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Comparison of high-flow nasal oxygenation and standard low-flow nasal oxygenation during rigid bronchoscopy: a randomized controlled trial

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Background: The efficacy of high-flow nasal oxygenation (HFNO) in improving oxygenation is influenced by several factors, and its effectiveness is not always guaranteed. Therefore, we aimed to compare the effects of HFNO and standard low-flow nasal oxygenation during rigid bronchoscopy in the apneic patients.

Methods: All patients were administered general anesthesia with full muscle relaxation and were randomly assigned to receive either HFNO (HFNO group) or standard low-flow oxygenation (Standard group). The study endpoints included the lowest peripheral oxygen saturation (SpO_2), hypoxemia-related surgical interruptions ($SpO_2 \leq 94\%$), and changes in arterial oxygen tension (PaO_2) and carbon dioxide tension ($PaCO_2$) during the apnea period for rigid bronchoscopy.

Results: A total of 53 patients completed the study. No significant differences were found between the HFNO and the Standard groups in the lowest SpO_2 levels (median [Q1, Q3]; 99 [98, 100]% vs. 98 [94, 100]%, P = 0.059) and in the increase rate of $PaCO_2$ (mean ± standard deviation [SD]; 1.6 ± 0.7 mmHg/min vs. 2.0 ± 0.8 mmHg/min, P = 0.064). However, the HFNO group had fewer patients with hypoxemia-related surgical interruptions than the Standard group (1 [3.8%] vs. 8 [29.6%], P = 0.024) and exhibited an attenuated decline rate in PaO_2 (median [Q1, Q3]: 4.6 [0.0, 7.9] mmHg/min vs. 10.5 [6.4, 12.9] mmHg/min, P = 0.005).

Conclusions: While HFNO did not enhance the lowest SpO_2 levels in comparison with standard low-flow oxygenation, it did reduce hypoxemia-related surgical interruptions with an attenuated decline in PaO_2. Therefore, HFNO has considerable clinical efficacy for rigid bronchoscopy.

Keywords: Anesthesia, general; Bronchoscopy; Humans; Hypoxia; Oxygen inhalation therapy; Thoracic surgical procedures.

Introduction

Rigid bronchoscopy facilitates access to the tracheobronchial lumen without the need for open tracheal incision. However, employing a surgical approach through rigid bronchoscopy necessitates the sacrifice of securing a definitive airway that leads to the use of tubeless anesthesia. Therefore, anesthesiologists must pay careful attention to ventilation and oxygenation during this procedure.

High-flow nasal oxygenation (HFNO) is associated with improved oxygenation in surgical patients, those with obesity, and critical patients in emergency and intensive care settings, possibly aiding in the reduction of CO_2 accumulation [1–3]. However, factors such as the degree of mouth opening, level of patient sedation, and status of respiratory muscle paralysis can alter the efficacy of HFNO [4]. The rigid bronchoscope is inserted through the patient's open mouth and often requires deeper sedation, enhanced pain control, and immobilization owing to its stiffness and size [5].

The rigid bronchoscope has a ventilating side port that can be connected to an anesthesia circuit, enabling oxygen supply during the procedure [6]. However, empirical research has not yet substantiated the potential benefits of combining HFNO with this side port oxygen supply for improved oxygenation and ventilation.

Therefore, we aimed to determine whether the application of HFNO improved oxygenation and ventilation in paralyzed and apneic patients undergoing rigid bronchoscopic surgery under general anesthesia. We hypothesized that the application of HFNO would increase the lowest peripheral oxygen saturation (SpO_2) levels and attenuate changes in arterial oxygen and carbon dioxide tension.

Materials and Methods

Ethics

This prospective, open-label, randomized controlled trial was conducted in accordance with the Declaration of Helsinki, 2013. This study was approved by the Institutional Review Board (IRB no. 1-2019-0005, March 2019) and registered at ClinicalTrials.gov (NCT03892408, March 27, 2019) before patient enrollment (April 21, 2019). Written informed consent was obtained from all the patients. This manuscript adheres to the Consolidated Standards of Reporting Trials (CONSORT) guidelines.

Study design and patients

In this prospective, open-label, randomized controlled trial, we enrolled patients who underwent general anesthesia with stent placement or removal, bougination, biopsy, or removal of a foreign body or mass through a rigid bronchoscope between April 2019 and August 2022. The inclusion criteria were age ≥ 19 years and American Society of Anesthesiologists physical class II–IV. The exclusion criteria were as follows: (1) dementia or cognitive impairment; (2) current pregnancy; (3) undergoing extracorporeal membrane oxygenation; (4) active nasal hemorrhage, significant nasal obstruction, recent nasal trauma, or surgery; (5) current maxillofacial trauma or basal skull fractures; (6) previous rigid bronchoscopy within one month; and (7) inability to provide written informed consent due to illiteracy or being a non-native speaker.

Randomized allocation

Patient allocation sheets were generated by N.K. using a random number generator in Microsoft Excel 2016® (Microsoft Corp.), employing a fixed block size of four and a 1:1 allocation ratio. The patients were assigned either to the HFNO or the standard low-flow nasal oxygenation group (Standard group) by K.L. Owing to the visible nature of the application of HFNO, blinding was deemed unfeasible; therefore, this study was conducted as an open-label trial.

Anesthesia protocol

Upon arrival in the operating room, the patients were monitored using essential monitoring devices, including a three-lead electrocardiogram, non-invasive blood pressure monitor, finger-mounted pulse oximeter, and bispectral index (BIS) monitor. Following the completion of monitoring, glycopyrrolate 4 μg/kg (maximum 0.2 mg) was administered intravenously, and the patients were provided with 100% oxygen via a mask for a minimum duration of 3 min. Anesthesia was induced and maintained using propofol (Fresofol 1% MCT®; Fresenius Kabi Austria GmbH) and remifentanil (Ultian®; Hanlim Pharm. Co., Ltd.) using a target-controlled infusion approach for total intravenous anesthesia. For induction, the concentration of propofol was set between 3 and 4 μg/ml, and that of remifentanil was between 2 ng/ml and 4 ng/ml. Subsequent adjustments were made at the discretion of the anesthesiologist. Upon loss of consciousness, 0.6–1.0 mg/kg rocuronium (Rocumeron®; Ilsung Pharmaceuticals Co., Ltd.) was administered, followed by mask ventilation with 100% oxygen.

Thereafter, we confirmed no response to 50-Hz train-of-four (TOF) stimulation of the ulnar nerve at the adductor pollicis muscle using a peripheral nerve stimulator (Innervator 252®; Fisher & Paykel Healthcare). A supraglottic airway (i-gel®; Intersurgical Ltd.) was inserted, and an arterial catheter was concurrently inserted into the radial artery for real-time arterial pressure monitoring. The patients with dental instability were intubated. The initial ventilator settings were established with a tidal volume of 6 ml/kg, ideal body weight (IBW), respiratory rate (RR) of 16, and positive end-expiratory pressure (PEEP) of 0 cmH_2O. The RR was

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adjusted to a target end-tidal CO_2 ($EtCO_2$) of 30–40 mmHg. Subsequently, dexamethasone 0.2 mg/kg (maximum 10 mg) was administered intravenously. An Optiflow® device (Fisher & Paykel Healthcare) was installed for the HFNO group, whereas a conventional nasal cannula was applied for the Standard group, and neither group received oxygen delivery through the cannulas before the start of apnea.

The moment of removal of the supraglottic airway or endotracheal tube for oral entry of the rigid bronchoscope was considered the start of apnea. The last measured $EtCO_2$ immediately before the onset of apnea was recorded, and arterial blood gas analysis (ABGA) was performed. At apnea initiation, the HFNO group received 100% oxygen at 70 L/min, whereas the Standard group received 100% oxygen at 5 L/min. Upon passing the rigid bronchoscope through the vocal cords to reach the target within the trachea, the ventilator circuit was connected to the ventilating side port. The tidal volume was set to 12 ml/kg of IBW with an RR of 30, PEEP at 0 cmH_2O, and an oxygen flow of 18 L/min in a volume-controlled ventilation mode. The design of the rigid bronchoscope, with its open multifunctional head in the direction of the surgeon and the gap between the device and the larynx, resulted in significant oxygen leakage. Oxygen supplementation through the ventilating side port with significant leakage was sustained in both groups, while the rigid scope was in the trachea.

Intraoperatively, the BIS target was maintained at 40–60. Hypotension was managed by an anesthesiologist with either fluid loading or administration of phenylephrine or norepinephrine based on their discretion. TOF monitoring was conducted at 20-second intervals, and an additional 10 mg of rocuronium was administered if a TOF count of 1 was detected. If the transcutaneous SpO_2 decreased to ≤ 94%, the procedure was paused, and the instrument that had been inserted through the multifunctional head was removed. The multifunctional head hole was then sealed to enhance oxygen supplementation through the ventilating side port. We refer to this as hypoxemia-related surgical interruption. If the SpO_2 further decreased to ≤ 90%, the rigid bronchoscope was removed, and interventions such as mask ventilation, endotracheal intubation, or insertion of a laryngeal mask were provided. If the patient's SpO_2 subsequently remained > 94% for at least 10 s, surgery was resumed. The study was terminated if recovery did not occur within 5 min or if new arrhythmias developed.

Upon completion of surgery and removal of the rigid bronchoscope, the supraglottic airway or endotracheal tube used during induction was reinserted, marking the end of apnea as ventilation resumed. Arterial blood was sampled for the analysis of oxygen and carbon dioxide tension immediately before resuming mechanical ventilation (MV), and the $EtCO_2$ of the third breath after restarting MV was recorded. Heart rate (HR), systolic blood pressure (SBP), diastolic blood pressure (DBP), and SpO_2 were documented immediately upon entry into the operating room and at the start and end of apnea along with the lowest oxygen saturation during the apneic period. Extubation was performed according to standard hospital protocols, and sugammadex was administered according to the recommended dosage based on TOF count. The occurrence of nosebleeds and skin breakdown around the nostrils after nasal cannula application were investigated postoperatively.

Study endpoints

The primary endpoint was the lowest SpO_2 level. The secondary endpoints were hypoxemia-related surgical interruptions in rigid bronchoscopy (SpO_2 ≤ 94%), changes in arterial oxygen tension (PaO_2) per minute during the apneic period, and changes in arterial carbon dioxide tension ($PaCO_2$) per minute during the apneic period.

Sample size calculation

In a previous study [7], the lowest SpO_2 observed during endobronchial ultrasound under a standard oxygen supply was 91.0% on average, with a standard deviation of 5.1%. In contrast, patients who received HFNO therapy exhibited lowest oxygen saturation of 95.4% on average, with a standard deviation of 5.9%.

To assess if the lowest SpO_2 levels were significantly different between the two groups, we used a two-sample t test for independent means. We aimed to detect a difference of 4.4% in the lowest SpO_2 levels based on the observed means (91.0% for standard oxygen supply and 95.4% for HFNO therapy) and standard deviations (5.1% and 5.9%, respectively). A sample size of 25 patients per group was calculated based on a two-tailed significance level of 5% ($\alpha = 0.05$) and power of 80% ($\beta = 0.20$). Considering an attrition rate of approximately 10%, 28 patients were required per group (56 patients).

Statistical analysis

The data analysis was limited to patients without missing values for the lowest SpO_2. With respect to baseline characteristics, patients were deemed to have an imbalance if the absolute standardized difference (ASD) exceeded 0.54 [8,9]. Continuous variables were analyzed using the independent t test or Mann–Whitney test after evaluating the normality of the data distribution using the Shapiro–Wilk test. Normally and non-normally distributed con-

tinuous data are presented as the mean ± standard deviation (SD) and median (Q1, Q3), respectively. The estimated median difference and 95% CI were computed using bootstrapping that involved random resampling with replacement with 10,000 repetitions. Categorical variables were analyzed using the chi-square test or Fisher exact test and are presented as numbers (%). The between-group differences in the rates of change in arterial blood gas tension during the apneic period were analyzed separately for the entire cohort and for the subset of patients who proceeded without hypoxemia-related surgical interruption. All statistical analyses were performed using the Statistical Package for the Social Sciences version 26® software (IBM Corp.) and R version 4.3.1® (The R Foundation for Statistical Computing). Statistical significance was set at $P < 0.05$.

Results

Of the 59 patients screened for eligibility, 56 were enrolled in the study. Of the enrolled patients, two withdrew consent and one patient was excluded because of a change in the surgical plan. None of the patients were excluded because of their inability to recover oxygen saturation or the development of new arrhythmias during apnea. Consequently, 53 patients (26 in the HFNO group and 27 in the Standard group) completed the study (Fig. 1).

Tables 1 and 2 present preoperative baseline characteristics and operative data, respectively. Despite the higher proportion of female patients in the HFNO group (57.7% vs. 22.2%, standardized mean difference = 0.777), the age, BMI, comorbidity profiles, and types of surgery were similar between the groups. Moreover, no significant between-group differences were found in HR, SBP, and DBP values immediately upon entry into the operating room, at the start of apnea, and at the end of apnea. Additionally, the anesthesia time, apnea duration, and volume of administered fluids were similar between the groups.

No significant differences were found between the HFNO and Standard groups in terms of the lowest SpO_2 levels (99 [98, 100]% vs. 98 [94, 100]%, P = 0.059) (Table 3). However, fewer patients in the HFNO group experienced hypoxemia-related surgical interruptions (1 [3.8%] vs. 8 [29.6%], P = 0.024), with a relative risk (95% CI) of 0.13 (0.02–0.97) (Fig. 2). Additionally, ABGA revealed an attenuated decrease in oxygen tension (4.6 [0.0, 7.9] mmHg/min vs. 10.5 [6.4, 12.9] mmHg/min, P = 0.005) during apnea in the HFNO group, compared to the Standard group (Fig. 3). This difference remained significant even when patients with hypoxemia-related surgical interruptions were excluded from the analysis. However, the rate of increase in carbon dioxide tension

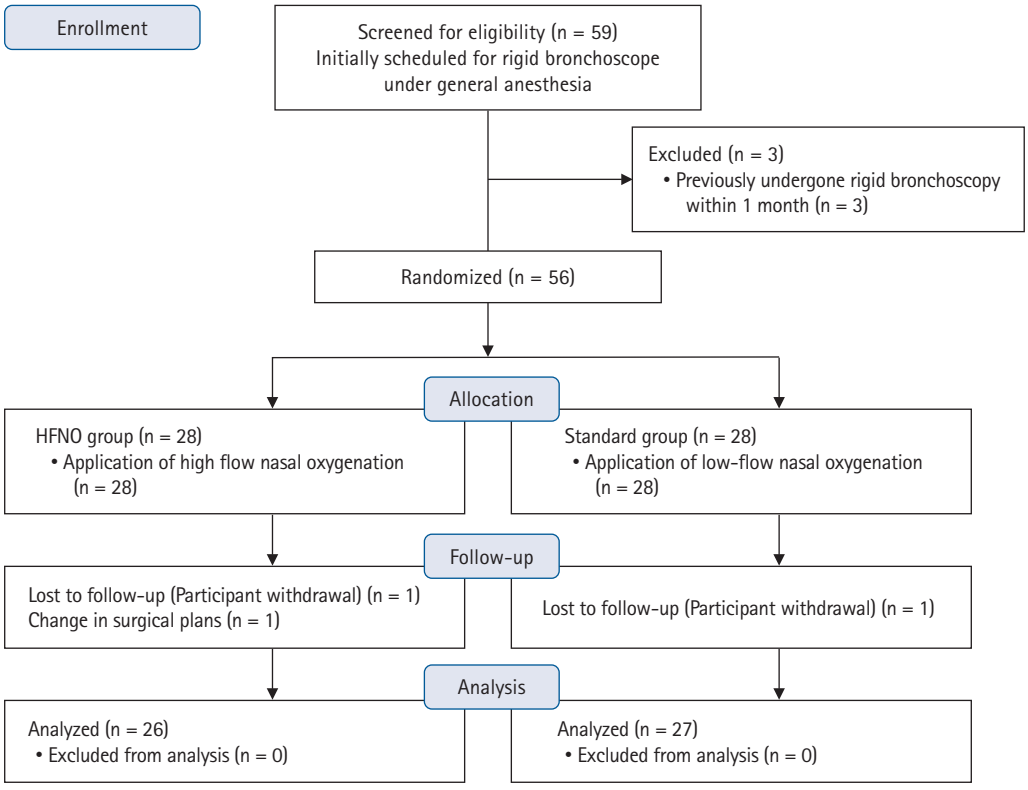

Fig. 1. Consolidated Standards of Reporting Trials (CONSORT) diagram of patient recruitment.

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during apnea (1.6 ± 0.7 mmHg/min vs. 2.0 ± 0.8 mmHg/min, P = 0.064) did not differ significantly between the HFNO group and the Standard group.

Discussion

This study demonstrated that HFNO was not beneficial for the lowest oxygen saturation during the apneic period for rigid bronchoscopy. However, hypoxemia-related surgical interruptions at a saturation level of 94% as a primary safety measure occurred less frequently with HFNO. Additionally, although the application of HFNO did not significantly alter the rate of carbon dioxide tension accumulation, it attenuated the decrease in arterial oxygen tension during the apneic period.

The underlying mechanisms of HFNO include delivery of a high concentration of inspired oxygen, reduction of anatomical dead space, and generation of PEEP in the oropharyngeal cavity [10]. Among these, PEEP generation significantly depends on the respiratory state (apneic, passive, or spontaneous ventilation) and whether the mouth is open or closed [4,11,12]. Despite the lower efficacy of PEEP generation with an open mouth than that with a closed mouth [4], HFNO can still enhance oxygenation in patients with an open mouth. In patients undergoing endobronchial ultrasound and those receiving dental treatment under sedation with an open mouth, HFNO resulted in higher minimum oxygen saturation levels than standard oxygenation at 10 L/min delivered through a bite block or nasal cannula oxygenation at 5 L/min [7,13]. These two studies involved sedated but spontaneously breathing patients with open mouths. Considering that the generation of PEEP in patients with paralyzed apnea with an open mouth is negligible [4,11], the effect of PEEP is expected to be even less significant in our setting. However, disregarding the effects of PEEP, several studies have reported that HFNO aids in maintaining saturation in patients with an open mouth in an apneic state [14–16] that is not consistent with our findings; no benefit in the lowest SpO_2 in the HFNO group. To enhance patient safety, we halted the procedure at an SpO_2 of 94%, sealed the porthole facing the surgeon's direction, and attempted ventilation through the side port. This approach may explain the minimal between-group difference in the lowest oxygen saturation, suggesting that the implemented safety measures could have introduced a potential bias in the primary outcome.

Table 1. Baseline Patient Characteristics by Group

Variable	HFNO group (n = 26)	Standard group (n = 27)	ASD
Age (yr)	61 ± 15	62 ± 10	0.079
Sex (F)	15 (57.7)	6 (22.2)	0.777
Body mass index (kg/m^2)	22.5 ± 4.2	21.1 ± 3.5	0.373
ASA-PS			
II	1 (3.8)	5 (18.5)	0.479
III	24 (92.3)	22 (81.5)	0.325
IV	1 (3.8)	0 (0.0)	0.283
Comorbidities			
Hypertension	11 (42.3)	11 (40.7)	0.032
Diabetes mellitus	8 (30.8)	7 (25.9)	0.108
Coronary artery occlusive disease	1 (3.8)	0 (0.0)	0.283
Cerebrovascular accident	3 (11.5)	0 (0.0)	0.511
Asthma	5 (19.2)	2 (7.4)	0.353
Current smoker	2 (7.7)	2 (7.4)	0.011

Values are presented as mean ± SD, or number of patients (%). ASD > 0.54 indicates imbalance, where 0.54 is derived from the following formula[8,9]: $1.96 \times \sqrt{((n1- + -n2)/n1n2)} = 0.54$. HFNO: high-flow nasal oxygenation, Standard group: standard low-flow nasal oxygenation group, ASD: absolute standardized difference, ASA-PS: American Society of Anesthesiologists physical status classification.

Table 2. Operative Data by Group

Variable	HFNO group (n = 26)	Standard group (n = 27)	P value
Initial SpO_2 (%) in the operating room	98.5 (96, 100)	98.0 (96. 100)	0.957
Types of surgery			0.093
Stent placement	17 (65.4)	24 (88.9)	
Removal of a foreign body or a mass without stent placement	8 (30.8)	3 (11.1)	
Stent removal	1 (3.8)	0 (0.0)	
Duration of anesthesia (min)	60 (50, 70)	60 (53, 75)	0.525
Fluid infused (ml)	300 (250, 400)	450 (200, 600)	0.293
Duration of apnea (s)	985 (710, 1802)	1040 (863, 1460)	0.783

Values are presented as median (Q1, Q3), or number of patients (%). HFNO: high-flow nasal oxygenation, Standard group: standard low-flow nasal oxygenation group, SpO_2: peripheral oxygen saturation.

Table 3. Between-group Comparison of Oxygenation and Ventilation Parameters

Variable	HFNO group (n = 26)	Standard group (n = 27)	Relative risk or estimated difference (95% CI)	P value
Lowest SpO_2 (%)	99 (98, 100)	98 (94, 100)	1.00 (−0.50 to 3.00)	0.059*
Number of patients with hypoxemia-related surgical interruptions	1 (3.8)	8 (29.6)	0.13 (0.02–0.97)	0.024†
Start of apnea				
SpO_2 (%)	100 (100, 100)	100 (100, 100)	0.00 (0.00–0.00)	0.744*
PaO_2 (mmHg)	408.7 ± 131.6	433.3 ± 133.8	−24.6 (−97.8 to 48.6)	0.503‡
$PaCO_2$ (mmHg)	42.0 (39.0, 47.0)	43.0 (37.7, 46.5)	−1.00 (−4.00 to 4.50)	0.755*
$EtCO_2$ (mmHg)	37 ± 4	37 ± 4	−0.01 (−2.30 to 2.28)	0.995‡
End of apnea				
SpO_2 (%)	100 (98, 100)	99 (98, 100)	1.00 (0.00–2.00)	0.046*
PaO_2 (mmHg)	335.0 (203.0, 418.0)	207.5 (127.0, 380.0)	122 (−48.5 to 222)	0.062*
$PaCO_2$ (mmHg)	72.4 ± 18.8	79.0 ± 13.7	−6.55 (−15.59 to 2.50)	0.152‡
$EtCO_2$ (mmHg)	56 (50, 64)	56 (53, 66)	−0.50 (−9.50 to 7.00)	0.624*
Decrease in PaO_2 per minute (mmHg/min)	4.6 (0.0, 7.9)	10.5 (6.4, 12.9)	−5.52 (−8.85 to −1.65)	0.005*
Increase in $PaCO_2$ per minute (mmHg/min)	1.6 ± 0.7	2.0 ± 0.8	−0.40 (−0.83 to 0.02)	0.064‡
Excluding patients with hypoxemia-related surgical interruptions				
	HFNO group (n = 25)	Standard group (n = 19)	Estimated difference (95% CI)	P value
Decrease in PaO_2 per minute (mmHg/min)	4.2 (0.0, 7.9)	9.5 (6.4, 12.5)	−4.98 (−9.42 to −0.46)	0.030*
Increase in $PaCO_2$ per minute (mmHg/min)	1.6 ± 0.7	1.9 ± 0.8	−0.35 (−0.82 to 0.13)	0.151‡

Values are presented as median (Q1, Q3), number of patients (%) or mean ± SD. HFNO: high-flow nasal oxygenation, SpO_2: peripheral oxygen saturation, PaO_2: arterial oxygen tension, $PaCO_2$: arterial carbon dioxide tension, $EtCO_2$: end-tidal carbon dioxide. *P values for the Mann–Whitney test. †P values for the chi-squared test or Fisher exact test. ‡P values for the independent t test.

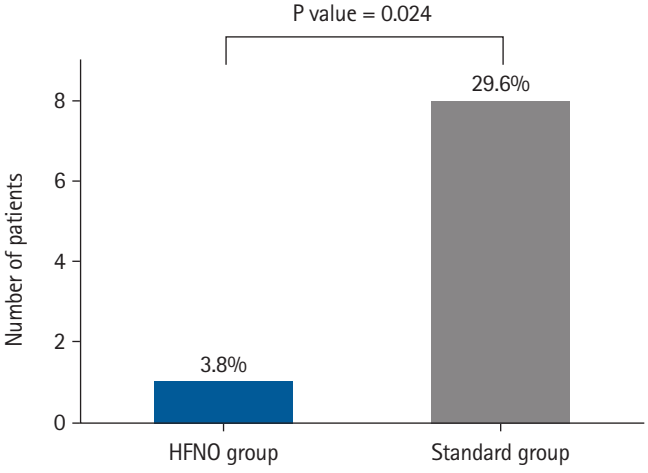

Fig. 2. Number of patients with hypoxemia-related surgical interruptions. Fewer patients had hypoxemia-related surgical interruptions in the HFNO group than in the Standard group (P = 0.024). HFNO: high-flow nasal oxygenation, Standard group: standard low-flow nasal oxygenation group.

In this context, it is noteworthy that the Standard group had a higher incidence of patients experiencing an SpO_2 drop to 94%. This implies more frequent procedural interruptions for the surgeons. This trend was also observed in sedated dental patients, potentially influencing surgeon satisfaction [13]. Thus, despite not being a primary endpoint, this finding is clinically relevant.

The rate of decrease in arterial oxygen tension during the apneic period varied with HFNO [14,17]. In a study on apneic oxygenation with HFNO in patients with morbid obesity [17], arterial oxygen tension exhibited a nonlinear decline during the apneic period, initially decreasing rapidly and then slowly. Additionally, the slope and inflection points varied significantly among patients. An additional factor to consider is that our study administered oxygen through a ventilating side port of the rigid bronchoscope simultaneously, and the combined effect of oxygenation with HFNO can be complex. Therefore, presenting quantitative values for the rate of decrease in arterial oxygen tension in our study may not have been clinically significant. Nevertheless, our study was conducted as a randomized controlled trial and demonstrated similar apnea durations between the groups. Therefore, the conclusion that HFNO application reduces the rate of decrease in the oxygen tension remains valid.

HFNO may assist in carbon dioxide removal in patients experiencing apnea [14,18], presumably through the flow-dependent washout effect of the dead space [2,18]. However, although HFNO

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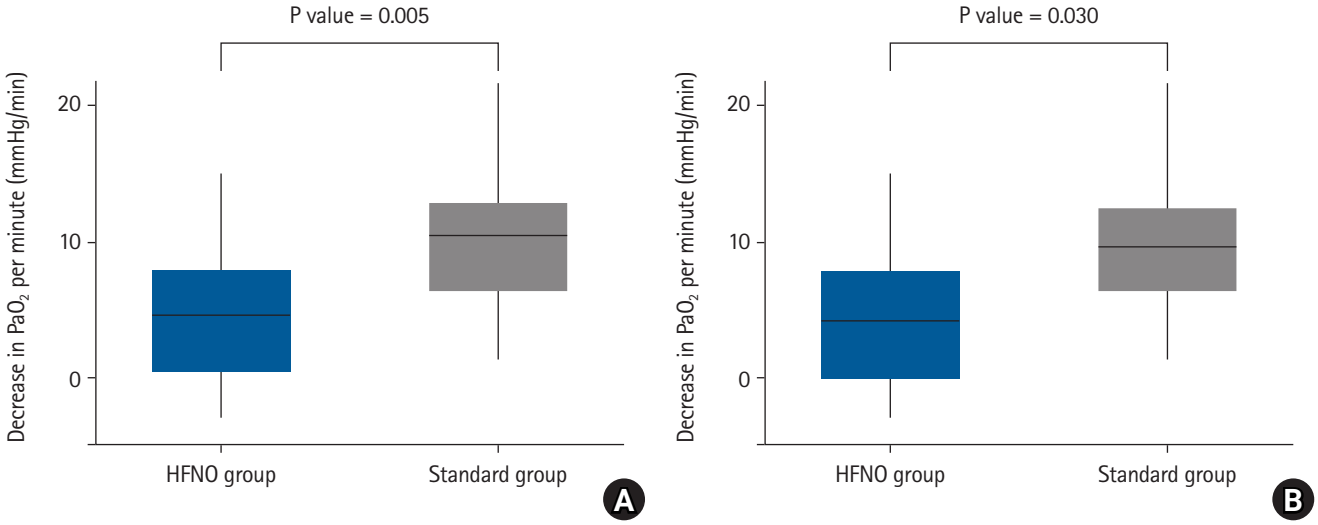

Fig. 3. Comparison of the decrease in PaO_2 per minute between the HFNO group and the Standard group. (A) Patients with hypoxemia-related surgical interruption were included. (B) Patients with hypoxemia-related surgical interruptions were excluded. Boxes represent the median (Q1, Q3), with the median value depicted as a line within the box. The whiskers indicate the full range of the data, excluding outliers. HFNO: high-flow nasal oxygenation, Standard group: standard low-flow nasal oxygenation group.

may effectively meet the oxygen demand in patients with apnea, it seems less capable of suppressing CO_2 elevation. Compared with spontaneous breathing in adults, the use of HFNO in patients with apnea results in a doubling of CO_2 accumulation over 30 min under tubeless anesthesia, indicating limited efficacy [19]. HFNO was not beneficial in reducing the $PaCO_2$ accumulation in adult patients with morbid obesity [17], and two pediatric studies also showed no benefit in the rate of transcutaneous CO_2 increase [16,20]. These two groups, characterized by high CO_2 production or relatively large dead space, are populations in which the effects of CO_2 flushing can be maximized. Nevertheless, because these studies did not consider the impact of CO_2 as the primary outcome, there are concerns that the sample size may have been too small to detect a significant effect. Similarly, our study did not show a clear benefit with respect to CO_2 clearance, probably for the same reason. Notably, a recent non-inferiority study comparing oxygen flow applications from 0.25 L/min to 70 L/min demonstrated comparable increases in the $PaCO_2$ levels [21].

Our study has some limitations. First, the intervention was performed at an SpO_2 of 94% that could have unevenly affected the lowest SpO_2 between the groups. However, it is part of the standard anesthesia procedures conducted at our institution to ensure patient safety. Second, the small sample size may have led to underestimation of the effects of HFNO on CO_2 accumulation. Nevertheless, our research findings can assist in calculating the sample sizes for future related studies. Third, in conventional research methodology, an ASD > 0.1 is generally considered indicative of imbalance. However, following Austin's suggestion [8], we set the ASD threshold above 0.54 to evaluate discrepancies in baseline characteristics between the two groups that may be questioned for exceeding the conventional 0.1. Nonetheless, the items in Table 1 with an ASD of 0.1 or above, including those exceeding 0.54, are unlikely to influence the study's outcomes substantially.

In conclusion, in settings equipped with safety measures during mild hypoxia, HFNO was not associated with better minimum oxygen saturation levels than conventional low-flow nasal oxygenation. However, it significantly reduces hypoxemia-related surgical interruptions and thus has considerable clinical efficacy. Moreover, it attenuates the decline in PaO_2 and thus has potentially greater utility for prolonged periods of apnea. Nevertheless, caution is advised regarding CO_2 levels. Our research expands the operational scenarios for HFNO. The accumulation of $PaCO_2$ in settings of prolonged apnea needs to be clarified in future studies.

Funding

None.

Conflicts of Interest

No potential conflict of interest relevant to this article was reported.

Data Availability

The datasets generated during the current study are available from the corresponding author on reasonable request.

Author Contributions

Hye Jin Kim (Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Visualization; Writing – original draft; Writing – review & editing)
Chang Young Lee (Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Validation; Writing – review & editing)
Kyuho Lee (Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Writing – review & editing)
Namo Kim (Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Writing – review & editing)
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References

1. Wong DT, Dallaire A, Singh KP, Madhusudan P, Jackson T, Singh M, et al. High-flow nasal oxygen improves safe apnea time in morbidly obese patients undergoing general anesthesia: a randomized controlled trial. Anesth Analg 2019; 129: 1130-6.
2. Drake MG. High-flow nasal cannula oxygen in adults: an evidence-based assessment. Ann Am Thorac Soc 2018; 15: 145-55.
3. Renda T, Corrado A, Iskandar G, Pelaia G, Abdalla K, Navalesi P. High-flow nasal oxygen therapy in intensive care and anaesthesia. Br J Anaesth 2018; 120: 18-27.
4. Karim HM, Esquinas AM, O'Brien B. Flow effects of high-flow nasal oxygenation: comment. Anesthesiology 2023; 138: 566-7.
5. Pathak V, Welsby I, Mahmood K, Wahidi M, MacIntyre N, Shofer S. Ventilation and anesthetic approaches for rigid bronchoscopy. Ann Am Thorac Soc 2014; 11: 628-34.
6. Galway U, Zura A, Wang M, Deeby M, Riter Q, Li T, et al. Anesthetic considerations for rigid bronchoscopy: a narrative educational review. Trends Anaesth Crit Care 2022; 43: 38-45.
7. Douglas N, Ng I, Nazeem F, Lee K, Mezzavia P, Krieser R, et al. A randomised controlled trial comparing high-flow nasal oxygen with standard management for conscious sedation during bronchoscopy. Anaesthesia 2018; 73: 169-76.
8. Austin PC. Balance diagnostics for comparing the distribution of baseline covariates between treatment groups in propensity-score matched samples. Stat Med 2009; 28: 3083-107.
9. Ma J, Xiong W, Guo D, Wang A, Qiao H, Han R. Effects of sevoflurane-propofol-balanced anesthesia on flash visual evoked potential monitoring in spine surgery: a randomized noninferiority trial. Anesth Analg 2022; 134: 1054-61.
10. Milési C, Boubal M, Jacquot A, Baleine J, Durand S, Odena MP, et al. High-flow nasal cannula: recommendations for daily practice in pediatrics. Ann Intensive Care 2014; 4: 29.
11. Riva T, Meyer J, Theiler L, Obrist D, Bütikofer L, Greif R, et al. Measurement of airway pressure during high-flow nasal therapy in apnoeic oxygenation: a randomised controlled crossover trial. Anaesthesia 2021; 76: 27-35.
12. Millette BH, Athanassoglou V, Patel A. High flow nasal oxygen therapy in adult anaesthesia. Trends Anaesth Crit Care 2018; 18: 29-33.
13. Sago T, Harano N, Chogyoji Y, Nunomaki M, Shiiba S, Watanabe S. A nasal high-flow system prevents hypoxia in dental patients under intravenous sedation. J Oral Maxillofac Surg 2015; 73: 1058-64.
14. Gustafsson IM, Lodenius A, Tunelli J, Ullman J, Jonsson Fagerlund M. Apnoeic oxygenation in adults under general anaesthesia using Transnasal Humidified Rapid-Insufflation Ventilatory Exchange (THRIVE) - a physiological study. Br J Anaesth 2017; 118: 610-7.
15. Lyons C, Callaghan M. Apnoeic oxygenation with high-flow nasal oxygen for laryngeal surgery: a case series. Anaesthesia 2017; 72: 1379-87.
16. Humphreys S, Lee-Archer P, Reyne G, Long D, Williams T, Schibler A. Transnasal humidified rapid-insufflation ventilatory exchange (THRIVE) in children: a randomized controlled trial. Br J Anaesth 2017; 118: 232-8.
17. Schutzer-Weissmann J, Wojcikiewicz T, Karmali A, Lukosiute A, Sun R, Kanji R, et al. Apnoeic oxygenation in morbid obesity: a randomised controlled trial comparing facemask and high-flow nasal oxygen delivery. Br J Anaesth 2023; 130: 103-10.
18. Patel A, Nouraei SA. Transnasal humidified rapid-insufflation

https://doi.org/10.4097/kja.24517

ventilatory exchange (THRIVE): a physiological method of increasing apnoea time in patients with difficult airways. Anaesthesia 2015; 70: 323-9.
19. Booth AW, Vidhani K, Lee PK, Coman SH, Pelecanos AM, Dimeski G, et al. The effect of high-flow nasal oxygen on carbon dioxide accumulation in apneic or spontaneously breathing adults during airway surgery: a randomized-controlled trial. Anesth Analg 2021; 133: 133-41.
20. Riva T, Pedersen TH, Seiler S, Kasper N, Theiler L, Greif R, et al. Transnasal humidified rapid insufflation ventilatory exchange for oxygenation of children during apnoea: a prospective randomised controlled trial. Br J Anaesth 2018; 120: 592-9.
21. Riva T, Greif R, Kaiser H, Riedel T, Huber M, Theiler L, et al. Carbon dioxide changes during high-flow nasal oxygenation in apneic patients: a single-center randomized controlled noninferiority trial. Anesthesiology 2022; 136: 82-92.