International Journal of EXERCISE SCIENCE

Original Research

Acute Blood Flow Responses to Varying Blood Flow Restriction Pressures in the Lower Limb

BJOERN HORNIKEL‡[1,2], KEITH S. SAFFOLD†[1], JACOB A. MOTA‡[1,3], MICHAEL R. ESCO‡[1], MICHAEL V. FEDEWA‡[1], STEFANIE A. WIND‡[4], and LEE J. WINCHESTER‡[1]

[1]Department of Kinesiology, The University of Alabama, Tuscaloosa, AL, USA; [2]Department of Epidemiology, The University of Alabama-Birmingham, Birmingham, AL, USA; [3]Deparment of Kinesiology and Sport Management, Texas Tech University, Lubbock, TX, USA; [4]Department of Educational Studies in Psychology, Research Methodology, and Counseling, The University of Alabama, Tuscaloosa, AL, USA

†Denotes graduate student author, ‡Denotes professional author

ABSTRACT

International Journal of Exercise Science 16(2): 118-128, 2023. The purpose of this study was to investigate lower limb blood flow responses under varying blood flow restriction (BFR) pressures based on individualized limb occlusion pressures (LOP) using a commonly used occlusion device. Twenty-nine participants (65.5% female, 23.8 ± 4.7 years) volunteered for this study. An 11.5cm tourniquet was placed around participants' right proximal thigh, followed by an automated LOP measurement (207.1 ± 29.4mmHg). Doppler ultrasound was used to assess posterior tibial artery blood flow at rest, followed by 10% increments of LOP (10-90% LOP) in a randomized order. All data were collected during a single 90-minute laboratory visit. Friedman's and one-way repeated-measures ANOVAs were used to examine potential differences in vessel diameter, volumetric blood flow (VolFlow), and reduction in VolFlow relative to rest (%Rel) between relative pressures. No differences in vessel diameter were observed between rest and all relative pressures (all $p < .05$). Significant reductions from rest in VolFlow and %Rel were first observed at 50% LOP and 40% LOP, respectively. VolFlow at 80% LOP, a commonly used occlusion pressure in the legs, was not significantly different from 60% ($p = .88$), 70% ($p = .20$), or 90% ($p = 1.00$) LOP. Findings indicate a minimal threshold pressure of 50%LOP may be required to elicit a significant decrease in arterial blood flow at rest when utilizing the 11.5cm Delfi PTSII tourniquet system.

KEY WORDS: Blood flow velocity, hemodynamics, regional blood flow

INTRODUCTION

Blood flow restriction (BFR) used in conjunction with low-intensity resistance training (i.e., 20% 1RM) has shown promise in promoting muscular hypertrophy (13, 32). BFR involves the use of an inflatable tourniquet cuff or elastic wraps to restrict distal blood flow in a limb. The purpose of BFR during exercise is to reduce the arterial blood supply and eliminate venous return, leading to venous pooling. This leads to an ischemic and hypoxic muscular environment causing

high levels of metabolic stress. Increased metabolic stress during low-intensity BFR exercise is believed to be the primary moderator of hypertrophy through secondary mechanisms (26). These include elevated anabolic hormones, increased recruitment of fast-twitch muscle fibers, increased production of reactive oxygen species, and cell swelling (24, 26). These physiological responses to resistance exercise lead to improvements in muscular strength and hypertrophy through enhanced muscle protein synthesis (24).

The occlusion of blood flow is achieved through an external pressure to the limb through the application and pressurization of the tourniquet, with higher pressures restricting blood flow to a greater extent. Previous BFR research methodologies largely utilized the same arbitrary absolute pressures for all participants within a study, with tourniquet pressures ranging from 140-240 mmHg in the lower limbs and 100-160 mmHg in the upper limbs (4). This can lead to difficulties in interpreting and comparing study results, as occlusion pressure requirements can vary based on tourniquet and participant characteristics (18). Tourniquet width plays a significant role in the level of restriction achieved at a given pressure, with wider tourniquets requiring lower absolute pressures to fully occlude arterial blood flow (6, 11). Limb circumference may also affect the required pressure in the arms and legs (14), with larger limb circumferences and soft tissue thickness requiring greater pressures to occlude arterial blood flow (27). In addition, the composition and muscle thickness of the limb may also influence the amount of intramuscular pressure under the tourniquet (30).

To account for these differences, the use of personalized occlusion pressures has been recommended (18). Personalized tourniquet pressures tailored to the individual participant, reduce the variability in blood flow responses caused by tourniquet and participant characteristics. This personalized relative pressure can be based on an individualized limb occlusion pressure (LOP). LOP is the minimum pressure required to stop the flow of arterial blood into a specific limb distal to the tourniquet (18). LOP has typically been manually determined using Doppler ultrasound or estimated using existing prediction equations (18). Once LOP is determined, a personalized relative pressure based on a percentage of LOP may be used as the blood flow restriction stimulus during exercise. The use of 40-80% LOP has been recommended for use during BFR exercise (23). Higher occlusion pressures during exercise increase participant discomfort (11), using an individualized relative pressure rather than arbitrary pressures ensures the use of the lowest required pressure to achieve adequate restriction, providing a consistent occlusion stimulus and reducing participant discomfort and potential for attrition. While personalized pressures are recommended for use with BFR exercise, the blood flow response to the relative pressures needs further research. Previous studies have examined blood flow responses to relative tourniquet pressures in the legs, finding that reductions in arterial blood flow are not linear with increases in occlusion pressure (19, 21). This non-linear decrease was observed across two different tourniquet widths (10 and 12cm) when using relative pressures (21).

The Delfi Personalized Tourniquet System II (PTSII) (Delfi PTSII, Delfi Medical, Vancouver, BC, Canada) benefits from an internal pressure sensor that can determine LOP and self-regulate

relative pressures. Agreement between PTSII and the gold standard Doppler ultrasound technique for determining LOP has been previously assessed, with observed mean differences between techniques of 1 ± 8 mmHg (p = 0.14) in upper limbs and 0 ± 15 mmHg (p = 0.95) in lower limbs (16, 17). Additionally, the device provides excellent test-retest reliability across repeated LOP measurements in supine (ICC: 0.98; 95%CI [0.93–0.99]), seated (0.98; [0.93–0.99]), and standing body positions (0.95; [0.82–0.99]) (5). The use of this dual-purpose tourniquet system eliminates the need for manual LOP by Doppler ultrasound, reducing complexity and cost (17). Weatherholt et al. previously demonstrated the ability of the PTSII to achieve full blood flow occlusion in the leg, with the tourniquet cuff on the thigh, at a mean occlusion pressure of 239.4 mmHg among 30 participants, verified by ultrasound measure of blood flow in the popliteal artery (29). To date, no research has examined blood flow responses to relative pressures applied by the PTSII system. Therefore, the purpose of this study was to examine the effect of relative pressures, based on PTSII LOP, on blood flow in the leg using Doppler ultrasound to assess vessel diameter, volumetric flow, and relative flow. LOP by the PTSII is determined at rest, therefore this study sought to examine blood flow responses to restriction at rest. Relative pressures were examined in 10% increments of LOP (10-90%), in a randomized order. We hypothesized that blood flow will decrease in a non-linear fashion with increases in pressure, with increased pressure causing greater reductions in blood flow at higher pressures (i.e., 50-90%) compared to lower pressures (i.e., 10-40%). The results from this study will add to the knowledge of the PTSII and allow practitioners to more accurately make pressure recommendations to maximize BFR potential benefits while minimizing user discomfort.

METHODS

Participants

Participants were recruited via word-of-mouth advertisement and through recruitment from undergraduate kinesiology courses. The sample consisted of twenty-nine participants (65.5% female). Descriptive characteristics of the participants are presented in Table 1. Participant age ranged from 19 to 36 years (23.8±4.7 years) with 65.5% of the sample between 18-24 years. BMI ranged from 17.7 to 33.7 kg·m^{-2} (25.0±3.8 kg·m^{-2}) with 2 participants underweight, 12 normal weight, 12 overweight, and 3 obese. Relative adiposity (%Fat) ranged between 7.9 and 35.7% (23.7±8.4%). Persons were considered eligible if they were between the ages of 18 and 45 years and apparently healthy with no self-reported cardiovascular, pulmonary, and metabolic disease. Individuals with musculoskeletal injuries and current smokers were excluded from this study. Health status and participants' inclusion eligibility were assessed by the Physical Activity Readiness Questionnaire (PAR-Q+). Written informed consent was obtained from each participant prior to data collection. All study procedures were approved by the university's Institutional Review Board. This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (22).

An *a priori* power analysis was performed (G*Power, version 3.1.9.6, Universität Kiel, Germany) following one way within-subjects ANOVA recommendations (1). An effect size of f = 0.25 was determined based on 12cm tourniquet blood flow (mL·min^{-1}) data from Mouser et al. (21), using

occlusion pressures ranging from 30-60%LOP, to exclude pressure extremes. Using repeated-measures, within-factors ANOVA, effect size: $f = 0.25$, with an alpha (α) level of .05 and desired power (1-β) of 0.80 indicated a minimum sample size of 24 participants to detect a statistically significant effect. Additional participants were enrolled to account for attrition or incomplete data collection.

Table 1. Descriptive characteristics of study participants.

	All (n=29)	Female (n=19)	Male (n=10)
Age (yrs)	23.8 ± 4.7	22.8 ± 3.9	25.5 ± 5.7
Height (cm)	171.5 ± 8.2	167.4 ± 6.9	179.2 ± 8.2
Weight (kg)	73.9 ± 14.9	66.5 ± 11.1	88.1 ± 10.4
BMI ($kg \cdot m^{-2}$)	25.0 ± 3.8	23.6 ± 3.5	27.5 ± 3.3
%Fat	23.7 ± 8.4	27.4 ± 6.0	15.5 ± 7.0
LOP (mmHg)	207.1 ± 29.4	198.6 ± 24.3	223.3 ± 32.5

Data are presented as mean ± standard deviation. yrs – years; cm – centimeters; kg – kilograms; BMI - body mass index; %Fat - relative adiposity; LOP - limb occlusion pressure; mmHg - millimeters of mercury.

Protocol

A repeated-measures design was utilized to assess the blood flow response to relative pressures. The LOP was determined for each participant before assessing each relative pressure in a randomized order. Testing occurred during a single 90-minute visit in a quiet and climate-controlled laboratory (21±1°C). Participants were asked to refrain from exercise and ingestion of any caffeine for at least 12 and 4 hours, respectively, prior to reporting to the laboratory.

Demographic Characteristics: Standing height was measured without shoes to the nearest 0.1 cm with a manual stadiometer (SECA 213, Seca Ltd., Hamburg, Germany). Body mass (BM) was measured to the nearest 0.1 kg using a digital scale (Tanita BWB-800, Tanita Corporation, Tokyo, Japan). For descriptive purposes, body mass index (BMI) was calculated as BMI = weight (kg) ÷ [height (m)]^2 and reported in $kg \cdot m^{-2}$. Underweight, normal weight, overweight, and obese were categorized using thresholds of <18.5 $kg \cdot m^{-2}$, 18.5-24.9 $kg \cdot m^{-2}$, 25-29.9 $kg \cdot m^{-2}$, and ≥30 $kg \cdot m^{-2}$, respectively, for descriptive purposes (31). Relative adiposity (%Fat) was measured via 7-site skinfold assessment (Lange Skinfold Caliper, Beta Technology Inc., Cambridge, Massachusetts, USA), with body density calculated using sex specific Jackson-Pollock equations (10). Body fat (%Fat) was calculated from body density using the Siri equation: %Fat = (4.95/body density - 4.50) x 100 (28).

Resting Blood Flow and Limb Occlusion Pressure: Participants rested for five minutes in the Semi-Fowler's position (torso and head raised to 45-degree incline and feet off the ground) in a power-adjustable examination chair (Ritter 317, Midmark Corporation, Dayton, OH). All blood flow measurements were obtained using ultrasonography (Philips iU22 ultrasound Doppler imager, L9-3 transducer) and ultrasound gel (Aquasonic 100, Parker Laboratories, Inc., Fairfield, CT) at the posterior tibial artery. All ultrasound measurements, resting and relative, were taken by a single experienced examiner. After the five-minute stabilization period, a resting blood flow

measurement was obtained. The analysis of the posterior tibial artery began posterior to the medial malleus and the transducer was moved proximally until the artery walls and lumen were clearly visible and strong blood flow pattern was detected (7). The analysis site was marked with a small piece of kinesiology tape (Mueller Sports Medicine, Prairie Du Sac, WI) for consistency in measurement location.

Next, participants were outfitted with the BFR tourniquet. The participant's right upper thigh circumference (75% of the distance between the proximal border of the patella and superior anterior iliac spine) was measured with a flexible, tension-sensitive, non-elastic vinyl tape measure (Gulick, Lafayette Instrument Co. Lafayette, IN). The average of two circumference measurements was used for determining the appropriate tourniquet size. The PTSII was used with the Delfi Easi-Fit Tourniquet Cuffs (11.5 cm width). Tourniquet circumference sizes (18, 24, and 34in) were chosen based on thigh circumference for best fit, per manufacturer recommendation. The BFR tourniquet was applied as proximally as possible on the right thigh (i.e., 75% of the distance between the proximal border of the patella and superior anterior iliac spine). Next, LOP was determined using the PTSII automated system. The PTSII increases tourniquet pressure in increments of 10 mmHg and analyzes characteristics of pneumatic pressure pulsations in the tourniquet bladder caused by arterial pressure pulsations following each increase in pressure to determine LOP (17). During this time, no ultrasound measures were obtained as the device is very sensitive to movement and sound and may influence the value or cause the device to abort the measurement. Measurements obtained using the PTSII LOP are comparable to the criterion ultrasound Doppler technique for determining LOP (16, 17). Following resting blood flow and LOP measurements, the participants remained at rest in the examination chair.

Relative Pressure Measures: Following the resting blood flow analysis and LOP, relative pressures were tested. To ensure consistency between relative pressure measures, the tourniquet remained in place on the thigh while deflated and participants remained seated so that the tourniquet position did not change.

Relative pressures were calculated based on the LOP, in increments of 10%. A total of 9 relative pressures were tested: 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%. The order of relative pressure testing was randomized for each participant using a random number generator (Microsoft Excel 2016 for Windows, Microsoft Corporation, Redmond, WA). The randomization of relative pressures may account for possible time-order effects. Additionally, incrementally increasing pressure from 10% to 90% may not allow for full occlusion due to possible cardiovascular pressor responses as pressure increases (20). For each relative pressure, the tourniquet was inflated to the corresponding relative pressure for 2 minutes. A doppler blood flow analysis measure was obtained following one minute of inflation. Following the two-minute inflation time, the tourniquet was deflated for a 3-minute rest period. The 3-minute rest period was selected based on published protocols (19) and pilot data, accounting for reactive hyperemic effects following occlusion. This process was repeated until all relative pressures were tested. Vessel diameter, volumetric flow (VolFlow), and relative blood flow (%Rel) were measured at baseline and each relative pressure. Posterior tibial artery diameter (vessel

diameter) was determined using digital calipers to measure 2d distance. The calipers were placed on the lumen of the artery to measure vessel diameter in centimeters (cm). VolFlow was calculated using proprietary manufacturer software (iU22 Vision 2010; Philips, Seattle, WA, USA). VolFlow (mL·min^{-1}) was calculated automatically as: VolFlow = Time mean flow rate (cm·s^{-1}) x Lumen cross-sectional area (cm^2) (3, 12). %Rel represents the percent reduction of VolFlow relative to Rest condition and was calculated for each relative occlusion pressure. %Rel was calculated as: %Rel = ([RelativeVolFlow – RestingVolFlow] / RelativeVolFlow) x 100.

Statistical Analysis

Data were managed using Microsoft Excel for Windows (Microsoft Corporation, Redmond, WA, USA). Statistical analyses were completed using SPSS for Windows (Version 27.0, IBM, Somers, NY, USA). The independent variable was the relative occlusion pressure (10-90% LOP) utilized, while the dependent variables were vessel diameter (cm), VolFlow (mL·min^{-1}), and %Rel. Prior to statistical comparison, the assumption of normality of the studied variables was assessed using the Shapiro-Wilk test. Mauchly's test was used to test the assumption of sphericity and a Greenhouse-Geisser correction was applied when the assumption of sphericity was not met. For normally distributed data (%Rel), a parametric one-way repeated-measures ANOVA was carried out to examine potential differences between relative pressures. For data not normally distributed (VolFlow and Vessel Diameter), non-parametric Friedman's ANOVAs were carried out. Following significant findings, pairwise comparisons were used to assess differences in dependent variables between relative occlusion pressures. Bonferroni post hoc comparisons and Dunn's multiple comparison tests were used for pairwise comparisons following for parametric and non-parametric data, respectively. Statistical significance was accepted at $p<.05$. For the one-way repeated measures ANOVA, effect sizes were calculated by partial eta squared (ηp^2) and Bonferroni post hoc by Cohen's *d*. Cohen's *d* was used to describe the magnitude of the observed change in each dependent variable from resting values and calculated as the mean difference between treatment conditions (relative pressure - resting), divided by the pooled SD, such that a negative *d* indicated a decrease in the dependent variable. Kendall's *W* was used to determine effect size following Friedman's ANOVAs. Cohen's interpretation guidelines of 0.20, 0.50, and 0.80 corresponded to small, medium, and large effect sizes, respectively, were used for Cohen's *d* and Kendall's *W* (2). All data are presented as mean ± SD, unless otherwise noted.

RESULTS

Vessel Diameter: Vessel diameter ranged from 0.19 to 0.30 cm (0.23±0.02 cm) under resting conditions. When examining the potential change in vessel diameter, Friedman's ANOVA revealed no significant change in vessel diameter with increasing relative tourniquet pressure ($\chi^2_{(9)}=6.740$, $p=.664$).

Volumetric Flow: VolFlow ranged from 8.18 to 32.10 mL·min^{-1} (18.66±10.16 mL·min^{-1}) at rest. When examining the potential change in VolFlow, Friedman's ANOVA revealed a significant change in VolFlow with increasing relative tourniquet pressure ($\chi^2_{(9)}=187.030$, $p<.001$). Dunn's comparisons with Bonferonni adjustment revealed with increasing pressure, the first significant

decrease in VolFlow from rest was observed at 50%LOP (p=.03, W=0.52). Subsequent higher relative pressures were also significantly decreased from rest 60%LOP (p<.001, W=0.74), 70%LOP (p<.001, W=1.00), 80%LOP (p<.001, W=1.00) and 90%LOP (p<.001, W=1.00) (Table 2, Figure 1). 90%LOP was significantly different from all other pressures (all p<.05), except 70%LOP (p=.13) and 80%LOP (p=1.00). 70%LOP and 80%LOP were also not significantly different from 60%LOP (p=1.00, p=.88, respectively). However, VolFlow at 90%LOP was significantly less than 60%LOP (p<.001).

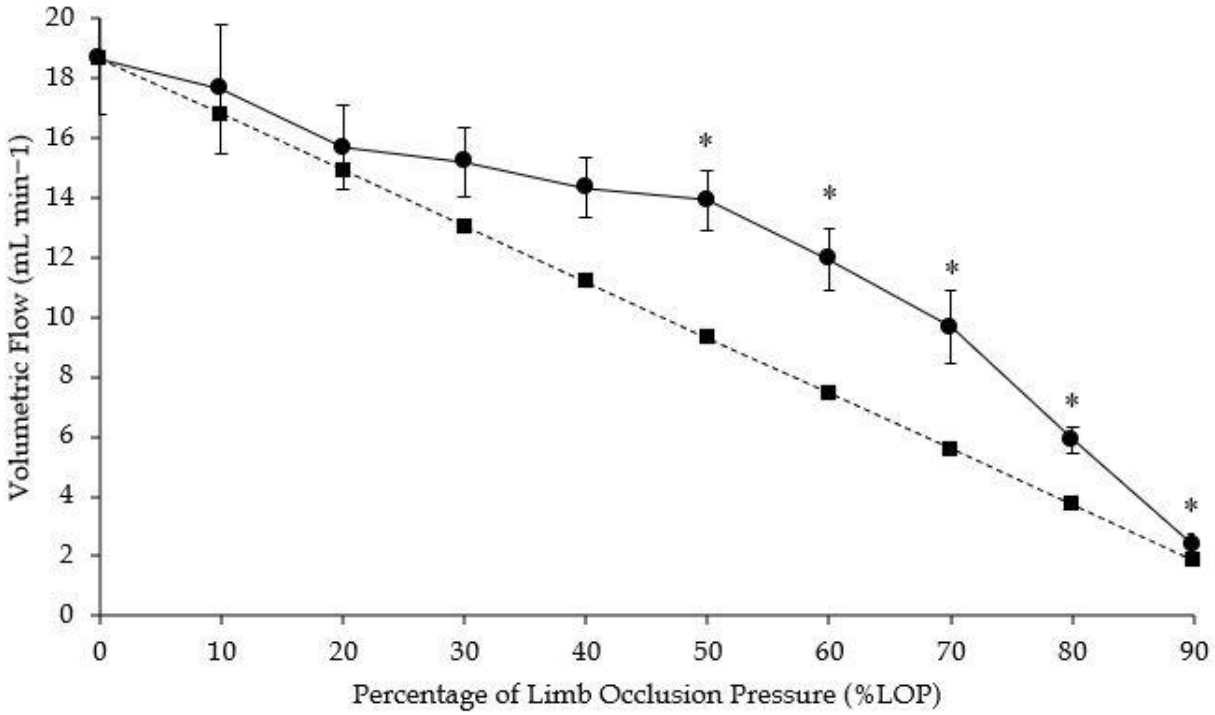

Figure 1. Changes in volumetric flow with increases in occlusion pressure. Circles represent measured mean volumetric flow. Error bars represent standard error. Squares and dashed line represent a modeled linear decrease in blood flow volume in relation to relative pressure. * significantly different from Rest.

Relative Flow: When examining the potential change in %Rel, Mauchly's test indicated that the assumption of sphericity was violated (p<.05), therefore, a Greenhouse-Geisser correction was applied. The results of the repeated measures ANOVA revealed a significant effect of relative tourniquet pressure on relative blood flow ($F_{(5.336,\ 149.405)}$=99.850, p<.001, ηp^2=.781). Post hoc comparisons with Bonferonni adjustment demonstrated statistically large reductions in relative blood flow (mean difference [95% CI]; p; Cohen's d) at 40%LOP (-17.57 [-32.24, -2.91] mL min^{-1}; p=.007 ; d=-0.81), 50%LOP (-20.31 [-35.04, -5.56] mL min^{-1}; p=.001 ; d=-0.93), 60%LOP (-32.28 [-45.68, -18.87] mL min^{-1}; p=.03 ; d=-1.63), 70%LOP (-46.85 [-60.73, -32.98] mL min^{-1}; p<.001 ; d=-2.28), 80%LOP (-63.71 [-74.32, -53.10] mL min^{-1}; p<.001 ; d=-4.05), and 90%LOP (-83.84 [-94.70, -72.98] mL min^{-1}; p<.001; d=-5.21) when compared to Rest. No significant decrease in relative flow was observed between Rest and the range of pressures up to 30%LOP (all p>.05) (Table 2).

Table 2. Blood Flow Responses to Relative Pressure

OP (%)	Tourniquet Pressure (mmHg)	VolFlow (mL·min^{-1})	Kendall's *W*	RelativeFlow (%)	Cohen's *d*
Rest	0.00 ± 2.94	18.66 ± 10.16 ^{e,f,g,h,i}		100.00 ± 0.00 ^{d,e,f,g,h,i}	
10%	20.71 ± 5.88	17.64 ± 11.64 ^{f,g,h,i}	0.27	93.29 ± 21.17 ^{f,g,h,i}	- 0.32
20%	41.42 ± 8.81	15.68 ± 7.61 ^{f,g,h,i}	0.21	88.02 ± 24.33 ^{f,g,h,i}	- 0.49
30%	62.13 ± 11.75	15.20 ± 6.22 ^{f,g,h,i}	0.20	87.51 ± 26.45 ^{f,g,h,i}	- 0.47
40%	82.84 ± 14.69	14.34 ± 5.48 ^{f,g,h,i}	0.40	82.43 ± 21.74 ^{†f,g,h,i}	- 0.81
50%	103.55 ± 17.63	13.91 ± 5.31 ^{†f,g,h,i}	0.52	79.70 ± 21.84 ^{†f,g,h,i}	- 0.93
60%	124.26 ± 20.57	11.94 ± 5.53 ^{†a,b,c,d,i}	0.74	67.72 ± 19.87 †*	- 1.63
70%	144.97 ± 23.50	9.67 ± 6.55 ^{†a,b,c,d,e}	1.00	53.15 ± 20.56 †*	- 2.28
80%	165.68 ± 23.50	5.88 ± 2.32 ^{†a,b,c,d,e}	1.00	36.29 ± 15.72 †*	- 4.05
90%	186.39 ± 26.44	2.35 ± 2.11 ^{†a,b,c,d,e,f}	1.00	16.16 ± 16.10 †*	- 5.21

Data are presented as mean ± standard deviation. LOP - limb occlusion pressure. mmHg - millimeters of mercury. VolFlow - volumetric flow. RelativeFlow - blood flow relative to resting value, † significantly different from Rest, ^{a} significantly different from 10%, ^{b} significantly different from 20%, ^{c} significantly different from 30%, ^{d} significantly different from 40%, ^{e} significantly different from 50%, ^{f} significantly different from 60%, ^{g} significantly different from 70%, ^{h} significantly different from 80%, ^{i} significantly different from 90%.

DISCUSSION

The purpose of this study was to examine blood flow responses to relative pressures applied by a common clinical BFR device, the PTSII. While the device has been validated for measuring LOP (16), to the understanding of the authors, the present current study was the first to examine the incremental reductions in blood flow volume at rest using the PTSII. Overall findings from this study support the hypothesis that there is a non-linear decrease in blood flow in the posterior tibial artery with linear increases in pressure. The non-linear decrease in blood flow demonstrates the resiliency of the vascular and circulatory systems to overcome lower occlusion pressures.

Previous literature by Iida et al. (8, 9) and Hunt et al. (6) observed linear decreases in blood flow with increases in occlusion pressure. However, these studies did not use individual LOPs and rather used incremental absolute pressures for all participants to determine changes in blood flow. While absolute pressures are still widely used in rehabilitative and research settings, personalized occlusion pressures are recommended for the increased efficacy of BFR techniques (18). In agreement with the current study, when examining blood flow responses utilizing personalized pressures, based on AOP, Mouser et al. previously demonstrated that decreases in blood flow are non-linear and not proportional to the applied relative pressure (19, 20). Only a single tourniquet width (11.5 cm) was examined in this study, but previous research findings indicate that while tourniquet widths affect LOP, varying tourniquet widths (5 cm, 10 cm, and 12 cm) all similarly occlude blood flow when using relative personalized occlusion pressures for each tourniquet width (20).

The tourniquet pressure must overcome the systolic pressure in order to occlude blood flow. Based on the findings of this study, 50%LOP using the 11.5cm tourniquet is likely the threshold for occlusion at which point the achieved compression and shear stress are able to significantly impact blood flow. At this point, a significant reduction in blood flow volume was observed and the decrease in blood flow became more linear with increases in tourniquet pressure. While no significant reduction in arterial blood flow, measured by VolFlow and %Rel, was observed at ≤ 40%LOP, the second component of BFR training relates to venous return. Previous research has indicated that venous return is occluded at lower relative pressures, 45-50mmHg, compared to arteries (9). These lower pressures may increase tissue pressure and venous occlusion but are not sufficient for occluding arterial blood supply in the legs.

While the current study did not examine blood flow response to BFR during exercise, 50%LOP was the lowest relative pressure to differ significantly from Rest, with another significant reduction in blood flow from 50% to 60%LOP. Similar responses to BFR have been observed during exercise, with the use of higher restriction pressures (≥ 60%LOP) not eliciting additional benefits compared to lower pressures in low-load resistance training (15). Reis et al. found that during 4 sets of knee extensions working at 20%1RM, 80%LOP caused no significant additional deoxygenation in the vastus lateralis compared to 60%LOP (25). Additionally, the authors suggested that 60%LOP during exercise may represent a physiological threshold for increased tissue deoxygenation and metabolite accumulation (25). While 50%LOP was the first relative pressure to show significant reductions in blood flow in the present study, 60%LOP may be more efficacious in enhancing metabolic stress during BFR exercise. Additional research is required examining blood flow responses to occlusion during exercise, which may show higher blood flow at each occlusion pressure.

While the strength of the current study is bolstered by systematically assessing the changes in blood flow across a wide range of LOP in a relatively large sample of young adult male and female participants, it is not without potential limitations. First, all blood flow measurements were obtained at rest. The hyperemic response to working skeletal muscles during exercise may cause a dissimilar reduction in blood flow to relative pressures, with greater blood flow during exercise compared to rest at the same occlusion pressure. Therefore, the findings of this study do not apply to blood flow during BFR exercise. Secondly, the findings of the current study may not be generalizable to clinical populations or individuals outside the age range of 18-45 years. Additionally, all measurements were taken in a Semi-Fowler's position, rather than seated or standing which would more closely mimic the body position during BFR exercise or research protocols. While the Semi-Fowler position is commonly used in clinical settings and was chosen with participant comfort in mind, seated and standing positions require higher LOPs (5) and may respond differently to incremental changes in relative pressures. While the findings of the current study are novel for the PTSII, future research should examine blood flow responses to varying pressures during exercise using the device to determine the optimal BFR pressures for enhanced BFR exercise. Additionally, further research is required to examine the effect of postural changes on relative blood flow responses.

The findings of the current study indicate the potential utility of lower restriction pressure in the lower limbs (i.e., 60% or 70%LOP) compared to the frequently used 80%LOP while achieving similar arterial blood flow reductions. Practitioners and researchers may benefit from using lower restriction pressure in the lower limbs (i.e., 60% or 70%LOP) while eliciting similar occlusion effects.

ACKNOWLEDGEMENTS

The authors would like to thank the participants for their time and participation.

REFERENCES

1. Beck TW. The importance of a priori sample size estimation in strength and conditioning research. J Strength Cond Res 27(8): 2323-2337, 2013.

2. Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale, NJ: Lawrence Erlbaum Associates; 1988.

3. Evans DH, Jensen JA, Nielsen MB. Ultrasonic colour doppler imaging. Interface focus 1(4): 490-502, 2011.

4. Fahs CA, Loenneke JP, Rossow LM, Tiebaud RS, Bemben MG. Methodological considerations for blood flow restricted resistance exercise. J Trainology 1(1): 14-22, 2012.

5. Hughes L, Jeffries O, Waldron M, Rosenblatt B, Gissane C, Paton B, Patterson SD. Influence and reliability of lower-limb arterial occlusion pressure at different body positions. PeerJ 6: e4697, 2018.

6. Hunt JE, Stodart C, Ferguson RA. The influence of participant characteristics on the relationship between cuff pressure and level of blood flow restriction. Eur J Appl Physiol 116(7): 1421-1432, 2016.

7. Hwang JY. Doppler ultrasonography of the lower extremity arteries: Anatomy and scanning guidelines. Ultrasonography (Seoul, Korea) 36(2): 111-119, 2017.

8. Iida H, Kurano M, Takano H, Kubota N, Morita T, Meguro K, Sato Y, Abe T, Yamazaki Y, Uno K, Takenaka K, Hirose K, Nakajima T. Hemodynamic and neurohumoral responses to the restriction of femoral blood flow by kaatsu in healthy subjects. Eur J Appl Physiol 100(3): 275-285, 2007.

9. Iida H, Takano H, Meguro K, Asada K, Oonuma H, Morita T, Kurano M, Sakagami F, Uno K, Hirose K, Nagata T, Takenaka K, Suzuki J, Hirata Y, Furuichi T, Eto F, Nagai R, Sato Y, Nakajima T. Hemodynamic and autonomic nervous responses to the restriction of femoral blood flow by kaatsu. Int J Kaatsu Train Res 1(2): 57-64, 2005.

10. Jackson AS, Pollock ML. Practical assessment of body composition. Phys Sportsmed 13(5): 76-90, 1985.

11. Jessee MB, Buckner SL, Dankel SJ, Counts BR, Abe T, Loenneke JP. The influence of cuff width, sex, and race on arterial occlusion: Implications for blood flow restriction research. Sports Med 46(6): 913-921, 2016.

12. Jia S, Wu Y, Wang W, Lin W, Chen Y, Zhang H, Xia S, Zhou H. An exploratory study on the relationship between brachial arterial blood flow and cardiac output. J Healthc Eng 2021: 1251199, 2021.

13. Lixandrão ME, Ugrinowitsch C, Berton R, Vechin FC, Conceição MS, Damas F, Libardi CA, Roschel H. Magnitude of muscle strength and mass adaptations between high-load resistance training versus low-load resistance training associated with blood-flow restriction: A systematic review and meta-analysis. Sports Med 48(2): 361-378, 2018.

14. Loenneke JP, Allen KM, Mouser JG, Thiebaud RS, Kim D, Abe T, Bemben MG. Blood flow restriction in the upper and lower limbs is predicted by limb circumference and systolic blood pressure. Eur J Appl Physiol 115(2): 397-405, 2015.

15. Loenneke JP, Kim D, Fahs CA, Thiebaud RS, Abe T, Larson RD, Bemben DA, Bemben MG. Effects of exercise with and without different degrees of blood flow restriction on torque and muscle activation. Muscle Nerve 51(5): 713-721, 2015.

16. Masri BA, Day B, Younger AS, Jeyasurya J. Technique for measuring limb occlusion pressure that facilitates personalized tourniquet systems: A randomized trial. J Med Biol Eng 36(5): 644-650, 2016.

17. McEwen J, Masri B, Day B, Younger A. Development of personalized tourniquet systems using a new technique for measuring limb occlusion pressure. IFMBE Proceedings 51: 1325-1328, 2015.

18. McEwen JA, Owens JG, Jeyasurya J. Why is it crucial to use personalized occlusion pressures in blood flow restriction (bfr) rehabilitation? J Med Biol Eng 39(2): 173-177, 2018.

19. Mouser JG, Ade CJ, Black CD, Bemben DA, Bemben MG. Brachial blood flow under relative levels of blood flow restriction is decreased in a nonlinear fashion. Clin Physiol Funct Imaging 38(3): 425-430, 2018.

20. Mouser JG, Dankel SJ, Jessee MB, Mattocks KT, Buckner SL, Counts BR, Loenneke JP. A tale of three cuffs: The hemodynamics of blood flow restriction. Eur J Appl Physiol 117(7): 1493-1499, 2017.

21. Mouser JG, Dankel SJ, Mattocks KT, Jessee MB, Buckner SL, Abe T, Loenneke JP. Blood flow restriction and cuff width: Effect on blood flow in the legs. Clin Physiol Funct Imaging 38(6): 944-948, 2018.

22. Navalta JW, Stone WJ, Lyons TS. Ethical issues relating to scientific discovery in exercise science. Int J Exerc Sci 12(1): 1-8, 2019.

23. Patterson SD, Hughes L, Warmington S, Burr J, Scott BR, Owens J, Abe T, Nielsen JL, Libardi CA, Laurentino G, Neto GR, Brandner C, Martin-Hernandez J, Loenneke J. Blood flow restriction exercise: Considerations of methodology, application, and safety. Front Physiol 10: 533, 2019.

24. Pearson SJ, Hussain SR. A review on the mechanisms of blood-flow restriction resistance training-induced muscle hypertrophy. Sports Med 45(2): 187-200, 2015.

25. Reis JF, Fatela P, Mendonca GV, Vaz JR, Valamatos MJ, Infante J, Mil-Homens P, Alves FB. Tissue oxygenation in response to different relative levels of blood-flow restricted exercise. Front Physiol 10(407): 407, 2019.

26. Schoenfeld BJ. Potential mechanisms for a role of metabolic stress in hypertrophic adaptations to resistance training. Sports Med 43(3): 179-194, 2013.

27. Shaw JA, Murray DG. The relationship between tourniquet pressure and underlying soft-tissue pressure in the thigh. J Bone Joint Surg Am 64(8): 1148-1152, 1982.

28. Siri WE. The gross composition of the body. Adv Biol Med Phys 4: 239-280, 1956.

29. Weatherholt AM, Vanwye WR, Lohmann J, Owens JG. The effect of cuff width for determining limb occlusion pressure: A comparison of blood flow restriction devices. Int J Exerc Sci 12(3): 136-143, 2019.

30. Wernbom M, Augustsson J, Thomee R. Effects of vascular occlusion on muscular endurance in dynamic knee extension exercise at different submaximal loads. J Strength Cond Res 20(2): 372-377, 2006.

31. WHO. Obesity: Preventing and managing the global epidemic. Report of a who consultation. World Health Organ Tech Rep Ser 894: i-xii, 1-253, 2000.

32. Yasuda T, Ogasawara R, Sakamaki M, Ozaki H, Sato Y, Abe T. Combined effects of low-intensity blood flow restriction training and high-intensity resistance training on muscle strength and size. Eur J Appl Physiol 111(10): 2525-2533, 2011.