Blood-Flow-Restriction Training: Validity of Pulse Oximetry to Assess Arterial Occlusion Pressure

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Purpose: Setting the optimal cuff pressure is a crucial part of prescribing blood-flow-restriction training. It is currently recommended to use percentages of each individual's arterial occlusion pressure, which is most accurately determined by 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). The main purpose of this study was to evaluate validity between PO and DU measurements and to investigate whether sex has a potential influence on these variables. **Methods:** A total of 94 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 limbs. The cuff pressure was successively increased until pulse was no longer detected by DU and PO. **Results:** There were no significant differences between the DU and PO methods when measuring arterial occlusion pressure at the upper limb ($P = .308$). However, both methods showed considerable disagreement for the lower limbs ($P = .001$), which was evident in both men ($P = .028$) and women ($P = .008$). No sex differences were detected. **Conclusions:** PO is reasonably accurate to determine arterial occlusion pressure of the upper limbs. For lower limbs, PO does not seem to be a valid instrument when assessing the optimal cuff pressure for blood-flow-restriction interventions compared with DU.

Keywords: Doppler ultrasound, vascular occlusion, KAATSU, cuff pressure

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.¹⁻³ Besides cuff width⁴⁻⁶ and the duration of BFR,⁷ cuff pressure intensity is considered to be one of the most important determinants for optimal training adaptations^{8,9} with both acute and chronic studies demonstrating pressure-dependent physiological responses.¹⁰⁻¹²

While some studies use the same absolute pressure across all individuals,^{13,14} 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 lower limbs on the subjects' brachial blood pressure.¹⁵ This procedure is, however, questionable, because the brachial blood pressure does not necessarily explain substantial variance in the prediction of blood pressure in the lower limb.⁶ 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^{16,17} 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). The 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 BFR as well as assessing the AOP in BFR research.¹⁷⁻²¹ However, there is a lack of evidence regarding the accuracy of PO in determining both lower- and upper-limb AOP for BFR protocols.

Therefore, the main purpose of this study was to evaluate the validity between PO for measuring the AOP and hand-held DU as the current gold standard in the upper and lower limbs. As previous studies have reported substantial gender differences in limb circumference²² and composition²³ as well as oxygen dissociation curves,²⁴ which in turn can affect PO readings and AOP,⁶ a secondary aim of this study was to evaluate whether gender has a potential influence on the AOP measurement.

Methods

Subjects

Based on the results of a power analysis ($\alpha = .05$, power = 0.9, number of repeated observations = 2), 94 (47 males and

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47 females) subjects (31.3 [12.7] y) 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 reassessing the AOP to the nearest 5 mm Hg after a 10-min resting period (intraclass correlation coefficient $>.9$). For this 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. In addition, 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

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 limbs with DU and PO, respectively. Before the AOP determination, participants were asked to rest in the supine position for 10 minutes. In addition, a rest period of 10 minutes was provided between the 4 measurements to ensure normalization of hemodynamics.²⁵ All measurements were conducted in a quiet and temperature-controlled room (22°C [1°C]). One experimenter completed all measurements to reduce interrater 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) 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 fit⁵ 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 mm Hg 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 Pulse Oximeter

With the cuff being at exactly the same position, a pulse oximeter (Zimmer Biomet) 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 mm Hg 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, NY) and the alpha level was set to $P < .05$. 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 2 investigated methods. All analyses were conducted for females and males, as well as for the mixed population. For all data, an outlier analysis (mean [3 SD]) was performed and 5 subjects were excluded from the analysis. Statistical analysis of the AOP difference was completed after the removal of 5 paired measurements as outliers. All data are presented as mean (SD) unless otherwise stated.

Results

Table 1 summarizes the subjects' descriptive and anthropometric characteristics. The AOP differences for all measurements are shown in Figure 1.

All subjects completed the investigation and no dropouts were reported. However, due to invalid PO readings, data from $n=9$ lower limbs and $n=4$ upper limbs were not included in 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] mm Hg, $P = .308$). 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] mm Hg, $P = .001$).

In a subsequent subgroup analysis, we discriminated for gender and found that male (Figure 2[A]) and female subjects (Figure 3[A]) showed a nonsignificant difference in means of -1.17 (12.68) mm Hg ($P = .533$) and 4.48 (14.78) mm Hg ($P = .057$) for upper limbs, respectively. However, significant differences in lower limbs have been identified with 6.53 (18.80) mm Hg ($P = .028$) and 10.59 (23.52) mm Hg ($P = .008$) for males (Figure 2[B]) and females (Figure 3[B]), respectively.

Discussion

This study aimed to compare the accuracy of the DU and PO methods in determining 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 mm Hg around the mean difference.²⁵ 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 with the DU as the current gold standard. This is

Table 1 Descriptive Characteristics for Participants, Mean (SD)

Group	N	Age, y	Weight, kg	Height, cm	Arm circumference, cm	Thigh circumference, cm
Female	47	29 (11)	62.2 (9.8)	165.6 (5.5)	28.0 (2.7)	54.9 (4.0)
Male	47	34 (14)	82.0 (12.5)	181.4 (6.5)	31.8 (2.5)	55.8 (4.2)
Both sexes	94	31 (13)	72.1 (15.0)	173.5 (9.9)	29.9 (3.2)	55.4 (4.1)

Figure 1 — Bland–Altman plot of the differences in arterial occlusion pressure between Doppler ultrasound and pulse oximetry for upper limbs (A) and lower limbs (B) in male (circles) and female (squares) participants.

also highlighted by the Bland–Altman plot revealing substantial disagreement.

Currently available oximeters use 2 light emitting electrodes that emit red (660 nm wavelength) and near-infrared (940 nm wavelength) light through the region of interest.^{26–28} The light absorbance is then measured by a photodiode. Oxyhemoglobin and reduced hemoglobin have different absorption spectra, and this allows to determine oxygen saturation and thus also pulse, because the blood volume in the arteries (and thus light absorption) fluctuates with the cardiac cycle.²⁶ In general, the rate of absorption can be influenced by several factors including probe positioning, cold temperature, skin pigmentation, excessive movement, poor perfusion,²⁶ or fingernail polish.^{26,29} The fact that there is generally an increased epidermal thickness at the sole of the foot³⁰ might help explain the substantial levels of inaccuracy of the PO when measuring the AOP at the lower limb compared with the upper limb. In addition, the blood flow in both feet and hands seems to be greatly dependent on temperature changes.^{31,32} However, it appears that blood flow in the hand is considerably greater compared with that in the foot when temperatures lower than 32°C are applied.^{31,32} 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.

Previous investigations have noted that nail polish negatively affects PO readings, reducing its values by up to 10%.^{29,33} In particular, black and brown polish seem to induce the greatest bias.³⁴ 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 by Sieljacks et al⁵ 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. Because of the novelty of our results and the corresponding research

question, limited comparisons can be made between other studies. According to the AOP determination, previous investigations³⁵ have reported similar pressures (224 mm Hg), which are comparable with an AOP of 207 mm Hg that was found for the male subjects in this study. The observed differences in AOP (~17 mm Hg) might likely be attributable to slight variations in cuff width, which was 10.5 cm in the study by Clarkson et al.³⁵ This is in accordance with evidence from the literature showing that higher pressure intensities are required with narrow cuffs compared with wide cuffs.³⁶

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 electromyography amplitude.^{10–12} Loenneke et al¹¹ and Fatela et al,¹⁰ for instance, reported that muscle activation changes with a function of cuff pressure intensity, with greater pressures inducing greater electromyography activities. In addition, evidence from a longitudinal study suggests that a higher occlusion pressure increases muscular hypertrophy at lower training intensities.¹² This highlights the necessity to individually determine the AOP before engaging in BFR training. Besides avoiding arbitrary pressures, investigators should aim to assess AOP during each training visit and not just once or on a weekly basis,³ because AOP has been shown to underlie diurnal variations.³⁷ 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. It is well-known that poor signal quality during PO assessment can result in invalid readings,³⁸ which further limits the applicability of PO in

Figure 2 — Bland–Altman plot of the differences in arterial occlusion pressure between Doppler ultrasound and pulse oximetry for upper limbs (A) and lower limbs (B) in male participants.

Figure 3 — Bland–Altman plot of the differences in arterial occlusion pressure between Doppler ultrasound and pulse oximetry for upper limbs (A) and lower limbs (B) in female participants.

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 PO, because various diseases, including Raynaud's disease, scleroderma³⁹ or jaundice,⁴⁰ might interfere with pulse oximetric detection.

Conclusions

From these data, it can be concluded that PO is a reasonably accurate method for determining AOP for the upper limbs. For the lower limbs, however, PO seems to be less accurate when aiming for standardized BFR in BFR exercise interventions compared with DU as the current gold standard.

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