Sports Med
DOI 10.1007/s40279-015-0407-7

REVIEW ARTICLE

The Effects of Blood Flow Restriction on Upper-Body Musculature Located Distal and Proximal to Applied Pressure

Scott J. Dankel[1] **· Matthew B. Jessee**[1] **· Takashi Abe**[2] **· Jeremy P. Loenneke**[1]

Abstract Blood flow restriction (BFR) training has been shown to increase muscle size and strength when combined with low-load [20–30 % one-repetition maximum (1RM)] resistance training in the lower body. Fewer studies have examined low-load BFR training in combination with upper body exercise, which may differ as some musculature cannot be directly restricted by the BFR stimulus (chest, shoulders). The objective of this study was to examine muscle adaptations occurring in the upper body in response to low-load BFR training. Google Scholar, PubMed, and SPORTDiscus were searched through July 2015 using the key phrases 'blood flow restriction training', 'occlusion resistance training', and 'KAATSU'. Upper body training studies implementing the BFR stimulus and providing a pre and post measure of muscle size and/or strength were included. A total of 19 articles met the inclusion criteria for this review. The effectiveness of low-load BFR training appears to be minimally impacted by alterations to the intensity and restrictive pressures used; however, the ability to quantitatively analyze our results was limited by unstandardized protocols. Low-load BFR training increased muscle size and strength in limbs located proximal (chest, shoulders) and distal (biceps, triceps) to the restrictive stimulus; while volume-matched exercise in the absence of BFR did not elicit beneficial muscle adaptations. Some of the musculature in the upper body cannot be directly restricted by the application of BFR. Despite this, increases in muscle size and strength were observed in muscles placed under direct and indirect BFR.

Key Points

Low-load resistance exercise in combination with blood flow restriction (BFR) in the upper body produces similar muscle adaptations to high-load resistance training.

Increases in muscle size and strength are observed in muscles not directly under BFR (i.e., muscles proximal to the applied pressure).

The benefits observed with resistance exercise in combination with BFR in the upper body appear to occur with relatively low loads and pressures.

1 Introduction

It was originally thought that training with loads lower than 70 % one-repetition maximum (1RM) would not result in muscle hypertrophy [1]. Recent studies have provided some insight that both low-load training to volitional fatigue [2–4], and low-load blood flow restriction (BFR) training [5, 6] can produce increases in muscle size comparable to high-load training. While mechanical tension is thought to be the primary driver of muscle hypertrophy during high-load training [7], the mechanisms behind low-load BFR training-induced muscle growth are not well

---

✉ Jeremy P. Loenneke
jploenne@olemiss.edu

[1] Department of Health, Exercise Science, and Recreation Management, Kevser Ermin Applied Physiology Laboratory, The University of Mississippi, PO Box 1848, University, MS 38677, USA

[2] National Institute of Fitness and Sports in Kanoya, Kanoya, Kagoshima, Japan

understood. Some of the proposed mechanisms involved in the hypertrophic response from low-load BFR training include an accumulation of metabolites, cell swelling [8], increased motor unit recruitment [9], reactive hyperemia [10], decreased myostatin messenger RNA (mRNA) expression [3], reduced protein breakdown [11], and the proliferation of satellite cells [12]. It can be hypothesized that these alternative mechanisms responsible for muscle growth (i.e., metabolic accumulation, cell swelling) may be able to augment the muscle hypertrophic response during low-load BFR training in the absence of sufficient mechanical tension. Additionally, while both low-load BFR training and traditional high-load training may work through alternate mechanisms, they appear to both be reliant on the activation of the mechanistic target of rapamycin (mTOR) pathway, as evident by the blunted protein synthetic response when rapamycin, an mTOR suppressor, is administered [13, 14]. While an in-depth review of the mechanisms behind BFR-induced growth is outside the scope of this review and can be found elsewhere [15], one constant that seems to be important for robust muscle hypertrophy is a high level of muscle activation [2].

Despite similar muscle adaptations occurring from both low-load BFR training, and low-load unrestricted training to volitional fatigue, the application of BFR is unique in that it reduces the workload needed to reach the point of fatigue [16], therefore reducing the number of repetitions necessary to see similar muscle adaptations (75 vs. 165) [17]. Additionally, BFR has been shown to attenuate strength loss [18, 19] and muscle atrophy [20, 21] independent of any muscular contraction, and it has also been shown to increase muscle size when applied in conjunction with low-intensity aerobic activity [22–24]. Therefore, BFR may serve as a beneficial tool for increasing muscle size and strength among those who are unable to perform high-load resistance training (i.e., clinical populations). Further support for the use of BFR in clinical populations exists, in that low-load BFR training has been shown to be a safe stimulus [25] and has been demonstrated effective at increasing muscle size and strength in elderly [26] and diseased (myositis) [27] populations, as well as those rehabilitating from injury [28, 29].

While numerous interventions have focused on low-load BFR training performed in the lower body [30], much less is known about its effectiveness in the upper body, which consists of some musculature that cannot be placed directly under BFR due to its anatomical location (e.g., chest, shoulders). Therefore, the purpose of this review was (1) to quantitatively analyze, via meta-analysis, the effectiveness of low-load BFR training at increasing muscle size and strength in the upper body; and (2) to compare different training variables utilized and how they potentially modulate changes in muscle size and strength.

2 Methods

2.1 Literature Search

Peer-reviewed journal databases (Google Scholar, PubMed, and SPORTDiscus) were searched up until July 2015 using the terms ‘blood flow restriction training’, ‘occlusion resistance training’, and ‘KAATSU’. Only studies written in English were considered for evaluation, and all relevant articles and included citations were reviewed to ensure all published studies pertaining to BFR were analyzed. Initially, all abstracts were reviewed, and those meeting the full inclusion criteria were obtained for further evaluation. The inclusion criteria included that (1) BFR must be applied to the upper arm before exercise and remain restrictive until its completion; (2) a chronic training study consisting of at least five sessions must be employed to allow sufficient time for measurable muscle adaptations; and (3) a pre and post measure of muscle size and/or strength must be provided.

2.2 Calculation of Effect Size

Effect sizes (ESs) were calculated with the formula (mean2 − mean1/pooled standard deviation). All inclusive studies containing values [means and standard deviations (SDs)] that were not reported in the text, but were illustrated in graphical form, were estimated using a graph digitizer (GetData Graph Digitizer 2.26). If standard errors (SEs) were presented, they were converted to SDs using the formula (SE $\times \sqrt{n}$).

3 Results

A total of 19 articles were found meeting all inclusion criteria [31–49] (Tables 1, 2, 3). A meta-analysis was conducted to quantitatively compare increases in muscle size and strength occurring from low-load BFR training with that of volume-matched unrestricted low-load training (i.e., the same protocol in the absence of the BFR stimulus). While all studies were included for the analysis of training variables (Table 2), and outcome measures of muscle size and strength (Table 3), additional criteria were established for inclusion in the meta-analysis (Table 1): (1) A pre and post measure of both muscle size and strength for the biceps, triceps, and/or chest muscles must be identified; (2) Muscle size must be assessed using magnetic resonance imaging (MRI), ultrasound, or computed tomography (CT) scan; (3) Strength tests must be conducted using a 1RM or maximal voluntary isometric contraction (MVC); (4) There must be a control group

Table 1 Inclusion/exclusion from meta-analysis

Study	Rationale for exclusion
Burgomaster et al. [31]	No measure of muscle size, protocol involved one set to fatigue
Credeur et al. [32]	Handgrip exercise was performed, and muscle size were measured using circumference
Counts et al. [33]	Control group also performed low-load BFR training under a different restrictive pressure
Farup et al. [34]	Control group performed low-load training to failure, and 1RM was estimated from 3RM
Hunt et al. [35]	Handgrip exercise was performed, and muscle size was measured by water displacement
Luebbers et al. [36]	Elastic wraps were used for practical BFR, control group performed high-load training, muscle size was measured using circumference
Lowery et al. [37]	Elastic wraps were used for practical BFR, control group performed high-load training
Moore et al. [38]	No measure of muscle size, protocol involved one set to fatigue
Ozaki et al. [39]	Control group performed high-load training
Sakamaki et al. [40]	Control group performed no exercise
Takarada et al. [41]	No standard deviations were presented
Thiebaud et al. [42]	Control group performed moderate- to high-intensity exercise
Weatherholt et al. [43]	INCLUDED
Yamanaka et al. [44]	Elastic wraps were used for practical BFR, muscle size was measured using circumference
Yasuda et al. [45]	INCLUDED
Yasuda et al. [46]	Control groups either performed no training or high-load training
Yasuda et al. [47]	Control groups either performed no training or high-load training
Yasuda et al. [48]	Control group performed eccentric only exercise with BFR
Yasuda et al. [49]	INCLUDED

BFR blood flow restriction, *RM* repetition maximum

performing a volume-matched protocol in the absence of BFR; (5) BFR must be applied using a pneumatic cuff that can be set to specific pressures, and (6) SDs or SEs must be presented for all pre and post measurements.

Our attempt to conduct a meta-analysis was severely limited for reasons detailed in Table 1, with the extrapolation of data limited to three studies, two of which compared muscle size and strength of biceps and triceps using elbow flexion and extension exercises [43, 46], and a third [47] comparing chest and triceps muscle adaptations via bench press exercise. Therefore, to avoid over-generalizing the results of our findings, the focus of this review was primarily narrative. Table 3 details the changes in muscle size and strength, as well as ES, for each individual study included in this review.

4 Discussion

Throughout the literature, only a limited number of studies have incorporated BFR in combination with upper body resistance exercise, and these results are difficult to compare due to unstandardized protocols varying in intensity, volume, duration, and frequencies of exercise performed. Various testing methods have been employed for the determination of both muscle size and strength, making direct comparisons across studies difficult. To illustrate, isotonic and isometric strength have been shown to produce varied results when low-load training is employed [2] (e.g., isometric strength will be less impacted by training specificity), and the assessment of muscle size via anthropometric measures (i.e., girth measurements) possesses obvious limitations (e.g., increased fat mass can be misconstrued as muscle growth). Furthermore, several studies [31, 38] implemented protocols involving sets to volitional fatigue (Table 2), and thus, the groups were neither repetition nor volume matched, therefore limiting our ability to compare low-load BFR training to a high-load or low-load unrestricted control group. Low-load resistance training to volitional fatigue eliminates the primary benefit of BFR, which is a reduction in the time necessary to induce muscular fatigue [16]. Therefore, low-load resistance training to volitional fatigue will produce increases in muscle size similar to low-load BFR training [34, 50]; however, it will require a much greater number of repetitions (75 vs. 165) [17]. The lack of volume-matched protocols comparing low-load BFR training to either high-load or low-load unrestricted training (three in total) did not warrant the completion of a meta-analysis. The following sections aim to discuss different muscle adaptations occurring in the upper body and training variables that may modulate the BFR stimulus.

Table 2 All study protocols included in qualitative analysis

Study	*n*	Sessions	%1RM	Cuff width (cm)	Highest cuff pressure (mmHg)	Final protocol	Method of muscle size measurement
Burgomaster et al. [31]	8	16	50	12	100	5 sets of 10, 6th set to failure	
Credeur et al. [32]	12	12	60	NA	80	300 contractions	Circumference
Counts et al. [33]	7	22	30	5	40/90 % arterial occlusion	1 set of 30 followed by 3 sets of 15	Ultrasound
Farup et al. [34]	10	18	40	8	100	4 sets to failure	MRI
Hunt et al. [35]	9	12	40	13	80	3 sets to failure	Water displacement
Luebbers et al. [36]	15	14	20	7.6	NA	1 set of 30 followed by 3 sets of 20	Circumference
Lowery et al. [37]	21	16	30	7.6	NA	3 sets of 30	Ultrasound
Moore et al. [38]	8	24	50	7	100	2 sets of 10, 3rd set to failure	
Ozaki et al. [39]	10	18	30	3	160	1 set of 30 followed by 3 sets of 15	MRI
Sakamaki et al. [40]	13	6	30	3	100	1 set of 30 followed by 3 sets of 15	MRI
Takarada et al. [41]	11	32	50	2.5	100	3 sets to failure	MRI
Thiebaud et al. [42]	6	24	10–30	3.3	120	1 set of 30 followed by 3 sets of 15	Ultrasound
Weatherholt et al. [43]	20	24	20	3	180	3 sets of 15	pQCT scan
Yamanaka et al. [44]	16	12	20	5	NA	1 set of 30 followed by 3 sets of 20	Circumference
Yasuda et al. [45]	10	18	30	NA	160	1 set of 30 followed by 3 sets of 15	MRI
Yasuda et al. [46]	9	24	30	3	270	1 set of 30 followed by 3 sets of 15	MRI
Yasuda et al. [47]	5	24	30	NA	160	1 set of 30 followed by 3 sets of 15	Ultrasound
Yasuda et al. [48]	10	18	30	NA	160	1 set of 30 followed by 3 sets of 15	MRI
Yasuda et al. [49]	10	18	30	3	160	1 set of 30 followed by 3 sets of 15	MRI

MRI magnetic resonance imaging, *NA* data not reported, *pQCT* peripheral quantitative computed tomography, *RM* repetition maximum

4.1 Upper Extremity Muscle Adaptations with Blood Flow Restriction

4.1.1 Upper Extremity Muscle Size

The average increase in biceps and triceps muscle size per session was similar for both elbow flexion and elbow extension exercises; that is, the relative increase in triceps muscle size occurring from elbow extension exercise was similar to that of biceps muscle size resulting from elbow flexion exercise (Table 3). In comparison, increases in triceps muscle size tended to be lower during bench press exercise as opposed to elbow extensions [42, 45, 47, 48]. This can likely be attributed to the triceps being the primary muscles involved in elbow extensions, whereas the triceps take a more complementary role in the bench press exercise. The reduced growth of muscles that were not directly trained was also demonstrated by Thiebaud et al. [42], reporting only a 3 % increase in biceps muscle size, which was not statistically significant. While all other studies reported increased bicep growth, the results of Thiebaud et al. [42] can likely be attributed to the fact that the biceps were not directly trained and, therefore, the only stimulus the biceps received was from their synergistic involvement in the seated row exercise.

Table 3 Muscle adaptations occurring in all included studies

References	Muscle size	% Δ per session	% Total Δ	Effect size	Muscle strength	% Δ per session	% Total Δ	Effect size
Burgomaster et al. [31]	NA				Isokinetic 60°/sec	0.69	11.0	1.48
	NA				Biceps 1RM	1.40	22.5	4.13
Credeur et al. [32]	NA				Handgrip MVC	1.34	16.1	6.7
Counts et al. [33]	Biceps upper MTH	0.56	12.5	0.56	Biceps 1RM	0.80	17.9	0.37
	Biceps 10cm MTH	0.45	10	0.45	Isokinetic 60°/sec	0.51	11.2	0.23
Farup et al. [34]	Biceps CSA	0.64	11.5	0.54	Biceps 3RM	1.08	19.4	0.60
					Biceps MVC	−0.29	−5.2^{a}	−0.14
Hunt et al. [35]	Forearm volume	0.14	1.7^{a}	0.16	Handgrip 1RM	1.00	11.9	0.59
Leubbers et al. [36]	NA				Bench press 1RM	0.16	2.3^{a}	0.20
Lowery et al. [37]	Biceps MTH	0.69	11.1	3.90	NA			
Moore et al. [38]	NA				Elbow flex 1RM	0.90	21.7	6.63
					Elbow flex MVC	0.32	7.7	0.95
Ozaki et al. [39]	Chest CSA	0.38	6.8	1.00	Bench press 1RM	0.49	8.7	1.54
Sakamaki et al. [40]	Biceps volume	0.88	5.3	0.39	Biceps MVC	1.1	6.6	0.33
Takarada et al. [41]	Biceps brachii CSA	0.63	20.3	NA	Biceps isokinetic 60°/sec	0.58	18.4	NA
	Biceps brachialis CSA	0.56	17.8		Biceps MVC	0.52	16.5	
Thiebaud et al. [42]	Biceps MTH	0.13	3.0^{a}	0.21	Bench press 1RM	0.43	10.4	0.44
	Triceps MTH	0.27	6.5^{a}	0.32	Back row 1RM	0.29	7.0	0.31
	Deltoid MTH	0.16	3.8^{a}	0.22	Shoulder press 1RM	0.22	5.3	0.49
	Chest MTH	0.73	17.4	1.02				
Weatherholt et al. [43]	Arm CSA	0.15	3.6	0.47	Biceps 1RM	0.56	13.5	1.35
					Triceps 1RM	0.64	15.4	1.57
Yamanaka et al. [44]	NA				Bench press 1RM	0.60	7.2	0.55
Yasuda et al. [45]	Triceps CSA	0.26	4.7	0.24	Bench press 1RM	0.48	8.7	0.46
	Chest CSA	0.47	8.5	0.47				
Yasuda et al. [46]	Biceps CSA	0.73	17.7	0.62	Elbow flex MVC	0.35	8.5	0.22
	Triceps CSA	0.68	16.3	0.50	Elbow ext MVC	0.68	16.3	0.50
Yasuda et al. [47]	Chest MTH	0.75	17.9	0.22	Bench press 1RM	0.26	6.2	0.63
	Triceps MTH	0.31	7.5	0.07				
Yasuda et al. [48]	Chest CSA	0.47	8.4	0.46	Bench press 1RM	0.51	9.1	0.49
	Triceps CSA	0.26	4.6	0.23	Tricep MVC	−0.01	−0.2^{a}	−0.01
Yasuda et al. [49]	Biceps volume	0.69	12.3	1.64	Biceps MVC	0.44	8.0	0.79
	Biceps mid-upper CSA	0.56	10.1	1.2				
	Biceps 10 cm CSA	0.64	11.6	1.42				

CSA cross-sectional area, *ext* extension, *flex* flexion, *MTH* muscle thickness, *MVC* maximal voluntary isometric contraction, *NA* data not measured or, in the case of effect sizes, no standard deviations were reported, *RM* repetition maximum

[a] Insignificant change

In control groups performing volume- and repetition-matched low-load exercise in the absence of BFR, no hypertrophy of the biceps or triceps was present regardless of the exercise performed [45–47], corroborating the findings of Loenneke et al. [30] in the lower body. One exception involved a study by Weatherholt et al. [43] reporting similar increases in both low-load unrestricted and low-load BFR training for reasons that could not be elucidated, and the authors' suggestion of a cross-over effect from systemic hormones has been scrutinized elsewhere [51]. Additionally, it would seem unlikely that the volume of exercise, consisting of just three sets of 15 repetitions with a 20 % 1RM load, would produce any measurable increases in muscle size in the absence of BFR.

Therefore, this study demonstrated results that conflicted with all other included studies in several areas throughout this review.

Farup et al. [34] investigated low-load BFR training compared with unrestricted low-load training, with both groups performing exercise to volitional fatigue. Similar to the results found in the lower body [50], no differences were found despite a much greater volume of exercise completed by the unrestricted group. Therefore, while both low-load resistance training to volitional fatigue and low-load BFR resistance training appear to elicit similar muscle adaptations in muscles located distal to the restrictive stimulus, the primary benefit of BFR may lie in the reduced workload necessary to induce these adaptations [17].

Loenneke et al. [30] also examined lower extremity BFR in conjunction with aerobic exercise and found that, albeit not to the extent of resistance exercise, low-intensity aerobic activity elicited muscle growth, whereas unrestricted volume-matched exercise did not. There were no studies found that examined the impact of aerobic exercise performed using the upper body extremities (i.e., arm ergometer). Therefore, its effectiveness remains unknown. If demonstrated to be effective, arm ergometry may provide an alternative avenue for increasing or maintaining muscle size and strength among those who are not ambulatory, as this exercise can be performed in a variety of positions (e.g., wheelchair, bed rest). Considering the effectiveness of lower body cycling [22], it is plausible to hypothesize that arm ergometry would induce muscle growth; however, the arms are located at heart level during exercise, and therefore may be less inclined to benefit from the pooling of venous blood that appears important for muscle adaptations in response to BFR training.

Only one study compared low-load BFR training with high-load training [37]. The authors found that when BFR was administered in the form of knee wraps, increases in biceps muscle size tended to be similar between unrestricted high-load training and low-load BFR training. These results demonstrate that high-load training, and low-load BFR training administered to limbs distal to the pressure cuff, appear to produce similar increases in muscle size, although more research is necessary to make this comparison.

4.1.2 *Upper Extremity Muscle Strength*

With the exception of two studies [42, 48], muscle strength was increased in the biceps and triceps across all low-load BFR training studies. The two exceptions [42, 48] were likely a result of testing the biceps and triceps muscles that were not trained during the intervention. The increases in muscle strength tended to be greater during isotonic testing than isometric or isokinetic testing, which is likely due to the principle of specificity, considering training was performed isotonically in almost all studies. To illustrate, Burgomaster et al. [31] and Moore et al. [38], respectively, reported 22.5 and 21.7 % increases in bicep 1RM strength, while only reporting 11 % (isokinetic) and 7.7 % (isometric) strength increases via alternate testing methods (Table 3). Similarly, Farup et al. [34] reported a 19.4 % increase in bicep 3RM strength and no increase in isometric strength (Table 3). As supported by Table 3, the increases in strength from low-load BFR training appeared to be mainly driven by increases in muscle mass [52], while those from high-load training appeared to be primarily neurological [45].

Only one study demonstrated that a repetition-matched protocol in the absence of BFR resulted in increases in muscle strength [43], which is difficult to explain, but may have been due to participants learning the movement pattern of the 1RM. Two additional studies with similar protocols involved a final set performed to volitional fatigue [31, 38] and thus were not repetition or volume matched. It has previously been shown that even lower loads can produce increases in muscle strength when performed to volitional fatigue [2]; therefore, the strength increases seen following low-load BFR training support previous research [34, 50].

With the exception of the two studies previously mentioned [42, 48], muscle strength at the conclusion of upper extremity exercise was greater following low-load BFR training than following low-load unrestricted training; however, no studies made a direct strength comparison between low-load BFR training and high-load training. It has previously been suggested that both high- and low-load training produce similar increases in overall strength when the specificity of training is eliminated through alternative modalities of strength testing (i.e., isometric testing following isotonic training) [2, 6]. However, only one study [37] examined biceps exercises comparing high-load training with low-load BFR training, and since no measure of muscle strength was reported, no comparisons for upper extremity strength could be made.

4.2 Trunk and Shoulder Muscle Adaptations with Blood Blow Restriction

4.2.1 *Chest Muscle Size*

The chest, back, and shoulder muscles are provided with a unique stimulus from BFR as they are located proximal to the pressure cuff, and, therefore, blood flow to the trunk and shoulder musculature is not directly restricted. It has been speculated that since these muscles are not placed under direct restriction, they may not see any benefit from the application of BFR. However, this review provides insight that despite not being directly restricted, muscle size and strength of the chest muscles can be increased following low-load BFR training (Table 3). Additionally, as previously mentioned, several studies demonstrated that chest muscle size increased to a greater extent than triceps muscle size following low-load BFR bench press [42, 45, 47, 48] or high-load bench press exercise [53, 54]. It would also appear that, despite only the triceps being placed under direct BFR, the relationship of chest to triceps muscle growth at the conclusion of low-load BFR bench press is similar to that seen with high-load bench press [48], albeit to a lesser extent of total muscle growth. To illustrate, the ratio of absolute chest to triceps muscle growth was identical (2.6 and 2.7) between low-load BFR and high-load bench press exercise following two separate studies by Yasuda and colleagues [45, 48]. This suggests that both low-load BFR and high-load bench press training fatigue the chest and triceps proportional to one another.

The increases in chest muscle size can likely be attributed to increased electromyography (EMG) activity of the chest muscles, which, during the final set of low-load BFR training, were increased to high levels of muscle activation typically associated with traditional high-load training [47]. The increased EMG activity of the chest musculature is indicative of greater type II fiber recruitment, which appears to be of critical importance for pronounced muscle growth [41]. The authors hypothesized that this may have occurred through increased fatiguing of the triceps muscles, as they are placed under direct BFR, thus causing a greater stress on the chest musculature to make up for the loss of force production. While increased stress was placed on the triceps from the BFR stimulus, the increased EMG activity of the chest would suggest that the relative contribution of the chest and triceps during low-load BFR bench press was still maintained despite the chest not being directly restricted.

The idea that low-load BFR training elicits chest muscle hypertrophy through its fatiguing effects of synergistic muscles is supported by the results of Abe et al. [55]. The authors demonstrated that the gluteus maximus (located proximal to the pressure cuff), which was synergistically involved in performing the squat exercise, increased in muscle size at the completion of low-load BFR training. Furthermore, Yasuda et al. [48] noted a greater increase in swelling of the chest muscles compared with the triceps at the conclusion of low-load BFR bench press exercises, which is important as muscle cell swelling has been proposed as a potential mechanism driving muscle hypertrophy during BFR training [8]. Increased EMG activity and muscle swelling of the chest detail potential hypertrophic mechanisms augmenting muscle growth even in muscles that are proximal to the pressure cuff and not placed under direct BFR.

Additionally, the increase in chest and triceps muscle size following traditional high-load training appears to be slightly greater than that with low-load BFR training [45, 48]. This may be due to the larger quantity of muscle mass that needs to be fatigued. For example, robust muscle growth during compound exercises with BFR may require more volume than that needed for single joint exercises taxing only muscles located distal to the restrictive stimulus. In other words, BFR in combination with low-load bench press exercise may require a larger number of repetitions than the commonly used protocol of 1 set of 30 repetitions, followed by 3 sets of 15; however, this number will likely be less than what is required for unrestricted low-load bench press training.

4.2.2 *Shoulder and Back Muscle Size*

Only one study examined deltoid muscle size through the use of elastic band training, revealing a 3.8 % increase, which was not statistically significant [42]. One possible explanation for this may have been the low load used, which the authors speculated to be around 10–30 % 1RM. Considering the group training with moderate to heavy resistance (estimated at 70–90 % 1RM) also did not see significant muscle growth, it is plausible to assume that the load may have been overestimated or that the stimulus was inadequate at inducing growth over the time period allotted. Another possible explanation exists in that the synergistic involvement of the triceps muscles during shoulder press exercise is likely minuscule compared with that of the bench press exercise. Therefore, the triceps are only marginally fatigued, and the amount of increased stress placed on the shoulders is not great enough to induce muscle hypertrophy.

No studies provided a measure of back muscle size, and therefore we can only speculate on the effects of low-load BFR training in combination with this type of exercise. Considering the involvement of the biceps in exercises such as the lat pull-down and seated row, it may be plausible to assume that the synergistic involvement of the biceps is large enough to induce greater fatigue of the back musculature and provide greater muscle activation through the BFR stimulus. Although speculative, this would allow a greater stress to be placed on the back musculature, thus activating type II fibers in an attempt to make up for the loss of force production due to fatiguing of the biceps.

4.2.3 *Chest, Back and Shoulder Muscle Strength*

Improvements in isotonic 1RM strength of the chest musculature appear to be greater at the conclusion of high-load training than low-load BFR training. This may be partly related to the slightly reduced muscle growth that occurs in muscles located proximal to the pressure cuff. However, it would also make sense that high-load training would increase 1RM strength to a greater extent due to the principle of specificity. Individuals who have been consistently exercising at or near their respective 1RM would likely become much more proficient at lifting a heavier weight for that specific exercise being practiced, whereas someone who has become accustomed to lifting lighter loads will have less practice exercising near their 1RM in that particular lift. Therefore, performing a test that eliminates the skill involved in a 1RM would eliminate differences in training specificity and allow for a strict and unbiased testing of muscular strength.

Yasuda et al. [45] reported that strength per cross-sectional area (CSA) increased more at the completion of high-load training than low-load BFR training. This demonstrates a potentially greater increase in strength from neural adaptations and is supported by other studies reporting greater 1RM strength after high-load training [39, 48]. Only one study compared isometric testing at the conclusion of low-load BFR training with that of high-load training [45]. It was demonstrated that high-load bench press training increased maximal isometric elbow extension strength, whereas low-load BFR bench press training did not. This may be due to the combination of neural adaptations and the slightly greater muscle mass that was observed in the triceps at the conclusion of high-load training.

Additionally, muscle strength of the back (seated row) and shoulder (shoulder press) muscles appeared to be similar upon the completion of low-load BFR training and high-load training with resistance bands [42]. The increase in muscle strength would presumably be driven by muscle growth, although the increase in muscle size was not statistically significant. Additionally, no control group performed low-load resistance exercise in the absence of BFR, and, therefore, the possibility of a learning effect cannot be ruled out. It would appear that the BFR stimulus is effective at increasing muscle strength of the shoulder and back musculature [42], although a larger volume of exercise may be necessary to achieve greater muscle strength compared with muscles located distal to the restrictive stimulus (e.g., biceps, triceps).

4.3 Training Load

It has been reported that the benefits of BFR increase linearly with an increase in exercise intensity [56]; however, this has only been speculated using loads between 10 and 30 % and may only pertain to very low intensities. To illustrate, one study [42] implementing elastic band training noted that significant increases in shoulder muscle size may not have been present due to the extremely low load implemented (10–30 % 1RM). However, the authors reported increases in chest muscle size that were similar to those of other studies implementing bench press exercise at 30 % 1RM [47]. It is possible the resistance provided from the elastic bands was insufficient for stimulating muscle growth of the shoulder; however, no other studies measured shoulder muscle growth from low-load BFR training, so a direct comparison was not possible. The greatest increases in muscle strength were seen using loads of 50 and 60 % 1RM; however, of the two exercise protocols using a 50 % 1RM load [31, 38], one involved a set to volitional fatigue, and the other implemented a 60 % 1RM load used a handgrip protocol [32], making direct comparison difficult. Due to reasons associated with training specificity previously mentioned, it seems logical that muscle strength would increase to a greater extent through the lifting of heavier loads, although individuals already lifting heavier loads will likely see no further benefit by adding the BFR stimulus [57]. It would seem reasonable to hypothesize that the load used during upper extremity BFR training is important to an extent; however, once sufficient muscle activation is achieved, further increasing the load may provide no further beneficial adaptations (i.e., increasing from 10 to 30 % may be beneficial, but increasing from 30 to 60 % may not), although this is speculative.

While a 30 % load may maximize the benefits of BFR in the upper extremities, a greater load or number of repetitions may be beneficial when more compound lifts are being performed. It is likely that individuals performing the standard low-load BFR training protocol (1 set of 30 followed by 3 sets of 15) are at, or close to, volitional fatigue when single joint exercises (i.e., elbow flexion/extension) are performed. This may be due to the fatiguing effects of BFR being placed directly on the muscles being exercised. In contrast, this same protocol (1 set of 30 followed by 3 sets of 15) performed with a compound exercise (e.g., bench press, seated rows) will likely elicit muscle growth; however, the extent of growth may be slightly less than with high-load training. This may be attributed to the amount of muscle mass that needs to be indirectly fatigued by the BFR stimulus. Therefore, upper body exercises involving musculature proximal to the restrictive stimulus may see added benefit from either an increased load or a greater number of repetitions. This differs from compound exercises performed in the lower body (e.g., squats) because all of the involved musculature is located in the extremities distal to the restrictive stimulus.

4.4 Restriction Stimulus

It has previously been demonstrated that smaller limbs will require lower pressures to reach arterial occlusion [58].

Given the idea that wider cuffs appear to restrict more blood flow at a given pressure [59], it seems reasonable to suggest that smaller limbs in the upper body may allow for the use of lower pressures and narrower cuffs (3–5 cm) while still providing an adequate restriction stimulus and allowing for an increased range of motion. Additionally, arbitrary pressures (same pressure for all individuals independent of individual differences) are most commonly used in the upper and lower body, despite the suggestion that the restriction stimulus be made relative to the individual [58, 59]. This can be seen in Table 2, as only one study [33] made the pressure relative to the individual by prescribing it as a percent of arterial occlusion rather than simply applying the same pressure for all individuals. The prescription of a relative pressure can be done by directly measuring arterial occlusion, or appropriately estimating it based on limb circumference, as this has been shown to be the greatest predictor of arterial occlusion [58]. However, since arterial occlusion can be directly measured quite easily in the upper body, even with narrow cuffs (~5 cm), it may be ideal to directly measure arterial occlusion to increase the precision of the measure and ensure a safe and common stimulus is implemented across the entire study population. Studies should make mention of cuff widths used, in addition to pressures, as a set pressure will provide a much greater level of restriction using a 13.5-cm cuff than using 5-cm cuff [59]. To allow greater replication and evaluation of results, we suggest that BFR be prescribed as a percent of arterial occlusion. Despite not being able to apply specific pressures using knee wraps, two studies in this review [36, 44] demonstrated the application of BFR in a more practical setting, with both studies reporting greater increases in strength than that of a repetition-matched control group in the absence of BFR. Therefore, BFR can be appropriately administered through the use of elastic wraps, which is likely more practical than using a pneumatic cuff inflator throughout training [60].

Tables 2 and 3 illustrate that increasing the pressure applied during low-load BFR training does not appear to further augment increases in muscle size and strength over lower pressures. Three studies [40, 46, 49] implementing identical protocols and cuff widths illustrated that slightly greater increases in muscle size and strength were present using lower (100 mmHg) as opposed to higher (160, 270 mmHg) pressures. Therefore, it can be assumed that as long as a great enough restriction pressure is applied, further increasing this pressure will provide no further adaptation, although the minimal pressure required is unknown. This hypothesis is supported by Counts et al. [33], who demonstrated that increases in muscle size and strength are similar when exercising with either 40 or 90 % arterial occlusion. If this is further supported, it would seem that lower pressures would be more ideal for lowering the potential risk of an adverse event, which, while rare, would conceivably be more likely to occur under higher restrictive pressures [61].

4.5 Limitations

A variety of limitations inhibit the true generalizability of this review. The lack of a common control group made the completion of a widely inclusive meta-analysis incorporating all studies difficult. Additionally, muscle size and strength were measured with various methods and therefore could not be directly compared with one another. For example, measures of muscle strength will be altered by the specificity of resistance training (greater increases in isotonic testing following isotonic training; Table 3), and anthropometric measures of muscle size pose obvious limitations (i.e., they are not reflective of composition) as muscle mass only makes up a portion of arm circumference. The lack of a standardized protocol also created difficulties, as some studies implemented sets to volitional fatigue, while others used a more common protocol consisting of 1 set of 30 repetitions followed by 3 sets of 15.

5 Conclusion

This review illustrates that, contrary to common resistance training guidelines, increases in muscle size and strength can be achieved from the lifting of lighter loads provided a great enough stimulus, such as the application of BFR, is applied. It can be inferred that low-load BFR training produces greater increases in muscle size and strength than low-load training utilizing identical protocols in the absence of BFR. However, the comparison between low-load BFR and high-load training in the upper body requires further research utilizing more standardized protocols for appropriate comparison. An important finding from this review illustrated that BFR can increase muscle size and strength of various muscle groups in the upper body and is not strictly limited to the limbs; however, exercises targeting muscle groups located proximal to the restrictive stimulus (e.g., chest, shoulders, back) may further benefit from additional repetitions. Furthermore, it appears that the restrictive pressures applied are of minimal importance, as using higher pressures does not appear to augment muscle size and strength. The efficacy of low-load BFR in conjunction with upper body resistance training appears similar to that of the lower body [30] despite various anatomical and physiological differences. The efficacy of upper body aerobic exercise (arm ergometry) remains untested but provides an intriguing avenue for further research.

Compliance with Ethical Standards

Funding No external sources of funding were used to assist in the preparation of this article.

Conflicts of interest Scott Dankel, Matthew Jessee, Takashi Abe and Jeremy Loenneke declare that they have no conflicts of interest relevant to the content of this review.

References

1. ACSM. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. Med Sci Sports Exerc. 2009;41(3):687–708.
2. Mitchell CJ, Churchward-Venne TA, West DW, et al. Resistance exercise load does not determine training-mediated hypertrophic gains in young men. J Appl Physiol. 2012;113(1):71–7.
3. Ogasawara R, Loenneke JP, Thiebaud RS, et al. Low-load bench press training to fatigue results in muscle hypertrophy similar to high-load bench press training. Int J Clin Med. 2013;4:114–21.
4. Bemben DA, Fetters NL, Bemben MG, et al. Musculoskeletal responses to high- and low-intensity resistance training in early postmenopausal women. Med Sci Sport Exerc. 2000;32(11):1949–57.
5. Laurentino GC, Ugrinowitsch C, Roschel H, et al. Strength training with blood flow restriction diminishes myostatin gene expression. Med Sci Sports Exerc. 2012;44(3):406–12.
6. Martin-Hernandez J, Marin PJ, Menendez H, et al. Muscular adaptations after two different volumes of blood flow-restricted training. Scand J Med Sci Sports. 2013;23(2):e114–20.
7. Marcotte GR, West DW, Baar K. The molecular basis for load-induced skeletal muscle hypertrophy. Calcif Tissue Int. 2015;96(3):196–210.
8. Loenneke JP, Fahs CA, Thiebaud RS, et al. The acute muscle swelling effects of blood flow restriction Acta Physiol Hung. Acta Physiol Hung. 2012;99(4):400–10.
9. Loenneke JP, Fahs CA, Wilson JM, et al. Blood flow restriction: the metabolite/volume threshold theory. Med Hypotheses. 2011;77(5):748–52.
10. Patterson SD, Ferguson RA. Increase in calf post-occlusive blood flow and strength following short-term resistance exercise training with blood flow restriction in young women. Eur J Appl Physiol. 2010;108(5):1025–33.
11. Manini TM, Vincent KR, Leeuwenburgh CL, et al. Myogenic and proteolytic mRNA expression following blood flow restricted exercise. Acta Physiol (Oxf). 2011;201(2):255–63.
12. Nielsen JL, Aagaard P, Bech RD, et al. Proliferation of myogenic stem cells in human skeletal muscle in response to low-load resistance training with blood flow restriction. J Physiol. 2012;590(Pt 17):4351–61.
13. Drummond MJ, Fry CS, Glynn EL, et al. Rapamycin administration in humans blocks the contraction-induced increase in skeletal muscle protein synthesis. J Physiol. 2009;587(7):1535–46.
14. Gundermann DM, Walker DK, Reidy PT, et al. Activation of mTORC1 signaling and protein synthesis in human muscle following blood flow restriction exercise is inhibited by rapamycin. Am J Physiol Endocrinol Metab. 2014;306(10):E1198–204.
15. Pearson SJ, Hussain SR. A review on the mechanisms of blood-flow restriction resistance training-induced muscle hypertrophy. Sports Med. 2015;45(2):187–200.
16. Loenneke JP, Balapur A, Thrower AD, et al. Blood flow restriction reduces time to muscular failure. Eur J Sport Sci. 2012;12(3):238–43.
17. Loenneke JP, Kim D, Fahs CA, et al. Effects of exercise with and without different degrees of blood flow restriction on torque and muscle activation. Muscle Nerve. 2015;51(5):713–21.
18. Kubota A, Sakuraba K, Koh S, et al. Blood flow restriction by low compressive force prevents disuse muscular weakness. J Sci Med Sport. 2011;14(2):95–9.
19. Kubota A, Sakuraba K, Sawaki K, et al. Prevention of disuse muscular weakness by restriction of blood flow. Med Sci Sports Exerc. 2008;40(3):529–34.
20. Clark BC, Fernhall B, Ploutz-Snyder LL. Adaptations in human neuromuscular function following prolonged unweighting: I. Skeletal muscle contractile properties and applied ischemia efficacy. J Appl Physiol (1985). 2006;101(1):256–63.
21. Takarada Y, Takazawa H, Ishii N. Applications of vascular occlusion diminish disuse atrophy of knee extensor muscles. Med Sci Sports Exerc. 2000;32(12):2035–9.
22. Abe T, Fujita S, Nakajima T, et al. Effects of low-intensity cycle training with restricted leg blood flow on thigh muscle volume and $VO_{2\max}$ in young men. J Sports Sci Med. 2010;9(3):452–8.
23. Abe T, Kearns CF, Sato Y. Muscle size and strength are increased following walk training with restricted venous blood flow from the leg muscle, Kaatsu-walk training. J Appl Physiol. 2006;100(5):1460–6.
24. Sakamaki M, Bemben MG, Abe T. Legs and trunk muscle hypertrophy following walk training with restricted leg muscle blood flow. J Sports Sci Med. 2011;10:338–40.
25. Loenneke JP, Wilson JM, Wilson GJ, et al. Potential safety issues with blood flow restriction training. Scand J Med Sci Sports. 2011;21(4):510–8.
26. Vechin FC, Libardi CA, Conceicao MS, et al. Comparisons between low-intensity resistance training with blood flow restriction and high-intensity resistance training on quadriceps muscle mass and strength in elderly. J Strength Cond Res. 2015;29(4):1071–6.
27. Mattar MA, Gualano B, Perandini LA, et al. Safety and possible effects of low-intensity resistance training associated with partial blood flow restriction in polymyositis and dermatomyositis. Arthritis Res Ther. 2014;16(5):473.
28. Hylden C, Burns T, Stinner D, et al. Blood flow restriction rehabilitation for extremity weakness: a case series. J Spec Oper Med. 2015;15(1):50–6.
29. Ohta H, Kurosawa H, Ikeda H, et al. Low-load resistance muscular training with moderate restriction of blood flow after anterior cruciate ligament reconstruction. Acta Orthop Scand. 2003;74(1):62–8.
30. Loenneke JP, Wilson JM, Marin PJ, et al. Low intensity blood flow restriction training: a meta-analysis. Eur J Appl Physiol. 2012;16(112):1849–59.
31. Burgomaster KA, Moore DR, Schofield LM, et al. Resistance training with vascular occlusion: metabolic adaptations in human muscle. Med Sci Sports Exerc. 2003;35(7):1203–8.
32. Credeur DP, Hollis BC, Welsch MA. Effects of handgrip training with venous restriction on brachial artery vasodilation. Med Sci Sports Exerc. 2010;42(7):1296–302.
33. Counts BR, Dankel SJ, Barnett BE, et al. The influence of relative blood flow restriction pressure on muscle activation and muscle adaptation. Muscle Nerve. 2015. doi:10.1002/mus.24756.
34. Farup J, de Paoli F, Bjerg K, et al. Blood flow restricted and traditional resistance training performed to fatigue produce equal muscle hypertrophy. Scand J Med Sci Sports. 2015. doi:10.1111/sms.12396.
35. Hunt JE, Walton LA, Ferguson RA. Brachial artery modifications to blood flow-restricted handgrip training and detraining. J Appl Physiol (1985). 2012;112(6):956–61.

36. Luebbers PE, Fry AC, Kriley LM, et al. The effects of a 7-week practical blood flow restriction program on well-trained collegiate athletes. J Strength Cond Res. 2014;28(8):2270–80.
37. Lowery RP, Joy JM, Loenneke JP, et al. Practical blood flow restriction training increases muscle hypertrophy during a periodized resistance training programme. Clin Physiol Funct Imaging. 2014;34(4):317–21.
38. Moore DR, Burgomaster KA, Schofield LM, et al. Neuromuscular adaptations in human muscle following low intensity resistance training with vascular occlusion. Eur J Appl Physiol. 2004;92(4–5):399–406.
39. Ozaki H, Yasuda T, Ogasawara R, et al. Effects of high-intensity and blood flow-restricted low-intensity resistance training on carotid arterial compliance: role of blood pressure during training sessions. Eur J Appl Physiol. 2013;113(1):167–74.
40. Sakamaki M, Yasuda T, Abe T. Comparison of low-intensity blood flow-restricted training-induced muscular hypertrophy in eumenorrheic women in the follicular phase and luteal phase and age-matched men. Clin Physiol Funct Imaging. 2012;32(3):185–91.
41. Takarada Y, Takazawa H, Sato Y, et al. Effects of resistance exercise combined with moderate vascular occlusion on muscular function in humans. J Appl Physiol. 2000;88(6):2097–106.
42. Thiebaud RS, Loenneke JP, Fahs CA, et al. The effects of elastic band resistance training combined with blood flow restriction on strength, total bone-free lean body mass and muscle thickness in postmenopausal women. Clin Physiol Funct Imaging. 2013;33(5):344–52.
43. Weatherholt A, Beekley M, Greer S, et al. Modified Kaatsu training: adaptations and subject perceptions. Med Sci Sports Exerc. 2013;45(5):952–61.
44. Yamanaka T, Farley RS, Caputo JL. Occlusion training increases muscular strength in division IA football players. J Strength Cond Res. 2012;26(9):2523–9.
45. Yasuda T, Ogasawara R, Sakamaki M, et al. Combined effects of low-intensity blood flow restriction training and high-intensity resistance training on muscle strength and size. Eur J Appl Physiol. 2011;1(111):2525–33.
46. Yasuda T, Fukumura K, Uchida Y, et al. Effects of low-load, elastic band resistance training combined with blood flow restriction on muscle size and arterial stiffness in older adults. J Gerontol A Biol Sci Med Sci. 2015;70(8):950–8.
47. Yasuda T, Fujita S, Ogasawara R, et al. Effects of low-intensity bench press training with restricted arm muscle blood flow on chest muscle hypertrophy: a pilot study. Clin Physiol Funct Imaging. 2010;30(5):338–43.
48. Yasuda T, Ogasawara R, Sakamaki M, et al. Relationship between limb and trunk muscle hypertrophy following high-intensity resistance training and blood flow-restricted low-intensity resistance training. Clin Physiol Funct Imaging. 2011;31(5):347–51.
49. Yasuda T, Loenneke JP, Thiebaud RS, et al. Effects of blood flow restricted low-intensity concentric or eccentric training on muscle size and strength. PLoS One. 2012;7(12):e52843.
50. Fahs CA, Loenneke JP, Thiebaud RS, et al. Muscular adaptations to fatiguing exercise with and without blood flow restriction. Clin Physiol Funct Imaging. 2015;35(3):167–76.
51. Fahs CA, Loenneke JP, Rossow LM, et al. Cross-over muscular adaptation to blood flow-restricted exercise. Med Sci Sports Exerc. 2013;45(5):1018.
52. Fujita T, Brechue WF, Kurita K, et al. Increased muscle volume and strength following six days of low-intensity resistance training with restricted muscle blood flow. Int J KAATSU Training Res. 2008;4(1):1–8.
53. Ogasawara R, Thiebaud RS, Loenneke JP, et al. Time course for arm and chest muscle thickness changes following bench press training. Interv Med Appl Sci. 2012;4(4):217–20.
54. Ogasawara R, Yasuda T, Sakamaki M, et al. Effects of periodic and continued resistance training on muscle CSA and strength in previously untrained men. Clin Physiol Funct Imaging. 2011;31(5):399–404.
55. Abe T, Yasuda T, Midorikawa T, et al. Skeletal muscle size and circulating IGF-1are increased after two weeks of twice daily "KAATSU" resistance training. Int J KAATSU Training Res. 2005;1:6–12.
56. Abe T, Loenneke JP, Fahs CA, et al. Exercise intensity and muscle hypertrophy in blood flow-restricted limbs and non-restricted muscles: a brief review. Clin Physiol Funct Imaging. 2012;32(4):247–52.
57. Laurentino G, Ugrinowitsch C, Aihara AY, et al. Effects of strength training and vascular occlusion. Int J Sports Med. 2008;29(8):664–7.
58. Loenneke JP, Allen KM, Mouser JG, et al. Blood flow restriction in the upper and lower limbs is predicted by limb circumference and systolic blood pressure. Eur J Appl Physiol. 2015;115(2):397–405.
59. Loenneke JP, Fahs CA, Rossow LM, et al. Effects of cuff width on arterial occlusion: implications for blood flow restricted exercise. Eur J Appl Physiol. 2012;112(8):2903–12.
60. Loenneke LP, Pujol TJ. The use of occlusion training to produce muscle hypertrophy. Strength Cond J. 2009;31(3):77–84.
61. Loenneke JP, Thiebaud RS, Abe T, et al. Blood flow restriction pressure recommendations: The hormesis hypothesis. Med Hypotheses. 2014;82(5):623–6.