

# 血流限制训练在中老年人心血管疾病和膝关节运动功能康复中的应用进展

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**【摘要】** 血流限制训练(BFRT)是中老年人心血管和运动康复是一种相对安全、有效的训练方法,可增强中老年人的肌肉力量、改善其心血管功能和关节活动度,并缓解疼痛。本文综述了BFRT在中老年人心血管疾病和膝关节运动功能康复中的临床应用进展,以期BFRT的临床推广提供理论支持。

**【关键词】** 血流限制训练; 中老年人; 心血管疾病; 膝关节运动功能

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研究发现,老年人骨骼肌的质量和力量会随着年龄的增长,每年以1%和3%的幅度下降<sup>[1]</sup>。骨骼肌形态和功能的老化会增加老年人对跌倒的恐惧,并降低其生活质量<sup>[2]</sup>。研究表明,运动是提高骨骼肌质量和力量的有效手段<sup>[3]</sup>。美国运动医学学会已证实,高强度的抗阻运动[≥70%的1次重复最大力量(one repetition maximum, 1RM)]是增加肌肉力量、耐力和肌肉肥大的最佳运动形式<sup>[4]</sup>,但高强度的运动也会增加老年人心血管负担<sup>[5]</sup>,损伤其肌肉的超微结构<sup>[6]</sup>,引发迟发性肌肉酸痛,并增加受伤风险,进而减少运动频率<sup>[7]</sup>。运动量的减少可能增加老年人心血管疾病的患病风险<sup>[8]</sup>。

血流限制训练(blood flow restricted training, BFRT)作为一种新型的训练方式,用袖带加压肢体的近心端,结合较低强度的运动,通过改变袖带宽度和限制压力大小,较易调整训练方案<sup>[9]</sup>。研究表明,正确的BFRT在增大肌肉体积、增强肌肉力量<sup>[10-12]</sup>、缓解关节疼痛<sup>[13-17]</sup>以及改善心血管功能等方面均有较好的疗效<sup>[9,18-20]</sup>。因此,本文综述了BFRT在中老年人心血管疾病和膝关节运动功能康复中的临床应用进展,旨在为BFRT的临床推广提供理论支持。

## BFRT 的概述

BFRT于1966年由日本的Yoshiaki Sato博士提出,也称为加压疗法或血管闭塞训练法(vascular occlusion training, VOT)<sup>[9]</sup>。BFRT主要针对四肢进行训练,即采用袖带加压肢体的近心端,允许部分动脉血液流入,限制静脉血液流出,使静脉血液堆积在毛细血管,造成袖带下方出现红斑的现象<sup>[21]</sup>,通过“代谢压力”使肌肉增粗,结合较低强度的运动(常用20%~40% 1RM)<sup>[21]</sup>,以达到增强肌力和肌肉肥大的目的<sup>[22]</sup>。BFRT可能存在以下生理机制:①袖带加压可使代谢产物堆积增多,增强“代谢压力”,增加细胞肿胀程度,营造肌肉生长所需的酸性环境,促进类胰岛素一号增长因子、睾酮、生长激素的合成<sup>[23]</sup>,激活与肌肉蛋白合成有关的mTORC1信号通路<sup>[24]</sup>,同时提高I型肌纤维和IIA型肌纤维的募集能力,使肌肉肥大和肌力增加<sup>[25]</sup>;②运动时,对血管的加压和解压可减缓交感神经过度激活,减轻心脏负担。

## BFRT 对心血管系统的影响

中老年人的心血管系统随年龄的增长会表现出血管僵硬程度增加、动脉硬化、外周血管阻力增大、血压升高<sup>[26]</sup>等症状。欧洲心脏病学会建议,有心血管疾病的患者每周应进行肌力和耐力训练,但是中老年人可能难以适应高强度的抗阻训练(特别是患有心血管疾病或运动功能障碍的患者)<sup>[27]</sup>。低强度抗阻训练虽然对运动时血压的影响较小,但需要增加运动频率和运动持续时间来增强肌肉力量<sup>[28]</sup>。BFRT可通过对血管的加压、解压以及调整袖带宽度和限制压力大小来改变血管阻力和血流流速,从而降低运动过程中的心脏负荷<sup>[29]</sup>,对健康中老年人的心血管功能可能有促进作用。

### 一、BFRT 对血压和心率变化的影响

中老年人心血管系统自我调节能力会随着年龄的增大而减弱(如心率变快、心输出量减少、血压升高)。BFRT结合抗阻训练对血压和心率的改善有一定效果,但当患者存在高血压等心血管问题时,其安全性取决于运动肌群和运动处方的制定<sup>[30]</sup>。

对于健康的中老年人,6周的步行结合BFRT改善心率和降低心率变异性<sup>[18]</sup>。对患有冠状动脉疾病的中老年人,持续8周的BFRT可使冠心病患者的收缩压降低6.77 mmHg<sup>[9]</sup>。但Domingos等<sup>[31]</sup>的Meta分析表明,血压正常的受试者在BFRT训练时,其收缩压和舒张压与无BFRT的运动相比有下降趋势;高血压患者在BFRT训练时的收缩压和舒张压显著高于无BFRT运动时;但BFRT30~60 min后,高血压患者的血压降低程度明显高于无BFRT运动时。研究表明,高血压患者在BFRT时的血压高于中、低强度运动时,这可能是因为高血压患者在抗阻结合BFRT加压时流向运动肌群的血液减少,使其肌肉传入神经敏感,容易使交感神经过度激活,引起运动压力反射(exercise pressor reflex, EPR),从而导致了血压升高<sup>[32-33]</sup>。因此,中老年人在BFRT前需要提前确定是否患有高血压或心肌缺血等心血管疾病,以便制定合适的运动处方。还有研究表明,不同体位(坐位和仰卧位)或不同的袖带宽度也会影响动脉闭塞压(arterial occlusion pressure, AOP)的测量结果<sup>[34]</sup>,该结果提

示,设定 BFRT 的限制压力时,需确保动脉闭塞压的测量体位和袖带宽度与运动时保持一致。

## 二、BFRT 对血管功能的影响

研究证明,中老年人的血管内皮细胞形态不规则,血管活性物质产生减少,主动脉顺应性降低,僵硬度高,动脉管壁增厚,缓冲能力下降,因此改善和维持中老年人的血管功能对其心血管系统的健康至关重要<sup>[35]</sup>。目前,BFRT 对动脉顺应性、僵硬度的影响存在较大的差异。

Takano 等<sup>[19]</sup>的研究表明,抗阻结合 BFRT 可使生长激素、胰岛素以及血管内皮生长因子显著升高,降低心脏负荷,改善动脉顺应性。Shimizu 等<sup>[20]</sup>的研究也表明,4 周的低强度抗阻结合 BFRT 对健康老年人的血管内皮功能和外周循环的改善效果显著优于低强度抗阻训练。但还有研究表明,低强度的 BFRT 只能轻微改变或不改变动脉僵硬<sup>[36]</sup>、动脉顺应性和血管功能<sup>[10,37]</sup>。类似的研究出现不同的结果,可能的原因在于以上研究的纳入标准和干预周期不同,如 Shimizu 等<sup>[20]</sup>的研究中,其受试者均为没有运动习惯的老年人,干预时间只有 4 周;而文献<sup>[10]</sup>和<sup>[37]</sup>中的受试者均为有运动习惯的老年人,其干预时间分别为 8 周和 12 周。因此不同的 BFRT 周期或受试者不同的运动习惯均可能使血管功能的变化产生差异。

有研究提出,低强度的 BFRT 训练会引发反应性充血,可能导致血管内皮细胞功能障碍和血管自我调节功能下降<sup>[38]</sup>。同时,相比于窄的袖带宽度,宽的袖带宽度在低强度 BFRT 时会增加受试者的疼痛感和疲劳程度,加重心血管反应<sup>[39]</sup>。

因此,本课题组认为,合理地运用 BFRT 在一定程度上对血管功能的改善有促进作用。首先,BFRT 应根据袖带的宽度选择更合适的限制压力;其次,BFRT 的训练过程应采取渐进式,逐步增加限制压力大小至目标限制压力,并及时监控受试者在训练过程中的主观疲劳感觉和疼痛状况<sup>[29]</sup>,及时发现不良事件,以增加 BFRT 的安全性。

## BFRT 对膝关节运动功能的影响

中老年人因其机体老化、关节炎或运动损伤等容易发生急性或慢性疼痛,常导致其肌力下降、肌肉萎缩、关节活动度受限等,是影响中老年人生活质量和社会活动参与的重要问题<sup>[40-41]</sup>。膝关节作为下肢的承重关节,对运动能力的维持和提高具有重要作用,且膝关节相较于其他关节具有更大的灵活性,是当前关节炎或运动损伤高发部位,其临床症状常表现为伸膝肌力下降、关节活动度受限和疼痛等,膝关节疾病现已成为影响中老年人日常生活活动的主要因素之一<sup>[42-43]</sup>。研究发现,BFRT 和高强度抗阻训练均可显著增强老年男性的肌肉力量<sup>[44]</sup>;但 BFRT 可避免关节疼痛加重,因此 BFRT 具有一定的安全性<sup>[45]</sup>。

### 一、BFRT 对膝关节伸肌肌力的影响

膝关节伸肌肌力不足是中老年人活动减少的原因之一<sup>[46]</sup>。系统性回顾结果表明,低强度抗阻结合 BFRT 可增强膝关节术后(前交叉韧带重建和膝关节镜)、髌股关节综合征和膝骨关节炎患者的肌力<sup>[45]</sup>。低强度抗阻结合 BFRT 和高强度抗阻训练对增加肌力<sup>[13]</sup>和肌肉肥大<sup>[14]</sup>的疗效相似。BFRT 可使肌肉处于较大的缺氧和缺血环境,可提高肌肉的氧合水平<sup>[47]</sup>;而高强度抗阻训练可能会加快中老年人体力消耗和加重临床症状。

因此 BFRT 可能是增强中老年人肌力和增加肌肉横截面积的有效方法。

研究表明,低强度抗阻结合 BFRT 的健康老年人的股四头肌肌力和横截面积增大情况均优于单纯的高强度抗阻运动(70%~90% 1RM)<sup>[10]</sup>。老年女性经 45% 的储备心率步行结合 BFRT 干预后,与正常步行相比,其伸膝肌力平均增加 5.9%,屈膝肌力平均增加 16.1%,大腿肌肉横截面积平均增加 3.1%,起立-行走测试时间缩短了 10.7%<sup>[11]</sup>。膝关节术后患者经低强度开链伸膝结合 BFRT 干预后,其大腿周径和伸膝肌力均显著提高<sup>[12]</sup>。还有研究显示,低强度抗阻结合 BFRT 可增强冠心病患者的伸膝肌力<sup>[9]</sup>。Meta 分析结果显示,低强度抗阻运动或步行时结合 BFRT 对受试者肌力和肌肉横截面积的影响均优于各自的单纯运动<sup>[15]</sup>。

Hackney 等<sup>[48]</sup>的研究表明,负重侧腿经高强度抗阻训练和低强度 BFRT 干预后,其肌肉横截面积和肌力会显著增加,但非负重侧腿仅高强度抗阻训练可增加其肌肉横截面积和肌力,增加 BFRT 后,非负重侧腿的肌肉会出现肿胀和反应性充血,因此该研究认为,BFRT 不能作为提高膝关节伸肌肌力的主要训练方式,应该仅作为肌力训练的一种辅助训练手段。

### 二、BFRT 对膝关节活动度的影响

中老年人骨折或术后制动是关节挛缩和活动度受限的常见原因,这可能与关节源性肌肉抑制(arthrogenic muscle inhibition, AMI)有关(AMI 指的是关节损伤后出现疼痛、肿胀等导致周围肌肉出现反射性肌肉抑制,减少肌肉收缩,进而出现关节制动)<sup>[49]</sup>。BFRT 是通过袖带加压后进行关节活动度训练,运动过程中会缓解疼痛、并减少渗出液,且袖带的加压和解压还可让营养物质迅速地流入活动受限位置,有利于改善关节的活动能力<sup>[50]</sup>。Erickson 等<sup>[51]</sup>采用物理治疗结合 BFRT 治疗前交叉韧带损伤患者 60 例(综合组),结果发现,其膝关节屈曲角度显著优于单纯的物理治疗组。目前,鲜见针对 BFRT 对中老年人膝关节活动度影响的研究,尚需要后续研究对此进行补充。

### 三、BFRT 对膝关节疼痛的影响

肌肉骨骼疼痛与中老年人骨折<sup>[17]</sup>、跌倒<sup>[52]</sup>、睡眠障碍<sup>[53]</sup>有关。有效缓解中老年人的肌肉骨骼疼痛可提高中老年人的社会参与,降低社会和家庭负担<sup>[54]</sup>。Bryk 等<sup>[13]</sup>的研究表明,高强度抗阻训练与低强度 BFRT 结合,可显著改善老年女性膝骨关节炎患者的膝关节疼痛和起立-行走测试时间,且低强度 BFRT 时的痛感明显低于高强度抗阻运动时。Libardi 等<sup>[14]</sup>的研究也发现,健康中老人在 BFRT 训练前、后未出现疼痛、疲劳等不良反应。

## BFRT 的运动处方和不良事件

中老年人中常见的 BFRT 运动形式包括低强度抗阻结合 BFRT 和有氧训练结合 BFRT,血流限制压力建议为 40%~80% 静息时动脉闭塞压<sup>[21]</sup>。

1. 低强度抗阻结合 BFRT:运动负荷为 20%~40% 1RM;运动强度建议 4 组共 75 次重复训练,第一组 30 次,第二至第四组均为 15 次,组间休息 30~60 s;1~2 次/天,2~3 次/周,持续 3 周及以上<sup>[21]</sup>。

2. 有氧训练结合 BFRT:主要运动形式为步行和骑车,运动强度为 45% 储备心率或 < 50% 最大摄氧量;5~20 min/次,

2 次/天(1~3 周)或 2~3 次/周(>3 周),持续 6 周及以上<sup>[21]</sup>。

3. BFRT 注意事项:BFRT 前,需判别 BFRT 的适用人群及禁忌人群,学习 BFRT 限制压力的加压步骤<sup>[55]</sup>。对于保守治疗的患者,应使用 BFRT 风险筛查工具对中老年人心血管功能进行详细检查<sup>[15]</sup>,已有研究表明,有高血糖的患者易出现血栓<sup>[56]</sup>,有高血压的患者可能在 BFRT 过程中出现血压升高<sup>[31,57]</sup>等风险;对膝关节术后患者,应对 BFRT 是否会增加术后并发症风险的清单列表进行筛查<sup>[58]</sup>,训练过程中应避免限制压力过大而导致神经损伤或肢体缺血<sup>[58]</sup>。本课题组认为,由于目前的研究对个体化 BFRT 的压力仍无明确的共识,限制压力与 BFRT 的设备和袖带的宽度密切相关,且 40%~80% 静息时动脉闭塞压是一个相对安全的限制压力,因此康复治疗师需根据情况及及时调整适宜的限制压力,以确保安全<sup>[59]</sup>。

4. BFRT 的不良事件:目前,BFRT 的不良事件发生率较小,主要表现在加压会引起动脉畸形导致袖带远端动脉血流紊乱,增加血管内皮细胞剪切力,刺激血管舒张和多种活性物质分泌,导致晕厥<sup>[60-61]</sup>,而过度加压还可能导致肌肉缺血、疼痛和水肿,出现横纹肌溶解<sup>[62]</sup>。

### 总结与展望

BFRT 是一种新兴的康复训练方法,对改善心血管功能,保持和增加肌肉质量、肌肉力量均有一定的疗效,可能是对现有的康复训练手段的补充。虽然 BFRT 已经广泛应用于心血管功能和运动功能康复训练,但当前的研究群体主要集中于青年人,在中老年人的研究和应用相对较少。另外,目前中老年人 BFRT 的运动处方尚难以统一,对心血管高危风险人群的安全性和适用性亦存在较大争议,这些均需进行更深入的研究,方可作为 BFRT 的临床应用提供更多的参考。

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## Accelerated rTMS and cognitive training in chronic stroke: a safety and feasibility study 【Fleischmann H, Lopez J, Caulfield K, et al. *Brain Stimul*, 2021, 14(6): 1625.】

**Objective** We examined the safety of accelerated rTMS as well as its feasibility in a delivery schedule interleaved with computerized cognitive training in individuals with chronic stroke and cognitive impairment.

**Methods** Fourteen chronic stroke patients with intact left prefrontal cortex who met DSM-5 criteria for mild neurocognitive disorder completed open-label high-dose rTMS (intermittent theta burst) to left dlPFC (600 pulses, eight sessions/day for three days), interleaved every 15 minutes between cognitive training sessions. Participants completed at pre- and post-treatment: 1) neuroradiological lesion characterization and safety assessment with flair, diffusion, susceptibility, angiography, perfusion gradient and volumetric scans, 2) neuropsychological and psychosocial assessment as well as assessment of neglect and aphasia, and 3) ratings of treatment acceptability and credibility.

**Results** No study-related adverse events occurred as indexed in neuroradiological, neuropsychological or subjective quantitative or qualitative report of side effects. Accelerated rTMS was rated as acceptable and credible with no more than minor discomfort in line with conventional once daily delivery schedules. Retention was feasible as all participants who began treatment completed.

**Conclusions** This is the first comprehensive neuroradiological and neuropsychological examination of the safety of accelerated rTMS in chronic stroke, or any condition. Across objective and subjective indices, up to 24 sessions of accelerated intermittent theta burst rTMS was safe, acceptable, and tolerable, even in a neurologically vulnerable condition such as chronic stroke.