Performance of Different Low-Flow Oxygen Delivery Systems

Frédéric Duprez, Florence Dupriez, Julien De Greef, Julie Gabriel, Arnaud Bruyneel, Grégory Reychler, Christophe De Terwangne, and William Poncin

BACKGROUND: The delivery of a high and consistent F_{IO_2} is imperative to treat acute hypoxemia. The objective of this study was to analyze the effective inspired oxygen concentration delivered by different low-flow oxygen therapy systems challenged with different oxygen flows and respiratory patterns in an experimental lung model. METHODS: An adult lung model ventilated in volume control mode simulated different respiratory patterns to obtain mean inspiratory flow of 22.5, 30.0, 37.5, or 45.0 L/min. The oxygen concentration sampled inside the lung model by nasal cannula, simple face mask, non-rebreather mask, and double-trunk mask above nasal cannula tested at oxygen flows of 10, 12.5, and 15 L/min was quantified. The 3 masks were sealed tight onto the model's airway opening. They were also tested with standardized leaks to determine their clinical performance. RESULTS: All oxygen delivery systems delivered higher oxygen concentration with increasing oxygen flows, regardless of the respiratory pattern. Within each device, the increase in inspiratory flow decreased oxygen concentration when using nasal cannula ($P = .03$), the simple face mask ($P = .03$), but not the non-rebreather mask ($P = .051$) nor the double-trunk mask ($P = .13$). In sealed condition, the double-trunk mask outperformed the non-rebreather mask and simple face mask ($P < .001$); mean oxygen concentration was 84.2%, 68.5%, and 60.8%, respectively. Leaks amplified oxygen concentration differences between the double-trunk mask and the other masks as the oxygen delivery decreased by 4.6% with simple face mask (95% CI 3.1–6.1%, $P < .001$), 7.8% with non-rebreather mask (95% CI 6.3–9.3%, $P < .001$), and 2.5% with double-trunk mask (95% CI 1–4%, $P = .002$). With leaks, the oxygen concentration provided by the simple face mask and the non-rebreather mask was similar ($P = .15$). CONCLUSIONS: Lung oxygen concentration values delivered by the double-trunk mask were higher than those obtained with other oxygen delivery systems, especially when leaks were present. *Key words: respiratory distress; oxygen face mask; non-rebreather mask; double-trunk mask; performance; low-flow oxygen therapy.* [Respir Care 2022;67(3):322–330.

Introduction

Oxygen administration is one of the most prescribed intervention for hypoxemic patients in both acute and chronic care.[1] In patients breathing spontaneously, oxygen is routinely delivered via low-flow oxygen therapy systems. In acute emergency setting, the most reliable low-flow oxygen therapy system is the one that delivers an appropriate and consistent F_{IO_2} regardless of patient's breathing pattern. Among the wide range of available low-flow oxygen

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therapy systems, nasal cannula, simple face mask, or non-rebreather mask are the most commonly used.[2]

Oxygen delivered by a nasal cannula is typically the initial step to correct mild hypoxemia. Since the nasal cannula is an open system, air entrainment occurs around the oxygen source and dilutes oxygen concentration, limiting its capacity to deliver a F_{IO_2} level to a maximum of 0.40–0.45.[2] In addition, nasopharyngeal mucous dryness and epithelial irritation increase concurrently to the rate of oxygen output and can lead to pain and epistaxis with prolonged use.[3] Oxygen face masks are used as a second step to achieve higher F_{IO_2} values than those obtained with a nasal cannula. Indeed, the simple face mask and non-rebreather mask are thought to provide high to very high F_{IO_2} levels.[4] However, because face masks are associated with an additional dead-space volume, they are used at oxygen flows > 6 L/min to limit carbon dioxide rebreathing. Therefore, they also cause drying of the upper airways. In addition, in vitro experiments mimicking varying breathing patterns have found that the oxygen delivery of these masks falls at elevated minute ventilation.[5,6] Yet these masks are often used in acute respiratory distress patients who typically present with high minute ventilation.

Another weakness of the oxygen face mask concerns leaks around the patient's face. A suboptimal mask seal or fit to the face is commonly observed in clinical practice and substantially decreases the delivery of oxygen concentration.[7-9] However, patients with severe hypoxemia need high and consistently administered F_{IO_2} levels to maintain adequate tissue oxygenation. Due to the above-mentioned concerns, some authors previously proposed to add an additional face mask on top of the nasal cannula. In 2009, Caille et al[10] showed that the addition of a nebulizer face mask applied on the face of a cadaveric specimen receiving oxygen through a nasal cannula or a catheter provided higher F_{IO_2} values than the non-rebreather mask. Moreover, Hayes-Bradley et al[7] showed that supplemental nasal cannula oxygen improved the performance of the non-rebreather mask both with and without a mask leak. Further studies showed that the double-trunk mask, an aerosol mask in which 2 tubes have been fixed in each of the side holes, also improved the performance of nasal cannula.[11-13]

This study was, therefore, designed to analyze the performance of commonly used low-flow oxygen therapy systems challenged with different oxygen flows and respiratory patterns encountered in acute emergency setting using an experimental lung model. This study also evaluated the impact of a standardized mask leak on oxygen delivery into the lung model in order to appreciate the clinical performance of the oxygen face masks.

QUICK LOOK

Current knowledge

Patients with severe hypoxemia need high and consistent F_{IO_2} administration to maintain an adequate tissue oxygenation. In the acute emergency setting, the most reliable low-flow oxygen therapy system is the one that delivers an appropriate and consistent F_{IO_2} regardless of patient's breathing pattern. Previous studies have generally assessed the performance of low-flow oxygen masks sealed tight onto the patient's face or the bench model, which may not reflect their performance in clinical use.

What this paper contributes to our knowledge

This bench study showed that, under oxygen flows between 10–15 L/min, the non-rebreather mask did not provide a higher oxygen concentration than the simple face mask when leaks were present. Conversely, the double-trunk mask outperformed all other systems tested, regardless of the simulated breathing pattern. The double-trunk mask may represent a better alternative to the non-rebreather mask for maintaining suitable oxygenation in acute respiratory distress.

Methods

Experimental Adult Model

Each oxygen delivery system was attached onto a board with a hole (diameter 22 mm) mimicking upper airway opening. This opening was connected via a hose representing proximal airways to an adult lung model (5600i Dual Test Lung, Michigan Instrument, Grand Rapids, Michigan) composed of 2 independent artificial lungs. The lung model was ventilated by a mechanical ventilator (Servo, Maquet, Wayne, New Jersey). With a special lung coupling clip, one lung was ventilated and used to drive the second lung to mimic spontaneous breathing simulation (Fig. 1).

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The authors have disclosed no conflicts of interest.

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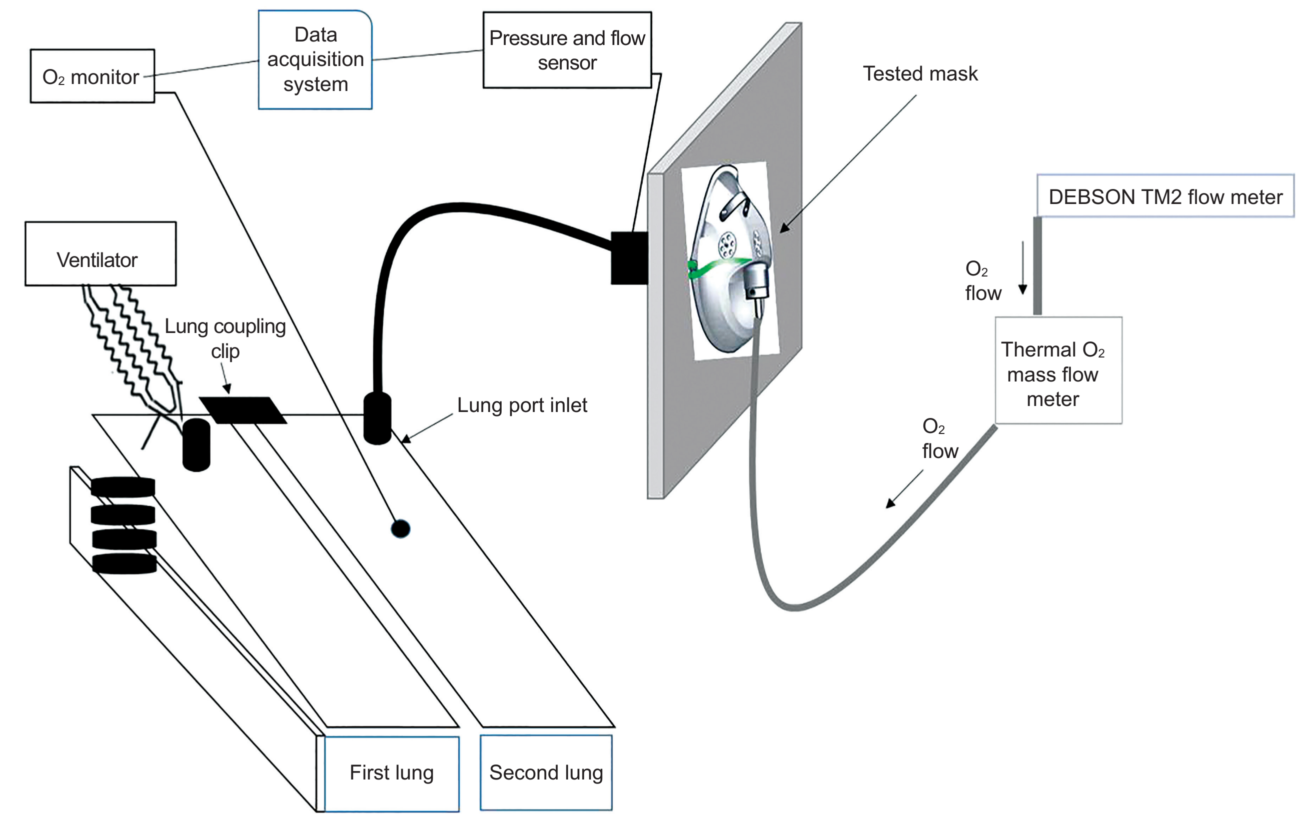

Fig. 1. Setup of the experimental adult lung bench model.

Ventilator settings used were volume control mode (descending ramp flow waveform without autoflow, time pause and inspiratory rise time at 0%, inspiratory-expiratory ratio set at 1:2, PEEP of 0 cm H_2O, trigger set at –20 cm H_2O to avoid self-triggering, flow cycled at 25% of inspiratory peak flow), and breathing flow/volume was generated in ambient temperature and pressure saturated conditions. Resistive and elastic characteristics of Dual Test Lung were set at 5.0 cm H_2O/L/s and 0.06 L/cm H_2O, respectively. When an experimental setting was changed, a stabilization period of 2 min was respected. The oxygen concentration, hereafter referred to as effective inspired oxygen concentration, was sampled at the second lung port (Fig. 1). All settings were performed in triplicate, and the average of the 3 measurements was reported. Data acquisition was performed via the LabScribe 3 software (iWorx, Dover, New Hampshire) after the 2-min stabilization period.

Oxygen Delivery Systems

The low-flow oxygen therapy systems evaluated were nasal cannula, simple face mask (Hudson RCI adult elongated oxygen mask, Teleflex, Wayne, Pennsylvania), non-rebreather mask (Hudson RCI adult non-rebreathing mask, Teleflex), and double-trunk mask above nasal cannula (Fig. 2). The double-trunk mask is a patent-free system that consists of a jet nebulizer and an aerosol mask (Sidestream, Philips Respironics, Murrysville, Pennsylvania) in which 2 corrugated tubes (ISO 22, length 15 cm) or "trunks" have been inserted in each side hole of the mask. The system is applied over the nasal cannula and acts as a reservoir system for oxygen that would otherwise be vented to the atmosphere. Oxygen is delivered exclusively through the nasal cannula.

In addition, because the effects of injecting oxygen flow directly into the double-trunk mask through the nebulizer gas inlet (ie, without nasal cannula) are not known, the performance of the latter system was further compared to the double-trunk mask over the nasal cannula, independently of other devices.

Experimental Settings

The performance of each system was evaluated using oxygen flows of 10, 12.5, and 15 L/min delivered by a flow meter (DEBSON TM2, Technologie Médicale, Noisy-le-Sec, France) and verified continuously via a calibrated thermal oxygen mass flow meter (red-y, Vögtlin Instruments, Muttenz, Switzerland). Furthermore, for each oxygen flow set, each system was challenged at breathing frequency of

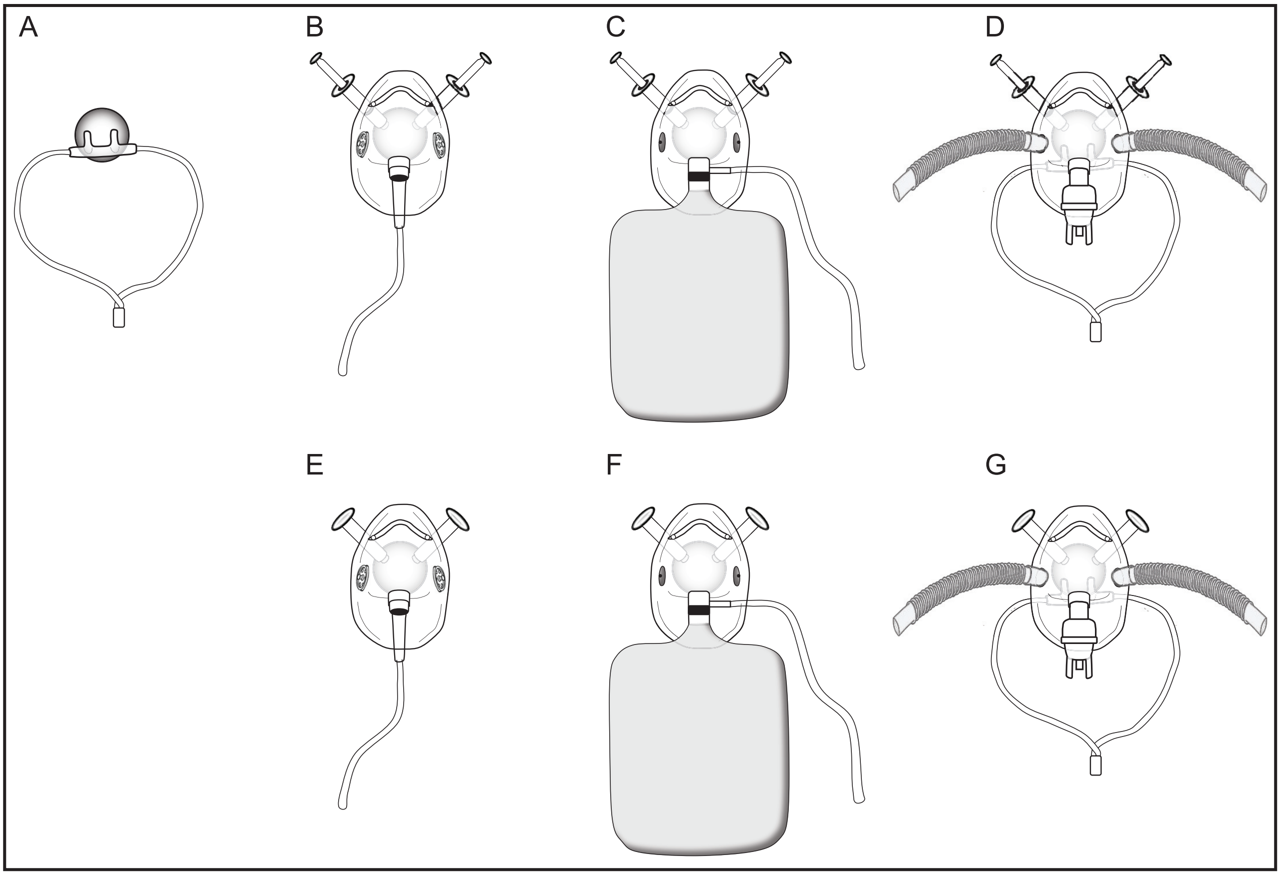

Fig. 2. Low-flow oxygen therapy systems tested with and without mask seal. Boards with holes prepared beforehand, on top of which are taped different low-flow oxygen therapy systems: nasal cannula (A), simple face mask (B, E), non-rebreather mask (C, F), and the double-trunk mask (D, G). A 2-mL syringe with the tip cut was introduced on both sides of the nose wing region of each mask. These syringes were either sealed with the plunger inserted into the barrel (B, C, D) or kept opened (the plunger was removed) to simulate leaks (E, F, G). For the sake of clarity, the tape is not illustrated.

Table 1. Settings Used to Assess the Performance of Low-Flow Oxygen Therapy Systems

Settings	Tested Conditions
Mechanical ventilator	
Tidal volume (mL)	500
Frequency (breaths/min)	15, 20, 25, 30
Minute ventilation (L/min)	7.5, 10.0, 12.5, 15.0
Mean inspiratory flow (L/min)	22.5, 30.0, 37.5, 45.0
Peak inspiratory flow (L/min)	36, 48, 60, 72
Delivery systems	
Devices	Nasal cannula
	Simple face mask
	Non-rebreather mask
	Double-trunk mask over nasal cannula
	Double-trunk mask without nasal cannula
Oxygen flow (L/min)	10.0, 12.5, 15.0
Sealing	Sealed, leaked

15, 20, 25, and 30 breaths/min. Tidal volume was set at 500 mL. Hence, mean inspiratory flow was set at 22.5, 30.0, 37.5, and 45.0 L/min.

Finally, the simple face mask, non-rebreather mask, and double-trunk mask were taped and sealed tight onto the board above the upper airway opening. In addition, a 2-mL syringe with the tip cut was introduced on both sides of the nose wing region of each of these masks. These syringes were either sealed with the plunger inserted into the barrel or kept opened (the plunger was removed) to simulate standardized leakages (Fig. 2). Thus, the simple face mask, non-rebreather mask, and double-trunk mask were tested tight sealed or with leaks. Table 1 summarizes the different settings.

Statistical Analysis

Normality of data was verified with Shapiro-Wilk tests. The effective inspired oxygen concentration (%) delivered in the lung model was the only dependent variable and was presented as mean ± SD or median and range according to data distribution.

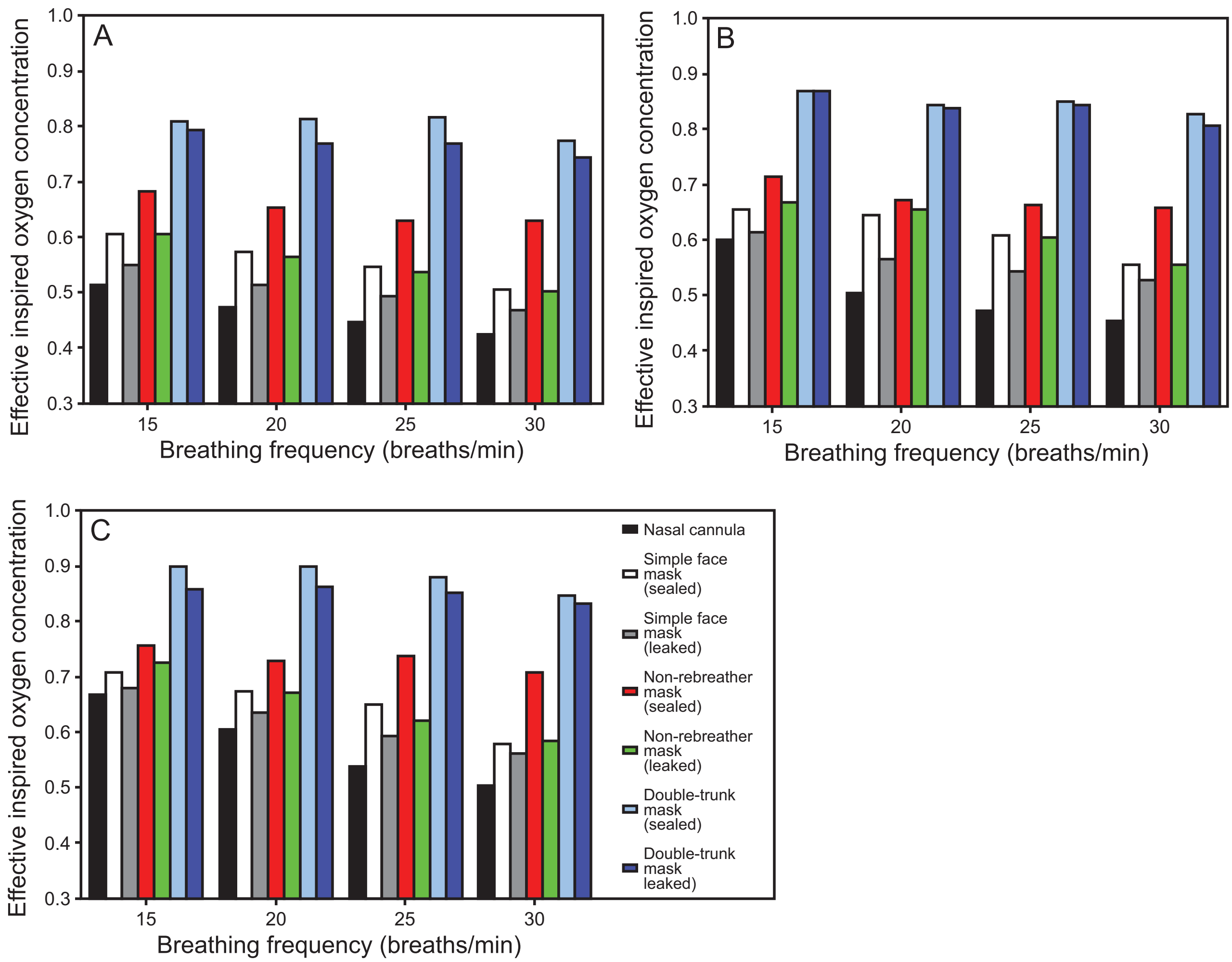

Fig. 3. Effective inspiratory oxygen concentration measured with nasal cannula and oxygen face masks sealed tight according to the different respiratory patterns. The bar graphs show the effective inspiratory oxygen concentration (%) sampled in the lung port with oxygen flow set at A: 10 L/min, B: 12.5 L/min, and C: 15 L/min. The corresponding effective inspiratory flow for breathing frequency set at 15, 20, 25, and 30 breaths/min are 22.5, 30.0, 37.5, and 45.0 L/min, respectively.

First, we tested the effects of oxygen flow and respiratory patterns within the following oxygen delivery systems (ie, devices): nasal cannula, simple face mask, non-rebreather mask, and double-trunk mask sealed tight. The effect of oxygen flows and respiratory patterns on effective inspired oxygen concentration was tested with the Friedman test. Second, the effects of sealing (sealed, leaked) and the devices on oxygen concentration, along with their interactions, were examined by performing a 2-way mixed ANOVA. The devices were considered as a between-subjects factor. Nasal cannula was removed from the latter analysis as it was not tested under a sealed condition because of clinical irrelevance. The Bonferroni post hoc test was performed when multiple comparison analysis was required. Finally, the oxygen concentration difference between the double-trunk mask over the nasal cannula and the double-trunk mask without nasal cannula was tested using the unpaired *t* test. In addition, because the effects of injecting oxygen flow directly into the double-trunk mask through the nebulizer gas inlet (ie, without nasal cannula) are not known, the performance of the latter system was further compared to the double-trunk mask over the nasal cannula, independently of other devices. All statistical tests were 2-sided, and P values $< .05$ were considered statistically significant. Analyses were performed using SPSS v27 software (IBM, Armonk, New York).

Results

Each device provided consistently higher effective inspired oxygen concentration with increase in oxygen flow ($P = .01$) (Fig. 3, Table 2). The increase in inspiratory flow (or breathing frequency) decreased effective inspired oxygen concentration when using the nasal cannula ($P = .03$), the simple face mask ($P = .03$), but not the non-

Table 2. Effective Inspired Oxygen Concentration Delivered by Nasal Cannula and Oxygen Masks Sealed Tight, at Different Settings

	Device			
	Nasal Cannula	Simple Face Mask	Non-Rebreather Mask	Double-Trunk Mask
Oxygen flow				
10 L/min	0.46 [0.42–0.51]	0.56 [0.51–0.61]	0.64 [0.53–0.68]	0.81 [0.77–0.82]
12.5 L/min	0.49 [0.45–0.60]	0.63 [0.55–0.65]	0.67 [0.66–0.71]	0.83 [0.82–0.86]
15 L/min	0.57 [0.50–0.67]	0.66 [0.58–0.71]	0.73 [0.71–0.75]	0.89 [0.84–0.90]
P	.02	.02	.02	.02
Mean Inspiratory Flow				
22.5 L/min	0.60 [0.51–0.67]	0.65 [0.61–0.71]	0.71 [0.68–0.75]	0.86 [0.81–0.90]
30.0 L/min	0.50 [0.47–0.60]	0.64 [0.57–0.67]	0.67 [0.65–0.73]	0.84 [0.81–0.90]
37.5 L/min	0.47 [0.45–0.54]	0.61 [0.55–0.65]	0.66 [0.63–0.74]	0.85 [0.82–0.88]
45.0 L/min	0.45 [0.42–0.50]	0.55 [0.51–0.58]	0.66 [0.63–0.71]	0.82 [0.77–0.84]
P	.03	.03	.051	.13

Data represent the median [min – max] values of oxygen concentration sampled in the lung model. Values displayed next to a given oxygen flow summarize the data collected with the set oxygen flow and the different mean inspiratory flow conditions and vice versa for values displayed next to a given mean inspiratory flow.

Table 3. Comparison of Effective Inspired Oxygen Concentration Provided Between Oxygen Masks in Sealed and Leaked Conditions

	Device			*P*		
	Simple Face Mask	Non-Rebreather Mask	Double-Trunk Mask	Within-Condition (Sealing)	Between-Condition (Devices)	Interaction Sealing x Devices
Sealing						
Sealed	0.61 ± 5.9	0.69 ± 4.1	0.84 ± 3.7	< .001	< .001	< .001
Leaked	0.56 ± 6.0	0.61 ± 6.3	0.82 ± 4.0			

Data are displayed as means ± SD.

rebreather mask ($P = .051$) nor the double-trunk mask ($P = .13$) (Fig. 3, Table 2). The 2-way mixed ANOVA analysis revealed there was a significant interaction between the effects of sealing and devices, $P < .001$ (Table 3). Bonferroni-adjusted comparisons for simple main effect analysis showed that leaks decreased the oxygen concentration delivered by the simple face mask, the non-rebreather mask, and the double-trunk mask by 4.6% (95% CI 3.2–6.1, $P < .001$), 7.8% (95% CI 6.3–9.3, $P < .001$), and 2.5% (95% CI 1.0–4.0, $P = .002$), respectively, (Fig. 3, Table 3).

In the sealed condition, the oxygen concentration provided by the double-trunk mask (84.2%) was higher than those obtained with the non-rebreather mask (68.5%, mean difference 15.6% [95% CI 10.8–20.4], $P < .001$) or the simple face mask (60.8%, mean difference 23.4% [95% CI 18.6–28.2], $P < .001$). In addition, the non-rebreather mask generated higher oxygen concentration values than the simple face mask (mean difference 7.8% [95% CI 2.9–12.6], $P = .001$). In the leaked condition, the oxygen concentration differences were more pronounced between the double-trunk mask and the non-rebreather mask (mean difference 21.0% [95% CI 15.3–26.7], $P < .001$) or the simple face mask (mean difference 25.6% [95% CI 19.8–31.3], $P < .001$). With leaks, the non-rebreather mask did not provide significantly different oxygen concentration values than the simple face mask (mean difference 4.6% [95% CI −1.1 to 10.3], $P = .15$) (Fig. 3, Table 3).

It was not possible to evaluate the double-trunk mask without nasal cannula at oxygen flows > 10 L/min as the injection of such flows through the nebulizer gas inlet connector generated overpressure disconnecting the tubing. Therefore, the performance of the double-trunk mask with and without nasal cannula was exclusively compared at oxygen flow of 10 L/min. There was a large oxygen concentration difference in favor of the double-trunk mask over nasal cannula (median difference 19%, $P < .001$). Depending on the respiratory patterns, the difference ranged from 17–20% (Fig. 4).

Discussion

This study demonstrated that, for each low-flow oxygen therapy system assessed, effective inspired oxygen concentration values were influenced by the oxygen flow, the respiratory pattern (ie, inspiratory flow), and the presence of leaks. In addition, this study highlighted that the performance of the non-rebreather mask is strongly affected by the presence of leaks, unlike the other masks.

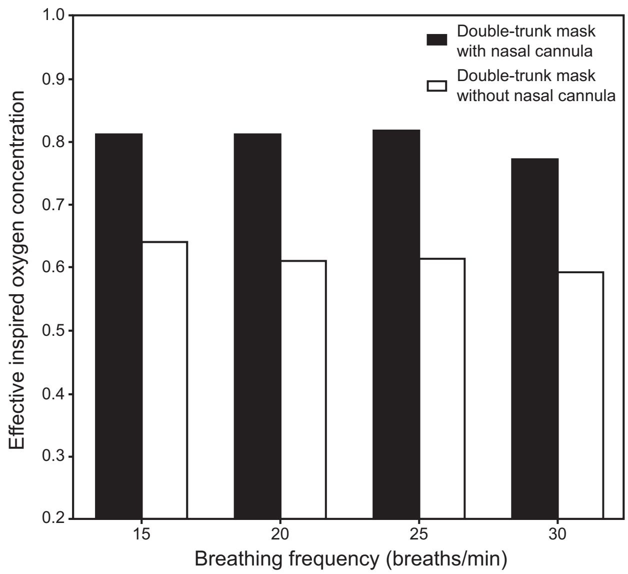

Fig. 4. Effective inspiratory oxygen concentration measured with the double-trunk mask with and without nasal cannula according to the different respiratory settings. The graph shows the effective inspiratory oxygen concentration (%) sampled in the lung port with the double-trunk mask placed above nasal cannula or the double-trunk mask without nasal cannula. The corresponding mean inspiratory flow for respiratory rate set at 15, 20, 25, and 30 breaths/min are 22.5, 30.0, 37.5, and 45.0 L/min, respectively.

The influence of tidal volume and breathing frequency on the measured F_{IO_2} was previously demonstrated in a bench model as well as in healthy subjects.[14,15] However, the inspiratory flow, which is a function of minute ventilation and inspiratory-expiratory ratio, determines the effective inspired oxygen concentration. The greater the inspiratory flow for a given oxygen flow the lower the oxygen concentration. Indeed, once the inspiratory flow demand exceeds the oxygen flow delivered, entrainment of room air occurs,[16] thereby diluting the delivered oxygen concentration. In our settings, the peak inspiratory flow ranged between 36–72 L/min, but it can reach flows up to 120 L/min in patients with respiratory failure.[16,17] Therefore, all things being equal, increasing the oxygen flow will lessen the dilution of oxygen concentration. As a matter of fact, increasing the oxygen flow provided higher oxygen concentration values regardless of the low-flow oxygen therapy system tested. These results are in accordance with previous studies using similar oxygen delivery systems.[5,8,9,15,18] Oxygen flows $>$ 15 L/min via low-flow oxygen therapy systems would presumably further increase the oxygen concentration,[15] albeit this could give rise to poor tolerance in a clinical setting due to insufficient humidification and heating.[16] Conventional nasal cannula tested with oxygen flows $>$ 6 L/min could likewise be regarded as clinically meaningless. At elevated oxygen flows, nasal cannula are indeed associated with poor tolerance due to drying of the nasal mucosa, pain, and nosebleed.[3,19] It should be emphasized that high-flow nasal cannula has to be preferred over low-flow oxygen therapy devices when patients require high levels of F_{IO_2} to correct hypoxemia. However, high-flow nasal cannula devices are not widely available in emergency units. These systems are even lacking in some parts of the world such as in low- and middle-income countries. Therefore, our in vitro design aimed to simulate clinical situations encountered in the emergency setting, where oxygen flows of 10–15 L/min can be provided for short periods of time, pending the patient is transferred to a higher level of care.

The effective inspired oxygen concentration values delivered with the nasal cannula are in agreement with the formula proposed by Duprez et al,[20] which takes into account the oxygen flow and the minute ventilation. The mean difference $\pm$ SD between calculated and predicted oxygen concentration was 1.0 $\pm$ 3.1%. Interestingly, the oxygen concentration values delivered through the 3 masks tested with leaks follow a very similar pattern than the predicted values with nasal cannula.[20] However, a bias proportional to the dead space of the device should be added to the prediction formula. Indeed, during oxygen therapy through a mask, oxygen accumulates in the dead-space volume, leading to increased oxygen concentration. Moreover, minute ventilation and more specifically the inspiratory flow and the expiratory time will influence oxygen accumulation in the mask. Hence, the higher the mask dead space and the lower the inspiratory flow/expiratory time the higher the oxygen accumulation and thus the effective inspired oxygen concentration. The addition of the 2 corrugated tubing (trunks) constituting the double-trunk mask further increases the dead space, hence the oxygen concentration. The trunks act as an added reservoir for oxygen with low resistance. When the inspiratory flow exceeds the oxygen flow delivered, the gas from this reservoir is first inspired before inhaling room air, thereby limiting air-oxygen mixture. The large amount of gas captured in the double-trunk mask may explain why the effective inspiratory oxygen concentration is less affected by the inspiratory flow with this mask compared to the other systems. These findings are consistent to those found using variant masks with tubes inserted on each side.[15,21,22]

Consequently, the similar dead-space volume between the simple face mask and the non-rebreather mask may explain why they provided very close oxygen concentration values when leaks were present. Conversely, the performance of the non-rebreather mask perfectly sealed was less compromised by the variability of the inspiratory flow. These findings are likely due to the one-way lateral valves at the exhalation ports limiting air admixture. However, in a clinical setting, the latter condition generates an additional work of breathing from the patient to overcome the resistance of the non-rebreathing valve (ie, the one between the face mask and the plastic reservoir bag), which may be difficult to tolerate in acute respiratory distress.[9,15] This may explain why, according to clinical experience, the non-rebreather mask is often not perfectly fitted on the patient's face, particularly in emergency settings. In addition, the masks are rarely fully adapted to the facial morphology of each patient, making leaks inevitable.

This study showed that open low-flow oxygen therapy systems (ie, nasal cannula or masks with leaks) can be classified, in descending order of efficiency, as follows: the double-trunk mask over nasal cannula, the non-rebreather mask or the simple face mask, and then the nasal cannula. The substantial drop in oxygen concentration (ie, 7.8%) once the non-rebreather mask is not perfectly tight has been consistently demonstrated by others in healthy volunteers.[7,9,18] The unexpected finding was the negligible difference in oxygen concentration values between the simple face mask and the non-rebreather mask with leaks. This suggests the volume of room air entrained in the masks could be the same. The simple face mask is equipped with small side holes that act as vents. The same holes are present on both sides of the non-rebreather mask, except that they are covered by one-way expiratory valves. Our results theorize that once small mask leaks to the face are present the one-way expiratory valve provides no added value to counteract the room air entrainment. Gas follows the path of least resistance; thus, we hypothesize that the resistance imposed by the non-rebreathing valve of the non-rebreather mask facilitates air entry via face leaks. On the contrary, the double-trunk mask remains an open low-resistance system due to the trunks even when it is tested tightly sealed, thus explaining why adding face leaks had a marginal impact on its performance in delivering high oxygen concentrations.

To the best of our knowledge, the double-trunk mask at oxygen flows between 10–15 L/min has not yet been tested on patients. The double-trunk mask used at standard low-flow therapy was, however, shown to improve the oxygen delivery to patients when compared to nasal cannula alone.[12,13] The large dead-space volume associated with the double-trunk mask (210 mL, including 60 mL per trunk[11]) could be a subject of concerns because of potential CO_2 rebreathing. Nevertheless, the P_{aCO_2} increase with the double-trunk mask was shown to be mild and of limited clinical importance.[12,13] Most likely these findings are explained by (1) the leaks between the patient's face and the mask and (2) the continuous oxygen flow beneath the double-trunk mask through the nasal cannula reducing the dynamic dead-space volume.[23-25] In the second hypothesis, the dead-space elimination of CO_2 is expected to be hastened as oxygen flow increases. Therefore, the double-trunk mask may be particularly well suited for patients with acute respiratory distress who require high oxygen concentration during a short period of time. This hypothesis is only speculation and is currently being investigated (NCT04383821).

Finally, this study confirmed that the double-trunk mask alone (ie, without nasal cannula) should not be used for oxygen therapy. Nasal cannula should remain the source of oxygen delivery while the double-trunk mask is placed over the device, serving only as a reservoir to collect oxygen flow that would otherwise be wasted during expiration. Consistent with this, Caille et al[10] observed that the combination of nasal cannula oxygen therapy with air-driven jet nebulization achieved higher F_{IO_2} values than those collected with oxygen-driven jet nebulization. The poorer performance observed in the double-trunk mask alone compared to the double-trunk mask over the nasal cannula may be explained by differences in airstream dispersion and fluid dynamics. For instance, Wagstaff and Soni[5] have shown on a manikin that nasal cannula produced higher F_{IO_2} than oxygen masks, presumably due to a better oxygen filling into the nasopharynx. In addition, the injection of oxygen flow at the nebulizer inlet connector propels oxygen at high velocity toward the nebulizer baffle, potentially dispersing oxygen molecules toward all directions, including leaks. Computational fluid dynamics studies would be helpful to clarify this assumption. Whatever the performance obtained with the double-trunk mask without nasal cannula, it should be noted that a practical issue is associated with the standard use of the double-trunk mask (ie, above nasal cannula). Indeed, if the patient removes the double-trunk mask for any reason, such as drinking, for example, a source of oxygen is preserved through nasal cannula. This is possibly an appreciable source of comfort in a clinical setting.

Although we tested the performance of oxygen delivery systems in providing high and consistent F_{IO_2}, the risk of oxygen toxicity should be stressed. An elevated level of P_{aO_2}, or hyperoxemia, can cause injury in the lungs and the central nervous system as well as absorption atelectasis in poorly ventilated lung areas. Liberal oxygen use is associated with increased mortality and must be avoided.[26,27] Therefore, oxygen saturation should be monitored in acutely ill patients receiving oxygen therapy, even for a short duration. The optimal titration of lung oxygen concentration for acutely ill medical patients is the lowest possible concentration that alleviates hypoxia, not exceeding an S_{pO_2} upper limit of 96%.[28]

The present study had several limitations. First, our in vitro model does not take into account alveolar-capillary gas exchange. Consequently, there were minor differences between exhaled and inhaled oxygen concentration. At the end of expiration, the airways of the dual test lung contained more oxygen than in physiological condition. This may have led to an overestimation of effective inspired oxygen concentration. However, this should not have influenced the direction and magnitude of the differences observed between low-flow oxygen therapy systems. Second, we did not use a manikin or a cadaveric specimen to reproduce the anatomical upper airways. We are thus unable to determine the influence of nasal or mouth breathing on our results as well as the impact of the oxygen passage through the nasopharynx. However, closed-mouth or open-mouth breathing during nasal cannula oxygen therapy has not shown to generate appreciable effects on the delivered oxygen concentration in healthy subjects.[29,30] These limitations are balanced by a strength being the sampling of the oxygen concentration beyond airways entry, thereby reflecting the effective inspired oxygen concentration instead of the F_{IO_2} generally influenced by local oxygen-air mixing due to leaks and breathing pattern. Indeed, previous studies found that oxygen sampling at different sites inside the mask yields different concentrations.[31]

Conclusions

This study showed that simulated lung oxygen concentration values delivered by the double-trunk mask were higher than those obtained with other oxygen delivery systems, especially when leaks were present. Moreover, when there is an imperfect mask seal to the face during oxygen therapy with flows set between 10–15 L/min, the simple face mask is similar to the performance of the non-rebreather mask. This suggests that the double-trunk mask over nasal cannula could be a better alternative to a non-rebreather mask for maintaining suitable oxygenation in acute respiratory distress. Future clinical studies are warranted to clarify this hypothesis.

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