Blood Flow Restriction (BFR) training in rehabilitation: A comprehensive review of safety, contraindications, dosage parameters, clinical effectiveness, and applications across diverse patient populations

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Abstract:

Blood Flow Restriction (BFR) training has emerged as a transformative rehabilitation strategy that enables significant improvements in skeletal muscle strength, hypertrophy, and functional recovery while utilising substantially lower exercise loads than conventional resistance training. Originally developed in Japan as KAATSU training, BFR has evolved into an evidence-based intervention widely adopted in sports medicine, orthopaedic rehabilitation, neurological rehabilitation, geriatric care, and postoperative recovery programmes. By partially restricting arterial inflow while substantially limiting venous return through specialised pneumatic cuffs, BFR creates a hypoxic intramuscular environment that stimulates metabolic stress, cellular swelling, endocrine activation, and recruitment of fast-twitch muscle fibres. These physiological responses closely resemble those achieved through high-intensity resistance exercise despite the application of only 20–40% of one-repetition maximum (1RM), making BFR particularly valuable for individuals unable to tolerate heavy mechanical loading due to injury, surgery, pain, or chronic disease (Patterson et al., 2019).

Although clinical evidence increasingly supports the efficacy of BFR training, concerns regarding patient safety, vascular complications, optimal cuff pressure, exercise dosage, contraindications, and implementation protocols continue to limit widespread clinical adoption. Improper application may increase the risk of nerve compression, excessive pain, tissue injury, or thrombotic events, particularly in patients with cardiovascular disease, peripheral vascular disorders, uncontrolled hypertension, or coagulation abnormalities (Hughes et al., 2017). Consequently, evidence-based screening, individualised occlusion pressure determination, and clinician supervision are essential components of safe practice.

Recent systematic reviews and clinical guidelines demonstrate that appropriately prescribed BFR training significantly improves muscle strength, muscle cross-sectional area, functional mobility, pain reduction, and rehabilitation outcomes across diverse patient populations, including individuals recovering from anterior cruciate ligament reconstruction, total knee arthroplasty, osteoarthritis, sarcopenia, neurological disorders, and chronic musculoskeletal conditions (Scott et al., 2015; Centner et al., 2019). Emerging evidence also suggests potential applications in cardiovascular rehabilitation, intensive care unit recovery, and age-related muscle preservation.

This review comprehensively examines the physiological mechanisms underlying BFR training, current evidence regarding safety and contraindications, recommended dosage parameters, clinical effectiveness across various rehabilitation settings, and future research directions. By synthesising contemporary literature, this review aims to provide healthcare professionals with practical guidance for integrating BFR safely and effectively into evidence-based rehabilitation programmes.

Keywords:

Blood flow restriction training, KAATSU, rehabilitation, muscle hypertrophy, occlusion training, resistance exercise, physical therapy, patient safety.

1. Introduction:

The maintenance of skeletal muscle mass and strength is fundamental to functional independence, mobility, metabolic health, and quality of life. Muscle weakness resulting from injury, surgery, prolonged immobilisation, ageing, or chronic disease significantly impairs physical function and delays rehabilitation. Conventional rehabilitation programmes rely heavily on progressive resistance exercise performed at intensities exceeding 60–70% of one-repetition maximum (1RM) to induce meaningful muscular adaptations (American College of Sports Medicine, 2021). However, many clinical populations cannot tolerate such mechanical loading because of postoperative restrictions, joint pain, and tissue healing constraints, inflammation, neurological impairment, or frailty (Hughes et al., 2017).

Patients recovering from orthopaedic surgery often experience prolonged muscle atrophy due to reduced weight-bearing and restricted physical activity. Similar challenges occur among older adults with sarcopenia, individuals with osteoarthritis, patients following tendon repair, and people with neurological disorders who are unable to generate sufficient exercise intensity to stimulate muscle adaptation (Lixandrão et al., 2018). Consequently, rehabilitation professionals have sought alternative interventions capable of promoting muscle preservation while minimising joint stress and tissue loading.

Blood Flow Restriction (BFR) training represents one of the most significant innovations in modern rehabilitation. Initially introduced by Dr Yoshiaki Sato in Japan during the 1960s under the term KAATSU training, BFR was originally developed based on observations that temporary vascular compression during prolonged kneeling produced sensations similar to muscular fatigue experienced during resistance exercise (Sato et al., 2005). Over subsequent decades, technological advances in pneumatic cuff systems, improved understanding of vascular physiology, and increasing scientific investigation have transformed BFR from an experimental technique into an internationally recognised therapeutic modality.

Unlike traditional resistance exercise, BFR combines low-load exercise with partial vascular occlusion. A pneumatic cuff is positioned proximally around the upper arm or thigh and inflated to an individually determined pressure that partially restricts arterial inflow while substantially reducing venous outflow. During exercise, blood enters the working muscles but exits more slowly, creating a temporary hypoxic and metabolically stressful environment (Patterson et al., 2019).

This localised reduction in oxygen availability promotes rapid accumulation of metabolites such as lactate, hydrogen ions, inorganic phosphate, and other metabolic by-products. These changes stimulate multiple anabolic pathways that collectively enhance muscle protein synthesis, satellite cell activation, hormonal responses, and recruitment of high-threshold motor units despite the use of relatively light external loads (Pearson & Hussain, 2015). Consequently, exercises performed at only 20–30% of 1RM may produce muscle adaptations comparable to those observed with conventional high-load resistance training.

The physiological rationale supporting BFR has been strengthened considerably over the past decade. Investigations demonstrate significant increases in muscle cross-sectional area, maximal voluntary contraction, electromyographic activity, and functional performance following low-load BFR interventions across healthy adults, athletes, postoperative patients, and older populations (Loenneke et al., 2012). These findings challenge the traditional belief that substantial mechanical loading is essential for muscle hypertrophy and indicate that metabolic stress represents an equally important stimulus for muscular adaptation.

Beyond skeletal muscle hypertrophy, BFR training influences multiple physiological systems. Acute sessions stimulate secretion of anabolic hormones including growth hormone, insulin-like growth factor-1 (IGF-1), vascular endothelial growth factor (VEGF), and nitric oxide-related signalling molecules that contribute to muscle regeneration and angiogenesis (Pearson & Hussain, 2015). Repeated training also enhances capillary density, mitochondrial adaptations, neuromuscular activation, tendon stiffness, and functional capacity, thereby supporting comprehensive rehabilitation outcomes.

Clinical interest in BFR has expanded rapidly because numerous patient populations are unable to perform heavy resistance exercise safely. Following anterior cruciate ligament (ACL) reconstruction, patients often experience substantial quadriceps atrophy within the first postoperative weeks. Traditional strengthening protocols are frequently delayed to protect surgical graft integrity, resulting in prolonged weakness and functional deficits. Low-load BFR training provides an attractive alternative by promoting muscle maintenance while respecting postoperative loading restrictions (Hughes et al., 2017).

Similarly, individuals undergoing total knee arthroplasty, rotator cuff repair, Achilles tendon repair, or fracture rehabilitation often experience extended periods of reduced mechanical loading. BFR enables clinicians to introduce strengthening exercises earlier during recovery without exposing healing tissues to excessive stress (Patterson et al., 2019).

Age-related sarcopenia presents another major healthcare challenge. Progressive declines in muscle mass and strength contribute to falls, disability, hospitalisation, and loss of independence among older adults.

Unfortunately, many elderly individuals cannot tolerate conventional high-intensity resistance programmes because of osteoarthritis, cardiovascular disease, chronic pain, or frailty (Centner et al., 2019). BFR training offers a feasible alternative capable of improving muscle strength and physical performance while imposing minimal joint loading.

Growing evidence also supports BFR in neurological rehabilitation. Patients with stroke, multiple sclerosis, spinal cord injury, and Parkinson's disease commonly experience muscle weakness secondary to impaired neural activation and reduced physical activity. Preliminary studies indicate that appropriately supervised BFR may enhance muscle activation, walking performance, balance, and functional recovery in selected neurological populations, although further research remains necessary (Nascimento et al., 2020).

Despite these promising applications, several concerns continue to influence clinical acceptance of BFR. Questions remain regarding appropriate cuff width, optimal occlusion pressure, exercise intensity, treatment frequency, duration of cuff inflation, and safe progression strategies. Inappropriate application may increase discomfort, excessive blood pressure responses, nerve compression, or vascular complications (Scott et al., 2015).

One of the most frequently debated issues involves thromboembolic risk. Because BFR intentionally alters blood flow dynamics, clinicians have expressed concerns regarding deep vein thrombosis, pulmonary embolism, endothelial dysfunction, and vascular injury. However, contemporary evidence indicates that when evidence-based screening protocols and individualised occlusion pressures are employed, the incidence of serious adverse events remains extremely low in appropriately selected patients (Patterson et al., 2019). Nevertheless, individuals with active thrombosis, severe peripheral arterial disease, uncontrolled hypertension, advanced cardiovascular disease, sickle cell disease, severe infection, or other contraindications require careful evaluation before BFR implementation.

Standardisation represents another challenge. Numerous studies employ different cuff widths, occlusion pressures, exercise prescriptions, and outcome measures, making comparisons difficult. International consensus recommendations now advocate determining cuff pressure according to each patient's limb occlusion pressure (LOP) rather than using arbitrary pressures, thereby improving both safety and treatment consistency (Patterson et al., 2019).

As the evidence base expands, BFR is increasingly incorporated into multidisciplinary rehabilitation programmes delivered by physiotherapists, sports medicine clinicians, athletic trainers, rehabilitation physicians, and strength and conditioning specialists. Integration with conventional resistance training, neuromuscular exercise, aerobic conditioning, and functional rehabilitation may further optimise patient outcomes while reducing rehabilitation duration.

Given the rapid expansion of scientific literature, healthcare professionals require a comprehensive understanding of the physiological mechanisms, clinical indications, safety considerations, contraindications, dosage recommendations, and therapeutic effectiveness of BFR training. An evidence-based synthesis is particularly important because inappropriate application may compromise patient safety despite the technique's considerable clinical potential.

Therefore, the objective of this review is to critically evaluate current evidence regarding Blood Flow Restriction training, with particular emphasis on its physiological mechanisms, recommended dosage parameters, safety profile, contraindications, effectiveness across different patient populations, and future directions for clinical practice and research. Through comprehensive analysis of contemporary literature, this review aims to provide practical guidance for clinicians seeking to incorporate BFR into evidence-based rehabilitation programmes.

2. Physiological basis of blood flow restriction (BFR) training:

Blood Flow Restriction (BFR) training is founded on the principle that substantial muscular adaptations can be achieved using low mechanical loads when exercise is performed under controlled vascular restriction. Unlike conventional resistance training, which depends primarily on high mechanical tension to stimulate muscle hypertrophy and strength, BFR combines low-load exercise (20–40% of one-repetition maximum [1RM]) with partial arterial occlusion and near-complete venous occlusion through the application of an inflatable cuff around the proximal portion of the exercising limb. This approach creates a unique physiological environment characterised by reduced oxygen availability, metabolite accumulation, increased intramuscular pressure, and enhanced neuromuscular activation, all of which contribute to muscle adaptation despite relatively light external resistance (Patterson et al., 2019).

The physiological foundation of BFR lies in its ability to manipulate local haemodynamics without completely obstructing arterial blood flow. When an appropriately calibrated cuff is inflated to a percentage of the individual's limb occlusion pressure (LOP), arterial inflow continues at a reduced rate while venous return is markedly impeded. Consequently, blood pools within the exercising muscles, producing local hypoxia and increasing metabolic demand. This transient hypoxic state stimulates several intracellular signalling pathways responsible for protein synthesis, angiogenesis, mitochondrial adaptation, and muscle regeneration (Pearson et al., 2015).

One of the earliest physiological responses during BFR exercise is the rapid depletion of oxygen within active muscle fibres. Oxygen extraction increases because venous outflow is restricted while muscular contractions continue to consume available oxygen. The resulting imbalance between oxygen delivery and oxygen utilisation promotes an anaerobic metabolic environment similar to that experienced during high-intensity resistance exercise. As glycolysis becomes the dominant energy pathway, lactate and hydrogen ions accumulate rapidly within the muscle tissue, leading to decreased pH and increased metabolic stress (Loenneke et al., 2012).

Metabolic stress is now recognised as one of the principal drivers of skeletal muscle hypertrophy. Although mechanical tension remains an important stimulus, increasing evidence suggests that metabolite accumulation independently activates anabolic signalling pathways capable of promoting muscle growth. During BFR exercise, elevated concentrations of lactate, inorganic phosphate, adenosine, and reactive oxygen species stimulate intracellular signalling molecules such as mammalian target of rapamycin (mTOR), extracellular signal-regulated kinase (ERK), and mitogen-activated protein kinase (MAPK), ultimately increasing muscle protein synthesis and inhibiting protein degradation (Scott et al., 2015).

Cell swelling represents another critical physiological mechanism. Restricted venous return causes plasma and intracellular fluid to accumulate within muscle fibres, increasing osmotic pressure and producing transient cellular oedema. Muscle cells interpret this swelling as a potential threat to structural integrity, thereby activating anabolic pathways that reinforce cellular architecture through enhanced protein synthesis. This protective response contributes significantly to muscle hypertrophy observed following repeated BFR training sessions (Pearson et al., 2015).

In addition to local muscular adaptations, BFR elicits substantial endocrine responses. Numerous investigations have demonstrated marked increases in circulating growth hormone concentrations following low-load BFR exercise. Growth hormone concentrations may increase several-fold compared with conventional low-load resistance exercise without vascular restriction, primarily because lactate accumulation strongly stimulates pituitary hormone release (Takarada et al., 2000). Growth hormone subsequently enhances collagen synthesis, tissue repair, satellite cell proliferation, and muscle regeneration, thereby supporting rehabilitation following injury or surgery.

Insulin-like growth factor-1 (IGF-1) also plays a pivotal role in mediating muscular adaptation. Elevated IGF-1 activates the phosphatidylinositol 3-kinase (PI3K)/Akt/mTOR signalling pathway, which regulates protein synthesis and muscle fibre growth. Repeated BFR sessions have been associated with increased IGF-1 activity and enhanced satellite cell proliferation, facilitating muscle repair and hypertrophy even under low mechanical loading conditions (Fry et al., 2010).

Satellite cells, commonly referred to as skeletal muscle stem cells, remain quiescent under normal physiological conditions but become activated following muscle injury or intense exercise. These cells proliferate, differentiate, and fuse with existing muscle fibres, contributing additional myonuclei required for sustained muscle growth. Evidence indicates that BFR significantly increases satellite cell activation through combined effects of hypoxia, mechanical strain, inflammatory mediators, and endocrine stimulation (Nielsen et al., 2012).

Another important physiological adaptation involves enhanced recruitment of fast-twitch (Type II) muscle fibres. Under normal low-intensity exercise conditions, the body primarily recruits slow-twitch oxidative fibres because energy demands remain relatively modest. However, during BFR exercise, reduced oxygen availability accelerates fatigue of slow-twitch fibres, necessitating earlier recruitment of fast-twitch motor units. Since Type II fibres possess greater hypertrophic potential than Type I fibres, their early activation contributes substantially to improvements in muscle size and strength despite the use of light resistance (Loenneke et al., 2012).

Recent research has also highlighted the influence of BFR on vascular function. Repeated exposure to transient hypoxia stimulates expression of vascular endothelial growth factor (VEGF), promoting angiogenesis and capillary formation within skeletal muscle. Increased capillary density improves oxygen delivery, nutrient transport, and metabolic waste removal during subsequent exercise sessions, thereby enhancing muscular endurance and functional performance (Patterson et al., 2019).

Nitric oxide (NO) signalling constitutes another important physiological pathway affected by BFR. Mechanical compression and reperfusion stimulate endothelial nitric oxide synthase (eNOS), increasing nitric oxide production. Nitric oxide promotes vasodilation, improves endothelial function, reduces vascular resistance, and facilitates nutrient delivery during recovery. These vascular adaptations may partially explain the favourable cardiovascular safety profile observed in appropriately screened patients undergoing supervised BFR rehabilitation (Centner et al., 2019).

Inflammatory responses following BFR differ substantially from those associated with conventional high-load resistance training. While traditional heavy exercise often produces considerable muscle damage and delayed-onset muscle soreness (DOMS), low-load BFR induces relatively modest structural damage despite producing significant metabolic stress. Consequently, patients frequently experience reduced post-exercise soreness while still achieving meaningful improvements in muscle strength and hypertrophy (Hughes et al., 2017).

The cumulative interaction of hypoxia, metabolite accumulation, hormonal stimulation, cell swelling, satellite cell activation, fast-twitch fibre recruitment, and intracellular anabolic signalling creates a physiological environment capable of producing adaptations comparable to conventional resistance training. This unique combination explains why BFR has become particularly valuable for individuals unable to tolerate heavy mechanical loading because of pain, surgery, immobilisation, or chronic musculoskeletal disorders.

3. Mechanisms of action of blood flow restriction training:

The clinical effectiveness of Blood Flow Restriction training depends upon several interconnected physiological mechanisms rather than a single biological pathway. These mechanisms operate simultaneously during cuff inflation and low-load exercise, producing muscular adaptations that resemble those achieved through traditional high-intensity resistance training. Understanding these mechanisms is essential for clinicians seeking to optimise treatment protocols while ensuring patient safety.

3.1. Metabolic stress:

Metabolic stress is widely regarded as the primary mechanism responsible for the efficacy of BFR training. During cuff inflation, venous blood becomes trapped within the exercising limb while arterial inflow remains partially preserved. This imbalance results in rapid accumulation of lactate, hydrogen ions, inorganic phosphate, potassium, and other metabolic by-products. Elevated metabolite concentrations stimulate group III and IV afferent nerve fibres, increasing central motor drive and facilitating greater motor unit recruitment than would normally occur during low-load exercise (Scott et al., 2015).

Metabolic stress also enhances expression of anabolic signalling proteins, including mTOR and p70S6 kinase, thereby promoting muscle protein synthesis while suppressing proteolytic pathways responsible for muscle degradation. Consequently, repeated BFR sessions progressively increase muscle cross-sectional area and muscular strength.

3.2. Muscle fibre recruitment:

According to Henneman's size principle, motor units are normally recruited from smaller slow-twitch fibres to larger fast-twitch fibres as exercise intensity increases. However, reduced oxygen availability during BFR accelerates fatigue of oxidative fibres, forcing premature recruitment of glycolytic Type II fibres despite the relatively low exercise intensity (Loenneke et al., 2012).

Fast-twitch fibres exhibit greater capacity for hypertrophy and force production than slow-twitch fibres. Their enhanced recruitment therefore contributes substantially to strength gains observed following BFR rehabilitation programmes.

3.3. Cell swelling:

Restricted venous return increases hydrostatic pressure within skeletal muscle, promoting intracellular water accumulation. This transient swelling stretches cellular membranes and cytoskeletal structures, activating mechanosensitive pathways that increase protein synthesis while inhibiting protein breakdown. Cell swelling therefore functions as an independent anabolic stimulus even in the absence of substantial mechanical loading (Pearson et al., 2015).

3.4. Hormonal responses:

One of the most extensively investigated responses to BFR is the marked elevation in anabolic hormone secretion. Blood lactate concentrations achieved during BFR stimulate the anterior pituitary gland to release large quantities of growth hormone. Growth hormone subsequently enhances collagen synthesis, tendon healing, satellite cell activation, and muscle regeneration (Takarada et al., 2000).

Additional endocrine responses include increased insulin-like growth factor-1 (IGF-1), vascular endothelial growth factor (VEGF), and norepinephrine. Collectively, these hormones facilitate tissue repair, angiogenesis, neuromuscular adaptation, and functional recovery.

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3.5. Intracellular signalling pathways:
Several intracellular pathways contribute to muscular adaptation during BFR:
1. Activation of the **PI3K/Akt/mTOR pathway** increases muscle protein synthesis.
2. Increased **ERK1/2 signalling** enhances cellular growth.
3. Reduced expression of **myostatin** removes inhibitory influences on muscle hypertrophy.
4. Increased phosphorylation of **p70S6 kinase** accelerates ribosomal protein synthesis.
5. Activation of **AMPK** improves metabolic adaptation under hypoxic conditions (Fry et al., 2010).

These molecular adaptations collectively promote sustained improvements in muscle mass following repeated training sessions.

3.6. Satellite cell activation:
Satellite cells represent resident skeletal muscle stem cells responsible for regeneration and repair. BFR significantly increases satellite cell proliferation through combined effects of hypoxia, growth hormone secretion, IGF-1 activation, and local inflammatory mediators. These newly activated cells donate additional nuclei to existing muscle fibres, increasing their capacity for protein synthesis and long-term hypertrophy (Nielsen et al., 2012).

3.7. Neural adaptations:
Beyond muscular changes, BFR induces important neural adaptations. Improved motor unit synchronisation, enhanced corticospinal excitability, and increased voluntary muscle activation contribute to early strength gains frequently observed before measurable hypertrophy develops. These neural mechanisms are particularly valuable during postoperative rehabilitation when muscle activation is often inhibited because of pain or joint effusion (Hughes et al., 2017).

3.8. Vascular and endothelial adaptations:
Repeated cycles of vascular occlusion followed by reperfusion stimulate endothelial adaptation. Increased nitric oxide availability, enhanced endothelial function, and greater capillary density improve tissue perfusion and oxygen delivery over time. These adaptations support muscular endurance while potentially reducing cardiovascular risk in appropriately selected patients (Centner et al., 2019).

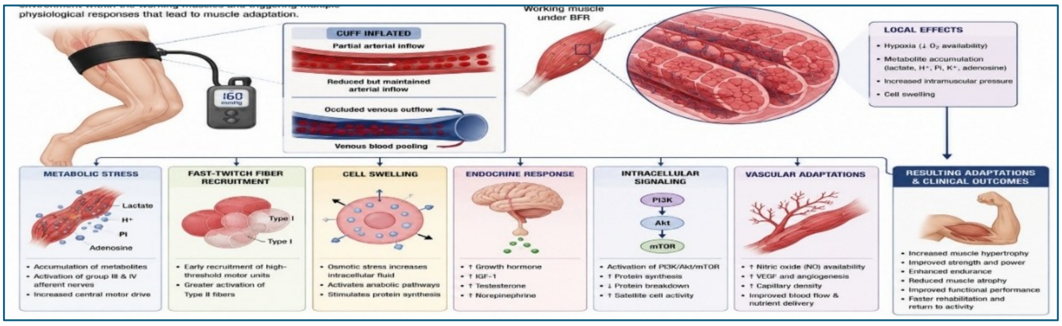

Figure. 1: Physiological mechanisms responsible for muscular adaptation during Blood Flow Restriction training

4. Equipment and cuff technologies in blood flow restriction (BFR) training:
The effectiveness and safety of Blood Flow Restriction (BFR) training are highly dependent on the equipment used to achieve controlled vascular occlusion. Advances in cuff technology have transformed BFR from the early KAATSU elastic band systems into sophisticated pneumatic devices capable of accurately regulating limb occlusion pressure (LOP). Modern equipment allows clinicians to individualise treatment parameters according to patient characteristics, thereby improving therapeutic outcomes while minimising the risk of vascular or neurological complications (Patterson et al., 2019).
Appropriate cuff selection is not merely a matter of convenience; it directly influences arterial occlusion pressure, patient comfort, exercise tolerance, and physiological responses. Variations in cuff width, cuff material, inflation mechanisms, and pressure-monitoring systems can substantially alter blood flow restriction levels, highlighting the importance of evidence-based equipment selection in clinical rehabilitation (Hughes et al., 2017).

4.1. Evolution of blood flow restriction equipment:
The earliest BFR systems, introduced by Dr Yoshiaki Sato during the development of KAATSU training, consisted of manually tightened elastic bands that produced vascular compression based primarily on

subjective perception rather than objective pressure measurements (Sato et al., 2005). Although these devices demonstrated promising clinical outcomes, their inability to quantify occlusion pressure limited reproducibility and raised concerns regarding patient safety.

Technological advancements have since led to the development of automated pneumatic cuff systems incorporating electronic pressure regulators, Doppler integration, and limb occlusion pressure calculations. Contemporary systems permit clinicians to maintain constant cuff pressure throughout exercise despite changes in limb circumference caused by muscle contractions. Such innovations have significantly improved the standardisation of BFR interventions across rehabilitation and sports medicine settings (Patterson et al., 2019).

Several commercially available devices now include microprocessor-controlled inflation systems capable of automatically adjusting pressure during movement, thereby maintaining a consistent percentage of arterial occlusion throughout treatment. These systems reduce operator variability and improve both safety and treatment reproducibility (Scott et al., 2015).

- **Types of BFR Cuffs**
- BFR cuffs are broadly classified into two categories:
- **Pneumatic Cuffs**

Pneumatic cuffs represent the gold standard for clinical rehabilitation because they allow precise regulation of occlusion pressure. These cuffs are connected to electronic inflation units that continuously monitor internal pressure and compensate for pressure fluctuations during exercise. Most research investigating BFR safety and efficacy has utilised pneumatic systems, making them the preferred option in hospitals, rehabilitation centres, and research laboratories (Patterson et al., 2019).

Advantages include:

1. Accurate pressure control
2. Individualised limb occlusion pressure assessment
3. Enhanced patient safety
4. Improved treatment reproducibility
5. Reduced operator error

Despite their advantages, pneumatic systems are relatively expensive and require specialised equipment and clinician training.

4.2. Elastic cuffs and bands:

Elastic cuffs are commonly used in fitness environments because they are inexpensive, portable, and easy to apply. However, these devices generate pressure based on elastic tension rather than measured vascular occlusion, making it difficult to determine the actual degree of blood flow restriction.

Pressure varies considerably according to limb circumference, band elasticity, and application technique. Consequently, elastic systems may either under-restrict blood flow, reducing treatment effectiveness, or over-restrict circulation, increasing discomfort and potential complications (Loenneke et al., 2012).

For this reason, international consensus statements generally discourage the use of non-measured elastic bands in clinical rehabilitation unless objective pressure assessment is available (Patterson et al., 2019).

4.3. Cuff width:

Cuff width is one of the most important determinants of arterial occlusion pressure. Wider cuffs require substantially lower inflation pressures to achieve comparable vascular restriction than narrower cuffs because pressure is distributed over a larger surface area.

Current evidence categorises cuffs into:

- Narrow cuffs (5–8 cm)
- Medium cuffs (10–12 cm)
- Wide cuffs (13–18 cm)

Wide cuffs generally provide greater patient comfort and require lower occlusion pressures, thereby reducing mechanical stress on superficial nerves and soft tissues (Jessee et al., 2016). However, excessively wide cuffs may increase the risk of complete arterial occlusion if pressure is not carefully individualised.

Conversely, narrow cuffs require considerably higher inflation pressures to achieve equivalent restriction. Elevated pressures may increase discomfort, skin compression, and nerve irritation during prolonged exercise. Current clinical recommendations therefore advocate selecting cuff width according to limb size rather than applying a universal cuff dimension (Patterson et al., 2019).

4.4. Cuff material:

Cuff material influences pressure transmission and patient comfort.

Nylon pneumatic cuffs provide relatively rigid pressure distribution, allowing highly reproducible occlusion measurements.

Elastic cuffs generate variable compression because baseline tension exists even before inflation. This characteristic complicates accurate estimation of limb occlusion pressure and may explain differences observed among research studies comparing various cuff systems (Loenneke et al., 2012).

Modern rehabilitation devices frequently incorporate multilayer composite materials that improve comfort while maintaining accurate pressure transmission.

4.5. Limb occlusion pressure (lop):

Limb occlusion pressure (lop) refers to the minimum pressure required to completely occlude arterial blood flow within a specific limb under resting conditions. Determination of LOP has become the cornerstone of contemporary BFR prescription because it accounts for individual differences in:

- Limb circumference
- Blood pressure
- Vascular compliance
- Tissue composition
- Cuff width
- Cuff material

Rather than prescribing identical cuff pressures for all individuals, clinicians calculate exercise pressure as a percentage of each patient's LOP (Patterson et al., 2019).

LOP is typically measured using Doppler ultrasound or integrated electronic sensors while gradually inflating the cuff until arterial pulse disappears. Exercise pressure is then prescribed as a percentage of this measured value.

Individualised pressure prescription substantially improves both treatment safety and clinical effectiveness.

4.6. Pressure monitoring systems:

Modern BFR equipment incorporates several pressure-monitoring technologies.

4.7. Doppler ultrasound:

Portable Doppler ultrasound remains the clinical gold standard for determining limb occlusion pressure. The Doppler probe detects arterial blood flow distal to the cuff while pressure is gradually increased. Complete disappearance of arterial signals indicates full occlusion.

Although highly accurate, Doppler assessment requires clinician expertise and additional equipment.

4.8. Automatic electronic sensors:

Many commercial BFR systems now include integrated electronic sensors capable of estimating limb occlusion pressure without external Doppler devices.

These systems automatically calculate recommended exercise pressures, reducing operator variability and facilitating routine clinical implementation (Patterson et al., 2019).

4.9. Handheld inflation systems:

Portable handheld pumps equipped with digital pressure gauges provide an intermediate option between sophisticated automated systems and simple elastic bands.

Although less expensive than automated devices, clinicians must regularly monitor pressure throughout exercise because muscle contractions may alter cuff compression.

4.10. Selection of upper and lower limb cuffs:

Upper-limb cuffs differ from lower-limb cuffs because arm circumference is considerably smaller than thigh circumference.

Typical recommendations include:

Table. 1:

Limb	Recommended Cuff Width	Typical Application Site
Upper arm	5–10 cm	Most proximal portion of the arm
Thigh	10–18 cm	Most proximal portion of the thigh

Correct positioning ensures effective vascular restriction while minimising compression of superficial nerves.

4.10.1. Emerging technologies:
Recent technological developments are expanding the capabilities of BFR systems.
Emerging innovations include:

- Wireless Bluetooth pressure monitoring
- Smartphone-controlled inflation devices
- Artificial intelligence-assisted pressure adjustment
- Motion sensors that regulate cuff inflation during movement
- Real-time tissue oxygen monitoring using near-infrared spectroscopy (NIRS)
- Wearable rehabilitation platforms integrating BFR with electromyography (EMG)

These technologies may enable highly personalised rehabilitation protocols based on continuous physiological feedback rather than fixed pressure prescriptions (Centner et al., 2019).
Future BFR systems are expected to integrate vascular monitoring, muscle oxygenation assessment, and exercise performance metrics into a single wearable platform, facilitating precision rehabilitation across diverse patient populations.

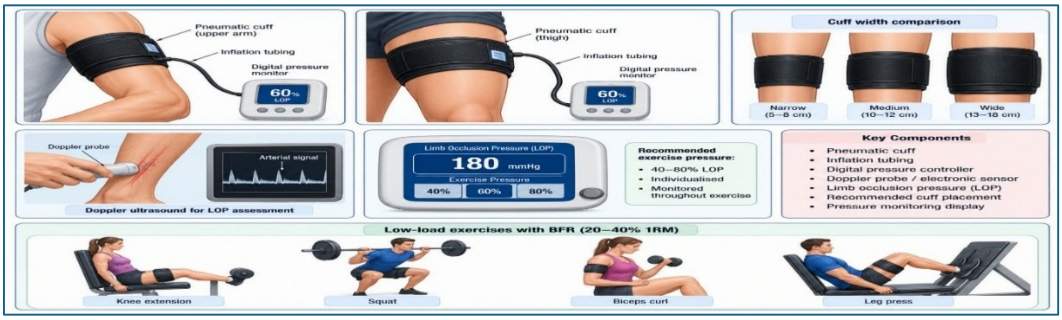

Figure. 2: Components of an Evidence-Based Blood Flow Restriction Training System

5. Dosage parameters of blood flow restriction (BFR) training:
The therapeutic effectiveness of Blood Flow Restriction (BFR) training depends not only on vascular occlusion but also on the precise prescription of exercise variables. Unlike conventional resistance training, where exercise intensity is the primary determinant of muscular adaptation, BFR requires careful adjustment of cuff pressure, exercise load, repetitions, sets, rest intervals, cuff inflation duration, and treatment frequency. Appropriate dosage maximises muscle hypertrophy and strength while minimising discomfort and the risk of adverse events (Patterson et al., 2019).
Current international guidelines recommend that BFR should always be individualised according to patient characteristics, limb size, vascular status, rehabilitation goals, and tolerance rather than applying a single standard protocol to all individuals (Hughes et al., 2017).

5.1. Principles of bfr dosage prescription:
BFR dosage consists of seven major components:

1. Limb Occlusion Pressure (LOP)
2. Exercise intensity
3. Number of repetitions
4. Number of sets
5. Rest interval
6. Exercise frequency
7. Duration of cuff inflation

Each variable interacts with the others to determine the physiological stimulus produced during training. Excessive pressure or exercise volume may increase discomfort without improving outcomes, whereas insufficient occlusion may fail to induce the metabolic stress necessary for muscle adaptation (Scott et al., 2015).

5.2. Limb occlusion pressure (lop):
Limb Occlusion Pressure (LOP) is the minimum cuff pressure required to completely stop arterial blood flow to the limb at rest. Modern clinical practice recommends prescribing exercise pressure as a percentage of LOP rather than using fixed inflation pressures.

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Individualised LOP accounts for several factors including:
1. Limb circumference
2. Blood pressure
3. Cuff width
4. Soft tissue thickness
5. Vascular compliance
6. Sex
7. Age

Using a percentage of LOP improves safety and ensures that each patient receives an equivalent physiological stimulus regardless of anatomical differences (Patterson et al., 2019).

5.3. Recommended exercise pressure:

Table. 2:

Limb	Recommended Pressure
Upper limb	40–50% LOP
Lower limb	60–80% LOP

Lower limbs generally require higher pressures because of larger muscle mass and greater arterial pressure. Pressures exceeding 80% LOP rarely improve training outcomes but substantially increase discomfort and the likelihood of complete arterial occlusion (Jessee et al., 2016).

5.4. Exercise intensity:
One of the greatest advantages of BFR training is that significant muscular adaptations occur despite the use of extremely light resistance.
Most rehabilitation protocols recommend:

5.5. 20–40% of one-repetition maximum (1rm):
This intensity is considerably lower than traditional resistance training, which usually requires 60–80% 1RM to stimulate hypertrophy (American College of Sports Medicine, 2021).
Low-load BFR is particularly advantageous for patients recovering from:
1. ACL reconstruction
2. Total knee arthroplasty
3. Rotator cuff repair
4. Tendon injuries
5. Fractures
6. Osteoarthritis
7. Sarcopenia

because healing tissues cannot tolerate heavy mechanical loading.
Multiple meta-analyses have demonstrated that low-load BFR produces muscle hypertrophy comparable to conventional heavy-load resistance exercise while substantially reducing joint stress (Lixandrão et al., 2018).

5.6. Number of sets and repetitions:
The most widely adopted BFR protocol consists of four sets performed under continuous cuff inflation.
Standard Protocol
- **First set:** 30 repetitions
- **Second set:** 15 repetitions
- **Third set:** 15 repetitions
- **Fourth set:** 15 repetitions

Total = 75 repetitions
This protocol has been extensively validated across orthopaedic rehabilitation, sports medicine, and geriatric populations (Patterson et al., 2019).
Alternative protocols include:
- 20-20-20-20
- 15-15-15-15

- Continuous exercise to fatigue
- Time-based exercise (30–60 seconds)

However, the 30-15-15-15 protocol remains the most frequently recommended because it consistently produces substantial metabolic stress while maintaining acceptable patient comfort.

5.7. Rest intervals:

Short rest periods are essential for maintaining metabolite accumulation during BFR.
Current recommendations include:
30–60 seconds between sets:
Importantly, the cuff generally remains inflated during these rest periods.
Maintaining cuff inflation preserves the hypoxic environment and prevents rapid clearance of lactate and other metabolites, thereby enhancing anabolic signalling (Loenneke et al., 2012).
Longer rest periods allow metabolic recovery and reduce the physiological stimulus responsible for muscle hypertrophy.

5.8. Duration of cuff inflation:

Continuous cuff inflation throughout the exercise bout is the most commonly used approach.
Typical inflation duration:

- Upper limb: 5–8 minutes
- Lower limb: 6–10 minutes

Following completion of each exercise, cuffs are deflated to restore normal circulation.
Excessively prolonged inflation (>15–20 minutes) is generally discouraged because it may increase discomfort and neurological symptoms without improving clinical outcomes (Hughes et al., 2017).

Training Frequency

Training frequency depends upon rehabilitation goals and patient tolerance.
Evidence suggests:

Muscle Strength

2–3 sessions/week

Muscle Hypertrophy

2–4 sessions/week

Postoperative Rehabilitation

2–3 supervised sessions/week

Athletic Performance

3–4 sessions/week

Clinical improvements generally become apparent within 4–6 weeks of consistent training (Centner et al., 2019).

Programme Duration

The majority of clinical trials utilise intervention periods ranging from:

6–12 weeks

Significant improvements are commonly observed after:

- 2 weeks (early neural adaptations)
- 4 weeks (strength gains)
- 6–8 weeks (muscle hypertrophy)
- 12 weeks (functional improvements)

Longer intervention periods may produce additional muscular adaptations, although evidence beyond six months remains limited (Lixandrão et al., 2018).

5.9. Exercise selection:

Nearly every rehabilitation exercise can be performed using BFR provided appropriate loads are selected.
Common lower-limb exercises include:

- Knee extension
- Leg press
- Squat
- Step-up
- Hamstring curl
- Calf raise

- Walking
- Cycling

Upper-limb exercises include:

- Biceps curl
- Triceps extension
- Shoulder press
- Wrist flexion
- Wrist extension
- Chest press
- Seated row

Selection depends on rehabilitation stage, tissue healing status, and functional goals.

5.10. Aerobic blood flow restriction training:

Although BFR is commonly associated with resistance exercise, aerobic exercise performed with vascular restriction has also demonstrated promising outcomes.

Typical aerobic prescription includes:

Walking

- 15–20 minutes
- 4–6 km/h

Cycling

- 30–40% VO_2max
- 15–20 minutes

These protocols improve aerobic capacity, muscle endurance, and lower-limb strength while maintaining very low mechanical loading (Scott et al., 2015).

5.11. Progression of exercise:

Progression should occur gradually according to patient tolerance.

Recommended progression:

Week 1–2

- Familiarisation
- 20% 1RM
- Lower LOP

Week 3–4

- Increase to 25–30% 1RM
- Maintain repetition scheme

Week 5–8

- Increase resistance
- Introduce functional exercises

Week 8 onwards

- Transition toward conventional resistance training where appropriate.

This gradual progression reduces pain while allowing progressive muscular adaptation.

5.12. Monitoring during treatment:

Clinicians should continuously monitor patients throughout BFR sessions.

Parameters include:

- Pain intensity
- Perceived exertion
- Limb colour
- Skin temperature
- Distal pulse
- Capillary refill
- Numbness
- Dizziness
- Blood pressure
- Heart rate

Any excessive pain, numbness, cyanosis, or neurological symptoms should prompt immediate cuff deflation and reassessment (Patterson et al., 2019).

5.13. Factors influencing dosage:

Several patient-specific variables influence the optimal BFR prescription.
These include:

- Age
- Sex
- Limb circumference
- Body composition
- Cardiovascular health
- Diabetes mellitus
- Peripheral vascular disease
- Previous surgery
- Pain severity
- Exercise experience

Consequently, BFR dosage should always be individualised rather than standardised across all patients.

5.14. Evidence-based clinical recommendations:

Current consensus recommendations include:

- Determine Limb Occlusion Pressure individually.
- Use **40–50% LOP** for upper limbs.
- Use **60–80% LOP** for lower limbs.
- Perform exercises at **20–40% 1RM**.
- Adopt the **30-15-15-15 repetition protocol**.
- Maintain **30–60-second rest intervals**.
- Train **2–3 sessions weekly** during rehabilitation.
- Continuously monitor patient comfort and vascular status.
- Progress exercise gradually according to functional recovery.

Collectively, these recommendations provide an evidence-based framework for integrating BFR safely into rehabilitation practice while optimising muscle strength, hypertrophy, and functional outcomes (Patterson et al., 2019).

Figure. 3: Evidence-Based Dosage Parameters for Blood Flow Restriction Training

6. Conclusion:

Blood Flow Restriction (BFR) training has become a transformative adjunct in contemporary rehabilitation, offering a scientifically supported method to improve muscle strength, hypertrophy, and functional recovery while employing substantially lower exercise loads than traditional resistance training. By combining low-load exercise with controlled partial vascular occlusion, BFR induces metabolic stress, hypoxia, endocrine activation, satellite cell proliferation, and enhanced fast-twitch muscle fibre recruitment, collectively promoting muscular adaptations comparable to those achieved through high-intensity resistance exercise

(Patterson et al., 2019; Hughes et al., 2017). These physiological mechanisms make BFR particularly valuable for patients who cannot tolerate heavy mechanical loading because of postoperative restrictions, pain, immobilisation, or chronic musculoskeletal conditions.

The growing body of evidence indicates that BFR training is effective across a wide range of clinical populations, including individuals recovering from anterior cruciate ligament reconstruction, total knee arthroplasty, rotator cuff repair, fractures, osteoarthritis, sarcopenia, and selected neurological disorders (Lixandrão et al., 2018; Centner et al., 2019). Improvements in muscle mass, muscular strength, functional mobility, pain reduction, and return-to-activity outcomes have been consistently demonstrated when evidence-based protocols are followed. Furthermore, the ability to stimulate meaningful adaptations using only 20–40% of one-repetition maximum considerably reduces joint loading, making BFR an attractive rehabilitation option for vulnerable patient populations.

Despite these advantages, BFR should not be regarded as a universal intervention suitable for every individual. Appropriate patient screening remains fundamental because contraindications such as active thromboembolic disease, severe peripheral arterial disease, and uncontrolled hypertension, advanced cardiovascular disorders, severe infection, or impaired vascular integrity may increase the risk of complications (Patterson et al., 2019). Individual determination of limb occlusion pressure, careful selection of cuff width, appropriate exercise prescription, and continuous clinical monitoring are essential to ensure treatment safety and effectiveness.

Current international recommendations emphasise the importance of personalised BFR prescription rather than fixed cuff pressures or generic exercise protocols. Exercise pressures based on a percentage of limb occlusion pressure, combined with low-load resistance exercise, standardised repetition schemes, and gradual progression, provide the safest and most reproducible clinical approach (Patterson et al., 2019). Advances in pneumatic cuff technology, automated pressure regulation, Doppler-assisted occlusion measurement, and wearable monitoring devices are further improving treatment precision and reducing clinician-dependent variability.

Although substantial progress has been made, several research gaps remain. Additional high-quality multicentre randomised controlled trials with longer follow-up periods are required to establish optimal dosage parameters, investigate long-term cardiovascular safety, determine the effectiveness of BFR in paediatric and medically complex populations, and compare different cuff technologies and pressure algorithms. Future investigations integrating imaging biomarkers, muscle oxygenation monitoring, artificial intelligence-assisted pressure regulation, and personalised rehabilitation programmes may further refine BFR implementation in clinical practice.

Overall, Blood Flow Restriction training represents a safe and effective rehabilitation strategy when applied by appropriately trained healthcare professionals using evidence-based protocols. Its capacity to enhance muscle strength and functional recovery while minimising mechanical stress positions BFR as an increasingly important component of modern rehabilitation programmes. As clinical evidence continues to expand and technological innovations improve treatment standardisation, BFR is likely to become an integral element of personalised rehabilitation across orthopaedic, sports medicine, geriatric, neurological, and chronic disease management settings.

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