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REVIEW

Non-invasive respiratory support for postoperative acute hypoxemic respiratory failure: a narrative review

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Abstract

Pulmonary complications after surgery continue to represent a significant postoperative challenge, accounting for considerable rates of morbidity and mortality. Among these, acute hypoxemic respiratory failure (AHRF) is particularly critical, with mortality rates of up to 27%. In recent years, non-invasive respiratory strategies have been increasingly adopted to lower the risk of reintubation and reduce complications related to invasive ventilation. This narrative review examines the application of non-invasive ventilation (NIV)—namely Continuous Positive Airway Pressure (CPAP), Bilevel Positive Airway Pressure (BiPAP), and High-Flow Nasal Cannula (HFNC)—in the perioperative management of AHRF. We synthesized current evidence and guideline recommendations, with attention to patient selection criteria, preventive versus therapeutic use, and key outcomes, such as gas exchange, atelectasis, reintubation rates, morbidity, and mortality. CPAP and BiPAP may be advantageous in specific subsets of patients, such as those with chronic obstructive pulmonary disease (COPD) or cardiogenic pulmonary edema, while HFNC is increasingly favored for its comfort and ability to deliver consistent oxygenation. However, findings remain heterogeneous across surgical settings, and robust head-to-head trials are still lacking. Further studies are essential to refine patient stratification, optimize initiation timing, and determine the impact on long-term outcomes.

Keywords

Hypoxia; Postoperative pulmonary complication; Continuous positive airway pressure (CPAP); BiPAP; High-flow nasal cannula (HFNC)

1. Introduction

Postoperative pulmonary complications (PPCs) represent one of the most common and clinically significant adverse events after major surgery, being responsible for substantial increases in morbidity, mortality, and length of hospital stay [1, 2]. They are generally defined as respiratory abnormalities that result in clinically relevant disease or dysfunction, thereby worsening the postoperative course. The most frequent PPCs include pneumonia, atelectasis, bronchospasm, exacerbations of chronic obstructive pulmonary disease (COPD), and respiratory failure [3–5]. The reported incidence of PPCs is approximately 8% in the surgical population, while in high-risk patients undergoing major procedures, morbidity and mortality may reach nearly 30% [6].

The development of PPCs is influenced by both patient-related and procedure-related risk factors [7]. Among the former, advanced age (≥60 years), abnormal findings on chest imaging, COPD, heart failure, arrhythmias, American Society of Anesthesiologists (ASA) physical status ≥3, and severe functional dependence are particularly relevant. It is widely accepted that the prevention of postoperative complications should begin in the preoperative setting, with careful risk stratification and patient optimization. Interventions such as smoking cessation, nutritional support, anemia correction, and control of medical comorbidities are essential, together with intraoperative protective ventilation strategies, including the use of low tidal volumes [8].

The choice of postoperative respiratory support may substantially affect the risk of PPCs. Conventional oxygen therapy (COT)—delivered through nasal cannulae, simple face masks, or Venturi masks—can provide flow rates of up to 15 L/min, but often fails to meet the inspiratory demands of patients experiencing dyspnea [9]. When COT proves insufficient, non-invasive ventilation (NIV) represents an alternative strategy, providing airway splinting, reducing the work of breathing, and improving respiratory compliance. Both NIV and continuous positive airway pressure (CPAP) have shown benefits in patients developing postoperative acute hypoxemic respiratory failure (AHRF) [10].

Atelectasis is a central contributor to the pathogenesis of PPCs. Its postoperative incidence may be as high as 85%, and it considerably increases the likelihood of pneumonia and AHRF. Indeed, while postoperative mortality is around 1% in patients without respiratory failure, the development of AHRF is associated with mortality rates of up to 27% [11]. The risk of acute respiratory failure is influenced by multiple factors, including surgical procedure, type of anesthesia, intraoperative mechanical ventilation, and patient comorbidities [10]. The clinical presentation of AHRF is highly variable, ranging from mild hypoxemia to acute respiratory distress syndrome (ARDS) [12]. Operationally, AHRF is identified by the presence of tachypnea and reduced oxygen saturation or partial pressure of oxygen in arterial blood/ fraction of inspired oxygen (PaO_2/FiO_2) ratio despite supplemental oxygen (*e.g.*, a respiratory rate of 25 breaths/min with PaO_2/FiO_2 = 300 mmHg) [13, 14]. The severity of hypoxemia is graded according to PaO_2/FiO_2: mild (201–300 mmHg), moderate (101–200 mmHg), or severe ($\leq$100 mmHg). ARDS represents the most severe subset of AHRF [15], with comparable outcomes, degree of hypoxemia, and extent of lung involvement [16]. Consequently, AHRF and ARDS can be viewed along the same spectrum of acute lung injury, characterized by impaired oxygenation, altered respiratory mechanics, increased dead space, and heightened respiratory drive. Both the depth of hypoxemia and the degree of respiratory drive dysregulation have been linked to increased mortality [17–21].

Non-invasive oxygenation strategies, such as high-flow nasal oxygen (HFNO), NIV delivered via helmet or face mask, and CPAP, have been demonstrated to reduce the risk of intubation in patients with mild hypoxemia [22, 23]. Nevertheless, the failure of non-invasive support followed by delayed intubation has been associated with worse outcomes, likely due to sustained injurious respiratory effort superimposed on the compromised lung [9]. The rationale for non-invasive support rests not only on improved oxygenation, but also on the preservation of spontaneous breathing, which maintains diaphragm function, prevents muscle atrophy, preserves cardiac preload and output, and promotes recruitment of dependent lung regions, thereby reducing ventilation/perfusion mismatch [24–27]. Consequently, in patients in whom COT fails, non-invasive modalities constitute the least invasive and most physiologically favorable approach to managing hypoxemia [28–31].

Despite these promising findings, comparative data among HFNO, NIV, and COT in the specific setting of postoperative patients remain limited. This narrative review aims to synthesize current evidence, with particular focus on clinical outcomes, feasibility, and the role of non-invasive respiratory support in the perioperative management of patients undergoing major head and neck surgery.

2. Methods

This narrative review was designed to provide an overview of current evidence on the role of non-invasive respiratory support strategies—including high-flow nasal cannula (HFNC), non-invasive ventilation (NIV), and conventional oxygen therapy (COT)—in the immediate postoperative setting. A structured literature search was conducted in PubMed and Embase for studies published between January 2005 and December 2024. The following search terms, used individually and in combination, were applied: “postoperative respiratory failure”, “non-invasive ventilation”, “CPAP”, “BiPAP”, and “high-flow nasal cannula”.

Eligible studies included randomized controlled trials (RCTs), prospective and retrospective cohort studies, and meta-analyses involving both adult and pediatric surgical populations. Exclusion criteria comprised case reports, animal or in vitro studies, and narrative reviews lacking original data. Studies were screened for clinical relevance, with selection focused on those addressing perioperative outcomes in surgical patients.

3. Non-invasive positive pressure ventilation

Non-Invasive Positive Pressure Ventilation (NIPPV) is a modality of ventilatory assistance that provides pressurized airflow to the lungs via a facial or nasal interface. This technique enhances arterial oxygenation while decreasing the patient’s work of breathing (WOB). Its clinical applications include chronic obstructive pulmonary disease (COPD), acute respiratory failure (ARF), obstructive sleep apnea, and respiratory support during the postoperative period. In comparison with invasive endotracheal intubation, NIPPV offers several advantages, such as improved patient comfort, preservation of the ability to speak, cough, and eat, as well as a reduced incidence of ventilator-associated infections. Nevertheless, its use is limited by issues such as mask intolerance, leakage due to inadequate fitting, patient discomfort leading to poor adherence, and insufficient ventilatory support in cases of severe respiratory compromise.

Two principal modes of NIPPV are currently employed: Continuous Positive Airway Pressure (CPAP) and Bilevel Positive Airway Pressure (BiPAP). CPAP maintains a continuous and uniform positive pressure throughout the respiratory cycle, generating Positive End-Expiratory Pressure (PEEP), which promotes alveolar recruitment and re-expansion of collapsed lung tissue. BiPAP, by contrast, provides two distinct pressure levels: a higher inspiratory positive airway pressure (IPAP) to support inhalation and a lower expiratory positive airway pressure (EPAP) to facilitate exhalation. Optimal ventilatory settings should be individualized according to the patient’s clinical status and respiratory mechanics, with continuous monitoring of physiological response and tolerance. Arterial blood gas (ABG) analysis and patient comfort should be regularly assessed, as intolerance or poor compliance may lead to treatment failure, requiring escalation to alternative modalities, such as high-flow nasal cannula (HFNC) or invasive mechanical ventilation.

BiPAP is commonly indicated for disorders such as obstructive sleep apnea, COPD exacerbations, or to mitigate postoperative pulmonary complications. Unlike CPAP, which applies a constant pressure, BiPAP alternates between two pressure levels, providing additional comfort and ventilatory unloading for selected patients. Recent systematic evaluations have frequently analyzed both CPAP and BiPAP collectively; therefore, the present review will also discuss these modalities together, highlighting distinctions where relevant.

The "Indian Society of Critical Care Medicine (ISCCM) Guidelines for the Use of Non-invasive Ventilation in Acute Respiratory Failure in Adult Intensive Care Units (ICUs)", published in 2020, provide evidence-based recommendations for the use of NIV in ARF [32]. These guidelines address multiple etiologies, including COPD exacerbations, cardiogenic pulmonary edema, and postoperative respiratory failure (PRF). Non-invasive ventilation is strongly recommended in patients with acute exacerbations of COPD presenting with hypercapnic respiratory failure or respiratory acidosis, to prevent the need for invasive mechanical ventilation. In cardiogenic pulmonary edema, both CPAP and BiPAP are considered effective, with BiPAP being preferable when hypercapnia is present. NIV may also be considered as an alternative to conventional oxygen therapy (COT) in early, mild hypoxemic failure (PaO_2/FiO_2 ratio 200–300), provided that expert supervision is available. However, its use is discouraged in cases of severe hypoxemia (PaO_2/FiO_2 <150), as efficacy is limited and reliance on NIV may delay the initiation of necessary invasive ventilation. Importantly, NIV is recommended in postoperative ARF, particularly following abdominal or thoracic surgery, as it can lower the risk of reintubation. Conversely, it is contraindicated after esophageal surgery due to the potential compromise of anastomotic integrity from elevated airway pressures. In patients undergoing bariatric surgery with pre-existing obstructive sleep apnea (OSA) or obesity hypoventilation syndrome (OHS), NIV can be safely applied, with current evidence showing no increased risk of anastomotic dehiscence. Furthermore, following lung transplantation, NIV has been associated with shorter weaning times, reduced reintubation rates, and improved survival. Overall, the guidelines emphasize that the choice of modality should be tailored to the underlying pathophysiology and to the clinician's expertise with the available devices.

The European Society of Anaesthesiology (ESA) together with the European Society of Intensive Care Medicine (ESICM) have issued evidence-based recommendations regarding the management of perioperative hypoxemia. Robust data indicate that NIPPV, particularly CPAP, is beneficial in hypoxemic patients after upper abdominal surgery, significantly reducing the risk of hospital-acquired pneumonia and related complications. The expert consensus evaluated studies on organ transplantation, cardiac surgery, and abdominal interventions, consistently demonstrating reduced 30-day reintubation rates in patients receiving non-invasive respiratory support. Based on these findings, perioperative or periprocedural NIPPV is strongly advised over conventional oxygen therapy (COT), although the overall quality of evidence is rated moderate to low [33]. Other available recommendations also favor NIPPV and HFNC over COT, but these are supported mainly by lower-quality data, underlining the need for further trials.

European guidelines also suggest the immediate use of CPAP following extubation in hypoxemic patients at risk of ARF after abdominal surgery. A multicenter investigation in patients with a PaO_2/FiO_2 ratio below 300 mmHg one hour after extubation reported that helmet CPAP significantly reduced both reintubation rates at 7 days and nosocomial infection incidence. In post-cardiac surgery patients, CPAP appears to be an effective strategy for preventing respiratory deterioration in hypoxemic individuals [24]. Similarly, prophylactic NIV before and after cardiac procedures has been shown to decrease the incidence of cardiopulmonary failure following high-risk operations [34].

In thoracic surgery, CPAP reduces the likelihood of atelectasis after lobectomy and lowers the incidence of postoperative pulmonary complications. Studies comparing CPAP with COT in this context were discontinued prematurely due to markedly higher reintubation and mortality rates in the COT arm at 120 days. CPAP has also shown superiority over COT in hypoxemic patients during bronchoscopy. In bariatric populations, CPAP administration was associated with fewer episodes of postoperative hypoxemia and related adverse events compared with oxygen therapy alone.

However, results from the PRISM trial, involving nearly 4800 patients undergoing major abdominal surgery, revealed that prophylactic CPAP did not significantly reduce pneumonia, reintubation, or 30-day mortality compared to standard care, nor did it improve secondary outcomes or one-year survival [35]. Despite being generally safe, CPAP was poorly tolerated, with one-third of patients unable to complete the prescribed four-hour sessions. Limitations included poor adherence, heterogeneous device application, lower-than-expected event rates, and lack of blinding, thereby restricting generalizability. Consequently, routine postoperative CPAP cannot be recommended as a universal preventive intervention. In contrast, Boscolo *et al.* [36] demonstrated that CPAP, compared with COT, significantly reduced the incidence of ventilator-associated pneumonia (VAP) and post-extubation respiratory failure in high-risk patients. Furthermore, a recent trial comparing helmet CPAP with mask CPAP reported comparable oxygenation outcomes and pulmonary complication rates, although helmet use was associated with higher levels of patient-reported claustrophobia [37].

A systematic review and meta-analysis by João *et al.* [38] evaluated the use of BiPAP in acute hypoxemic respiratory failure of varying etiologies, highlighting its efficacy particularly after abdominal surgery and in immunocompromised post-transplant patients. The beneficial effects were attributed to the role of PEEP in redistributing interstitial fluid, resolving atelectasis, and lowering WOB. The authors also emphasized that earlier initiation of NIV improves survival and reduces reintubation rates. Notably, included studies focused primarily on mild-to-moderate hypoxemic failure (PaO_2/FiO_2 100–300), as severe hypoxemia carries a risk of cardiac arrest and higher reintubation rates under NIV. The meta-analysis was limited by a scarcity of large-scale RCTs, preventing definitive conclusions. Consequently, European guidelines do not strongly recommend NIV in hypoxemic failure outside of COPD exacerbations.

A retrospective observational study by Melton examined BiPAP use after cardiac surgery in 859 patients, divided into a BiPAP plus COT group and a COT-only group [39]. The findings revealed no significant difference in reintubation rates, although BiPAP recipients experienced shorter intubation times and reduced lengths of hospital stay (LOS). Baseline differences between groups included higher smoking rates, more frequent heart failure and pneumonia, and worse preoperative pulmonary function in the BiPAP cohort, limiting interpretability. In addition, some patients failed to tolerate the mask and were switched to HFNC, which represented another limitation. The study nevertheless highlighted possible risk factors for reintubation to be addressed in future trial designs.

Ahmed *et al*. [40] also conducted a retrospective cohort study on postoperative BiPAP use after cardiac surgery, focusing primarily on patients with high Body Mass Index (BMI) and COPD. They reported significant improvement in PaO_2 within 30 minutes of BiPAP application in patients with pulmonary edema, especially in those with severe hypoxemia (PaO_2 <60 mmHg). BiPAP settings were individualized, and intraoperative predictors of BiPAP requirement included positive fluid balance and postoperative cardiac dysfunction requiring inotropes. These findings suggest that BiPAP use should be tailored to patient-specific characteristics, as not all individuals are suitable candidates. Similarly, Hamid investigated the interplay between BiPAP and hemodynamics, showing improved ventilatory parameters and reduced reintubation in post-cardiac surgery patients, with no significant hemodynamic instability [41].

Obese patients represent a particularly high-risk group due to their predisposition to atelectasis and impaired ventilatory mechanics. Non-invasive respiratory support (NRS) has therefore been widely investigated in this population. A systematic review and network meta-analysis by Li *et al*. [42] included 20 RCTs with 1184 patients, comparing CPAP, BiPAP, HFNC, and COT. Both BiPAP and HFNC significantly reduced atelectasis compared with COT, whereas CPAP primarily improved oxygenation. HFNC shortened LOS and ranked highest in outcomes such as hypoxemia, respiratory failure, and LOS reduction, although no clear differences were observed in oxygen therapy failure or anastomotic leak rates.

The multicenter RCT by Jaber *et al*. [43] further compared NIV with COT in obese patients after abdominal surgery. Reintubation within 7 days was significantly lower in the NIV group (31% *vs*. 56%), with patients in this group also experiencing more invasive ventilation-free days at 30 days and lower ICU-acquired pneumonia rates (2% *vs*. 18%). Thirty-day survival was higher in the NIV group (98% *vs*. 85%), although not statistically significant. Outcomes did not differ significantly in patients with BMI <30 kg/m^2. Overall, NIV improved key postoperative parameters independent of obesity, although obesity did not substantially alter treatment effect.

In addition, NIV has been linked to faster recovery of postoperative pulmonary function and oxygenation in obese individuals, reducing ICU utilization [44]. Kokotovic *et al*. [45] conducted a systematic review and meta-analysis of 25 studies (n = 2068), investigating postoperative respiratory and mobilization interventions after abdominal surgery. The meta-analysis confirmed that high expiratory resistance techniques, such as CPAP, EPAP, BiPAP, and NIV, significantly lowered the risk of PPCs, although trial sequential analysis indicated insufficient sample size to confirm conclusive benefit. Other modalities, including incentive spirometry and breathing exercises, did not significantly affect complication rates.

Einav also demonstrated that postoperative NIV improved blood gas exchange and reduced reintubation, although no significant effect was seen on mortality, LOS, or sepsis incidence [46]. Comparative analyses between HFNC and BiPAP revealed no clear superiority of one method over the other. Preoperatively, NIV may be advantageous in selected groups, such as obese or pregnant patients, while in the postoperative context, both NIV and HFNC have been associated with lower reintubation rates.

In summary, substantial evidence supports the role of CPAP and BiPAP in reducing postoperative pulmonary complications compared with standard oxygen therapy, but their application should be tailored to the underlying pathophysiology. CPAP is particularly effective in preventing atelectasis and managing hypoxemia after abdominal or thoracic surgery, being linked to lower pneumonia rates and improved oxygenation, though large RCTs, such as PRISM, have yielded inconsistent mortality benefits due to heterogeneous populations. BiPAP, by contrast, provides additional ventilatory unloading and CO_2 clearance, which is especially beneficial in patients with hypercapnia, COPD, or cardiogenic pulmonary edema. After cardiac surgery, BiPAP may shorten ICU stay and mechanical ventilation duration, though results on reintubation remain inconsistent due to mask intolerance and methodological differences across studies.

Overall, CPAP and BiPAP should be regarded as complementary rather than interchangeable strategies: CPAP is more appropriate for hypoxemic postoperative patients with predominant atelectasis, whereas BiPAP is preferable in those with hypercapnia or increased ventilatory drive. In obese patients, both modalities confer advantages, with BiPAP offering additional benefits when hypoventilation or sleep-disordered breathing is present. Timely recognition of the underlying mechanism of respiratory failure and early initiation of the most suitable modality remain essential for optimizing clinical outcomes.

4. High-flow nasal cannula (HFNC)

High-flow nasal cannula (HFNC) therapy is a non-invasive system for oxygen administration at high concentrations, developed to address the limitations of conventional oxygen therapy (COT). With flow rates that can reach 50–60 L/min, HFNC is able to match the inspiratory demands of patients experiencing acute hypoxemic respiratory failure (AHRF) more closely. It can consistently deliver an FiO_2 up to 100% while simultaneously generating a mild level of positive end-expiratory pressure (PEEP) in the proximal airways, which may assist alveolar recruitment [8]. Studies have shown that HFNC, particularly when used at elevated flow rates, can provide PEEP values around 5 cmH_2O. However, once the mouth is opened, this pressure falls to approximately 1 cmH_2O, making the contribution to alveolar recruitment limited [47].

Non-invasive ventilation (NIV) enhances oxygenation by raising mean airway pressures but can also result in excessive lung volumes, exposing patients to the risk of patient self-inflicted lung injury (P-SILI). In contrast, HFNC produces lower positive pressures, which may reduce the likelihood of

P-SILI and tends to be better tolerated [10]. Other advantages of HFNC over COT include stabilization of transpulmonary pressures, clearance of carbon dioxide from the upper airways, improved ventilatory efficiency, and consistent humidification. These features enhance secretion removal and patient comfort [48].

At present, the best non-invasive support strategy for AHRF remains uncertain. Few randomized trials directly compare HFNC and NIV, and those that do are mainly focused on intensive care populations. The largest study to date demonstrated that, in ICU patients with purely hypoxemic respiratory failure, HFNC reduced mortality compared with NIV [48]. For this reason, HFNC may be especially useful in hypoxemic patients with poor tolerance of mask-based ventilation.

Post-operative NIV or CPAP is limited by the requirement for close monitoring and by frequent intolerance due to pressure effects, interface discomfort, or skin injury. HFNC may overcome many of these barriers. This is particularly relevant in surgical patients, where positive pressure from NIV or mechanical ventilation can increase the risk of anastomotic leak or impair wound healing. COT also carries disadvantages, such as inadequate heating and humidification of inspired gas [49]. By improving mucociliary function, reducing anatomical dead space, and optimizing pulmonary mechanics, HFNC emerges as a suitable option in the post-operative setting, where hypoxemia is often related to alveolar collapse [50]. Evidence indicates that HFNC reduces escalation to higher levels of support and lowers the risk of reintubation. Its use has proven safe following extubation after cardiothoracic procedures [51], and it improves oxygenation after esophagectomy.

HFNC should therefore be considered as an early post-extubation support strategy, not only as a rescue intervention in established respiratory failure, but also to optimize post-operative pulmonary recovery [47]. The technique employs nasal prongs to deliver warmed, humidified gas into the airways, which increases functional residual capacity, improves mechanics, and enhances gas exchange. These physiological effects provide a rationale for its use in post-operative oxygen supplementation. An RCT comparing HFNC with simple face mask oxygen in patients undergoing major elective upper abdominal surgery showed that HFNC reduced atelectasis, improved oxygenation with lower respiratory rates, and shortened ICU and hospital stays (Fig. 1 (Ref. [52]), Table 1).

Among adults at high risk of extubation failure, HFNC has been shown to be non-inferior to NIV for preventing reintubation, mortality, and recurrent respiratory failure. Additional benefits may include shorter LOS, fewer complications, and improved comfort, although significant heterogeneity exists in outcomes such as arterial partial pressure of carbon dioxide ($PaCO_2$), respiratory rate, and LOS. Therefore, further large-scale RCTs are required to determine whether HFNC can provide consistent improvements in these endpoints [53].

The OPERA trial, one of the largest multicenter RCTs investigating HFNC after major abdominal surgery, did not demonstrate a significant reduction in post-operative hypoxemia compared with COT [49]. Several methodological issues likely influenced these results: the control group had a lower-than-expected incidence of hypoxemia, reducing the study's statistical power; the primary endpoint ($PaO_2/FiO_2 \leq 300$) may not reflect clinically meaningful outcomes such as reintubation or survival; and the relatively homogeneous patient population with moderate baseline risk limits generalizability to higher-risk surgical cohorts [54].

Retrospective analyses support the role of HFNC in head and neck surgery, where its use has been associated with lower early post-operative hypoxemia and avoidance of reintubation. Improvements in oxygenation indices, such as the PaO_2/FiO_2 ratio and Respiratory rate-Oxygenation (ROX) index over the first 24 hours, confirm its physiologic benefit. Reported hypoxemia incidence was only 4%, with no reintubations, supporting HFNC as a safe and tolerable option in complex oncologic maxillofacial surgery. Despite the absence of formal hypothesis testing, these findings encourage routine consideration of HFNC in post-operative ICU management, though prospective studies are still needed [55].

Systematic reviews and meta-analyses assessing routine HFNC use in the immediate post-operative period show that HFNC decreases the need for intubation in acute hypoxemic respiratory failure compared with COT. In one study, reintubation occurred in 0.9% of patients in the HFNC group versus 4.3% in the COT group, although the estimate remains imprecise due to small sample sizes. HFNC also lowered escalation to more invasive support, albeit with low-certainty evidence. When compared with NIV, no significant differences were observed in rates of reintubation or treatment failure [56].

Close clinical monitoring is crucial, particularly in the first hour of HFNC therapy, as most responders improve within this timeframe. Failure to improve should prompt timely escalation, since delayed intubation correlates with higher mortality. Monitoring parameters typically include respiratory rate, accessory muscle use, WOB, Peripheral capillary oxygen saturation (SpO_2), and PaO_2/FiO_2.

Overall, HFNC is emerging as the preferred initial support modality for post-operative hypoxemic respiratory failure. It provides superior comfort relative to NIV and more consistent oxygen delivery than COT. Nonetheless, management should be individualized: NIV may remain the best choice in hypercapnic states or when HFNC proves insufficient [10].

The ROX index (SpO_2/FiO_2 divided by respiratory rate) has been validated as a predictor of HFNC failure in AHRF due to pneumonia, with a cut-off of 4.88 [57]. More recent work shows that a value of 8.78 at six hours after initiation may predict success, offering clinicians a dynamic tool for early assessment of therapy effectiveness and guiding escalation decisions [58].

Taken together, evidence supports HFNC as a reliable alternative to COT, offering higher and more stable FiO_2, mild PEEP effects, and improved humidification, which together enhance patient comfort, oxygenation, and secretion clearance. In high-risk post-operative patients, HFNC has been associated with lower reintubation rates compared with COT, though results vary and some large trials have not confirmed reductions in hypoxemia. When compared with CPAP or BiPAP, HFNC demonstrates similar effectiveness for preventing reintubation, with the added benefit of greater tolerance and fewer interface-related issues.

HFNC is particularly advantageous in patients poorly toler-

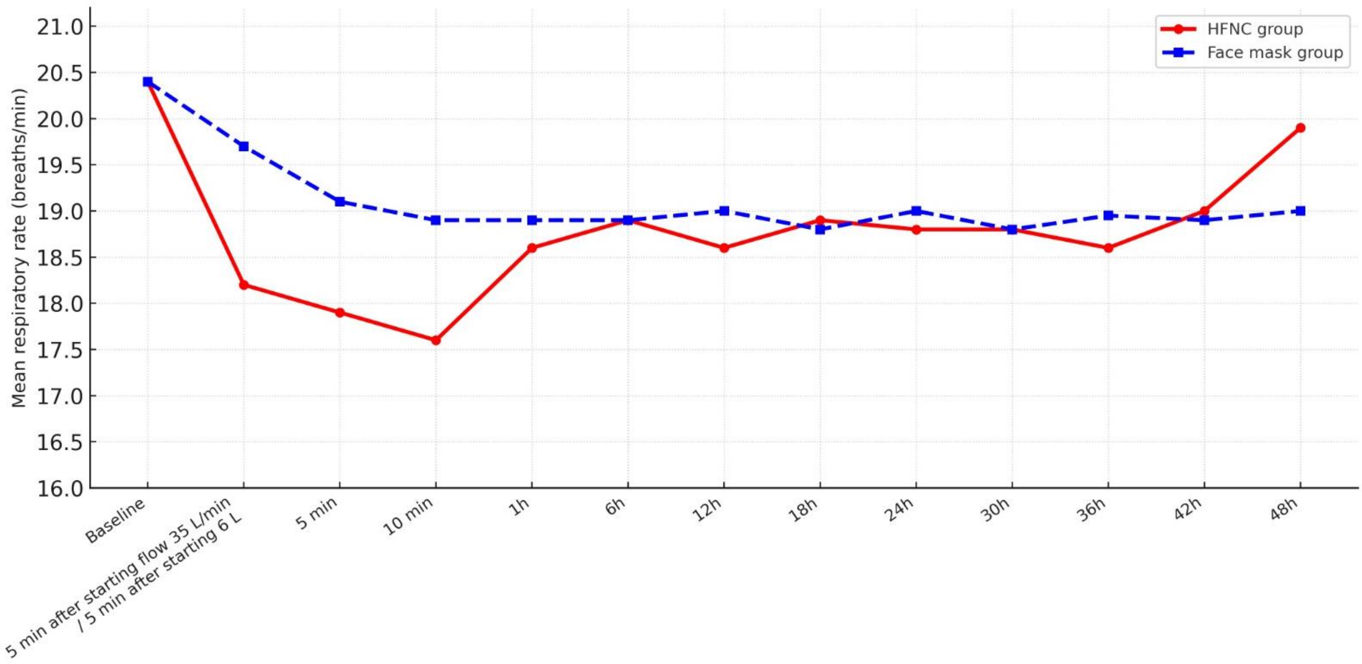

FIGURE 1. Comparison between the two studied groups according to respiratory rate (breath/min). (Adapted from Soliman *et al*. [52], 2022). HFNC: High-Flow Nasal Cannula.

TABLE 1. Comparison between the two studied groups according to incidence of PPCs.

	HFNC (n = 40)		Face mask (n = 40)		Chi-square test	
	No.	%	No.	%	χ^2	^{FE}p
Pneumonia	1	2.5	5	12.5	2.883	0.201
Pleural effusion	2	5.0	5	12.5	1.409	0.432
Atelectasis	1	2.5	8	20.0	6.135*	0.029*
Pneumothorax	0	0.0	0	0.0	-	-

χ^2: Chi-square test; ^{FE}: Fisher's exact test.
p: p value for comparison between the two studied groups.
**: Statistically significant at $p < 0.05$.*
HFNC: High-Flow Nasal Cannula.

ant of mask ventilation or in surgical settings where positive pressure could compromise healing (*e.g.*, esophagectomy or free flap procedures). In cardiothoracic surgery, HFNC improves oxygenation and reduces escalation of support, whereas in abdominal surgery results are mixed, suggesting selective rather than routine use.

In obese patients, network meta-analyses indicate that HFNC decreases atelectasis and LOS, performing as well as or better than CPAP/BiPAP in terms of oxygenation and comfort. However, in hypercapnic states or with very high inspiratory drive, HFNC may be inadequate, and escalation to BiPAP is advisable.

In summary, HFNC stands as a first-line option for most hypoxemic post-operative patients who cannot tolerate mask ventilation, while CPAP or BiPAP remain more suitable when atelectasis, hypercapnia, or excessive inspiratory effort predominate. The incorporation of dynamic assessment tools, such as the ROX index, further refines clinical decision-making by predicting success or failure and supporting timely escalation when required.

5. Pediatric settings

There are important differences in respiratory physiopathology between pediatric and adult patients that influence the application of non-invasive respiratory support. After birth, fetal hemoglobin is progressively replaced by adult hemoglobin, and surfactant molecules stratify on the alveolar surface, reducing surface tension. In the first years of life, alveolar development is incomplete, ribs are more horizontal, and intercostal muscle contribution to inspiration is lower. The pediatric rib cage, due to its high compliance, predisposes children to hyperinflation during inspiration and atelectasis during expiration. Hypoxemia is a common postoperative complication and represents the main indication for oxygen therapy [33]. Oxygen supplementation is recommended when SpO_2 falls below 94%, targeting 94–98% with the lowest FiO_2. In cases of severe failure where SpO_2 cannot be measured, maximum FiO_2 should be initiated until monitoring becomes available [59].

Non-invasive ventilation (NIV) is increasingly used in pediatrics, particularly for preventing post-extubation failure and managing acute respiratory failure (ARF) [60, 61]. Contraindications include the need for a protected airway, poor tolerance, and hemodynamic instability. Modern ventilators can compensate for unintentional leaks and deliver FiO_2 up to 1.0. Success is closely tied to the choice of interface, which should minimize leaks and maximize comfort, with options including oronasal and full-face masks, helmets, and nasal interfaces.

Nasal CPAP remains the most established modality in neonates and infants. By delivering continuous pressure, CPAP increases nasopharyngeal area, decreases resistance, improves compliance, stimulates surfactant release, enhances diaphragmatic activity, reduces apnea frequency, and improves ventilation-perfusion matching. Multiple interfaces are available, and recent studies indicate nasal masks reduce CPAP failure [57]. When HFNC fails, CPAP may be delivered with variable-flow ventilators via specialized nasal cannulas and humidification systems [62].

Bi-level modes (BiPAP, NIPPV, and NonInvasive Mechanical Ventilation (NIMV)) provide inspiratory pressure support (PIP) above baseline PEEP, thereby improving tidal volume and alveolar recruitment [63]. In pediatrics, synchronized bi-level support can be set with additional flow and abdominal sensors [62]. Observational studies show benefits in children with hypoventilation or neuromuscular weakness, but large RCTs remain lacking. Limitations include variable tidal volume delivery and frequent asynchronies due to rapid respiratory rates, compliance changes, or air leaks.

HFNC has gained popularity as a simpler, more comfortable alternative to CPAP [61, 64–67]. Delivering heated, humidified air/oxygen mixtures up to 60 L/min, HFNC improves mucociliary clearance, reduces WOB, and provides better tolerance compared with CPAP, with lower rates of nasal trauma. However, excessive occlusion of nares can generate dangerously high pressures [62]. Careful monitoring is crucial, with indices such as SpO_2/FiO_2 ratio helping to predict failure. HFNC has been shown to reduce reintubation rates and is not inferior to NIV in high-risk pediatric patients [65].

Novel modalities include neurally adjusted ventilatory assist (NAVA-NIV), which improves patient-ventilator synchrony and reduces asynchronies, thus increasingly used in pediatric and neonatal populations [61]. Non-invasive high-frequency nasal ventilation (NIHFV) merges features of high-frequency oscillatory ventilation with non-invasive delivery, though current evidence remains preliminary [61].

Interfaces and innovations are also evolving. Helmets specifically designed for children have been reported as well tolerated [68]. Innovative approaches such as 3D-printed connectors adapting anesthetic masks for NIV demonstrate feasibility, as shown in a case of a 4-year-old with acute hypoxemic respiratory failure [69].

Evidence synthesis suggests that CPAP remains the cornerstone in preventing atelectasis and hypoxemia, particularly in neonates and infants. HFNC is increasingly favored as first-line support due to its superior tolerance and ease of use, while BiPAP/NIPPV is particularly beneficial for patients with hypercapnia, high respiratory drive, or neuromuscular disease. Guaranteed-volume and synchronized modes may improve outcomes in pressure support ventilation, but data remain limited [70].

In conclusion, non-invasive respiratory support is fundamental in pediatric perioperative and intensive care. CPAP continues to be the gold standard for alveolar recruitment and atelectasis prevention; HFNC is increasingly applied for its comfort, tolerance, and feasibility; and BiPAP/NIPPV is reserved for hypercapnic states or increased WOB. Early monitoring and timely escalation to invasive ventilation remain essential to avoid deterioration.

6. Conclusions

Postoperative acute hypoxemic respiratory failure (AHRF) remains a major contributor to morbidity and mortality following major surgery. Non-invasive respiratory support strategies—including Continuous Positive Airway Pressure (CPAP), Bilevel Positive Airway Pressure (BiPAP), and High-Flow Nasal Cannula (HFNC)—have significantly expanded the therapeutic armamentarium for its management. These modalities share common benefits such as reducing the need for reintubation, preserving spontaneous breathing, and decreasing the risk of ventilator-associated pneumonia. However, their mechanisms, indications, and limitations differ, making accurate patient selection essential.

CPAP exerts continuous positive pressure that recruits the alveoli and prevents atelectasis. Evidence supports its efficacy after abdominal and thoracic surgery, with reduced pneumonia and reintubation in high-risk patients, although large trials have yielded mixed results regarding mortality. BiPAP, by providing inspiratory support in addition to PEEP, is particularly valuable in the presence of hypercapnia, COPD exacerbations, or cardiogenic pulmonary edema, and may shorten mechanical ventilation and ICU stay after cardiac surgery, though benefits on reintubation remain inconsistent. HFNC provides reliable FiO_2 delivery with enhanced comfort, improved secretion clearance, and lower risk of barotrauma compared with mask NIV. It is especially attractive for patients intolerant of positive-pressure interfaces or in surgical settings where excessive airway pressure may threaten anastomotic integrity (*e.g.*, esophageal or head-and-neck free-flap surgery).

Emerging evidence also highlights potential population-specific effects. In obese patients, both CPAP and BiPAP reduce postoperative pulmonary complications, but BiPAP may be preferable when hypoventilation or OSA/OHS coexist, whereas HFNC may optimize comfort and LOS. In pediatrics, nasal CPAP remains the cornerstone to prevent atelectasis, while HFNC offers superior tolerance and feasibility in infants and small children.

Overall, CPAP, BiPAP, and HFNC should be regarded as complementary strategies rather than interchangeable tools. Their success depends on tailoring the modality to the underlying pathophysiology—CPAP for atelectasis-driven hypoxemia, BiPAP for hypercapnia or high respiratory drive, and HFNC for patients requiring better comfort or in whom positive pressure is undesirable. Early monitoring and timely escalation remain crucial, as delayed intubation continues to be associated with poor outcomes.

This review has some limitations that should be acknowledged. The available evidence is heterogeneous in terms of study design, patient populations, surgical procedures, and outcome definitions, which hampers the ability to draw firm conclusions. Large RCTs, such as PRISM and OPERA, provided valuable insights but were limited by patient heterogeneity, moderate event rates, and difficulties in standardizing interventions. Moreover, most comparative studies between CPAP, BiPAP, and HFNC remain underpowered, and head-to-head analyses are scarce, especially in high-risk surgical populations. Several subgroups of particular clinical relevance—including obese patients, those with multiple organ dysfunction, and pediatric cohorts—remain insufficiently studied, limiting the external validity of current evidence.

Future research should focus on adequately powered randomized trials that stratify patients according to specific risk factors and surgical settings. Comparative effectiveness studies are needed to clarify the optimal timing, modality, and duration of CPAP, BiPAP, and HFNC across diverse perioperative scenarios. Standardized outcome measures, including patient-centered endpoints, such as comfort, tolerance, and quality of recovery, should be incorporated. Finally, integration of predictive tools, such as the ROX index, may refine patient selection and guide timely escalation strategies. Addressing these gaps will be essential to optimize the role of non-invasive respiratory support in improving postoperative outcomes.

AVAILABILITY OF DATA AND MATERIALS

No new data were generated for this narrative review. All data discussed are available from the referenced literature.

AUTHOR CONTRIBUTIONS

FC, PS, VP—conceptualization. GC, LMB, SB, SDS, MDP—writing-original draft preparation. MBP, MF, CE, MCP, VP—writing-review and editing, supervision.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This is a narrative review based on previously published data. No new data involving human or animal subjects were collected or analyzed. Therefore, ethical approval and patient consent were not required.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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