Repeated freediving – An efficient and safe method to rescue subjects trapped in cars underwater

Erika Schagataya,*, Pontus Albertsson Amanb,c

a Environmental Physiology Group, Department of Health Sciences, Mid Sweden University, Östersund, Sweden
b Emergency and Disaster Medical Centre, Umeå University Hospital, Umeå, Sweden
c Country Council for Health Care, Region Norrbotten, Gällivare, Sweden

ABSTRACT

A method based on repeated freediving was developed to rescue subjects trapped in cars underwater – a scenario leading to 5–6 annual deaths in Sweden, and thousands globally. We determined rescue time and whether the divers were at risk of hypoxic blackout. Cars containing 5 kg negatively buoyant rescue-dummies strapped with seatbelts were placed on 5 m and 8 m depth. Eight freediving-instructors made 230 freedives, working in pairs with one diver always at the surface. For each rescue, two freedivers, equipped with mask, snorkel, fins, weight-belt, wetsuit and a buoy with belt-cutter and glass-breaker freedived alternating in turns between the divers. They accomplished a maximum of one of the following tasks per dive; (1) Finding the car; (2) Marking car with buoy; (3) Opening door/crushing window; (4) Opening/cutting belt; (5) Retrieving dummy to surface; (6) Transporting dummy to shore. Dummies were retrieved to shore from 5 m depth within a mean (SD) duration of 4 min 16 s (1 min 36 s) and from 8 m within 6 min 22 s (2 min 13 s; P < 0.05). Mean dive duration was 28(7) s (14–46 s), with 3 dives over 40 s duration. Freedivers arterial oxygen saturation (SaO2) levels were measured in dives of 30, 35, 40 and 45 s using pulse oximetry. Mean (SD) SaO2 at 20 s after surfacing was 90% for 45 s dives. This allows rapid recovery and gives a safety margin to the 50% SaO2 level when divers may risk blackout. We concluded that repeated freediving is efficient for rescuing victims trapped in cars underwater within their survival time, and following recommended methods and dive durations, rescue divers are not exposed to risk.

1. Introduction

Freediving is defined as all diving done between two breaths of air, i.e. without the use of any breathing apparatus or external gas supply. This diving is also called “apnea” or breath-hold diving, and it is practiced as a recreational activity, as well as a competition sport (reviewed in Schagatay, 2009; 2010; 2011) and as a profession (Schagatay et al., 2011; Schagatay, 2014). In many parts of the world people show a remarkable ability to freedive repeatedly to collect food or hunt fish underwater (Rahn and Yokoyama, 1965; Schagatay et al., 2011; Abrahamsson and Schagatay, 2014). They do this by making short serial dives aiming to maximize total underwater working time, which is quite different from the freediving done in sports competitions, where the athletes try to produce the longest diving time, dive the longest horizontal distance underwater or reach the greatest depth on one breath (Schagatay, 2009; 2010; 2011). The exploration of maximal human capacity has shown that our performance is quite impressive. The world record apneic duration is 11 min 35 s, longest horizontal distance swum is 300 m and the greatest depth in self-propelled dives is 130 m (AIDA-international, 2018), which is in the range of that of several species of semiaquatic mammals (Fahlman and Schagatay, 2014). Professional divers can also spend 50–60% of the working time underwater during many hours by using short dives (Schagatay et al., 2011). Mean dive time was only 30–40 s in the working dives of the Ama, which allows short recovery times as there is no accumulation of lactate (Schagatay et al., 2009; Rahn and Yokoyama, 1965).

Despite this impressive potential human diving capacity people may drown in various situations, and drowning is one of the most common causes of accidental death globally with over ½ million cases annually (Srpsilman et al., 2012) While a main cause of drowning is poor swimming ability, special cases are when swimmers are failing to swim in cold water or when people are trapped underwater. Car accidents may end with the car entering water and persons being trapped inside – a scenario leading to 5–6 deaths annually in Sweden (Stjernbrandt et al., 2008), approximately 400 annually in North America, where they represent 10% of all drownings, and an estimated 2000–5000 in all...
industrialized nations together (Giesbrecht et al., 2017). Most of the victims have no or minor injuries and die from drowning (Wintemute et al., 1990). The car may float for a few minutes, but after only 1–2 min the water level will make it very difficult for the victim to exit the car due to the hydrostatic pressure acting on doors and windows, making it impossible to open them from the inside while there is still air in the car. Therefore, active rescue from the outside is often necessary.

Most humans can breath-hold voluntarily for 1–2 min and may survive submerged without breathing for up to 21 min with no or mild neurological injury (Suominen et al., 2002). There are exceptional cases reported where survival times exceed one hour in cold water in both children (Bolte et al., 1988) and adults (Huckabee et al., 1996), but in general the time available for rescuing victims is relatively short once submerged. The time available for rescue is prolonged with the time the victim is breathing before the car is filled with water. Thus for successful rescue the available time could be limited to approximately 30 min. However, the currently available rescue of victims in submerged cars is by SCUBA diving, which requires considerable time to be put in place. Current underwater rescue models are thus often too slow to rescue these individuals. Rescue swimmers of the general rescue services in Sweden have restrictions that limit underwater rescue and they lack the proper knowledge and equipment for such activity (Swedish Civil Contingencies Agency guidelines, 2011). Our idea was to use the remarkable human freediving capacity to develop a rescue system to assist people trapped underwater. We developed a free-diving based method to rescue subjects trapped underwater and tested the dive times and the total rescue time needed at different depths.

A risk with breath-hold diving is that if duration is long enough to cause the arterial blood oxygen saturation (SaO2) to drop too low for the brain to support consciousness, the diver will suffer from syncope, commonly called “blackout” (Schagatay, 2009). In this situation, without assistance from a safety diver, the diver may drown. We therefore also investigated in a separate test series if this method would expose rescue freedivers to risk of hypoxic syncope, which may occur at an arterial oxygen saturation (SaO2) of around 50% in non divers and even lower levels in trained freedivers (Schagatay, 2009; 2010). Loss of motor control may occur at an earlier stage (Lindholm et al., 2007). There is currently no data suggesting that repeated hypoxic syncope has long term neurological effects (Raichle and Hornbein, 2001; Ridgeway and McFarland, 2006), however the risk of drowning should blackout occur must be taken seriously. Normally the urge to breathe will be triggered by the accumulated carbon dioxide during apnea and force the free-diver to interrupt the dive well before the risk of syncope develops, except if the diver hyperventilates before the dive, lowering the CO2 levels, which can abolish this warning (Craig, 1961; 1976).

The main aims of the study were thus to a) Evaluate rescue attempts using repeated freediving, focusing on the dive times and total rescue times needed at 5 and 8 m depth.

b) Evaluate if there was a risk of hypoxic blackout in the rescue divers using the diving patterns involved in the rescue attempts.

2. Methods

2.1. Part A

The rescue tests were done at the facilities of the Swedish Rescue Services Agency in Sandö, Sweden. Participating freedivers were eight freediving instructors certified in the Swedish Sports Diving Federation (SSDF). Six were from the freediving club High Coast Apnea and two from other Swedish diving clubs. The procedures had been approved by the local research ethics committee and by the Swedish Work Environment Authority. After receiving oral and written information about the tests, subjects signed an informed consent form, and were aware they could interrupt their participation without motivation at any time in accordance with the Helsinki declaration.

Freedivers were equipped with mask, snorkel, freediving fins, a weight belt, a 5 mm wetsuit with a hood, diving gloves and socks, and a freediving buoy with a line and 4 kg bottom weight. The specially designed buoy had pockets containing glass-breakers and belt-cutters.

Cars containing 5 kg negatively buoyant rescue-dummies strapped with seat belts were placed on 5 m and 8 m depths on the bottom of the river, at 10–15 m distance from the shore. Cars used were two Volvo 745, one Volvo 850 and one Audi combi. Cars were intact except the engines had been taken out to not pollute the water. Adult size rescue dummies were seated belted in the left or right front seat. Location of cars and placement of dummies were unknown to the divers at the start of the operations. Over all inspection of the dive site general conditions was done by the rescue leader before the start of each rescue attempt.

Divers worked in pairs with one doing the decided task while the other was securing the first one from the surface. For each rescue attempt, the two freedivers alternated in making short freedives to accomplish a maximum of one of the following tasks per dive:

1. Search for/find the car.
2. Marking car with buoy.
3. Opening door/crushing window.
4. Opening/cutting belt.
5. Retrieving dummy to surface.
6. Transporting dummy to shore.

Divers were instructed to communicate what had been done between each dive and to try to keep dives short and surface before or as soon as they felt a respiratory drive. They were told to refrain from hyperventilation, to avoid developing hypocapnia which may cause delay of the urge to breathe and unnecessary prolongation of the dives.

As a backup safety, surface supplied air divers were observing the rescue procedures, ready to assist the freedivers if necessary. They could also interrupt the rescue attempt should any risk for the freedivers be detected, and inspected dive sites before the rescue operations started. During the whole testing period, no risks were identified and no assistance was necessary. Freedivers were not allowed to enter the cars with their bodies at any point of the operation, but arms could be used for cutting free and grabbing the dummy. Water temperature was 6–8 °C and visibility was 1–4 m (Table 1). The eight freediving-instructors made a total of 230 short dives to accomplish 30 complete rescue operations; 10 from 5 m with entrance from the door (1:1), 10 from 5 m with entrance by crushing the window (1:2), and 10 from 8 m with entrance from either the door or window (2; Table 1). Dive durations were measured from the surface with a stopwatch in 50% of the 5 m rescue operations and in 8 of the 10 8 m operations.

2.2. Part B

In this separate set of tests, the levels of hypoxia in the divers

<table>
<thead>
<tr>
<th>Test</th>
<th>Number of rescues</th>
<th>Depth (meters)</th>
<th>Water temperature (°C)</th>
<th>Visibility (meters)</th>
<th>Entrance used to car</th>
<th>Number of dives</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1</td>
<td>10</td>
<td>5 (4.5–5.5)</td>
<td>8°</td>
<td>3–4</td>
<td>Door</td>
<td>70</td>
</tr>
<tr>
<td>1:2</td>
<td>10</td>
<td>5 (4.5–5.5)</td>
<td>8°</td>
<td>2–3</td>
<td>Window</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>8 (7.5–8.5)</td>
<td>6°</td>
<td>1–3</td>
<td>Door/window</td>
<td>70</td>
</tr>
</tbody>
</table>
resulting from the dives were investigated. The tests were designed when the timing of rescue dives had been established in study A, and focused on the longest dives observed. While average dive time was 28 s, the 10 longest single dives in the 8 m deep rescue section were 35–46 s. We used experimental dives to 8 m depth at target durations of 30, 35, 40 and 45 s. Dives within ± 2 s of these durations were included.

Four freedivers made two dives each per duration. Divers swam down along a weighted line from a boat diving platform and around the line near the bottom for the specified time. A safety diver was always observing the diver. The diver could surface at any time, but a sound signal was given from the boat when the diver was supposed to swim up to the surface. SaO2 was measured on the dried finger using a pulse oximeter (Nonin Onyx 9500) directly after the diver had surfaced, while resting in the water. Due to the circulation time from the lungs to the heart and to the finger, SaO2 nadir reflecting the oxygen cost of the dive usually occurs at 20–30 s after surfacing, and can therefore be recorded after the dive. The nadir SaO2 was identified from the recordings during recovery, as well as the time needed for reaching full recovery (> 97% SaO2). When the diver surfaces, there is normally an increase in peripheral bloodflow to compensate for the vasoconstriction during diving, which makes it easy to measure SaO2 on the finger.

**Statistical analysis**

In both parts of the study, subjects served as their own controls, and statistical analysis was performed using paired Students t-test for differences between conditions and for pre versus post dive SaO2 values. Significance was accepted at P < 0.05.

3. Results

3.1. Part A

3.1.1. Rescue durations

Dummies were retrieved to shore from 5 m depth within 4 min 16 s (1 min 36 s), and from 8 m within 6 min 22 s (2 min 13 s; P < 0.05), including the whole operation from the start of the search until the dummy was on the shore (Fig. 1).

The main difference in duration between 5 and 8 m rescues was the mean search time; 55 s at 5 m versus 1 min 47 s at 8 m (P < 0.05; Fig. 2). The mean (SD) number of dives per full rescue operation was 6.9 (2.2) with a minimum of 5 and maximum of 11 dives. Time increased across the series as visibility decreased when mud had been stirred up by the previous rescue (Fig. 3).

3.1.2. Dive durations

Dive durations for 5 m dives were 15–40 s and for 8 m dives durations were 14–46 s. Mean (SD) dive durations for all operations was 28 s and the 10 longest dives in the 8 m deep rescue section had durations from 35 to 46 s (Fig. 3). Only 3 dives were longer than 40 s.

3.2. Part B

The actual mean (SD) dive durations produced in mimic dives were 30.5 (1.3), 35.3 (0.9), 39.6 (2.1) and 45.5 (1.1) s and the mean depth was 7.8 (0.6) m. Desaturation continued after surfacing with a nadir SaO2 at the finger at 20–30 s post dive (Fig. 4).

The dives of 30 s duration did not lead to any significant desaturation (97.7%) at 20 s after surfacing; Fig. 5). The mean SaO2 at 20 s was similar after 35 s dives and somewhat lower after the 40 s dives, and it was 90% after 45 s dives (P < 0.05; Fig. 5). Complete recovery occurred within 30 s after the 30 and 35 s dives, within 40 s after the 40 s dives and within 50 s after the longest dives (Fig. 5).

When the nadir saturations for all dives were calculated,
30, 35, 40 and 45 s durations. Each duration mean represents values from 8 dives. The lowest SaO2 observed in any single dive was 71% after a 45 s dive, 92.0 (12.7)% for the 40 s dives and 89.4 (11.2)% for 45 s dives respectively.

**Fig. 6.** Mean (SD) arterial oxygen saturation (SaO2) at individual nadir after surfacing from 8 m dives of 30, 35, 40 and 45 s durations. Each duration mean represents values from 8 dives irrespective of where within the recovery period the nadir occurred. The mean nadir SaO2 was 96.8 (0.7)% for 30 s dives, 94.8 (5.4)% for 35 s dives, 92.0 (12.7)% for the 40 s dives and 89.4 (11.2)% for 45 s dives (Fig. 6). The lowest SaO2 observed in any single dive was 71% after a dive of 46 s duration.

4. Discussion

This study shows that “repeated freediving” with two divers alternating in making short dives is an efficient method for rescuing victims trapped in cars underwater within their possible survival time. We found that this operation can be done efficiently in depths down to 8 m, which covers a major part of the depth range 0.5–12 m where the majority of cases reported of drownings in cars occur (Stjernbrandt et al., 2008). We think the method thereby can provide a means to rescue victims also at somewhat greater depths than the average 2 m depth reported for such accidents (Stjernbrandt et al., 2008).

With full rescue done within 5 min for 5 m depth and within seven minutes from 8 m depth, this method provides a much faster rescue opportunity than the use of SCUBA based diving or other currently used methods. When people are trapped in cars, there may initially breathe until the car is filled with water, and the lifesaving attempts should go on for at least 60 min in warm water and for longer in cold water (Claesson, 2013; Bolte et al., 1988; Huckabee et al., 1996). However, most smaller rescue services do not have the access to SCUBA divers within this time frame, and our fast and efficient method may provide a good complement to other methods used.

A prerequisite for using the repeated freediving method is that it does not put rescue divers at risk. The main risk identified is hypoxic blackout if too long dive durations are used. After the longest dives of 45 s mean nadir SaO2 was 89% and less desaturation resulted in the shorter dives, and hypoxic blackout is considered to occur at around 50% SaO2 in untrained subjects (Rahn and Penn, 1955; Ferretti, 2001), with lower values observed in trained freedivers (Schagatay, 2009). Therefore, using this method, the dive durations needed were found to be short enough not to put rescuers at danger of hypoxic blackout. However, we believe the aim should be to keep rescue dive durations within 40 s to increase the safety margin, and the fact that only 3 of the 230 dives were above 40 s duration shows this rescue method could be carried out with short dives.

With the studied dive durations, recovery is also rapid and the freediver can dive again within one minute. Recovery intervals can be kept short as long as dive duration is within the aerobic dive limit (Schagatay, 2010; 2014). Recovery occurred within 50 s at all dive durations. This shows that when two rescue divers work together, there is sufficient time for recovery while the other diver dives, also allowing communication at the surface between dives. The dive durations used were in the typical ranges seen in professional freedivers in Japan and Indonesia, who work continuously for many hours by doing short dives with short breathing pauses (Schagatay et al., 2011). With the aim to keep dives within 40 s there is also an increased safety margin allowing assistance from the other diver should problems arise and the diver not surface in time. This duration is also well within the recommended 60 s freediving limit proposed in other studies (Butler, in Lindholm Pollock, Lundgren, 2006).

As the dive durations used in the alternating freediving method resulted in SaO2 levels well above those associated with syncope, with complete recovery between dives, the diving can continue uninterrupted until the rescue is completed. For safe operations, it is important to follow the alternating freediving guidelines, and keep limitations considering diving duration and depth, and to use adequately trained freedivers. Detailed guidelines on how to use the method have been given in an internal report in Swedish to the Swedish Rescue Authorities (Schagatay and Albertsson, 2009). Central aspects of the method is that the freedivers use appropriate equipment; A wetsuit and weights are necessary to prevent too high buoyancy and allow the diver to dive without too much effort. Over-weighting should be avoided to allow the freediver to rise to the surface without much effort. Using a drysuit without weights should be avoided as this would cause too much effort and the increased oxygen cost for diving would most likely put the diver at risk of syncope, or dramatically shorten dive durations. A buoy allowing the diver to rest without exertion during recovery between dives is important, as well as a line assisting the diver in finding the way to the car despite mud being stirred up during the operation. The system should always involve two divers who take turns in diving, and act as safety for each other between dives, as done in organized sport freediving activities.

The freedivers taking part in this study were fairly experienced but recreational and not specifically trained for the task. Freediving can be learned surprisingly rapidly (Johansson and Schagatay, 2014) with most healthy people learning how to breath-hold for 2 min, swim 25 m underwater and dive to 10 m depth within short time (Schagatay and Albertsson, 2009). Apneic duration is related to the human “diving response” (Schagatay and Andersson, 1998) which increases with a short training program (Schagatay et al., 2000). Training of breath-hold divers is done in professional diving schools in most countries, and freediving is a growing sport globally, both for recreation and competition. Courses are taught within various organizations including e.g., AIDA, SSI, CMAS and PADI, with safety aspects central in the training (Schagatay, 2009). We believe that these organizations, in cooperation with the Rescue Services, could develop a special training program for e.g. the Rescue Services current surface rescuers, to add to their current water rescue training.

4.1. Limitations of the study

The study used cars in an upright position with one dummy strapped inside. In a real life scenario, cars can be in other positions, with full rescue done within 5 min for 5 m depth and within seven minutes from 8 m depth, this method provides a much faster rescue opportunity than the use of SCUBA based diving or other currently used methods. When people are trapped in cars, there may initially breathe until the car is filled with water, and the lifesaving attempts should go on for at least 60 min in warm water and for longer in cold water (Claesson, 2013; Bolte et al., 1988; Huckabee et al., 1996). However, most smaller rescue services do not have the access to SCUBA divers within this time frame, and our fast and efficient method may provide a good complement to other methods used.
and there may be more victims inside and in other positions that the tested ones. The cars may also be at a greater depth that the 8 m tested, and immersed in more adverse water conditions, limiting the possibilities for safe and rapid rescue. Such scenarios should be further studied to determine if the repeated freediving method is suitable. It should be emphasized that rescue freedivers involved must receive proper training, and keep the dive times within the 40 s suggested by alternating between two divers when accomplishing each task. The method could be further tested in real life in selected fire departments with adequately trained individuals with feasibility and safety as primary measures.

5. Conclusions

This study shows that repeated freediving could efficiently assist victims trapped in cars underwater when SCUBA-divers are not available in time and present surface rescuers cannot operate today. We concluded that repeated freediving is fast enough for rescuing victims trapped in cars under water within their possible survival time. When following our methods regulations and time limits, repeated freediving can be done with minimal risk of rescue diver blackout under the studied conditions.

Acknowledgements

We thank freedivers Martin Roth, Filip Schagatay, Johanna Berglund, Fanny Schagatay, Christoffer Andersson, Hildur Sahliström, Sebastian Näsund and Annelie Pompe for their efforts during diving and development of the rescue method and equipment. We also thank air-divers Mikael Furberg, Thomas Wikner, Håkan Ormmark, Andreas Sellin and Anna Berglund at the Coastguards in Härnösand for safety input and assistance during welding. We also thank Angelica Lodin and Fanny Schagatay for assistance during measurements, and Owe Niia at SRSA Sandö, Janez Marinko at Swedish Work Environment Authority, Professor Ulf Björnstig and MD Albin Stjernbrandt at Umeå University for their contributions to safety and methods development. The project was supported by MSB/SRSA and Mid Sweden University.

References

Claesson, A., 2013. Search should go on longer at drownings in cold waters (In Swedish). Läkartidningen 110, C77R.