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Article

Effect of High-Flow Nasal Cannula vs. Facemask on Arterial Oxygenation During Liver Radiofrequency Ablation: A Randomized Controlled Trial

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Abstract: *Background and Objectives:* Percutaneous liver radiofrequency ablation (RFA) under monitored anesthesia care (MAC) carries a risk of hypoxia due to respiratory depression. Ensuring adequate oxygenation during such procedures is essential for patient safety. This study aimed to evaluate whether high-flow nasal cannula (HFNC) improves oxygenation compared to a simple facemask during RFA. *Materials and Methods:* In this prospective, randomized controlled trial, 51 patients undergoing ultrasound-guided RFA under MAC were allocated to receive oxygen via HFNC (30 L/min) or a facemask (6 L/min). Arterial blood gases were collected at baseline and 5 minutes after oxygenation. Primary outcome was arterial partial pressure of oxygen (PaO₂). Secondary outcomes included hypoxia incidence (SpO₂ <95%), difference in the ratio of arterial partial pressure of oxygen to the fraction of inspired oxygen concentration ($\Delta P/F$ ratio), difference in arterial partial pressure of carbon dioxide ($\Delta PaCO_2$), respiratory rate (RR) changes, and patient satisfaction. *Results:* After adjustment for baseline PaO₂, the HFNC group showed significantly higher intra-procedural PaO₂ compared to the facemask group (299 ± 18.6 vs. 194 ± 19.0 mmHg, p < 0.001). No significant differences were found in $\Delta P/F$ ratio, $\Delta PaCO_2$, or patient satisfaction. Among secondary outcomes, RR was more stable in the HFNC group throughout the procedure (Group × Time interaction, p = 0.003). *Conclusions:* HFNC significantly improved intra-procedural PaO₂ during RFA under MAC but did not reduce hypoxia incidence or improve other clinical outcomes compared to facemask oxygenation. The stability of RR observed with HFNC may reflect a physiological advantage, though further studies are needed to determine its clinical relevance.

Keywords: high-flow nasal cannula; facemask oxygenation; monitored anesthesia care; radiofrequency ablation; hepatic neoplasm; oxygenation; procedural sedation

1. Introduction

Percutaneous liver radiofrequency ablation (RFA) is a minimally invasive and effective treatment for hepatocellular carcinoma and metastatic liver tumors [1]. By inducing thermal coagulative necrosis, ultrasound-guided RFA minimizes tissue trauma, avoids radiation exposure, and enables faster recovery compared to surgical resection [2,3]. However, this procedure can cause significant pain and discomfort, often necessitating deep sedation to achieve adequate analgesia [4]. Deep sedation is commonly administered via monitored anesthesia care (MAC), which combines local anesthesia, sedatives, and analgesics, particularly in non-operating room settings [5]. A well-recognized complication of MAC is oversedation-induced respiratory depression, which may result

in hypoventilation, upper airway collapse, and subsequent hypoxia [6,7]. Therefore, adequate oxygenation is essential to ensure patient safety and procedural success.

Conventional oxygen delivery methods, such as nasal cannulae and simple facemasks, are limited in their ability to provide consistent oxygenation during deep sedation. In contrast, high-flow nasal cannula (HFNC) delivers heated and humidified oxygen at high flow rates, offering high inspired oxygen fractions (FiO_2) and producing a mild positive end-expiratory pressure (PEEP)-like effect [8]. HFNC has shown promise in minimizing hypoxic events during procedural sedation and general anesthesia in various settings [9–11]. However, its effectiveness during percutaneous liver RFA under MAC has not been well established.

This study aimed to evaluate whether HFNC improves arterial oxygenation, assessed by intra-procedural PaO_2 , compared to a conventional facemask during percutaneous liver RFA under MAC. Secondary outcomes included the incidence of hypoxia, changes in P/F ratio and PaCO_2 , respiratory rate, and patient satisfaction.

2. Materials and Methods

2.1. Patients

This prospective, randomized, controlled study was approved by the Institutional Review Board of Asan Medical Center (approval number: 2021-0714, 13/05/2021) and registered at the Clinical Research Information Service (registration number: KCT0006221, 17/05/2021). Written informed consent was obtained from all patients prior to enrollment. The study was conducted in accordance with the principles of the Declaration of Helsinki.

Patients aged 20 to 80 years with an American Society of Anesthesiologists (ASA) physical status of I or II and scheduled for ultrasound-guided percutaneous RFA under MAC between July and November 2021 were enrolled. Exclusion criteria included severe chronic pulmonary, cardiovascular, or cerebrovascular disease; a negative modified Allen test; and contraindications to remifentanyl or propofol.

Eligible participants were randomized in a 1:1 ratio to either the HFNC or facemask group using a computer-generated block randomization (block size = 2) and sealed opaque envelopes. On the day of the procedure, an investigator (A) who was blinded to outcomes assigned the intervention. A separate investigator (B), also blinded, conducted all post-procedural assessments.

2.2. Anesthetic Management

All patients underwent continuous monitoring, including non-invasive blood pressure, electrocardiography, peripheral oxygen saturation (SpO_2), and bispectral index (BIS). Following confirmation of collateral circulation with a modified Allen's test, a 20-G radial arterial catheter was inserted for arterial blood sampling.

Baseline arterial blood gas analysis (ABGA, T0) was performed before oxygen delivery. In the facemask group, 100% oxygen was delivered at 6 L/min via a simple facemask, which approximates an FiO_2 of 0.5. In the HFNC group, 100% heated and humidified oxygen was delivered at 30 L/min using an OptiFlow system (Fisher & Paykel®, New Zealand).

Sedation was maintained with a target-controlled infusion of propofol (Marsh model, effect-site concentration 0.8–1.5 $\mu\text{g}/\text{mL}$) and remifentanyl (starting at 0.5 ng/mL , titrated as needed). Sedation depth was targeted to a BIS of 60–80 and a Modified Observer's Assessment of Alertness/Sedation (MOAA/S) score ≤ 3 [12]. ABGA was repeated 5 minutes after oxygen delivery (T1). Monitored hemodynamic parameters were recorded at T0 (pre-procedure), T1 (5 minutes after starting RFA), and T2 (end of procedure). When SpO_2 dropped below 95%, a triple airway maneuver (head tilt, jaw thrust, mouth opening) was applied, as oxygen reserve rapidly depletes below 94%, risking a swift drop to $<90\%$ [13]. If SpO_2 further decreased below 90% despite intervention, an airway device was inserted and manual ventilation initiated. All patients were transferred to the post-anesthesia care unit (PACU) for monitoring after the procedure.

2.3. Ablation Procedure

After planning sonography, percutaneous RFA or microwave ablation (MWA) was performed. Artificial ascites (500–1000 mL of 5% dextrose) were used when needed. The choice of ablation modality and electrode type (Cool-tip™, Jet-tip®, or Proteus®) was determined by the interventional radiologist. RFA was conducted using a 200-W generator (Mygen M-2004, RF Medical) with impedance control for 8 to 18 minutes. For microwave ablation (MWA), a single 13-G antenna was used with a 150-W generator (Emprint™ HP, Covidien) for 6 to 10 minutes. Additional time was provided for patients with multiple hepatic masses.

2.4. Outcome Measurements

The primary outcome was the intra-procedural arterial partial pressure of oxygen (PaO₂) measured at T1. Secondary outcomes included incidence of hypoxia, difference in the ratio of arterial partial pressure of oxygen to the fraction of inspired oxygen concentration between T0 and T1 ($\Delta P/F$ ratio), difference in arterial partial pressure of carbon dioxide between T0 and T1 ($\Delta PaCO_2$), changes in respiratory rate (RR), and patient satisfaction.

Hypoxia was defined as SpO₂ <95% for procedural safety, and severe hypoxia was defined as SpO₂ <90% despite airway maneuvers, requiring mask ventilation. The 95% threshold was selected based on our institutional protocol to enable early recognition of airway compromise during deep sedation. Unlike procedures performed in the lateral or semi-lateral position, percutaneous liver RFA is conducted in the supine position, which significantly increases the risk of glossoptosis. Furthermore, concurrent opioid administration due to severe procedural pain elevates the risk of respiratory depression. Therefore, a conservative SpO₂ threshold was adopted to identify subtle ventilatory impairment at an early stage and enhance patient safety.

For the calculation of the P/F ratio, FiO₂ was assumed to be 1.0 in the HFNC group and 0.5 in the facemask group, based on estimated oxygen delivery via a simple facemask at 6 L/min. Patient satisfaction was assessed using a modified Iowa Satisfaction with Anesthesia Scale (ISAS) [14]. The ISAS is composed of 11 items rated on a 6-point scale ranging from –3 to +3, with total scores ranging from –33 to +33. Higher scores indicate greater overall satisfaction. The scale has been validated in monitored anesthesia care and has been applied in procedural sedation settings [15].

2.5. Sample Size Calculation

The sample size was calculated using G*Power 3.1 ($\alpha = 0.05$, power = 0.8), based on a previous study by Heinrich et al., which reported PaO₂ values as median (IQR): 406 (362–446) mmHg for HFNC and 335 (292–389) mmHg for facemask [16]. These were converted to mean \pm SD using Meta-Converter (<https://meta-converter.com/conversions/mean-sd-iqr>), yielding 405 \pm 71.3 mmHg and 339 \pm 82.3 mmHg, respectively. Based on this, a sample size of 23 per group was required; allowing for a 10% dropout, 26 participants per group (total n = 52) were enrolled.

2.6. Statistical Analysis

Continuous variables are presented as mean \pm standard deviation or median with interquartile range, and categorical variables as frequencies and percentages. Between-group comparisons were performed using Student's t-test or Mann–Whitney U test for continuous data, and chi-square test or Fisher's exact test for categorical data, as appropriate.

To compare intra-procedural PaO₂ between groups, analysis of covariance (ANCOVA) was performed with baseline PaO₂ as a covariate. Similarly, the $\Delta P/F$ ratio was adjusted for pre-procedural values using ANCOVA. Linear regression analysis was used to evaluate changes in PaCO₂, adjusting for potential confounders including age, body mass index (BMI), chronic obstructive pulmonary disease (COPD), asthma, and smoking status. Given the multiple secondary outcomes—including hypoxia incidence, $\Delta P/F$ ratio, $\Delta PaCO_2$, respiratory rate, and patient satisfaction—Bonferroni correction was applied to control for type I error. For repeated measures of

respiratory rate, a generalized linear mixed model (GLMM) with random intercepts was fitted. The model included group, time, and group \times time interaction as fixed effects, and subject as a random effect. An unstructured covariance matrix was used without assuming homogeneity across groups. Model assumptions, including normality of residuals and homogeneity of variance, were assessed for all parametric tests. When assumptions were not fully met, a ranked ANCOVA was performed as a non-parametric alternative to confirm the robustness of the results. As the findings were consistent, the original parametric results were retained for reporting. All statistical analyses were performed using SPSS Statistics version 29.0.2.0 (IBM Corp., Armonk, NY, USA), and a two-sided p -value < 0.05 was considered statistically significant.

3. Results

A total of 136 patients scheduled for RFA under MAC between July and November 2021 were screened. Of these, 40 did not meet the inclusion criteria, 39 declined to participate, and 5 were excluded due to changes in the therapeutic plan. Finally, 52 patients were randomized; however, one patient in the facemask group was excluded because of clotted blood samples. Therefore, 51 patients (25 in the facemask group and 26 in the HFNC group) were included in the final analysis (Figure 1). Baseline characteristics were comparable between groups (Table 1), despite significantly different pre-procedure PaO_2 levels ($p = 0.037$). Using ANCOVA with pre-procedure PaO_2 as a covariate, the adjusted mean PaO_2 during the procedure was significantly higher in the HFNC group (298.8 ± 18.6 mmHg; 95% confidence interval [CI]: 261.4–336.2) compared to the facemask group (194.2 ± 19.0 mmHg; 95% CI: 156.0–232.3, $p < 0.001$) (Figure 2A). Similarly, the adjusted mean ΔPaO_2 ($T_1 - T_0$) was significantly greater in the HFNC group (203.4 ± 18.6 vs. 98.8 ± 19.0 ; difference = 104.6, $p < 0.001$) (Figure 2B).

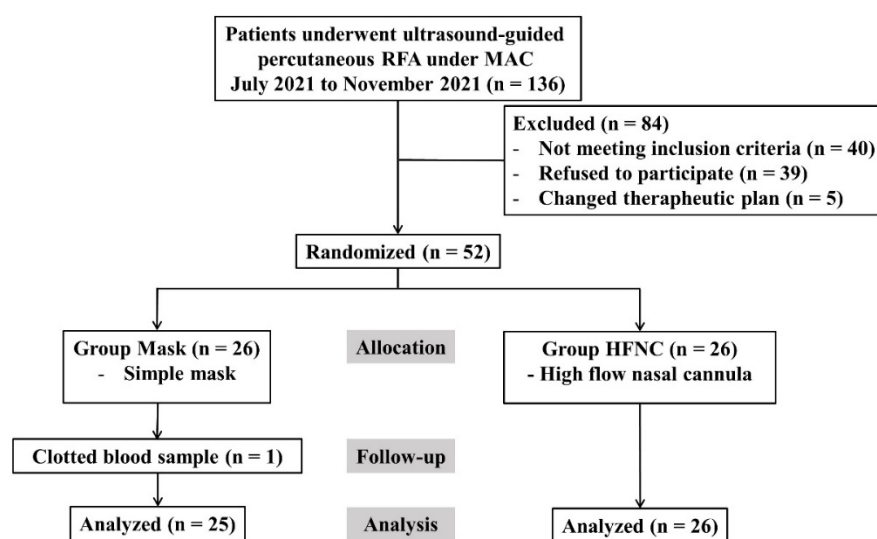


Figure 1. Flow chart of study inclusion according to the CONSORT statement. RFA, radiofrequency ablation; MAC, monitored anesthesia care; HFNC, high-flow nasal cannula.

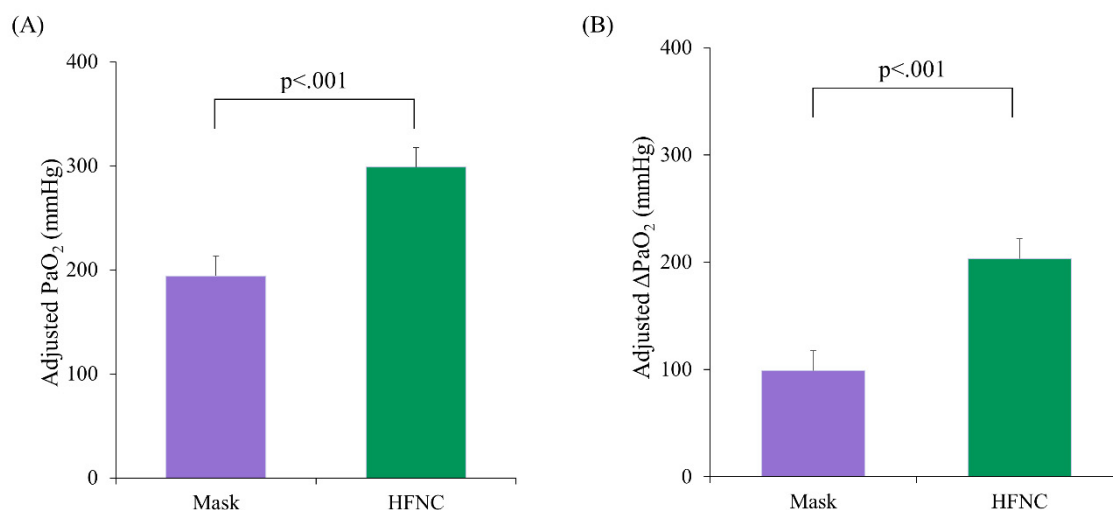


Figure 2. Comparison of arterial oxygen partial pressure (PaO₂) between the facemask (Mask) and HFNC groups during liver radiofrequency ablation. (a) Intra-procedure adjusted mean PaO₂ between the Mask and HFNC groups during the procedure, analyzed using analysis of covariance (ANCOVA) with baseline PaO₂ as a covariate. (b) Changes in PaO₂ (ΔPaO₂) from baseline to intra-procedure between the two groups. Adjusted ΔPaO₂ values were also analyzed using ANCOVA. Error bars represent the standard error of the mean (SE). HFNC, high-flow nasal cannula.

Table 1. Baseline characteristics and clinical variables.

	Mask (n = 25)	HFNC (n = 26)	p-value
Age (y)	61.1 ± 8.5	63.2 ± 7.9	0.360
Sex (male/female)	21 (84.0)/4 (16.0)	23 (88.5)/3 (11.5)	0.703
BMI (kg/m ²)	24.6 ± 3.6	24.9 ± 3.1	0.762
Diabetes	7 (28.0)	10 (38.5)	0.428
Hypertension	9 (36.0)	9 (34.6)	0.918
COPD	4 (16.0)	2 (7.7)	0.419
ASA classification			0.110
I	3 (12.0)	0(0.0)	
II	22 (88.0)	26 (100.0)	
Tumor type			1.000
HCC	24 (96.0)	23 (88.5)	
Metastatic	1 (4.0)	2 (7.7)	
Cryptogenic LC	0 (0.0)	1 (3.8)	
Tumor size (cm)	1.6 ± 0.5	1.5 ± 0.4	0.310
Pre-procedure ABGA			
pH (mmHg)	7.4 (7.4, 7.4)	7.4 (7.4, 7.4)	0.572
PaCO ₂ (mmHg)	38.3 (35.6, 40.4)	37.5 (31.8, 39.0)	0.158
PaO ₂ (mmHg)	85.8 (77.9, 98.8)	95.4 (86.2, 107.0)	0.037
HCO ₃ ⁻ (mmol/l)	24.3 ± 2.6	23.2 ± 3.0	0.173
P/F ratio	171.6 (155.7, 197.6)	95.4 (86.2 107.0)	<0.001
Total ablation time (min)	8.0 (6.0, 10.0)	6.5 (5.0, 12.0)	0.374
Sedation time (min)	34.0 (29.5, 47.5)	28.0 (26.0, 40.5)	0.262
Total dose of propofol (mg)	77.0 (67.0, 103.0)	75.0 (57.1, 99.0)	0.445
Total dose of remifentanil (ng)	88.7 (70.6, 108.0)	76.1 (63.5, 96.3)	0.366
Type of procedure			0.301
Conventional	17 (68.0)	14 (53.8)	

Microwave	8 (32.0)	12 (46.2)	
Use of artificial ascites	7 (28.0)	7 (26.9)	0.931

Data are expressed as the means \pm standard deviations, median (interquartile range), or number of patients (percentage), as appropriate. HFNC, high flow nasal cannula; BMI, Body mass index; COPD, chronic obstructive pulmonary disease; ASA, American Society of Anesthesiologists; HCC, hepatocellular carcinoma; LC, liver cirrhosis; AGBA, arterial blood gas analysis; PaCO₂, partial pressure of arterial carbon dioxide; PaO₂, partial pressure of arterial oxygen; P/F ratio, the ratio of the partial pressure of arterial oxygen to the fraction of inspired oxygen concentration.

Hypoxia occurred in 14 patients (27.5%), including 8 (32.0%) in the facemask group and 6 (23.0%) in the HFNC group ($p = 0.475$) (Figure 3). Severe hypoxia occurred more frequently in the facemask group (24.0% vs. 11.5%), corresponding to a risk ratio of 0.48 (95% CI: 0.13–1.72). However, the difference was not statistically significant ($p = 0.291$). Other ABGA parameters, including Δ P/F ratio and Δ PaCO₂, did not differ significantly between groups (Table 2). Patient satisfaction, as assessed by the ISAS, was also similar between groups (Table 2).

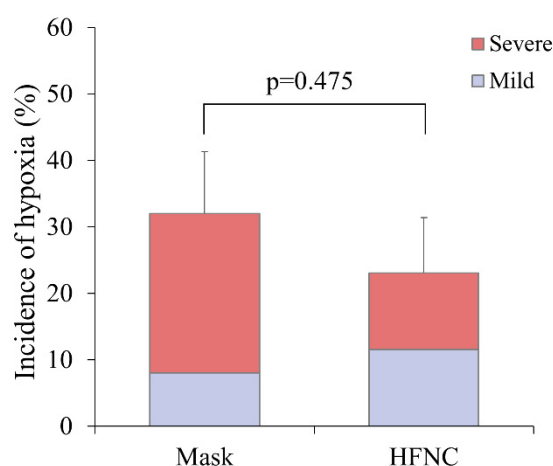


Figure 3. Comparison of the incidence of hypoxia between the facemask (Mask) and HFNC groups during liver radiofrequency ablation. Hypoxia was categorized into mild (SpO₂<95%) and severe (SpO₂<90% despite triple airway maneuver). The stacked bar graph illustrates the proportion of mild and severe hypoxia in each group. While the incidence of severe hypoxia was higher in the Mask group, the overall incidence of hypoxia did not differ significantly between the two groups ($p=0.475$).

Table 2. Comparison of adjusted outcomes and patient satisfaction between the Mask and HFNC groups.

	Mask (n = 25)	HFNC (n = 26)	Crude p-value	Bonferroni- corrected p-value
Incidence of hypoxia (95% CI)	32.0 \pm 9.3 (13.7-50.3)	23.1 \pm 8.3 (6.9-39.3)	0.475	1.000
Intra-procedure ABGA				
Δ P/F ratio (95% CI)*	246.1 \pm 30.8 (184.2–308.0)	158.6 \pm 30.0 (98.3–218.9)	0.084	0.336
Δ PaCO ₂ (mmHg) (95% CI)†	13.6 \pm 4.59 (4.30–22.8)	14.2 \pm 5.00 (4.13–24.3)	0.789	1.000
Satisfaction				
Patient Satisfaction (95% CI)	25.0 \pm 2.1 (20.7-29.4)	21.1 \pm 2.4 (16.1-26.1)	0.270	1.000

All intra-procedure ABGA measurements were adjusted for baseline differences using analysis of covariance (ANCOVA). Adjusted values are expressed as mean \pm standard error (95% confidence interval). *Adjusted for pre-procedure P/F ratio. †Adjusted for body mass index, age, COPD, asthma, and smoking status. Patient satisfaction is presented as median (interquartile range). HFNC, high flow nasal cannula; ABGA, arterial blood gas analysis; Δ P/F ratio, the difference between ratio of the partial pressure of arterial oxygen to the fraction of inspired oxygen concentration measured at T1 and T0; Δ PaCO₂, the difference between partial pressure of arterial carbon dioxide measured at T1 and T0. COPD, chronic obstructive pulmonary disease. T0: pre-procedure, T1: intra-procedure; CI, confidence interval.

At T0, the mean RR was 13.7 ± 2.4 and 14.7 ± 2.5 breaths/min in the HFNC and facemask groups, respectively ($p = 0.131$). At T1 and T2, the mean RR was significantly higher in the HFNC group (T1: 12.2 ± 3.0 vs. 9.8 ± 4.7 breaths/min, $p = 0.036$; T2: 14.2 ± 4.5 vs. 11.0 ± 4.9 breaths/min, $p = 0.031$). A generalized linear mixed model (GLMM) revealed a significant Group \times Time interaction ($p = 0.003$) and a main effect of Time ($p = 0.024$). Within-group analysis demonstrated significant RR reductions in the facemask group from T0 to T1 ($p < 0.001$) and from T0 to T2 ($p = 0.002$), whereas RR in the HFNC group remained stable (Figure 4).

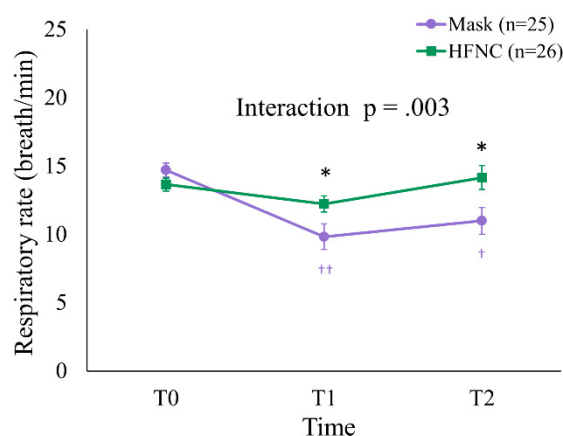


Figure 4. Changes in respiratory rate (RR) over time in the facemask (Mask) and HFNC groups during liver radiofrequency ablation. Data are presented as mean \pm standard error. A significant group-by-time interaction was observed ($p=0.003$, generalized linear mixed model (GLMM)). Between-group differences were significant at T1 and T2 ($*p=0.036$ and $*p=0.031$, respectively). Within-group analysis showed that RR in the Mask group decreased at T1 ($††p<0.001$) and T2 ($†p=0.002$) compared to T0, with no significant changes in the HFNC group. Symbols: * $p < 0.05$, ** $p < 0.001$ (between groups); † $p < 0.05$, †† $p < 0.001$ (within group). HFNC, high flow nasal cannula; T0, pre-procedure; T1, intra-procedure; T2, post-procedure.

Table 3. Time-course changes of Respiratory rate (breath/min). (Value: Mean \pm SD).

Variable	Group			p	Analysis for repeated measures	
	Overall (n=51)	Mask (n = 25)	HFNC (n = 26)		Source	p*
Respiratory rate (breath/min)						
T0	14.2 \pm 2.5	14.7 \pm 2.5a	13.7 \pm 2.4a	.131 ²	Group	.090
T1	11.1 \pm 4.1	9.8 \pm 4.7b	12.2 \pm 3.0a	.036 ²	Time	.024

T2	12.6±4.9	11.0±4.9b	14.2±4.5a	.031 ³	Group x Time	.003
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¹ Values are the mean±SD and Bonferroni's post-hoc test was used for multiple comparisons between each the four time points. Means with different scripts are different from each other (P<0.05). ² P values were derived from independent t-test. ³ P values were derived from Mann-Whitney's U test. * P values were derived from Generalized Linear Mixed Model. Shapiro-Wilk's test was employed for test of normality assumption.

4. Discussion

This randomized controlled trial demonstrated that HFNC significantly improved intra-procedural arterial oxygenation compared to a simple facemask during percutaneous liver RFA under MAC. The marked difference in ΔPaO_2 highlights the dynamic effect of HFNC in enhancing alveolar oxygenation beyond baseline levels. However, despite this physiological improvement, the incidence of hypoxia ($\text{SpO}_2 < 95\%$) did not differ significantly between groups, raising questions about the clinical translation of improved oxygenation.

The lack of difference in hypoxia incidence likely reflects the multifactorial nature of oxygen desaturation during deep sedation. Notably, our institutional protocol mandated predefined interventions when SpO_2 dropped below 95%, which included a triple airway maneuver to rapidly restore oxygen saturation. These early responses may have mitigated desaturation severity and reduced between-group differences. In fact, most desaturation events resolved promptly without escalation to invasive support; only two patients required manual ventilation, and none required intubation. Taken together, these observations imply that upper airway obstruction, rather than inadequate oxygen delivery, may be a dominant cause of hypoxia during MAC. Glossoptosis induced by sedation, especially in the supine position with opioid co-administration, can precipitate airway collapse and compromise ventilation despite high FiO_2 delivery [18,19]. This is consistent with previous observations that HFNC improves oxygenation but may not prevent desaturation when upper airway patency is lost [6,7].

Although HFNC theoretically offers continuous positive airway pressure (PEEP)-like effects through high flow rates, the flow setting of 30 L/min in our study was likely insufficient to generate clinically meaningful airway pressure. Prior studies indicate that flow rates ≥ 40 –60 L/min are required to produce measurable PEEP and facilitate alveolar recruitment [20,21]. However, higher flows were not feasible during RFA due to patient discomfort and interference with procedural accuracy. Therefore, while this moderate flow setting reflects real-world procedural constraints, it may have limited the physiological potential of HFNC. Still, the significant PaO_2 improvement observed in the HFNC group suggests enhanced oxygenation even without optimal PEEP. Another consideration is the role of gas reabsorption atelectasis associated with high FiO_2 delivery. Deep sedation and supine positioning predispose patients to alveolar collapse, and the administration of 100% oxygen via HFNC may exacerbate this through nitrogen washout and resorption. This phenomenon may counteract the benefits of increased FiO_2 and help explain the unchanged incidence of hypoxia [22].

Although the observed difference in severe hypoxia (11.5% in the HFNC group vs. 24.0% in the facemask group) corresponds to a risk ratio of 0.48, the wide 95% CI (0.13–1.72) reflects substantial uncertainty. While not statistically significant, the trend toward reduced severe hypoxia in the HFNC group may be clinically relevant and warrants further evaluation in larger, adequately powered studies.

Moreover, the FiO_2 delivered via HFNC is theoretically fixed but may be diluted by ambient air due to mouth breathing or irregular respiratory patterns, particularly under sedation. Studies have shown that FiO_2 dilution increases with open-mouth breathing and high inspiratory flow demands, potentially limiting effective oxygen delivery [20,23]. In our study, although we assumed FiO_2 values of 1.0 (HFNC) and 0.5 (facemask) for P/F ratio calculations, these estimates are subject to variability and should be interpreted cautiously.

Interestingly, RR remained more stable in the HFNC group throughout the procedure. This contrasts with the facemask group, which exhibited a reduction in RR that persisted post-procedurally. A stable RR is clinically meaningful, as irregular or suppressed respiratory patterns may lead to hypoventilation and hypoxemia. While sedation level and opioid dosing were equivalent across groups, the observed difference may reflect the physiological benefits of HFNC, such as reduced inspiratory workload and improved comfort [24–26].

Despite this, we observed no significant difference in arterial PaCO₂ levels between groups. This aligns with previous reports in settings such as bronchoscopy, thoracic surgery, and COPD care, where HFNC had minimal impact on PaCO₂ due to its limited effect on minute ventilation [11,13,23,27–30]. While HFNC can flush out nasopharyngeal dead space and aid CO₂ elimination, deep sedation-induced hypoventilation likely blunts its effectiveness in this context [26,31]. Patient satisfaction, assessed using the validated ISAS, was similarly high in both groups, suggesting that the method of oxygen delivery did not negatively affect patient experience under deep sedation. The lack of difference in satisfaction may be explained by several factors. Although previous studies have demonstrated improved comfort with HFNC compared to noninvasive ventilation or other oxygen delivery methods [31,32], the large-bore nasal cannula may have caused mild discomfort in our patients. Moreover, the relatively short procedural duration and the use of deep sedation likely reduced patients' awareness of external stimuli, making it difficult for them to perceive differences between oxygen delivery methods. These factors, in combination, may have contributed to the absence of a measurable difference in satisfaction between groups.

This study has several limitations. First, the small sample size was powered only for the primary outcome (PaO₂) and not for secondary outcomes such as hypoxia, $\Delta P/F$ ratio, $\Delta PaCO_2$ or satisfaction. Post-hoc power analysis indicated that the statistical power for these variables was insufficient (e.g., 11.1% for hypoxia, 5.1% for $\Delta PaCO_2$), introducing the possibility of type II error and limiting definitive conclusions. Second, ABGA was collected at a fixed intra-procedural time point rather than during actual desaturation events. This limits its utility in assessing real-time respiratory compromise and weakens correlation with SpO₂-based hypoxia. Future studies should consider transcutaneous gas monitoring or real-time ABG sampling during desaturation episodes to better capture dynamic gas exchange. Lastly, although we assumed an FiO₂ of 0.5 for the facemask and 1.0 for the HFNC group based on conventional estimates, interindividual variability in FiO₂ delivery remains a limitation. Our study aimed to evaluate whether HFNC, which generally provides higher and more consistent FiO₂, improves oxygenation compared to standard oxygen therapy commonly used during deep sedation. However, given the practical limitations of HFNC application during liver RFA, future studies comparing HFNC with other high-flow oxygen delivery methods, such as non-rebreather masks, may help identify more effective alternatives.

5. Conclusions

In conclusion, HFNC improved intra-procedural arterial oxygenation and stabilized respiratory rate in patients undergoing liver RFA under MAC, despite no observed differences in clinical endpoints such as hypoxia incidence or patient satisfaction. These findings support the physiological utility of HFNC in this setting and highlight the need for further studies examining optimized flow rates, individualized FiO₂ delivery, and patient subgroups at higher risk of desaturation.

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Abbreviations

The following abbreviations are used in this manuscript:

RFA	Radiofrequency ablation
MAC	Monitored anesthesia care
HFNC	High-flow nasal cannula
FiO ₂	Fraction of inspired oxygen
PEEP	Positive end-expiratory pressure
SpO ₂	Peripheral oxygen saturation
PaO ₂	Arterial oxygen partial pressure
PaCO ₂	Arterial partial pressure of carbon dioxide
RR	Respiratory rate
BIS	Bispectral index
ABGA	Arterial blood gas analysis
P/F	Ratio of arterial partial pressure of oxygen to the fraction of inspired oxygen
ISAS	Iowa Satisfaction with Anesthesia Scale
ANCOVA	Analysis of covariance
COPD	Chronic obstructive pulmonary disease
CI	Confidence interval

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