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

Denise F Blake[1,2], Melissa Crowe[3], Daniel Lindsay[4], Annie Brouff [5], Simon J Mitchell[6,7], Peter A Leggat[4], Neal W Pollock[8,9]

[1] *Emergency Department, The Townsville Hospital, Townsville, Queensland, Australia*
[2] *Marine Biology and Aquaculture, James Cook University, Townsville, Queensland, Australia*
[3] *Sport and Exercise Science, James Cook University, Townsville, Queensland, Australia*
[4] *College of Public Health, Medical and Veterinary Sciences, James Cook University, Townsville, Queensland, Australia*
[5] *Hyperbaric Medicine Unit, The Townsville Hospital, Townsville, Queensland, Australia*
[6] *Department of Anaesthesiology, University of Auckland, Auckland, New Zealand*
[7] *Department of Anaesthesia, Auckland City Hospital, Auckland, New Zealand*
[8] *Department of Kinesiology, Faculty of Medicine, Université Laval, Québec, Canada*
[9] *Service de médecine hyperbare, Centre de médecine de plongée du Québec, Levis, Québec, Canada*

Corresponding author: *Dr Denise Blake, IMB 23, Emergency Department, The Townsville Hospital, 100 Angus Smith Drive, Douglas, Queensland Australia, 4814*
denise.blake@health.qld.gov.au

Key words
Decompression sickness; Decompression illness; First aid; Masks; Medical kits; Oxygen; Transcutaneous oximetry; Scuba diving

Abstract
(Blake DF, Crowe M, Lindsay D, Brouff A, Mitchell SJ, Leggat PA, Pollock NW. Comparison of tissue oxygenation achieved breathing oxygen using different delivery devices and flow rates. Diving and Hyperbaric Medicine. 2020 March 31;50(1):34–42. doi: 10.28920/dhm50.1.34-42. PMID: 32187616.)

Introduction: Divers with suspected decompression illness require high concentration oxygen (O_2). There are many different O_2 delivery devices, with few data comparing their performance. This study evaluated O_2 delivery, using tissue O_2 partial pressure ($P_{tc}O_2$), in healthy divers breathing O_2 via three different delivery devices.

Methods: Twelve divers had $P_{tc}O_2$ measured at six limb sites. Participants breathed O_2 from: a demand valve using an intraoral mask with a nose clip (NC); a medical O_2 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} O_2 flow. In-line inspired O_2 (F_IO_2) and nasopharyngeal F_IO_2 were measured. Participants provided subjective ratings of device comfort, ease of breathing, and overall ease of use.

Results: $P_{tc}O_2$ values and nasopharyngeal F_IO_2 were similar with the demand valve with intraoral mask, MORS with both masks and the NRB at 15 L·min^{-1}. $P_{tc}O_2$ and nasopharyngeal F_IO_2 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 O_2 delivery to injured divers, similar $P_{tc}O_2$ and nasopharyngeal F_IO_2 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}. $P_{tc}O_2$ and nasopharyngeal F_IO_2 values were significantly lower when the flow rate using the NRB was decreased to 10 L·min^{-1}.

Introduction

High concentration oxygen (O_2) 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 O_2 therapy.[1] The current pre-hospital care recommendation for divers with symptoms and signs of DCI is for O_2 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 O_2 delivery system for a dive operation.[3,4]

A variety of portable O_2 delivery units have been designed to provide divers with pre-hospital O_2.[3,5] These units incorporate one of two basic operating configurations: (1) a constant O_2 flow configuration used with a non-rebreather mask (NRB), medical O_2 rebreathing system (MORS) or other constant flow delivery devices; and (2) a patient triggered demand valve configuration. The recommended initial O_2 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 O_2 flow rate to between 10 to 15 L·min^{-1}, to extend the duration of often limited O_2 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 O_2 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 O_2 ($P_{tc}O_2$) achieved after 10 min of breathing O_2 with any of the different O_2 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 O_2 (F_IO_2, paramagnetic) and end-tidal carbon dioxide (E_TCO_2, 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 $P_{tc}O_2$[10] and was thought to provide a relevant measurement of tissue O_2 delivery in a study drawing an inference about tissue inert gas elimination. $P_{tc}O_2$ was measured using the TCM400 transcutaneous (tc) PO_2 Monitoring System (Radiometer, Copenhagen, Denmark) with tc Sensor E5250. Zero current calibration of the $P_{tc}O_2$ electrode was performed using CAL2 gas (10% CO_2 with N_2 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 $P_{tc}O_2$ 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 O_2 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 O_2 units was used for this study. A flexible high-pressure O_2 hose was used to connect the demand valve to the hospital wall medical grade O_2 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

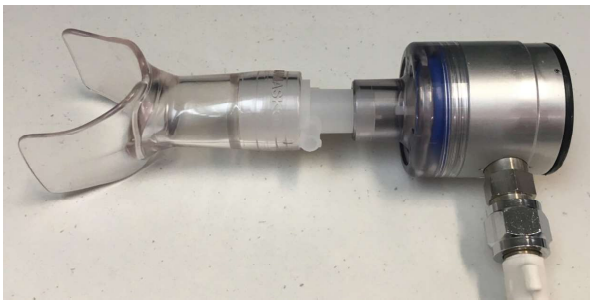


Figure 2
Medical oxygen rebreathing system (Wenoll-System)

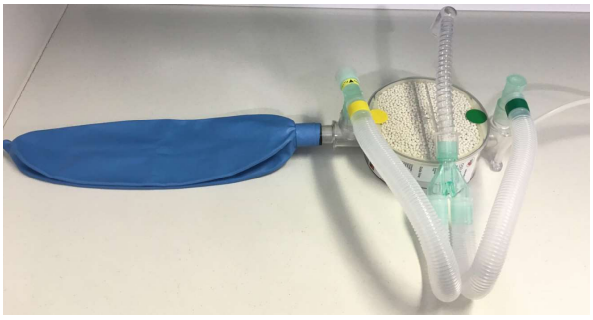


Figure 3
Oronasal mask provided with the Wenoll-System and four-strap holder; oronasal mask secured in position on participant's face

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 O_2 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 $L \cdot min^{-1}$ of O_2 until the rebreathing bag was completely filled, and the oronasal mask was attached with a four-strap holder. The O_2 flow was 1.5 $L \cdot min^{-1}$ during the 10-min breathing periods as outlined in the Wenoll-System operation manual.

In-line F_IO_2, nasopharyngeal F_IO_2, $P_{tc}O_2$, and other respiratory measures were recorded at the end of the 10-min breathing period, once $P_{tc}O_2$ had stabilized. In-line and nasopharyngeal F_IO_2 measurements were performed to determine if there is a difference between O_2 delivered by a device (in-line) and the O_2 reaching the upper airway (nasopharyngeal). Nasopharyngeal gas sampling was intermittent (every two min) throughout the O_2 breathing periods to prevent clogging of the catheter and to capture peak values. After each 10-min O_2 breathing period, participants breathed room air for 10 min, allowing all $P_{tc}O_2$ 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 O_2.

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% O_2, mean $P_{tc}O_2$ 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 $\alpha = 0.05$) to detect clinically significant reductions in tissue oxygenation. In this context, 'clinically significant' was intended to mean a reduction in tissue O_2 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 $P_{tc}O_2$ at one sensor site breathing 100% O_2 with a hood[12]) was agreed by consensus of the physiologists and clinicians involved in the study.

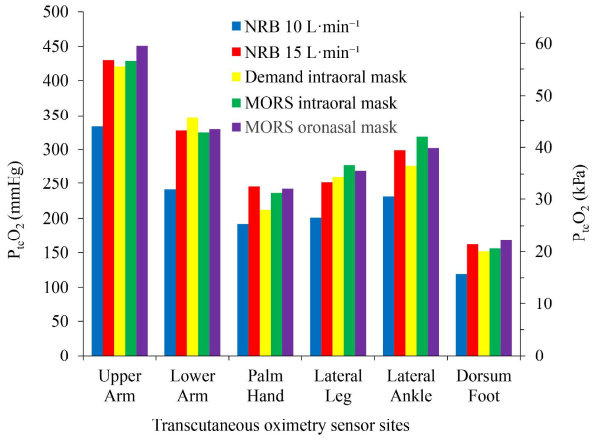
Table 1

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 ($kg \cdot m^2$)	19 (15, 22)	15–24
Waist-to-hip ratio Males Females	 0.86 (0.82, 0.87) 0.74 (0.72, 0.80)	 0.82–0.87 0.67–0.93
Heart rate ($beats \cdot min^{-1}$)	67 (59, 70)	50–94
Systolic BP (mmHg)	112 (111, 119)	100–128
Diastolic BP (mmHg)	66 (57, 73)	54–82
Respiratory rate ($breaths \cdot min^{-1}$)	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 $P_{tc}O_2$, E_TCO_2, in-line, and peak and across device over time nasopharyngeal F_IO_2 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 $P_{tc}O_2$ values and a corrected *P*-value of 0.01 (0.05/4) for the 2-min nasopharyngeal F_IO_2 values.

The primary outcome measure was a comparison of the median $P_{tc}O_2$ measurements recorded across the six sensor sites after breathing O_2 for 10 min using each device and flow rate. Secondary outcome measures included in-line and nasopharyngeal F_IO_2, E_TCO_2, 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 $P_{tc}O_2$ readings across all sensor sites and breathing devices and flow rates. Baseline $P_{tc}O_2$ values, median and IQR for each sensor site after breathing O_2 for 10 min are presented in Table 2. $P_{tc}O_2$ 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 $P_{tc}O_2$ values between the NRB 15 $L \cdot min^{-1}$, demand valve and MORS with intraoral or oronasal mask. Some differences in median $P_{tc}O_2$ 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 $L \cdot min^{-1}$ with other devices. The median $P_{tc}O_2$ readings achieved using the NRB 10 $L \cdot min^{-1}$ were more than 75 mmHg (10 kPa) less than all other devices (including the NRB 15 $L \cdot min^{-1}$) 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 $P_{tc}O_2$ between other devices met the threshold for clinical significance.

Peak nasopharyngeal F_IO_2 was highest breathing O_2 at 15 $L \cdot min^{-1}$ with the NRB and lowest when breathing O_2 at 10 $L \cdot min^{-1}$ with the NRB (Table 3). One participant's nasopharyngeal F_IO_2 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_IO_2 for the MORS (Figure 5). It was shown that for the MORS with intraoral mask, nasopharyngeal F_IO_2 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	*P*-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_TCO_2 = 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	*P-value
In-line F_IO_2 (%)	n/a	n/a	95 (92, 95)	93 (89, 95)	91 (88, 93)	0.045
Peak nasopharyngeal F_IO_2 (%)	89 (75, 93)	97 (94, 98)	92 (88, 94)	91 (88, 95)	90 (88, 92)	0.013
E_TCO_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_IO_2 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_IO_2 over O_2 administration time. There was no statistical difference between the nasopharyngeal F_IO_2 values at each time point for any of the other breathing devices. Figure 6 illustrates the rise in $P_{tc}O_2$ values over the 10-min O_2 breathing periods, mirroring the rise in F_IO_2 values for the MORS.

E_TCO_2 was similar for all devices and flow rates. In-line F_IO_2 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 O_2 is the primary first aid treatment for divers suspected of having DCI.[2,3,13] O_2 has been shown in retrospective reviews to improve symptoms and decrease the subsequent number of hyperbaric treatments required.[1] Of the tested commercially available O_2 delivery systems designed for diver first aid, our study has shown that all systems can provide similar levels of tissue oxygenation and nasopharyngeal F_IO_2. However, when breathing with the NRB, an O_2 flow rate of 15 L·min^{-1} is required to reach these levels.

Peak nasopharyngeal F_IO_2 was highest with the NRB with a flow rate of 15 L·min^{-1} (Table 3) though 10-min $P_{tc}O_2$ values were similar for each device. This probably reflects the variability in breathing patterns of each participant and flow direction of the O_2. 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

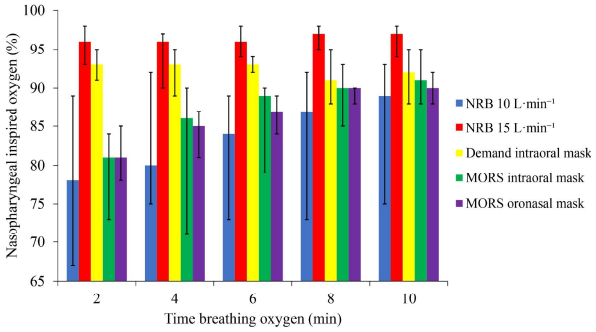
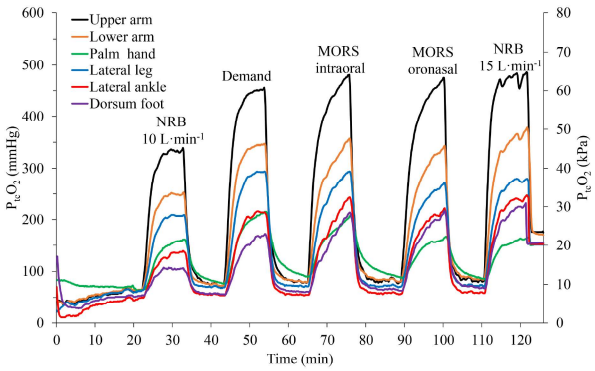


Figure 6

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



may explain the favourable nasopharyngeal F_IO_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_IO_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 findings[8] 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 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 4
Mask 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 5
Ease 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 6
Overall 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 O_2 more quickly if a procedure to remove nitrogen (N_2) from the participants' lungs had been employed at the start of breathing on the MORS (typically, by exhaling to atmosphere completely, then inhaling O_2 from the system and exhaling it to the atmosphere for several breaths before breathing exclusively on the MORS). Examination of the $P_{tc}O_2$ values while breathing O_2 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 O_2 eliminates N_2 from the inspired gas and enhances N_2 elimination from the body.[3] Open circuit systems release exhaled gas into the environment, allowing for the elimination of N_2. In MORS, the higher O_2 flow rate in the first hour not only improves oxygenation[16] but allows for excess gas in the breathing circuit to be automatically vented through the over-pressure valve, which serves to purge accumulated N_2 into the environment.[5] Other suggestions for purging excess N_2 from the MORS circuit when used in injured divers include: periodic increase in O_2 flow rates and periodic use of a purge button, if equipped.[5,16] Monitoring for colour change of the carbon dioxide (CO_2) absorber and spontaneous increase in tidal volume are ways to evaluate scrubber function.[5] Limiting the usage time of the absorber can prevent CO_2 intoxication.[5] Formal training in the use of a MORS for O_2 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 O_2 delivery systems were evaluated for O_2 delivery, comfort, ease of breathing, and overall use. There are many other factors that need to be considered when selecting the most appropriate O_2 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 O_2 delivery and CO_2 elimination. Cost, availability and O_2 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 O_2 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 O_2 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 $P_{tc}O_2$ results by sex.[12]

Even though a higher $P_{tc}O_2$ 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 O_2 devices in treating DCI or achieving bubble resolution.[21] Similarly, the arbitrary nature of the consensus decision to use a 75 mmHg (10 kPa) $P_{tc}O_2$ threshold to power the study and to indicate a meaningful difference in O_2 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 $P_{tc}O_2$ 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 F_IO_2 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 O_2 breathing period could provide additional information.

Conclusion

The three tested O_2 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 $P_{tc}O_2$ and nasopharyngeal F_IO_2 values. $P_{tc}O_2$ and nasopharyngeal F_IO_2 values were lower when the flow rate using the NRB was decreased from 15 to 10 L·min^{-1}. O_2 delivery and supply conservation are important factors to be considered when selecting an O_2 delivery system for a dive operation.

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Acknowledgements

The authors gratefully acknowledge the financial assistance received from the Emergency Medicine Foundation (EMF), Queensland and the in-kind support from Divers Alert Network Asia-Pacific. We also thank our participants, especially those who shaved their facial hair.

Conflicts of interest and funding

Professor Mitchell and Associate Professor Pollock are members of the editorial board of Diving and Hyperbaric Medicine but were not involved in the peer review or publication decision-making process for this article. This process was managed by the European Editor Dr Lesley Blogg.

Submitted: 14 May 2019
Accepted after revision: 07 November 2019