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**Section:** Original Investigation

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Blood flow restriction training - validity of pulse oximetry to assess arterial occlusion pressure

Original Investigation

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Abstract

Purpose: Setting the optimal cuff pressure is a crucial part when prescribing blood flow restriction (BFR) training. It is currently recommended to use percentages of each individual’s arterial occlusion pressure (AOP), which is most accurately determined by the Doppler ultrasound (DU). However, the practicality of this gold standard method in daily training routine is limited due to high costs. An alternative solution is pulse oximetry (PO). Therefore, the main purpose of this study was to evaluate the validity between PO compared to DU measurements. In addition, we aimed to investigate whether sex has a potential influence on these variables.

Methods: Ninety-four subjects were enrolled in the study. Participants were positioned in a supine position and a 12-cm-wide cuff was applied in a counterbalanced order at the most proximal portion of the right upper and lower limb. The cuff pressure was successively increased until pulse was no longer detected by DU and PO, respectively.

Results: The results indicated that there were no significant differences between the DU and PO method when measuring the AOP at the upper limb ($p = 0.308$). However, both methods showed considerable disagreement for the lower limbs ($p = 0.001$), which was evident in both men ($p = 0.028$) and women ($p = 0.008$). No sex differences were detected.

Conclusions: PO is reasonably accurate to determine the AOP of the upper limbs. For lower limbs, PO does not seem to be a valid instrument when assessing the optimal cuff pressure for BFR interventions compared to DU.

Keywords: blood flow restriction, arterial occlusion pressure, Doppler ultrasound, pulse oximetry
Introduction

The combination of physical exercise with a partial blood flow restriction (BFR) in the exercising extremity has gained increasing interest in both research settings and practical training applications. Previous investigations have demonstrated that low-load resistance training in combination with BFR promotes increases in muscle mass and strength to a similar extent as traditional high-load training. Besides cuff width and the duration of BFR, cuff pressure intensity is considered to be one of the most important determinants for optimal training adaptations with both acute and chronic studies demonstrating pressure-dependent physiological responses.

While some studies use the same absolute pressure across all individuals, setting an arbitrary absolute pressure does not necessarily restrict the same amount of blood flow for each individual and does thus not allow adequate standardization across subjects. With respect to relative pressure intensities, some studies have adjusted the applied cuff pressure on the subjects’ brachial blood pressure. This procedure is, however, questionable, since the brachial blood pressure does not necessarily explain substantial variance in the prediction of blood pressure in the lower limb. In order to provide an accurate and comparable degree of blood flow during BFR for each individual, it has been proposed to apply pressure intensities relative to the pressure, which is needed to completely occlude arterial blood flow (arterial occlusion pressure, AOP).

The most frequently applied method to determine blood flow and thus AOP is the Doppler Ultrasound (DU) technique. However, despite its high accuracy, the practicability of this gold standard method is limited, mainly owing to the limited availability of DU and the sum of the costs that arise with additional equipment. An alternative solution to assess changes in blood volume and pulse pressure is pulse oximetry (PO). PO is a clinically established easy to use low
cost method. Implementing this method into BFR training regimes could therefore help to make BFR training more accessible for the population at large with the chance of being able to set the optimal cuff pressure without having a specialized training in applying DU technique.

Accordingly, an increasing number of studies have used PO to define the extent of blood flow restriction as well as assessing the AOP in BFR research 18-22. However, there is a lack of evidence regarding the accuracy of PO in determining both, lower- and upper-limb arterial occlusion pressure for BFR protocols.

Therefore, the main purpose of this study was to evaluate the validity between pulse oximetry for measuring the arterial occlusion pressure and hand-held Doppler ultrasound as the current gold standard in the upper and lower limbs. As previous studies have reported substantial gender-differences in limb circumference 23 and composition 24 as well as oxygen dissociation curves 25, which in turn can affect pulse oximetry readings and AOP 6, a secondary aim of this study was to evaluate whether gender has a potential influence on the arterial occlusion pressure measurement.

Methods

Subjects

Based on the results of a power analysis (alpha = 0.05, power = 0.9, number of repeated observations = 2), ninety-four (47 male, 47 female) subjects (31.3 ± 12.7 years) volunteered to participate in the study. Before study initiation, test-retest reliability of the DU measurement (N = 11) was assessed in an additional pilot project. The results demonstrated high reliability when re-assessing the AOP to the nearest 5 mmHg after a 10-min resting period (ICC > 0.9). For the present study, all participants were healthy and had no history of coagulation disorders including deep vein thrombosis. Further exclusion criteria were smoking, pregnancy, the presence of chronic
degenerative diseases, uncontrolled hypertension or medications affecting blood flow regulation. All participants gave written informed consent prior to participation. If subjects were eligible, anthropometric data including weight, height, brachial blood pressure and limb circumference on the right arm and thigh were assessed. For assessing the circumference of the right arm, the distance between the acromion process and the olecranon was measured and a mark was made at 50% of the total length. Additionally, the circumference of the right leg was determined at 25% of the femur length measured from the greater trochanter to the lateral epicondyle.

Experimental Design

In order to compare the accuracy of the DU and PO method, a repeated measures cross-over design was chosen. The AOP of each participant was determined in a random and counterbalanced fashion on both right upper and lower limb with DU and PO, respectively. Before the AOP determination, participants were asked to rest in supine position for 10 minutes. Additionally, a rest period of ten minutes was provided between the four measurements in order to ensure normalization of hemodynamics. All measurements were conducted in a quiet and temperature-controlled room (22 ± 1°C). One experimenter completed all measurements to reduce inter-rater variability.

Determination of AOP with Doppler Ultrasound

For determining the AOP with the DU method, a 12-cm-wide pneumatic nylon tourniquet [Zimmer Biomet, Warsaw, IN, USA] was placed at the most proximal portion of the right arm (50% of the length) or leg (25% of the femur length). The cuff was attached with a snug fit by the same assessor. Subsequently, the posterior tibial artery or radial artery pulse was detected with a hand-held Doppler Ultrasound [Handydop, Kranzbühler, Solingen, Germany]. The cuff pressure
was then gradually increased by 10 mmHg until a pulse was no longer detected. At this point an arterial occlusion of 100% was assumed. The lowest pressure, at which the auditory signal was no longer detected, was documented and cuff pressure subsequently deflated.

Determination of AOP with the pulse oximeter

With the cuff being at exactly the same position, a pulse oximeter [Zimmer Biomet, Warsaw, IN, USA] was placed at the index finger and first toe after cleaning the respective location with an alcoholic solution for skin disinfection. The cuff pressure was then stepwise increased by 10 mmHg until the signal of the PO indicated that periodic changes in blood volume could no longer be detected.

Statistical Analysis

Statistical analyses were conducted with SPSS version 24.0 (IBM, Armonk, USA) and the alpha level was set to $p < 0.05$. After checking for normal distribution of all variables, a paired t-test was used to investigate the difference between DU and PO.

The distribution of the differences was plotted using a Bland-Altman plot. The Bland-Altman plot demonstrated the degree of agreement between the two investigated methods. All analyses were conducted for females and males, as well as for the mixed population. For all data, an outlier analysis (mean ± 3SD) was performed and five subjects were excluded from the analysis. Statistical analysis of the AOP difference was completed after the removal of five paired measurements as outliers. The following data are presented as means ± SD unless otherwise stated.
Results

Table 1 provides a summary of the subjects’ descriptive and anthropometric characteristics. The AOP differences for all measurements are shown in fig.1.

All subjects completed the investigation and no dropouts were reported. However, due to invalid PO readings, the data of n = 9 lower limbs and n = 4 upper limbs were not included into the data analysis. The results indicated that there were no significant differences between the DU and PO method when measuring the AOP at the upper limb (1.52 ± 13.94 mmHg, \( p = 0.308 \)). However, after calculation of a paired t-test, statistically significant differences were detected, when determining the AOP at the lower limb (8.46 ± 21.15 mmHg, \( p = 0.001 \)).

In a subsequent subgroup analysis, we discriminated for gender and found that male (fig. 2A) and female subjects (fig. 3A) showed a non-significant difference in means of -1.17 ± 12.68 mmHg \( (p = 0.533) \) and 4.48 ± 14.78 mmHg \( (p = 0.057) \) for upper limbs respectively. However, significant differences in lower limbs have been identified with 6.53 ± 18.80 mmHg \( (p = 0.028) \) and 10.59 ± 23.52 mmHg \( (p = 0.008) \) for males (fig. 2B) and females (fig. 3B), respectively.

Discussion

The present study aimed to compare the accuracy of the DU and PO method in determining arterial occlusion pressure (AOP). The main findings indicated that there was no significant difference between both methods when the AOP was measured at the upper limb. Although the statistical tests for differences did not reach significance in the upper limbs, this does not necessarily indicate a good agreement between the methods. However, we observed a reasonable agreement between PO and DU with most observations being located within a range of 15 mmHg around the mean difference \(^{26}\). Setting relative pressures during BFR training interventions in upper limbs further decreases the observed AOP differences between PO and DU in practice.
When measuring the AOP at the lower limb, the PO method demonstrated considerable differences, compared to the DU as the current gold standard. This is also highlighted by the Bland-Altman plot revealing substantial disagreement.

Currently available oximeters use two light-emitting electrodes that emit red (660 nm wavelength) and near-infrared (940 nm wavelength) light through the region of interest. The light absorbance is then measured by a photodiode. Given the principle that oxyhemoglobin and reduced hemoglobin have different absorption spectra, allows to determine oxygen saturation and thus also pulse, since the blood volume in the arteries (and thus light absorption) fluctuates with the cardiac cycle. In general, the rate of absorption can be influenced by several factors including probe positioning, cold temperature, skin pigmentation, excessive movement, poor perfusion or fingernail polish. The fact that there is generally an increased epidermal thickness at the sole of the foot, might help to explain the substantial levels of inaccuracy of the PO when measuring the AOP at the lower limb compared to the upper limb. Additionally, the blood flow in both feet and hands seem to be greatly dependent on temperature changes. However, it appears that the hand blood flow is considerably greater compared to the foot when temperatures being lower than 32°C are applied. Thus, it might be argued that the accuracy of the PO readings at the foot are more biased than measurements at the hand, due to temperature-induced decreases in perfusion.

Earlier investigations noted that nail polish negatively affects PO readings, with reducing its values by up to 10%. Thereby, especially black and brown polish seem to induce the greatest bias. In this study we did not assess nail polish as a covariate and can thus not eliminate the influence of this variable. Furthermore, no conclusions can be drawn about the level of AOP in a sitting or standing position. A study from Sieljacks et al. indicated that body position influences lower limb AOP, with significantly higher values in a sitting position. Therefore, future
studies need to determine whether the PO may give more accurate readings when measuring the AOP in different body positions. Due to the novelty of our results and the corresponding research question, limited comparisons can be made between other studies. According to the AOP determination, previous investigations 36 have reported similar pressures (224 mmHg), which are comparable to an AOP of 207 mmHg that was found for the male subjects in the present study. The observed differences of AOP (~ 17 mmHg) might likely be attributable to slight variations in cuff width, which was 10.5 cm in the study from Clarkson et al. 36. This is in accordance with evidence from the literature, showing that higher pressure intensities are required with narrow compared to wide cuffs 37.

**Practical Applications**

Setting a relative cuff pressure is of essential importance when training with partial vascular occlusion. This is underpinned by the fact that both acute and chronic studies have demonstrated cuff pressure-dependent changes in EMG amplitude 10-12. Loenneke et al. 11 and Fatela and colleagues 10, for instance, reported that muscle activation changes with a function of cuff pressure intensity, with greater pressures inducing greater EMG activities. Additionally, evidence from a longitudinal study suggests that a higher occlusion pressure increases muscular hypertrophy at lower training intensities 12. This highlights the necessity of individually determining the AOP before engaging in BFR training. Besides avoiding arbitrary pressures, investigators should aim for assessing AOP during each training visit and not just once or on a weekly basis 3, since AOP has been shown to underlie diurnal variations 38. In both research and practice, the PO method can make the AOP assessment during BFR training more accessible and easier to use, even without being specially trained in ultrasound technique. Although our findings suggest that the PO method is a sufficiently valid tool for determining the AOP in the upper limbs,
no acceptable accuracy was found for the lower limbs. The fact that a poor signal quality during PO assessment can result in invalid readings \(^3^9\), further limits the applicability of pulse oximetry in research and practice. The limits of agreement might have also been taken into account when setting the cuff pressure during both acute and chronic BFR interventions. Even a slight disagreement in the procedure of AOP assessment with PO might have an immediate effect on training adaptations and physiological responses.

In this matter, the aspect of safety considerations needs to be mentioned. Especially in clinical settings it is particularly necessary to cautiously apply pulse oximetry, since various diseases, including raynaud’s disease, scleroderma \(^4^0\) or jaundice \(^4^1\), might interfere with pulse oximetric detection.

**Conclusion**

From these data, it can be concluded that pulse oximetry is a reasonably accurate method when the valid arterial occlusion pressure should be determined for the upper limbs. For the lower limbs, however, pulse oximetry seems to be less accurate when aiming for standardized blood flow restriction in BFR exercise interventions compared to Doppler ultrasound as the current gold standard.

**Acknowledgements**

We thank the subjects who voluntarily participated in this study.

**Conflict of Interest**

None of the authors declare any conflict of interest.
References


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Figure 1 Bland-Altman Plot of the arterial occlusion pressure (AOP) differences between Doppler ultrasound (DU) and pulse oximetry (PO) for upper limbs (A) and lower limbs (B) in male (circles) and female (squares) participants.
Figure 2 Bland-Altman Plot of the arterial occlusion pressure (AOP) differences between Doppler ultrasound (DU) and pulse oximetry (PO) for upper limbs (A) and lower limbs (B) in male participants.
Figure 3 Bland-Altman Plot of the arterial occlusion pressure (AOP) differences between Doppler ultrasound (DU) and pulse oximetry (PO) for upper limbs (A) and lower limbs (B) in female participants.
Table 1: Descriptive characteristics for male and female participants, mean ± SD.

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Age (years)</th>
<th>Weight (kg)</th>
<th>Height (cm)</th>
<th>Arm Circumference (cm)</th>
<th>Thigh Circumference (cm)</th>
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<tbody>
<tr>
<td>female</td>
<td>47</td>
<td>29 ± 11</td>
<td>62.2 ± 9.8</td>
<td>165.6 ± 5.5</td>
<td>28.0 ± 2.7</td>
<td>54.9 ± 4.0</td>
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<td>male</td>
<td>47</td>
<td>34 ± 14</td>
<td>82.0 ± 12.5</td>
<td>181.4 ± 6.5</td>
<td>31.8 ± 2.5</td>
<td>55.8 ± 4.2</td>
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<tr>
<td>mixed</td>
<td>94</td>
<td>31 ± 13</td>
<td>72.1 ± 15.0</td>
<td>173.5 ± 9.9</td>
<td>29.9 ± 3.2</td>
<td>55.4 ± 4.1</td>
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</tbody>
</table>