT conditions were analyzed with the Wilcoxon signed-rank test within subjects. Later the data of standard deviation and entropy were analyzed by a two-way repeated analysis of variance (RM-ANOVA). Individual factors were cuff pressures (10, 20, 30, 40 kPa) and cuff type (air-cuff, water-cuff). The Bonferroni test was used for all pairwise comparisons as post-hoc test in the case of significant factors. Moreover, the Pearson correlation method was performed to evaluate the association between the painful pressure thresholds and the entropy values. $P < 0.05$ was considered significant in all statistical analysis.

RESULTS

Pressure algometry data and interface pressure

The cuff and interface pressures for one subject during the air-cuff and water-cuff inflation are illustrated in Fig. 2. Across all subjects the PDT assessed with the air-cuff (18.3±3.5 kPa) was significantly lower than the PDT assessed with the water-cuff (28.0±10.1 kPa; $P < 0.008$). Similarly, the PTT was smaller for the air-cuff (42.7±11.6 kPa) compared with the water-cuff (72.0±11.6 kPa; $P < 0.002$). The mean interface pressure did not show a significant change between the air-cuff and water-cuff at PDT (18.4±3.6 kPa vs. 20.8±5.8 kPa; $P < 0.06$) and PTT (41.5±10.6 kPa vs. 41.3±10.0 kPa; $P < 0.81$) conditions.

For the air-cuff the mean interface pressure was not significantly different from the cuff pressure at the PDT condition (18.4±3.6 kPa vs 18.3±3.5 kPa; $P < 0.75$) or at the PTT condition (42.7±11.6 kPa vs. 41.5±10.6 kPa; $P < 0.16$). Interestingly, there was a significant decrease in the mean interface pressure compared with the cuff pressure at both the PDT (20.8±5.8 kPa vs 28.0±10.1 kPa; $P < 0.002$) and PTT (41.3±10.0 kPa vs 72.0±11.6 kPa; $P < 0.002$) conditions during the water-cuff algometry.

Fixed pressure stimulation and interface pressure

The distribution of interface pressure around the limb for one subject at 30 kPa cuff pressure stimulation with the air-cuff and water-cuff is represented in Fig. 3. Generally the interface pressure around the limb showed a bell-shaped pattern along the axial direction (z-axis) meaning that the magnitude of pressure reached its minimum in the edges and maximum in the center of the cuff (Fig. 3). The standard deviation of interface pressure distribution as a function of cuff pressure is demonstrated in Fig. 4. In both kinds of cuff algometry the standard deviation of pressure increased while increasing the cuff pressure (RM-ANOVA $F_{3,33}$=661.1; $P < 0.001$). Based on post-hoc analysis this increase was observed for all pressure values (Bonferroni: $P < 0.003$). Interestingly, during the cuff algometry there was a significant difference between the standard deviation of interface pressure of water-cuff and air-cuff (RM-ANOVA $F_{1,11}$=9.67; $P < 0.027$). Also, it was demonstrated that the interaction between the cuff type and stimulation intensity was significant (RM-ANOVA $F_{3,33}$=13.28; $P < 0.036$). Based on the results of post-hoc analysis the standard deviation of interface pressure distribution which was generated by the water-cuff was significantly lower than the air-cuff for pressure values more than 10 kPa (Bonferroni: $P < 0.04$).

Homogeneity of interface pressure during cuff inflation

The entropy of interface pressure was not constant while increasing the cuff pressure (Fig. 5). The mean entropy of all subjects during the cuff inflation had an upward trend over stimulation intensities (RM-ANOVA $F_{3,33}$=141.4; $P < 0.001$). Post-hoc analysis also confirmed the increase of entropy for cuff pressure values higher than 10 kPa (Bonferroni: $P < 0.019$). Moreover, the entropy of water-cuff stimulation was significantly lower than the air-cuff while increasing cuff pressure intensities (RM-ANOVA $F_{1,11}$=8.73; $P < 0.032$).

Homogeneity of interface pressure and pain intensity

The data of regression analysis showed that the correlation between the PDT values and entropy of interface pressure distribution was not significant in the air-cuff algometry (Pearson correlation 0.54; $P < 0.07$) whereas there was a significant correlation between the PTT and entropy (Pearson correlation 0.85; $P < 0.001$). Interestingly, in water-cuff algometry the correlation between entropy of interface pressure and both the PDT (Pearson correlation 0.91; $P < 0.001$) and PTT (Pearson correlation 0.73; $P < 0.008$) was significant.

DISCUSSION

The current study assessed the pressure pain sensitivity by air and water cuff algometry and compared the characteristics of pressure distribution on the interface of limb-cuff. An important difference was observed between the interface pressure and cuff pressure in water-cuff algometry that was intensified at higher values of cuff pressure. Moreover, the variability of interface pressure distribution of the water-cuff was significantly lower than the air-cuff. The homogeneity of the pressure distribution was less scattered (i.e. more homogeneous) when using the water-cuff compared with air-cuff algometry.

Pressure variations and cuff types

The higher intensity (> 50%) of cuff pressure in the water-cuff compared with the air-cuff at both the pain detection threshold and pain tolerance threshold conditions is a fundamental difference in the two approaches. Thus, for a given pain intensity more pressure is needed in the chamber of the water-cuff compared with the air-cuff. Interestingly, no significant change was observed between the mean interface pressure of water-cuff and air-cuff at pain detection and also at pain tolerance conditions. This confirms that the main factor which determines the pain intensity is the average of interface pressure that actually exists between the cuff and skin.

There was a big difference between the interface pressure and cuff pressure while using the water-cuff algometer. The interface pressure decreased by 26% and 43% compared with the cuff pressure at the PDT and PTT conditions in the water system, respectively. This decline of interface pressure increases at higher cuff compression intensities and is in line with observations as the amount of cuff pressure at PDT and PTT conditions using the water-cuff is higher than the air-cuff.

The pressure loss in water-cuff algometry may be associated with different physical factors. Due to the physical structure of the water-cuff which prevents the mixture of water and compressed air, the higher pressure in water-cuff algometry might be needed to distribute the water inside the cuff to fill the uneven surfaces. At low cuff compression intensities local pressure variations were observed but the mean interface pressure is not significantly different from cuff pressure (< 20 kPa; Fig. 2B). However, an intimate contact is gradually established between the inner wall of the inflating water-cuff and the tissue while the applied pressure is increasing which may result in that water acts as a barrier like an incompressible ring between the compressed air and limb and inhibits pressure transfer to the limb surface at high pressure intensities. According to Young-Laplace equation the pressure difference between the two sides of a curved liquid layer is linearly related to the surface tension of that liquid and curvature of the surface (14). The high surface tension of water and curvature of water layer circumferentially covering the limb explain the pressure loss between the inner and outer surfaces of water layer.

Interface pressure behavior

The pressure distribution along the axial direction of the limb peaks at its maximum in the middle of cuff while it reaches the minimal value in the proximal and distal edges of the cuff (Fig. 3). This pressure gradient may generate a shear stress inside the limb which is one of the most important factors that challenges the superficial and deep tissues (9). Decreasing the cuff width intensifies this pressure gradient. This is in line with expectations that a cuff with less width is more painful in terms of the generation of shear force inside the limb (15).

An efficient cuff uniformly stimulates larger areas around the limb. The analysis of the standard deviation of the interface pressure distribution shows that both types of cuffs demonstrate variability which increases during the cuff compression intensities (Fig. 4). This may be due to the local increasing of pressure around the limb which leads to more irregular pattern of interface pressure distribution at higher pressure intensities. Interestingly, the amount of variability was less observed in the water-cuff compared to the air-cuff meaning that the water-cuff is better capable to distribute the pressure on the limb surface and affect the tissues over the larger areas with pressure values around the mean interface pressure.

A two-dimensional finite element modeling of the transverse plane at the center of cuff has previously shown that a uniform pressure distribution along the circumference of the limb is more effective than the non-uniform distribution in producing bulk deformations of the calf (16). However, the three-dimensional deformations of the limb under the uniform and non-uniform interface pressure distribution of cuff are less understood. Moreover, the influence of pressure uniformity on the pain response is unclear. Heterogeneity of interface pressure along the circumferential direction of the limb may also affect different anatomical structures. The relationship between the stress and strain distribution and stimulation on two specific points around the limb representing the soft or harder muscles has been investigated (17). It was shown that the strain in the muscle tissue is higher for the stimulation on the gastrocnemius muscle compared with the stimulation on the tibialis anterior muscle (17). However, no studies have shown that stimulation from which circumferential site of the limb can mostly challenge the different structures e.g. muscle tissue or periosteal layers which mainly contribute to the pain response. In the present study a regular pattern was not observed for the location of the areas subjected to the pressure concentration at pain detection and pain tolerance conditions. However, the results of the entropy test for evaluation of the uniformity of interface pressure should be considered from different perspectives. The increasing entropy during the air-cuff and water-cuff inflation confirms that the uniformity of interface pressure decreases during the both kinds of cuff algometry. Biomechanically the limb is a non-symmetric structure including various soft and hard tissues with different shear and bulk modulus. The increasing heterogeneity of interface pressure may be due to the mechanical interaction between the cuff and limb and different responses of various tissues composing the limb which becomes more irregular at higher cuff compression intensities. Alternatively, it might be due to a limitation of cuff expansion at high compression intensities.

It was also found that the entropy was lower in water-cuff compared with the air-cuff confirming the more uniform pattern of interface pressure distribution during the water-cuff algometry. The post-hoc analysis showed that this difference between the air-cuff and water-cuff becomes more distinct at high pressure intensities. While cuff pressure increases, water uniformly fills the chamber and makes an interface ring that prevents the direct contact between the compressed air and limb surface and diminishes the effects of mechanical interaction between the cuff and tissues which results in more homogeneity of interface pressure distribution compared with the air-cuff. A finite element modeling of the limb including various deep structures based on different interface pressure distributions extracted from this study will definitely play a complementary role to define a standard stimulation technique for efficient provoking of deep-tissue nociceptors and providing reliable pain response. Interestingly, in water-cuff algometry the correlation between the painful pressures and entropy of interface pressure distribution was significant. Although this analysis may not necessarily confirm the dependency of painful pressure values on the homogeneity, according to the values of correlation coefficient there is a direct relationship between entropy and painful threshold values during water cuff algometry. This suggests that the pain thresholds have lower values when the interface pressure is more homogeneous. The water-cuff is more capable to generate a homogeneous pressure, but the decline of interface pressure from cuff pressure in this kind of algometry may compensate the effect of pressure homogeneity.

CONCLUSION

The water-cuff provided a more homogeneous pressure distribution around the extremity during the cuff inflation which is a favorable feature of cuff algometry. However, the large decrease of cuff pressure to the interface pressure in water-cuff algometry counteracts the effects of pressure homogeneity on painful threshold values. The implications of the current findings suggest that the cuff systems with liquid medium may optimize the activation of deep structures by improving the pressure distribution although the deviation of interface pressure from cuff inflating pressure should be considered as one of the important characteristics of this kind of algometry.

AKNOWELDGMENTS

The study was supported by a Proof of Concept grant from the Ministry of Higher Education and Science, Denmark. Nocitech is a company partly owned by Aalborg University. Center for Neuroplasticity and Pain (CNAP) is supported by the Danish National Research Foundation (DNRF121). There is no conflict of interest related to this study.

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Figure 1

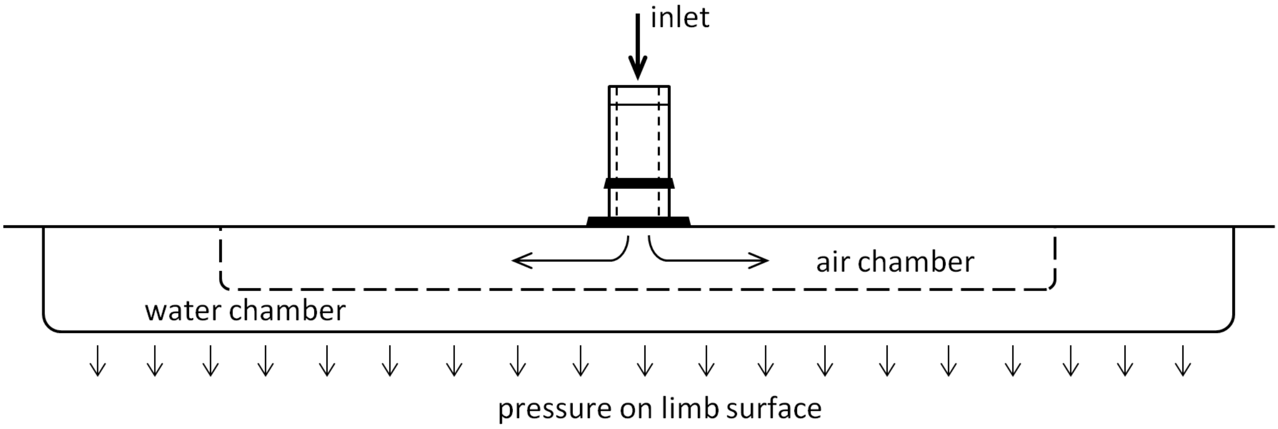

Fig. 1. Schematic demonstration of water-cuff. The air which is pumped (1 kPa/s) into the air chamber does not mix with water.

Figure 2

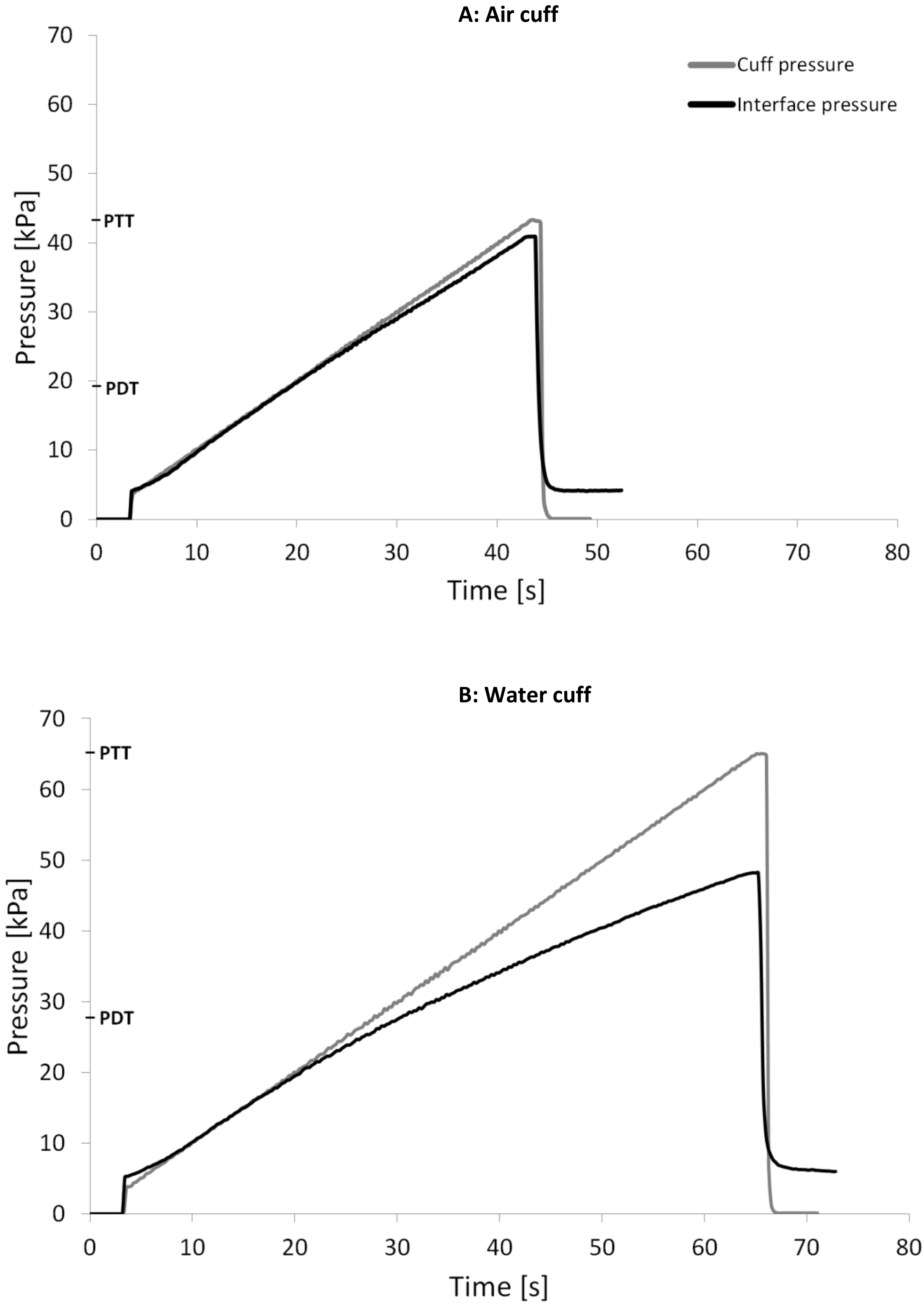

Fig. 2. The cuff and interface pressure as a function of time for one subject during inflation (1 kPa/s) of the air-cuff (A) and the water-cuff (B). The interface pressure is the mean value across the entire interface surface. Although the water-cuff was linearly inflated, the mean interface pressure was nonlinearly increasing.

Figure 3

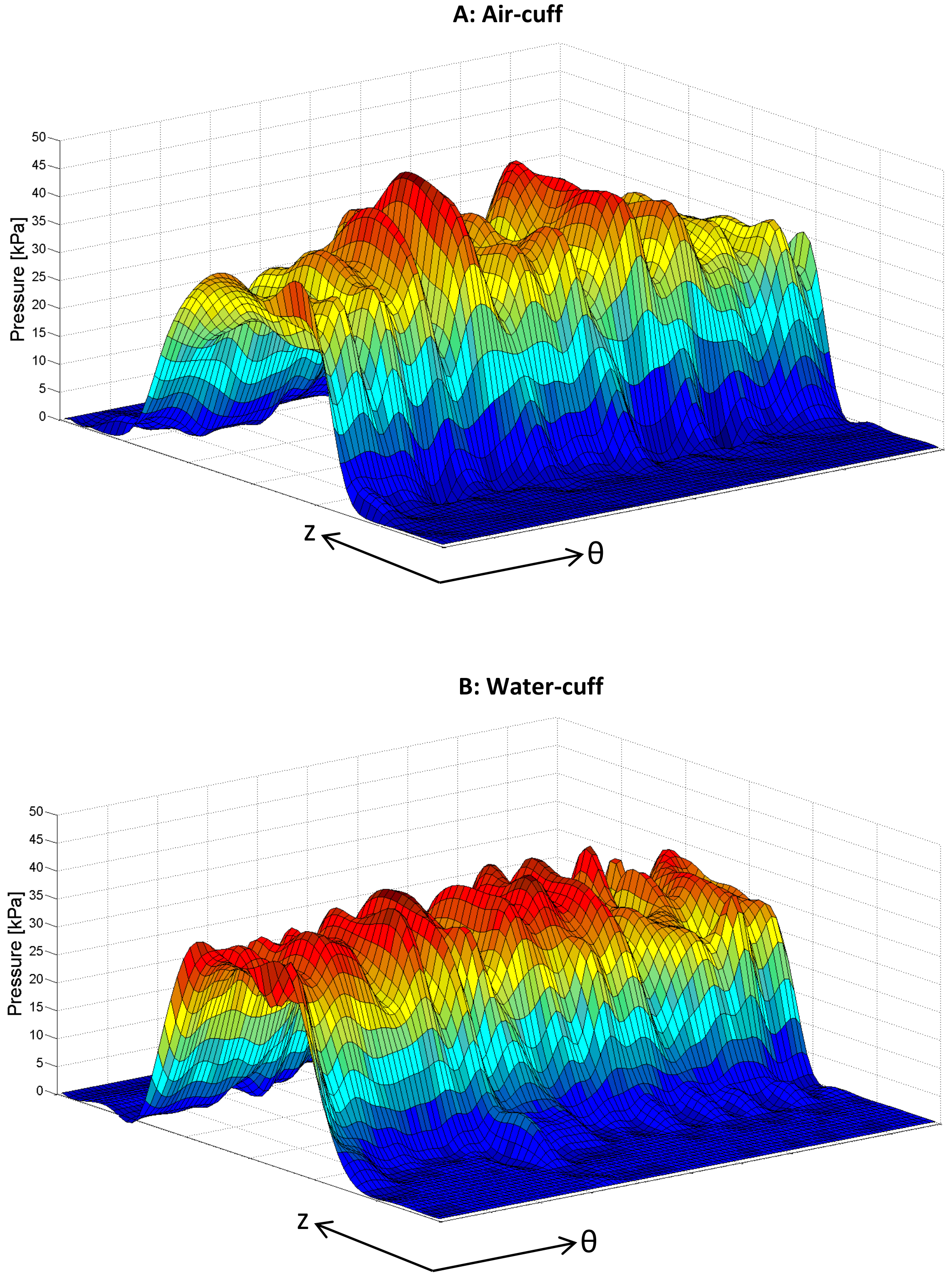

Fig. 3. Three-dimensional distribution of interface pressure on the limb surface of one subject as a function of Z along the axial direction and θ along the circumferential direction of the limb at 30 kPa cuff pressure using the air-cuff (A) and water-cuff (B). A bell-shaped pressure distribution was observed along the axial direction.

Figure 4

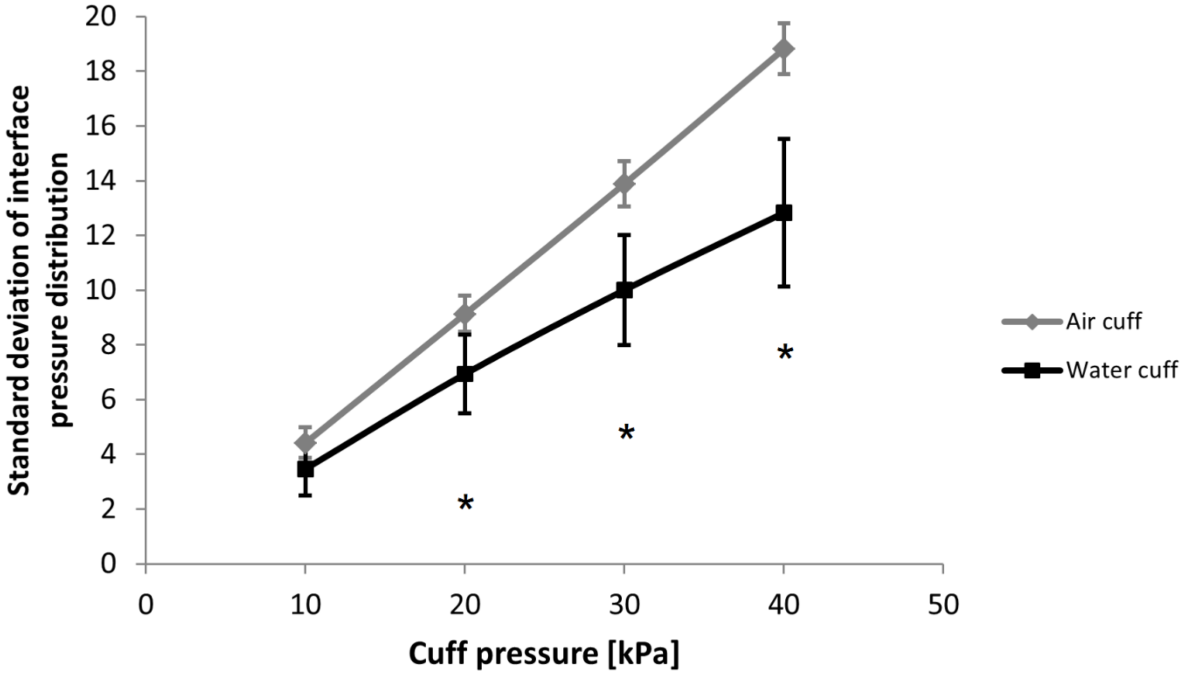

Fig. 4. Mean (± SD, N= 12) standard deviation of interface pressure distribution as a function of cuff pressure (of non-zero pressure components). The variability showed an increasing trend during the air and water cuff inflation (P < 0.001). The interaction between the stimulation intensity and cuff type was significant (P < 0.036). The standard deviation of interface pressure distribution of the air-cuff was significantly higher than the water-cuff stimulation (*: P < 0.04).

Figure 5

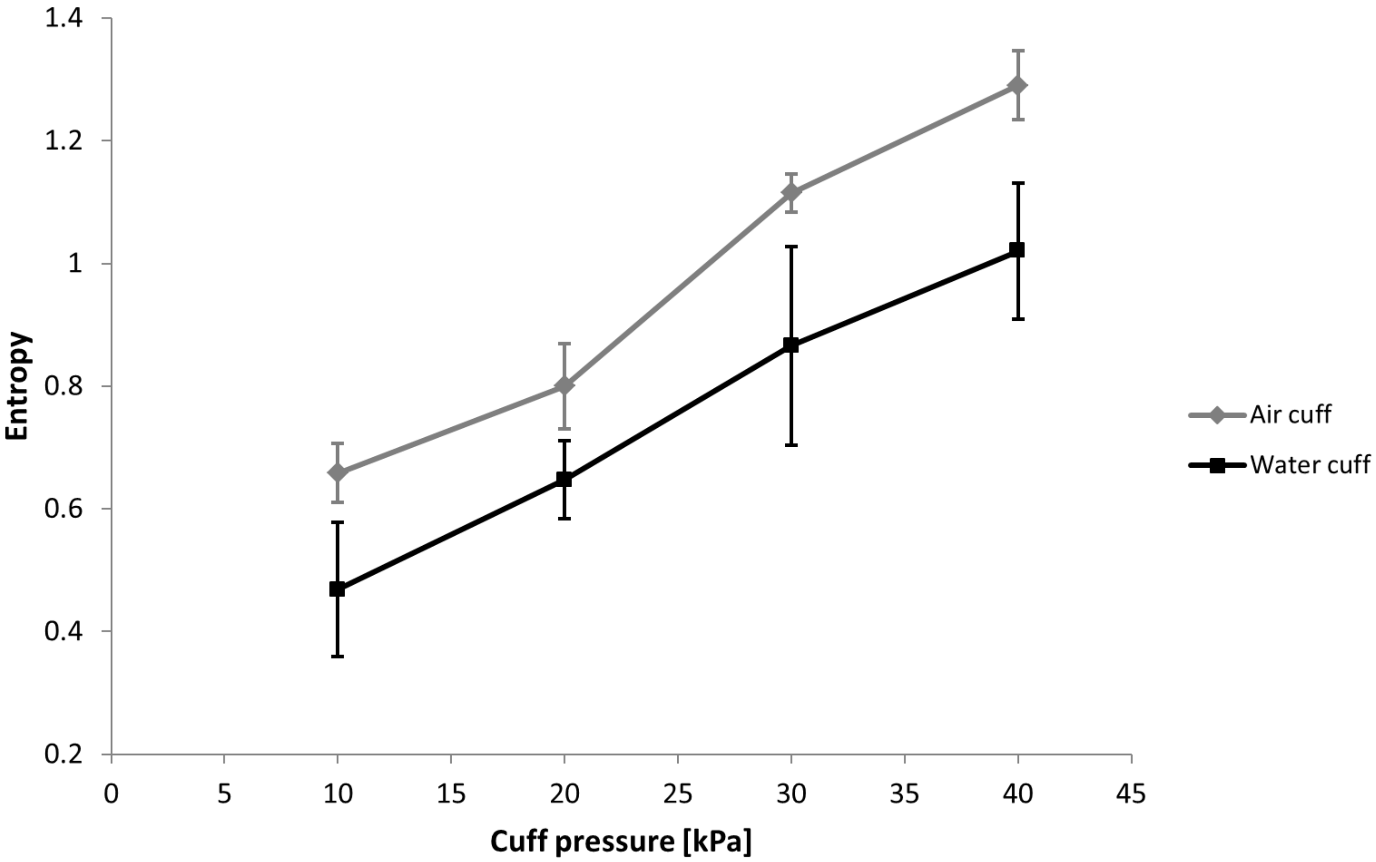

Fig. 5. Mean (± SD, N= 12) interface pressure entropy as a function of cuff pressure for the air-cuff and water-cuff. The entropy in both types of the cuffs increased during the cuff inflation (P < 0.001) indicating that the homogeneity of interface pressure decreased over cuff inflation. The entropy of interface pressure distribution generated by the water-cuff was less than the air-cuff (P < 0.032).