

Comparison of tissue oxygenation achieved breathing oxygen using different delivery devices and flow rates

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Key words

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Abstract

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Introduction: Divers with suspected decompression illness require high concentration oxygen (O₂). There are many different O₂ delivery devices, with few data comparing their performance. This study evaluated O₂ delivery, using tissue O₂ partial pressure (P_{tc}O₂), in healthy divers breathing O₂ via three different delivery devices.

Methods: Twelve divers had P_{tc}O₂ measured at six limb sites. Participants breathed O₂ from: a demand valve using an intraoral mask with a nose clip (NC); a medical O₂ rebreathing system (MORS) with an oronasal mask and with an intraoral mask; and a non-rebreather mask (NRB) at 15 or 10 L·min⁻¹ O₂ flow. In-line inspired O₂ (F_IO₂) and nasopharyngeal F_IO₂ were measured. Participants provided subjective ratings of device comfort, ease of breathing, and overall ease of use.

Results: P_{tc}O₂ values and nasopharyngeal F_IO₂ were similar with the demand valve with intraoral mask, MORS with both masks and the NRB at 15 L·min⁻¹. P_{tc}O₂ and nasopharyngeal F_IO₂ values were significantly lower with the NRB at 10 L·min⁻¹. The NRB was rated as the most comfortable to wear, easiest to breathe with, and overall the easiest to use.

Conclusion: Of the commonly available devices promoted for O₂ delivery to injured divers, similar P_{tc}O₂ and nasopharyngeal F_IO₂ values were obtained with the three devices tested: MORS with an oronasal or intraoral mask, demand valve with an intraoral mask and NRB at a flow rate of 15 L·min⁻¹. P_{tc}O₂ and nasopharyngeal F_IO₂ values were significantly lower when the flow rate using the NRB was decreased to 10 L·min⁻¹.

Introduction

High concentration oxygen (O₂) therapy is an important early first aid treatment for injured divers. Complete relief or improvement of the symptoms of decompression illness (DCI) has been seen in divers receiving pre-hospital normobaric O₂ therapy.¹ The current pre-hospital care recommendation for divers with symptoms and signs of DCI is for O₂ delivery at the highest possible inspired fraction (close to 100%).² However, there are many factors that need to be considered when choosing the most appropriate O₂ delivery system for a dive operation.^{3,4}

A variety of portable O₂ delivery units have been designed to provide divers with pre-hospital O₂.^{3,5} These units incorporate one of two basic operating configurations: (1) a constant O₂ flow configuration used with a non-rebreather mask (NRB), medical O₂ rebreathing system (MORS) or other constant flow delivery devices; and (2) a patient triggered demand valve configuration. The recommended initial O₂ flow rate with the NRB mask for divers with suspected DCI has long been 15 L·min⁻¹.⁶ Divers Alert Network (DAN) America reduced its recommended O₂ flow rate to between 10 to 15 L·min⁻¹, to extend the duration of often limited O₂ supplies in the field, while still providing high levels of oxygenation.⁷ However, the effect of lower

flow rates on tissue oxygenation is unknown. A previous study comparing tissue oxygenation found that the NRB at 15 L·min⁻¹ performed better than the demand valve with an oronasal mask.⁸ However, a subsequent study showed that the demand valve provided the best tissue oxygenation when used with an intraoral mask and nose clip (NC);⁹ almost certainly because the intraoral mask eliminated leaks that were occurring with the oronasal mask.

The present study used transcutaneous oximetry measurement (TCOM) to determine tissue oxygenation at multiple standardised sites in participants breathing O₂ from a demand valve using an intraoral mask with a NC; a MORS with an oronasal mask and with an intraoral mask; and a NRB at 15 and 10 L·min⁻¹. The primary null hypothesis was that there would be no clinically significant difference in the partial pressure of transcutaneous tissue O₂ (P_{tc}O₂) achieved after 10 min of breathing O₂ with any of the different O₂ delivery devices or flow rates.

Methods

Ethics approval was granted from The Townsville Health Service District Human Research Ethics Committee (HREC16/QTHS/196). Healthy, non-smoking, adult certified scuba divers of both sexes were recruited for the study. Facial hair or anatomical abnormality that may impair mask seal, any medical condition or medication that may affect tissue oxygenation, or an allergy to topical anaesthetic were exclusion criteria. Written informed consent was provided by all participants prior to their participation.

Participants refrained from consuming food or caffeine or performing heavy exercise for six hours prior to participating in the study. Demographic data, anthropometric measurements, and resting baseline measurements were collected. Tidal volume (VT) was measured at rest using the EasyOne Spirometer (ndd Medical Technologies, Andover MA, USA) according to the manufacturer's instructions (average over 3–5 breaths). The participants rested in a supine position with their head on one pillow for the duration of the study. The test-room temperature was maintained between 22.4 and 22.9°C; to limit any vasoconstrictive effects of being cold, participants were covered with a blanket.

An 8 French paediatric feeding tube (ConvaTec Ltd., Deeside, UK) was inserted into the right nares after application of topical lignocaine (5%) and phenylephrine (0.5%) (Co-Phenylcaine™ forte spray, ENT Technologies Pty Ltd., Hawthorne East, Australia). Tube position was visually verified with the tip just proximal to the soft palate.⁹ The tube was then attached to the E-sCO-OO module of a bedside monitor (GE Carescape Monitor B650, GE Healthcare Finland OY, Helsinki, Finland) allowing for both inspired O₂ (F_IO₂, paramagnetic) and end-tidal carbon dioxide (E_tCO₂, infrared) measurements via a water trap (D-fend Pro+ Water Trap™, GE Healthcare Finland OY,

Helsinki, Finland). Room air gas calibration was completed before each breathing system was used. The gas sampling rate was 120 ml·min⁻¹.

TCOM is a non-invasive technique that uses heated electrodes on the skin to measure the P_{tc}O₂¹⁰ and was thought to provide a relevant measurement of tissue O₂ delivery in a study drawing an inference about tissue inert gas elimination. P_{tc}O₂ was measured using the TCM400 transcutaneous (tc) PO₂ Monitoring System (Radiometer, Copenhagen, Denmark) with tc Sensor E5250. Zero current calibration of the P_{tc}O₂ electrode was performed using CAL2 gas (10% CO₂ with N₂ as balance) prior to commencement of the study, and calibration with atmospheric air occurred prior to each monitoring period. A 'humidity correction factor' was entered into the machine prior to each monitoring period. All assessments were performed by the same technician. The TCM400 displayed P_{tc}O₂ values in units of mmHg (average of previous monitoring intervals).

Six sensors were used: three on the left arm and three on the left leg.⁹ Arm sensors were placed on the upper arm, lateral aspect of the lower arm, and the palm of the hand. Leg sensors were placed on the lateral leg, lateral ankle, and dorsum of the foot. Participants rested quietly while the sensors were placed. They were requested to minimise talking during the study as a method of control but were not allowed to sleep. Initial normobaric room air readings from all sensors were recorded after a minimum 20-min equilibration period that allowed all sensors to stabilize.

The participants were then asked to breathe O₂ for 10 min from the following devices in randomized order determined using the random number generator in Microsoft® Excel (Microsoft Corporation, Redmond Washington, USA):

- Demand valve (L324-020, Life Support Products, Allied Healthcare Products, St. Louis, MO, USA) with intraoral mask and NC held in place by the participant (NuMask® Inc., Woodlands Hills, CA, USA) (Figure 1);
- MORS (Wenoll-System, EMS GmbH, Möhrendorf, Germany) (Figure 2) with intraoral mask and NC held in place by the participant;
- MORS with air-cushion oronasal mask and a 4-strap mask holder (Figure 3);
- NRB mask at 15 L·min⁻¹ with elastic strap (Sturdy Industrial Co. Ltd, New Taipei City, Taiwan);
- NRB mask at 10 L·min⁻¹ with elastic strap.

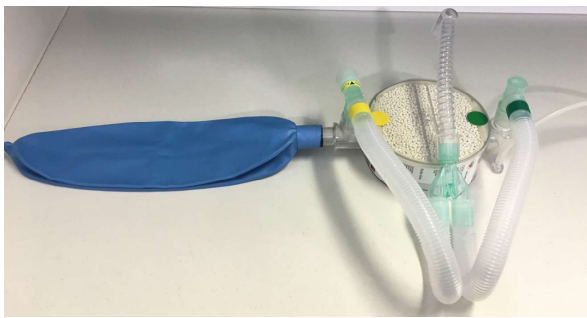
The demand inhalator valve provided in portable DAN O₂ units was used for this study. A flexible high-pressure O₂ hose was used to connect the demand valve to the hospital wall medical grade O₂ outlet (415 kPa delivery pressure). The demand valve was attached to a spacer with a side port allowing pressure and gas measurements (Figure 1). A pressure line was attached to the side port and then to the bedside monitor via a BD DTXPlus™ pressure transducer (Argon Medical Devices Inc., Frisco, TX, USA). The monitor was configured to settings used for central venous

Figure 1

Configuration of demand valve, spacer with side port (allowing pressure and gas measurements), and intraoral mask

**Figure 2**

Medical oxygen rebreathing system (Wenoll-System)

**Figure 3**

Oronasal mask provided with the Wenoll-System and four-strap holder; oronasal mask secured in position on participant's face



pressure monitoring to give a high sensitivity in the lower range and zeroed before each participant. A single, new demand valve was used in the study and verification of inspiratory opening pressure required to trigger the valve and the expiratory resistance pressure was made prior to the commencement of each new participant. The demand valve configuration with intraoral mask and NC, from previous optimization trials, was used in this current research.⁹ Mask and circuit dead space was determined by measuring the amount of water required to fill each device. Mask fill levels were estimated by filling the masks with water and then placing a mannequin's face into the mask.

The NRB was examined to ensure there were three one-way valves in place and then primed with O₂ to inflate the reservoir bag. The NRB was positioned and adjusted to obtain the best seal possible. Participants were asked to

breathe normally, and the reservoir bag was monitored for persistent inflation during the breathing periods.

When using the demand valve participants were asked to breathe deeply enough to trigger the valve as outlined in DAN educational material.^{6,7}

The Wenoll MORS system was primed with 40 L·min⁻¹ of O₂ until the rebreathing bag was completely filled, and the oronasal mask was attached with a four-strap holder. The O₂ flow was 1.5 L·min⁻¹ during the 10-min breathing periods as outlined in the Wenoll-System operation manual.

In-line F_IO₂, nasopharyngeal F_IO₂, P_{tc}O₂, and other respiratory measures were recorded at the end of the 10-min breathing period, once P_{tc}O₂ had stabilized. In-line and nasopharyngeal F_IO₂ measurements were performed to determine if there is a difference between O₂ delivered by a device (in-line) and the O₂ reaching the upper airway (nasopharyngeal). Nasopharyngeal gas sampling was intermittent (every two min) throughout the O₂ breathing periods to prevent clogging of the catheter and to capture peak values. After each 10-min O₂ breathing period, participants breathed room air for 10 min, allowing all P_{tc}O₂ levels to return to baseline before the next device was trialled.¹¹ At the end of the data collection period all participants used a five-point Likert scale to rate each configuration on mask comfort, ease of breathing, and overall ease of use of each device. A final open-ended question asked about any adverse effects while breathing O₂.

ANALYSIS

All collected data were de-identified and entered into an Excel worksheet, and subsequently exported into Statistical Package for the Social Sciences version 25.0.0 (SPSS, IBM® Corporation, Armonk, New York, USA) for analysis.

Based on previous research when participants breathed 100% O₂, mean P_{tc}O₂ values between 199 mmHg (26 kPa) (dorsum of foot) and 454 mmHg (60 kPa) (upper arm) were expected.¹² Each sensor site generally has slightly different values, however, a decrease of 75 mmHg (10 kPa) across any of these sites was assumed to be clinically significant. Based on the values above and allowing for substantial correlation (r = 0.90) between the repeated measures, a sample size of 12 participants would provide a power of 90% (with α = 0.05) to detect clinically significant reductions in tissue oxygenation. In this context, 'clinically significant' was intended to mean a reduction in tissue O₂ delivery sufficient to indicate a potentially important corresponding reduction in the diffusion gradient for inert gas from tissues into blood. There are no published data which demonstrate how such gradients can be inferred from changes in tissue oxygenation, so a threshold tissue oxygenation change of 75 mmHg (10 kPa) (smallest increase in P_{tc}O₂ at one sensor site breathing 100% O₂ with a hood¹²) was agreed by consensus of the physiologists and clinicians involved in the study.

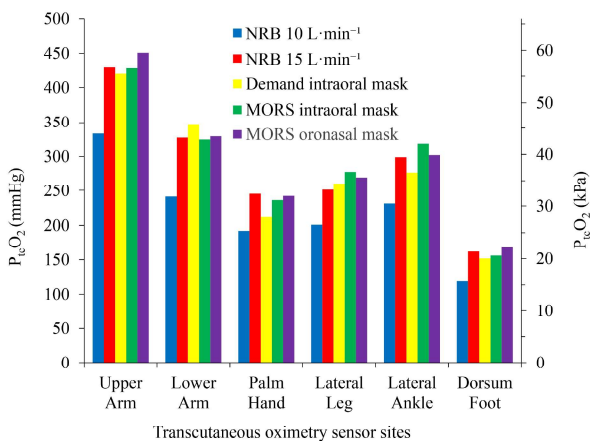
Table 1

Demographic and baseline measurements for the 12 participants breathing air. Optimal waist-to-hip ratios are < 0.82 for males and < 0.71 for females. BP = blood pressure. IQR = inter-quartile range

Characteristic	Median (IQR)	Range
Age (years)	30 (28, 32)	21–34
Body mass index (kg·m ²)	19 (15, 22)	15–24
Waist-to-hip ratio		
Males	0.86 (0.82, 0.87)	0.82–0.87
Females	0.74 (0.72, 0.80)	0.67–0.93
Heart rate (beats·min ⁻¹)	67 (59, 70)	50–94
Systolic BP (mmHg)	112 (111, 119)	100–128
Diastolic BP (mmHg)	66 (57, 73)	54–82
Respiratory rate (breaths·min ⁻¹)	14 (12, 16)	12–16
Tidal volume (ml)	745 (533, 913)	470–1130
Oxygen saturation (%)	97 (96, 98)	96–99
End-tidal CO ₂ (mmHg)	39 (37, 45)	36–46

Figure 4

Median transcutaneous oxygen partial pressures (mmHg) after breathing oxygen for 10 min with different devices and flow rates; NRB = non-rebreather mask; MORS = medical oxygen rebreathing system



The Shapiro-Wilk test was used to evaluate normality of data distribution. None of the data were normally distributed. Differences between median P_{tc}O₂, E_TCO₂, in-line, and peak and across device over time nasopharyngeal F_IO₂ readings using the various devices and flow rates were analysed using the Friedman test with *post hoc* paired analyses completed using the Wilcoxon signed-rank test with Bonferroni correction. For the *post hoc* tests, a corrected *P*-value of 0.005 (0.05/10) was considered significant for the P_{tc}O₂ values and a corrected *P*-value of 0.01 (0.05/4) for the 2-min nasopharyngeal F_IO₂ values.

The primary outcome measure was a comparison of the median P_{tc}O₂ measurements recorded across the six sensor sites after breathing O₂ for 10 min using each device and flow rate. Secondary outcome measures included in-line and

nasopharyngeal F_IO₂, E_TCO₂, and participant-rated mask comfort, ease of breathing and overall use of each device.

Results

Twelve healthy volunteers, nine females and three males, met all inclusion criteria and completed the study protocol. Their demographic and baseline measures breathing room air are shown in Table 1.

Figure 4 displays the median P_{tc}O₂ readings across all sensor sites and breathing devices and flow rates. Baseline P_{tc}O₂ values, median and IQR for each sensor site after breathing O₂ for 10 min are presented in Table 2. P_{tc}O₂ values were statistically different across each breathing device and flow rate for each sensor site (Table 2). *Post hoc* analysis showed there were no significant differences in P_{tc}O₂ values between the NRB 15 L·min⁻¹, demand valve and MORS with intraoral or oronasal mask. Some differences in median P_{tc}O₂ readings between devices at the same sites met the 75-mmHg (10 kPa) threshold for clinical significance, but only in comparisons between the NRB 10 L·min⁻¹ with other devices. The median P_{tc}O₂ readings achieved using the NRB 10 L·min⁻¹ were more than 75 mmHg (10 kPa) less than all other devices (including the NRB 15 L·min⁻¹) at the upper and lower arm sites, and at the lateral leg and ankle sites in comparison to the MORS with intraoral mask. No comparisons of the median P_{tc}O₂ between other devices met the threshold for clinical significance.

Peak nasopharyngeal F_IO₂ was highest breathing O₂ at 15 L·min⁻¹ with the NRB and lowest when breathing O₂ at 10 L·min⁻¹ with the NRB (Table 3). One participant’s nasopharyngeal F_IO₂ value at 10 min while breathing using the demand valve was unattainable due to catheter clogging. There was a significant effect of time on nasopharyngeal F_IO₂ for the MORS (Figure 5). It was shown that for the MORS with intraoral mask, nasopharyngeal F_IO₂ was

Table 2

Transcutaneous oxygen partial pressures (median and inter-quartile range shown in mmHg) while breathing oxygen using the different devices and flow rates; * statistically significantly greater than NRB 10 L·min⁻¹ based on Wilcoxon signed-rank test with Bonferroni correction; # *P*-values based on the Friedman test; NRB = non-rebreather mask; MORS = medical oxygen rebreathing system

Site	Baseline (room air)	10 L·min ⁻¹ NRB	15 L·min ⁻¹ NRB	Demand with intraoral mask	MORS with intraoral mask	MORS with oronasal mask	<i>P</i> -value [#]
Upper arm	70 (61,77)	333 (285, 382)	429 (408, 464)*	420 (373, 465)	428 (385, 476)*	451 (375, 480)*	0.002
Lower arm	65 (58,70)	241 (217, 304)	327 (296, 405)*	348 (264, 370)	324 (286, 405)*	329 (313, 370)*	0.004
Palm hand	66 (63,74)	192 (151, 266)	245 (202, 275)	212 (179, 239)	236 (190, 293)*	242 (163, 289)	0.008
Lateral leg	57 (49,64)	201 (172, 233)	251 (217, 335)*	261 (208, 353)	278 (224, 350)*	270 (219, 330)*	0.004
Lateral ankle	62 (48, 67)	231 (152, 260)	299 (228, 336)*	277 (235, 342)	318 (221, 361)	302 (246, 319)*	0.002
Dorsum foot	54 (50, 65)	119 (88, 149)	162 (133, 226)*	152 (118, 220)	156 (93, 205)	168 (125, 198)*	0.008

Table 3

Inspired oxygen and respiratory measures while breathing oxygen using different devices and flow rates (median and inter-quartile range) and estimated mask and circuit dead space; NRB = non-rebreather mask; MORS = medical oxygen rebreathing system; n/a = not applicable; E_TCO₂ = end-tidal carbon dioxide; **P*-values based on the Friedman test

Parameter	10 L·min ⁻¹ NRB	15 L·min ⁻¹ NRB	Demand with intraoral mask	MORS with intraoral mask	MORS with oronasal mask	* <i>P</i> -value
In-line F _I O ₂ (%)	n/a	n/a	95 (92, 95)	93 (89, 95)	91 (88, 93)	0.045
Peak nasopharyngeal F _I O ₂ (%)	89 (75, 93)	97 (94, 98)	92 (88, 94)	91 (88, 95)	90 (88, 92)	0.013
E _T CO ₂ (mmHg)	39 (35, 43)	38 (34, 43)	38 (33, 41)	38 (32, 44)	39 (36, 43)	0.743
Respiratory rate (breaths·min ⁻¹)	12 (10, 15)	12 (10, 16)	10 (8, 12)	11 (8, 12)	12 (8, 14)	0.055
Mask + circuit dead space (ml)	95	95	14	14 + 350	136 + 350	n/a

significantly higher at time points 3, 4 and 5 (6, 8 and 10 min) compared to time 1 (*P* < 0.01). Nasopharyngeal F_IO₂ at all time points (4, 6, 8 and 10 min) was significantly higher than time point 1 breathing with the MORS and oronasal mask (*P* < 0.01). Both sets of results reflect a roughly linear increase in F_IO₂ over O₂ administration time. There was no statistical difference between the nasopharyngeal F_IO₂ values at each time point for any of the other breathing devices. Figure 6 illustrates the rise in P_{tc}O₂ values over the 10-min O₂ breathing periods, mirroring the rise in F_IO₂ values for the MORS.

E_TCO₂ was similar for all devices and flow rates. In-line F_IO₂ did not exceed 97% with any of the devices and was lowest using the MORS with oronasal mask (80%; Table 3). Estimated mask assembly and circuit dead space is presented in Table 3. Actual individual NRB and oronasal mask volumes would vary slightly depending on each participant's facial features.

Participant ratings for mask comfort are presented in Table 4. Ease of breathing rating for each device is listed

in Table 5. The NRB was rated as overall easiest to use (Table 6). On *post hoc* analysis no statistical difference was found between each device.

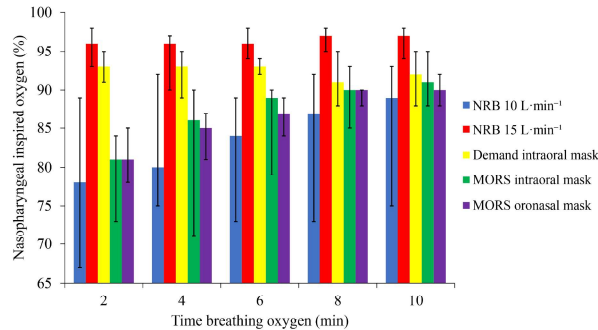
Discussion

High concentration O₂ is the primary first aid treatment for divers suspected of having DCI.^{2,3,13} O₂ has been shown in retrospective reviews to improve symptoms and decrease the subsequent number of hyperbaric treatments required.¹ Of the tested commercially available O₂ delivery systems designed for diver first aid, our study has shown that all systems can provide similar levels of tissue oxygenation and nasopharyngeal F_IO₂. However, when breathing with the NRB, an O₂ flow rate of 15 L·min⁻¹ is required to reach these levels.

Peak nasopharyngeal F_IO₂ was highest with the NRB with a flow rate of 15 L·min⁻¹ (Table 3) though 10-min P_{tc}O₂ values were similar for each device. This probably reflects the variability in breathing patterns of each participant and flow direction of the O₂. Nose breathing during use of the NRB

Figure 5

Median (IQR) nasopharyngeal inspired oxygen percentage recorded every two min for each delivery device and flow rate; NRB = non-rebreather mask; MORS = medical oxygen rebreathing system



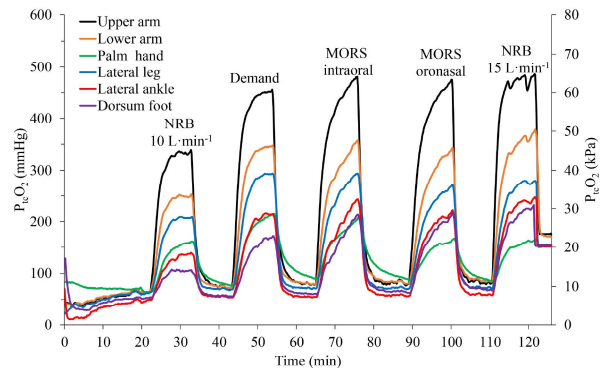
may explain the favourable nasopharyngeal $F_{I}O_2$ results. When breathing with the MORS on the oronasal mask, some participants stated that they kept their mouths slightly open to ensure good fit of the mask, potentially bypassing the nasopharyngeal catheter through mouth breathing. Using the intraoral mask, the O_2 flow may have been directed slightly below the nasopharyngeal catheter through obligatory mouth breathing. This illustrates the importance of clearly describing the position of sampling ports in a research protocol and the potential variability in results if O_2 is measured at different sites. $P_{tc}O_2$ better reflects actual O_2 delivery to the body tissues whereas the nasopharyngeal $F_{I}O_2$ is subject to the above possible confounders.

Portable O_2 delivery units can provide a constant flow capability or operate as a pressure-triggered demand valve. The demand valve only delivers O_2 when the diver inhales and therefore allows for conservation of O_2 , dependent on the respiratory minute volume of the user. The ease of use, familiarity for divers, potential to deliver high inspired O_2 concentrations,¹⁴ as well as the potential for O_2 supply conservation, has led to the recommendation of the demand valve as the O_2 delivery method of choice in the prehospital treatment of DCI.³ However, previous research unexpectedly showed that the demand valve with oronasal mask provided less tissue O_2 than a constant flow NRB.⁸ In the present study, $P_{tc}O_2$ readings whilst breathing O_2 via the demand valve with an intraoral mask and NC were similar to those achieved with a NRB at 15 L·min⁻¹. The previous contradictory findings⁸ were almost certainly explained by poor fit of the oronasal mask and subsequent entrainment of ambient air.⁹

The MORS provided similar oxygen levels regardless of the mask used. The oronasal mask provided with the system has an adjustable air-filled cushion to optimize mask fit and seal. The 4-point mask strap held the mask onto the face to aid with the seal. Fitting of the mask onto the participants' face prior to the study allowed for a good seal to limit if not eliminate any entrainment of ambient air. Oronasal masks

Figure 6

Transcutaneous oxygen partial pressures (mmHg) for one participant while breathing O_2 using different devices and flow rates over a complete iteration of the study. First 20-min equilibration period, followed by alternating 10-min O_2 and air breathing periods on different devices in randomized order. NRB = non-rebreather mask; MORS = medical oxygen rebreathing system



supplied with a demand valve system do not have the mask strap system, and the diver or first aider must therefore apply pressure to the mask to ensure an adequate seal. The technical difficulty of this almost certainly leads to breaks in the mask seal and entrainment of ambient air, especially because the user must generate negative pressure inside the mask to trigger the demand valve. While both oronasal or intraoral masks provide good O_2 delivery with the MORS, an intraoral mask may provide the highest levels of oxygenation with a demand valve.⁹

The NRB functions as a variable performance device with better oxygenation at a higher flow rate.¹⁵ Unfortunately, this means a greater consumption of O_2 . Demand regulators using an intraoral mask and NC behave as fixed performance devices,⁹ with O_2 consumption based on minute ventilation. The NRB and demand valve are both open systems with exhaled gas lost into the environment. A closed system is most beneficial for O_2 conservation as only low flow O_2 is required.^{5,16} MORS for first aid O_2 delivery are not commonly used by recreational divers, largely due to increased complexity and operational requirements^{3,17} and generally limited availability. However, it is possible that the growing popularity of closed-circuit rebreathers for diving will drive an increased interest in MORS systems for first aid use.

The Wenoll System MORS comes with an air-cushion mask (like a pocket face mask) held tightly in place with a 4-strap holder and a regulator mouthpiece. In this study an intraoral mask rather than the regulator mouthpiece was used with the MORS for better comparison with the demand system. Both masks provided good peak O_2 levels at 10 min, but the MORS took longer to reach peak inspired O_2 than the NRB and demand valve (Figure 5). This is consistent with previous research showing a seven-minute time frame to reach 98–100% inspired O_2 .¹⁶ It is possible that the MORS

Table 4Mask comfort rating for each delivery device (*n (%)*). MORS = medical oxygen rebreathing system; **P*-value = 0.052, Friedman test

Comfort assessment	Non-rebreather mask	Demand: intraoral mask	MORS: intraoral mask	MORS: oronasal mask
1. Very uncomfortable	0	0	0	0
2. Uncomfortable	0	4 (33.3)	3 (25.0)	3 (25.0)
3. Neither	2 (16.7)	2 (16.7)	1 (8.3)	3 (25.0)
4. Comfortable	3 (25.0)	4 (33.3)	6 (50.0)	5 (41.7)
5. Very comfortable	7 (58.3)	2 (16.7)	2 (16.7)	1 (8.3)
Median score (IQR)*	5.0 (4.0–5.0)	3.5 (2.0–4.0)	4.0 (2.3–4.0)	3.5 (2.3–4.0)

Table 5Ease of breathing rating for each delivery device (*n (%)*); MORS = medical oxygen rebreathing system; **P*-value = 0.061, Friedman test

Breathing assessment	Non-rebreather mask	Demand: intraoral mask	MORS: intraoral mask	MORS: oronasal mask
1. Very difficult	0	0	0	0
2. Difficult	0	3 (25.0)	2 (16.7)	1 (8.3)
3. Neither	0	2 (16.7)	1 (8.3)	4 (33.3)
4. Easy	3 (25.0)	1 (8.3)	5 (41.7)	3 (25.0)
5. Very easy	9 (75.0)	6 (50.0)	4 (33.3)	4 (33.3)
Median score (IQR)*	5.0 (4.3–5.0)	4.5 (2.3–5.0)	4.0 (3.3–5.0)	4.0 (3.0–5.0)

Table 6Overall ease of use for each delivery device (*n (%)*); MORS = medical oxygen rebreathing system; **P*-value = 0.009, Friedman test

Overall ease of use assessment	Non-rebreather mask	Demand: intraoral mask	MORS: intraoral mask	MORS: oronasal mask
1. Very difficult	0	0	0	0
2. Difficult	0	3 (25.0)	1 (8.3)	1 (8.3)
3. Neither	0	3 (25.0)	1 (8.3)	2 (16.7)
4. Easy	3 (25.0)	2 (16.7)	4 (33.3)	6 (50.0)
5. Very easy	9 (75.0)	4 (33.3)	6 (50.0)	3 (25.0)
Median score (IQR)*	5.0 (4.3–5.0)	3.5 (2.3–5.0)	4.5 (4.0–5.0)	4.0 (3.3–4.8)

may have delivered greater fractions of O₂ more quickly if a procedure to remove nitrogen (N₂) from the participants' lungs had been employed at the start of breathing on the MORS (typically, by exhaling to atmosphere completely, then inhaling O₂ from the system and exhaling it to the atmosphere for several breaths before breathing exclusively on the MORS). Examination of the P_{tc}O₂ values while breathing O₂ with the MORS showed a plateau at eight to 10 min and therefore the data reported here probably accurately reflect peak values.

Breathing high concentration O₂ eliminates N₂ from the inspired gas and enhances N₂ elimination from the body.³ Open circuit systems release exhaled gas into the environment, allowing for the elimination of N₂. In MORS, the higher O₂ flow rate in the first hour not only improves oxygenation¹⁶ but allows for excess gas in the breathing circuit to be automatically vented through the over-pressure valve, which serves to purge accumulated N₂ into the environment.⁵ Other suggestions for purging excess N₂ from the MORS circuit when used in injured divers include: periodic increase in O₂ flow rates and periodic use of a purge button, if equipped.^{5,16} Monitoring for colour change of the carbon dioxide (CO₂) absorber and spontaneous increase in tidal volume are ways to evaluate scrubber function.⁵

Limiting the usage time of the absorber can prevent CO₂ intoxication.⁵ Formal training in the use of a MORS for O₂ delivery is recommended.

The NRB was rated as the overall easiest to use (Table 6), even though divers are accustomed to breathing from a demand valve with a mouthpiece. Some participants commented on the change in their breathing patterns when using the demand valve, they used their 'diving breathing pattern' of slower deeper breaths. Although not statistically significant, there was a trend towards a slower respiratory rate when breathing with the demand valve (*P* = 0.055) (Table 3).

Three commonly available pre-hospital O₂ delivery systems were evaluated for O₂ delivery, comfort, ease of breathing, and overall use. There are many other factors that need to be considered when selecting the most appropriate O₂ delivery system for a dive operation.^{3,15} Remoteness of diving operations, and therefore a protracted time to arrive at medical care, may increase the need for a system that is more comfortable for the diver but also a system that provides a longer duration of O₂ delivery and CO₂ elimination. Cost, availability and O₂ supplies in different countries may also play an important part in the decision-making process.

Knowledge of individual country guidelines and training requirements are necessary to make educated decisions about appropriate O₂ delivery system selection.

LIMITATIONS

There was a low number of male participants in this study due to a predominance of facial hair. Facial hair was an exclusion factor, as it was thought it could contribute to mask leak.¹⁸ In real world use, facial hair in males may reduce the efficacy of O₂ delivery by a NRB in comparison to a device that does not rely on a facial seal, such as the demand valve or MORS used with an intraoral mask and NC. Previous research shows no significant difference in P_{tc}O₂ results by sex.¹²

Even though a higher P_{tc}O₂ value likely indicates a greater drive for tissue inert gas elimination, bubble resolution and oxygenation of hypoxic tissues,^{3,19,20} this study did not address the clinical efficacy of these O₂ devices in treating DCI or achieving bubble resolution.²¹ Similarly, the arbitrary nature of the consensus decision to use a 75 mmHg (10 kPa) P_{tc}O₂ threshold to power the study and to indicate a meaningful difference in O₂ delivery / outgassing gradient between devices is acknowledged. Therefore, although perhaps indicative, these data do not prove that one device will be associated with greater clinical efficacy than another.

The nasopharyngeal catheter provided valuable information on the oxygenation provided by each delivery system but may have compromised the seal of both the NRB and oronasal mask. The catheter was secured to the nares and laid against the face, passing under the edge of the masks. The oronasal mask has an air-filled cushion which can easily mould around irregular facial features. The NRB has a more rigid edge and may have been more affected by the presence of the catheter.

The oxygen breathing period was limited to 10 min based on previous research^{8,11} where P_{tc}O₂ values had stabilized at that time point. The TCM400 machine has a built-in arrow indicator that depicts upward or downward trends to help clinicians to identify stable peak values (when the arrows disappear). However, in visualizing the nasopharyngeal F₁O₂ values it seems that the values were still rising for the MORS and NRB at 10 L·min⁻¹. Although there was no statistical difference in the values at eight and 10 min, extending the monitoring time beyond the 10 min O₂ breathing period could provide additional information.

Conclusion

The three tested O₂ delivery systems used to treat injured divers (MORS with an oronasal or intraoral mask, demand valve with an intraoral mask and NRB at a flow rate of 15 L·min⁻¹) delivered similar P_{tc}O₂ and nasopharyngeal F₁O₂ values. P_{tc}O₂ and nasopharyngeal F₁O₂ values were lower when the flow rate using the NRB was decreased from

15 to 10 L·min⁻¹. O₂ delivery and supply conservation are important factors to be considered when selecting an O₂ delivery system for a dive operation.

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