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Unilateral bicep curl hemodynamics: Low-pressure continuous vs high-pressure intermittent blood flow restriction

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Light-load exercise training with blood flow restriction (BFR) increases muscle strength and size. However, the hemodynamics of BFR exercise appear elevated compared with non-BFR exercise. This questions the suitability of BFR in special/clinical populations. Nevertheless, hemodynamics of standard prescription protocols for BFR and traditional heavy-load exercise have not been compared. We investigated the hemodynamics of two common BFR exercise methods and two traditional resistance exercises. Twelve young males completed four unilateral elbow flexion exercise trials in a balanced, randomized crossover design: (a) heavy load [HL; 80% one-repetition maximum (1-RM)]; (b) light load (LL; 20% 1-RM); and two other light-load trials with BFR applied (c) continuously at 80% resting systolic blood pressure (BFR-C) or (d) intermittently at 130% resting systolic blood pressure (BFR-I). Hemodynamics were measured at baseline, during exercise, and for 60-min post-exercise. Exercising heart rate, blood pressure, cardiac output, and rate–pressure product were significantly greater for HL and BFR-I compared with LL. The magnitude of hemodynamic stress for BFR-C was between that of HL and LL. These data show reduced hemodynamics for continuous low-pressure BFR exercise compared with intermittent high-pressure BFR in young healthy populations. BFR remains a potentially viable method to improve muscle mass and strength in special/clinical populations.

Exercise training with light loads [20–30% one-repetition maximum (1-RM)] in combination with blood flow restriction (BFR) develops both muscle strength and muscle size over that of light-load resistance exercise (LLRE) training without BFR (Abe et al., 2012; Fahs et al., 2012; Loenneke et al., 2012a). These improvements have also been shown to be equivalent to those achieved with traditional training using heavy-load resistance exercise (HLRE; > 65% 1-RM) (Takarada et al., 2000; Clark et al., 2011; Karabulut et al., 2011; Laurentino et al., 2012; Thiebaud et al., 2013). Consequently, due to the lower mechanical stress on the musculo-skeletal system LLRE with BFR may provide a training method for potential use by some clinical and elderly populations where HLRE is not possible or not recommended (Takarada et al., 2000; Karabulut et al., 2010, 2011; Vieira et al., 2013). With this in mind, and despite the effects of BFR exercise training on increasing muscle strength, size, and endurance being well founded (Abe et al., 2012; Pope et al., 2013), it is important to identify the hemodynamic effects of BFR exercise to further establish and support its safe application prior to making any recommendations for prescription in populations where HLRE may be contraindicated. Of importance is the method by which BFR may be applied. Techniques vary with respect to factors such as the type of restrictive cuff (size and material), and the magnitude, timing, and duration of the applied restriction (Fahs et al., 2012; Loenneke et al., 2012a, 2013a,b). Therefore, it is important to examine the hemodynamic responses to different methods of BFR application in order to evaluate the parameters that limit hemodynamic stress, and as a consequence would seem most suitable for guiding prescription in *at-risk* populations.

BFR is most commonly applied continuously throughout an entire exercise bout including the rest periods (Hollander et al., 2010; Karabulut et al., 2010; Patterson & Ferguson, 2010; Clark et al., 2011). An alternative is to apply an intermittent restriction whereby cuff deflation occurs during the inter-set rest periods (Cook et al., 2007; Laurentino et al., 2008; Evans et al., 2010; Kacin & Strazar, 2011). We previously observed (unpublished) that unilateral elbow flexion exercise (20% 1-RM) using a relatively wide cuff (14 cm) was not well tolerated by participants, with most being unable to complete the exercise requirements when BFR was applied continuously using pressures equal or greater than resting systolic blood pressure (SBP;

~120 mmHg). In contrast, all participants were able to complete the exercise during intermittent application of the restriction, and this was despite the use of higher pressures up to the maximum pressure tested (130% of SBP; ~155 mmHg). Although individualized selection of restriction pressures may be preferential (Loenneke et al., 2012a, 2013a; Downs et al., 2014), and albeit also dependent on cuff width (Rossow et al., 2012), it appears that when using relatively wide cuffs for continuous BFR exercise that low pressures should be used (< SBP; i.e., 90–100 mmHg), whereas higher pressures (≥ SBP; i.e., 150–160 mmHg) could be used during intermittent application.

Although the chronic muscular adaptations (increased muscle strength and size) to BFR exercise have been characterized (Wernbom et al., 2008; Loenneke et al., 2012b; Pope et al., 2013), the acute hemodynamic responses are less well understood but appear moderately elevated when compared with LLRE (Takano et al., 2005; Hollander et al., 2010; Patterson & Ferguson, 2010; Vieira et al., 2013). Cardiac output $(\dot{Q})$ is similar between load-matched BFR and non-BFR LLRE, yet is derived from an elevated heart rate (HR) combined with a reduced stroke volume (SV) and venous return during BFR exercise (Takano et al., 2005). In addition, mean arterial pressure (MAP) and SBP during BFR exercise appear elevated in comparison with non-BFR LLRE (Takano et al., 2005). However, attempts to characterize the acute hemodynamics during standard BFR exercise methods have typically only compared BFR with non-BFR during LLRE (Takano et al., 2005; Patterson & Ferguson, 2010; Vieira et al., 2013), with no direct comparisons between BFR, LLRE, and HLRE in the same participant group. This is despite recent reports where measures were taken pre-exercise but only as early as 15-min (Fahs et al., 2011) and 30-min post-exercise (Rossow et al., 2011). Recently, Downs et al. (2014) showed that for fatiguing exercise the immediate post-exercise (within 90 s) HR, $\dot{Q}$, and SV were greater during HLRE and LLRE (leg press and plantar flexion) when compared with both high- and low-pressure BFR exercise. Conversely, and of some concern, both SBP and diastolic blood pressure (DBP) were higher during BFR exercise (range: 140–156 and 67–80 mmHg for SBP and DBP, respectively) compared with HLRE (134 ± 4 and 58 ± 3 mmHg for SBP and DBP, respectively) and LLRE (127 ± 4 and 57 ± 3 mmHg for SBP and DBP, respectively). However, these data seem largely complicated by the exercise being undertaken to failure, such that less work was performed during the BFR exercise than during a typical BFR protocol where sets comprise an initial 30 contractions followed by three sets of 15 repetitions (Fahs et al., 2012). Despite being the first study to compare the hemodynamic responses between continuous high- and low-pressure BFR and more traditional resistance exercise methods, to our knowledge no study has assessed the hemodynamic responses between continuous and intermittent BFR. Moreover, no study has assessed these responses during upper body resistance exercise.

Therefore, the purpose of this study was to compare the acute hemodynamic responses to unilateral bicep curl BFR exercise with both HLRE and LLRE in the same young healthy participants. In addition, we also compared two methods to conduct BFR exercise (continuous low-pressure and intermittent high-pressure BFR application). It was hypothesized that the hemodynamic stress of unilateral elbow flexion would be greatest with HLRE, lowest with LLRE, with responses to BFR exercise residing between these two more traditional forms of exercise. It was also expected that the intermittent high-pressure application of BFR during exercise would induce a greater elevation in hemodynamic stress in comparison with continuous low-pressure BFR, due to the higher cuff pressure.

Methods

Participants

Twelve ($n = 12$) recreationally active male participants volunteered to participate in the study [mean ± standard deviation (SD); 23 ± 3 years; 179.9 ± 7.5 cm; 72.6 ± 8.2 kg]. None had involvement in any resistance training in the previous 6 months. Participants completed a medical prescreening via questionnaire and provided written informed consent prior to entry into the study. Exclusion criteria included any known cardiovascular disease or musculo-skeletal impairments that may hinder ability to perform resistance exercise and those taking prescribed medications for cardiovascular/blood pressure control. In addition, participants attended the laboratory at the same time of day to avoid any diurnal influences and refrained from exercise, caffeine, and alcohol consumption 12 h before data collection. This study was approved by the Human Research Ethics Committee, Deakin University.

Experimental design

Participants completed an initial familiarization session that comprised an assessment of maximal voluntary dynamic strength of the elbow flexors (1-RM), and measurement of resting hemodynamics. Following this, participants attended the laboratory on four separate occasions separated by at least 7 days to complete the exercise trials in a balanced, randomized crossover design. Trials were (a) heavy load resistance exercise (HL; 80% 1-RM); (b) light-load resistance exercise (LL; 20% 1-RM); (c) LLRE with a continuous low-pressure BFR (BFR-C; 20% 1-RM); (d) LLRE with an intermittent high-pressure BFR (BFR-I) (Table 1). For BFR-C, cuff pressure was applied continuously throughout the duration of the exercise bout including inter-set recovery periods. For BFR-I, cuff pressure was applied intermittently during exercise only, with the cuff inflated prior to every set and released immediately after the final repetition of each set (Suga et al., 2012). Hemodynamic responses for each trial were measured at rest prior to exercise (baseline), during exercise (set 2 and set 4), and at 5, 20, 40, and 60-min post-exercise. All exercise was performed while standing and used only the dominant limb.

Exercise trials

In all trials participants performed supervised unilateral elbow flexion/extension exercise (i.e., a standard series of dumbbell

Table 1. Maximum strength (1-RM) and exercising workload characteristics for each trial (mean ± SD)

Trial	1-RM	Load (kg)	Sets (reps)	Restriction pressure	
				(%SBP)	(mmHg)
1-RM	17.7 ± 2.3 kg				
HL	80%	14.2 ± 1.8	4 (6–8)		
LL	20%	3.6 ± 0.5	4 (30, 15, 15, 15)		
BFR-C	20%	3.6 ± 0.5	4 (30, 15, 15, 15)	80	91 ± 2
BFR-I	20%	3.6 ± 0.5	4 (30, 15, 15, 15)	130	151 ± 4

1-RM, one-repetition maximum; BFR-C, continuous blood flow restriction; BFR-I, intermittent blood flow restriction; HL, heavy load; LL, light load; SBP, systolic blood pressure; SD, standard deviation.

bicep curls) to a repetition timing monitored by a metronome (2-s concentric; 2-s eccentric). The sets/reps regimen for all trials was according to standard protocols to conduct each type of exercise (Fahs et al., 2012). For HL, participants completed four sets (six to eight repetitions; 80% 1-RM) with 2.5-min rest between sets. For LL, BFR-C, and BFR-I, participants completed a set of 30 repetitions followed by three sets of 15 repetitions (20% 1-RM) with 30-s rest between sets. The total time to complete HL was 9 min, whereas all other trials were 6.5 min. The average relative work of exercise (total reps × relative load; i.e., 0.2 for 20% 1-RM and 0.8 for 80% 1-RM; mean ± SD) was 23 ± 3 for HL, which was approximately 1.5-fold greater when compared with all other trials (15 ± 0 for LL; 15 ± 1 for both BFR-C and BFR-I).

Maximal voluntary elbow flexor strength

To establish the exercising load used during each trial, participants performed a standard unilateral elbow flexion 1-RM test as previously described (Munn et al., 2005). Briefly, a starting weight was chosen based on participant-estimated strength. With elbow in full extension, forearm supinated, and the opposite arm placed behind the back while standing against a wall to prevent excessive body movement, participants performed elbow flexion (bicep curl) to lift the dumbbell. Single repetition lifts were conducted with progressively heavier loads until failure, which was defined as the final load that could be successfully lifted with correct technique where an additional 0.5 kg could not be successfully lifted. Rest intervals between 1-RM attempts were dependent on participant readiness but ranged from 2 to 5 min, while not more than four repetitions were completed during any test. If further repetitions were required, participants attended a subsequent testing session 3–7 days later to continue the assessment.

BFR protocol

For both BFR trials (BFR-C and BFR-I), participants wore a pneumatic cuff (52-cm long, 10.5-cm wide; bladder length 45 cm, bladder width 8 cm) around the most proximal portion of the arm, connected to an automatic tourniquet system (A.T.S. 3000, Zimmer Inc., Dover, Ohio, USA). With the participant standing, cuff pressure was set to 50 mmHg for 30 s, then released for 10 s. This cycle was repeated with an additional 20 mmHg on each inflation until reaching the final exercise pressure for BFR-C (80% resting SBP; 91 ± 2 mmHg) and BFR-I (130% SBP; 151 ± 4 mmHg). For BFR-I only, the cuff was completely deflated (i.e., 0 mmHg) during the rest periods between sets. This deflation was performed to improve participant comfort and tolerance, and is a method of BFR application used previously (Wernbom et al., 2006; Cook et al., 2007; Kacin & Strazar, 2011; Suga et al., 2012).

Measurement of cardiac and hemodynamic parameters

During each trial, participants wore a facemask connected to an online metabolic system (Innocor, Innovision A/S, Odense, Denmark) to enable measurement of $\dot{Q}$ via an inert gas re-breathing technique as previously described (Jakovljevic et al., 2008; Fontana et al., 2010). HR was recorded continuously via a standard chest strap and watch (FT1, Polar Electro, Kempele, Finland). SV was subsequently derived as the quotient of $\dot{Q}$ and HR. Blood pressures (SBP, DBP) were measured on the non-exercised arm via manual auscultation using a handheld sphygmomanometer (8-cm cuff width, 54-cm cuff length) and stethoscope. At baseline and 20, 40, and 60-min post-exercise, the average blood pressure was recorded from two measurements separated by 1–2 min. If these were > 5 mmHg apart for SBP, another measure was included in the recorded average (Pickering et al., 2005). Multiple measurements of blood pressure were not taken during exercise (set 2 and set 4) due to the time constraints of the exercise protocol, or at 5-min post-exercise due to the expectation that blood pressure may be falling. The same experienced researcher performed all blood pressure measurements. Average coefficients of variation (CV) for test–retest reliability of blood pressures taken at baseline for each participant's first and second trial were 5.7% for SBP and 13.4% for DBP. MAP was estimated according the methods of Moran et al. (1995) with test–retest reliability CV of 8.9%. Total peripheral resistance (TPR) and rate–pressure product (RPP) were also subsequently derived (Nelson et al., 1974).

To minimize any effect of changing abdominal pressures throughout the exercise repetitions (i.e., Valsalva maneuver) on both $\dot{Q}$ and blood pressure, participants were instructed to inspire throughout the eccentric phase and expire throughout the concentric phase to enable maintenance of a constant breathing rate (15 breaths/min) as monitored by a metronome.

Statistical analysis

A split-plot in time, repeated measures analysis of variance was used to compare the hemodynamic responses for trial (HL, LL, BFR-C, and BFR-I) by time (baseline, set 2, set 4, and 5, 20, 40, and 60-min post-exercise). Where significant interactions were observed, a univariate post-hoc analysis (Tukey's) for pairwise comparisons was performed. Alpha was set at $P < 0.05$. Unless otherwise stated, all data are displayed as mean ± standard error of the mean.

Results

Mean elbow flexor strength is displayed in Table 1, along with the average exercising load for each trial.

Hemodynamic variables

All hemodynamic measures (HR, blood pressures, $\dot{Q}$) were not different at baseline between trials. In addition, all hemodynamic variables returned to baseline within 5 min upon completion of each trial.

Cardiac parameters

HR increased from baseline during exercise in all trials (Fig. 1(a); $P < 0.0001$). This increase was greatest in HL and BFR-I compared with both LL and BFR-C during set 2 ($P < 0.0001$). During set 4, HR was also higher during HL compared with both LL and BFR-C ($P > 0.0001$), while also being greater during BFR-I compared with LL ($P < 0.01$) but not BFR-C.

$\dot{Q}$ increased from baseline during exercise in all trials (Fig. 1(b); $P < 0.0001$) and was similar between HL, BFR-C, and BFR-I during set 2 and set 4. This increase was greatest in HL compared with all other trials at set 2 ($P < 0.0001$) and set 4 ($P < 0.01$), with no differences observed between LL, BFR-I, and BFR-C.

SV remained unchanged from baseline, and throughout exercise and recovery in all trials, although during HL SV tended to increase from baseline to set 2 ($P < 0.08$) (Fig. 1(c)).

Blood pressures

Blood pressures (SBP, DBP, MAP) all increased from baseline to exercise in all trials ($P < 0.0001$), and returned to baseline again within 5 min upon completion of exercise (Fig. 2). SBP was higher in HL and BFR-I compared with both BFR-C and LL during set 2 ($P < 0.01$), and tended to be higher for BFR-C compared with LL ($P < 0.09$). SBP increased from set 2 to set 4 for BFR-C ($P < 0.01$). Therefore, SBP during set 4 was lower in LL compared with all other trials ($P < 0.01$).

DBP during set 2 was higher in HL and BFR-I compared with LL only ($P < 0.01$), but was not different between any other trials. While during set 4, the increase in DBP from baseline was higher for BFR-I compared with LL only ($P < 0.01$).

MAP during set 2 was higher in HL and BFR-I compared with both BFR-C ($P < 0.05$) and LL ($P < 0.001$). During set 4 MAP remained elevated for HL ($P < 0.05$) and BFR-I ($P < 0.001$) compared with LL, and tended to be higher for BFR-C compared with LL ($P < 0.06$).

TPR and RPP

There was a significant time-by-trial interaction ($P < 0.0001$) such that TPR was lower in HL than all other trials at set 2 ($P < 0.05$) (Table 2). No differences were evident between trials at any other time point. TPR increased from baseline to set 4 in BFR-I ($P < 0.05$), and also tended to increase for BFR-C ($P = 0.06$) and LL ($P = 0.054$), while then being significantly elevated from baseline in LL at 5-min post-exercise ($P < 0.01$). No other differences were evident across time within trials.

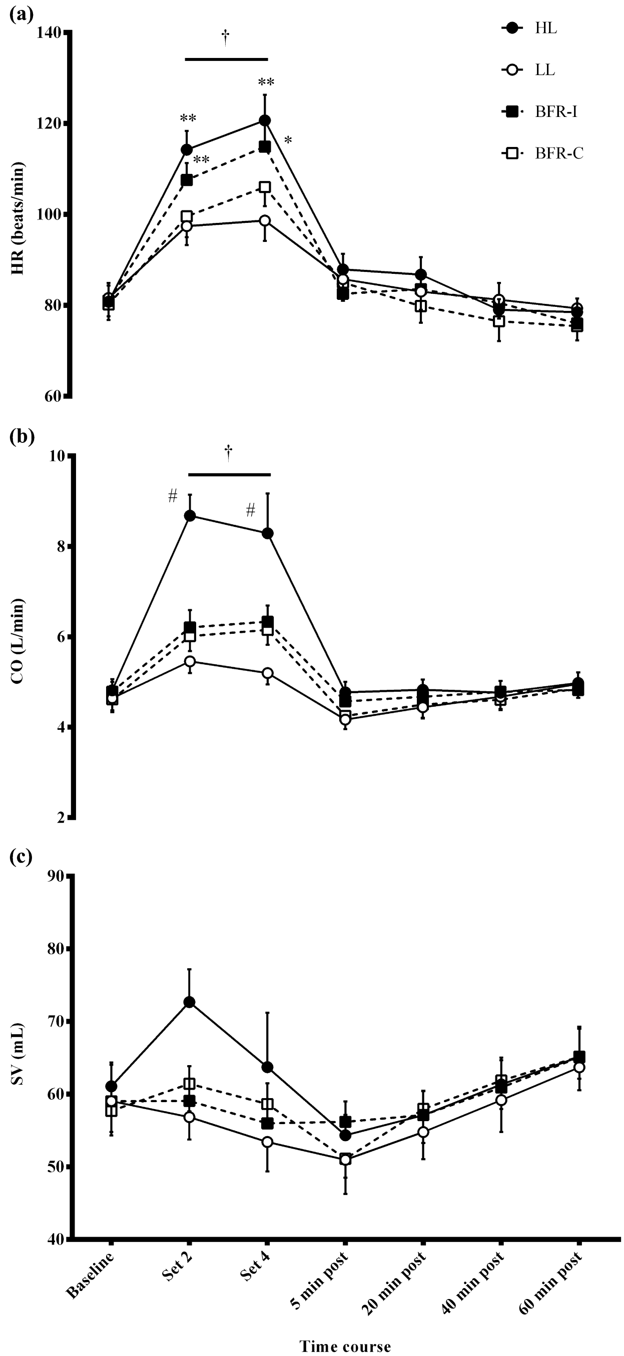

Fig. 1. Heart rate (a), cardiac output (b), and stroke volume (c) during all four trials [heavy load (HL), light load (LL), intermittent blood flow restriction (BFR-I), continuous BFR (BFR-C)]. †$P < 0.01$ vs baseline and all post-exercise measurements. #$P < 0.05$ vs all other trials. *$P < 0.01$ vs LL. **$P < 0.05$ vs LL and BFR-C. DBP, diastolic blood pressure; MAP, mean arterial pressure; SBP, systolic blood pressure.

There was also a significant time-by-trial interaction such that RPP increased from baseline during exercise (set 2 and set 4) in all trials ($P < 0.0001$) (Table 2). For set 2, RPP was greater in HL compared with LL ($P < 0.01$) and tended to be greater than BFR-C

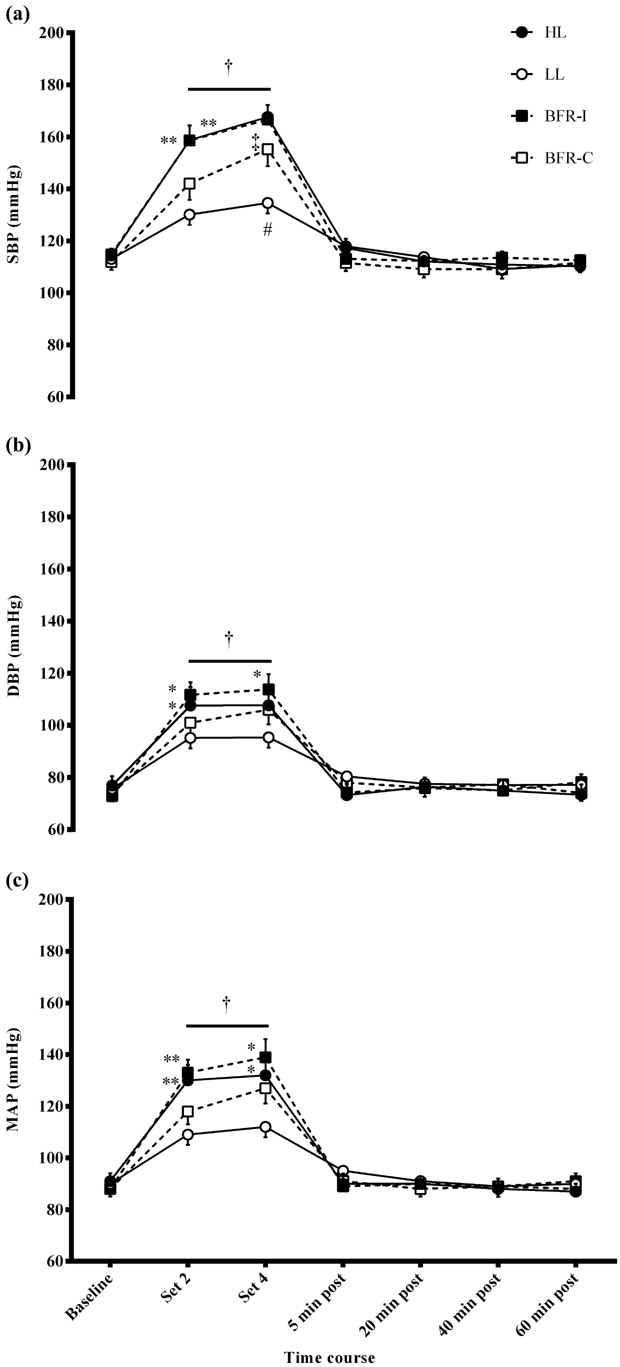

Fig. 2. Systolic (a), diastolic (b), and mean arterial (c) blood pressure responses during all four trials [heavy load (HL), light load (LL), intermittent blood flow restriction (BFR-I), continuous BFR (BFR-C)]. †$P < 0.01$ vs baseline and all post-exercise measurements. ‡$P < 0.02$ vs set 2. #$P < 0.02$ vs all other trials. *$P < 0.05$ vs LL. **$P < 0.05$ vs LL and BFR-C. CO, cardiac output; HR, heart rate; SV, stroke volume.

($P < 0.09$), but was not different from BFR-I. In addition, at set 2 RPP was higher in BFR-C and BFR-I compared with LL ($P < 0.05$). Interestingly, at set 4 RPP was similar between HL, BFR-C, and BFR-I, which were all greater than LL ($P < 0.05$).

Table 2. Total peripheral resistance (TPR) and rate pressure product (RPP) responses during all four trials (HL, LL, BFR-C, and BFR-I)

	HL	LL	BFR-C	BFR-I
TPR (% baseline)				
Baseline	100	100	100	100
Set 2	84 ± 2†	104 ± 1	106 ± 1	114 ± 1
Set 4	74 ± 5	115 ± 1	117 ± 1	124 ± 4*
5-min post	103 ± 1	118 ± 1*	112 ± 1	108 ± 1
20-min post	101 ± 1	107 ± 1	105 ± 1	104 ± 1
40-min post	101 ± 1	99 ± 1	100 ± 1	102 ± 0
60-min post	94 ± 1	93 ± 1	95 ± 1	103 ± 1
RPP (% baseline)				
Baseline	100	100	100	100
Set 2	186 ± 15*‡	138 ± 5*	156 ± 6*	185 ± 7*‡
Set 4	217 ± 16*‡	142 ± 5*†	187 ± 8*	204 ± 12*
5-min post	111 ± 3	110 ± 4	106 ± 4	101 ± 4
20-min post	104 ± 3	103 ± 3	97 ± 3	101 ± 3
40-min post	95 ± 3	96 ± 3	93 ± 3	98 ± 12
60-min post	93 ± 3	95 ± 3	94 ± 2	93 ± 2

*$P < 0.01$ vs baseline and all post-exercise measurements.
†$P < 0.05$ vs all other trials.
‡$P < 0.05$ vs LL.
BFR-C, continuous blood flow restriction; BFR-I, intermittent blood flow restriction; HL, heavy load; LL, light load.

Discussion

The present study examined the acute hemodynamic responses to BFR exercise in comparison with more traditional resistance exercise techniques, while also examining these responses under different methods of BFR application (continuous low-pressure BFR vs intermittent high-pressure BFR). The major findings showed HR, blood pressures, $\dot{Q}$, and RPP to be significantly greater during HL and BFR-I, in comparison with LL, while the magnitude of the hemodynamic responses during BFR-C resided between HL/BFR-I and LL. Following exercise we also observed a rapid return to baseline of all hemodynamic variables independent of trial, which suggests that there is no persistent effect of BFR on autonomic control of hemodynamics. These results support our hypothesis and suggest that in order to limit the hemodynamic stress during light-load (20% 1-RM) exercise in combination with BFR, continuous low-pressure application is preferential to intermittent high-pressure application.

The present study directly compared the hemodynamic responses to BFR exercise with both HLRE and LLRE. It is of particular interest to compare against HLRE because light-load BFR exercise has been suggested as an alternative to HLRE when used chronically over a period of training to develop muscle strength and increase muscle mass (Takarada et al., 2000; Wernbom et al., 2008; Clark et al., 2011; Karabulut et al., 2011). During HLRE the magnitude of the increase in blood pressure is substantial (MacDougall et al., 1985; Fleck, 2008). MAP would be expected to rise to ~200 mmHg during a single set of elbow flexion exercise at 95% 1-RM (MacDougall et al., 1985), and to even greater levels during unilateral or bilateral leg press exercise (> 250 mmHg) (MacDougall et al., 1985). Investigations of BFR exercise have also reported significant elevations in blood pressure when compared with resting values (Takano et al., 2005; Renzi et al., 2010; Downs et al., 2014). However, rarely have comparisons been made with responses to HLRE in the same participants. Therefore, a novel element of the present study was that the blood pressure responses during HL, and also during BFR-I, were elevated to a larger extent compared with LL. These are similar to previous observations where HR and blood pressure were elevated with BFR when compared with non-BFR LLRE (Takano et al., 2005; Downs et al., 2014). However, with continuous low-pressure restriction in the present study (BFR-C), these elevations in blood pressure were attenuated (Fig. 2). In contrast, Downs et al. (2014) showed both SBP and DBP to be higher during lower body resistance exercise with continuous BFR compared with both LLRE and, interestingly, HLRE. However, it is important to note that these participants exercised to failure, rather than the somewhat standard sets/reps regimen conducted in the present study.

Although $\dot{Q}$ increased during exercise in all trials, it was greatest during HL, and was not different between LL, BFR-I, and BFR-C. These findings are consistent with previous observations where $\dot{Q}$ increased to a similar extent with both BFR and LLRE (Takano et al., 2005). In contrast, Downs et al. (2014) showed the increase in $\dot{Q}$ be greatest with HLRE as well as LLRE when compared with BFR exercise, while only low-pressure BFR exercise increased $\dot{Q}$ and not high-pressure BFR exercise (Downs et al., 2014). Again, these contrasting results are likely explained by the exercise being to fatigue (Downs et al., 2014) rather than a less fatiguing BFR training regimen (Takano et al., 2005).

Although SV is expected to decline during BFR exercise due to the reduction in venous return (Takano et al., 2005; Ozaki et al., 2010; Renzi et al., 2010), it is interesting that we found no change in SV during either BFR-C or BFR-I. The absence of a reduction in SV does not appear to be related to the applied pressure given the similar response in both BFR-C and BFR-I, and so may be related to the use of a single limb and small muscle group, whereby no change in SV was also evident for both HL and LL trials. Therefore, under these conditions the increase in $\dot{Q}$ during BFR appears largely driven by the increase in HR and TPR, but not SV.

Although there is no standard method for the application of BFR during exercise, in the present study we sought to compare the acute hemodynamic responses between continuous low-pressure and intermittent high-pressure BFR exercise. Our data demonstrate that a high-pressure restriction applied during exercise only (BFR-I, 130% SBP; 151 ± 4 mmHg) generally produced a greater elevation in a number of hemodynamic variables in comparison with a low-pressure restriction applied continuously throughout a whole bout of exercise (BFR-C, 80% SBP; 91 ± 4 mmHg). Of note, HR and blood pressures were typically much higher during BFR-I. This indicates that a high-pressure restriction combined with relatively wide cuffs (i.e., BFR-I) increases myocardial work in comparison with a low-pressure restriction applied continuously without release (i.e., BFR-C). This low-pressure continuous restriction eliminates the likelihood of complete arterial occlusion and, therefore, any possibility of thrombus formation (Rossow et al., 2012; Loenneke et al., 2014). Nerve conduction velocity is likely unaffected by low-pressure BFR (Mittal et al., 2008), and while tissue oxygen saturation is reduced (Downs et al., 2014), exercise is often reported to be more tolerable (Hollander et al., 2010; Loenneke et al., 2011; Vieira et al., 2014). Taken together with previous studies, in comparison with high-pressure BFR exercise a low-pressure continuous restriction seems preferential when using relatively wide cuffs like those of the present study given the reduced hemodynamic stress, but should not be expected to provide any lesser beneficial adaptations to muscle strength and size when undertaken across a training period (Wernbom et al., 2008).

Limitations

The present study examined healthy young participants and so limits the extrapolation to other populations. However, recently using a similar exercise protocol, hemodynamics were not different for BFR exercise between both young (30 ± 3 years) and older (66 ± 7 years) healthy and recreationally active participants (Vieira et al., 2013). Therefore, it seems likely that BFR exercise may indeed be particularly useful to gain muscle strength and size in populations that are often contraindicated to HLRE. Second, the present exercise protocol reflects acute hemodynamic responses to exercise with a small muscle mass. Although these results may not directly apply to exercise using multiple/larger muscle groups, our findings are similar to previous experiments in young healthy participants during lower body resistance exercise (Takano et al., 2005) and walking (Renzi et al., 2010). Similarly, the upper body exercise in the present study was undertaken in an upright standing position and so may not extrapolate to other upper body exercises that utilize different postures such as the supine bench press. Finally, the use of SBP to determine BFR pressure during exercise has been questioned (Loenneke et al., 2012a). Although we acknowledge this, subsequent data from our laboratory (unpublished) suggest that the final pressure used during BFR-C was equivalent to ~60% of participants limb occlusion pressure (LOP) as determined by digital plethysmography, which has been shown to be accurate and reliable in determining cessation of limb blood flow in comparison with Doppler (McEwen et al., 2002;

Younger et al., 2004). Given the dependence of limb blood flow on cuff pressure and limb size/circumference (Downs et al., 2014) then perhaps the use of LOP technology might provide a more appropriate and individualized means to determine final exercising BFR cuff pressures in future studies.

In conclusion, the present study showed that light-load strength exercise in combination with a continuous BFR (80% SBP; 91 ± 2 mmHg) demonstrates a limited rise in HR, blood pressure, $\dot{Q}$, and RPP to levels between those observed for HLRE and LLRE. However, when a higher BFR pressure was applied intermittently during exercise only, HR and blood pressures were similar to HLRE and greater than LLRE. Therefore, continuous low-pressure BFR exercise appears a preferential BFR training method to target gains in strength and muscle size in healthy young populations, and perhaps more importantly in special populations such as the elderly and a variety of clinical conditions where gains in muscle strength and size are beneficial.

Perspective

BFR resistance exercise training increases muscle strength and size above that for non-BFR LLRE (not to failure) and similar to traditional HLRE. However, the acute hemodynamic responses have not been compared between these three exercise protocols. Our results demonstrate that high-pressure BFR exercise elicits similar HR, blood pressure, and RPP responses to HLRE despite an intermittent application of restriction. Therefore, when applying BFR using relatively wide cuffs similar to those of the present study, a low-pressure continuous restriction is recommended over higher restriction pressures in order to limit the hemodynamic response and improve participant comfort. Although the present study examined hemodynamic responses to healthy young participants, BFR resistance exercise with light loads shows potential viability to enhance strength and muscle size in older participants. However, additional research is warranted to further evaluate the safe use of BFR exercise in clinical populations.

Key words: Kaatsu, vascular occlusion, hypoxia, blood flow, strength training, resistance exercise.

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