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CLINICAL INVESTIGATION

The Impact of High-Flow Nasal Cannula Therapy on Diaphragmatic Function Assessed by Ultrasound: A Pilot Clinical Study

Miriam Gotti, MD[1]
Michele Umbrello, MD[2]
Giovanni Sabbatini, MD[1]
Elena Alessandra Mantovani, MD[1]
Lorenzo Foggetti, MD[1]
Alessandro Menozzi, MD[3]
Andrea Galimberti, MD[1]
Angelo Pezzi, MD[1]
Paolo Formenti, MD[1]

OBJECTIVES: High-flow nasal cannula is increasingly used in patients with acute hypoxemic respiratory failure. However, its impact on diaphragmatic function remains poorly understood.

DESIGN: Observational crossover pilot study.

SETTING: Single-center ICU.

PATIENTS: Twenty-eight adult ICU patients with a $\text{Pao}_2/\text{Fio}_2$ ratio less than or equal to 300 mm Hg were enrolled.

INTERVENTIONS: Patients underwent sequential 60-minute phases of noninvasive respiratory support using a Venturi mask, high-flow nasal cannula (40 L/min), and helmet continuous positive airway pressure (CPAP).

MEASUREMENTS AND MAIN RESULTS: Diaphragmatic function was assessed using ultrasound, while inspiratory effort was evaluated through esophageal pressure swings. Arterial blood gases were also collected. High-flow nasal cannula significantly improved the diaphragmatic thickening fraction compared with the Venturi mask (27% ± 9.9% vs. 20% ± 6%; $p = 0.0013$). Conversely, diaphragmatic excursion was lower with high-flow nasal cannula than with both the Venturi mask and CPAP (1.1 ± 0.63 cm vs. 1.5 ± 0.95 cm and 1.4 ± 0.59 cm, respectively; $p = 0.0002$). High-flow nasal cannula also reduced inspiratory effort compared with the Venturi mask. In patients with diaphragmatic dysfunction index greater than 100, both high-flow nasal cannula and CPAP enhanced diaphragmatic thickening and decreased esophageal pressure swings relative to the Venturi mask.

CONCLUSIONS: This study shows that high-flow nasal cannula improves diaphragmatic function compared with Venturi mask oxygen therapy. Larger studies are needed to confirm these findings.

KEYWORDS: diaphragmatic ultrasound; high-flow nasal cannula; transpulmonary pressure

In the last decades, innovative devices delivering conditioned gas through a nasal cannula at high-flow rates emerged as safe and valuable supportive therapy for various clinical scenarios (1). Their use has become increasingly widespread during the COVID-19 pandemic (2). Several clinical trials highlighted the benefits of high-flow nasal cannula, mediated by various physiologic mechanisms (3–7). While these mechanisms are relatively well described in pediatric respiratory distress (8, 9), data in adults with acute hypoxemic respiratory failure (AHRF) remain limited, particularly concerning respiratory muscle function. Compared with conventional oxygen masks, high-flow nasal cannula improves oxygenation, reduces dyspnea, and decreases anatomical

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KEY POINTS

Question: Does high-flow nasal cannula improve diaphragmatic function and reduce inspiratory effort in patients with acute hypoxemic respiratory failure?

Findings: In this observational cross-sectional pilot study involving 28 ICU patients, high-flow nasal cannula significantly increased diaphragmatic thickening fraction and reduced inspiratory effort compared with Venturi mask. Diaphragmatic excursion was lower with high-flow nasal cannula than with Venturi mask and continuous positive airway pressure.

Meaning: High-flow nasal cannula may offer superior support for diaphragmatic function and respiratory unloading in patients with acute hypoxemic respiratory failure.

dead space (10, 11). It may also reduce inspiratory effort and increase lung volume, thereby helping to prevent muscle fatigue (6, 12). Assessing respiratory effort during noninvasive support is clinically relevant but challenging. Esophageal balloon catheters provide accurate monitoring of work of breathing (13–15) but are limited by invasiveness and technical complexity. Ultrasound represents a simpler bedside tool to evaluate diaphragmatic function by measuring thickness, thickening fraction, and excursion (16–19). Thickening fraction correlates with tidal volume (20), but its relationship with transdiaphragmatic pressure—the gold standard for diaphragmatic function—remains debated (21, 22). Few studies have investigated high-flow nasal cannula effects on diaphragmatic function with ultrasound, yielding inconclusive and noncomparable results (23–26). Although previous studies have described components of diaphragmatic function during noninvasive respiratory support, systematic ultrasound evaluation of diaphragmatic performance specifically during high-flow nasal cannula therapy in AHRF remains limited. The primary aim of this study was to compare the effects of high-flow nasal cannula therapy on diaphragmatic function described by ultrasound, with those of the Venturi mask and helmet-applied continuous positive airway pressure (CPAP) in patients with AHRF. The comparison was based on parameters obtained from diaphragmatic ultrasound analysis, esophageal catheter monitoring, and blood gas analysis.

METHODS

We conducted a single-center clinical study in a mixed medical-surgical ICU. The study was approved by the Institutional Review Board ("Effetti sulla funzionalità diaframmatica delle cannule nasali ad alto flusso valutate con metodica ecografica," Comitato Etico Lombardia 3 No. 3991—20/03/2024_N). Procedures followed the Helsinki Declaration (1975) and local regulations; informed consent was obtained. Adult patients with AHRF ($\text{Pao}_2/\text{Fio}_2 \le 300$ mm Hg), spontaneously breathing with oxygen supplementation, were eligible. Exclusion criteria were $\text{Pao}_2/\text{Fio}_2$ less than 150 mm Hg, hemodynamic instability (mean arterial pressure < 60 mm Hg after fluid challenge), inability to undergo esophageal monitoring or diaphragmatic ultrasound, body mass index greater than 40 kg/m^2, pregnancy, neuromuscular disease, spinal cord injury or surgery, abdominal wounds interfering with probe placement, tracheostomy, hyperactive delirium, or agitation.

Each patient underwent three phases lasting 60 minutes each which included: Venturi mask; high-flow nasal cannula delivered with medium or large nasal prongs (Optiflow+; Fisher and Paykel Healthcare, Auckland, New Zealand) to occlude approximately 50% of the nostril area. Heated and humidified oxygen was administered via a dedicated flow generator for high-flow nasal cannula (Servo U; Maquet Getinge ventilator, Goteborg, Sweden) set at a flow rate of 40 L/min; the helmet CPAP (StarMed Intersurgical, Mirandola, Italy) set with positive end-expiratory pressure (PEEP) 3 cm H_2O. The choice of PEEP for helmet CPAP was guided by the intent to approximate the positive airway pressure generated by high-flow nasal cannula at 40 L/min (27). This approach allowed us to isolate the effects of different noninvasive modalities while maintaining comparable baseline distending pressures. The interface used was a standard helmet with an internal volume of approximately 15–18 L, adjusted to patient morphology. An intentional leak was maintained through the open circuit configuration and high continuous flow, aimed at minimizing Co_2 rebreathing. Helmet CPAP was delivered using a continuous flow generated by the ICU ventilator (Servo U; Maquet Getinge), connected through a dedicated circuit to both inspiratory and expiratory ports, as previously described (21). This configuration ensured stable flow delivery and minimized CO_2 rebreathing. Antibacterial/antiviral filters were placed on both inspiratory and expiratory limbs. Antibacterial/antiviral filters were positioned on both inspiratory and expiratory limbs to reduce aerosol dispersion and ensure infection control. Pressure within the helmet was continuously monitored through the pressure line connected to the ventilator's transducer, located near the helmet port, allowing real-time verification of effective PEEP and compensation for any resistance induced by the expiratory filter. FIO_2 was set clinically during standard oxygen mask breathing to maintain saturation 90–95% and then kept constant throughout all phases. Measurements were obtained during the last 3–5 minutes of each intervention. Arterial blood gases, respiratory rate, hemodynamics, and diaphragmatic ultrasound were recorded. Baseline demographic and clinical data were collected for Sequential Organ Failure Assessment (SOFA) (28) and Simplified Acute Physiology Score (SAPS) II (29).

Ultrasound examinations were performed using a 10–15 MHz linear transducer in B mode (Alpinion, E-CUBE i7, Seoul, Republic of Korea) and a 7.5-MHz convex phased-array probe by a well-trained operator (P.F.). Diaphragm end-expiratory thickness was measured in the right hemi-diaphragm in the zone of apposition as described elsewhere (17). The percentage of thickening, defined as thickening fraction, was calculated as the difference between the thickness at end-inspiration and the thickness at end-expiration, divided by the thickness at end-expiration, and then multiplied by 100 (19). Diaphragmatic excursion were assessed by M-mode (30). Only the right side was used, due to higher reproducibility (31–33). The investigator conducted and recorded three sets of measurements, which were then averaged. The diaphragmatic rapid shallow breathing index (RSBI) was computed as respiratory rate divided excursion (breaths/min/cm). This index serves as an alternative to the well-known RSBI (34). Additionally, we proposed a novel parameter we named the "diaphragmatic dysfunction index," to classify patients based on the presence or absence of diaphragmatic dysfunction. The diaphragmatic dysfunction index was calculated as the respiratory rate (breaths/min) divided by thickening fraction (%), multiplied by diaphragmatic excursion (cm). The cutoff value for the diaphragmatic dysfunction index was determined using threshold values for each component: a respiratory rate of 4 breaths per minute (35, 36), a thickening fraction of 20%, and a diaphragmatic excursion of 1.2 cm (37), resulting in a cutoff value of 100 (breaths/min/cm/%). Patients with a diaphragmatic dysfunction index less than 100 were considered to have normal diaphragmatic function, while those with a diaphragmatic dysfunction index greater than 100 were classified as having diaphragmatic dysfunction. Ultrasound was performed at end-expiration, confirmed by esophageal pressure waveform and thoracoabdominal inspection, to standardize within patients despite individual variability.

An esophageal balloon catheter (Smart Cath; Viasys, Palm Springs, CA) was positioned and confirmed by cardiac oscillations, phasic respiratory variation, and correlation with tidal volume (14). The balloon was inflated following manufacturer instructions with 1.5 mL of air and periodically checked, in line with previously published methods (38, 39). In particular, to reduce the risk of pressure signal loss due to balloon leakage or underfilling, the balloon was systematically deflated and reinflated between each ventilatory condition. Esophageal pressure waveforms were measured by a pressure transducer (TruWavw/VAMP Plus, Edwards Lifesciences, Unterschleissheim, Germany) connected to multiparametric monitor (Philips, INTELLvue MX800; Koninklijke Philips N.V., Amsterdam, The Netherlands). Values were acquired in mm Hg and converted to cm H_2O. Esophageal pressure swing (ΔPes) was defined as the absolute difference between maximal and minimal inspiratory pressure during each breath.

Analyses were performed with RStudio (R Foundation for Statistical Computing, Vienna, Austria, 2023). Data normality was assessed with Shapiro-Wilk test; results are expressed as mean ± SD. Comparisons between supports (Venturi mask, high-flow nasal cannula, CPAP) were performed with repeated-measure one-way analysis of variance (ANOVA). When significant, post hoc Wilcoxon signed-rank tests with Bonferroni correction were applied. A p value of less than 0.05 was considered statistically significant. Sample size was based on diaphragmatic thickening fraction (23), assuming an increase from 19% (SD 6%) with Venturi mask to 28% (SD 9.9%) with high-flow nasal cannula (24). With α = 0.05, power 80%, pooled SD 8%, and difference 7%, 26 patients were required; to account for dropouts, 28 were enrolled.

RESULTS

We enrolled 28 of 46 screened patients. Exclusions were due to rapid intubation ($n = 3$), inadequate ultrasound ($n = 4$) or esophageal pressure signal ($n = 1$), neuromuscular disease ($n = 2$), delirium/agitation ($n = 5$), and abdominal wounds/obstacles to probe placement ($n = 3$). Patients had a mean age of 65 ± 13 years; 61% were male. Body mass index was 26 ± 7.3, SOFA 3 (2–4), and SAPS II 40 (36–46). Under Venturi mask, $\text{Pao}_2/\text{Fio}_2$ was 194 ± 46 mm Hg.

The effects on diaphragmatic function, esophageal pressure, and gas exchange are summarized in **Table 1**. Diaphragmatic thickening fraction was lower with Venturi mask and increased with both high-flow nasal cannula and CPAP (20% ± 6% vs. 27% ± 9.9% vs. 29% ± 13%; $p = 0.0013$; and **Fig. 1*A***). Diaphragmatic excursion differed significantly across devices, being lower with high-flow nasal cannula (1.1 ± 0.63 cm vs. 1.5 ± 0.95 cm with Venturi mask and 1.4 ± 0.59 cm with CPAP; $p = 0.0002$; and **Fig. 1*B***).

ΔPes was reduced with high-flow nasal cannula compared with Venturi mask and similar to CPAP (5.9 ± 1.9 vs. 8.1 ± 3.5 vs. 5.9 ± 2.1 cm H_2O; $p = 0.0002$, with post hoc $p = 0.0018$ vs. Venturi mask and $p = 0.0039$ vs. CPAP). Inspiratory and expiratory esophageal pressure increased as respiratory support was escalated from Venturi mask to high-flow nasal cannula to CPAP (–1.4 ± 1.9 cm H_2O with Venturi mask vs. 1.4 ± 2 cm H_2O with high-flow nasal cannula

TABLE 1.
Comparison of Diaphragmatic, Esophageal, Respiratory Gas Exchange, and Hemodynamic Variables Across Different Devices

Variables	Venturi Mask	High-Flow Nasal Cannula	Continuous Positive Airway Pressure	*p* Analysis of Variance
Diaphragmatic ultrasound				
Diaphragmatic thickening fraction (%)	20 ± 6^{b,c}	27 ± 10^{a}	29 ± 13^{a}	0.0013
Diaphragmatic excursion (cm)	1.5 ± 0.9^{c}	1.1 ± 0.6^{a,b}	1.4 ± 0.6^{c}	0.0002
Diaphragmatic rapid shallow breathing index (breaths/min/cm)	21 ± 10	27 ± 18	22 ± 12	0.0255
Diaphragmatic dysfunction index (breaths/min/cm/%)	117 ± 81	110 ± 71	91 ± 56	0.1920
Respiratory mechanics				
Esophageal pressure swing (cm H_2O)	8.1 ± 3.5^{b,c}	5.9 ± 1.9^{a}	5.9 ± 2.1^{a}	0.0002
Inspiratory esophageal pressure (cm H_2O)	−1.4 ± 1.9^{b,c}	1.4 ± 2.0^{a,b}	3.8 ± 1.1^{a,c}	< 0.0001
Expiratory esophageal pressure (cm H_2O)	6.7 ± 3.7^{b}	7.3 ± 2.6^{b}	9.7 ± 2.6^{a,c}	0.0003
Respiratory rate (breaths/min)	25 ± 6	23 ± 7	25 ± 7	0.0853
Gas exchanges				
pH	7.47 ± 0.06	7.46 ± 0.06	7.45 ± 0.05	0.5180
Pco_2 (mm Hg)	39 ± 10	39 ± 11	39 ± 8	0.9040
Po_2 (mm Hg)	63 ± 14^{b}	70 ± 12^{b}	77 ± 17^{a,c}	< 0.0001
Hemodynamic monitoring				
Mean arterial pressure (mm Hg)	87 ± 9.7	91 ± 11	91 ± 12	0.2950
Central venous pressure (mm Hg)	5.8 ± 4.3^{c}	6.3 ± 4.2^{a}	6.4 ± 4.4	0.0469

[a] Statistically different from Venturi mask in post hoc analysis of variance (ANOVA).

[b] Statistically different from continuous positive airway pressure in post hoc ANOVA.

[c] Statistically different from high-flow nasal cannula in post hoc ANOVA.

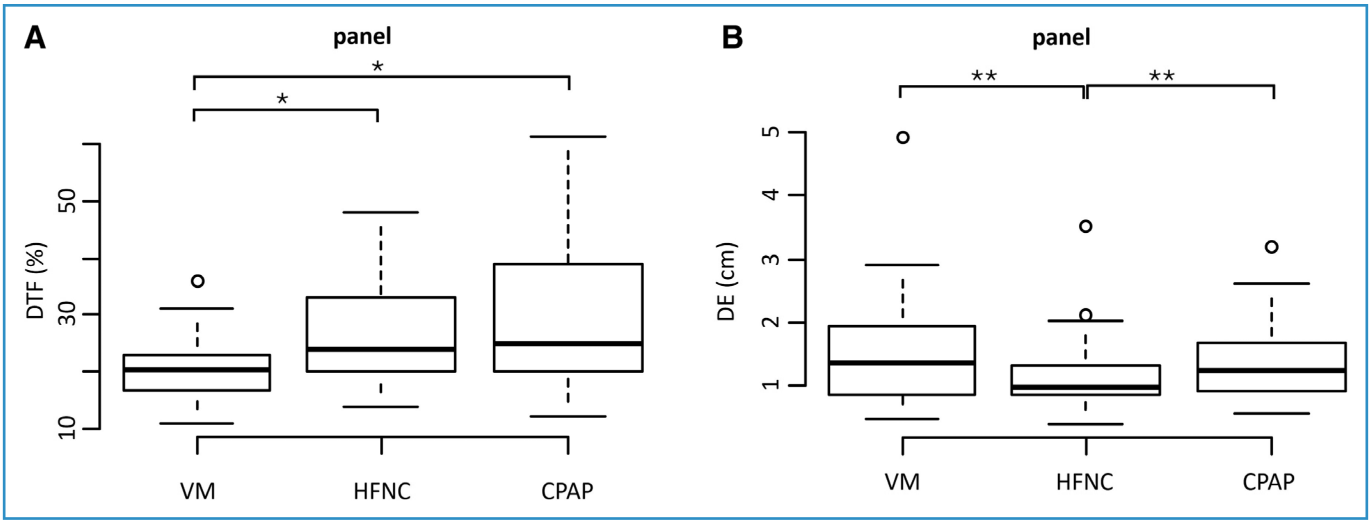

Figure 1. Comparisons of diaphragmatic effects of different devices. **A**, Diaphragm thickening fraction (DTF, %) in Venturi mask (VM), high-flow nasal cannula (HFNC), and continuous positive airways pressure (CPAP) is shown. The post hoc pairwise comparisons using Wilcoxon signed-rank test with continuity correction results is reported (**$p < 0.01$, *$p < 0.05$). **B**, Diaphragm excursion (DE, cm) in VM, HFNC, and CPAP is shown. The post hoc pairwise comparisons using Wilcoxon signed-rank test with continuity correction results is reported (**$p < 0.01$, *$p < 0.05$).

vs. 3.8 ± 1.1 cm H_2O with CPAP; $p < 0.0001$ for inspiratory esophageal pressure, and 6.7 ± 3.7 cm H_2O with Venturi mask vs. 7.3 ± 2.6 cm H_2O with high-flow nasal cannula vs. 9.6 ± 2.6 cm H_2O with CPAP; $p = 0.0003$ for expiratory esophageal pressure). As support increased, Pes waveforms became entirely positive. Respiratory rate remained unchanged across conditions.

The diaphragmatic RSBI differed overall between devices (21 ± 10 high-flow nasal cannula vs. 27 ± 18 CPAP; 22 ± 12 breaths/min/mm; ANOVA $p = 0.025$), but post hoc tests were not significant.

$\mathrm{F_{IO_2}}$ was predefined during the Venturi mask phase according to each patient's clinical requirement and then maintained unchanged during the high-flow nasal cannula and helmet CPAP phases. As such, $\mathrm{F_{IO_2}}$ remained stable across the three study phases within each patient, although the specific $\mathrm{F_{IO_2}}$ values differed slightly between patients (40 [30–40]). $\mathrm{Pa_{O_2}}$ rose with CPAP compared with Venturi mask and high-flow nasal cannula (63 ± 14 vs. 70 ± 12 vs. 77 ± 17 mm Hg; $p < 0.0001$). $\mathrm{Pa_{CO_2}}$ did not change significantly. Based on the diaphragmatic dysfunction index measured during Venturi mask phase, we stratified patients into those with or without diaphragmatic dysfunction. Results are shown in **Supplemental Table 1** (https://links.lww.com/CCM/H858). In patients with diaphragmatic dysfunction as defined by diaphragmatic dysfunction index greater than 100, thickening fraction increased with high-flow nasal cannula and CPAP (17% ± 3.5% with Venturi mask vs. 25% ± 8.3% with high-flow nasal cannula and 26% ± 11% with CPAP; $p = 0.007$), while it did not change significantly in those without dysfunction (24% ± 6.4% with Venturi mask vs. 29% ± 11% with high-flow nasal cannula and 33% ± 15% with CPAP; $p = 0.07$). Excursion was consistently lower in dysfunctional patients (Venturi mask 0.98 ± 0.42 cm vs. 2.1 ± 1 cm, $p = 0.0011$; high-flow nasal cannula 0.81 ± 0.26 cm vs. 1.4 ± 0.75 cm, $p = 0.01007$; and CPAP 1.1 ± 0.34 cm vs. 1.6 ± 0.67 cm, $p = 0.0154$).

ΔPes significantly decreased only in patients with diaphragmatic dysfunction when using high-flow nasal cannula and CPAP compared with Venturi mask (Venturi mask 9.1 ± 3 cm vs. high-flow nasal cannula 5.8 ± 2 cm and CPAP 6.3 ± 1.9 cm; $p = 0.0003$). Regarding blood gas analysis, pH was normal in non-dysfunctional patients but alkalotic in dysfunctional ones across all supports (Venturi mask 7.4 ± 0.055 vs. 7.5 ± 0.058, $p = 0.07539$; high-flow nasal cannula 7.4 ± 0.052 vs. 7.5 ± 0.067, $p = 0.09$; and CPAP 7.4 ± 0.04 vs. 7.5 ± 0.049, $p = 0.0091$, respectively).

DISCUSSION

The main findings of this exploratory study were: 1) high-flow nasal cannula improved diaphragmatic function by increasing thickening fraction and reducing excursion compared with Venturi mask; 2) it decreased inspiratory effort, as shown by lower ΔPes; 3) CPAP further improved oxygenation, while $Paco_2$ remained unchanged; and 4) in patients with diaphragmatic dysfunction, high-flow nasal cannula enhanced thickening fraction and reduced inspiratory effort.

Diaphragm ultrasound has been widely investigated, mainly as a predictor of weaning success or failure (37, 40–44). Most studies focused on cutoff values, often based on excursion because it is easy to measure (43, 44). However, excursion is limited for assessing dysfunction since it depends on lung volume, pressure, or PEEP (43, 45, 46). Limited research explored the effects of noninvasive respiratory support methods such as high-flow nasal cannula on diaphragm function. In the present study, high-flow nasal cannula improved diaphragmatic contraction by increasing thickening fraction. This parameter measures the rise in diaphragm thickness during inspiration (47). The concurrent increase in thickening fraction and reduction in ΔPes should not be interpreted as unequivocal evidence of improved neuromechanical coupling. Rather, this combination might reflect changes in diaphragm geometry or operating volume, possibly related to increased lung volume. Thus, while these findings are consistent with a reduction in inspiratory effort, they should be interpreted cautiously, acknowledging that altered diaphragm configuration may also contribute to the observed pattern. Several authors have demonstrated that diaphragmatic thickening fraction increases at higher lung volumes indicating its correlation with the intensity of diaphragm contraction (14, 41). Still, its correlation with transdiaphragmatic pressure, the gold standard, remains uncertain (48). Although lung volume was not directly measured in this study, the observed increase in diaphragmatic thickening fraction with both high-flow nasal cannula and helmet CPAP suggested a corresponding rise in lung volume. This inference is supported by the decrease in respiratory effort, as indicated by the change in ΔPes without a change in respiratory rate. Additionally, it is well-documented that high-flow nasal cannula applies minimal positive pressure and can lead to alterations in ventilatory volumes (49–51). Since these effects were observed mainly in dysfunctional patients, it is plausible that high-flow nasal cannula reduces effort by delivering continuous flow and maintaining upper airway patency (52). Diaphragmatic excursion also differed among supports, being lower with high-flow nasal cannula. Furthermore, across all devices, excursion was reduced in dysfunctional patients compared with others. Excursion is sensitive to respiratory pattern changes (40) and reflects diaphragm volume-generating capacity. In our study, diaphragmatic excursion followed the same trend as thickening fraction, suggesting that high-flow nasal cannula may improve lung volume and diaphragm contractile efficiency, thereby reducing effort. In addition, PEEP is known to alter diaphragm geometry by increasing end-expiratory volume and displacing the muscle downward (53), potentially affecting ultrasound measures (54). Specifically, higher PEEP has been associated with lower thickness and thickening fraction (46). Although PEEP was not measured directly here, changes observed with high-flow nasal cannula may reflect both functional improvement and indirect geometric effects.

There are limited reports detailing the association of driving transpulmonary pressure with diaphragmatic function. Goligher et al (55) observed a correlation between higher driving pressure and a reduction in diaphragmatic thickness and contractile activity measured by ultrasound. Previous studies in both pediatric (56) and adult populations (1, 52) showed that high-flow nasal cannula reduces work of breathing, as indicated by lower ΔPes. More recently, Poulard et al (22) investigated the correlation between diaphragmatic thickening fraction and transdiaphragmatic pressure in healthy subjects and mechanically ventilated patients, finding modest correlation in healthy individuals and weak or inconsistent results in the critically ill. Our findings align with these previous physiologic data, supporting the hypothesis that high-flow nasal cannula may protect the lung by promoting more homogeneous tidal volume distribution compared with conventional oxygen.

Additionally, we observed improved oxygenation compared with baseline. This may have contributed to the observed reduction in respiratory effort; however, the role of hypoxic drive in ICU patients is typically modest unless hypoxemia is severe and unaccompanied by hypocapnia. Alternative explanations such as reduced anatomical dead space, improved ventilatory efficiency, and enhanced comfort with high-flow nasal cannula are also likely contributors. Compared with Venturi mask, high-flow nasal cannula produced a small $Paco_2$ reduction without changing respiratory rate, consistent with enhanced Co_2 clearance through upper airway washout, reducing ventilatory demand and work of breathing (52, 57). We acknowledge that 60 minutes of helmet CPAP may not be sufficient to reach full Co_2 steady state, particularly given the large internal volume of the interface. This limitation may have affected the accuracy of gas exchange measurements during the CPAP phase. By replacing tidal volume with diaphragmatic excursion, RSBI has been suggested to better reflect diaphragmatic function and the balance between load and capacity during spontaneous breathing (34). In the original report, the authors showed how it was more accurate than traditional RSBI in predicting weaning outcomes. Our results showed how this index did not clearly change in overall population, but it was significantly different among dysfunctional or nondysfunctional patients. Although RSBI originally was developed for extubation prediction (58), it has also been evaluated as a predictor of intubation (59) and noninvasive ventilation failure (60). In settings like ours, where tidal volume cannot be directly measured, the modified index may be superior to respiratory rate or excursion alone in distinguishing patient groups and tracking improvements during transitions between supports. Still, excursion is affected by factors such as patient condition, weaning strategy, and thoracoabdominal pressures, so results require cautious interpretation.

Finally, we introduced a new index for assessing diaphragmatic function. The diaphragmatic dysfunction index derived from previous work on RSBI, replacing tidal volume with the ratio of excursion to thickening fraction. We arbitrarily selected potential normal values for respiratory rate, diaphragmatic excursion, and thickening fraction to establish a cutoff for defining diaphragmatic dysfunction. In our cohort, this score divided patients into two homogeneous groups and identified dysfunctional cases more consistently than individual parameters. In dysfunctional patients, high-flow nasal cannula improved contractility and reduced effort. However, the index is exploratory: it lacks validation against physiologic standards (e.g., transdiaphragmatic pressure) or clinical outcomes, and its dichotomous classification has not been externally tested. Its state dependence, since components vary with support modality, further limits robustness. The paradoxical finding of higher ΔPes and alkalosis in dysfunctional patients may reflect increased drive rather than impaired contractility. On the other hand, CPAP might be more suitable for nondysfunctional patients, given its associated improvement in oxygenation.

Our study has several limitations. first, we did not directly monitor absolute lung volumes, restricting interpretation of lung aeration, although electrical impedance tomography studies suggest increased volume with high-flow nasal cannula (4, 52). Then, we did not assess the impact of the tested methods on dyspnea, although this aspect has been well-documented by other investigators (11, 61). Furthermore, we did not track the evolution of diaphragmatic function over time or the potential development of diaphragmatic weakness. Dysfunction was defined using an ultrasound-based cutoff that remains arbitrary and not widely validated. Finally, the small sample size limited statistical power healthy volunteers were not included in this study, as our primary aim was to evaluate physiologic responses in ICU patients with AHRF. Furthermore, our findings apply only to the tested settings; higher flows or PEEP might yield different effects and should be investigated. Despite these limitations, diaphragm ultrasound remains a promising bedside tool to stratify patients by muscle performance in acute respiratory failure. Early identification of dysfunction (reduced thickening fraction or excursion) may help tailor support to reduce effort and preserve contractility. As this is an exploratory physiologic study, our findings should be viewed as hypothesis-generating, requiring confirmation in larger cohorts.

CONCLUSIONS

This study provides valuable insights into how high-flow nasal cannula may influence diaphragmatic function, positively affecting both its motion and contraction dynamics compared with Venturi mask oxygen delivery. Additionally, our findings confirm previous observations regarding the physiologic benefits of high-flow nasal cannula in AHRF patients, including improvements in gas exchange, and reduced respiratory effort. Nonetheless, given the preliminary nature of our study and its limited sample size, larger-scale investigations are imperative to validate and deepen our understanding of these observed effects.

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1 *SC Anestesia, Rianimazione e Terapia Intensiva, ASST Nord Milano, Ospedale Bassini, Cinisello Balsamo, Italy.*

2 *Department of Intensive Care, New Hospital of Legnano, Legnano, Italy.*

3 *School of Medicine and Surgery, University of Milano-Bicocca, Milano, Italy.*

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Dr. Gotti was involved in data collection and article writing. Dr. Umbrello was involved in statistical analysis and article revision. Dr. Sabbatini was involved in data collection and clinical assessments. Dr. Mantovani was involved in study design and patient recruitment. Dr. Foggetti was involved in patient recruitment. Drs. Menozzi and Galimberti were involved in clinical management and article revision. Dr. Pezzi was involved in data collection and article revision. Dr. Formenti was involved in study design, data analysis, and article writing.

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For information regarding this article, E-mail: formenti.paolo80@gmail.com

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