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Effect of Cuff Pressure on Blood Flow During Blood Flow-Restricted Rest and Exercise

Kent Westerberg Crossley

A dissertation submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

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ABSTRACT

Effect of Cuff Pressure on Blood Flow During Blood Flow-Restricted Rest and Exercise

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Doctor of Philosophy

Purpose: The purpose of this study was to investigate the blood flow/pressure relationship (linear or nonlinear) in the superficial femoral artery when seated, as well as to investigate blood flow changes with exercise using varying cuff pressures and a preexercise (PE) condition. The presence of venous outflow with occlusion at rest and exercise was also investigated.

Methods: Twenty-three subjects visited the lab on 3 occasions. First to determine linearity of blood flow using 0% to 90% arterial occlusion pressure (AOP), and venous outflow at rest and during exercise with cuff inflated to 40% AOP. Subsequent visits compared blood flow between rest and PE conditions to determine average blood flow, heart rate, systolic and diastolic blood pressure changes in response to a blood flow-restricted (BFR) exercise protocol.

Results: Blood flow/pressure relationship is nonlinear at the superficial femoral artery ($p < 0.01$). No significant differences in average blood flow, conductance or mean arterial pressure (MAP) were found between 30% to 80% AOP ($p = 1.0$ to .08). Blood flow is not significantly different between rest and PE groups ($p = 0.49$) although initial 40% AOP and 40% exercise arterial occlusion pressure (EAOP) values were different between rest and PE groups. ($p < 0.01$).

Conclusion: The nonlinear relationship at the superficial femoral artery demonstrates higher cuff pressures are not necessary to reduce blood flow in BFR exercise of the lower extremity. Furthermore, PE or warm-up is not necessary prior to determining EAOP as it does not alter blood flow responses during BFR exercise. We found evidence of venous outflow above the cuff both at rest and during exercise at 40% AOP.

Keywords: relative BFR, arterial occlusion pressure, nonlinear

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Introduction

The concept of exercise training with blood flow restriction (BFR) has been around for nearly 40 years and was popularized in Japan by Yoshiaki Sato in the mid-1980s (1) and seeks to increase strength and muscle hypertrophy (2) with as little weight as 20% of a 1 repetition maximum (1RM) (3). BFR exercise commonly utilizes a pneumatic cuff, which surrounds the proximal end of the exercising limb (1). The cuff pressure is thought to occlude venous return and cause a decrease in arterial blood flow and velocity distal to the cuff (1). Restricting venous blood flow results in acute venous pooling and muscular swelling distal to the cuff (4,5) which reduces intramuscular oxygen delivery (6) and decreases venous clearance of metabolites (7). This leads to exaggerated levels of metabolic acidosis within the active skeletal muscle and reduced time to fatigue during resistance exercise sets (8,9). Application of cuff pressures to reduce blood flow is dependent on a few different variables such as cuff size, material, and extremity circumference. Ultimately, the goal of BFR exercise methods is to create a reproducible stimulus across subjects. The application of suggested pressures has changed over the course of BFR studies (3,10,11), but is still a topic of concern.

Protocols for BFR have varied in the application of cuff pressures. Earlier BFR studies used absolute pressures (250 mm Hg) (10,12,13); while others have set relative pressures based solely on the brachial systolic blood pressure of each individual (11,14,15). In an effort to minimize arterial occlusion and standardize BFR occlusion pressures (same stimulus) across all individuals, research has moved towards determining total arterial occlusion pressure (AOP) (minimum pressure applied by the cuff to completely occlude arterial flow) of each subject by Doppler ultrasound, and then use a set relative percentage of AOP (%AOP) during BFR exercise (3,16). Using %AOPs helps standardize the application of BFR and reduces the likelihood that participants are placed in full arterial occlusion during rest or exercise, thus improving the safety of the BFR stimulus (17).

Utilizing the lowest possible pressure to achieve a training response is considered the safest BFR training application, and it is also advantageous as it is perceptually less stressful to the individual performing the training, which in turn can improve exercise/therapeutic treatment adherence (18). Performing BFR exercises at higher %AOP does not necessarily equate to greater muscle hypertrophy, but does result in higher ratings of perceived discomfort compared to lower occlusion pressures (19). Low-load resistance exercise training in combination with either 40% or 90% AOP produced similar increases in muscle size, strength, and endurance in the upper extremity (19). This suggested that the relationship between arterial occlusion and blood pressure is not linear, and that 40% AOP may be all that is needed to maximize the anabolic response to low-load BFR training (19). However, since exercise increases blood pressure (20–22), Barnett et al reported an increase in AOP from preexercise to immediately postexercise and suggested a 40% AOP obtained during rest was equal to 32% immediately postexercise (23). This presents a potential issue where %AOP may decrease below the suggested occlusion training range, even if cuff pressure remains the same, which could limit the desired outcomes of the BFR stimulus. It would be beneficial to investigate whether this drop can be mitigated or whether it is even important to control for this decrease. This change has only been shown in the upper arm, and the magnitude and timing of this decrease is presently unknown and warrants further research (23).

Even though it is common practice to utilize a warm-up prior to performing a physical test such as a 1RM (10,19,23–25), research has not reported on the effect of preexercise (PE) on the starting %AOP. Therefore, additional research is needed to determine if exercising prior to determining AOP will influence both the PE and postexercise AOP change as reported by Barnett et al (23). Determining if PE will both adjust and prevent a drop in the %AOP may be important for determining how to improve the methodological approach to the application of %AOPs for BFR exercise.

Body position is another important consideration when evaluating %AOP. Measurement of AOP in the posterior tibial artery has been reported to increase from the supine to seated position (26). Arterial blood flow has been reported to decrease with increasing cuff pressure in a linear fashion in the posterior tibial artery in the supine position (27) as opposed to a nonlinear fashion in the brachial artery in a standing position (28). Further research is needed to determine if blood flow response in the lower extremities is linear or nonlinear in a seated position. Furthermore, no study to date has established the presence of venous outflow proximal to the cuff either before or during BFR exercise. Since the goal of BFR is to occlude venous outflow (24), it is important to determine if the current suggested protocol of 40% AOP is sufficient to accomplish this. Therefore, the aim of this study was to: 1) determine if blood flow in the lower leg exhibits a linear or nonlinear response to variable %AOPs; 2) determine if PE alters both starting %AOP and blood flow through a BFR exercise protocol; and 3) to assess the presence of venous outflow at rest and during BFR exercise.

Methods

Experimental Design

The study used a randomized crossover design, where each subject served as his or her own control in each of the experiments.

Subjects

Twenty-three subjects (11 male, 12 female; 175.2 ± 7.95 cm, 70.33 ± 11.45 kg, and 22.78 ± 2.21 years [mean ± SD]) were recruited from a university setting. All subjects were classified as being recreationally active (defined in this study as exercising at least 3x/wk for 30 min or more per exercise session). Participants were excluded if they had more than one of the following risk factors for thromboembolism (29), which included the following: obesity (BMI $\geq$ 30 kg$\cdot$m^2); diagnosed Crohn's disease, past fracture of the hip, pelvis or femur; major surgery within the last 6 months; varicose veins; a family or personal history of deep vein thrombosis or pulmonary embolism.

Procedures

Subjects reported to the lab for an initial orientation meeting, and to be screened for all qualification factors included above, and to read and sign an university IRB-approved informed consent. Qualified subjects had anthropometric measurements recorded and a 1RM assessed for ankle plantar flexion on a Hammer Strength selectorized leg press (Life Fitness, Inc., Schiller Park, IL, USA). The assessment of the 1RM was completed using an established protocol (30). Subjects were instructed to wear loose fitting exercise shorts each day they reported to lab (3 visits total), as well as to avoid exercise within 24-h, be in a 4-h fasting state, and to abstain from caffeine for at least 8-h prior to testing. The first phase (visit 1) for each subject was designed to assess whether the change in blood flow in the superficial femoral artery was linear in response to different %AOPs, while measured in a seated position. Phase two involved two separate days (visits 2 & 3) to determine if utilizing 40% AOP changed blood flow in a PE vs. no preexercise condition (NE, no exercise prior to determining AOP).

Setup Protocol

Each day subjects reported to the lab, the following setup protocol included an acclimation procedure followed by measurement of resting blood flow and resting AOP. An uninflated 10 cm Hokanson cuff (Hokanson E20, Hokanson, Inc., Belleview, WA, USA) was placed on the upper thigh near the inguinal crease of the selected leg. Subjects were seated in a specialized chair and a continuous noninvasive arterial pressure monitor (CNAP) and finger photoplethysmography blood pressure monitor (CNSystems Medizintechnik Graz, Austria) was placed on the subject's right arm along with the second and third fingers for continuous measurement of 6 hemodynamic factors (heart rate, stroke volume, cardiac output, systolic and diastolic blood pressure, and mean arterial pressure (MAP). Biopac Acqknowledge 4.0 data acquisition software (Biopac Systems, Inc., Goleta, CA, USA) was used for collection of data captured by the CNAP. Subjects then remained in a seated position for 30 min to establish a "resting" condition. A recalibration of the CNAP was completed approximately every 15 min to ensure accuracy. Subjects remained in this seated position for the entirety of the data collecting session.

Measure Resting Arterial Flow

Following the setup protocol, resting blood flow was measured over the superficial femoral artery (60% of the distance from the anterior superior iliac spine to the top edge of the patella) just distal to the inferior border of the cuff using a 9 MHz ultrasound sound probe (Logiq e, 9L probe; General Electric Company, Fairfield, CT, USA). Ultrasound gel (Aquasonic 100, Parker Laboratories, Inc., Fairfield, NJ, USA) was used as a medium between the sound head and the subject's skin. Insonation angle of the probe was set and maintained at 60°. Doppler velocity waveforms (DVW) and color flow mode (CFM) was inspected for the presence of arterial blood flow through the superficial femoral artery. Once a clear visualization of the artery was obtained, resting blood flow was recorded for 60 s. The Doppler ultrasound recordings were used to determine vessel diameter along with antegrade, retrograde and average blood flow.

Measure Arterial Occlusion Pressure

Once resting arterial blood flow measurements were completed, AOP was measured. The cuff was inflated to 50 mm Hg for 30 s and then deflated for 10 s, each additional inflation was increased by 30 mm Hg (30 s on, 10 s off) until blood flow had been occluded. Occlusion was determined by DVW (no tracings) and CFM (no color). Once occluded, the pressure was decreased in increments of 10 mm Hg (30 s on, 10 s off) until blood flow reappeared. Pressure was then increased 1 mm Hg until blood flow was no longer detected. The lowest pressure at which arterial blood flow was occluded became the AOP. Once AOP was determined, the cuff was deflated and subjects rested quietly for 5 min.

Visit 1

The experimental leg was randomly selected on visit 1 (legs were alternated for all other visits). Relative AOPs were calculated and measured in randomized fashion (eg, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90%) for each subject in order to account for possible time order effects with the application of the various cuff pressures. Each percentage was calculated based upon the individual's AOP. The cuff was then inflated to the randomized relative pressure and a Doppler ultrasound measurement of the superficial femoral artery was recorded for 60 s. The cuff was then deflated and subjects rested for a period of 5 min followed by another relative pressure measurement until all %AOPs and Doppler ultrasound measurements were recorded. After all %AOP measurements were completed, subjects rested another 15 min in the same sitting position prior to assessment of venous flow.

A no-exercise, time-matched control group was used to assess the influence of BFR and time on the venous system. While our original interest lies in determining if the muscle pump is sufficient to overcome BFR pressure in the cuff, we were also interested in determining if the buildup of pressure in the venous system over time from the application of BFR would overcome cuff pressure independent of exercise/muscle pump. To assess this, cuff pressure was increased to 40% AOP for 60 s and venous blood flow was monitored just proximal to the superior border of the cuff in the femoral triangle without leg movement or exercise. After 5 min of rest, a Velcro foot strap was attached to the subject’s forefoot. The strap was connected to a weighted cable pulley (NK664-75 DeLuxe wall pulley, NK Products, Lake Elsinore, CA, USA) at 20% of their 1RM. The cuff was inflated to 40% AOP and subjects completed 60 s of plantar flexion activity while Doppler ultrasound measurements were taken of the femoral vein just proximal to the cuff to assess venous blood flow. This exercise was performed at a tempo of 1 s (paced by a metronome) in each direction. The subjects were instructed to complete each phase of the lift (concentric/eccentric) and not let the weight fall back to the original starting position. This was done to determine if venous blood flow remained occluded throughout the 60 s activity.

Visits 2 and 3

All subjects completed a plantar flexion BFR exercise bout under 2 conditions in random order over the next 2 visits (NE, PE). Subjects returned to the lab 2 days following visit 1 procedures. Subjects used the opposite leg than that used in visit 1.

NE Condition

Following the setup protocol, a Velcro™ strap attached to a cable pulley was placed around the forefoot with the weight set to 20% of 1RM. The cuff was then inflated to 40% AOP as determined in the setup protocol. Subjects then completed a 4-set series of 30-15-15-15 repetitions of plantar flexion exercise at a tempo (metronome) of 1 s each concentric/eccentric phase with a 60 s rest period between each set. Subjects were again instructed to not let the weight fall back to the original starting position. The 9 MHz probe was placed over the superficial femoral artery and kept in place for continuous measurements throughout the entire measurement period. The Doppler ultrasound recordings were used to determine average blood flow.

PE Condition

Following the setup protocol, we determined the subject's arterial occlusion pressure during exercise (EAOP). Subjects began PE performing plantar flexion exercise with 20% of 1RM attached around the forefoot. Blood flow of the superficial femoral artery was monitored via Doppler ultrasound for 2 to 3 min of continuous exercise. A 60 s recording of peak blood flow was then taken as they continued exercise. The cuff was then inflated to resting AOP and adjusted as needed to establish EAOP.

After subjects had rested for 20 min, the cuff was inflated to 40% of EAOP and the same exercise and measures described in the NE condition were followed. Subjects performed the same protocol as the 4-set series of plantar flexion exercises as the NE condition. The same absolute weight was used for both conditions.

Statistical Analysis

A mixed model analysis of variance (ANOVA) with blocking on subjects was used to determine significance in our studies. A Tukey post hoc test was performed to determine level of significance. All data was analyzed using JMP Pro version 14.0 (JMP, Cary, NC, USA). Our statistical significance was set at $P \leq 0.01$. Comparisons of %AOPs and their effects on average blood flow, antegrade and retrograde blood flow, vessel diameter, conductance, and hemodynamic factors previously listed in the setup protocol were analyzed.

Results

Visit 1

Average blood flow (fitted mean) was compared at rest (0% occlusion) to incremental increases (10% to 90%) in relative occlusion pressure. A significant relationship found between different %AOPs and resting blood flow demonstrated that the relationship between pressure and blood flow in the lower extremity is nonlinear in a seated position. A significant lack-of-fit test ($p < 0.0001$) determined that a straight line does not fit our nonlinear model for average blood flow. Average blood flow at 10% AOP is significantly different than 50% to 100% AOP ($p < 0.0002$) and 20% is different from 80% to 100% AOP (p value range = 0.009 to < 0.0001) however, between 30% to 80% AOP blood flow values were not significantly different (p value range = 1.0 to 0.08) from one another. Our resting condition (0%) as well as 90% and 100% AOP were significantly different from all other conditions ($p \leq 0.0002$). A representation of blood flow at different occlusion pressures is demonstrated in Figure 1.

Vascular conductance was also compared to all %AOPs. Significant differences were found in conductance ($p < 0.01$) with decreases in nearly an identical manner as blood flow at differing %AOPs (see Figure 2). However, no significance was found in MAP ($p = 0.8$) at differing %AOPs (see Figure 3). A summary of our results for visit 1 can be found in Table 2.

Ultrasound measurements of the femoral vein during our resting control condition showed evidence of venous outflow at 40% AOP (ie, visible wave forms and color flow) as well as during plantar flexion exercise.

Visits 2 and 3

A significant difference was found in AOP ($p < 0.01$) between NE (201.49 mm Hg) and PE (228.87 mm Hg) groups as well as a significant difference in occlusion pressures between legs ($p < 0.01$) with the right leg averaging 235.7 mm Hg compared to 194.6 mm Hg on the left leg (see Figure 4a). There was also a significant difference ($p < 0.01$) in 40% AOP between legs (left 78 mm Hg, right 94 mm Hg) and groups (NE 80.5 mm Hg, PE 91.4 mm Hg) (see Figure 4b).

We found no significant difference ($p = 0.49$) in average blood flow between NE (209.26 mL/m) and PE conditions (224.84 mL/m). We then compared blood flow between the 4 sets of exercise (30-15-15-15) and associated rest periods. We found that during exercise, blood flow was significantly greater ($p < 0.01$) during the first 30 repetitions, however, there was no difference in blood flow between the next 3 sets of 15 repetitions. Blood flow was significantly greater during all exercise bouts than all resting periods ($p < 0.01$), and blood flow was also significantly different ($p < 0.01$) for rest periods 1, 2, and 4 than blood flow at rest. Blood flow was not different between rest and rest period 3 ($p > 0.01$) (see Figure 5). A summary of the within-group comparisons and their levels of significance can be found in Table 3 below.

Discussion

Our results for visit 1 show that the relationship between cuff-induced pressure and blood flow in the superficial femoral artery is nonlinear when measured in a seated position. This is contrary to the findings of Mouser et al (27), who reported a linear blood flow/pressure relationship in the posterior tibial artery, however, consistent with a previously reported (17) nonlinear blood flow/pressure relationship in the brachial artery. Both studies were performed in the supine position (17,27). Since the site of occlusion in our study was similar to Mouser et al

(27), the difference may be due to measurement of blood flow at a different site (artery) and/or different positioning of the subject. With regards to position in non-BFR studies, Wu et al reported shear rates in the superficial femoral artery to be lower than the brachial artery when measured in a supine position (31). Newcomer et al later studied superficial femoral and brachial artery responses (shear rates, diameter and blood velocity) in supine to sitting and standing (32). They reported that the superficial femoral artery demonstrated no significant difference in blood flow, mean blood velocity, conductance and diameter (32). For the brachial artery they reported no significant effect of position on blood flow, conductance and diameter, however, they noted that maximum blood velocity was reduced in standing compared to both seated and supine positions (32). It is possible that change in the blood pressure gradient caused by a difference in the hydrostatic column may play a role in our results, however, when normalizing blood flow for MAP (ie, vascular conductance) the nonlinear relationship persisted (see Figure 2), challenging the role of a hydrostatic effect on blood pressure in our nonlinear response.

The nonlinear relationship between %AOP and flow in our study could potentially be explained by either a compensatory increase in perfusion pressure with cuffing to maintain a relatively constant flow from 30% to 80% AOP, or a nonlinear effect of cuff pressure on the vasculature deep to the tissue. Vascular conductance, which is flow normalized for perfusion pressure, is indicative of the role of artery diameter in determining flow. Both vascular conductance and MAP responses support our nonlinear findings. We found no significant interactions ($p = 0.83$) between MAP and occlusion pressure (see Figure 3), which supports our finding that pressure did not increase to maintain blood flow. The MAP was unchanged and unrelated to %AOP, supporting the notion that a compensatory increase in perfusion is not the cause of the nonlinear effect of %AOP on blood flow. The relationship between %AOP and vascular conductance was explored in order to determine if the nonlinear relationship between %AOP and flow could be explained by a nonlinear effect of the cuff pressure on the artery. As illustrated in Figure 2, vascular conductance exhibited a nonlinear relationship with %AOP, suggesting that the effect of the cuff pressure on the artery deep to the cuff was not linear. This could be potentially due to movement of the tissues from the cuffing pressure producing unequal pressure distribution. However, due to the inability to view the artery deep to the cuff, a direct measure of artery diameter was unavailable.

In our study, we also compared blood flow response between two different starting %AOP conditions (NE and PE) during visits 2 and 3. We hypothesized that the starting %AOP measured at rest may not provide a sufficient compensatory reduction in blood flow with increases in exercising blood pressure. Initially we expected that PE would alter starting AOP and could offset the effect noted by Barnett et al (23), who reported that %AOP decreased from 40% to 32% following a traditional 30-15-15-15 BFR exercise set due to an increase in AOP resulting from exercise (23). Having not analyzed our data from visit 1 beforehand, we used 40% resting AOP (NE) and 40% of EAOP (PE) during exercise in an attempt to control for the effect reported by Barnett et al (23). We found a significant difference in starting %AOP for each condition with EAOP (PE) being 11 mm Hg higher than the resting AOP (Figure 4b). If the relationship between AOP and blood flow was linear, this would likely result in a smaller reduction in blood flow with cuff occlusion during exercise than anticipated. Yet, in agreement with our nonlinear blood flow/pressure findings (Figure 1), the nonlinear relationship between %AOP and blood flow meant that the increase in pressure applied to the leg with EAOP and resting AOP had no impact in blood flow during plantar flexion exercise (Figure 5). These findings support the idea that when performing BFR exercise, establishing a resting %AOP is sufficient. Further supporting this notion, a post hoc analysis showed no significant change in blood pressure between our NE and PE groups (systolic p = 0.39, diastolic p = 0.34), however, there were interset differences in systolic and diastolic blood pressure, heart rate, cardiac output, and MAP within group as expected (see Table 3).

We noted venous outflow proximal to the cuff at rest and during plantar flexion exercise while the cuff was inflated to 40% AOP. We feel that venous outflow warrants further research based on the stated goal of BFR exercise to restrict arterial blood supply to the muscle and occlude venous return (24). This is thought to initiate a cascade of events ending in the reported muscular adaptations (4–9).

Results of our study have significant clinical and practical implications for the application of pressure during BFR exercise. Our data suggest that blood flow does not change significantly between the use of 30% to 80% AOP in the superficial femoral artery, suggesting no need to increase %AOP above 30% for blood flow restriction exercise in the lower extremity when considering hemodynamic responses only. Occlusion pressure was previously shown to be directly related to pain and rating of perceived exertion (33). Furthermore, it has been reported that wider cuffs cause inherently more tissue compression at any given pressure than narrow cuffs (5) and elevated pressures increase the rating of both perceived exertion and perceived pain even when comparing different cuff sizes (22).

Studies have shown that BFR exercise can result in muscle hypertrophy and strength increases (10,34–36), and comparisons have been made between BFR exercise and high-intensity resistance training (10,36–38). A recent meta-analysis suggests that while both forms of resistance training result in expected muscle adaptations (ie, strength, hypertrophy, activation), high intensity resistance training tends to show slightly greater strength and activation responses while hypertrophy responses are similar (33). The greater gains in strength from high intensity resistance training could be a result of level of activation of muscle needed for higher loads as well as the overall load/volume difference when making comparisons between these two protocols (33). Although various muscle adaptations are to be expected from BFR exercise, previous studies have varied in the cuff sizes and pressures used to report such findings. To date, it has been suggested that cuff width does not have a significant effect on muscle size and strength gains in the upper extremity when using the same relative pressure after a long term (12 wk) training protocol (34). Conversely, in a 12-wk lower extremity study, BFR across a combination of 20% to 40% 1RM at either 40% or 80% AOP produced similar muscle strength gains, but muscle mass changes were only found utilizing work at the lower intensity (20% 1RM) with both occlusion pressures (39). Specific comparisons utilizing lower %AOPs are limited in the current body of literature. In a recent study by Counts et al, (19) it was reported that low-load exercise utilizing either 40% or 90% AOP on opposite arms produced similar increases in muscle size, strength, and endurance in the upper extremity. It was also noted that the higher pressure condition produced higher ratings of discomfort throughout the training program (19). Considering our results, future studies are needed to compare lower %AOPs (30% to 40%) to determine if adaptive muscle responses are comparable to prior research in the lower extremity (35,36). Counts et al (19) also suggested that the first set of 30 repetitions may be the most important stimulus and that hypertrophic responses can be maximized with fewer reps as long as the muscle reaches maximal fatigue. Future studies on repetitions and sets for BFR exercise are needed to determine the number of sets/repetitions needed to maximize skeletal muscle fatigue, improve muscular adaptations and minimize rating of perceived pain.

During the course of our study we noted a significant interleg difference ($p < 0.0001$) in AOPs (fitted mean: left 195 mm Hg, right 236 mm Hg: range L: 145-270 mm Hg, R: 168-300 mm Hg) as well as in %AOPs (left 78 mm Hg, right 94 mm Hg: range L: 58-108 mm Hg, R: 67-120 mm Hg). Additional research into AOP differences between legs and leg dominance needs to be completed in order to determine the salience of this finding.

Our results were limited to subjects being placed in a seated position, cuff size (10 cm), and inflation device (Hokanson E-20 Rapid Cuff Inflator). There are several other types of devices (Kaatsu, B-strong, Delphi) that can be utilized for exercise, whereas Hokanson is primarily a clinical device. The Kaatsu and B-strong bands can be disconnected from the inflation device and worn during normal exercise bouts in any position. We also delimited our population to healthy young adults. BFR research on older adults has shown to be beneficial for muscle adaptations as well (40), but does tend to increase both systolic and diastolic pressures at low work loads more than high intensity repetitions without BFR (41). To date the linearity of blood flow has only been studied in a younger population (17,27,28) and it remains unknown if age plays a factor in the relationship between blood flow and %AOPs.

Conclusion

Our nonlinear relationship between pressure and blood flow results match those results of the upper body with blood flow being stable from 30% to 80% AOP. Adjusting for AOP following PE or possibly warm-up exercise does not appear to be warranted since blood flow responses are similar to the use of resting AOP. Consequently, small differences in cuff pressure during exercise have no effect on exercising blood flow. Lower %AOPs allow for BFR training to be more comfortable, have a comparable stimulus, and may provide similar muscle adaptive responses, although future research is needed to verify this.

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Table 1: Percent change in blood flow response to occlusion pressures

Occlusion Pressures	Percent Decrease in Blood Flow	Percent of Resting Flow
0	0.0	100.0
10	23.4	76.6
20	32.9	67.1
30	36.1	63.9
40	42.0	58.0
50	47.6	52.4
60	47.0	53.0
70	48.8	51.2
80	51.5	48.5
90	71.0	29.0
100	100.0	0.0

Table 2: Summary of blood flow/pressure relationship

Percent Arterial Occlusion Pressure	Percent Arterial Occlusion Pressure (mm Hg) (SE = 5.74)	Vessel Diameter (cm) (SE = 0.013)	Average Flow (mL/min) (SE = 6.43)	Antegrade Flow (mL/min) (SE = 6.71)	Retrograde Flow (mL/min) (SE = 3.44)	Diastolic Blood Pressure (mm Hg) (SE = 2.4)	Systolic Blood Pressure (mm Hg) (SE = 3.52)	Mean Arterial Pressure (mm Hg) (SE = 2.55)
0	0	0.567^{a}	125^{a}	163^{a}	38^{c}	65^{a}	114^{a}	84.00^{a}
10	22^{a}	$0.561^{a,b}$	96^{b}	138^{b}	$43^{b,c}$	62^{a}	109^{a}	80.00^{a}
20	43^{b}	$0.554^{a,b}$	$84^{b,c}$	131^{b}	$47^{a,b,c}$	62^{a}	108^{a}	81.00^{a}
30	65^{c}	$0.550^{a,b}$	$80^{b,c,d}$	133^{b}	$53^{a,b}$	64^{a}	109^{a}	82.00^{a}
40	86^{d}	$0.543^{a,b}$	$73^{c,d}$	126^{b}	$54^{a,b}$	65^{a}	112^{a}	83.00^{a}
50	108^{e}	0.538^{b}	$66^{c,d}$	$122^{b,c}$	56^{a}	63^{a}	112^{a}	81.00^{a}
60	129^{f}	0.536^{b}	$66^{c,d}$	$121^{b,c}$	$54^{a,b}$	62^{a}	112^{a}	80.00^{a}
70	150^{g}	0.536^{b}	$64^{c,d}$	104^{c}	40^{c}	61^{a}	105^{a}	78.00^{a}
80	172^{h}	0.535^{b}	61^{d}	79^{d}	18^{d}	66^{a}	114^{a}	84.00^{a}
90	193^{i}	0.496^{c}	36^{e}	43^{e}	$7^{d,e}$	62^{a}	107^{a}	80.00^{a}
100	215^{j}	0.464^{d}	0^{f}	0^{f}	0^{e}	63^{a}	108^{a}	81.00^{a}

Blood flow/pressure relationship for each %AOP (0% to 100%). Values not connected by the same letter are significantly different within each column ($p < 0.01$). Standard error = SE.

Table 3: Summary of blood flow and hemodynamic measurements for within-group comparisons

	Average Blood Flow (mL/min) (SE = 14.45)	Systolic Blood Pressure (mm Hg) (SE = 2.43)	Diastolic Blood Pressure (mm Hg) (SE = 1.93)	Mean Arterial Pressure (mm Hg) (SE = 1.96)	Heart Rate (bpm) (SE = 1.42)	Cardiac Output (mL/min) (SE = 0.12)	Stroke Volume (mL/Min) (SE = 0.02)
REST	116^{a}	109.68^{a,b}	62.72^{a}	81.50^{a,b}	65.75^{a}	5.84^{a}	0.09^{a}
EP1	356^{b}	113.24^{a,b}	66.06^{a,b,c}	84.31^{a,b}	71.85^{b,c,d}	6.00^{a,b}	0.08^{a}
RP1	174^{c}	109.00^{b}	63.29^{a,b}	81.14^{b}	60.4^{b}	6.10^{b}	0.09^{a}
EP2	266^{d}	112.36^{a,b}	65.38^{a,b,c}	83.72^{a,b}	71.96^{c,d}	5.99^{a,b}	0.08^{a}
RP2	171^{c}	110.72^{a,b}	64.65^{a,b,c}	82.41^{a,b}	69.58^{b,c}	6.09^{b}	0.09^{a}
EP3	263^{d}	115.04^{a,b}	67.37^{b,c}	85.71^{a}	72.81^{d}	6.03^{a,b}	0.08^{a}
RP3	168^{a,c}	113.33^{a,b}	65.76^{a,b,c}	83.80^{a,b}	70.39^{b,c,d}	6.15^{b}	0.09^{a}
EP4	261^{d}	115.39^{a}	67.70^{c}	85.87^{a}	72.46^{d}	6.01^{a,b}	0.13^{a}
RP4	178^{c}	112.90^{a,b}	65.91^{a,b,c}	83.85^{a,b}	71.14^{b,c,d}	6.17^{b}	0.12^{a}

Within-group comparisons of hemodynamics factors and average blood flow for rest and exercise periods 1-4 (EP) and rest periods 1-4 (RP). Values not connected by the same letter are significantly different within each column ($p < 0.01$). Standard error = SE.

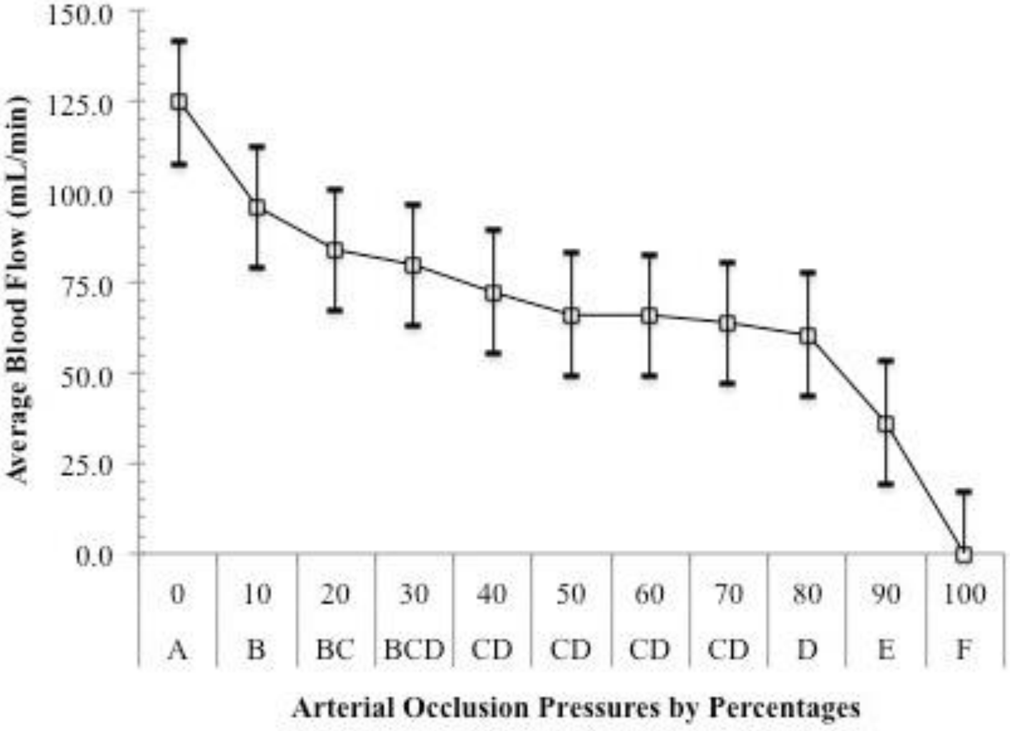

Figure 1: Blood flow/pressure relationship. Average blood flow (mL·min) plot for each %AOP and respective confidence intervals (CIs) (99%). Pressures not connected by the same letter are significantly different ($p < 0.01$).

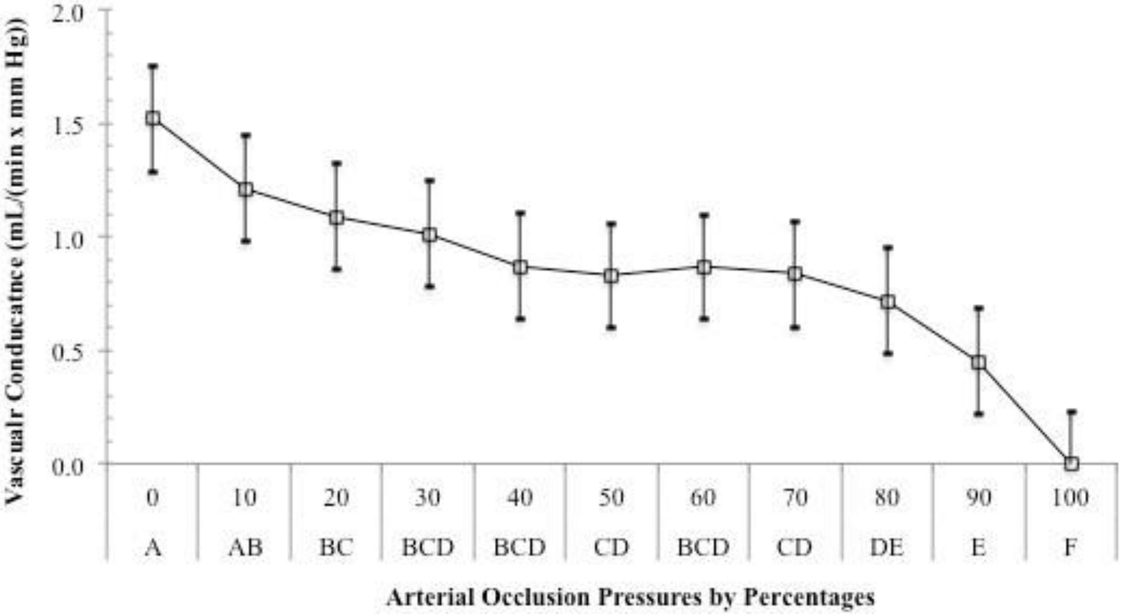

Figure 2: Vascular conductance (average blood flow / MAP) by %AOPs with respective CIs (99%). Pressures not connected by the same letters are significantly different ($p < 0.01$).

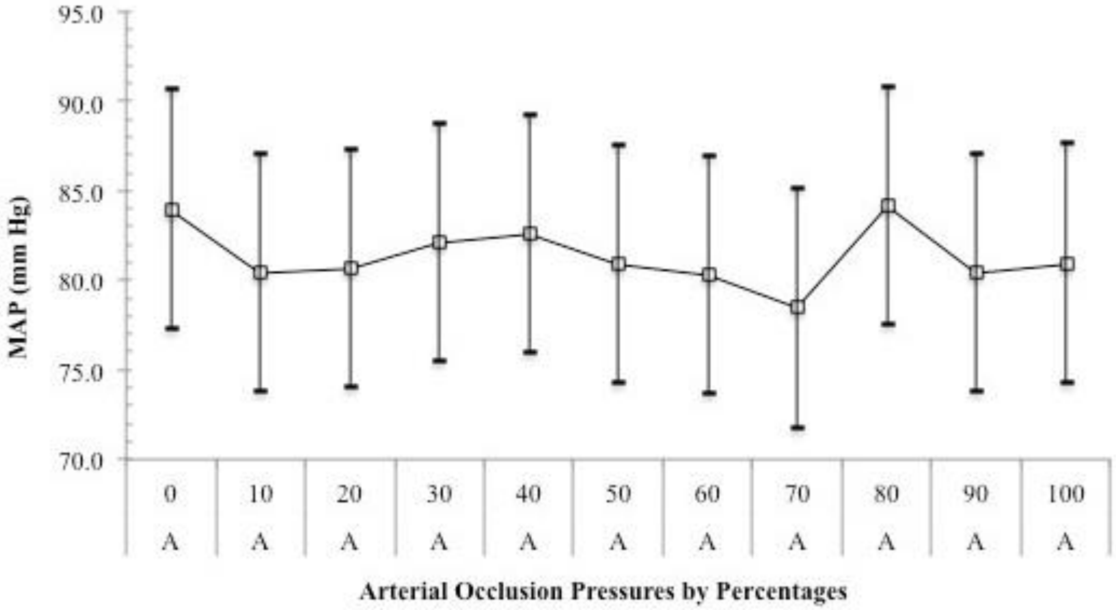

Figure 3: MAP by %AOP plot with respective CIs (99%). Pressures not connected by the same letter are significantly different (p = 0.8).

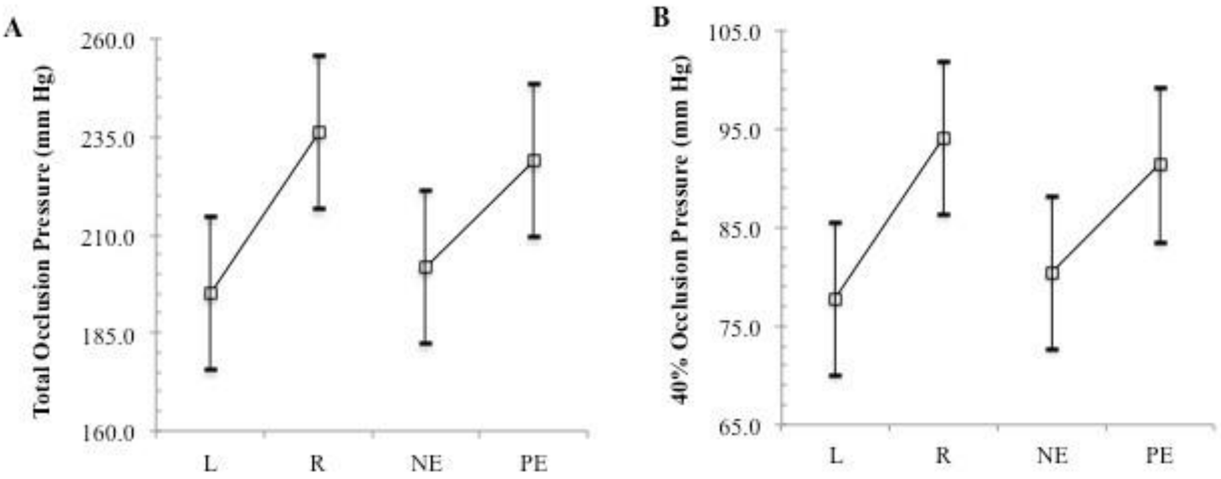

Figure 4: AOP and 40% AOP for left and right legs as well as NE and PE groups. A) AOP for left and right legs as well as NE and PE groups, B) 40% AOP for legs and Groups ($p < 0.01$). Confidence intervals included (99%). Note the difference in scale between the graphs.

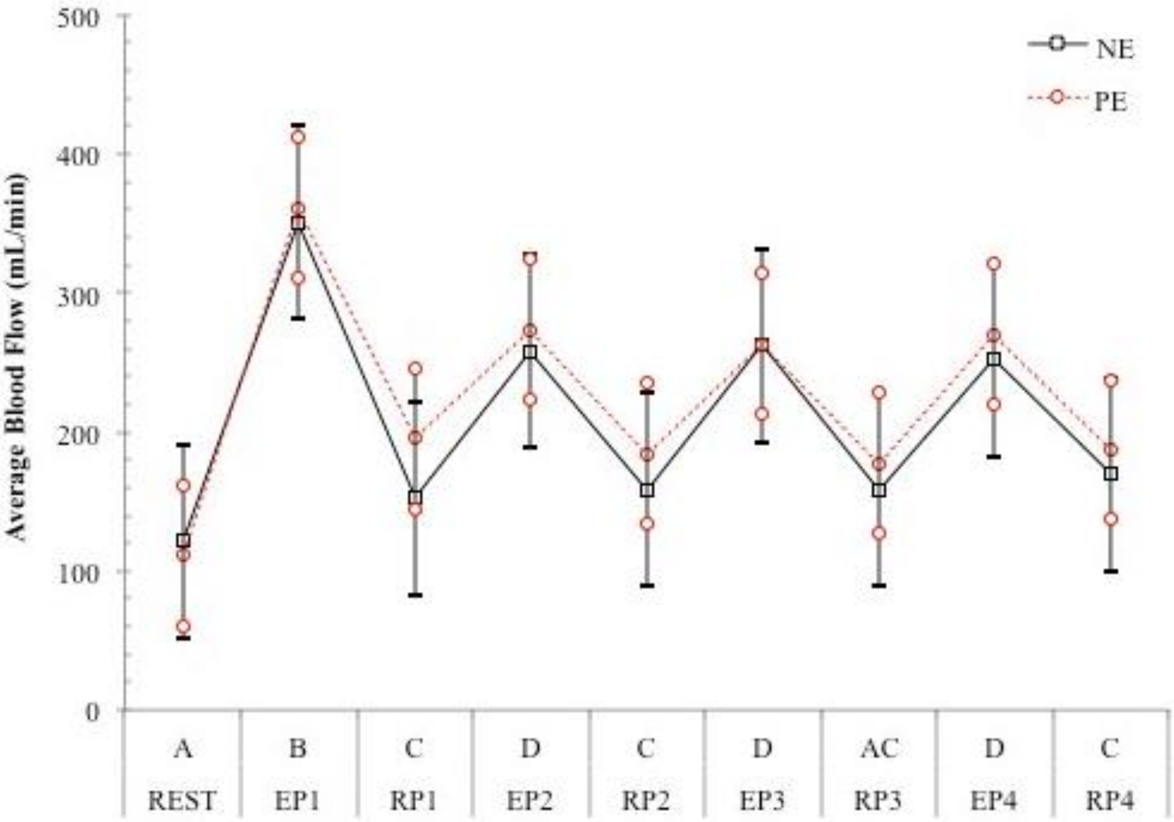

Figure 5: Blood flow comparisons between no exercise and preexercise. No significant difference in blood flow between NE and PE groups (confidence intervals included 99%). However, there is significance in blood flow within groups. Measurements not connected by the same letter are significantly different ($p < 0.01$).