Hemodynamic Responses to Blood Flow Restriction and Resistance Exercise to Muscular Failure

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Introduction

Resistance exercise (RE) is the most effective exercise mode to increase muscle mass [1]. Accordingly, the American College of Sports Medicine recommends lifting loads between 70–85% 1-RM (i.e., high-intensity resistance exercise [HI-RE]) to achieve muscular hypertrophy [1]. However, the high intramuscular pressure, produced by strong muscle contractions during HI-RE, mechanically compresses local blood vessels causing marked increases in hemodynamic responses (e.g., blood pressure [BP]) [13,20,27]. For instance, HI-RE increases systolic (SBP) and diastolic blood pressure (DBP), heart rate (HR), stroke volume (SV), cardiac output (CO) and total peripheral vascular resistance (TPR) were measured on a beat-to-beat continuous basis by a noninvasive photoplethysmographic arterial pressure device. The HI-RE and LI-RE showed higher values ($P<0.05$) in all of the sets than the BFR-RE for SBP, DBP, HR. Additionally, HI-RE showed higher SBP (4th set) and DBP (all sets) ($P<0.05$) values than the LI-RE. However, the SV, CO and TPR showed significantly greater values for LI-RE compared to HI-RE and BFR-RE ($P<0.05$). In conclusion, the results of this study indicate that the BFR-RE promotes a lower hemodynamic response compared to the HI-RE and LI-RE performed to muscular failure.
An alternate approach to HI-RE and LI-RE performed to muscle failure is the combination of low-intensity resistance exercise with blood flow restriction (BFR-RE). It has been shown that this strategy produces significant muscle hypertrophy without the necessity of using high loads and/or muscle failure [24, 26, 40]. Recently, our group reported that LI-RE (20–40 % 1-RM) combined with partial blood flow restriction (cuff pressure 40–50 % of SBP) (i.e., BFR-RE) is as effective as HI-RE (80 % 1-RM) in inducing muscle hypertrophy [25, 26, 40]. Additionally, BFR-RE results were obtained with lower TV (~30–40 %) than HI-RE [25, 26, 40]. Despite cuff pressure being an important factor increasing hemodynamic responses during BFR-RE [3], the lower number of repetitions, TV and session duration may attenuate hemodynamic responses in comparison to HI-RE and LI-RE to muscle failure. However, it was recently demonstrated that BFR-RE may produce greater increases in SBP and DBP compared to HI-RE (65 % 1-RM) and LI-RE (20 % 1-RM) in hypertensive individuals [34]. However, BFR-RE was not compared to HI-RE (80 % of 1-RM) or LI-RE protocols performed until muscle failure [30, 38], which greatly affect hemodynamic responses. Additionally, these results were obtained from hypertensive individuals, which did not allow extrapolating these findings to normotensive individuals, who are frequently seeking new training methods to maximize muscle growth. Therefore, the aim of the present study was to compare the hemodynamic responses (blood pressure, heart rate, stroke volume, cardiac output and total peripheral resistance) between BFR-RE with HI-RE and LI-RE to muscle failure.

Methods

Participants

12 healthy young men were recruited for the present study (age: 20 ± 3 years; body mass: 73.5 ± 9 kg; height: 174 ± 6 cm). Participants had to be absent from resistance and endurance training for at least 6 months prior to the beginning of the study and should not have taken anti-inflammatory, analgesic, anti-hypertensive, beta-blockers and central nervous system depressant drugs 2 months before and throughout the experimental protocol. They were also instructed to not consume caffeinated beverages for 24-h before the experimental protocols. The experimental procedures and possible risks associated with the study were explained to each participant, and an informed consent was obtained from all of the individuals in the study. The Human Research Ethics Committee of the local University approved the study. All of the procedures performed were in accordance with the Declaration of Helsinki. Our study met the ethical standards of the International Journal of Sports Medicine [16].

Experimental design

A randomized cross-over design was used in the present study. Participants were requested to visit the laboratory at 72-h intervals. Initially, participants engaged in 2 familiarization sessions to become acquainted with the exercise protocol and testing procedures. 2 days after the last familiarization session, participants performed a 45° leg press 1-RM test. Then, participants performed 3 RE protocols in a balanced and randomized order: HI-RE, LI-RE or BFR-RE. Hemodynamic parameters were measured during all exercise protocols using a non-invasive beat-to-beat device.

Maximum dynamic strength test

The maximum dynamic strength was assessed by 1-RM test on the 45° leg press machine (Pro-Fitness, São Paulo, Brazil) following previously described procedures [4]. In short, participants performed a general warm-up on a treadmill at 6 km·h⁻¹ for 5 min, followed by specific warm-up sets. In the first set, individuals performed 8 repetitions with a load corresponding to 50% of their estimated 1-RM, obtained during the familiarization sessions. In the second set, they performed 3 repetitions with 70% of their estimated 1-RM. A 2-min interval was allowed between warm-up sets. After the completion of the second set, participants rested for 3 min, and then they had up to 5 attempts to achieve their 1-RM. A 3-min interval was enforced between attempts. Tests were conducted by an experienced researcher, and strong verbal encouragement was provided during the attempts.

Resistance exercise protocols

HI-RE and LI-RE protocols were performed with 4 sets to muscular failure (1-min of rest interval between sets) with a load corresponding to 80 and 30 % 1-RM, respectively. Muscular failure was defined as an inability to move the 45° leg-press platform through the range of motion of 90°. The BFR-RE protocol was comprised of 4 sets of 15 repetitions at 30 % 1-RM. Occlusion pressure was maintained throughout the BFR-RE protocol (i.e., exercise sets and rest intervals). Session duration was recorded with a standard chronometer.

Blood flow restriction pressure

In order to determine the pressure in millimeters of mercury (mmHg) necessary to occlude blood flow to the lower limbs, participants were asked to lie in a supine position while resting comfortably. A vascular Doppler probe (DV-600; Marted, Ribeirão Preto, São Paulo, Brazil) was placed over the tibial artery to capture its auscultatory pulse. A standard blood pressure cuff [175 mm (width) 920 mm (length)] was put on the participant’s most proximal region of the thigh (i.e., inguinal fold) and then inflated up to the point in which the auscultatory pulse was interrupted [15]. Cuff pressure used during the BFR-RE protocol was determined as 50 % of blood flow occlusion pressure [25, 40]. Average pressure used throughout the exercise protocol was 75.8±7.4 mmHg.

Hemodynamic parameters

Before the beginning of the experimental protocols, participants were seated on the 45° leg press machine and rested for 10 min to stabilize the cardiovascular variables. Arterial pressure wave was obtained by photoplethysmography using the Finometer Pro® (Finapres Medical Systems, Amsterdam, the Netherlands) positioned on the right arm. Previously at each experimental session, a self-automated physiological calibration of blood pressure values was carried out, followed by a correction of the values of finger arterial pressure by the values of brachial blood pressure [2]. The ECG signals (CM5 lead) were collected using the BioAmp FE132 (ADInstruments, Sidney, NSW, Australia). The analog signal was recorded through an analog/digital board (PowerLab 8/35, ADInstruments, Sidney, NSW, Australia) and sampled at 1 kHz. HR values were obtained from R-R intervals on the electrocardiography (ECG) signal using the software LabChart Pro (ADInstruments, Sidney, NSW, Australia). SBP, DBP, cardiac output (CO), stroke volume (SV) and total peripheral vascular resistance (TPR) were analyzed using the software.
BeatScope® Easy (Finapres Medical Systems, Amsterdam, the Netherlands) [2, 36]. After 5 min of rest, data were collected for one minute averaged, and considered as a pre-exercise value. The highest and the lowest values achieved during each set and each rest interval, respectively, were used to calculate the differences from pre-exercise values (i.e., delta change). Coefficient of variation and the typical error at rest and during exercise of the hemodynamic variables were, respectively: SBP: rest = 8.26 mmHg and 6.6%, exercise = 11.9 mmHg and 9.1%; DBP: rest = 4.91 mmHg and 7.0%, exercise = 10.5 mmHg and 14.1%; HR: rest = 7.5 bpm and 11.5%, exercise = 11.4 bpm and 13.4%; SV: rest = 7.0 ml and 7.1%, exercise = 10.5 ml and 11.5%; CO: 0.91 m⁻¹ and 14.1%; exercise = 1.01 m⁻¹ and 12.4%; TPR: rest = 220.4 dyn·s·cm⁻⁵ and 19.3%, exercise = 182.0 dyn·s·cm⁻⁵ and 17.7%.

Statistical analyses
Data normality and variance equality were assessed through the Shapiro-Wilk and Levene tests, respectively. A mixed model, assuming protocol (HI-RE, LI-RE and BFR-RE) and sets (S1, S2, S3 and S4) as fixed factors and participants as a random factor was implemented for each hemodynamic variable (SBP, DBP, HR, SV and TPR) during rest intervals between sets. In case of significant F-values a Tukey adjustment was used for multiple comparison purposes. The significance level was set at P ≤ 0.05. Data are presented as mean ± standard error.

Results ▼
Total volume and session duration of resistance exercise
The number of repetitions, total volume and session duration were significantly greater for LI-RE (P < 0.0001) compared with HI-RE and BFR-RE. However, exercise load was significantly greater in HI-RE (P < 0.0001) than in the other 2 RE protocols.

Hemodynamic parameters
During exercise (Fig. 1), there was a significant interaction effect for protocol by set for SBP and DBP (both P = 0.01). HI-RE protocol produced significant increases in SBP from S1 to S4 (P = 0.0009). SBP also increased from S1 to S2 (P = 0.0003), S3 (P < 0.0001), S4 (P < 0.0001) for the BFR-RE protocol. In addition, BFR-RE showed significant increases in SBP from S2 to S4 (P = 0.03). Between-protocol comparisons revealed significantly greater SBP for HI-RE and LI-RE than BFR-RE at S1 (P < 0.0001), S2 (P = 0.0002; P = 0.009, respectively), S3 (P = 0.0008; P = 0.04, respectively) and S4 (P = 0.001; P = 0.05, respectively). Additionally, SBP showed significantly greater values in S4 for HI-RE compared to LI-RE (P = 0.03). Regarding DBP, HI-RE protocol showed significant increase from S1 to S4 (P = 0.02), while the BFR-RE protocol increased from S1 to S2 (P = 0.002), S3 (P < 0.0001), and S4 (P < 0.0001). DBP also increased from S2 to S4 (P = 0.05) for the BFR-RE protocol. Between-protocol comparisons revealed significantly lower DBP for LI-RE and BFR-RE than for HI-RE at S1 (P = 0.05; P < 0.0001, respectively), S2 (P = 0.0007; P = 0.0001, respectively), S3 (P = 0.001; P = 0.0001, respectively) and S4 (P = 0.005; P < 0.0001, respectively). Additionally, DBP showed significantly lower values in S1, S2, S3 and S4 for BFR-RE compared to LI-RE (P < 0.0001; P = 0.003; P = 0.04; P = 0.009, respectively). There was also a significant main set effect for CO (P = 0.03) and HR (P = 0.04). The CO showed significant increase from S1 to S3 and S4 (P = 0.05; P = 0.003, respectively), from S2 to S4 (all P < 0.001), and from S3 to S4 (all P = 0.05), but HR increased only from S3 to S4 (P = 0.007). A significant main protocol effect was observed for HR (P = 0.009), SV (P = 0.01) and CO (P = 0.0001). HR showed significantly greater values for HI-RE and LI-RE compared to BFR-RE (P = 0.04; P = 0.002, respectively). However, the SV and CO showed significantly greater values for LI-RE compared to HI-RE (P = 0.005; P = 0.001, respectively) and BFR-RE (P = 0.02; P = 0.0001, respectively). Finally, there was a significant protocol by set interaction effect for TPR (P = 0.003). LI-RE protocol showed significant decreases in TPR from S1 to S2 (P = 0.003), S3 (P < 0.002) and S4 (P < 0.0001) for the BFR-RE protocol. Between-protocol comparisons revealed significantly lower TPR for HI-RE and BFR-RE than LI-RE at S1 (P = 0.003; P = 0.005, respectively). During pauses (Fig. 2), there was a significant main protocol effect for SBP and DBP (both P = 0.008). The SBP showed significantly lower values for HI-RE and BFR-RE compared to LI-RE (P = 0.04; P = 0.002, respectively). However, the DBP showed significantly lower values for HI-RE and LI-RE compared to BFR-RE (P = 0.005; P = 0.007, respectively). A main set effect was observed for HR (P = 0.05). The values of HR at P2 and P3 were significantly higher than at P1 (both P = 0.03). There was a significant protocol by set interaction effect for SV (P = 0.0004) and CO (P = 0.01). LI-RE protocol showed significantly lower SV values during P3 compared to P1 and P2 (P = 0.01; P < 0.0001, respectively). Regarding CO, LI-RE protocol shows higher values in P3 than BFR-RE (P = 0.01). There was no significant main effect or interaction effect for TPR during pauses (P = 0.05).

Discussion ▼
The aim of the present study was to compare the hemodynamic responses (blood pressure, heart rate, stroke volume, cardiac output and total peripheral resistance) among different RE protocols. Our results showed that BFR-RE promoted lower hemodynamic responses when compared with HI-RE and LI-RE performed to muscular failure. It has been suggested that vascular compression of the muscles involved in a given RE would be one of the factors responsible for increasing hemodynamic response [27]. In this regard, the magnitude and duration of the muscle compression may be different according to the load, number of repetitions and session duration of RE, thus influencing the hemodynamic responses [29]. Accordingly, HI-RE protocol showed greater SBP (4th set) and DBP (all sets) values compared to LI-RE to muscle failure. These results are in line with some studies [35] but not others [11, 23]. For instance, Poton & Polito [35] showed greater SBP and DBP values for HI-RE (3 × 8 repetitions; 80% 1-RM) compared to LI-RE (3 × 15 repetitions; 20% 1-RM). On the other hand, Lamotte et al. [23] compared the hemodynamic responses during LI-RE and HI-RE protocols (4 sets of 10 repetitions at 40 and 70% of the 1-RM load, respectively) and showed higher values of HR and SBP during the LI-RE. Recently, Gjoavag et al. [11] also found greater SBP and DBP values for the 20-RM (~50% 1-RM) protocol than for the 4-RM (~90% 1-RM) one, in young men. It may be suggested that the intensities used during the LI-RE protocols and exercises produced such discrepant results. We used a load corresponding to 30% 1-RM on the 45° leg press exercise while
Lamotte et al. [23] and Gjovaag et al. [11] used 40% and 50% 1-RM on the leg extension exercise, respectively. It is possible to suggest that intensities between 40–50% 1-RM leads to increases in total training volume producing greater enhancements in blood pressure compared to loads corresponding to 30% 1-RM. Additionally, differences between exercises used in our (45° leg press machine) and other studies (leg extension machine) is a factor that makes it difficult to compare studies. Thus, future studies should investigate the SBP and DBP response to the manipulation of LI-RE variables to muscle failure such as exercise intensity, body position and number of active muscle groups.

Regarding the comparison between HI-RE and BFR-RE protocols, our results showed greater increases in SBP, DBP and HR values for HI-RE than for the BFR-RE. Interestingly, our results are similar to studies comparing BFR-RE with HI-RE performed at 80% 1-RM but contrast with studies that compared the BFR-RE with HI-RE at 65% 1-RM. For instance, Ponton & Polito [35] showed lower SBP and DBP values for BFR-RE (3 × 15 repetitions; 20% 1-RM) compared to HI-RE (3 × 8 repetitions; 80% 1-RM). On the other hand, Pinto & Polito [34] demonstrated that BFR-RE (3 × 8 repetitions; 20% 1-RM) may promote greater increases in SBP and DBP compared to HI-RE (3 × 15 repetitions; 65% 1-RM) in hypertensive individuals. Collectively, these findings suggest: 1) hypertensive individuals may be more sensitive to hemodynamic increases during BFR-RE [14]; 2) the increased motor units recruitment in the HI-RE performed at 80% of 1-RM compared with BFR-RE [22, 28] and HI-RE performed with 65% 1-RM [10], could lead to a greater accumulation of metabolites (e.g., H+ and lactate), which increases blood pressure via muscle metaboreflex [29, 37].

Several studies compared the impact of BFR-RE and LI-RE on hemodynamic responses [34, 35, 39, 41]. For instance, Poton & Polito [35] showed higher SBP and HR values during BFR-RE than LI-RE (both protocols with 3 sets of 15 repetitions with 20% 1-RM). In this context, more recently, Pinto & Polito [34] subjected middle-aged women with high blood pressure to protocols of BFR-RE and LI-RE (3 sets of 15 repetitions with 20% 1-RM), performed in the leg-press exercise. The results showed higher increases in SBP, DBP, CO and SV for BFR-RE protocol compared with LI-RE. Contrary to our findings, these authors reported that BFR-RE resulted in a greater hemodynamic
responses compared with low-intensity RE without the use of the cuff [34, 35]. Importantly, these authors did not perform the LI-RE to muscular failure, which enabled equalizing TV (i.e., sets × repetitions × load [kg]), where the cuff application was the only difference between BFR-RE and LI-RE. In this case, it is possible that the cuff application in BFR-RE protocol per se has increased systemic vascular resistance. The BFR-RE uses an external apparatus (e.g., cuff) positioned proximally around the limb, reducing blood flow to the working muscles, which seems to induce blood accumulation in the thighs, impairing venous return [21]. Importantly, in the present study, LI-RE was performed to muscle failure. This strategy has been previously demonstrated to be as effective as HI-RE to induce acute increases in miofibrilar protein synthesis [7] and long-term muscle mass accrual [30], which seems not to be the case when LI-RE is not performed to muscle failure [5, 19, 32]. However, performing LI-RE to failure resulted in a greater number of repetitions, session duration and TV compared to BFR-RE, which seem to have influenced the hemodynamic responses.

This study is not without limitations. First, SV, CO and TPR were estimated and not directly measured. Second, SBP obtained using photoplethysmography is overestimated at rest and during resistance exercise, while the DBP is underestimated both at rest and during exercise [12]. Regarding direct methods of blood pressure assessment, intra-arterial probes are considered as the gold standard. However, photoplethysmography devices provide similar changes in blood pressure values during resistance exercise than intra-arterial probes [12], which is why we presented delta values and not absolute BP values. Additionally, it is worth noting that the present results should not be extrapolated to different exercise types and volumes, as well as to distinct cuffs, occlusion pressures and populations (e.g., women, elderly, hypertensive and cardiopaths). Finally, we and others have previously shown that BFR-RE may promote increases in muscle mass similar to those observed after HI-RE [24, 26, 40] and LI-RE to muscular failure [9]. Altogether, these results suggest that BFR-RE can maximize muscle growth despite the lower intensity, volume, total training volume and session duration when compared with HI-RE. In other words, the BFR-RE may be similar to HI-RE and LI-RE performed to muscular failure to induce muscular adaptations, while resulting in lower hemodynamic responses, thus favoring the feasibility of this training approach.

**Fig. 2** Changes (Delta pause – pre-exercise) in systolic blood pressure (SBP, panel a), diastolic blood pressure (DBP, panel b), heart rate (HR, panel c), stroke volume (SV, panel d), cardiac output (CO, panel e) total peripheral resistance (TPR, panel f) during 3 pauses (P1, P2 and P3) of high-intensity resistance exercise (HI-RE), low-intensity resistance exercise (LI-RE) and blood flow-restricted resistance exercise (BFR-RE).

# Significantly different from LI-RE (main protocol effect, P < 0.05). ¥ Significantly different from HI-RE and LI-RE (main protocol effect, P < 0.05). £ Significantly different from P1 (main pause effect, P < 0.05). † Significantly different from BFR-RE (interaction effect, P < 0.05). ¥ Significantly different from P1 and P2 (interaction effect, P < 0.05).
In conclusion, the results of this study indicate that the BFR-RE promotes lower hemodynamic responses compared to HI-RE and LI-RE performed to muscular failure.

Acknowledgements

A.M.C., A.B.-S., C.U., H.R. and V.T. are supported by National Council for Scientific and Technological Development (CNPq) grants. We would like to acknowledge all the participants of this study.

Conflict of interest: The authors do not have any conflicts of interest financial or otherwise to declare.

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