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Impact of a 3-day preoperative inspiratory muscle training program on postoperative pulmonary complications in patients with prior abdominal radiotherapy undergoing major abdominal surgery: A randomized controlled trial

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ABSTRACT

Background: Postoperative pulmonary complications (PPCs) are a major concern after abdominal surgery, particularly in patients with prior abdominal radiotherapy for gastrointestinal malignancies such as gastric, colorectal, and pancreatic cancers. The effect of very short-term preoperative inspiratory muscle training (IMT) in this population remains unclear. ***Materials and Methods:*** This single-center, single-masked randomized controlled trial included 100 patients who had completed abdominal radiotherapy (three-dimensional conformal radiotherapy or intensity-modulated radiotherapy; total dose 45–50.4 Gy) prior to undergoing major abdominal surgery. Participants were randomly assigned to IMT at 15%, 20%, or 30% of maximal inspiratory pressure (MIP), or to a control group performing balloon-blowing exercises. Training was performed three times daily for three consecutive days before surgery. All patients received standardized postoperative physiotherapy. The primary outcome was the incidence of PPCs during hospitalization. Secondary outcomes included length of hospital stay (LOS), hospitalization costs, pulmonary function indices, arterial blood gas parameters, and inflammatory markers. ***Results:*** The overall PPC incidence was 5%, with no significant differences between groups. The IMT 20% group demonstrated a significantly shorter LOS and lower hospitalization costs compared with control. Improvements in pulmonary function and oxygenation were observed in IMT groups, most consistently at 20% intensity. ***Conclusion:*** A three-day preoperative IMT program did not significantly reduce PPC incidence in previously irradiated patients, likely due to the low event rate. However, moderate-intensity IMT (20% MIP) may enhance perioperative recovery and reduce healthcare utilization.

INTRODUCTION

Surgical management of gastrointestinal malignancies, especially in patients who have previously undergone radiotherapy, remains a complex and high-risk clinical undertaking. Among the adverse outcomes associated with major abdominal procedures, postoperative pulmonary complications (PPCs) represent one of the most frequent and clinically significant problems. These complications are strongly associated with increased short-term mortality, extended recovery periods, greater healthcare expenditures, and substantial deterioration in patients' overall quality of life [1]. The development of PPCs is multifactorial and primarily related to physiological alterations that occur after surgery. These include reductions in functional lung volumes, compromised respiratory muscle performance, impaired clearance of airway secretions, and restricted ventilation secondary to postoperative pain. Together, these factors promote atelectasis, secretion retention, and impaired gas exchange, ultimately increasing susceptibility to respiratory complications [2]. Epidemiological evidence suggests that the occurrence of PPCs varies according to the type and extent of surgery. In patients undergoing general abdominal operations, reported incidence rates range between 4% and 21%. However, the risk increases considerably in more extensive procedures, particularly upper abdominal and thoracic surgeries, where rates may reach 20% to 70% [3].

Radiotherapy is widely integrated into multimodality care for gastrointestinal cancers (gastric, colorectal/rectal, and pancreatic malignancies), but unavoidable irradiation of surrounding normal tissues can produce both early and late toxicities that are strongly influenced by total dose, fractionation, irradiated volume, and organ sensitivity [4]. In contemporary GI protocols, abdominal/pelvic courses commonly deliver total doses in the 45-50.4 Gy range using conformal techniques such as 3D-CRT or IMRT, balancing tumor control against normal-tissue constraints [5, 6]. From a mechanistic standpoint, radiation injury in normal tissues resembles a dysregulated wound-healing

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cascade: an initial inflammatory phase is followed by fibroblast activation and progressive extracellular matrix accumulation, ultimately leading to fibrosis, tissue thickening, and loss of compliance with organ-specific functional consequences (7). Parallel to this, radiation can damage the microvasculature and endothelium, promoting endothelial dysfunction, cytokine signaling, and a persistent pro-inflammatory milieu that may impair regional perfusion and tissue repair capacity over time (8).

These pre-existing alterations may act in concert with the physiological stress imposed by surgery, thereby amplifying the inherent susceptibility to postoperative pulmonary complications. Despite substantial progress in surgical practice including the adoption of minimally invasive approaches, refinement of anesthetic management, and improved perioperative ventilatory support PPCs continue to represent a frequent and clinically important consequence of abdominal procedures.

Evidence suggests that several perioperative physical rehabilitation interventions - including aerobic conditioning, respiratory muscle strengthening exercises, balloon inflation exercises, diaphragmatic breathing techniques, and pursed-lip breathing - may contribute to the prevention of postoperative pulmonary complications (PPCs) (9). These interventions are frequently implemented during the limited preoperative interval to optimize functional capacity, improve physiological resilience, and facilitate postoperative recovery (9). Among the available strategies, inspiratory muscle training (IMT) has emerged as a central element of perioperative pulmonary rehabilitation programs (10, 11). The most commonly applied modality is threshold inspiratory muscle training (TIMT) (12) which allows training loads to be prescribed according to an individual's inspiratory muscle strength and progressively adjusted in response to clinical improvement. This capacity for graded and patient-specific intensity modulation represents a major advantage of the method. Multiple investigations have reported that IMT may decrease the incidence of PPCs across a range of surgical settings, including upper and major abdominal procedures, as well as in specific populations such as patients with lung, colorectal, and esophagogastric malignancies. Beneficial effects have also been observed in cardiac and vascular surgeries (9, 10, 13). Nevertheless, the evidence regarding its efficacy in patients undergoing abdominal surgery for gastrointestinal tumors remains inconclusive. Furthermore, standardized and evidence-based IMT prescription protocols have yet to be clearly established, underscoring the need for further high-quality research in this area (9).

A considerable proportion of research examining postoperative pulmonary complications (PPCs) after abdominal surgery has included heterogeneous patient populations. These studies have often encompassed individuals undergoing procedures for benign abdominal conditions - such as cholecystectomy, hernia repair, or bowel obstruction - as well as urological surgeries, with preoperative inspiratory muscle training (IMT) programs commonly lasting two to three weeks (9, 13). Consequently, the specific effects of IMT in patients undergoing surgery for gastrointestinal malignancies remain less clearly defined.

Gastrointestinal cancers represent a substantial global health burden, accounting for approximately 30% of all newly diagnosed malignancies and nearly 36% of cancer-related deaths worldwide (14). Abdominal gastrointestinal tumors are typically characterized by aggressive biological behavior and frequently require technically demanding surgical interventions. These procedures are associated with elevated risks of postoperative complications and extended convalescence periods (14). Most surgeons believe that extending the preoperative preparation period for abdominal gastrointestinal cancer negatively impacts the psychological state and quality of life of cancer patients, especially those with advanced-stage cancer (15). Additionally, the incidence and mortality rates of gastrointestinal cancers in Gansu Province rank among the highest in China, particularly for gastric cancer (16).

Therefore, this randomized controlled trial aimed to investigate whether a pragmatic, short-term (three-day) preoperative IMT program could reduce the incidence of PPCs in patients undergoing abdominal surgery for gastrointestinal cancers with a history of prior abdominal radiotherapy. A secondary aim was to determine the most effective IMT intensity for improving respiratory outcomes in this specific patient population.

To our knowledge, this is the first randomized controlled trial specifically investigating the impact of an ultra-short, three-day preoperative inspiratory muscle training (IMT) program in patients who had previously completed abdominal radiotherapy and were scheduled for major abdominal surgery. While prior studies have demonstrated the benefits of preoperative IMT in general surgical populations, irradiated patients represent a physiologically distinct subgroup with potential radiation-induced alterations in tissue compliance, inflammatory status, and respiratory mechanics. Moreover, most previous IMT protocols have required longer prehabilitation periods, limiting feasibility in oncologic patients who often face narrow surgical timelines. By comparing three different IMT intensities (15%, 20%, and 30% of maximal inspiratory pressure) within a short preoperative window, this study uniquely explores both feasibility and dose–response effects in a high-risk population. Therefore, our trial addresses an important clinical gap by evaluating whether a pragmatic, time-efficient respiratory intervention can meaningfully influence postoperative outcomes in

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previously irradiated gastrointestinal cancer patients.

MATERIALS AND METHODS

Study design and participants

This single-center, single-masked randomized controlled trial included 100 adult patients with a history of completed abdominal radiotherapy for gastrointestinal malignancies (gastric, colorectal, or pancreatic cancer) who were scheduled for elective major abdominal surgery. The study was carried out at the Second Hospital of Lanzhou University following the Declaration of Helsinki.

The study protocol was approved by the independent ethics committee of the center, with strict monitoring of safety and ethics throughout the trial. All participants provided written informed consent. The trial was registered with the Chinese Clinical Trial Registry (http://www.chictr.org.cn/) under registration number ChiCTR2100046126.

Sample size was calculated based on the expected reduction in PPC incidence, assuming a power of 80% and a two-sided alpha level of 0.05. A total of 100 patients including 65 male and 35 females were included into the study.

Inclusion criteria for this study were: (1) signed informed consent; (2) age ≥ 40 years; (3) elective grade IV abdominal surgery in general surgery; (4) no pulmonary treatment within the past eight weeks before enrollment. Exclusion criteria included: (1) emergency surgery; (2) concurrent pulmonary diseases such as bronchial asthma, multiple pulmonary bullae, history of recurrent pneumothorax, or history of pulmonary surgery; (3) neuromuscular diseases such as periodic paralysis, progressive muscular dystrophy, myotonic dystrophy, or ataxia; (4) poor compliance, including patients with mental disorders, cognitive impairment, poor cooperation, or refusal to undergo all procedures of the trial. Eligible patients underwent data collection and baseline measurements after signing the informed consent.

Randomization

Preoperatively, researchers used sequentially numbered, sealed, opaque envelopes to randomly assign participants to one of four groups: Trial Group a (IMT 15%), Trial Group b (IMT 20%), Trial Group c (IMT 30%), and the control group, all undergoing respiratory function exercises for three consecutive days before surgery. The trial groups used a respiratory trainer, while the control group performed balloon-blowing exercises. The envelopes were labelled with patient details to document random assignments according to the recruitment order. The allocation sequence was determined by a web-based, computer-generated block randomization table (1:1). The physiotherapist guiding the intervention, participants, and the coordinating researcher were not blinded. However, baseline and follow-up measurements and postoperative outcome assessments were blinded to group allocation. Blood gas analysis and pulmonary function were monitored on admission and one day before surgery. Infection markers were observed on the day of admission, postoperative day 1, and day 4.

Interventions and procedures

The trial groups used an inspiratory muscle threshold loading device produced by Shengchang Medical Equipment Factory (Yuyao, Zhejiang Province), model C. The apparatus comprises a housing, adjustable switch, spring, mouthpiece, adjustable lever, and nasal clip, with a threshold load range of 9-41cm H_2O. The load is adjusted by modifying the spring compression, corresponding to the desired pressure load. Under normal conditions, the inspiratory valve remains closed and only opens when the spring is compressed during forceful inhalation. Studies have shown that incentive spirometry is a mechanical device and the most effective method for preventing pulmonary complications in high-risk postoperative patients [17-19].

Operation of the inspiratory muscle threshold loading device: rotate the adjustable lever to set the pressure pointer to the prescribed scale, connect the device to the mouthpiece, apply the nasal clip, and breathe through the mouth. Bite the mouthpiece, close lips tightly, and deeply inhale. When air passes through the device, the switch opens, allowing the exercise to begin according to medical instructions. The control group used the balloon-blowing method with standardized latex balloons (10-inch balloons from Guangdong Qipai Trading Co., Ltd.) and balloon inflators (material: ABS; size: length 5.5 cm, diameter 2 cm). The exercise involved instructing patients to take a deep breath and slowly inflate the balloon until no further inflation is possible, without taking additional breaths or allowing air leakage. This constituted one set of exercises.

Patients performed systematic respiratory muscle exercises during the three days of preoperative training using the respiratory trainer and balloon. Each day, the training was divided into three sessions: 8:00-8:40 AM, 12:00-12:40 PM, and 4:00-4:40 PM. Each session consisted of two parts: 1 minute of calm breathing for relaxation and 3 minutes of formal exercise. In terms of exercise intensity, patients in the trial group were divided into three subgroups: Group a (15% of maximum inspiratory pressure), Group b (20% of maximum inspiratory pressure), and Group c (30% of maximum inspiratory pressure) (figure 1).

For four consecutive days postoperatively, patients underwent physical therapy focusing on respiratory exercises (such as chest percussion for sputum clearance, coughing, deep breathing, and limb

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activity training). The daily training sessions were scheduled at 8:00-8:45 AM and 4:00-4:45 PM. Within 24 hours post-surgery, patients were encouraged to sit up with guidance from the researchers and perform upper and lower limb exercises in a seated position to promote recovery. Starting from the second postoperative day, patients were instructed to engage in more active chest percussion and limb movement exercises, gradually increasing activity levels and walking for at least 10 minutes daily. Breathing exercises, coughing, limb movement, and ambulation were repeated daily as part of the physical therapy regimen (figure 1).

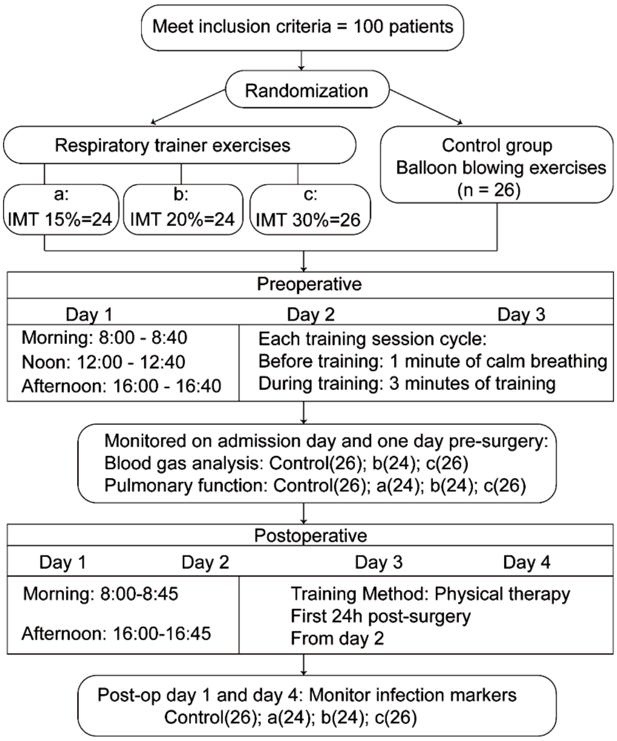

Figure 1. Flow of patients through trial.

All participants in this trial had a history of radiation therapy for their gastrointestinal cancer prior to enrollment in this preoperative IMT study. The radiotherapy was administered as part of their standard oncologic treatment plan. Radiotherapy was completed a minimum of 4 to 8 weeks prior to the planned date of elective abdominal surgery. This interval was selected to allow for adequate recovery from acute radiation-induced side effects (such as skin reactions, fatigue, and local inflammation) while ensuring the oncologic rationale for surgery (e.g., resection of the irradiated tumor bed) remained timely. Radiation was indicated as neoadjuvant or definitive treatment based on multidisciplinary tumor board decisions, primarily for locally advanced gastric, pancreatic, or rectal cancers where radiation is standard of care.

Treatment was delivered using modern, image-guided techniques (Volumetric Modulated Arc Therapy - VMAT or Intensity-Modulated Radiation Therapy - IMRT) to minimize dose to surrounding organs-at-risk (OARs), particularly the lungs, heart, and residual uninvolved bowel. The total prescribed dose ranged from 45 to 50.4 Gray (Gy), delivered in daily fractions of 1.8 to 2.0 Gy over 5 to 6 weeks, in accordance with international guidelines for gastrointestinal malignancies. Treatment planning was based on contrast-enhanced simulation CT scans with patients in a reproducible position. The clinical target volume (CTV) included the primary tumor site and involved regional lymph nodes, with appropriate margins to create the planning target volume (PTV). Efforts were made to contour and limit radiation exposure to the diaphragmatic crura, lower lung bases, and chest wall musculature where possible, recognizing that upper abdominal tumors (e.g., gastric or pancreatic) inherently involve these regions. Treatment verification was performed using cone-beam CT (CBCT) weekly. All patients completed their prescribed radiotherapy course without major interruptions (i.e., >5 consecutive days). Documentation of the total dose, fractionation, treatment dates, and radiation fields was obtained from the hospital's electronic medical record and radiotherapy planning system for each participant.

Outcome measures

The primary outcome measure was the incidence of PPCs at different training intensities using the inspiratory muscle threshold loading device. Postoperative complications included pneumonia, atelectasis, respiratory failure, unplanned intubation, and pleural effusion. Participants were screened using standardized and validated diagnostic tools, with PPC diagnostic criteria outlined in Table S1. Evaluators conducted prospective assessments of participants, with daily evaluations continuing until discharge. Secondary outcomes included changes in respiratory function indicators, blood gas-related indicators, length of hospital stay, and hospital costs.

Statistical analysis

All data analyses were conducted using R (version 4.1.1). Continuous data were presented as mean ± standard deviation (SD), while data such as hospital stay and costs were expressed as median and interquartile range (M [IQR]). Group differences were analyzed using paired t-tests, and changes over time were described using mean difference and percentage change (% Change). Categorical data were presented as frequencies and percentages, with differences analyzed using the chi-square (χ^2) test. Changes in lung function and infection markers were described using mean difference and percentage change, with paired t-tests used to analyze differences between groups at different time points. Multivariable analysis was performed using logistic regression to calculate odds ratios (OR) and 95% confidence intervals, adjusting for relevant confounders. All analyses were considered statistically significant at $P<0.05$.

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RESULTS

Baseline characteristics of study participants

Between January 2022 and September 2024, a total of 100 patients with a prior history of abdominal radiotherapy who were scheduled for surgery due to abdominal gastrointestinal malignancies were enrolled in the study. Participants were randomly allocated into four groups: an IMT 15% group (n = 24), an IMT 20% group (n = 24), an IMT 30% group (n = 26), and a control group (n = 26) that performed balloon-inflation exercises.

Of the overall cohort, 65 patients were diagnosed with gastric cancer. The median age differed slightly across groups, measuring 58 years in the control group, 60 years in the IMT 15% group, 61.5 years in the IMT 20% group, and 64.5 years in the IMT 30% group. Male participants comprised 65.38% of patients in the control, IMT 15%, and IMT 30% groups, while the proportion of males in the IMT 20% group was 62.5%. Detailed demographic and clinical baseline characteristics of the study population are presented in table S2.

Primary outcome

Postoperative pulmonary complications (PPCs) occurred in 5 of the 100 enrolled patients, corresponding to an overall incidence of 5%. Within the IMT 15% group (n = 24), one patient (4.16%) developed PPCs. Two cases (8.33%) were recorded in the IMT 20% group (n = 24), while one case was observed in each of the IMT 30% group (n = 26; 3.84%) and the balloon-blowing control group (n = 26; 3.84%).

In the crude (unadjusted) logistic regression analysis, the odds ratios (ORs) for PPCs were 1.09 for the IMT 15% group, 2.27 for the IMT 20% group, and 1.00 for the IMT 30% group, with none reaching statistical significance ($P > 0.05$). Following adjustment for potential confounders - including body mass index (BMI), age, peripheral oxygen saturation (SpO_2), and prior radiotherapy dose - no statistically significant associations were identified. The adjusted ORs were 0.39, 0.98, and 0.84 for the IMT 15%, 20%, and 30% groups, respectively (all $P > 0.05$).

Furthermore, application of the Firth penalized likelihood correction model to account for the small number of events yielded consistent findings. After controlling for BMI, age, SpO_2, preoperative hemoglobin and albumin levels, smoking status, alcohol consumption, and radiotherapy field (upper versus mid-lower abdomen), no significant relationship between IMT intensity and PPC incidence was detected (table 1).

Secondary outcomes

The unadjusted analysis showed that, compared to the control group, the IMT 20% group (OR=0.15, 95% CI: 0.04–0.49, P = 0.002) significantly reduced the length of hospital stay. After adjusting for covariates such as BMI, age, and SpO_2, all three groups showed significant reductions in hospital stay: IMT 15% group (OR=0.18, 95% CI: 0.03–0.83, P = 0.034), IMT 20% group (OR=0.07, 95% CI: 0.01–0.37, P = 0.003), and IMT 30% group (OR=0.20, 95% CI: 0.04–0.86, P = 0.037). In terms of hospital costs, the IMT 20% group showed a significant reduction in both unadjusted (OR=0.30, 95% CI: 0.09–0.95, P = 0.045) and adjusted analyses (OR=0.18, 95% CI: 0.04 –0.79, P = 0.029). However, hospital costs did not show significant changes in the IMT 15% and IMT 30% groups. Both unadjusted and adjusted analyses revealed no statistically significant differences in the risk of postoperative complications across all groups (table 1).

Table 1. Primary and secondary outcomes.

		Unadjusted analysis	*P* value	Adjusted analysis	*P* value
PPCs		**OR (95% CI)**		**OR (95% CI)**	
Balloon blowing exercises(n=26)	1 (3.84%)	1	1	1	1
IMT15% (n=24)	1 (4.16%)	1.09 (0.08- 14.07)	0.953	0.39 (0.00-7.53)	0.543
IMT 20%(n=24)	2 (8.33%)	2.27 (0.23- 21.79)	0.514	0.98 (0.03-16.34)	0.990
IMT 30%(n=26)	1 (3.84%)	1.00 (0.08- 12.94)	1.000	0.838 (0.05-14.12)	0.893
Length of hospital stay*					
Balloon blowing exercises(n=26)	20.5 (19-24)	1	1	1	1
IMT15% (n=24)	17.5 (17-22.2)	0.32 (0.10- 0.99)	0.053	0.18 (0.03- 0.83)	0.034
IMT 20%(n=24)	17.5 (16-19.2)	0.15 (0.04- 0.49)	0.002	0.07 (0.01- 0.37)	0.003
IMT 30%(n=26)	18 (16.2-26.8)	0.33 (0.10- 1.00)	0.053	0.20 (0.04- 0.86)	0.037
Hospitalization costs#					
Balloon blowing exercises(n=26)	60377 (53697- 67030)	1	1	1	1
IMT15% (n=24)	61298 (52919- 67534)	1.03 (0.33-3.19)	0.963	0.70(0.17-2.78)	0.616
IMT 20%(n=24)	53067 (46141- 59703)	0.30 (0.09- 0.95)	0.045	0.18 (0.04-0.79)	0.029
IMT 30%(n=26)	59673 (55598- 66098)	0.86 (0.28- 2.57)	0.780	0.67 (0.17-2.56)	0.561
Postoperative complications during hospital stay					
Balloon blowing exercises(n=26)	1 (3.84%)	1	1	1	1
IMT15% (n=24)	0 (0)	0.00 (NA-NA)	0.994	0.70 (0.17-2.78)	0.995
IMT 20%(n=24)	3 (12.5%)	3.57 (0.42- 75.21)	0.285	0.18 (0.04-0.79)	0.493
IMT 30%(n=26)	5 (19.2%)	5.95 (0.87- 118.86)	0.116	0.67 (0.17-2.56)	0.154

Continuous variables were expressed as median and interquartile range (M [IQR]), and differences between groups were analyzed using paired t-tests. Categorical variables were presented as frequency and percentage, with differences assessed using chi-square (χ^2) tests; * If OR < 1, it indicates a shorter length of stay for that group; OR > 1 indicates a longer length of stay. OR = 1 indicates no significant difference; If the OR < 1, it indicates that the hospitalization costs for this group are lower; OR > 1 indicates higher hospitalization costs; OR = 1 suggests no statistically significant difference. Due to insufficient data points, the model could not calculate relevant coefficients and confidence intervals, resulting in NA.

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Arterial blood gas analysis

After three days of preoperative training, this study compared arterial blood gas (ABG) changes in the IMT groups (20% and 30%) and the control group from admission to the day before surgery. The results showed that the IMT 20% group had a significant reduction in CO2 content (mean difference: -1.0, percentage change: -3.6%, P = 0.019), while the IMT 30% group showed a significant increase (mean difference: 1.3, percentage change: 4.8%, P = 0.016). The IMT 20% group also demonstrated significant increases in the alveolar-arterial oxygen gradient (A-a DO2) (P = 0.019) and alveolar oxygen partial pressure (PAO2) (P = 0.029), with no significant changes observed in the other groups (table 2).

Table 2. Comparison of ABG between preoperative IMT groups and control group.

ABG	Balloon blowing exercises(n=26)				IMT 20%(n=24)				IMT 30%(n=26)			
	Timepoint 1	Timepoint 2	Mean difference (% change)	P value	Timepoint 1	Timepoint 2	Mean difference (% change)	P value	Timepoint 1	Timepoint 2	Mean difference (% change)	P value
PaCO2(mmHg)	40.0 ±3.6	39.1±3.0	-1.0(-2.4%)	0.047	40.4 ±6.3	38.4±5.2	-2.0(-4.8)	0.059	39.4±3.4	39.8±4.2	0.4(1.0)	0.609
PaO2(mmHg)	71.7±7.1	72.0±9.0	0.4(0.5)	0.785	70.8±14.4	68.0±9.7	-2.9(-4.0)	0.277	72.7±6.0	73.9±13.4	1.3(1.7)	0.592
CO2 Content	26.9±2.6	26.4±2.7	-0.4(-1.6)	0.170	26.9±3.4	25.9±2.9	-1.0(-3.6)	0.019	25.9±1.8	27.2±2.5	1.3(4.8)	0.016
SaO2(%)	93.2±6.9	94.0±2.3	0.9(0.9)	0.405	93.5±2.6	93.0±2.5	-0.4(-0.4)	0.289	94.3±1.8	94.3±2.4	0.0(0.0)	1.000
A-a O2 Gradient	33.0±10.4	31.5±8.9	-1.5(-4.5)	0.322	32.9±11.2	57.9±45.8	25.0(76.1)	0.019	33.7±10.4	33.8±23.9	0.2(0.6)	0.974
PAO2	101.8±8.7	101.7±3.5	-0.1(-0.1)	0.908	100.0±8.1	124.4±48.8	24.5(24.5)	0.029	103.7±11.6	106.2±18.6	2.5(2.4)	0.590
FiO2(%)	21.2±1.2	21.0±0.0	-0.2(-0.8)	0.322	21.0±0.0	24.1±7.1	3.1(14.7)	0.053	21.3±1.6	21.8±2.8	0.5(2.2)	0.478

Continuous variables were expressed as median and interquartile range (M [IQR]), and differences between groups were analyzed using paired t-tests. Categorical variables were presented as frequency and percentage, with differences assessed using chi-square (χ^2) tests; * If OR < 1, it indicates a shorter length of stay for that group; OR > 1 indicates a longer length of stay. OR = 1 indicates no significant difference; If the OR < 1, it indicates that the hospitalization costs for this group are lower; OR > 1 indicates higher hospitalization costs; OR = 1 suggests no statistically significant difference. Due to insufficient data points, the model could not calculate relevant coefficients and confidence intervals, resulting in NA.

Pulmonary function analysis

This study compared pulmonary function changes among the IMT groups (15%, 20%, and 30%) and the control group. Results showed a significant increase in FEV1 (both actual and predicted values) in the control group (P = 0.026 and P = 0.014), while no significant change was observed in the IMT groups. FVC (actual value) significantly improved in the control group (P = 0.029), IMT 15% group (P = 0.012), and IMT 30% group (P = 0.027). Similarly, FVC% (predicted value) significantly increased in the control group (P = 0.019), IMT 15% group (P = 0.012), and IMT 30% group (P = 0.016). VC MAX significantly improved in the IMT 15% group (P = 0.003) and IMT 30% group (P = 0.007) but not in the control group. MVV (L/min) and MVV (%) significantly increased across the control, IMT 15%, IMT 20%, and IMT 30% groups, with the most notable improvement in the IMT 20% group (MVV (L/min): mean difference = +17.9, % change = +23.0%, P = 0.001; MVV (%): mean difference = +17.2, % change = +24.0%, P < 0.001), followed by IMT 15%, control, and IMT 30% groups (table 3).

Table 3. Comparison of pulmonary function between IMT groups and control group.

Pulmonary function	Balloon blowing exercises(n=26)				IMT 15%(n=24)				IMT 20%(n=24)				IMT 30%(n=26)			
	Timepoint 1	Timepoint 2	Mean difference (% change)	P value	Timepoint 1	Timepoint 2	Mean difference (% change)	P value	Timepoint 1	Timepoint 2	Mean difference (% change)	P value	Timepoint 1	Timepoint 2	Mean difference (% change)	P value
FEV1 (L) (actual)	2.7 ±0.6	2.8±0.5	0.1 (4.9)	0.026	2.7 ±0.7	2.8±0.7	0.1 (2.6)	0.054	2.4 ±0.8	2.4±0.8	0.0 (1.9)	0.489	2.5±0.6	2.6±0.5	0.1 (2.7)	0.190
FEV1 (L) (predicted)	3.0±0.4	3.0±0.4	0.0 (-0.3)	0.337	2.7±0.5	2.7±0.5	0.0 (0.5)	1.000	2.9±0.4	2.9±0.4	0.0 (-4.0)	0.122	2.8±0.4	2.8±0.4	0.0 (1.7)	0.605
FEV1% pre	87.5±16.5	92.1±13.4	4.5 (5.2)	0.014	99.3±18.4	101.6±17.7	2.3 (0.0)	0.090	83.3±27.1	87.1±30.8	3.8 (-0.5)	0.146	89.5±17.3	92.8±16.0	3.3 (-0.4)	0.080
FVC (L) (actual)	3.5±0.8	3.7±0.6	0.2 (5.4)	0.029	3.4±0.9	3.6±0.8	0.2 (5.3)	0.012	3.5±0.7	3.5±0.6	0.1 (1.8)	0.432	3.3±0.7	3.5±0.6	0.2 (5.4)	0.027
FVC (L) (predicted)	3.8±0.5	3.8±0.5	0.0 (-0.3)	0.337	3.5±0.7	3.5±0.7	0.0 (0.0)	0.965	3.6±0.5	3.6±0.6	0.0 (-0.5)	0.122	3.6±0.4	3.5±0.4	0.0 (-0.4)	0.583
FVC% pre	92.9±15.8	98.9±13.7	6.0 (6.4)	0.019	100.5±19.4	106.5±14.7	6.0 (6.0)	0.012	97.0±20.2	99.9±20.5	2.9 (3.0)	0.262	92.6±16.4	98.7±14.3	6.1 (6.6)	0.016
FEV1/FVC (actual)	75.9 ±7.9	75.0±5.6	0.9 (-1.2)	0.617	79.4 ±9.3	76.1±8.5	-3.3 (-4.1)	0.070	67.5 ±17.2	67.0±17.0	-0.5 (-0.8)	0.731	76.1±10.8	74.0±10.4	-2.1 (-2.8)	0.084
FEV1/FVC (predicted)	83.6±0.2	83.6±0.2	0.0 (0.0)	0.337	83.8±0.3	83.3±1.9	-0.5 (-0.6)	0.336	83.7±0.3	83.7±0.3	0.0 (0.0)	0.177	83.7±0.2	83.7±0.2	0.0 (0.0)	0.474
VC MAX	3.5 ±0.9	3.8±0.6	0.3 (7.1)	0.095	3.4 ±0.9	3.7±0.8	0.2 (6.2)	0.003	3.5 ±0.7	3.6±0.6	0.1 (3.2)	0.151	3.3±0.7	3.6±0.6	0.2 (6.4)	0.007
RV (L)	2.7±0.5	2.9±0.5	0.3 (9.4)	0.244	2.7±0.6	2.6±0.6	-0.1 (-4.6)	0.731	3.2±1.3	3.3±1.8	0.1 (3.1)	0.809	2.8±0.8	2.6±0.6	-0.3 (-9.4)	0.185
MVV (L/min)	88.5±19.2	103.0±21.4	14.5 (16.4)	0.001	88.1±30.0	102.8±26.2	14.7 (16.6)	0.003	77.9±29.0	95.7±32.2	17.9 (23.0)	0.001	85.6±21.4	97.0±23.6	11.5 (13.4)	0.009
MVV (%)	77.4±14.2	90.2±15.1	12.8 (16.6)	0.001	82.0±20.2	96.9±20.7	14.9 (18.2)	0.004	71.4±25.2	88.5±30.0	17.2 (24.0)	0.000	78.9±16.2	90.1±18.8	11.3 (14.3)	0.006
TLC (L)	6.0±0.7	6.5±0.6	0.5 (7.8)	0.037	6.3±1.2	5.8±1.2	-0.4 (-6.5)	0.301	6.3±1.3	6.6±1.7	0.3 (4.7)	0.505	6.0±1.2	5.8±0.9	-0.2 (-2.7)	0.485
RV/TLC	44.4±6.3	45.2±6.6	0.8 (1.8)	0.808	43.1±6.1	44.5±7.8	1.4 (3.2)	0.778	48.9±12.4	47.5±13.3	-1.4 (-2.9)	0.448	47.1±7.4	44.2±6.8	-3.0 (-6.3)	0.123
FRC (L)	3.9 ±0.6	4.3±0.7	0.4 (11.4)	0.167	4.2 ±1.6	3.6±0.7	-0.6 (-14.3)	0.293	4.4 ±1.6	3.8±1.2	-0.6 (-13.6)	0.033	4.0±0.8	3.5±0.7	-0.5 (-13.3)	0.049
FRC/TLC	64.0±8.3	65.6±9.5	1.7 (2.6)	0.909	59.4±9.0	60.5±9.2	1.1 (1.8)	0.836	64.3±11.0	60.8±12.3	-3.6 (-5.5)	0.321	65.8±8.8	60.2±6.4	-5.7 (-8.6)	0.048

Continuous variables were expressed as mean ± standard deviation (SD); FEV1 (L) (actual): Forced Expiratory Volume in 1 Second (actual value); FEV1 (L) (predicted): Forced Expiratory Volume in 1 Second (predicted value); FEV1% pre: Forced Expiratory Volume in 1 Second as a percentage of the predicted value; FVC (L) (actual): Forced Vital Capacity (actual value); FVC (L) (predicted): Forced Vital Capacity (predicted value); FVC% pre: Forced Vital Capacity as a percentage of the predicted value; FEV1/FVC (actual): Ratio of Forced Expiratory Volume in 1 Second to Forced Vital Capacity (actual value); FEV1/FVC (predicted): Ratio of Forced Expiratory Volume in 1 Second to Forced Vital Capacity (predicted value); VC MAX: Maximum Vital Capacity; RV (L): Residual Volume (actual value); MVV (L/min): Maximum Voluntary Ventilation (measured in liters per minute); MVV (%): Maximum Voluntary Ventilation as a percentage of the predicted value; TLC (L): Total Lung Capacity (actual value); RV/TLC: Ratio of Residual Volume to Total Lung Capacity; FRC (L): Functional Residual Capacity (actual value); FRC/TLC: Ratio of Functional Residual Capacity to Total Lung Capacity.

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Infection markers analyses

This study compared the changes in infection markers between IMT groups and the control group on the first day of admission and postoperative days one and four. On postoperative day one, white blood cell (WBC) counts significantly increased across all groups, with the IMT 15% (mean difference: 5.85, % change: 92.92, $P < 0.001$) and IMT 20% groups (mean difference: 6.51, % change: 94.24, $P < 0.001$) exhibiting the most pronounced inflammatory response. By postoperative day four, WBC counts in both the IMT and control groups remained elevated compared to admission, though the increase was smallest in the IMT 15% group (mean difference: 1.89, % change: 29.95, $P = 0.017$) (table 4).

Neutrophil counts also rose significantly in all groups on postoperative day one, with the IMT groups showing more prominent inflammatory responses. By postoperative day four, neutrophil counts remained higher than at admission in all groups, with the IMT 15% group exhibiting the smallest increase (mean difference: 2.50, % change: 60.32, $P = 0.002$) (table 4).

Lymphocyte counts significantly decreased in all groups on postoperative day one, with the IMT 30% and IMT 20% groups showing the most substantial immunosuppressive effects. Although lymphocyte counts began to recover by postoperative day four, they remained below admission levels. Compared to the control group (mean difference: -0.79, % change: -43.84, $P < 0.001$), lymphocyte recovery was faster in the IMT 20% group (mean difference: -0.62, % change: -38.98, $P < 0.001$), followed by the IMT 15% (mean difference: -0.65, % change: -41.64, $P < 0.001$) and IMT 30% groups (mean difference: -0.64, % change: -43.59, $P < 0.001$) (table 4).

Table 4. Comparison of infection markers between the IMT group and the balloon blowing group before and after surgery.

Infection markers	Balloon blowing exercises(n=26)	IMT 15%(n=24)	IMT 20%(n=24)	IMT 30%(n=26)
WBC (Mean ± SD)				
Day 1 of Admission	6.64±2.85	6.30±2.40	6.91±3.37	6.06±1.65
Postoperative 1st day	12.25±3.46	12.15±2.86	13.42±5.28	11.38±3.62
Postoperative 4th day	9.25±2.73	8.18±2.92	10.30±3.43	8.80±3.00
Mean difference between admission day and postoperative 1st day				
Mean difference	5.61	5.85	6.51	5.32
% change	84.39	92.90	94.24	87.85
P value	< 0.001	< 0.001	< 0.001	< 0.001
Mean difference between admission day and postoperative 4th day				
Mean difference	2.60	1.89	3.39	2.75
% change	39.18	29.95	48.99	45.34
P value	0.001	0.017	< 0.001	< 0.001
Neutrophils (Mean ± SD)				
Day 1 of Admission	4.23±1.99	4.15±2.24	4.67±3.21	3.98±1.42
Postoperative 1st day	10.71±3.45	10.87±2.64	12.02±5.01	10.16±3.36
Postoperative 4th day	7.50±2.46	6.65±2.79	8.59±3.25	7.29±2.85
Mean difference between admission day and postoperative 1st day				
Mean difference	6.47	6.72	7.35	6.17
% change	152.91	162.01	157.46	155.10
P value	< 0.001	< 0.001	< 0.001	< 0.001
Mean difference between admission day and postoperative 4th day				
Mean difference	3.27	2.50	3.93	3.31
% change	77.14	60.32	84.13	83.15
P value	< 0.001	0.002	< 0.001	< 0.001
Lymphocytes (Mean ± SD)				
Day 1 of Admission	1.80±1.40	1.56±0.62	1.59±0.79	1.46±0.48
Postoperative 1st day	0.78±0.72	0.64±0.32	0.65±0.33	0.57±0.26
Postoperative 4th day	1.01±0.67	0.91±0.40	0.97±0.35	0.83±0.28
Mean difference between admission day and postoperative 1st day				
Mean difference	-1.01	-0.92	-0.94	-0.89
% change	-56.39	-58.96	-59.19	-60.86
P value	< 0.001	< 0.001	< 0.001	< 0.001
Mean difference between admission day and postoperative 4th day				
Mean difference	-0.79	-0.65	-0.62	-0.64
% change	-43.84	-41.64	-38.98	-43.59
P value	< 0.001	< 0.001	< 0.001	< 0.001

Continuous variables were expressed as mean ± standard deviation (SD).

DISCUSSION

The present study demonstrated that short-term preoperative inspiratory muscle training (IMT) did not significantly decrease the incidence of postoperative pulmonary complications (PPCs) in patients undergoing surgery for abdominal gastrointestinal malignancies. Nevertheless, IMT - particularly at a moderate intensity corresponding to 20% of maximal inspiratory pressure (MIP) - was associated with meaningful physiological and clinical benefits. These included improvements in pulmonary

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function parameters, enhanced carbon dioxide elimination and oxygenation efficiency, reduced length of hospitalization, lower overall medical expenditures, and a more favorable balance between inflammatory response and postoperative recovery. In contrast, higher-intensity IMT (30% MIP) appeared to be accompanied by elevated inflammatory markers, highlighting the importance of carefully titrating training intensity to optimize benefit while minimizing potential adverse effects.

The development of PPCs is multifactorial, although respiratory muscle dysfunction has been identified as a central contributor [10]. Impairment of inspiratory muscle performance may predispose patients to atelectasis, ineffective cough, and disrupted respiratory control mechanisms [20]. These disturbances are often exacerbated by perioperative factors such as general anesthesia, systemic inflammatory responses, mechanical ventilation, and incisional pain, all of which can restrict lung expansion and compromise mucociliary clearance, thereby increasing susceptibility to pulmonary infection and pneumonia [9, 21]. The literature on preoperative IMT presents heterogeneous findings. Numerous randomized controlled trials have reported that IMT administered before abdominal surgery significantly lowers the incidence of PPCs [9, 10, 13, 22-25]. Hulzebos *et al.* demonstrated a 50% reduction in PPC occurrence among patients undergoing cardiac surgery following preoperative IMT [26]. Similarly, Boden *et al.*, in a prospective, multicenter, double-blind randomized trial involving elective major upper abdominal surgery, observed a 52% relative risk reduction in PPCs [13]. However, not all studies have reported consistent benefits. One randomized trial in patients undergoing surgery for esophageal cancer found that although preoperative IMT improved inspiratory muscle strength, it did not translate into a decreased rate of postoperative pneumonia [11]. Furthermore, a systematic review concluded that only a limited number of trials provided strong evidence supporting preventive respiratory therapy, and questioned the routine implementation of such interventions following abdominal surgery [27].

In this study, the incidence of PPCs was 5% (5/100), and short-term IMT did not significantly reduce PPC incidence in abdominal digestive tract cancer surgery patients. Possible explanations include: (1) Research suggests that abdominal surgeries with incisions near the diaphragm pose a higher risk for PPCs [17], with 65% (65/100) of the surgeries in this study being for gastric cancer; (2) All patients in this study placed great importance on respiratory training for postoperative recovery and actively engaged in preparation, motivation, and training pre-and postoperatively [13, 28]. Scholes *et al.* found that respiratory comorbidities and anesthesia duration were significantly associated with an increased risk of PPCs after abdominal surgery [29]. The Firth correction model in this study did not identify any risk factors related to PPCs, possibly due to the sample's low number of PPC cases.

Determining hospital length of stay involves multiple complex factors, and the standard deviation is significant after abdominal surgery [13]. This study showed that IMT significantly reduced hospital stay, with IMT 20% having the best effect. Similarly, Ge *et al.* found a reduction in hospital stay in the inspiratory muscle training group (mean difference 1.15 days; 95% CI: -2.10 to -0.20) [10]. Two meta-analyses, including 29 [9] and 6 [25] clinical trials respectively, also showed that preoperative IMT was associated with a reduction in hospital stay. However, some studies indicated that the effect of IMT on reducing hospital stay remains uncertain and requires further investigation [10, 13]. Additionally, this study demonstrated that moderate-intensity IMT (IMT 20%) significantly reduced hospital costs.

Most studies compared the effects of IMT on preoperative and postoperative lung function. The results showed that, compared to other respiratory training methods, IMT significantly increased maximal oxygen uptake and maximal inspiratory pressure [9, 10] and improved patients' inspiratory strength and respiratory muscle endurance [24]. It also significantly reduced the incidence of postoperative pulmonary complications [19, 24, 30]. However, some studies indicated that IMT did not affect lung function variables such as FEV1, FVC, and lung capacity [22, 31, 32]. Considering that patients undergoing major digestive tract cancer surgeries may have difficulty undergoing postoperative lung function tests, this study only analyzed lung function at admission and on the day before surgery. The results showed that the IMT 20% group demonstrated the best improvements across multiple lung function parameters.

Few studies have focused on the relationship between IMT and arterial blood gases. This study found that moderate-intensity IMT (20% MIP) significantly improved CO2 clearance and oxygen exchange in the short term before surgery, helping to optimize patients' respiratory status and potentially reduce the risk of postoperative respiratory complications. High-intensity IMT (30% MIP) did not provide additional gas exchange benefits and may have negatively impacted respiratory function. Therefore, these findings offer crucial clinical guidance for selecting preoperative IMT intensity, particularly in optimizing arterial blood gases. The study also examined the effects of IMT on infection markers on the day of admission, postoperative day 1, and day 4. The results showed that the IMT 20% and 30% groups might have triggered more robust inflammatory responses and immunosuppression. However, the recovery rate in the moderate-intensity group (IMT 20%) was faster. Clinically, IMT intensity

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should be adjusted based on the patient's condition to avoid excessive inflammation and immunosuppression that could hinder recovery.

Most randomized controlled trials selected an intervention period of 2 to 3 weeks [10, 23, 24, 33]. This study included patients with abdominal digestive tract cancer, and considering that the waiting period for elective cancer surgery could adversely affect patient prognosis and to avoid physical deterioration [24, 34], the study opted for intensive training over three days before surgery. Research has shown that short-term preoperative training can enhance physical fitness before significant surgery, reduce the incidence of PPCs, and promote postoperative recovery [9].

Currently, no evidence is identifying the optimal preoperative respiratory muscle training protocol for patients undergoing cardiothoracic or upper abdominal surgery [23]. A meta-analysis subgroup analysis on PPCs showed that preoperative IMT for 15 minutes or more per day was effective [10]. Studies indicated that moderate- to high-intensity endurance training increased peak oxygen uptake by 11% in cardiopulmonary exercise tests [35], enhanced respiratory muscle strength and endurance, reduced metabolic reflexes, and led to structural and functional adaptations [36]. However, this study demonstrated that compared to low-intensity (IMT 15%) and high-intensity (IMT 30%) training, moderate-intensity IMT (20%) more significantly improved lung function and balanced the inflammatory and recovery processes.

Several limitations should be acknowledged when interpreting the findings of this study. First, this was a single-center investigation with a relatively limited sample size, which may restrict statistical power and limit the generalizability of the results. Second, owing to the nature of the intervention, participant blinding was not feasible, potentially introducing performance bias. Third, the study was conducted in a real-world clinical environment where interventions were delivered by healthcare providers with varying levels of expertise and experience; this variability may have influenced intervention fidelity and clinical outcomes. Finally, given the practical and physical challenges faced by patients recovering from major abdominal surgery, postoperative pulmonary function testing was not performed, preventing direct evaluation of postoperative respiratory function changes.

CONCLUSION

Short-term, moderate-intensity preoperative IMT improved perioperative lung function, enhanced gas exchange, and was associated with shorter hospital stays and reduced healthcare costs. These findings support IMT as a feasible strategy to accelerate postoperative recovery in patients undergoing major surgery. Further large-scale, multicenter trials are needed to optimize training protocols and develop personalized prehabilitation approaches.

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Consent to participate: This study obtained written informed consent from all participants.

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