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Prediction and Prevention of Postoperative Pulmonary Complications: Role of High-Flow Nasal Oxygen (HFNO), Non-Invasive Ventilation (NIV), and Lung-Protective Ventilation.

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Abstract
Introduction: Postoperative pulmonary complications (PPCs) remain a major cause of postoperative morbidity, prolonged hospitalization, intensive care unit (ICU) admission, and mortality following major surgery. Lung-protective ventilation (LPV), high-flow nasal oxygen (HFNO), and non-invasive ventilation (NIV) have emerged as important perioperative respiratory strategies; however, comparative evidence regarding their effectiveness in preventing PPCs remains limited. This study evaluated the role of LPV, HFNO, and NIV in improving postoperative pulmonary outcomes and reducing PPCs among patients undergoing major surgery. ***Materials and Methods:*** A prospective comparative study was conducted in the Department of Anaesthesiology from November 2024 to November 2025. A total of 120 adult patients undergoing elective major surgery under general anesthesia were equally allocated into three groups (n=40 each): LPV, HFNO, and NIV. Baseline demographic characteristics, preoperative risk factors, surgical variables, intraoperative ventilatory parameters, postoperative oxygenation indices, PPCs, ICU admission, duration of ICU and hospital stay, and 30-day mortality were evaluated. ***Results:*** Baseline demographic, clinical, and surgical characteristics were comparable among the three groups. Patients receiving HFNO and NIV demonstrated significantly better postoperative oxygenation, with higher PaO_2/FiO_2 ratios and SpO_2 and lower respiratory rates than the LPV group ($p<0.05$). The overall incidence of PPCs was significantly lower in the NIV group (10.0%) compared with the HFNO (20.0%) and LPV (37.5%) groups ($p=0.009$). Atelectasis was significantly reduced with NIV (5.0%) compared with LPV (20.0%) ($p=0.049$). Patients managed with NIV had significantly shorter ICU stay (2.5 ± 1.2 days) and hospital stay (7.6 ± 2.2 days) than those receiving LPV ($p<0.05$). ICU admission and 30-day mortality were numerically lower with HFNO and NIV but were not statistically significant. ***Conclusion:*** Postoperative non-invasive ventilation provided the greatest clinical benefit by improving oxygenation, reducing postoperative pulmonary complications, and shortening ICU and hospital stay. Incorporating postoperative NIV, together with lung-protective ventilation, may represent an effective perioperative strategy for high-risk surgical patients to enhance recovery and reduce pulmonary morbidity.

Keywords: Postoperative pulmonary complications; Lung-protective ventilation; High-flow nasal oxygen; Non-invasive ventilation; Perioperative respiratory care.

INTRODUCTION
Postoperative pulmonary complications (PPCs) remain one of the most common causes of postoperative morbidity and mortality following major surgery, contributing substantially to prolonged hospitalization, increased intensive care unit (ICU) admissions, healthcare costs, and reduced quality of recovery [1,2]. PPCs encompass a spectrum of respiratory disorders, including atelectasis, pneumonia, respiratory failure, bronchospasm, and the need for re-intubation [1]. Their occurrence is influenced by patient-related factors such as advanced age, obesity, smoking, chronic obstructive pulmonary disease (COPD), and multiple comorbidities, as well as surgery-related factors including the type and duration of surgery, general anesthesia, and perioperative mechanical ventilation [3]. Consequently, early identification of high-risk patients and implementation of effective preventive strategies are essential components of perioperative care [4].

Lung-protective ventilation (LPV) has emerged as a cornerstone of intraoperative respiratory management [5,6]. It incorporates the use of low tidal volumes, appropriate positive end-expiratory pressure (PEEP), and periodic recruitment manoeuvres to minimize ventilator-induced lung injury and reduce alveolar collapse [7]. Several clinical studies have demonstrated that LPV improves pulmonary mechanics, preserves functional residual capacity, and decreases the incidence of postoperative respiratory complications, particularly in patients undergoing prolonged abdominal and thoracic surgeries [8]. Nevertheless, despite advances in intraoperative ventilation, PPCs continue to occur, highlighting the need for additional postoperative respiratory support strategies [9].

High-flow nasal oxygen (HFNO) and non-invasive ventilation (NIV) have gained increasing attention as effective postoperative respiratory interventions [10]. HFNO delivers heated and humidified oxygen at high flow rates, providing a stable fraction of inspired oxygen, reducing anatomical dead space, and generating a low level of positive airway pressure, thereby improving oxygenation and patient comfort [11]. NIV offers greater positive airway pressure support, enhances alveolar recruitment, decreases the work of breathing, and has been shown to reduce re-intubation rates and respiratory failure in selected high-risk surgical patients [12]. Although both modalities have demonstrated clinical benefits individually, evidence directly comparing their effectiveness alongside lung-protective ventilation in preventing PPCs remains limited, and the optimal perioperative respiratory strategy continues to be debated.

Accurate prediction of patients at increased risk of PPCs, combined with timely implementation of evidence-based preventive interventions, has the potential to significantly improve perioperative outcomes. Comparative evaluation of LPV, HFNO, and NIV may help identify the most effective strategy for reducing pulmonary complications, improving postoperative oxygenation, shortening ICU and hospital stay, and enhancing recovery after surgery. Therefore, the present study aimed to evaluate the role of lung-protective ventilation, high-flow nasal oxygen, and non-invasive ventilation in the prediction and prevention of postoperative pulmonary complications among patients undergoing major surgery, while comparing their effects on postoperative oxygenation and clinical outcomes.

MATERIALS AND METHODS

This prospective comparative study was conducted in the Department of Anaesthesiology over a one-year period from November 2024 to November 2025. A total of 120 adult patients scheduled to undergo elective major surgery under general anesthesia were enrolled after obtaining approval from the Institutional Ethics Committee and written informed consent from all participants. Eligible patients were allocated into three equal groups (n=40 each) based on the perioperative respiratory support strategy employed: Group A received lung-protective ventilation (LPV), Group B received postoperative high-flow nasal oxygen (HFNO), and Group C received postoperative non-invasive ventilation (NIV). Patients aged ≥18 years with American Society of Anesthesiologists (ASA) physical status II–III who were considered at moderate to high risk for postoperative pulmonary complications were included. Patients with pre-existing mechanical ventilation, severe hemodynamic instability, facial abnormalities precluding HFNO/NIV use, pregnancy, or refusal to participate were excluded.

Baseline demographic characteristics, including age, sex, body mass index (BMI), smoking history, ASA physical status, and preoperative comorbidities such as chronic obstructive pulmonary disease (COPD), diabetes mellitus, hypertension, chronic kidney disease, and obesity, were recorded. Surgical characteristics including type of surgery, duration of surgery, and intraoperative blood loss were documented. During surgery, intraoperative ventilatory parameters such as tidal volume (mL/kg predicted body weight), positive end-expiratory pressure (PEEP), peak airway pressure, and use of recruitment manoeuvres were recorded. Patients in the LPV group received lung-protective ventilation with low tidal volume and appropriate PEEP, while those in the HFNO and NIV groups received standard intraoperative ventilation followed by their respective postoperative respiratory support immediately after extubation.

Postoperative clinical assessment included arterial oxygenation (PaO_2/FiO_2 ratio), peripheral oxygen saturation (SpO_2), respiratory rate, and the occurrence of postoperative pulmonary complications (PPCs), including atelectasis, pneumonia, respiratory failure, and re-intubation. Secondary outcomes comprised intensive care unit (ICU) admission, duration of ICU stay, total hospital stay, and 30-day mortality. Patients were monitored throughout their hospital stay, and pulmonary complications were diagnosed based on clinical examination, radiological findings, and standard institutional diagnostic criteria.

Data were entered into Microsoft Excel and analyzed using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean ± standard deviation (SD) and compared using one-way analysis of variance (ANOVA), while categorical variables were presented as frequency and percentage and compared using the Chi-square test or Fisher's exact test, as appropriate. A p-value of <0.05 was considered statistically significant.

RESULTS

A total of 120 patients were included, with 40 patients each in the LPV, HFNO, and NIV groups. The mean age was comparable across the three groups (58.5 ± 11.2 years, p=0.89). Males constituted 60.0% of the study population, while females accounted for 40.0%. There were no significant differences in body mass index, smoking history, or ASA physical status between the groups, indicating well-balanced baseline demographic characteristics (Table 1).

Table 1. Baseline Demographic Characteristics

Variable	LPV (n=40)	HFNO (n=40)	NIV (n=40)	Total (N=120)	p-value
Age (years), Mean ± SD	57.8 ± 11.2	58.6 ± 10.9	59.1 ± 11.5	58.5 ± 11.2	0.89
Male	24 (60.0%)	23 (57.5%)	25 (62.5%)	72 (60.0%)	0.91
Female	16 (40.0%)	17 (42.5%)	15 (37.5%)	48 (40.0%)	
BMI (kg/m²)	26.1 ±3.8	26.6 ±4.2	26.9 ±3.9	26.5 ±4.0	0.74
Smoking history	12 (30.0%)	13 (32.5%)	14 (35.0%)	39 (32.5%)	0.88
ASA II	23 (57.5%)	21 (52.5%)	22 (55.0%)	66 (55.0%)	0.95
ASA III	17 (42.5%)	19 (47.5%)	18 (45.0%)	54 (45.0%)	

The distribution of surgical procedures was similar among the three groups, with abdominal surgery being the most common (44.2%), followed by major orthopaedic (33.3%) and thoracic surgery (22.5%). The mean duration of surgery and intraoperative blood loss were comparable across all groups without statistically significant differences (p>0.05), demonstrating similar operative characteristics (Table 2).

Table 2. Surgical Characteristics

Variable	LPV	HFNO	NIV	Total	p-value
Abdominal surgery	18 (45.0%)	17 (42.5%)	18 (45.0%)	53 (44.2%)	0.98
Thoracic surgery	9 (22.5%)	10 (25.0%)	8 (20.0%)	27 (22.5%)	0.86
Major Orthopaedic	13 (32.5%)	13 (32.5%)	14 (35.0%)	40 (33.3%)	0.96
Duration of surgery (minutes)	182 ±41	188 ±45	185 ±39	185 ±42	0.81
Blood loss (mL)	405 ±110	417 ±102	424 ±114	415 ±109	0.73

Preoperative comorbidities were evenly distributed among the study groups. Hypertension was the most frequent risk factor (55.0%), followed by diabetes mellitus (37.5%), smoking-related COPD (25.0%), obesity (22.5%), and chronic kidney disease (10.8%). None of the baseline risk factors differed significantly between the groups (all p>0.05), suggesting comparable preoperative risk profiles (Table 3).

Table 3. Preoperative Risk Factors

Risk factor	LPV	HFNO	NIV	Total	p-value
COPD	9 (22.5%)	10 (25.0%)	11 (27.5%)	30 (25.0%)	0.88
Diabetes	15 (37.5%)	16 (40.0%)	14 (35.0%)	45 (37.5%)	0.91
Hypertension	21 (52.5%)	22 (55.0%)	23 (57.5%)	66 (55.0%)	0.93
CKD	4 (10.0%)	5 (12.5%)	4 (10.0%)	13 (10.8%)	0.89
Obesity (BMI>30)	8 (20.0%)	9 (22.5%)	10 (25.0%)	27 (22.5%)	0.87

Significant differences were observed in intraoperative ventilatory parameters. Patients in the LPV group received lower tidal volumes and higher PEEP compared with the HFNO and NIV groups (p<0.001). Peak airway pressures were significantly lower in the LPV group, and recruitment manoeuvres were performed exclusively in this group (100%), reflecting adherence to lung-protective ventilation strategies (Table 4).

Table 4. Intraoperative Ventilatory Parameters

Variable	LPV	HFNO	NIV	p-value
Tidal volume (mL/kg PBW)	6.1 ±0.5	8.2 ±0.6	8.1 ±0.5	<0.001
PEEP (cmH_2O)	7.1 ±1.2	5.0 ±1.0	5.2 ±1.1	<0.001
Peak airway pressure (cmH_2O)	20.4 ±3.2	24.9 ±4.1	24.5 ±3.8	<0.001
Recruitment manoeuvre performed	40 (100%)	0	0	<0.001

Postoperative oxygenation parameters demonstrated significant improvement among patients receiving HFNO and NIV. The NIV group showed the highest PaO_2/FiO_2 ratio and oxygen saturation, while respiratory rate was lowest in this group.

All three parameters differed significantly across the study groups, indicating superior postoperative oxygenation with HFNO and NIV compared to LPV alone (Table 5).

Table 5. Immediate Postoperative Oxygenation

Variable	LPV	HFNO	NIV	p-value
PaO_2/FiO_2 ratio	335 ±48	356 ±52	368 ±49	0.013
SpO_2 (%)	97.4 ±1.1	98.2 ±0.8	98.5 ±0.7	0.002
Respiratory rate	18.7 ±2.4	17.2 ±2.1	16.8 ±2.0	0.001

The incidence of postoperative pulmonary complications progressively decreased from the LPV group to the HFNO and NIV groups. Atelectasis was significantly less frequent in the NIV group (5.0%) compared with the LPV group (20.0%) (p=0.049). Although pneumonia, respiratory failure, and re-intubation were numerically lower with HFNO and NIV, these differences were not statistically significant. Overall postoperative pulmonary complications were significantly reduced in the HFNO and NIV groups, with the lowest incidence observed in the NIV group (10.0%) compared with the LPV group (37.5%) (p=0.009) (Table 6).

Table 6. Postoperative Pulmonary Complications (Primary Outcome)

Complication	LPV	HFNO	NIV	Total	p-value
Atelectasis	8 (20.0%)	4 (10.0%)	2 (5.0%)	14 (11.7%)	0.049
Pneumonia	5 (12.5%)	2 (5.0%)	1 (2.5%)	8 (6.7%)	0.18
Respiratory failure	6 (15.0%)	2 (5.0%)	1 (2.5%)	9 (7.5%)	0.09
Re-intubation	4 (10.0%)	1 (2.5%)	0	5 (4.2%)	0.11
Any PPC	15 (37.5%)	8 (20.0%)	4 (10.0%)	27 (22.5%)	0.009*

Patients managed with NIV experienced the most favorable postoperative outcomes, with the shortest ICU and hospital stays, followed by the HFNO group. Both ICU stay (p=0.001) and hospital stay (p=0.002) differed significantly among the groups. Although ICU admission and 30-day mortality were numerically lower in the HFNO and NIV groups than in the LPV group, these differences were not statistically significant (Table 7).

Table 7. ICU and Hospital Outcomes

Outcome	LPV	HFNO	NIV	p-value
ICU stay (days)	3.8 ±1.6	2.9 ±1.3	2.5 ±1.2	0.001
Hospital stay (days)	9.7 ±2.8	8.2 ±2.4	7.6 ±2.2	0.002
ICU admission	12 (30.0%)	7 (17.5%)	5 (12.5%)	0.12
30-day mortality	2 (5.0%)	1 (2.5%)	0	0.36

DISCUSSION

The present study evaluated the effectiveness of lung-protective ventilation (LPV), high-flow nasal oxygen (HFNO), and non-invasive ventilation (NIV) in preventing postoperative pulmonary complications (PPCs) among patients undergoing major surgery. Baseline demographic characteristics, comorbidities, and surgical profiles were comparable across the three groups, minimizing the influence of confounding factors. Although the LPV group demonstrated significantly lower intraoperative tidal volumes and higher PEEP, patients managed with postoperative HFNO and particularly NIV exhibited superior postoperative oxygenation, with significantly higher PaO_2/FiO_2 ratios and SpO_2 values and lower respiratory rates. These findings suggest that postoperative respiratory support, especially NIV, complements intraoperative lung-protective strategies by improving gas exchange during the immediate postoperative period. Similar improvements in oxygenation with HFNO and NIV have been reported in recent systematic reviews, which demonstrated better oxygenation and reduced respiratory support escalation among surgical patients receiving these interventions [13,14].

A major finding of the present study was the significantly lower incidence of overall postoperative pulmonary complications in the NIV group (10.0%) compared with the HFNO (20.0%) and LPV (37.5%) groups. Atelectasis was also significantly reduced in patients receiving NIV, while pneumonia, respiratory failure, and re-intubation showed a favorable numerical trend despite not reaching statistical significance. These findings are consistent with the systematic review by Odor et al., which identified lung-protective ventilation and postoperative non-invasive respiratory support as effective perioperative strategies for reducing PPCs [15]. Likewise, recent network meta-analysis by Mo et al. demonstrated that low tidal volume ventilation combined with optimal PEEP and recruitment manoeuvres significantly decreases postoperative atelectasis, pneumonia, and overall PPCs compared with conventional ventilation strategies [16]. Although our study showed additional benefit with postoperative NIV over LPV alone, this likely reflects the combined advantages of improved alveolar recruitment and reduced work of breathing during the vulnerable post-extubation period.

Our findings also demonstrated significantly shorter ICU stay and overall hospital stay among patients receiving NIV, followed by HFNO, compared with LPV alone. These improvements are clinically relevant because PPCs are associated with prolonged hospitalization, increased healthcare expenditure, and higher postoperative morbidity. Similar reductions in hospital stay with HFNO have been reported in recent meta-analyses evaluating postoperative oxygen therapy, where HFNO improved oxygenation and reduced re-intubation and length of hospital stay compared with conventional oxygen therapy [14]. However, a large meta-analysis by Ferreyro et al. found that routine postoperative use of HFNO or NIV did not consistently reduce pneumonia across all surgical populations, suggesting that the greatest benefit may occur in carefully selected high-risk patients rather than universally applying these modalities [17]. The favorable outcomes observed in our cohort may therefore be attributed to inclusion of patients with moderate-to-high perioperative pulmonary risk, who derive greater benefit from enhanced postoperative respiratory support.

Overall, the present study supports a multimodal perioperative respiratory strategy incorporating lung-protective ventilation during surgery together with postoperative HFNO or NIV to minimize pulmonary complications. Among the evaluated interventions, NIV demonstrated the greatest improvement in postoperative oxygenation and clinical recovery while significantly reducing overall PPCs. These findings reinforce current evidence favoring individualized perioperative respiratory care based on patient risk profiles rather than reliance on a single intervention. Larger multicenter randomized controlled trials with longer follow-up are warranted to determine the optimal selection criteria and timing of postoperative respiratory support modalities for maximizing patient outcomes.

CONCLUSION

The present study demonstrates that postoperative respiratory support strategies significantly influence pulmonary outcomes following major surgery. Although lung-protective ventilation remains an essential intraoperative strategy, the addition of postoperative high-flow nasal oxygen and particularly non-invasive ventilation was associated with improved oxygenation, reduced incidence of postoperative pulmonary complications, and shorter ICU and hospital stay. Among the evaluated interventions, non-invasive ventilation showed the greatest clinical benefit, suggesting its potential role in high-risk surgical patients to enhance postoperative recovery and reduce pulmonary morbidity. Further large-scale multicenter randomized studies are warranted to validate these findings and optimize perioperative respiratory care protocols.

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