Rescue of drowning victims and divers: is mechanical ventilation possible underwater? A pilot study

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Abstract

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Introduction: In-water resuscitation has recently been proposed in the European resuscitation guidelines. Initiation of mechanical ventilation underwater might be considered when an immediate ascent to the surface is impossible or dangerous. The present study evaluated the feasibility of such ventilation underwater.

Methods: A resuscitation manikin was ventilated using an Interspiro® MK II full-face mask or with an Oxylator® ventilator via a facemask or a laryngeal tube, or with mouth-to-tube inflation. Tidal volumes achieved by the individual methods of ventilation were assessed. The ventilation tests were performed during dives in the wet compartment of a recompression chamber and in a lake. Ventilation was tested at 40, 30, 20, 12, 9 and 6 metres' depth.

Results: Ventilation was impossible with the cuffed mask and only sufficient after laryngeal intubation for a small number of breaths. Laryngeal tube ventilation was associated with the aspiration of large amounts of water and the Oxylator failed during the ascent. Efficient ventilation with the MK II full-face mask was also possible only for a short period. An absolutely horizontal position of the manikin was required for successful ventilation, which is likely to be difficult to achieve in open water. Leakage at the sealing lip of the full-face mask and the cuff of the laryngeal tube led to intrusion of water and resulted in subsequent complete failure of ventilation.

Conclusions: The efficacy of underwater ventilation seems to be poor with any of the techniques trialed. Water aspiration frequently makes ventilation impossible and might foster *emphysema aquosum*-like air trapping and, therefore, increase the risk of pulmonary barotrauma during ascent. Because the limitations of underwater ventilation are substantial even under ideal conditions, it cannot be recommended presently for real diving conditions.

Key words

Drowning, scuba diving, rescue, resuscitation, extraglottic airway devices, ventilators, equipment

Introduction

Drowning is a frequent cause of death in adolescents and young adults with a predominance of males.[1] Drowning accidents are associated with a poor outcome, high lethality and high long-term morbidity, especially when occurring in open water.[2,3] The current resuscitation guidelines of the European Resuscitation Council recommend that ventilation be started in the water during rescue swimming.[4] For the resuscitation of drowning victims, an early onset of oxygenation by bag-mask-ventilation or CPAP with a high inspiratory oxygen concentration has been shown to be beneficial.[5–6] Higher survival rates and a reduction in severe neurological damage have been reported when in-water resuscitation is performed.[7] The feasibility of in-water mouth-to-nose ventilation has been demonstrated in the pool.[8] Several techniques of out-of-water and in-water ventilation with modified scuba regulators and modified closed-circuit rebreathers have been reported previously.[9–12] Our group has previously demonstrated the feasibility of in-water ventilation with the Oxylator® ventilator (CPR Medical Devices INC, Toronto, Canada).[13]

However, in lethal diving accidents the victim is often still underwater and apneic, since drowning has been reported to be the most frequent cause of lethal diving accidents.[14–16] In the rescue of an apneic diver it can take several minutes until the surface is reached and ventilation is initiated. Especially in situations where a direct ascent is impossible, ventilation underwater might be beneficial to bridge the time until the surface is reached. Such scenarios include cave dives or injuries to military divers in hostile areas, in which an ascent could be lethal. In such situations, underwater ventilation could potentially enhance the survival rate by reducing hypoxia. This might further reduce arrest time and improve the outcome of submerged drowning patients.

Rescue and military divers are frequently equipped with full-face masks to protect the face from cold water and pollutants and enable the diver to communicate via a speakerphone. Whenever a diver who is wearing such a full-face mask is unconscious and apneic, the mask might be used to immediately ventilate the diver. When divers are not equipped with a full-face mask or when drowning victims have to be rescued by rescue divers, solutions other than a full-face mask should be considered. Mouth-to-mouth ventilation appears to be impracticable and dangerous. One possible method could be to use a ventilation mask, though this requires some degree of experience to achieve a satisfactory level of competence. Alternatively, supraglottic airway devices, which have become popular in pre-hospital and hospital emergency settings are relatively easy to

Figure 1
Test lung connected to manikin

operate. The laryngeal tube is a supraglottic airway device, some models having a distal cuff in the oesophagus in order to reduce the regurgitation of gastric content.

The aim of the study was to test the efficacy and feasibility of ventilation underwater via three devices: a full-face mask; a ventilation mask and a cuffed laryngeal tube.

Methods

The dives were performed in the diving (wet) compartment of the hyperbaric facility *Hydra 2000* of the German Navy in Kiel-Kronshagen, Germany. In this water-filled section, dives to a maximum depth of 40 metres (m) were performed with stops for further testing during ascent at 30, 20, 12, 9 and 6 m.

TEST SETTING

A Maquet® anaesthetic test lung was connected to a Laerdal Resuscitation Annie® (Laerdal Medical, Stavanger, Norway) via a non-return valve (Figure 1). The trachea-like hose of the manikin was connected to the inlet branch of the valve and a hose for the measurement of tidal volumes to the outlet branch. The tidal volumes were measured using an inverted, scaled cylinder. At the surface, the precision of an inverted cylinder is lower than the precision of spirometric devices. However, re-calibration is required for spirometric devices at all depths and these devices are not designed to work at 40 m of depth (approx. 507 kPa). For this reason, direct measurement of tidal volumes via the cylinder was chosen to provide a robust and fail-safe method. The tidal volumes were recorded by a person placed in the dry compartment of the recompression chamber.

Figure 2
The Interspiro® MK II mask (the left hand is not positioned on the forehead as described, so as not to obscure the photo)

METHODS OF VENTILATION

Ventilation was assessed using three devices: a full-face mask, a ventilation mask, and a laryngeal tube. Ventilation was provided by an Oxylator® ventilator. The Oxylator is a robust pressure-controlled emergency ventilator which had been tested in dry hyperbaric chambers and which is popular with special forces. In the present study, the Oxylator was operated when submerged in the water and obtained the operating air from a scuba cylinder. The peak pressure of the Oxylator was adjusted to 45 hPa and compressed air was used rather than oxygen to avoid a critical increase in oxygen partial pressure in the chamber.

Interspiro® MK II mask (Figure 2)
The Interspiro® MK II mask (Interspiro AB, Täby, Sweden) is one of the most popular full-face masks and, therefore, was used in the present study. The mask was attached to the manikin's head and excess hydrostatic pressure function was activated to avoid the intrusion of water. The left hand of the rescuer pressed the upper part of the mask to the forehead and the right hand pressed the mask to the chin and lifted the chin (Figure 2). Both hands were used to tilt the head. The purge button of the full-face mask was pressed with the thumb of the right hand for five seconds every time an inspiration was required, and released afterwards for exhalation.

Mask ventilation (Figure 3)
The cuff of the ventilation mask (Fortune Medical Instrument Corp, Taipei, Taiwan) was filled with water before the experiment to prevent pressure-dependent changes of the cuff volume. The mask was connected to

Figure 3
Ventilation mask held on manikin's face

Figure 4
The disposable VBM LTS-D laryngeal tube®

the Oxylator for automatic ventilation. The seal between the mask and the manikin's face was maintained by an experienced anaesthetist.

Laryngeal tube® (Figure 4)
A disposable VBM LTS-D laryngeal tube® (VBM Medical, Sulz, Germany) was used for airway protection and the cuff of the laryngeal tube was inflated with water to prevent changes of cuff volume with pressure changes. The insertion of the laryngeal tube was also performed by an experienced anesthetist, and the laryngeal tube was connected to the Oxylator with the same peak-pressure settings. Mouth-to-tube ventilation was also assessed at the shallower depths, when the Oxylator ceased to function.

ASSESSMENT IN OPEN WATER

The MK II full-face mask and the Oxylator in combination with the laryngeal tube were also tested in a freshwater lake at a depth of 10 metres.

Statistical analysis

Microsoft Excel 2007™, Microsoft Inc®, Washington, USA and SPSS 19, SPSS Inc, Chicago, Illinois, USA were used for statistical analysis. The analysis was limited to descriptive statistics because of the small sample size.

Results

The tidal volumes achieved with the different types of ventilation are presented in Table 1.

FULL-FACE MASK

Ventilation with the Interspiro® MK II full-face mask was initially satisfactory. However, large amounts of water entered the manikin within approximately two minutes of commencing ventilation, even though the full-face mask was used in the activated excess hydrostatic pressure mode. The intrusion of water resulted in a decrease of ventilation efficacy and finally made ventilation impossible. Further ventilation was only possible after removal of water from the lung and airways of the manikin at the surface. The volume of aspirated water exceeded 500 ml every time the lung was emptied.

VENTILATION MASK

The use of the Oxylator ventilator with a ventilation mask consistently failed after a single breath. Major amounts of water entered the mouth and trachea and resulted in a failure of ventilation.

LARYNGEAL TUBE AIRWAY

Ventilation with the laryngeal tube and the Oxylator was only possible for five to 10 breaths at 40, 30 and 20 m. Again, aspiration of water was the reason for the failure of ventilation, and the aspirated water exceeded 500 ml. As with the full-face mask, further ventilation was only possible after the removal of water from the airways and test lung. The Oxylator failed at the 12 m depth. Both the automatic ventilation and emergency gas flow failed. At depth, there was no way to open the top of the ventilator to gain access to the valves and repair them. In contrast, the pressure reducer was still working properly.

Mouth-to-laryngeal tube ventilation was also performed, although not part of the original study design, to maintain ventilation and to evaluate an emergency procedure in the case of a failure of the Oxylator. As with the Oxylator-based laryngeal tube ventilation, the number of successful ventilations was less than 10, and more than 500 ml of water entered the lung.

ASSESSMENT IN OPEN WATER

The open-water experiments at a depth of 10 m confirmed the problem of intrusion of water observed in the hyperbaric chamber. It was technically extremely difficult to achieve a horizontal position of the manikin even when one diver at the manikin's head was managing the ventilation and

Table 1
Tidal volumes, mean (range), measured at various depths using three resuscitation methods; mouth-to-tube ventilation was initiated at a depth of 12 msw as a result of the failure of the Oxylator ventilator

Depth (msw)	Tidal volume (ml)		
	Interspiro® MK II mask	Oxylator with mask/laryngeal tube® (LTS-D)	Mouth-to-laryngeal tube
40	163 (150–225)	356 (150–600)	Not tested
30	193 (150–300)	456 (150–750)	Not tested
20	363 (150–600)	450 (300–750)	Not tested
12	425 (150–750)	Device failure	400 (150–750)
9	214 (150–450)	Device failure	390 (150–600)
6	477 (150–600)	Device failure	400 (300–450)

two other divers were assisting the ascent. The test lung was not inflated if the manikin's thorax was too far below the ventilator and overinflated when the thorax was above the ventilator. Furthermore, expiration frequently failed completely leading to hyperinflation.

Discussion

Ventilation underwater with all devices tested in the present study was difficult and associated with serious problems.

VENTILATION WITH THE MK II FULL-FACE MASK

The Interspiro® MK II full-face mask provided a sufficient seal only at the beginning. A chin lift/head tilt was required to open the airway and achieve ventilation. As a consequence of this manoeuvre, the mask frequently slipped from the ideal position because of the slippery surfaces underwater. The leakages were large enough that the excess hydrostatic pressure feature of the mask was unable to compensate for this. Water entered the pharynx of the manikin, resulting in a failure of ventilation. Moreover, the tidal volumes applied by the MK II mask depended highly on depth.

OXYLATOR-MASK VENTILATION

The use of the Oxylator in combination with a ventilation mask was impossible. Leakage resulted in an intrusion of water, even though a face mask with a soft, water-filled silicon cuff was used and the mask-ventilation was performed by an experienced anesthetist. If an anesthetist with daily practice in mask ventilation is unable to achieve sufficient conditions for ventilation with the ventilation mask, it is extremely unlikely that paramedical and lay persons would be able to ventilate with a mask under realistic open-water conditions.

OXYLATOR-LARYNGEAL TUBE VENTILATION

Ventilation conditions were better with the laryngeal tube, most likely because of a better seal of the cuff of the tube compared to the mask. Nevertheless, there was still intrusion of water into the pharynx, causing the ventilation to fail after five to 10 ventilations. After the ascent to 12 m, the Oxylator ventilator failed completely. The most likely reason for this device failure air is trapped inside the ventilator when it was switched off during the ascent. As a consequence, there was most likely an excessive pressure inside the ventilator.

Even when the Oxylator is operating normally, there are several problems that need to be addressed. First, the PEEP level cannot be adjusted manually and is set to approximately 3–5 kPa which is rather low for drowning victims.[17] Second, the Oxylator is a pressure-controlled ventilator, i.e., the tidal volumes applied depend highly on the compliance of the patient's lungs.[18] Therefore, tidal volumes might vary during the rescue process.[19] Nevertheless, there are also studies which reported less stomach insufflation, more reliable tidal volumes and a greater chance of normocapnia when using the Oxylator compared to bag-mask ventilation.[20,21] Furthermore, hypo- or hypercapnia might be fostered by the fact that the tidal volumes applied by the Oxylator were pressure-dependent with depth.

LEAKAGES AND ASPIRATION

All the ventilation systems tested resulted in major aspiration. In most trials, the volume of aspirated water in the test lung exceeded 500 ml. Furthermore, the transparent hose that connected the pharynx of the manikin to the test lung was completely filled with water and air was unable to pass through it. This indicates that aspiration of water will rapidly result in a failure of ventilation. Under the ideal test conditions of the 'wet' chamber, the manikin could be lifted out of the water easily to remove water from the test lung, the trachea-like connecting hose and the mouth and pharynx, but in a realistic drowning scenario there is no way to remove water from the airways of the patient. Therefore, it is highly unlikely that ventilation would be possible over longer than five to ten breaths.

Even if aspiration did not result in a failure of mechanical ventilation, it would impair pulmonary gas exchange considerably. The average amount of fluid aspiration in drowning is comparatively small, rarely exceeding approximately 2.2 ml kg^{-1} body weight.[22] On the other hand, the amount of aspirated fluid plays a central role in the hypoxia from which drowning victims suffer, since even small quantities of aspirated fluids – as little as 1–2.2 ml kg^{-1} body weight – will result in a significant decrease of arterial oxygen content.[22–24] Therefore, it will take far longer until adequate oxygenation is restored in the case of aspiration compared to a situation without aspiration of fluid.[25–27]

PRESSURE DIFFERENCES AT DEPTH AND LIMITATIONS OF VENTILATION

Even if an optimal seal could be achieved, the hydrostatic pressure of the water is an important additional problem. In our test setting, a pressure as high as 45 hPa (the maximum pressure achievable with the Oxylator) was used, which is relatively high for an airway not secured with an endotracheal tube. It is uncertain whether the Oxylator actually reached this maximum pressure underwater or whether it cycled from inspiration to expiration earlier. Unfortunately we were unable to measure ventilation pressures underwater. During mask ventilation, peak pressures should not exceed 15–20 hPa because the risks of gastric insufflation, regurgitation and aspiration are increased at higher airway pressures.

In the context of Oxylator ventilation (45 hPa) this means that the resulting pressure in the lung is 25 hPa when the lung is 20 cm below the Oxylator or 65 hPa when the lung is 20 cm above the Oxylator. If the ventilator is set to 45 hPa and the patient is in upright position which is common during the rescue manoeuvre of divers, there will be only a minimal ventilation pressure in the lung and ventilation is likely to fail. If the patient's chest is above the ventilator, pressures in the lung can quickly reach and exceed 70 hPa potentially resulting in pulmonary hyperinflation and barotrauma.

Drowning results in a decrease in pulmonary compliance. Additionally, the diving equipment contributes to reduced chest wall compliance. Based on these two factors, high peak pressures will most likely be required to achieve sufficient tidal volumes. The median leak pressure of the laryngeal tube is only 28 hPa and the leak pressure of the Combi tube – which is the highest among all supraglottic devices – is only 34 hPa.[28] The peak pressures required for underwater ventilation might, therefore, be higher than the maximum leak pressure, which will probably limit the applicability of supraglottic airway devices for underwater ventilation.

Another critical aspect with respect to pulmonary barotrauma is so-called *emphysema aquosum*. *Emphysema aquosum* has been reported by pathologists, radiologists and forensic scientists in drowning victims.[29–31] Water in the bronchioli either causes bronchospasm or works like a valve by limiting the air flow from the alveoli to the bronchioli. If aspiration is aggravated by underwater ventilation, the ventilation efforts might foster *emphysema aquosum*, i.e., air trapping. During ascent, this trapped air could result in pulmonary barotrauma. Because pulmonary barotrauma is associated with a high morbidity and mortality, the advantages of underwater ventilation appear to be questionable, even when aspiration is minimal.

PRACTICAL USE IN OPEN WATER

Given the considerable difficulties in achieving a horizontal position, the aspiration of large volumes of water and low efficacy, underwater ventilation in open water appears to be virtually impossible with the techniques investigated.

Conclusions

The practical limitations encountered are too serious to make underwater ventilation with any of the methods tested feasible and, therefore, they cannot be recommended. The intrusion of water rapidly limits the efficacy of ventilation. Such aspiration could result in a valve-like mechanism leading to *emphysema aquosum*, which might foster pulmonary barotrauma. Furthermore, an absolutely horizontal position of the manikin was required for even a brief period of successful ventilation. This appears to be unrealistic when real drowning victims have to be rescued in open water. Even though underwater ventilation would make theoretical sense under some special circumstances such as cave diving or dives in hostile areas, the practical problems severely limit its applicability. New inventions and approaches might solve the considerable problems that currently limit the applicability of underwater ventilation.

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