

肺复张策略联合个体化呼气末正压对高血压患者肺切除术后肺部并发症和围手术期血流动力学的影响

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[摘要] 目的: 肺复张策略(lung recruitment maneuver, LRM)联合肺动态顺应性导向的呼气末正压(positive end-expiratory pressure, PEEP)策略可降低肺切除术患者术后肺部并发症(postoperative pulmonary complications, PPCs)风险, 然而该策略在高血压患者中的肺保护作用及其对血流动力学的影响尚不明确。本研究旨在评估LRM联合肺动态顺应性导向的PEEP策略对合并高血压的胸腔镜肺切除术患者PPCs和围手术期血流动力学的影响, 以期为该策略在此类人群中的安全应用提供科学依据。方法: 选择2024年11月28日至2025年8月15日江南大学附属医院收治的合并高血压、拟在单肺通气下行胸腔镜肺切除术的100例患者, 采用随机数字表法将其分为常规保护性通气组(对照组)和LRM联合个体化PEEP组(试验组), 每组50例。对照组术中PEEP设定为5 cmH₂O (1 cmH₂O=0.098 kPa); 试验组于单肺通气开始后实施LRM联合递减PEEP滴定法, 以肺动态顺应性确定最佳PEEP。在单肺通气结束前, 2组患者均进行一次LRM操作。主要结局为术后5 d内PPCs发生率。次要结局包括术中低血压发生率、血管活性药物使用、术后5 d内心律失常和低血压发生率、术后肾功能指标及术后住院时间。结果: 对照组和试验组术前基线资料的差异均无统计学意义(均 $P>0.05$)。试验组的术中PEEP高于对照组, 驱动压低于对照组, 气道平台压(plateau pressure, Pplat)、脉搏氧饱和度(pulse oxygen saturation, SpO₂)、肺动态顺应性略高于对照组(均 $P<0.05$)。试验组术中低血压的发生率高于对照组[52%(26/50) vs 30%(15/50), $P<0.05$], 术中血管活性药物使用率也高于对照组[54%(27/50) vs 20%(10/50), $P<0.05$]。2组患者手术部位、手术类型、心率、平均动脉压(mean arterial pressure, MAP)、脉搏压变异度(pulse pressure variation, PPV)、术中补液量、呼吸频率、潮气量方面的差异无统计学意义(均 $P>0.05$)。试验组的PPCs发生率较对照组降低[22%(11/50) vs 42%(21/50), $P<0.05$], 2组患者的术后心律失常、术后低血压及住院时间方面的差异均无统计学意义(均 $P>0.05$)。试验组与对照组术后1 d的血肌酐(serum creatinine, SCr)和血尿素氮(blood urea nitrogen, BUN)、术后3 d的BUN均高于术前(均 $P<0.05$); 2组术前与术后1、3、5 d的SCr与BUN差异均无统计学意义(均 $P>0.05$)。经多因素Logistic回归校正年龄、体重指数(body mass index, BMI)、高血压分级、美国麻醉医师协会(American Society of Anesthesiologists, ASA)分级及手术类型后, 试验组术中低血压的发生风险为对照组的2.8倍 ($OR=2.8$, 95% CI 1.2~6.9; $P<0.05$)。针对术中低血压的亚组分析显示, 对于年龄 ≥ 65 岁、BMI >24 kg/m²、高血压3级、ASA III级或拟接受肺段切除手术的患者, 在接受LRM联合个体化PEEP策略时更容易发生术中低血压。结论: LRM联合个体化PEEP策略可降低PPCs发生率, 虽然术中低血压发生率较高, 但经及时干预后多能迅速纠正, 持续时间较短, 未影响术后心肾功能。高龄、高血压3级及超重患者术中发生低血压的风险可能较高, 需加强术中血流动力学监测, 并及时进行个体化治疗。

[关键词] 个体化呼气末正压; 肺复张策略; 肺切除术; 术后肺部并发症; 血流动力学

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Effects of a lung recruitment maneuver combined with individualized positive end-expiratory pressure on postoperative pulmonary complications and perioperative hemodynamics in hypertensive patients undergoing pulmonary resection

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ABSTRACT

Objective: A lung recruitment maneuver (LRM) combined with a dynamic lung compliance-guided positive end-expiratory pressure (PEEP) strategy can reduce the risk of postoperative pulmonary complications (PPCs) in patients undergoing pulmonary resection. However, the lung-protective effects of this strategy and its impact on hemodynamics in patients with hypertension remain unclear. This study aims to evaluate the effects of an LRM combined with a dynamic lung compliance-guided PEEP strategy on PPCs and perioperative hemodynamics in hypertensive patients undergoing thoracoscopic pulmonary resection, thereby providing scientific evidence for the safe application of this strategy in this population.

Methods: A total of 100 hypertensive patients scheduled to undergo thoracoscopic pulmonary resection with one-lung ventilation (OLV) at the Affiliated Hospital of Jiangnan University between November 28, 2024 and August 15, 2025 were enrolled. Using a random number table, the patients were assigned to a conventional protective ventilation group (control group) or an LRM combined with individualized PEEP group (intervention group), with 50 patients in each group. In the control group, intraoperative PEEP was set at 5 cmH₂O (1 cmH₂O=0.098 kPa). In the intervention group, an LRM followed by decremental PEEP titration was performed after the initiation of OLV, and the optimal PEEP was determined according to dynamic lung compliance. Before the end of OLV, an LRM was performed once in both groups. The primary outcome was the incidence of PPCs within 5 days after surgery. Secondary outcomes included the incidence of intraoperative hypotension, use of vasoactive drugs, incidence of arrhythmia and hypotension within 5 days after surgery, postoperative renal function indices, and length of postoperative hospital stay.

Results: There were no statistically significant differences in preoperative baseline characteristics between the control and intervention groups (all $P>0.05$). Compared with the control group, the intervention group had higher intraoperative PEEP, lower driving pressure, and slightly higher airway plateau pressure (P_{plat}), pulse oxygen saturation (SpO₂), and dynamic lung compliance (all $P<0.05$). The incidence of intraoperative hypotension was higher in the intervention group than in the control group [52% (26/50) vs

30% (15/50), $P<0.05$], as was the intraoperative use of vasoactive drugs [54% (27/50) vs 20% (10/50), $P<0.05$]. No statistically significant differences were observed between the 2 groups in surgical site, type of surgery, heart rate, mean arterial pressure (MAP), pulse pressure variation (PPV), intraoperative fluid volume, respiratory rate, or tidal volume (all $P>0.05$). The incidence of PPCs was lower in the intervention group than in the control group [22% (11/50) vs 42% (21/50), $P<0.05$]. There were no statistically significant differences between the 2 groups in postoperative arrhythmia, postoperative hypotension, or length of hospital stay (all $P>0.05$). In both the intervention and control groups, serum creatinine (SCr) and blood urea nitrogen (BUN) levels on postoperative day 1 and BUN levels on postoperative day 3 were higher than their respective preoperative levels (all $P<0.05$). No statistically significant between-group differences were observed in SCr or BUN levels preoperatively or on postoperative days 1, 3, and 5 (all $P>0.05$). After multivariable logistic regression adjustment for age, body mass index (BMI), hypertension grade, American Society of Anesthesiologists (ASA) physical status, and type of surgery, the risk of intraoperative hypotension in the intervention group was 2.8 times that in the control group ($OR=2.8$, 95% CI 1.2 to 6.9; $P<0.05$). Subgroup analysis for intraoperative hypotension showed that patients aged ≥ 65 years, those with a BMI >24 kg/m², grade 3 hypertension, ASA physical status III, or those scheduled to undergo segmentectomy were more likely to develop intraoperative hypotension when receiving the LRM combined with individualized PEEP strategy.

Conclusion: An LRM combined with individualized PEEP can reduce the incidence of PPCs. Although this strategy is associated with a higher incidence of intraoperative hypotension, most episodes can be rapidly corrected with timely intervention, are of short duration, and do not adversely affect postoperative cardiac or renal function. Older patients, those with grade 3 hypertension, and overweight patients may be at greater risk of intraoperative hypotension; therefore, enhanced intraoperative hemodynamic monitoring and timely individualized management are warranted.

KEY WORDS

individualized positive end-expiratory pressure; lung recruitment maneuver; pulmonary resection; postoperative pulmonary complications; hemodynamics

肺癌发病率持续攀升,且有年轻化趋势,手术量呈逐年快速增长态势^[1]。胸腔镜肺切除术作为肺癌外科治疗的主要手段,尽管其具有创伤小、恢复快的优势,但术后肺部并发症(perioperative pulmonary complications, PPCs)的发生率仍高达15%~37%,严重影响患者康复进程与转归质量^[2]。PPCs主要包括肺不张、肺炎、呼吸衰竭等,不仅延长住院时间、增加医疗费用,更与术后远期生存率下降密切相关^[3]。因此,围手术期肺保护策略的优化始终是胸外科麻醉领域的研究热点。传统保护性肺通气策略,即采用小潮气量、限制气道平台压(plateau pressure, Pplat)以及适当的呼气末正压(positive end-expiratory

pressure, PEEP)进行机械通气,虽已广泛应用,但其降低PPCs发生率的效果仍不理想^[4]。近年研究^[5-6]显示,肺复张策略(lung recruitment maneuver, LRM)联合肺动态顺应性导向的PEEP策略可进一步降低PPCs发生的风险。该策略的保护机制为LRM通过短时升高气道压使萎陷肺泡重新开放,个体化PEEP则维持肺泡开放状态,减少肺泡周期性塌陷与复张所致的剪切力损伤,同时降低驱动压、改善肺顺应性^[7-8]。

然而,LRM联合肺动态顺应性导向的PEEP策略在实施过程中,需较高的跨肺压以复张肺泡,因此存在诱发术中血流动力学紊乱的潜在风险^[9]。特别是

高血压患者, 其术中血流动力学紊乱风险高于普通人群^[10]。鉴于中国成人高血压患病率已达27.5%, 且发病呈年轻化趋势^[11], 此类患者在接受该策略时的安全性应受到更多关注。目前, 该策略在高血压人群中的应用尚无相关研究报道, 其能否兼顾肺保护作用与血流动力学稳定性也尚不明确。因此, 本研究旨在评估LRM联合肺动态顺应性导向的PEEP策略对合并高血压的胸腔镜肺切除术患者PPCs和围手术期血流动力学的影响, 以期为该策略在此类人群中的应用效果与安全性提供科学依据。

1 对象与方法

1.1 伦理声明

本研究已获得江南大学附属医院伦理委员会批准(审批号: LS2024058), 并已于2024年11月20日在中国临床试验注册中心完成注册(注册号: ChiCTR2400092643), 遵循《赫尔辛基宣言》的原则, 所有患者均签署知情同意书。

1.2 对象

本研究纳入2024年11月28日至2025年8月15日江南大学附属医院收治的合并高血压拟接受单肺通气下胸腔镜肺切除术的患者, 患者年龄 ≥ 18 岁, 高血压1~3级, 美国麻醉医师协会(American Society of Anesthesiologists, ASA)分级为I~III级^[5], 预计单肺通气时间超过60 min。排除标准: 1)存在气胸或巨大肺大疱, 既往曾行肺切除术。2)术中中转开胸手术, 实际单肺通气时间不足60 min。

采用PASS 2021软件计算样本量, 设定 $\alpha=0.05$ (双边检验), 检验效能 $(1-\beta)$ 为80%。根据预试验结果, 对照组PPCs发生率为48%, 试验组为20%。考虑10%的脱落率, 经计算至少需纳入96例患者。本研究最终共纳入100例患者, 符合样本量要求。

1.3 分组与处理

采用随机数字表法将患者分为2组: 常规保护性通气组(对照组)和LRM联合个体化PEEP策略组(试验组)。本研究为一项前瞻性、患者-结局评估者双盲、随机、对照的临床试验。分配方案隐藏于密封不透明信封中, 患者对分组不知情。由于干预策略的特殊性, 麻醉实施者未设盲, 但数据收集者、结局评估者及统计人员均设盲。对照组全程PEEP设置为5 cmH₂O (1 cmH₂O=0.098 kPa); 试验组在单肺通

气开始时行LRM联合PEEP滴定操作。在单肺通气结束前, 2组患者均进行一次LRM。在每次操作开始前, 麻醉医师要确保患者血流动力学稳定, 即平均动脉压(mean arterial pressure, MAP) >70 mmHg(1 mmHg=0.133 kPa)的时间至少为5 min, 脑电双频指数(electroencephalogram bispectral index, BIS)为40~60且肌松充分。

LRM操作流程: 将呼吸机由容量控制通气切换为压力控制通气, 压力设置为15 cmH₂O, 呼吸频率为15次/min, 吸呼气比为1:1, 吸入氧浓度(fraction of inspired oxygen, FiO₂)为0.8, PEEP为5 cmH₂O。随后每5个呼吸周期增加5 cmH₂O的PEEP水平, 直至达到20 cmH₂O的PEEP, 并在此水平维持10个呼吸周期(总操作时间为100 s)。如果在LRM阶段出现血流动力学不稳定(定义为MAP较基线下降 $>30\%$ 持续超过5 min)^[12], 则中断LRM操作, 并给予5~10 mg麻黄碱。一旦血流动力学恢复稳定, 可再次尝试LRM操作。随后进行递减PEEP滴定, 即肺动态顺应性导向的个体化PEEP: 在LRM操作的最后阶段, 即当PEEP为20 cmH₂O时, 将呼吸机切换回容量控制通气模式, 设定潮气量为5~6 mL/kg, 呼吸频率为15次/min, 吸呼气比为1:2, FiO₂为0.8。随后, 每隔15 s以2 cmH₂O的水平降低PEEP, 直至观察到肺动态顺应性开始下降或不再增加。若在滴定步骤中肺动态顺应性保持不变, 则选择对应最低驱动压力(驱动压=平台压力-PEEP)的PEEP为最佳PEEP, 随后整个操作结束^[8]。术中每40 min评估一次是否需要进行新的LRM操作和PEEP滴定。如果观察到动态顺应性下降 $>20\%$, 则进行一次新的LRM操作和PEEP滴定。2组患者双肺通气时潮气量均设定为6~8 mL/kg(理想体重)、呼吸频率为12~16次/min; 单肺通气时潮气量设定为5~6 mL/kg(理想体重)、呼吸频率为16~20次/min。整个手术过程中FiO₂设定为0.8。在单肺通气开始前, 2组的PEEP均设置为5 cmH₂O。若Pplat ≥ 25 cmH₂O, 则每次将潮气量降低1 mL/kg, 直到Pplat降至25 cmH₂O以下。若单肺通气期间出现脉搏氧饱和度(pulse oxygen saturation, SpO₂) $<90\%$ 且3 min内未上升, 或SpO₂进一步降至 $<88\%$, 需再次行纤维支气管镜检测导管位置, 排除导管移位后, 立即启动低氧血症补救措施(即恢复双肺通气)。

1.4 麻醉方法

患者入室后, 开放右侧颈内静脉通路, 常规监测心电图(electrocardiogram, ECG)、血压、SpO₂、

BIS、脉搏压变异度(pulse-pressure variation, PPV);行桡动脉穿刺置管,用于监测有创动脉压。所有患者由同一组麻醉医师实施全身麻醉并完成术中管理。麻醉诱导:2组患者均在面罩供氧3 min后,采用舒芬太尼0.4~0.6 $\mu\text{g}/\text{kg}$ 、依托咪酯0.20~0.25 mg/kg 、丙泊酚0.5~1.0 mg/kg 、顺式阿曲库铵0.2~0.25 mg/kg 进行麻醉诱导,诱导后面罩辅助通气3 min,随后由麻醉医师根据手术需要选择双腔支气管导管或单腔支气管导管配合支气管封堵器进行插管,连接麻醉机进行机械通气,并经纤维支气管镜确认气管导管位置合适后固定。麻醉维持:给予瑞芬太尼5.0~8.0 $\mu\text{g}/\text{kg}/\text{h}$ 、丙泊酚4~5 $\text{mg}/\text{kg}/\text{h}$,并联合吸入0.8%~2.0%七氟烷,视手术操作酌情追加顺式阿曲库铵维持肌松。术中液体管理参照PPV和MAP,实施目标导向液体治疗(goal-directed fluid therapy, GDFT)策略,调整维持药物以控制心率、血压波动在 $\pm 20\%$ 范围内,对难以控制的心率减慢(<45 次/min)使用阿托品进行调整,术中低血压定义为MAP较基线下降 $>30\%$ 持续超过5 min^[12]。当MAP下降超过基线20%时,首先通过GDFT调整;若仍无法纠正且MAP持续低于基线30%超过1 min,则启动血管活性药物干预:首选用药为去甲肾上腺素或麻黄碱。具体选择由麻醉医师根据心率和外周阻力进行综合判断。

1.5 评估指标

主要结局为术后5 d内PPCs发生情况,依据欧洲围手术期临床结局(European Perioperative Clinical Outcome, EPCO)的标准进行诊断,具体包含呼吸道感染、呼吸衰竭、支气管痉挛、肺不张、胸腔积液、气胸和吸入性肺炎^[6]。

次要结局包括术中低血压发生率,血管活性药物使用率(定义为术中使用去甲肾上腺素或麻黄碱),术后5 d内新发的心律失常和术后低血压,术后1、3、5 d的血肌酐(serum creatinine, SCr)和血尿素氮(blood urea nitrogen, BUN),以及术后住院时间。其中,术后低血压定义为需要持续泵入血管活性药物维持血压,即收缩压(systolic blood pressure, SBP) <90 mmHg或舒张压(diastolic blood pressure, DBP) <60 mmHg^[13]。

术前资料包括性别、年龄、体重指数(body mass index, BMI)、ASA分级、高血压分级、高血压药物用药史、加泰罗尼亚外科手术患者呼吸风险(Assess Respiratory Risk in Surgical Patients in Catalonia, ARISCAT)评分^[8]、SCr、BUN。

术中资料包括手术类型(楔形切除、肺段切除、

肺叶切除)、手术部位(左肺/右肺)、术中心率,以及MAP、PPV、呼吸频率、潮气量、 SpO_2 、PEEP、Pplat、驱动压、肺动态顺应性平均值(取自麻醉诱导开始后至麻醉结束时)、术中补液量。

1.6 统计学处理

采用SPSS 27.0软件进行数据分析。正态分布的计量资料以均数 $\pm$ 标准差表示,采用独立样本 t 检验进行组间比较;偏态分布的计量资料以中位数(第1四分位数,第3四分位数)表示,采用秩和检验进行组间比较。计数资料以频数(构成比或率)表示,采用Pearson卡方检验或Fisher确切概率法。亚组分析指标预先设定,结合既往研究^[3]报道的围手术期低血压危险因素及临床相关性,本研究选取性别、年龄、BMI、高血压分级、ASA分级及手术类型作为协变量。经多因素Logistic回归校正上述变量后,采用Logistic回归模型计算OR及95% CI,并作为探索性分析进行解释。 $P<0.05$ 为差异有统计学意义。

2 结果

2.1 患者基线资料比较

本研究共纳入108例患者,剔除单肺通气时间 <1 h者8例,最终对照组和试验组各纳入50例,均顺利完成研究(图1)。2组患者性别、年龄、BMI、ASA分级、ARISCAT评分、高血压分级、术前高血压药物用药史方面的差异均无统计学意义(均 $P>0.05$,表1)。

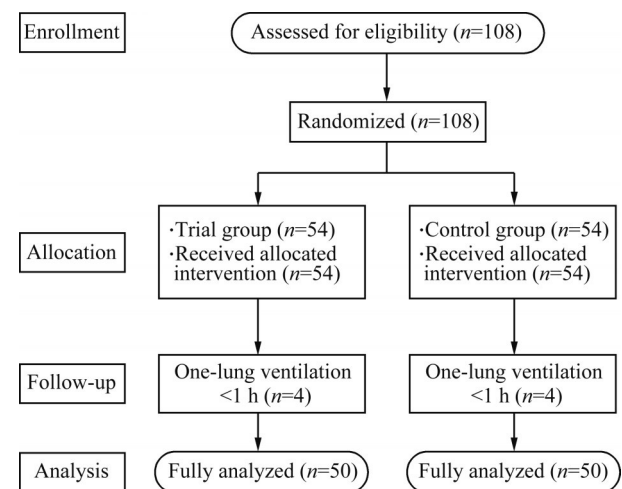


图1 流程图

Figure 1 Flow diagram

表 1 2组患者的基线特征($n=50$)Table 1 Demographic characteristics of the 2 groups ($n=50$)

Items	Intervention group	Control group	t/χ^2	P
Gender (male/female)	26/24	34/16	2.667*	0.102
Age/years	67.5±7.5	65.8±9.3	1.007†	0.317
BMI/(kg·m ⁻²)	24.1±3.3	23.9±3.1	0.445†	0.657
ASA (II/III)	38/12	35/15	0.457*	0.499
ARISCAT/[No.(%)]			1.953*	0.160
Medium risk	48(96)	43(86)		
High risk	2(4)	7(14)		
Hypertension/[No.(%)]			0.412*	0.814
Grade 1	26(52.0)	24(48.0)		
Grade 2	15(30.0)	18(36.0)		
Grade 3	9(18.0)	8(16.0)		
Antihypertensive medication history/[No.(%)]			3.368*	0.338
Diuretics	10(20.0)	4(8.0)		
CCBs	19(38.0)	22(44.0)		
ACEI/ARB	14(28.0)	18(36.0)		
BBs	7(14.0)	6(12.0)		

Continuous data are expressed as mean±standard deviation, and are analyzed with the independent samples t -test. Categorical data are presented as frequencies (proportions or rates), and are analyzed with χ^2 test. * χ^2 value, † t value. BMI: Body mass index; ASA: American Society of Anesthesiologists; ARISCAT: Assess Respiratory Risk in Surgical Patients in Catalonia (scores <26 defined as low risk, 26 to 44 as medium risk, and >44 as high risk); CCBs: Calcium channel blockers; ACEI/ARB: Angiotensin-converting enzyme inhibitor/angiotensin receptor blocker; BBs: β -Blockers.

2.2 术中数据比较

试验组的 PEEP 高于对照组, 驱动压低于对照组, Pplat、SpO₂、肺动态顺应性略高于对照组(均 $P<0.05$)。试验组术中低血压的发生率及术中血管活性药物的使用率均显著高于对照组(均 $P<0.05$)。2组患者手术部位、手术类型、心率、MAP、PPV、术中补液量、呼吸频率、潮气量方面的差异无统计学意义(均 $P>0.05$, 表2)。

2.3 术后数据比较

试验组术后 PPCs 发生率较对照组降低($P<0.05$), 但术后心律失常、术后低血压与住院时间方面差异均无统计学意义(均 $P>0.05$, 表3)。若将因实际单肺通气时间<60 min 而排除的8名患者纳入意向性治疗分析, 试验组 PPCs 发生率仍低于对照组[22%(12/54) vs 41%(22/54); $P<0.05$]。

试验组和对照组术后1 d的 SCr、BUN, 以及术后3 d的 BUN 均高于术前(均 $P<0.05$), 但2组间术前和术后1、3、5 d的 SCr 及 BUN 的差异无统计学意义(均 $P>0.05$, 表4)。术后第5天, 试验组有8例(16%)、对照组有10例(20%)患者因出院导致肾功能数据缺失, 但2组脱落率的差异无统计学意义($P>0.05$)。

2.4 2组患者术中低血压风险探索性亚组分析

经多因素 Logistic 回归校正年龄、BMI、高血压分级、ASA 分级及手术类型等协变量后, 试验组术中低血压的发生风险为对照组的2.8倍($OR=2.8$, 95% CI 1.2~6.9; $P<0.05$)。针对术中低血压的亚组分析显示, 对于年龄≥65岁、BMI>24 kg/m²、高血压3级、ASA III级或拟接受肺段切除手术的患者, 在接受 LRM 联合个体化 PEEP 策略时更容易发生术中低血压(均 $P<0.05$, 图2)。

表2 2组患者术中数据比较($n=50$)Table 2 Comparison of intraoperative data between the 2 groups ($n=50$)

Items	Intervention group	Control group	$t/Z/\chi^2$	P
Surgical site (left lung/right lung)	17/33	21/29	0.679*	0.410
Surgical type/[No.(%)]			0.286*	0.867
Wedge resection	13(26.0)	15(30.0)		
Segmentectomy	22(44.0)	22(44.0)		
Lobectomy	15(30.0)	13(26.0)		
Heart rate/BPM	69.5±10.4	67.7±7.1	1.061†	0.292
Mean arterial pressure/mmHg	86.5±9.2	85.9±9.9	0.294†	0.769
PPV/%	10.9±1.5	10.6±2.5	0.701†	0.525
Volume of fluids administered/mL	1 210.0±336.4	1 184.0±330.3	0.390†	0.697
Respiration/BPM	14.4±0.8	14.4±1.2	0.395†	0.694
Tidal volume/mL	393.0±40.4	394.6±51.5	0.178†	0.860
Driving pressure/cmH ₂ O	13.7±2.7	15.6±3.8	3.130†	0.007
Respiratory system compliance/(mL·cmH ₂ O ⁻¹)	31.9±8.9	27.7±7.0	2.597†	0.011
Intraoperative vasoactive drug usage/[No.(%)]	27(54.0)	10(20.0)	12.398*	<0.001
Intraoperative hypotension/[No.(%)]	26(52.0)	15(30.0)	5.002*	0.025
SpO ₂ /%	98.6(98.3, 99.7)	98.2(97.6, 99.1)	2.175‡	0.029
PEEP/cmH ₂ O	8.1(7.0, 9.1)	4.8(4.8, 5.1)	8.496‡	<0.001
Pplat/cmH ₂ O	21.3(19.6, 23.0)	20.1(16.6, 21.2)	3.34‡	<0.001

Continuous data are expressed as mean±standard deviation, and are analyzed with the independent samples t -test. Categorical data are presented as frequencies (proportions or rates), and are analyzed with χ^2 test. Continuous data with a skewed distribution are presented as median (25th percentile, 75th percentile), and are analyzed with Mann-Whitney U test. * χ^2 value; † t value; ‡ Z value. 1 mmHg=0.133 kPa, 1 cmH₂O=0.098 kPa. BPM: Beats per minute; PPV: Pulse pressure variation; SpO₂: Pulse oxygen saturation; PEEP: Positive end-expiratory pressure; Pplat: Plateau pressure.

表3 2组患者术后数据比较($n=50$)Table 3 Comparison of postoperative data between the 2 groups ($n=50$)

Group	PPCs/ [No.(%)]	Type of PPCs/[No.(%)]				Postoperative arrhythmias/ [No.(%)]	Postoperative hypotension/ [No.(%)]	Hospital length of stay/d
		Respiratory tract infection	Atelectasis	Pleural effusion	Aspiration pneumonia			
Intervention group	11(22.0)	8(16.0)	2(4.0)	1(2.0)	0(0.0)	6(12.0)	8(16.0)	6.3(5.0, 7.8)
Control group	21(42.0)	15(30.0)	4(8.0)	1(2.0)	1(2.0)	5(10.0)	5(10.0)	6.4(5.0, 7.0)
Z/χ^2	4.596*	5.268*				0.102*	0.796*	-0.180†
P	0.032	0.261				0.749	0.372	0.853

Categorical data are presented as frequency (proportion or rate). Continuous data with a skewed distribution are presented as median (25th percentile, 75th percentile). PPCs, type of PPCs, postoperative arrhythmias, and postoperative hypotension are analyzed with χ^2 test. Hospital length of stay are analyzed with Mann-Whitney U test. * χ^2 value; † Z value. PPCs: Postoperative pulmonary complications.

表4 2组患者不同时点SCr与BUN比较($n=50$)

Table 4 Comparison of SCr and BUN at different time points between the 2 groups ($n=50$)

Items	Baseline		Postoperative day 1		Postoperative day 3		Postoperative day 5	
	SCr/	BUN/	SCr/	BUN/	SCr/	BUN/	SCr/	BUN/
	($\mu\text{mol}\cdot\text{L}^{-1}$)	($\text{mmol}\cdot\text{L}^{-1}$)	($\mu\text{mol}\cdot\text{L}^{-1}$)	($\text{mmol}\cdot\text{L}^{-1}$)	($\mu\text{mol}\cdot\text{L}^{-1}$)	($\text{mmol}\cdot\text{L}^{-1}$)	($\mu\text{mol}\cdot\text{L}^{-1}$)	($\text{mmol}\cdot\text{L}^{-1}$)
Intervention group	68.2 $\pm$ 19.1	5.2(4.2, 6.3)	87.6 $\pm$ 21.3‡	7.6 $\pm$ 1.7‡	67.6(55.0, 76.0)	6.2(5.2, 7.3)‡	70.3 $\pm$ 19.1	5.4 $\pm$ 1.7
Control group	69.2 $\pm$ 17.6	5.2(4.1, 5.9)	88.9 $\pm$ 17.5‡	7.4 $\pm$ 1.8‡	72.4(62.6, 81.6)	6.2(5.1, 6.9)‡	70.7 $\pm$ 17.3	5.1 $\pm$ 1.5
<i>t/Z</i>	-0.410*	0.223†	-0.858*	1.034*	1.329†	0.824†	0.169*	0.555*
<i>P</i>	0.682	0.824	0.391	0.301	0.187	0.824	0.903	0.578

Continuous variables with a normal distribution are expressed as mean $\pm$ standard deviation and compared by the *t*-test. Continuous data with a skewed distribution are presented as median (25th percentile, 75th percentile) and compared by Mann-Whitney *U* test. **t* value; †*Z* value. Compared with the same index before surgery in the same group, ‡*P*<0.05. SCr: Serum creatinine; BUN: Blood urea nitrogen.

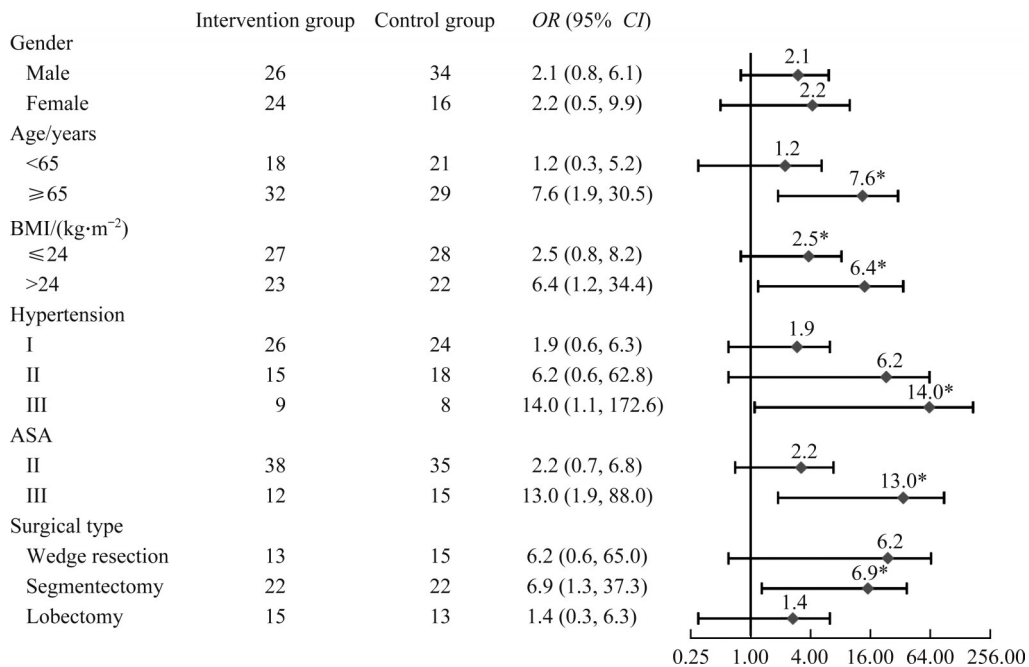


图2 2组患者术中低血压风险的亚组比较

Figure 2 Subgroup analysis of intraoperative hypotension risk between the 2 groups

Comparison of hypotension incidence between intervention and control groups within each subgroup, **P*<0.05. The *X*-axis represents OR and its 95% CI on a logarithmic scale. BMI: Body mass index; ASA: American Society of Anesthesiologists.

3 讨论

胸腔镜肺切除术患者属于PPCs的高危人群。PPCs频发会延长患者ICU停留时间和整体住院时间,增加术后病死率,加重医疗资源负担^[14]。本研究选择100例合并高血压的胸腔镜肺切除术患者,比较LRM联合肺动态顺应性导向的个体化PEEP策略与传统保护性通气策略对患者术后PPCs和围手术期血流动力学的影响。本研究结果显示,试验组术后PPCs风险

明显降低,但低血压的发生率升高;2组患者的术后心律失常、低血压发生率及术后第1、3、5天的SCr和BUN差异均无统计学意义,提示该联合策略可有效促进患者术后肺康复,且术中低血压的增加并未转化为明确的术后心肾功能损害,有助于患者整体康复与转归。

LRM联合肺动态顺应性导向的个体化PEEP策略的肺保护效应已获多项研究^[5-6]支持。其机制可能是LRM操作通过短时升高气道压使萎陷肺泡重新开放,

个体化 PEEP 则维持肺泡开放状态, 减少肺泡周期性塌陷与复张所致的剪切力损伤, 同时降低驱动压、改善肺顺应性^[7]。本研究中, 个体化 PEEP 的设定以肺动态顺应性为导向, 通过递减滴定法确定最佳 PEEP 水平。肺动态顺应性是反映肺组织弹性与可复张性的综合指标, 其达到峰值时所对应的 PEEP 能够最大程度平衡肺泡复张与过度膨胀的风险, 在避免肺泡萎陷的同时减少高 PEEP 对肺微循环和血流动力学的负面影响, 从而实现个体化的呼吸力学优化^[15]。本研究中, 试验组的驱动压低于对照组, 肺动态顺应性和 SpO_2 均优于对照组, 表明该策略有效改善了单肺通气期间的呼吸力学状态。试验组术后 PPCs 发生率较对照组降低近一半, 该结果与 Mo 等^[16]的荟萃分析结果一致, 该荟萃分析证实基于肺动态顺应性个体化 PEEP 滴定可显著降低 PPCs 发生率, 并改善肺顺应性与驱动压。

尽管肺保护获益显著, 但试验组术中低血压发生率显著高于对照组, 血管活性药物使用率亦明显增加。其机制可能在于 LRM 及高 PEEP 引起的胸腔内压显著增高, 进而压迫腔静脉、减少右心回心血量^[17]。Nijbroek 等^[9]在一项大型随机对照试验中报告了类似结果: 个体化高 PEEP 组低血压发生率为 45.7%, 显著高于标准低 PEEP 组的 23.1%。这可能与高血压患者因长期血压升高导致血管重构、压力反射敏感性下降及左心室舒张功能不全有关。Park 等^[18]的研究指出, 高血压患者对血容量减少及体位变化的耐受性显著低于非高血压患者。因此, 即使是操作诱导的短暂静脉回流减少, 也易导致心输出量骤降, 诱发低血压。然而, 本研究中 2 组术后 SCr 、 BUN 及心律失常发生率差异均无统计学意义, 提示试验组术中低血压的增加并未转化为术后心肾功能损害。推测这一结果可能与本研究中积极的术中血流动力学管理有关: 一方面, 试验组血管活性药物使用率显著更高, 及时的药物干预缩短了低血压的有效暴露时间、减轻了心肾低灌注程度; 另一方面, 本研究采用目标导向液体治疗, 维持了有效循环血容量, 缓冲了 LRM 对前负荷的冲击。综上, 本研究中试验组低血压虽发生率较高, 但经及时干预后持续时间短暂, 故未对术后心肾功能造成不良影响。

高龄与术中低血压的发生密切相关。Daum 等^[19]纳入 78 项非心脏手术研究、93.4 万例患者进行荟萃分析, 结果显示, 年龄每增长 1 岁, 术中低血压风险上升 3%。北京协和医院的一项关于非心脏手术的大型回顾性队列研究^[20]发现, BMI 与术中低血压呈 U 型

关联, 过低及过高的 BMI 都与术中低血压发生率的升高相关。本研究的亚组分析亦显示, 高龄与超重是发生术中低血压的危险因素, 可能是因为高龄患者常合并多种系统性疾病, 合并症负担重, 进一步增加了术中低血压的风险。上述结果提示, 对于高龄或超重的合并高血压患者, 在实施 LRM 联合个体化 PEEP 策略时, 应考虑减缓 LRM 的充气速度或降低最高气道压目标, 以保证更平稳的血流动力学过渡。

本研究尚存在一些不足之处。首先, 本研究为一项单中心临床试验, 尽管通过标准化手术与麻醉方案尽可能控制偏倚, 但研究结果的外推性仍受限于本中心的患者特征、手术团队经验及麻醉管理习惯。例如, 本中心倾向于更积极地使用血管活性药物, 这一临床实践可能缩短低血压的持续时间, 从而使得 2 组间 MAP 的平均值无显著差异, 但未能完全避免低血压事件的发生。因此, 后续有必要开展多中心研究以验证本策略的普适性。其次, 本研究样本量相对较小, 尽管主要结局的检验效能充足, 但部分亚组分析的检验效能不足, 置信区间较宽。例如, Lee 等^[21]的研究显示, 肺叶切除术是胸腔镜肺切除术术中低血压的危险因素之一, 而本研究中因相应亚组样本量有限, 未能检出肺叶切除术与术中低血压的显著关联。同时, 本研究对年龄、BMI、高血压分级、ASA 分级及手术类型等亚组变量进行了交互作用检验, 但受限于亚组内样本量过少, 检验效能不足, 均未观察到显著的交互效应, 故上述亚组结果仅能提示潜在风险人群, 尚需更大样本的研究进一步验证。此外, 尽管试验组总体 PPCs 发生率显著降低, 但由于各类单项 PPCs 的发生率较低, 组间差异均无统计学意义。最后, 本研究仅观察了术后 5 d 内的 PPCs。该时间窗的选择是基于此阶段可观察到绝大多数早期并发症, 且符合既往研究^[22]对 PPCs 的定义, 同时也是加速康复外科管理的关键期。然而, 这一窗口可能低估术后 7~30 d 的晚期 PPCs, 未来研究应延长随访周期以全面评估远期结局。

综上所述, LRM 联合肺动态顺应性导向的个体化 PEEP 策略可降低 PPCs 的发生率, 虽然术中低血压发生率较高, 但持续时间较短, 多为一过性, 未影响术后心肾功能。高龄、高血压 3 级及超重患者术中发生低血压的风险可能较高, 针对此类高危人群, 建议术中适当降低 LRM 中的最高气道压设定值, 减缓肺复张速度并加强有创血流动力学监测。

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析, 论文撰写与修改; 谷静雯 数据采集与分析; 柴华、刘命珩、刘怀顺、陈炳鑫 数据采集; 张继如 研究设计, 论文指导与修改。所有作者阅读并同意最终的文本。

利益冲突声明: 作者声称无任何利益冲突。

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