



SCIENTIFIC LETTER

Laboratory performance of oronasal CPAP and adapted snorkel masks to entrain oxygen and CPAP

To the Editors:

The coronavirus disease 2019 (COVID-19) pandemic has exhausted supplies of ventilators and patient mask interfaces in many countries around the world.¹ As such, innovative responses from healthcare workers and engineers are combining medical (i.e. continuous positive airway pressure (CPAP)/bi-level devices) and non-medical (e.g. adapted Decathlon snorkel mask; Fig. 1) equipment to provide non-invasive ventilatory support (i.e. oxygen and positive pressure delivery) for patients. In some instances, oxygen (O₂) is being entrained to standard CPAP circuits at high flow rates above the manufacturer specifications (e.g. 4 L/min for ResMed S10)² to provide both pressure support and supplemental O₂ to the patient. Two key limitations of such experimental mask and CPAP setups include: (i) the leak profile and rebreathing characteristics of non-medical grade masks when pressure and/or O₂ are applied are unknown and (ii) quantitative details about the relationship between above specification O₂ flow rate and desired inspired O₂ fraction (F_IO₂) levels in closed CPAP circuits are unknown.

In situations where clinicians have been in short supply of CPAP equipment, they have adapted the Decathlon snorkel mask to provide a ventilatory support interface to those in need. In addition to its role as a salvage option in equipment-depleted hospital settings, this prototype interface confers potential advantages over conventional medical-grade designs. It requires no training to fit and non-critically ill patients can secure the interface without assistance. The mask is versatile in its ability to deliver air/O₂ blends with or without positive airway pressure (PAP). Finally, because the Decathlon snorkel mask is sealed, it potentially harnesses infectious aerosols more effectively than conventional O₂ delivery systems.

Our aim was to compare the performance/safety characteristics of the adapted Decathlon Easybreath snorkel mask (Decathlon, France) and oronasal CPAP masks across a series of potential clinical applications. Specifically, these include: (i) delivery of high concentrations of O₂ and (ii) simultaneous delivery of high-flow oxygen and positive pressure support.

We conducted a series of experiments with controlled O₂ and positive pressure delivery to assess the impact on: (i) F_IO₂; (ii) inspired carbon dioxide (CO₂) and, where appropriate, (iii) mask leak and (iv) mask pressure. All experiments were performed with a sealed

oronasal CPAP mask (Airfit F10; Resmed, Sydney, Australia), and repeated with an adapted Decathlon snorkel mask (shown in Fig. 1). Both masks were modified to add sampling ports for measuring O₂/CO₂ and mask pressure, and to seal their expiratory ports. For the Decathlon mask, the direction of the existing one-way expiratory/purge valve was swapped (making a one-way inspiratory valve) and the existing snorkel connection was swapped with a three-dimensional (3-D) printed 'Charlotte valve' connector which allowed standard medical tubing to be connected to the mask for oxygen/CPAP delivery (Appendix S1 in Supplementary Information). For both masks, expiratory gas was vented through a bio-filter (SureGard [RJVKB6], Australia). The key aims of the experiments were to assess the performance of both mask interfaces to entrain various concentrations of O₂ (30%, 50%, 60%, 80% and 100%), and to determine maximal achievable F_IO₂ at varied CPAP levels (Resmed S9) with entrained O₂, using flow rates above manufacturer specifications.

Two healthy male volunteers were recruited. Participant one (55 years, BMI = 25 kg/m²) completed experiment 1 and participant two (37 years, BMI = 24 kg/m²) completed experiment 2. The participants lay supine with their torso elevated 25 to the horizontal. The participants wore each mask interface attached to each of the experimental respiratory circuits described above. CPAP level, as well as the O₂ flow rate and mix were manipulated from an adjoining room (see Appendix S1 (Supplementary Information) for details). Human research ethics approval for this project was obtained by the Monash Health HREC (RES-20-0000-227A-63 509). Integration across the engineering and clinical science teams was facilitated by the Monash Institute of Medical Engineering and Monash Partners Academic Health Science Centre.

Figure 2 shows the performance of the CPAP mask and Decathlon snorkel mask in delivering various O₂ concentrations. For the CPAP mask, F_IO₂ values were near consistent with the O₂ mix delivered. In contrast, the snorkel mask achieved lower F_IO₂ at every level of O₂ mix. The highest F_IO₂ values achieved (100% O₂, 15 breaths/min (bpm)) were 94% for the CPAP mask and 80% for the snorkel mask.

Higher levels of rebreathing (assessed by inspired CO₂) were also noted for the snorkel mask (inspired CO₂: 13.8–16.7 mmHg, 15 bpm) which was further elevated at the higher respiratory rate of 30 bpm. Rebreathing was minimal with the CPAP mask regardless of respiratory rate (0.1–4.7 mm Hg, 15 bpm).

Similar patterns in F_IO₂ and inspired CO₂ were observed when O₂ mixtures were entrained using the venturi valve (Fig. S5 in Supplementary Information).

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Figure 1 Decathlon Easybreath Adult Surface Snorkeling mask with additively manufactured modified valve.

Moreover, the application of a positive end-expiratory pressure (PEEP) valve to the expiratory line did not alter the performance of either mask, nor did the level of PEEP (range: 5–20 cmH₂O) systematically affect the F_IO₂ or degree of rebreathing (Fig. S6 in Supplementary Information). However, high levels of PEEP (15–20 cmH₂O) delivered to the Snorkel mask caused

significant leak resulting from the mask ‘lifting’ off the face.

Figure 3 demonstrates the effectiveness of both the CPAP and Decathlon snorkel mask to simultaneously deliver CPAP and high-flow O₂. As expected, the application of CPAP reduced (i.e. diluted) the O₂ delivered to the mask. Specifically, CPAP of 10 cmH₂O delivered with 15 L/min O₂ (100%) produced F_IO₂ values of 73% (sealed CPAP mask at 15 bpm) and 66% (snorkel mask at 15 bpm). For both masks, the magnitude of O₂ dilution increased with higher levels of CPAP. Entrainment of 30 L/min of O₂ largely offset this dilution effect and produced higher F_IO₂ values at all CPAP levels for both masks. These F_IO₂ values were comparable to delivering 100% O₂ alone (without CPAP) at 15 L/min. For the CPAP mask, increasing pressure resulted in a small linear decrease in F_IO₂ at a rate of 0.8%/cmH₂O (15 bpm). In contrast, the snorkel mask demonstrated a steeper, non-linear decline in F_IO₂, which accelerated at CPAP >12 cmH₂O. This was coincident with an increasing leak, which resulted in the delivered mask pressure plateauing at 14 cmH₂O, despite further increases in the CPAP setting. Data from the oronasal mask (and snorkel mask ≤12 cmH₂O) show CPAP level was stable and minimally affected by O₂ entrainment (Fig. 2).

Both participants indicated that the oronasal CPAP mask was more comfortable compared to the snorkel mask (further details regarding subjective assessments of mask tolerability are provided in Appendices S2, S3 in Supplementary Information).

Our study demonstrates that the Decathlon Easybreath snorkel mask (i) delivers consistently lower F_IO₂, (ii) demonstrates higher CO₂ rebreathing and (iii) leaks to a greater degree at high CPAP levels, when

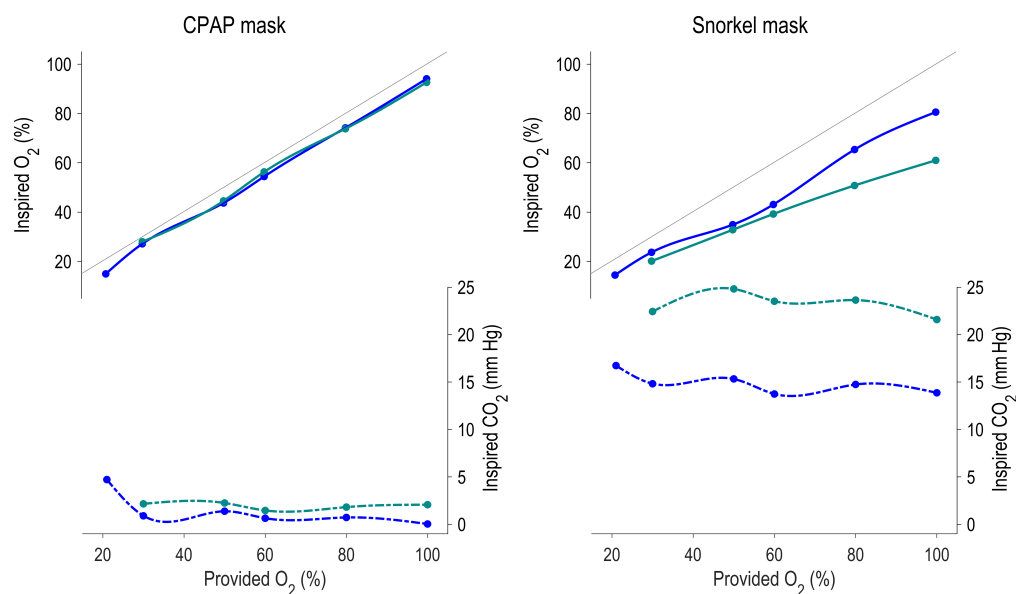


Figure 2 Mask performance of blended O₂ circuits. Inspired O₂ fraction (F_IO₂) (left y-axis) versus the provided O₂ (x-axis) for both continuous positive airway pressure (CPAP) and snorkel masks are shown for both 15 (—) and 30 (—) breaths/min (bpm) respiratory rates. Various F_IO₂ levels were achieved by blending 100% O₂ and medical air. The degree of inspired CO₂ due to rebreathing is shown for both masks on the lower panels (right y-axis). Grey line represents the line of identity.

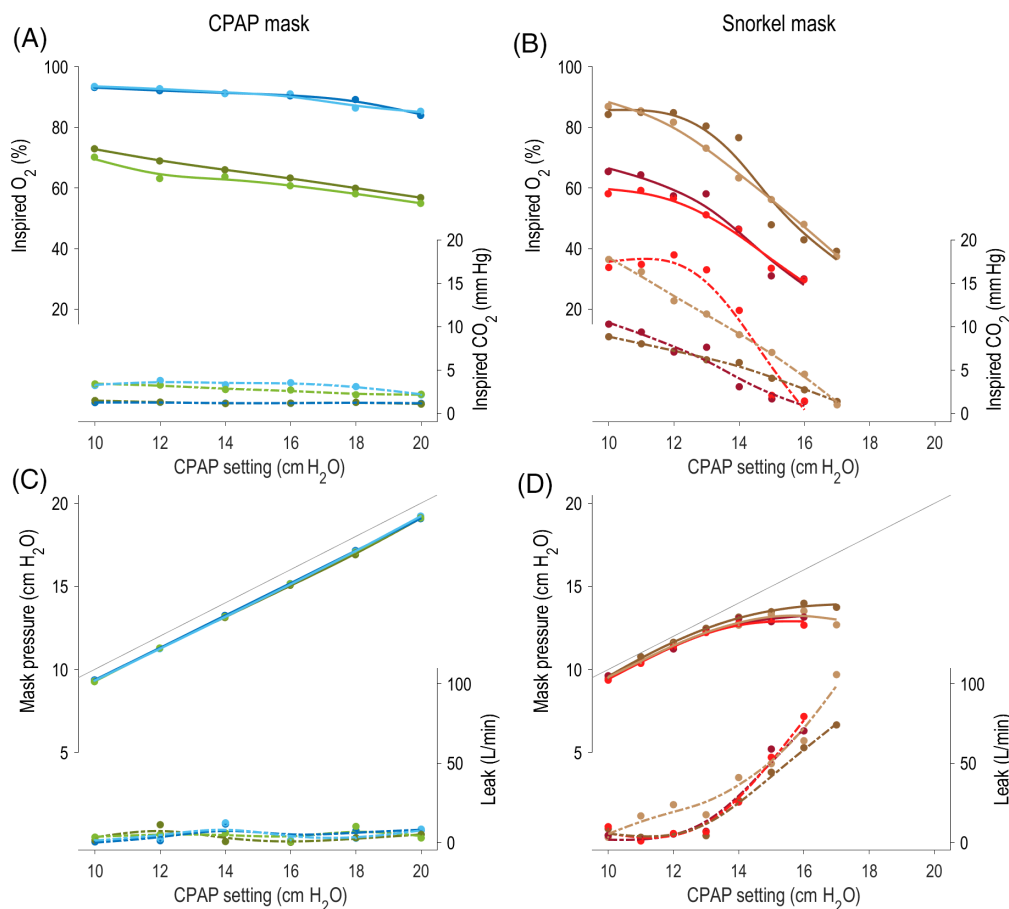


Figure 3 Mask performance for continuous positive airway pressure (CPAP) and O₂ entrainment. (A, B) Inspired O₂ fraction (F_IO₂) (left y-axis) and inspired CO₂ (right y-axis) across a range of CPAP settings (x-axis) for both the oronasal CPAP mask and the Decathlon snorkel mask. (C, D) Mask pressure (left y-axis) and mask leak (right y-axis) characteristics for the same CPAP settings. All data are shown at both 15 and 30 breaths/min (bpm) respiratory rates, and 15 and 30 L/min (lpm) O₂ entrainment (—, CPAP mask, O₂ 30 lpm, 15 bpm; —, CPAP mask, O₂ 30 lpm, 30 bpm; —, CPAP mask, O₂ 15 lpm, 15 bpm; —, CPAP mask, O₂ 15 lpm, 30 bpm; —, snorkel, O₂ 30 lpm, 15 bpm; —, snorkel, O₂ 30 lpm, 30 bpm; —, snorkel, O₂ 15 lpm, 15 bpm; —, snorkel, O₂ 15 lpm, 30 bpm).

compared to a sealed oronasal CPAP mask. However, its ease of fit and one-way valve to entrain room air make it a versatile alternative.

A possible reason for the consistently lower F_IO₂ with the snorkel mask compared to a CPAP mask is the one-way valve at the front of the snorkel mask that allows entrainment of room air. An advantage of this valve is that it creates a one-way open circuit such that delivered gases do not need to be precisely matched to minute ventilation, and allows for dilution of delivered O₂ with room air within the mask. Experiments applying positive pressure partly prevent opening of the valve and thus improve F_IO₂ delivery. The snorkel mask can effectively deliver CPAP levels up to 14 cmH₂O. However, above this level, significant leak develops across the forehead seal of the mask prohibiting the ability to deliver higher pressures (despite increases in set pressure). In a COVID-19 setting, any excessive leak could be problematic as virus aerosolization is a risk for nosocomial spread. Our data show that there was a sharp increase in leak from the snorkel mask beginning at 12 cmH₂O. In contrast, the

ornasal CPAP mask had fewer difficulties with higher CPAP levels and must be preferred in the setting of delivering higher pressures to COVID-19 patients.

Importantly, during the CPAP and O₂ pressure experiments, we were able to demonstrate the ability of standard CPAP with 30 L/min O₂ entrained to deliver high mask F_IO₂ at consistent CPAP levels. This is a critical demonstration of the equipment capabilities above manufacturer specifications that will give clinicians confidence in delivering treatment in this way.

The snorkel mask demonstrated a higher level of CO₂ accumulation at the mask (maximum recorded: 25 mmHg, ~3%) compared to the CPAP mask (5 mmHg, ~0.6%). We feel these levels are tolerable for several hours for most patients receiving care. Caution is advised for hypercapnic patients.

In summary, we have compared the performance characteristics of an adapted Decathlon Easybreath snorkel mask to a standard oronasal CPAP mask for a range of blended O₂ and CPAP delivery levels. The Decathlon snorkel mask presents a viable and simpler alternative for selected patients; however, use should

be limited to CPAP levels below 12 cmH₂O. Standard CPAP with entrained O₂ and oronasal mask performs above manufacturer specifications and delivers stable CPAP at high F_IO₂. In patients suspected of having COVID-19, mask leak levels should be closely monitored regardless of PAP level or interface type.

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Abbreviations: BMI, body mass index; bpm, breaths/min; CPAP, continuous PAP; COVID-19, coronavirus disease 2019; FIO₂, inspired O₂ fraction; lpm, L/min; PAP, positive airway pressure; PEEP, positive end-expiratory pressure

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Supplementary Information

Additional supplementary information can be accessed via the *html* version of this article at the publisher's website.

Appendix S1 Methods.

Appendix S2 Results.

Appendix S3 The Landry Intolerability Scale.

Figure S1 Decathlon Easybreath Adult Surface Snorkeling Mask with additively manufactured modified valve attached (left). Close-up photographs of the 3D printed valve (right).

Figure S2 Respiratory circuit for experiment 1 for both sealed CPAP mask (top two panels) and snorkel mask (bottom two panels).

Figure S3 Respiratory circuit for experiment 1b attached to sealed CPAP mask (left) and snorkel mask (right).

Figure S4 Respiratory circuit for experiment 2 attached to sealed CPAP mask (left) and snorkel mask (right).

Figure S5 Results from the venturi valve when set at 30% and 50% for sealed CPAP mask (left) and snorkel mask (right).

Figure S6 Results from the PEEP experiment for sealed CPAP mask (left) and snorkel mask (right).

Figure S7 General intolerability of each mask (CPAP mask and snorkel mask) for (A) venturi versus wall, (B) PEEP level and (C) CPAP level.

Table S1 Directions for mixing O₂ concentrations using O₂ and medical air.