Blood Flow Restriction Therapy: A Review of Physiology, Clinical Application, and Guidelines for Implementation

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Abstract

Blood flow restriction (BFR) therapy is an emerging clinical modality utilizing the metabolic stress of a hypoxic state to induce hypertrophic and strength adaptations in a manner allowing for reduced external loading. BFR has a variety of applications in rehabilitation settings, showing great potential for patients seeking the benefits of high intensity training without the associated degrees of mechanical stress. This literature review details the proposed mechanisms of BFR, along with various clinical applications of BFR including active and aerobic BFR. Concerns and contraindications for BFR usage are discussed regarding certain clinical populations, with risk stratification recommendations provided. Current BFR technology is considered, and clinical application guidelines are specified for safely inducing hypertrophic and aerobic benefits in clinical populations.

Blood Flow Restriction Therapy: A Review of Physiology, Clinical Application, and Guidelines for Implementation

Blood flow restriction (BFR) therapy as a clinical modality has quickly gained traction as a viable tool for stimulating adaptations similar to those of high intensity resistance training while only requiring low external loads. BFR's origins began in Japan in the 1960s with the development of Kaatsu Training, a technique involving strapping a tightly bound band on the proximal limb to restrict blood flow prior to training (Hwang & Willoughby, 2019). Since then, the technology has evolved as research supporting BFR's effectiveness has increased, with newer models consisting of pneumatic cuffs inflating to and maintaining individualized occlusion pressures with the touch of a button.

To perform BFR, individuals wrap the cuff around their affected limb, typically at a proximal location such as the upper thigh or the upper arm. The cuff is then inflated to between 40-80% of total occlusion to minimize venous return distal to the cuff while still maintaining sufficient arterial blood flow to avoid adverse effects (Miller et al., 2021; Scott et al., 2023). The accumulation of deoxygenated blood paired with a reduction in oxygenated blood artificially generates a hypoxic environment for the local musculature, which increases the metabolic stress experienced by the affected muscles (Miller et al., 2021). BFR training is often paired with low load resistance training, and the resultant decrease in oxygen available to the working muscles makes the resistance feel greater in intensity. Clinically, BFR provides increased intensity without the need for placing the stress of heavy external loads on vulnerable patients who may struggle to train at higher intensities due to injury risk, re-injury potential, or exercise inexperience.

Given the sudden rise in BFR's clinical usage, increasingly rigorous scientific research supporting its effectiveness, and expansion of available BFR technology, it is important for clinicians to have current evidence-based BFR guidelines to follow. It is essential for clinicians who are considering the implementation of BFR with their patients to adequately understand the theoretical physiological mechanisms, recognize available benefits with different BFR applications, know how to safely screen patients for BFR therapy, and be confident in following research-backed usage recommendations. The current literature review will include content in the areas of proposed physiological mechanisms, indications, concerns and contraindications, population considerations, clinical recommendations, and current BFR technology.

Proposed Physiological Mechanisms of BFR

Muscular Adaptations

The physiological foundations of BFR must be understood by providers for BFR to be safely and effectively implemented into treatment plans. In general, BFR usage has been linked to increases in muscular hypertrophy and strength. There are two primary underlying mechanisms contributing to muscular strength gains, one of which is neuromuscular adaptations including motor unit recruitment, rate coding, and motor unit synchronization (Kenney et al., 2020). The other mechanism of strength gains is increased muscle cross-sectional area (CSA); more muscle area allows for more actin and myosin filaments and in turn more cross-bridges within the sarcomere and thus a greater potential to generate force (Kenney et al., 2020). Strength gains associated with BFR training may be primarily linked to hypertrophic increases in CSA, although a degree of neuromuscular adaptations likely also occur. The following summary of muscular hypertrophy will better pinpoint BFR's mechanism.

There are three primary mechanisms for muscular hypertrophy: mechanical tension, muscle damage, and metabolic stress (Schoenfeld, 2010). Mechanical tension is the result of muscular force generation and the stretching of involved sarcomeres. The tensile force experienced by the muscle tissue incites a cellular signaling cascade that eventually results in muscle growth (Schoenfeld, 2010). In the context of resistance training, the lowering phase of a bicep curl involves the biceps brachii eccentrically contracting while the involved sarcomeres are being stretched due to the forced lengthening of the muscle fiber under tension. The second driver of hypertrophy is muscle damage. Myotrauma such as that associated with resistance training is hypothesized to trigger a cascade of growth factors and a proliferation of satellite cells that ultimately leads to a hypertrophic response (Schoenfeld, 2010). The third mechanism of hypertrophy is found by the accumulation of metabolites and metabolic stress. During exercise that requires anaerobic glycolysis, the muscle's environment is altered from its resting state to an acidic environment as hydrogen ions accumulate due to the exercise demands. This decrease in intramuscular pH is associated with a buildup of metabolites, increased muscle fiber breakdown, and a subsequent hypertrophic response (Schoenfeld, 2010).

Although these three mechanisms are distinct from each other, there are appreciable additive effects that may contribute to the holistic hypertrophic response (Schoenfeld, 2010). While it is not necessary to have all three mechanisms present for hypertrophy to take place, some combination of all three may provide an optimal stimulus. As an example, bodybuilders have the goal of maximizing hypertrophy, and their training typically consists of pairing high volume resistance training with minimal rest times. This style of training combines mechanical tension with metabolic stress and yields muscle damage. Along the same lines, the concept of BFR takes advantage of both the metabolic stress resultant from muscle ischemia and the mechanical tension associated with resistance training to induce hypertrophic changes (Cognetti et al., 2022).

BFR-Related Hypertrophic Responses

Given these physiological underpinnings, a deeper exploration of the hypertrophic responses specifically related to BFR usage is warranted. The theoretical foundational concept of BFR is the creation of a hypoxic environment for the muscles via occlusion of the venous return proximally to the muscle, although some degree of arterial occlusion will also occur. By blocking the venous return, the deoxygenated blood depleted by the working muscles accumulates distally, reducing the oxygen availability for the musculature to an extent that taxes the muscle to a greater degree than they would experience under a similar but non-occluded condition (Miller et al., 2021).

Notably, the metabolic stress experienced by the muscles during low-load BFR (LLBFR) has been shown to be comparable to that of traditional high intensity resistance training (Miller et al., 2021). By restricting blood flow and oxygen delivery to tissues distal to BFR cuff placement, BFR induces a hypoxic environment that leads to an increase in lactate production via the anaerobic pathways that take over when oxygen is absent. The presence of increased lactate indicates decreases in intramuscular phosphocreatine (PCr) and pH alongside increased metabolic stress, which is one of the mechanisms of muscle hypertrophy (Miller et al., 2021; Schoenfeld, 2010).

Once the cuff pressure is released, the rush of blood flow triggers a cascade effect where the response to the metabolic stress stimulates metabolic, adrenergic, and hormonal changes contributing to muscular adaptations such as increases in muscular strength and hypertrophy (Miller et al., 2021). One noteworthy hormonal change that has been implicated in BFR research is a proposed increase in growth hormone (GH), which plays a role in the process of muscular hypertrophy (Hwang & Willoughby, 2019). The low pH environment induced by BFR has been associated with GH secretion, further supporting BFR's efficacy as a tool to induce hypertrophic responses (Hwang & Willoughby, 2019).

BFR has also been shown to have notable effects on different cell signaling pathways that have important physiological implications for increasing muscular hypertrophy. BFR usage has been linked to the downregulation of myostatin, which negatively regulates muscle growth and promotes muscle fibrosis (Cognetti et al., 2022; Miller et al., 2021). Thus, the downregulation of myostatin ultimately supports muscular hypertrophy (Cognetti et al., 2022). Additionally, BFR has demonstrated the capacity to stimulate the mechanistic target of rapamycin (mTOR) pathway, leading to cellular growth and anabolic responses (Cognetti et al., 2022).

Another physiological mechanism for BFR's effectiveness in promoting muscular hypertrophy is the proliferation of satellite cells (Cognetti et al., 2022; Hedt et al., 2022). Satellite cells are stem cells that inhabit skeletal muscle and play are pivotal role in muscle hypertrophy due to their ability to add nuclei to muscle fibers during tissue repair (Sousa-Victor et al., 2022; Wackerhage et al., 2018). In response to muscle damage, these satellite cells proliferate to regenerate skeletal muscle as they differentiate into myocytes upon being triggered (Sousa-Victor et al., 2022). Satellite cells have been implicated in increasing muscle protein synthesis, myonuclei content, myofiber size, and muscle strength via their role in aiding in muscle growth and regeneration (Cognetti et al., 2022; Hedt et al., 2022).

Another noteworthy physiological benefit of BFR is its ability to recruit higher threshold motor units than possible with non-occluded equal loads of resistance training. Since BFR amplifies the metabolic stress experienced by the muscle tissues, an earlier onset of fatigue is experienced, resulting in "greater motor unit recruitment to compensate for the reduction of force development" (Cognetti et al., 2022; Hwang & Willoughby, 2019). Consequently, even with low loads, BFR allows for recruitment of the type II muscle fibers that tend to be reserved for preferential recruitment at higher intensities in accordance with the Henneman size principle (Cognetti et al., 2022; National Strength and Conditioning Association, 2016). This has implications for clinical application, where muscle fibers that may not conventionally be activated during rehab have the opportunity for muscle damage and subsequent hypertrophy because of BFR usage. Overall, BFR has been proposed to work through the avenues of reduced oxygen availability, elevated metabolic stress, the stimulation and downregulation of different cell signaling pathways, amplified secretion of GH, heightened satellite cell proliferation, and higher threshold motor unit recruitment to increase muscular hypertrophy and build strength.

Indications of BFR

Once the physiological underpinnings of BFR usage are sufficiently understood, the indications related to common applications of BFR must be grasped. The BFR benefit with the greatest clinical implications is the potential improvement in muscle strength and hypertrophy without the degree of physical and mechanical stress associated with traditional high intensity resistance training (Miller et al., 2021). With BFR, hypertrophic adaptations can be realized at loads as low as 20-30% 1RM while nonoccluded hypertrophy recommendations are at much higher loads of 67-85% 1RM (Hedt et al., 2022; National Strength and Conditioning Association, 2016). Studies have shown LLBFR to be comparable to heavy load resistance training in its hypertrophic effects, although the strength benefits of heavy load resistance training are superior to those of LLBFR (Davids et al., 2021). Clinically, BFR allows clinicians to elicit anabolic effects with reduced external load, which is key for a variety of clinical scenarios including reducing the muscle atrophic effects induced by surgical interventions, progressing patients early in the rehabilitation process, and for use with populations where heavy lifting may be contraindicated (Hedt et al., 2022).

There are two main applications of BFR from a rehabilitation perspective: active and aerobic. Active BFR is the primary use of BFR and involves the patient performing targeted exercises such as body weight movements or resistance training while the BFR cuff is inflated with the goal of affecting specific musculature. Aerobic BFR typically involves cycling, walking, or jogging with a BFR cuff attached with the primary goal of aerobic adaptations.

Benefits of Active BFR

Currently, active BFR is the most well-known application of BFR, likely because this was the original use of this concept in Kaatsu training (Hwang & Willoughby, 2019). The benefits of active BFR, namely the comparable increases in hypertrophy and strength with lower external loads in comparison to resistance training, may seem foundational, yet the implications of this concept to clinical practice are widespread (Miller et al., 2021). BFR allows post-operative patients to experience the benefits of higher exercise-associated stress without the potentially negative effects associated with heavy lifting while injured. BFR can also be used as a tool to provide a supplemental stimulus for individuals further along in rehab. Clinically, there are several noteworthy indications associated with the implementation of active BFR including bone mineral density improvements, heightened recruitment proximal to BFR cuff placement, as well as local and systemic hypoalgesic benefits.

BFR and Bone Mineral Density

A valuable study demonstrated BFR's potential to mitigate both sarcopenia and bone mineral density (BMD) loss following ACL reconstructive surgery (Jack et al., 2022). Implications of this study include BFR-augmented rehab shortening return-to-play timelines for athletes undergoing ACL surgery and the use of BFR for patients with osteopenia better preserving BMD (Jack et al., 2022). In support of this finding, a recent meta-analysis found statistically significant differences in BMD with LLBFR and walking BFR usage in comparison to their non-occluded counterparts, however, high intensity resistance training was shown to be more effective than LLBFR in its effect on BMD (Wang et al., 2023). Thus, BFR may be an effective alternative to high intensity resistance training in its ability to preserve BMD and lean mass when high intensity resistance training is not feasible or recommended (Wang et al., 2023). Elderly patients with frail bones, postmenopausal women, and osteopenic patients who all may have an increased risk for fractures with heavily loaded resistance training could instead substitute light weights and a BFR cuff to induce similar hypertrophic gains (Wang et al., 2023). However, all other risks would need to be diligently assessed by each clinician to ensure safe effective use in this special population. Thus, more research is needed in these special populations prior to BFR utilization.

Proposed Proximal Benefit

Interestingly, BFR not only impacts musculature distal to the cuff placement, but even muscles proximal to the occlusion have shown to have greater recruitment levels (Cognetti et al., 2022). Unlike the adaptations distal to the occlusion site, a synthesis of the multiple studies' findings suggests a certain duration under occlusion or volume threshold must be surpassed to observe proximal benefit (Hedt et al., 2022). Clinical implications of this discovery include the ability to use BFR to secondarily hypertrophy and strengthen muscles such as the deltoids and gluteals even though these muscle groups would not have their blood supply directly occluded via the pneumatic cuff (Cognetti et al., 2022). For example, despite some inconsistent research findings on its efficacy, BFR could be implemented as a rehabilitation tool following rotator cuff surgery (Lambert et al., 2021).

Studies have shown an increase in pectoralis major EMG activity and resultant muscle swelling while bench pressing with BFR occluding the upper extremity (Dankel et al., 2016).

Additional research has found similar outcomes with lower extremity BFR requiring greater gluteal involvement as indicated by muscle swelling to maintain force output during squats (Dankel et al., 2016). This demonstrates the ability of BFR to fatigue distal musculature to a degree at which proximal musculature must increase contribution to maintain overall force output during exercise (Dankel et al., 2016).

Another study yielded greater shoulder muscle mass, endurance, and some parameters of isometric strength when BFR was implemented with standard rotator cuff exercises commonly used in clinical settings (Lambert et al., 2021). The potential for increased recruitment in proximal musculature could hold particular benefit for the shoulder musculature since the glenohumeral joint requires high degrees of dynamic coordination of numerous muscles to ensure optimal force-coupling and co-contraction (Lambert et al., 2021). However, a few studies have concluded no significant difference exists between occluded and nonoccluded exercise for proximal musculature (Jessee et al., 2018). One study reports an increase in EMG activity at the beginning of each set for the BFR condition that then levels out to comparable to the control group in a manner that indicates minimal resultant hypertrophic differences (Jessee et al., 2018). Overall, the hypothetical mechanism of requiring extra work from proximal musculature in addition to resultant muscle swelling proximal to cuff placement generally supports the potential for some degree of proximal benefit with BFR.

BFR and Hypoalgesia

Hypoalgesic effects have also been discovered in relation to BFR usage, which could have vast clinical implications. For patients who are unaccustomed to the inherent discomfort associated with the stresses of resistance training, the addition of a BFR cuff may moderate these symptoms and increase compliance of patients' home exercise program (HEP) (Hedt et al., 2022). BFR has been shown to "potentially enhance the analgesic effects of exercise-induced hypoalgesia (EIH)" (Cervini et al., 2023). EIH describes the effect exercise has been shown to have on pain. Regarding its mechanism of pain reduction, EIH could be "manifest[ed] as an increase in pain threshold, an increase in pain tolerance, and/or a reduction in ratings of pain intensity" (Vaegter & Jones, 2020).

EIH has been shown to extend outside the exercising limb, indicating that nociceptive inhibition and can occur both systemically and locally in response to exercise (Cervini et al., 2023). Compared to load-matched resistance training, low pressure BFR induces comparable EIH effects comparable and high pressure BFR induces greater EIH effects (Hughes & Patterson, 2020). Clinical implications of these findings are vast. For patients with unilateral injury, BFR exercise of the unaffected limb may produce systemic hypoalgesic effects resulting in pain relief of the affected limb (Hughes & Patterson, 2020). High pressure BFR has a superior hypoalgesic effect to high load resistance training, so BFR can provide pain relief for load-compromised patients (Hughes & Patterson, 2020). Hypoalgesic effects of BFR are just one of many different benefits of active BFR use in rehabilitation settings.

Benefits of Aerobic BFR

Although less frequently employed in rehabilitation settings, BFR can also metabolically increase the intensity of aerobic exercise without having to increase intensity via higher speeds or longer durations. Similar to how musculoskeletal adaptations can be stimulated at lower loads with BFR in resistance training, BFR in aerobic training can stimulate cardiovascular adaptations typically associated with higher intensities. Certain populations such as the elderly, injured, or sedentary may be unable to tap into the benefits associated with high-intensity aerobic exercise due its associated mechanical stress and required level of exertion (Silva et al., 2019). Yet, BFR allows for various beneficial adaptations including an ability to simultaneously provide both aerobic and muscular strength benefits at an intensity level typically incapable of delivering these benefits without occlusion (de Oliveira et al., 2016). Low-intensity aerobic exercise with BFR is uniquely able to yield gains in muscular strength to an extent not observed with high-intensity aerobic training with or without BFR and with non-BFR low-intensity (de Oliveira et al., 2016). With low-intensity BFR aerobic training, muscular hypertrophy and strength adaptations are greater than work-matched aerobic training, although the improvements are not to the magnitude of resistance training with BFR (Scott et al., 2023).

With aerobic training, the degree of metabolic stress can be estimated by the decline in tissue saturation index (TSI), which measures the amount of oxygen present in specific musculature via near-infrared spectroscopy (Wei et al., 2021). As an individual performs aerobic exercise, they will consume oxygen to be converted into ATP at varying rates based on their level of fitness and the level of intensity of the performed exercise. At a certain point, the individual's oxygen stores are depleted, which is when the body diverts to anaerobic pathways for energy production to sustain their activity. Notably, similar declines in TSI have been shown between moderate-intensity aerobic training with BFR and non-occluded high-intensity training (Wei et al., 2021). This suggests comparable degrees of muscle hypoxia despite significant differences in peak power between the one study's conditions: 40% peak power for the moderate-intensity BFR group and 70% peak power for the high-intensity group (Wei et al., 2021).

Aerobic capacity is often measured via VO_{2max}, which is the peak amount of oxygen available for utilization during a maximal effort bout of exercise (Lan et al., 2022). The more aerobically fit an individual is, the higher VO_{2max} they will often have. Studies have shown aerobic training combined with BFR can yield similar VO_{2max} improvements as traditional aerobic exercise, yet with less volume and at a lower intensity (Miller et al., 2021). Given the hypoxic environment BFR induces, the intensity of aerobic training is elevated when BFR is applied and as a result lower aerobic stimuli still provide adaptations to an extent that non-occluded conditions would not realize at the same intensity (Miller et al., 2021). Low-intensity continuous aerobic training with BFR has even demonstrated comparable effects to both high-intensity interval training and moderate intensity continuous training over an 8-week period (Lan et al., 2022). Clinically, this has significant potential for elderly populations, load-compromised individuals, or patients overcoming injuries because improvements in muscular hypertrophy, aerobic capacity, and functional endurance can be acquired without undue mechanical or cardiovascular stress (Scott et al., 2023).

There is also an associated EIH effect with aerobic exercise. Notably, an intensity threshold must be met for EIH to occur, with studies showing this threshold to be crossed during continuous exercise at 70% VO2 max or short duration bouts at 85% VO2 max (Cervini et al., 2023). Higher intensity and longer duration aerobic exercise maximizes EIH, yet many clinical populations may not have the capacity to achieve these intensities (Hughes et al., 2021). However, the addition of BFR allows for similar EIH effects at lower exercise intensities. Low intensity aerobic exercise with BFR has the potential to induce local and systemic hypoalgesic effects that low intensity aerobic exercise alone cannot (Hughes et al., 2021).

Given the intensity threshold that must be met for EIH to occur, without BFR aerobic exercise at 40% VO2 max has no EIH effects. With BFR usage, it is hypothesized that “the ischemia and metabolite-induced pain, along with mechanical compression of the underlying tissues during BFR, may contribute to EIH through a conditioned pain modulation effect whereby the pain/discomfort generated during BFR exercise reduces the perception of pain" (Hughes et al., 2021). In clinical populations, patients unable to achieve high aerobic intensities may be able to incorporate the use of BFR to reap cardiovascular, aerobic, and hypoalgesic benefits at lower aerobic intensities.

Potential Adverse Effects and Contraindications

Adverse Effects

Possible side effects of BFR as a clinical modality include paresthesia, itching, dizziness, delayed onset muscle soreness (DOMS), excessive pain, or general discomfort (de Queiros et al., 2021; Prue et al., 2022). Generally, these adverse effects can be acutely mitigated by reducing the pressure of the BFR cuff during each set to improve patient tolerance. There are a mixture of studies supporting BFR as either a pro-inflammatory or an anti-inflammatory tool in relation to DOMS, although most agree that higher cuff pressures generally contribute to higher instances of DOMS (Rodrigues et al., 2022). Should DOMS occur after initial sessions of BFR, its severity will often be greatly diminished with subsequent sessions (Rodrigues et al., 2022). Bruising may also occur due to the cuff's tightness, but this is often related to the user's propensity towards bruising (de Queiros et al., 2021; Prue et al., 2022). There is also some degree of risk of rhabdomyolysis and fainting, however these risks are only slightly elevated compared to traditional resistance exercise (de Queiros et al., 2021; Prue et al., 2022). These potential side effects warrant clinical awareness and supervision, particularly during initial BFR sessions so that cuff pressure can be adjusted as necessary to alleviate symptoms.

Vascular Concerns

The increasing popularity of BFR usage comes with inherent concerns regarding its safety and hesitancy with its application to clinical populations. The most notable contributor to this apprehension is related to potential formation of a venous thromboembolism (VTE) that could manifest as deep vein thrombosis (DVT) or pulmonary embolism (PE) (Bond et al., 2018). This is a warranted concern since the premise of BFR is based on mechanically narrowing the vasculature where the pneumatic cuff is placed. However, minimal detrimental effects and no clinically noteworthy events concerning vascular issues have been reported to date in direct relation to BFR usage (Patterson et al., 2019).

Regarding blood clot formation and BFR usage, research on the acute effects of BFR have shown no significant increases in on key coagulation values such as D-dimer, prothrombin fragment, and thrombin-antithrombin III complex, and C-reactive protein (Patterson et al., 2019). Had research shown these values to be elevated, this would have indicated blood coagulation taking place and a potential increased risk of blood clot formation (Patterson et al., 2019). Furthermore, chronic studies lasting 6-12 weeks have also shown no significant increases in fibrin degradation product, d-dimer, or creatine kinase in healthy elderly subjects, indicating a minimal clotting risk for longer term BFR usage in healthy populations (Patterson et al., 2019). BFR has also demonstrated no appreciable thrombus formation as measured by duplex ultrasound scans following 12 sessions of BFR in patients 6 weeks after knee surgery (Patterson et al., 2019).

In general, current research shows minimal risk of vascular events related to BFR usage as indicated by a lack of clinical reports of BFR-related clots, by key research-driven coagulation values, and by direct imaging following BFR interventions. However, it would be prudent to air on the side of caution and refrain from BFR usage when treating patients with a history of blood clots or those considered elevated risk for blood clots until further research is conducted with these populations.

Hemodynamic Concerns

Another potential cause for concern is BFR's hemodynamic effects. Given the lack of blood flow to certain tissues during BFR, there are warranted concerns that blood pressure or heart rate may be significantly altered in response. However, appropriately prescribed BFR with an occlusion pressure of less than 200mmHg does not negatively affect hemodynamic responses in healthy adults, with its effects being comparable to that of traditional exercise (Miller et al., 2021). In general, using BFR with higher occlusion pressures of greater than 200mmHg yields limited return and may incur unfavorable vascular changes (Miller et al., 2021). Considering blood pressure (BP), mean arterial pressure (MAP), cardiac output (CO), stroke volume (SV), and heart rate (HR), the addition of BFR to low load resistance training does not show greater effects when compared to heavy load non-occluded training (Kesrouani et al., 2022). Rather, favorable measures of reduced CO and HR have been shown in comparison to traditional heavy loaded training, indicating that BFR may be a safe alternative to heavy load training in terms of hemodynamic responses (Kesrouani et al., 2022). BFR's possible side effects along with vascular and hemodynamic concerns merit clinical attention, patient education, and individualized clinical screening prior to BFR usage.

Population Recommendations and Contraindications

As with any clinical tool with any degree of risk, the clinician intending to use BFR on a patient should perform a brief risk stratification of that individual to ensure the benefits of implementing BFR into their program outweigh the potential risks. A useful algorithm to measure patients' risk of thromboembolism formation is the IMPROVE Risk Score, providing clinicians with insight into if BFR usage is prudent with their patient (Nascimento et al., 2022). Knowledge of the patient's medical history and current condition are key factors in the decision to introduce BFR training. Conditions such as diabetes mellitus (DM), hypertension (HTN), cardiovascular disease (CVD), as well as pregnant and post-surgical patients may be at increased risks of DVT, clot formations, or other adverse effects (Nascimento et al., 2022). Thus, patient education and risk stratification are of particular importance with these at-risk populations in order to optimize patient outcomes without undue risk.

Diabetic Patients

Individuals with DM are typically in a prothrombotic state, which indicates they have an increased risk for DVT (Nascimento et al., 2022). As a result, clinicians should proceed with caution when considering BFR use with DM. For patients with CVD, HTN, or other ischemic conditions, if they also have an elevated thromboembolism risk as determined by the IMPROVE Risk Score, then BFR usage is contraindicated and alternative methods should be considered (Nascimento et al., 2022). In cases where no additional risk factors have been identified and the patient is familiar with resistance training, BFR could be carefully implemented, although blood pressure should be diligently monitored throughout the training session (Nascimento et al., 2022).

Pregnant/Postpartum Patients

With pregnant or postpartum patients, stasis and hypercoagulability are cautionary conditions for BFR usage (Bond et al., 2018; Nascimento et al., 2022). The enlarged uterus obstructs venous return, leading to as much as a 50% reduction in blood flow to the lower extremities, which typically stabilizes at 6 weeks postpartum (Nascimento et al., 2022). This decreased venous return can also lead to stasis, or the slowing or stoppage of blood flow (Bond et al., 2018). Stasis increases the risk of thromboembolism greatly since blood that is not moving has greater chance to clot. Pregnancy may also induce a prothrombotic state, which further increases their risk of thromboembolism with BFR usage (Nascimento et al., 2022). After 6 weeks, BFR could be considered with clinical judgement, although the associated risks may still be elevated. Just as extra caution is warranted for resistance training with pregnant or postpartum individuals, BFR also requires high levels of clinical judgment to determine if BFR is safe for this population. Since there have been limited studies on the topic of pregnancy with BFR, it is recommended to implement alternative clinical methods until approximately 6 weeks postpartum.

Post-operative Patients

Post-operative patients have been shown to be an a highly elevated risk for DVT in the first 6 weeks following surgery, although the extent of the risk varies with the type of surgery and the degree of vascular damage incurred as a result of the procedure (Bond et al., 2018; Nascimento et al., 2022). There have been a variety of studies that have provided different timelines for when BFR can safely be implemented following surgical procedures. BFR application before 6 weeks post-surgery is accompanied by an increased risk of thromboembolisms, although several studies have explored BFR usage as early as 2 days after surgery without adverse effects (Nascimento et al., 2022).

Another consideration is protecting the sutures guarding the wound from the surgical site. With smaller arthroscopic surgeries, the wound may be small enough that BFR could be incorporated as tolerated within days following the procedures (DePhillipo et al., 2018a). However, for surgical interventions with larger incision sites and sutures, it is prudent to wait until after suture removal for BFR usage in order to allow for proper wound healing. In any case, clinical judgement is of utmost importance when considering the patient's risk. The clinician's decision regarding if and when to begin BFR must weigh the patient's current medical condition, their medical history, their IMPROVE Risk Scale score, the type of surgery, the region of the surgery, the duration of their recovery, and their acute and chronic response to the BFR stimuli.

Sedentary Patients

For inactive patients or those unfamiliar with exercise movements, BFR could provide an additional stimulus. However, it is recommended that they first be familiarized with resistance training movement patterns or aerobic conditioning prior to engaging in BFR training. Once the patient demonstrates movement pattern proficiency showing sufficient motor control, BFR could be introduced as a supplement to their regimen. Due to the metabolic stress induced by BFR, biomechanical movement patterns may be altered as the body must rely on higher threshold motor units to perform the tasks in the induced hypoxic state (Cognetti et al., 2022; Telfer et al., 2021). For resistance training, the biomechanical adjustments with BFR have been shown to be minimal (Telfer et al., 2021). However, from a motor control perspective, it would be beneficial to demonstrate movement pattern mastery of nonoccluded movements prior to the addition of BFR.

Similarly, a degree of compensatory kinematics in aerobic walking have been demonstrated with BFR due to the early onset of fatigue (Walden et al., 2023). Although this may have a minimal impact, the clinician must judge whether the cardiovascular benefits of walking with BFR outweighs the potential for the compensatory biomechanics of the exercise (Walden et al., 2023). Lastly, individuals using BFR tend to report higher RPE scores compared to nonoccluded training (Miller et al., 2021). From a compliance standpoint, patients who do not consistently participate in a resistance training program ought to first be familiarized with resistance training prior to engaging in BFR due to the degree of potential discomfort they may experience with BFR.

Elderly Patients

BFR shows potential for use with elderly patients since this population generally cannot tolerate the stresses of high intensity training, yet they stand to benefit greatly from physical training to combat sarcopenic and osteopenic effects associated with aging (Wang et al., 2023; Yuan et al., 2023). BFR training allows this population to reap the benefits of higher intensity training without the accompanying mechanical stresses. Even the addition of BFR to a low intensity walking regimen can develop the muscle strength and aerobic function of elderly patients that often struggle with diminishing physical functioning (Yuan et al., 2023). Pairing BFR with low-load resistance exercises has been shown to provide hypertrophic and muscle strengthening benefits in elderly populations, which is important in mitigating sarcopenia and lowering fall risks (Baker et al., 2020; Yuan et al., 2023).

Research has demonstrated gains in lower body strength has a substantial correlation to improvements in gait, balance, and coordination; deficits in these key factors contribute greatly to fall risk in elderly patients (Baker et al., 2020). With older patients, clinicians should not consider BFR use if they are not confident in their patient’s ability to safely perform nonoccluded resistance or aerobic training. If traditional exercise is viable, then BFR use could be applied with consideration to the individual’s activity status, medical history, IMPROVE Risk Score, and risk of adverse events (Nascimento et al., 2022).

Adolescent Patients

BFR studies have largely been conducted on adult subjects, although there are multiple studies with adolescent subjects that have demonstrated BFR to be safe and effective. Two recent studies investigated the effects of BFR in ACL reconstructive surgery (ACLR) rehabilitation. Given the prevalence of adolescent ACL injuries, the findings from these studies could have noteworthy implications for clinicians working with high school athletes. One study demonstrated the use of active BFR early in the rehab process to improve strength measures at the 3-month mark and at return to sport (RTS) testing compared to the control (Roman et al., 2023). This study reported no adverse effects and concluded BFR implementation to be effective for adolescent ACLR rehab in improving isometric and isokinetic knee extension strength as well as subjective knee function measures in comparison to traditional rehab procedures (Roman et al., 2023). The second study investigated adolescent patient tolerance of BFR. Findings include no reported adverse events as well as generally positive patient tolerance, with an 89.53% exercise completion rate and a pressure decrease request 3.55% of the sessions (Prue et al., 2022). Current research demonstrates BFR to be safe for use with healthy adolescents, although clinician discretion is advised to determine if the benefits of BFR outweigh potential risks inherent with BFR use (Prue et al., 2022; Roman et al., 2023).

Clinical Recommendations

Ideal candidates for BFR usage include patients who are generally active, free from temporary or permanent conditions altering blood flow, and are capable of safely performing traditional resistance training movement patterns yet are not able to safely tolerate high intensity training (Bond et al., 2018). For post-surgical patients, ideal candidates are further specified to include those with less traumatic injuries, less invasive orthopedic surgeries, limited vascular damage from the surgery, no open wounds, and operative sites away from the where the BFR cuff will be applied (Bond et al., 2018). Patients that fall outside of these broad parameters ought to receive additional caution and screening prior to BFR application (Bond et al., 2018).

General clinical guidelines include the potential use of active BFR as a prehab tool prior to surgical procedures in accordance with the preoperative exercise principle related to surgical recovery (Franz et al., 2022; Wang et al., 2021). For patients undergoing major surgeries, better preoperative states can be readily achieved via clinical prehab exercise sessions and are often indicative of better surgical outcomes (Wang et al., 2021). After surgery has taken place, active BFR can be implemented as an additional stimulus to traditional resistance training as tolerated. Patients should progress gradually from body weight to BFR with body weight to external loads to BFR with external loads. In keeping with the principle of progressive overload, clinician's goals at this stage of postsurgical rehabilitation should include reduced dependence on BFR with a smooth transition to traditional rehab with higher intensity exercises as tolerated.

Clinician supervision is vital with BFR usage, as there could be varying responses to this training modality. If the onset of adverse effects should occur, the overseeing clinician using their best judgment should either reduce the occlusion pressure or remove the BFR cuff entirely (Table 1). Although there are several conditions that have increased risks of negative effects associated with BFR use, the careful implementation of BFR can minimize risks to an extent where the risk is comparable to traditional exercise (Nascimento et al., 2022).

For BFR usage in rehabilitation settings, additional certification is not currently required for appropriately qualified practitioners. BFR training is considered by the American Physical Therapy Association (APTA) to be within the professional scope of practice for physical therapists given their educational foundation and clinical reasoning. However, various certifications are offered for clinicians interested in maximizing their knowledge of evidence-based practice with this emerging modality.

Table 1: Reasons to Discontinue BFR Training Sessions

- Development of significant cardiac arrhythmias
- Onset of chest pain or discomfort
- Dizziness, confusion, or deteriorating balance
- Paleness or other significant abnormal discolorations
- Vomiting or nausea
- Swelling or shortness of breath
- Subject requests to stop

An exact blueprint for the clinical application of BFR that minimizes patient risk and discomfort while maximizing musculoskeletal adaptations has not been agreed upon in current literature. However, researchers agree upon the general guidelines for active BFR to be low-load resistance, moderate volume, brief rest periods, and moderate occlusion pressures (Scott et al., 2023). Regarding specific protocols, many studies have demonstrated the merit of using 20-40% 1-rep maximum (1RM) resistance, an initial set of 30 reps following by 3 subsequent sets of 15 reps, rest periods of 30-60 seconds, and a limb occlusion pressure (LOP) of 40-80% as outlined in Table 2 (Das & Paton, 2022; Patterson et al., 2019; Scott et al., 2023).

For aerobic BFR, general guidelines include walking or cycling at >50% VO_{2max} or HRR, LOP of 30-40%, for 5-20 minutes as summarized in Table 3 (Patterson et al., 2019). Research has shown limiting returns with greater than 40% LOP during aerobic BFR (Wei et al., 2021). Regarding LOP, general recommendations are to gradually familiarize the patient with increasing occlusion pressures over the course of multiple sets or sessions as necessary until the desired LOP for the task is appropriately tolerated (Bond et al., 2018). For active BFR, there are three primary types of occlusion pressure application, with each application method having advantages and disadvantages. The three methods are continuous, intermittent, and resting BFR.

Table 2: Active BFR Guidelines in Clinical Settings

Active BFR Guidelines	20-40% 1RM	
	40-80% LOP	Upper Extremity: 40-50% LOP Lower Extremity: 50-80% LOP
	4 total sets per exercise	1st set 30 reps 3 sets 15 reps
	30-60 sec rest periods	

Table 3: Aerobic BFR Guidelines in Clinical Settings

Aerobic BFR Guidelines	>50% VO_{2max} or HRR
	30-40% LOP
	Walking or cycling
	5-20 min duration

Continuous BFR

Continuous BFR consists of the BFR cuff remaining inflated throughout the duration of the training session for each exercise. This is the most typical application of active BFR, because the hypoxic environment is maintained throughout the session and metabolic stress is able to be accumulated due to the lack of blood flow removing the metabolites from the working muscles (Schwiete et al., 2021). While this application is effective, a common complaint is elevated rates of perceived exertion (RPE) and discomfort while performing exercises (Schwiete et al., 2021). Although minor, this downside has led to further research into potential alternate active BFR applications, such as intermittent and resting BFR.

Intermittent BFR

In contrast to continuous BFR, intermittent BFR consists of deflating the cuff during rest periods to allow blood flow reperfusion before reinflating the cuff before the patient begins their next working set. Releasing the cuff during rest intervals has been shown to reduce discomfort and consequently increase the tolerability of BFR training (Freitas et al., 2020). Although allowing blood flow reperfusion may appear counterproductive in the BFR training context, conflicting research has demonstrated that it may be comparably effective with continuous BFR (Freitas et al., 2021). One study found similar metabolic stress and muscle activity during continuous and intermittent BFR resistance exercises, implying that the pressure release during rest periods did not affect potential hypertrophic adaptations (Freitas et al., 2020). Although more research is warranted, if intermittent BFR provides similar results while inducing less discomfort, intermittent BFR may be a highly valuable clinical application of BFR due to improvements in exercise tolerance and adherence (Freitas et al., 2020; Watson et al., 2022).

Resting BFR

Opposite of intermittent BFR, resting BFR consists of deflating the cuff while the patient performs the exercise and then keeping the cuff inflated during the patient's rest periods. This may also be a clinically beneficial application, as the perceived discomfort of resting BFR is greatly reduced in comparison to continuous BFR (Schwiete et al., 2021). One particular study demonstrated comparable effects between continuous BFR and resting BFR, although continuous BFR may be more effective in developing muscular strength (Schwiete et al., 2021). Yet, resting BFR may be a viable, well-tolerated alternative to continuous BFR in clinical settings because it maintains the metabolic stress accumulated over the course of the training set during the rest period without the discomfort of continuously occluding blood flow (Schwiete et al., 2021).

A suggested clinical progression for implementing BFR into a patient's regimen consists of initial exposure to resting BFR, a transition into intermittent BFR, and finally incorporating continuous BFR. This provides patients with opportunity to grow accustomed to the sensations associated with BFR usage in order to minimize discomfort and maximize adherence to the rehab program. Patients familiar with BFR may opt to directly begin with continuous BFR, but gradual introduction to this modality for new patients allows for comparable indications while mitigating potential discomfort (Freitas et al., 2021; Schwiete et al., 2021; Watson et al., 2022).

BFR Technology

The technology of BFR has evolved greatly from its original inception. Presently, there are numerous types of BFR tools, ranging from manually applied compression bands to Bluetooth-enabled and AI-powered systems. Current models often include rapid, individualized limb occlusion pressure (LOP) calibration, the ability to program continuous, intermittent, or resting BFR depending on the patient's needs, and even connectivity to a user-friendly phone application the clinician can use to remotely control the BFR cuff. When considering the application of BFR to clinical populations, accurate control of LOP is important to minimize patient risk and ensure consistency. Thus, the use of manually applied BFR such as bands or wraps is currently not advised for clinicians, particularly given the abundance of available BFR technology that can accurately ensure consistent, controlled occlusion pressures. It is worth noting that BFR products with FDA approval have the legal benefit of safeguarding providers from the potential legal consequences if an adverse event should occur with a patient using a non-FDA approved BFR tool.

There are several factors related to the dimensions of the cuff and how that can impact BFR training. The LOP, which is the minimum pressure to completely occlude blood flow distal to the cuff, varies with the width of the BFR cuff. The wider the cuff, the less absolute pressure necessary to cease blood flow. Wider cuffs have also been shown to have a reduced risk of adverse events due to greater distribution of pressure across the surface area of the limb compared to thinner cuffs due (Patterson et al., 2019). Further, participants with wide cuffs generally experience less muscle pain compared to thinner cuffs (DePhillipo et al., 2018b). Thus, wider cuffs are generally recommended when treating clinical populations as long as they are not too wide to the point that movement is impaired.

With the rapid emergence of BFR technology in clinical practice in recent years, the body of rigorous BFR research has grown at a comparable rate. The publication of BFR-related systematic reviews has been exponential over the past five years, with significant support for the efficacy of BFR in the stimulation of hypertrophic and strength adaptations with use in both healthy populations and load-compromised clinical populations with a variety of injuries or conditions (Patterson et al., 2019). This current review of literature has demonstrated strong evidence for the use of BFR in the development of muscular strength, muscular hypertrophy, and aerobic adaptations in various clinical populations given the safe implementation under clinical supervision. Potential areas of future research on this topic will include establishing optimized BFR protocols, verifying underlying physiological mechanisms, designing enhanced BFR cuff technology, exploring specific indications and side effects, and investigating the safety and efficacy of usage with certain special populations (Patterson et al., 2019; Rolnick et al., 2023).

Summary

BFR is a viable clinical modality that can be easily implemented into most rehabilitation programs. A majority of patients that would benefit from muscular strength, muscular hypertrophy, and aerobic adaptations could have BFR strategically incorporated into their regimen. By diligently ensuring maximal safety via risk stratification, clinical judgment, and the IMPROVE Risk Score, clinicians can safely implement BFR for their patients. Clinicians have several options for incorporating BFR, namely active or aerobic BFR, as well as continuous, intermittent, or resting applications of active BFR. By adhering to evidence-based BFR recommendations, following the principle of progressive overload, and using clinical judgment and supervision, patients can reap the benefits of BFR. BFR is a fast-growing tool that shows great potential for use in clinical populations.

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