Deep anaesthesia: The Thailand cave rescue and its implications for management of the unconscious diver underwater

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Abstract
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Introduction: In 2018 12 children and one adult were anaesthetised before being extricated through over a kilometre of flooded cave in Thailand. Full face dive masks (FFMs) putatively capable of maintaining constant positive airway pressure (CPAP) were employed. Here we describe the anaesthetic intervention and investigate the CPAP capability of the FFM.
Methods: Pressure was measured inside and outside the Interspiro Divator FFM during 10 tidal and 10 vital capacity breaths in divers at the surface and submerged with the mask deployed on open-circuit scuba (10 divers); and a closed-circuit rebreather (five divers). Relative in-mask pressure was calculated as the difference between inside and outside pressures. We also measured the in-mask pressure generated by activation of the second stage regulator purge valve in open-circuit mode.
Results: When submerged in open-circuit mode the mean relative in-mask pressure remained positive in normal tidal breathing (inhalation 0.6 kPa [95% CI 0.3–0.9]; exhalation 1.1 [0.8–1.4]) and vital capacity breathing (inhalation 0.8 [0.4–1.1]; exhalation 1.2 [0.9–1.4]). As expected, the relative in-mask pressure was predominantly negative when used on closed-circuit with back mounted counter-lungs due to a negative static lung load. Mean in-mask pressure during purge valve operation was 3.99 kPa (approximately equal to 40 cmH_2O) (range: 2.56 to 5.3 kPa).
Conclusions: The CPAP function of the Interspiro Divator FFM works well configured with open-circuit scuba. This may have contributed to the success of the Thailand cave rescue. Caution is required in generalising this success to other diving scenarios.

Introduction

There is consensus among diving medicine experts that prolonged attempts to maintain a safe airway in an unconscious diver underwater carry a high risk of drowning. The corollary is that if a diver loses consciousness underwater, they should be returned to the surface expeditiously even if the breathing system mouthpiece is retained when using a half-mask, or despite use of a full-face mask that appears not to be flooded. In discussing the related conundrum of a diver with a significant decompression obligation who becomes unconscious underwater (due, for example, to a hyperoxic seizure), a recent guideline on the rescue of an unconscious diver at depth highlighted the difficulty of protecting the airway for any length of time and concluded: "*Any attempt to do so might result in drowning, which […] would likely represent a greater threat to life than decompression sickness (DCS) arising from a direct ascent*".[1]

Even where equipment specifically designed to enhance airway protection underwater is used, the same guideline maintained a conservative stance, stating: "*It is evident that under some circumstances the airway could be protected adequately to allow a period of decompression under ideal conditions, and this would be even more likely if the victim were using a full-face mask or a properly designed and deployed mouthpiece retaining device. Any decision to attempt this would depend entirely upon context, and it is reiterated that the path of least risk in the majority of circumstances will be to bring the victim directly to the surface*".[1]

Concerns about airway management in an unconscious diver are not limited to scenarios in which unconsciousness ensues during a dive. There are other plausible scenarios in which an unconscious person may need to be taken underwater. For example, a cave explorer who is rendered unconscious by an accident or medical event in a dry section of a cave may subsequently need to be extricated through an underwater sump. Another improbable but now famous example is detailed in this paper.

While it has been suggested that mouthpiece retaining straps may be effective in preventing drowning after loss of consciousness underwater,[2] discussion of this issue has largely taken place in the absence of relevant evidence. This unsatisfactory situation was recognised at the 2012 'Rebreather Forum Three' meeting where a consensus of participants identified the study of airway protection by mouthpiece retaining straps and full-face masks as research priorities.[3] At the time this consensus was published there was little confidence that the question would ever be addressed in an experimental setting given the obvious ethical concerns with testing airway protection in immersed unconscious humans.

Remarkably, in 2018 an international rescue team was effectively forced into conducting such an experiment in attempting to save the lives of 12 boys and their soccer coach who had become trapped several kilometres inside a flooded cave in Thailand. It is a matter of record that all 12 boys and their coach were successfully brought out through approximately 2.6 km of cave, of which approximately 1.1 km was fully flooded, whilst anaesthetised and wearing full face masks.[4] We use the term 'anaesthetised' intentionally in this setting because the boys were asleep, unresponsive to voice, and not exhibiting purposive movement. In the aftermath of this event it seems appropriate to revisit the issue of managing the unconscious diver underwater, and to address the question of whether the success of this rescue implies a change in the previously quoted 2012 guidelines is appropriate.

The full-face mask (FFM) used in the Thai cave rescue was an Interspiro Divator Full Face Mask (Interspiro, Täby, Sweden), chosen for several reasons including a function designed to maintain a degree of constant positive pressure (referred to by the manufacturer as "*safety pressure*"), throughout the respiratory cycle. In medical terms, this effectively translates to a form of constant positive airway pressure (CPAP) and is henceforth referred to as such. CPAP could serve both to discourage water ingress, and to splint the airway open in an unconscious subject. We found no data available in the public domain which confirmed CPAP is maintained during use of the Interspiro mask, and given the important implications to practice around unconscious diver management, this was investigated in the present study.

This paper begins with an account of the anaesthetic administered to those rescued in Thailand. One of the present authors (RJH) was the anaesthesiologist who performed the initial anaesthetic procedures, while another author (CJC) was prominently involved in supplementary dosing during the rescue. It continues with the methods and results of the Interspiro FFM CPAP-function evaluation. The nature of both the anaesthesia and breathing apparatus are highly relevant to the rescue's implications for management of unconscious divers underwater. These implications are subsequently discussed.

Anaesthesia in the Thailand cave rescue

Reporting of this de-identified rescue narrative and outcome information was deemed out of scope by the New Zealand Health and Disability Ethics Committees but approved by the Chief Medical Commander of the Thailand Cave Rescue.

The relevant author (RJH) is an Australian consultant anaesthetist with over 30 years experience in cave diving. He has a longstanding professional and personal interest in search and rescue operations including some experience in training other cave divers in the practical aspects of through-sump rescue (a 'sump' is a completely flooded section of cave tunnel bounded at each end by areas of dry cave). RJH was called by the British cave divers in Thailand on 05 July 2018, 12 days after the Thai soccer team entered the cave and three days after they were found. The author and his regular dive partner (CJC) flew to Thailand that same day as a small Australian Medical Assistance Team (AUSMAT).

It rapidly became apparent that the best chance of a successful rescue lay in the option of anaesthetising the 13 stranded team members (including the coach). All other viable alternatives had been tried or considered, then eliminated. There were six sumps to traverse and it was felt by the rescuers that any attempt to extricate the team without anaesthesia would result in panic, and the subsequent drowning of either the boy and/or the rescue diver. Although the depths were trivial (≤ 4.5 metres' fresh water) diving conditions were hazardous with moderate strength flow of opaque turbid water, multiple tight restrictions, 'line traps' (places which permit the guiding line followed in the cave to pass, but are too narrow for a diver to follow), and a predicted egress duration of three hours.

Whilst developing the anaesthesia plan, RJH consulted widely with other specialists including paediatric anaesthetists and psychiatrists. With the exception of Edgar Pask during the Second World War,[5] no precedent could be found for immersing anaesthetised humans. Numerous medications were considered including benzodiazepines, clonidine and chloral hydrate. Ketamine hydrochloride was the obvious final choice due to its significant track record in austere environments and developing nations. It has a wide therapeutic index making it forgiving in less skilled hands and can be administered by multiple routes including by intramuscular injection. It has the advantage of maintaining spontaneous respiration in appropriate

dosage, with anaesthetised patients protecting their own airway better than with other sedative drugs and anaesthetic agents.[6] It offers good cardiovascular stability in volume replete patients, and may offer advantages in protecting from hypothermia compared to alternative agents due to the sympathetic activation of peripheral vasoconstriction.[6] Disadvantages of ketamine in the proposed setting included increased salivation, dysphoria and unpleasant emergence phenomena, and difficulty determining the end point of successful anaesthesia, especially by lay persons.

A final plan for the anaesthesia was derived. It was known that the weights of the rescuees were between 30 and 65 kg. For simplicity, especially for the non-medical cave divers who would need to supplement the initial loading dose of ketamine with 'top-up doses' further down the cave, the rescuees were classified as 'large' (approximately 50 kg) or 'small' (approximately 40 kg). Any individual less than 45 kg would be treated as 'small', and anyone over 45 kg would be treated as 'large'. Whilst RJH was able to adjust loading doses of ketamine for the initial induction of anaesthesia at the back of the cave, the other cave divers were instructed to simply give a pre-prepared 'small' (100 mg) or 'large' (125 mg) intra-muscular top-up dose to the rescuees when required (typically indicated by resumption of purposive movement). This meant that some of the rescuees were slightly under- or over-dosed (on a weight basis) during extrication, but this approach avoided the considerable risk of mis-dosage by cave divers trying to tailor dosing more precisely.

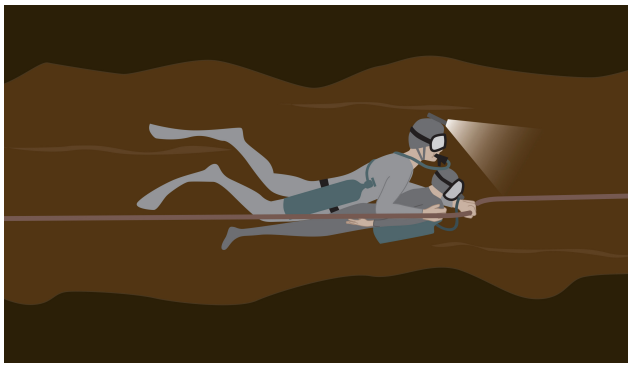
The operation began 15 days after the team entered the cave, and took place over three days (8–10 July) with four individuals rescued on days one and two, and five on day three. On each rescue day, those selected for rescue were fasted from 0600 with the knowledge the rescue team would be in place at approximately midday. First, the child was given 0.5 mg oral alprazolam for anxiolysis and to decrease the risk of awareness and dysphoria. Larger doses or longer acting benzodiazepines were avoided due to concerns around respiratory depression. Over the ensuing 15 minutes the child was dressed in their wetsuit (if not already on) and a horse collar style buoyancy compensation device. Elastic bungees were placed around the child's chest and pelvis which would later be used to retain a front mounted scuba cylinder.

The child then descended the 15 m muddy slope to the waiting anaesthetist (RJH) who administered an intramuscular injection of atropine (as an anti-sialagogue) in the anterolateral thigh with a 23 g hypodermic needle, penetrating the child's wetsuit. Atropine dosage was 20 $mcg \cdot kg^{-1}$ based on a body weight of either forty or fifty kilograms. Ketamine 5 $mg \cdot kg^{-1}$ was then injected into the contralateral thigh with body weight estimated from recently recorded weights with allowance for loss of several kilograms over the starvation period. Once it was clear that a deep level of general anaesthesia had been achieved (the child was unresponsive) with spontaneous respiration maintained, a rescue diver assisted RJH in placing the FFM on the child. The FFM straps were tightened to a degree perceived to exceed that which would normally be comfortable for a diver. The scuba cylinder providing gas to the mask was attached frontally to the two bungee cords placed earlier. The cylinder contained 80% oxygen and 20% nitrogen; the high oxygen fraction chosen to prolong safe apnoea time if the latter were to occur, with the smaller nitrogen fraction (in theory) reducing the extent of any absorption atelectasis. Additionally, the maximum inspired partial pressure of oxygen (PO_2) of 1.2 atmopheres absolute at the greatest depth was within acceptable limits for the expected exposure duration to avoid both pulmonary and cerebral oxygen toxicity. The FFM CPAP function automatically engaged when breathing commenced.

With the mask and cylinder in place and respiration established, the child was turned to the prone position with their faced immersed in the water. Occasionally at this point, or earlier when the mask was first placed, the child appeared to breath-hold / become apnoeic. On several such occasions a positive pressure breath was given by briefly pressing the FFM second stage regulator purge valve, which appeared to stimulate breathing. Spontaneous respiration with subjectively adequate tidal volumes was monitored by observing the volume of expiratory bubbling from the exhaust valve on the mask. After approximately thirty seconds, the child was sat up again to confirm the FFM remained dry. This was repeated two more times until both RJH and the rescue diver were satisfied with the mask seal. In the prone and immersed position, the child's hands were then clipped together with cable ties and a carabiner behind his back, and the ankles were loosely bound with more bungee cord. These restraints were performed both to prevent entanglement of the limbs on cave projections, and to stop the child pulling at the FFM should the anaesthesia wear off unexpectedly.

After performing final checks, the rescue diver submerged and left the chamber with the child positioned face down and beneath the rescuer as represented in Figure 1. Each traverse out to the dive base (from which point no further diving was required) would take approximately 3 hours on rescue day one, but only around 90 mins by day three as systems and procedures improved. On-route, support divers stationed at various chambers within the cave offered assistance to the rescue diver. One author (CJC) with his extensive veterinary experience of administering ketamine, was able to make an initial medical assessment in one of the between-sump dry chambers further out, and help supervise the other divers perform their first injections. Each child received 3 or 4 'top-up doses' of ketamine during the egress, successfully given by the cave divers when it was judged the child was rousing. These doses were administered in the cave sections between sumps, often in very difficult conditions (such as floating in the streamway, trying to deploy the medications whilst not losing hold of the child).

Figure 1
Depiction of the approximate configuration of the rescue diver and unconscious diver during passage through the flooded sections of cave



On reaching the chamber from which no further diving was required, a limited medical assessment was performed by a Thai Navy underwater medicine team and a full medical assessment was performed in the Thai Army field hospital outside the cave. Table 1 shows the initial observations of the rescuees measured during their brief stay in this field hospital. A protocol was developed which addressed airway, breathing, circulation, and hypothermia management (ABC+H).[7] Hypothermia was identified on day one as a critical issue. The water and air temperature in the cave was 23°C.

Resuscitation roles (ABC) were assigned to an anaesthesiologist, respirologist, and paediatric cardiologist, respectively. The hypothermia management was formalized and assigned to the anaesthesiologist (author CL). It is noteworthy that case nine (Table 1) exhibited severe hypothermia (29.6°C as measured by tympanic membrane temperature) without shivering. He was rewarmed before being transferred by air ambulance to Chang Rai hospital and suffered no adverse consequences. The management of hypothermia in this event is discussed in more detail elsewhere.[7]

At the field hospital, 12 of the subjects required no airway management beyond simple airway manoeuvres and supplemental oxygen via non-rebreather mask. One boy suffered a brief episode of laryngospasm which was managed with a bag-valve-mask device. Remarkably, none of these subjects, who spent considerable time underwater whilst unconscious, drowned or aspirated significant amounts of water. Three showed chest X-ray changes consistent with minor aspiration or infection. None of those rescued recalled any events between the induction of anaesthesia and emerging from the cave which is further evidence of a deep level of anaesthesia.

Methods

The study evaluated the pressure changes inside the Divator FFM with the safety pressure feature (Interspiro, Täby, Sweden) relative to the ambient water pressure during the respiratory cycle in immersed and fully conscious divers. The protocol was approved by the University of Auckland Human Participants Ethics Committee (Reference 022486). All participants provided written informed consent.

TRIAL DESIGN AND PARTICIPANTS

This was an observational cohort study conducted in the Exercise Physiology Laboratory at the University of Auckland during March 2019. Participants were certified healthy divers aged 18 to 60 years. Five rebreather divers and five open circuit divers were recruited. Their current health was assessed using the Recreational Scuba Training Council (RSTC) screening questionnaire at the beginning of their visit. All participants performed a spirometry test. Forced vital capacity (FVC) and the forced expiratory volume in one second (FEV_1) were measured, from which we calculated the FEV_1/FVC ratio (%).

EQUIPMENT

A circular frame pool (3 m diameter and 0.76 m depth) was installed in the laboratory and filled with fresh water (~20°C) to a standardised depth of 60 cm. The same model of FFM as used in the Thai cave rescue (specified above) was studied in its stock configuration for operation with an open circuit scuba pressurised gas supply, and in modified configuration (described below) for operation on a closed-circuit rebreather.

In operation with an open circuit gas supply the low-pressure hose on the FFM second stage demand valve was connected via a 2 m hose to a first stage scuba regulator (Apeks, Blackburn, England) on a pressurised scuba cylinder (as was done in Thailand). Air was supplied to the mask at an intermediate pressure of 9 bar (0.9 MPa) when the cylinder was pressurised to 200 bar (20.3 MPa). The scuba cylinder was situated adjacent to the pool. Non-compliant pressure tubing was potted through a bung fitted to the communication port of the mask to measure the pressure inside the mask via a physiological pressure transducer (MLT844, AD Instruments, Dunedin, New Zealand). Another non-compliant tube was affixed to the left side of the mask at a position we estimated to correspond with the mask centroid in a horizontal face-down diver, to measure the external water pressure via a second (identical) physiological pressure transducer. The pressure transducers were calibrated with a manometer (PM-9100HA, Lutron Electronic Enterprise, Taipei, Taiwan) using two-point calibration against atmospheric pressure and atmospheric pressure + 6 kPa. Reference atmospheric pressure was measured using a barometer (GPB330, Greisinger Electronic, Regenstauf, Germany).

In operation with a closed-circuit rebreather, the FFM second stage regulator was detached and the hole sealed with a plastic blinding plug that was 3D-printed locally. The mouthpiece valve assembly of an Inspiration Evolution

Table 1

Initial observations made at the cave field hospital. The salient feature of these data in relation to the issue of airway management is the lack of any evidence of gross water aspiration. T0 = temperature on arrival. T1 = temperature on departure for Chang Rai Hospital. NIBP = non-invasive blood pressure. RR = respiratory rate. SpO_2 = peripheral oxygen saturation (breathing supplemental oxygen via a non-rebreather mask). N = normal. RLL = right lower lobe. LLL = left lower lobe

Patient	Temp T0	Temp T1	Heart rate	NIBP	RR	SpO_2	Chest X-ray
1	35.0	36.4	78	128/78	14	97	N
2	34.0	34.8	96	130/90	32	100	RLL opacity
3	35.5	35.5	75	137/83	24	99	N
4	35.0	34.9	78	128/78	14	97	R hilar opacity
5	37.5	35.6	75	138/60	18	98	N
6	36.4	34.9	100	140/104	20	100	N
7	35.5	36.4	95	134/98	16	87	N
8	34.4	35.5	71	126/97	22	100	N
9	29.6	36.4	96	172/124	12	100	N
10	33.8	36.9	110	132/62	16	100	LLL opacity
11	33.4	38.5	102	128/100	18	94	N
12	32.9	37.0	82	140/100	20	100	N
13	34.0	36.9	89	135/81	12	96	N

Plus rebreather (Ambient Pressure Diving, Helston, Cornwall) with back mounted counter-lungs was attached via a 3D-printed plastic adaptor to the FFM communications port. A non-compliant tube penetrated the adaptor and was connected to a pressure transducer (as above) to measure pressure in the mask. The positioning of the external pressure sensor tubing on the mask was as described above. The rebreather was worn on the subject's back and operated with air diluent with an inspired PO_2 set point of 0.7 atmospheres absolute (atm abs) (70.9 kPa). In keeping with normal rebreather diving practice, participants were instructed to maintain 'minimum loop volume'; that is, sufficient gas in the loop such that respiratory excursions just avoid emptying the counter-lungs during inhalation.

Voltage signal from the two transducers was sampled at 1 kHz using a Powerlab 16/35, acquired and filtered using a 10 Hz low pass filter via LabChart data acquisition software (AD Instruments, Dunedin, New Zealand).

EXPERIMENTAL PROCEDURE

All 10 participants completed the experiment using the FFM connected to the pressurised open circuit scuba gas supply, and five divers trained on rebreathers also completed the experiment using the FFM connected to the closed-circuit rebreather.

For each equipment configuration, the experiment was conducted during spontaneous breathing at the surface and while submerged. For the surface measurements participants knelt upright with their face and all diving apparatus above the water. For the submerged measurements, they lay face down, horizontal in all planes, on the bottom of the pool with their face at ~50 cm depth. Under each of these conditions, resting participants were asked to breathe at normal comfortable tidal volume and frequency for 10 breaths ('normal breaths'), then take 10 vital capacity breaths. Finally, whilst submerged and in open circuit mode only, participants were asked to depress the purge button on the FFM second stage regulator for a burst of approximately 2 seconds.

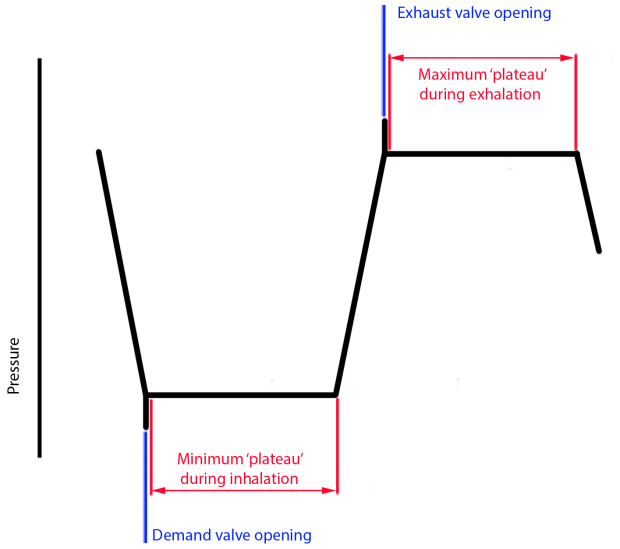
Lastly, we assessed the ability to create a leak across the mask flange seal using only auto-manipulation of the facial muscles.

OUTCOME MEASURES

The primary outcome measure was the minimum and maximum pressures inside the mask relative to ambient pressure at the mask centroid ('relative in-mask pressure') during the inhalation and exhalation phases of the respiratory cycle respectively. Because of the differing characteristics of the pressure vs time curves, the approach to calculating these pressures differed between open- and closed-circuit experiments.

In the open-circuit experiments breathing typically produced identifiable pressure 'plateaus' during inhalation and exhalation. The start of the 'minimum plateau' during inhalation began just after the negative pressure spike preceding demand valve opening and was considered to last until the beginning of the steep pressure rise. The 'maximum plateau' during exhalation began just after the positive pressure spike preceding exhaust valve opening and was considered to last until the beginning of the steep pressure fall (Figure 2). During these plateaus the relative in-mask pressure was calculated automatically at the same rate of the data sampling (see earlier) by subtracting the ambient

Figure 2
Schematic depiction of inhalation and exhalation pressure 'plateaus' during use of the FFM with open circuit scuba equipment



pressure from the in-mask pressure. All relative in-mask pressures captured during the inhalation and exhalation plateaus over 10 breaths were averaged to derive the average minimum and maximum relative in-mask pressures respectively. These minimum and maximum means for individual subjects were then averaged across the 10 subjects to give the average minimum and maximum relative in-mask pressure for the particular condition.

In the use of the rebreather the valve opening spikes were absent. The pressure-time curve was more sinusoidal and typically devoid of identifiable plateaus. We therefore took the simpler approach of recording absolute peak (exhalation) and trough (inhalation) pressures over 10 breaths in each subject in calculating the average minimum and maximum relative in-mask pressure for the particular condition, as described for the open-circuit experiments above.

The peak pressure generated during the use of the purge button at the surface and at depth was recorded and means were calculated from pooled data.

Mask leaks during facial muscle manipulation were described in a qualitative manner.

STATISTICAL ANALYSIS

Means and standard deviations (SD) were calculated for data describing subject characteristics. Means and 95% confidence intervals were calculated for the relative in-mask pressures measured under all conditions and equipment configurations. Data were tested for normality, all pressures were normally distributed. One-sample *t*-test, with α set at 5%, was used to test the hypothesis that the mean relative in-mask pressure in the various conditions was different from zero.

Table 2
Characteristics of the FFM study participants. Note that the CCR group is a subset of the total group. Data are mean (SD) unless otherwise indicated. BMI = body mass index. CCR = closed circuit rebreather group. FEV_1 = forced expiratory volume in one second. FVC = Forced vital capacity

Parameter	Total *n* = 10	CCR *n* = 5
Age (years)	32.6 (10.5)	34.0 (7.5)
Female gender	*n* = 4	*n* = 1
Beard	*n* = 3	*n* = 3
Small/long face	*n* = 2	*n* = 0
BMI ($kg \cdot m^2$)	24.6 (4.0)	25.9 (4.8)
FEV_1 / FVC	0.84 (0.12)	0.82 (0.11)

Results

Participant characteristics are described in Table 2. Mean relative in-mask minimum and maximum pressures during inhalation and exhalation in open and closed-circuit equipment configurations are given in Table 3 (surface measurements) and Table 4 (measurements while submerged).

The key finding was that when operated underwater with a pressurised open-circuit gas supply, the Divator FFM with the 'safety pressure' feature maintained positive pressure inside the mask relative to the surrounding water, even during maximal inhalations (Table 4 and Figure 3). This validates the manufacturer's claim of an effective CPAP function. Predictably, CPAP was not evident when the mask was operated with a non-pressurised closed-circuit gas supply. Indeed, when submerged in this configuration the mean relative in-mask pressures remained negative throughout the respiratory cycle, even during exhalation. The latter finding, not seen during operation at the surface where exhalation against the resistance of the circuit generated positive pressures (Table 3), almost certainly reflects the negative static lung load that exists when an immersed diver is horizontal and face-down during use of a rebreather with back mounted counter-lungs.[8]

Use of the purge button resulted in a mean in-mask pressure of 3.99 kPa (approximately equal to 40 cmH_2O) (range: 2.56 to 5.3 kPa), during submergence. At the surface it delivered on average a mean pressure of 3.05 kPa (~31 cmH_2O) (range: 1.20 to 5.31 kPa).

All participants were able to create leaks with purposefully excessive facial movements. No water ingress was noted in open circuit configuration (where relative in-mask pressure remained positive and outward bubbling was the principal manifestation of a leak), while some water entered the mask during the closed-circuit trials. Five participants had a small but constant leak of bubbles leaking out of the mask in open circuit configuration, all with potential explanations: two having small/long faces; and three having a beard.

Table 3
Mean relative in-mask pressures during inhalation and exhalation in open and closed-circuit equipment during surface measurements. CI = confidence interval. VC = vital capacity

Breathing mode at the surface	Inhalation In-mask relative pressure kPa [mean (95% CI)]	*P*-value	Exhalation In-mask relative pressure kPa [mean (95% CI)]	*P*-value
Open circuit				
Normal breaths	0.4 (-0.7 to 1.6)	0.42	0.3 (0.3 to 0.4)	< 0.001
VC breaths	-0.1 (-0.1 to 0.0)	0.004	0.3 (0.3 to 0.4)	< 0.001
Closed circuit				
Normal breaths	-0.6 (-1.3 to 0.1)	0.06	0.7 (0.3 to 1.1)	0.009
VC breaths	-1.7 (-4.1 to 0.6)	0.11	1.0 (0.7 to 1.3)	0.001

Table 4
Mean relative in-mask pressures during inhalation and exhalation in open and closed-circuit equipment configurations during submerged measurements. CI = confidence interval. VC = vital capacity

Breathing mode while submerged	Inhalation In-mask relative pressure kPa [mean (95% CI)]	*P*-value	Exhalation In-mask relative pressure kPa [mean (95% CI)]	*P*-value
Open circuit				
Normal breaths	0.6 (0.3 to 0.9)	0.002	1.1 (0.8 to 1.4)	< 0.001
VC breaths	0.8 (0.4 to 1.1)	< 0.001	1.2 (0.9 to 1.4)	< 0.001
Closed circuit				
Normal breaths	-1.9 (-2.9 to -1.0)	0.005	-0.6 (-1.4 to 0.2)	0.09
VC breaths	-2.0 (-2.9 to -1.0)	0.004	-0.3 (-1.1 to 0.5)	0.34

Discussion

The most striking aspect of the Thai cave rescue narrative is that 12 unconscious non-diver children and one adult were rescued through 1.1 km of flooded, tortuous cave passage in near zero visibility, and none drowned. These were not the 'ideal conditions' in which 'a period' of underwater airway management might be achievable according to the current rescue guideline.[1] Indeed, the Thai cave scenario represented the antithesis of 'ideal conditions' and seen through that lens, the success of the operation was remarkable. One obvious question arising is 'what are the implications of this event for recommendations about attempting airway management in an unconscious diver underwater'? In particular, should related guidelines be less discouraging of managing an unconscious diver underwater where lessons learned from the Thailand cave rescue are applied, and where there are compelling reasons to attempt it?

Any effort to address these questions must take account of the degree to which the factors associated with the success in Thailand are generalisable to other diving situations in which loss of consciousness may occur. These factors are enumerated and discussed in that context below.

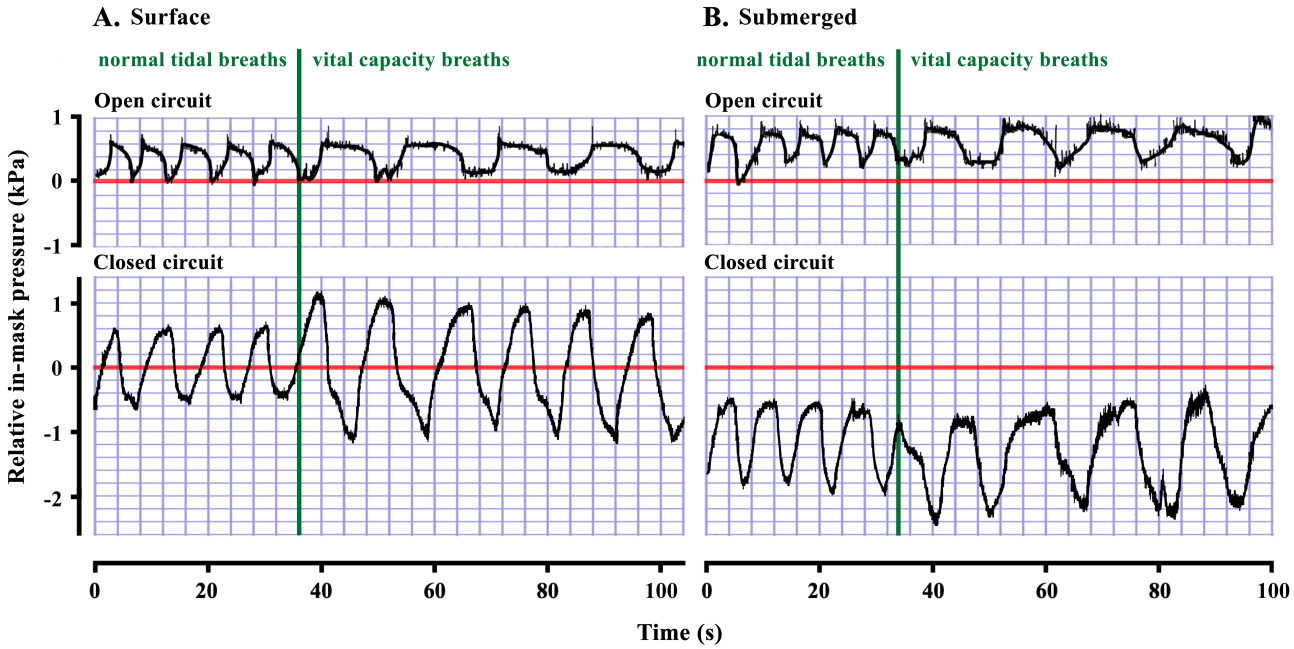
First, in the Thailand cave rescue, unconsciousness was induced with a drug rather than by a medical event such as a seizure, and the unconscious state in these respective settings may be qualitatively and quantitatively different. The principal anaesthetic drug (ketamine) was explicitly chosen for certain specific properties. It is effective when administered intra-muscularly, and the relatively long time-course of its action when absorbed from an intramuscular depot suited the needs of this scenario. Ketamine is sympathomimetic and is much less likely than other intravenous anaesthetic agents to cause hypotension.[6] It was therefore suited to this scenario in which no haemodynamic monitoring was available or possible. Perhaps most importantly, ketamine preserves respiratory drive and airway protective reflexes to a greater extent than other anaesthetics.[6] This was vital in a situation in which there was no means of continuously assisting ventilation, and in which it was possible that water could contaminate the airway if the FFM leaked.

It is difficult to evaluate the extent to which the depth of anaesthesia induced by ketamine administered to the rescuees equates with the depth of unconsciousness that, for example, would follow a hyperoxic seizure. It is clear from the earlier account that they were effectively anaesthetised (non-responsive and not moving) at least at the start of the diving transit. Nevertheless, the potential qualitative and quantitative differences between ketamine anaesthesia and unconsciousness induced by other events that might occur in diving potentially confound judgements on the generalisability of the Thai rescue outcomes.

Second, the Interspiro FFM with the safety pressure

Figure 3

Representative pressure – time waveforms showing relative in-mask pressure where zero represents the ambient pressure at the mask centroid under the various experimental conditions



feature investigated in this study appears to have prevented significant aspiration of water in the rescuees. The results presented here confirmed that when operated in open circuit mode the mask will provide a small degree of CPAP throughout the respiratory cycle. However, this was not a comprehensive evaluation. We only tested one mask, and the efficacy of the CPAP function was only tested at shallow depth in the prone horizontal position. It may behave differently in other attitudes. For example, allowing the neck to extend into a face up position in a prone subject could place the mask centroid several centimetres shallower than the expiratory diaphragm, and the degree of CPAP relative to surrounding water pressure would be correspondingly greater. Users of this mask in cave rescue training scenarios have noted that the buoyancy of this FFM tends to promote this attitude change in a prone subject.

The extent to which CPAP in the FFM influenced the positive outcome in Thailand is unknown but it is a highly plausible contributor. This can be inferred from the fact that our subjects could provoke water ingress through facial movement when the mask was used without CPAP on a rebreather, but not when used with CPAP in open circuit mode. Therefore, in considering generalisability of the Thailand outcomes, it must be observed that these FFMs do not provide CPAP to a prone diver in a horizontal attitude using a rebreather with back-mounted counter-lungs. We acknowledge that a prone diver using a rebreather with front-mounted counter-lungs or a supine diver using back-mounted counter-lungs (conditions not tested here) may experience a positive static lung load, and therefore CPAP. With these facts in mind, it seems plausible to conclude that the efficacy of an FFM – rebreather combination in preventing water ingress and aspiration in an unconscious diver may depend on the positions of the diver and the rebreather's counter-lungs. In some combinations a FFM may not be as effective as they appeared in Thailand. Our results also suggest that FFM efficacy in preventing leaks can also be degraded by facial shape and beards. Leaks could be a particular disadvantage in use of a rebreather with a small gas supply, but less problematic in use of open circuit apparatus with a larger gas supply.

Third, the Thailand rescue was conducted with the rescuees breathing from open circuit scuba. The consequent exhalation of bubbles with each breath facilitated monitoring of the children's respiration by the rescuing divers. In contrast, another potential problem with managing an unconscious rebreather diver underwater is that it could be difficult for the rescuer to tell if the victim is actually breathing because there are no bubbles. Direct observation of visible counter-lungs might be the only form of monitoring, and this is not possible in most rebreather models.

Fourth, the young age and lean body habitus of the rescuees may have been an advantage in preventing airway obstruction when they were unconscious. Irrespective of whether the airway remains dry it is possible that mechanical airway obstruction could occur more easily if the head were not held in an ideal position during rescue of an adult diver, particularly if they were obese. If the rescuee were held in a horizontal prone position, the positive buoyancy of a FFM may help keep the airway open by lifting the head into a face-up position.

Finally, the skill and expertise of the divers who managed each boy through the underwater sections of the cave, and the time afforded them to plan the approach, were surely contributors to the positive outcome. The rescue of unconscious divers underwater in other settings may involve less experienced and skilled divers who find themselves in an unexpected unplanned situation with extremely high levels of stress.

It is clear from the above there are several considerations which potentially confound interpretation of the Thailand cave rescue in revising general recommendations for managing unconscious divers underwater. We do not believe the positive outcomes in Thailand challenge the fundamental principle that the safest place for an unconscious diver is on the surface. Nevertheless, the Thailand event and the FFM investigation reported here do provide a degree of enhanced confidence that a FFM could prevent drowning during rescue of a diver who unexpectedly becomes unconscious underwater, but who continues to breathe. This would be especially relevant to a scenario where direct ascent to the surface is either not possible or is hazardous, such as an unconscious diver being swum out of a cave, or where completion of some decompression time might prevent fatal decompression sickness. To be in a position to accrue these advantages, divers would need to adopt an FFM for all their diving (so that they are wearing one if an adverse event were to occur), and this opens up legitimate debate about their cost, complexity, potential hazards and the need for proper training in their use.

We note a particular caveat in relation to divers who are not only unconscious, but also not breathing. The apparent success of using the purge button to provide a positive pressure stimulus to breathing in the Thailand cave rescue should not be interpreted as evidence that sustained positive pressure ventilation is feasible underwater using this approach. Our data show the highest relative in-mask pressure generated on purge button activation was high enough (54 cm H_2O) to potentially cause pulmonary barotrauma. The purge button is not designed to facilitate positive pressure ventilation, and must be employed cautiously if used for this purpose. Moreover, a diver in respiratory arrest may also be in cardiac arrest, and in that setting their only hope for survival is proper cardiopulmonary resuscitation at the surface.

Leaving aside the issue of whether FFMs are practical or desirable for general use, the Thailand cave rescue and the findings of the present study strengthen the argument for elective use of an FFM (particularly in an open-circuit CPAP mode) during procedures carrying an enhanced risk of loss of consciousness due to oxygen toxicity (such as in-water recompression).[9] Similarly, it seems justified to conclude that if faced in future with a similar situation to the Thailand cave rescue (such as rescue of an injured unconscious caver through a sump), the methods employed by the Thailand rescue team could be utilised again with a reasonable expectation of success. Such a conclusion would have seemed very implausible before the Thailand event.

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