Commentary
Advances in the delivery of cardiopulmonary resuscitation in a diving bell

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Abstract

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This commentary discusses the provision of cardiopulmonary resuscitation to casualties in a diving bell. This single resource consolidates recent advances in the field, published in different medical journals, to support dissemination across the wider diving industry. It summarises the evaluation of techniques for the provision of manual cardiopulmonary resuscitation (CPR) to a seated casualty, including head-to-chest, knee-to-chest, and prone knee-to-chest compression delivery, and concludes that the only safe and potentially effective approach in a diving bell setting without room for a supine casualty is knee-to-chest CPR. The evaluation of a mechanical CPR device is discussed; it is found to be as effective as existing devices and manual CPR in terms of compression efficacy and is well-suited to the setting. The development of a bespoke resuscitation algorithm, together with deviations from accepted advanced life support algorithm principles, is presented. A novel 'upright CPR' technique for the provision of CPR to a seated casualty, developed during the algorithm evaluation process, is described. Finally, areas where evidence is still lacking, and research priorities for the future, are discussed; a key area for future work is the development and testing of a defibrillator suited to a diving bell setting, where space constraints, a heliox atmosphere, and the risk of both fire and rescuer injury are ever-present.

Introduction

The process by which cardiopulmonary resuscitation (CPR) is delivered within a diving bell has, until recently, received little attention from either the diving or medical communities, with no evidence-based algorithm to guide resuscitation efforts in this most challenging of environments.

The diving bell setting provides significant environmental and contextual barriers to the delivery of both chest compressions and ventilations. A typical diving bell has an internal diameter of only 2 metres; accommodating two to three divers plus the equipment required for a commercial dive within this space is a challenge at the best of times. This limitation, coupled with the hyperbaric environment and technical issues associated repeated pressurisation/depressurisation cycles, mean that standard mechanical chest compression devices are unsuitable. The floor of the bell has a hatch which may render laying a casualty on it impossible; standard approaches to CPR delivery require a recumbent casualty. Safe defibrillation in such a wet, confined space is not currently possible, and recovery of the bell to the surface and the living accommodation can take up to 40 minutes, delaying access to expertise, equipment and external intervention.

Recommendations for the delivery of chest compressions and ventilations have previously been based on standard CPR protocols with unevidenced modifications. Previously taught techniques included either head-to-chest or knee-to-chest compressions to be delivered to a casualty who is either seated or suspended in a harness.[1]

Technological advancements[2] and prominent cases of both diver death[3] and diver survival,[4] together with an ageing commercial diver population,[5] have led to increased interest in the topic of diver resuscitation. We delivered a multi-stage project with multiple industry partners, with the overall aim of developing an evidence-based algorithm for diver recovery and resuscitation in a diving bell setting. The outputs of this work have been published in this and other medical journals. This commentary serves to consolidate the findings and recommendations of this work programme in a single article to support dissemination across the diving industry.

Manual chest compression techniques[6]

The key barrier to the delivery of effective chest compressions in a diving bell is the inability to lay a casualty flat in all but the largest of bells. Almost all resuscitation attempts are futile without the early provision of high-quality chest compressions, so the first stage of the project was therefore an evaluation of the various manual chest compression techniques taught for use in a diving bell to deliver compressions to a seated casualty (or to a casualty lay prone across a rescuer's knees). The study team comprised a multi-disciplinary group of emergency medicine consultants, life support instructors, doctors, nurses and divers. Assessments took place in both a decommissioned diving bell and in a simulation centre; a Laerdal Resusci-Annie qCPR mannikin provided compression efficacy metrics. Our primary outcome was the percentage of compressions delivered to the correct depth (5–6 cm) and we evaluated head-to-chest CPR, seated knee-to-chest CPR, and prone knee-to-chest CPR (Figure 1). Secondary outcomes included compression rate, recoil, hand placement, sustainability, and adverse events such as pain for the CPR provider.

Prone knee-to-chest compressions, with the casualty lay across the rescuer's knee could not be delivered to a sufficient depth by any single provider; this technique was therefore not evaluated further.

Head-to-chest CPR, with the rescuer's head used to deliver compressions to a seated casualty, was shown to deliver some effective compressions; over two-minute compression-only resuscitation periods, ten rescuers delivered a median of 32% of chest compressions to target depth (IQR 61%). However, the technique caused significant side effects; indeed, the only rescuer who did not report negative effects did not deliver a single effective compression, and no rescuer thought the technique would be sustainable for the duration of a diver recovery to the support vessel. This technique cannot therefore be recommended for use or for further evaluation.

Seated knee-to-chest compressions involve a standing rescuer using their knee to deliver compressions to a seated casualty. The efficacy data were nuanced; the study team delivered a median of only 15% of compressions to depth (IQR 42%) and the median of pooled data (study team plus emergency department staff volunteers) showed only 12% of compressions delivered to depth. However, some providers were able to deliver compressions with similar metrics to that achieved using standard CPR techniques and reported excellent perceived sustainability. Following instruction and observation of these providers, other providers achieved an improvement in their results.

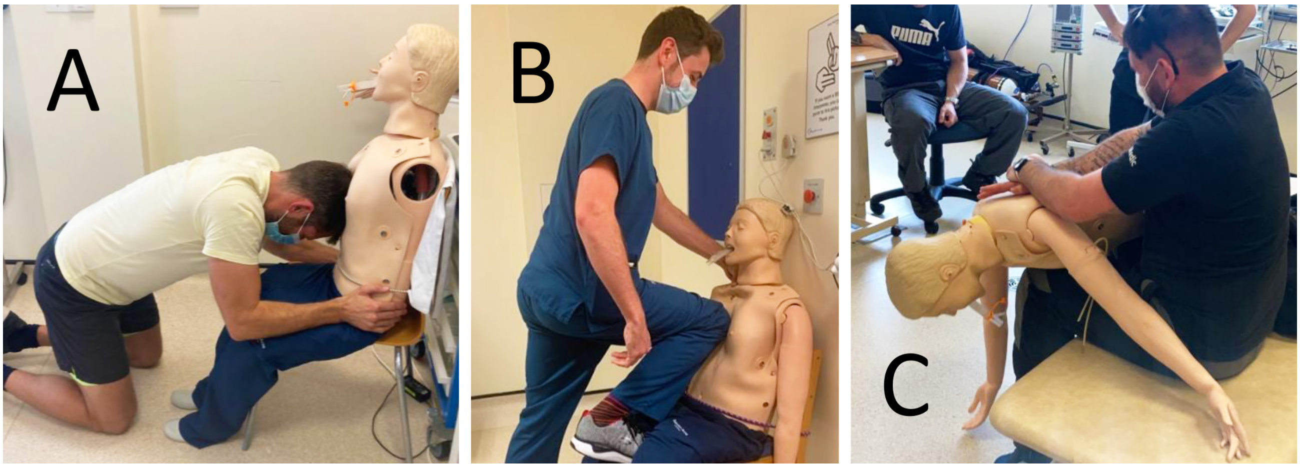
Mechanical CPR[7]

During the development of this study the Norwegian company NUI developed and released their Compact Compression Device (the NCCD). This device is low profile, gas driven, operated manually, and is specifically designed to be used in hyperbaric conditions. We assessed the device alongside the evaluation of manual chest compression techniques.

It showed excellent results, with 100% of compressions to target depth when applied to both supine and seated manikins and operated by those familiar with resuscitation.

However, we found that, particularly in the seated position, the device could become dislodged. This led to it slipping down and delivering compressions below the chest; the

Figure 1
A – head-to-chest cardiopulmonary resuscitation (CPR); B – seated knee-to-chest CPR; C – prone knee-to-chest CPR



manufacturer has since modified the device through the addition of a neck strap to prevent this from happening.

We examined what effect the diver's neoprene suit had on the efficacy of mechanical CPR (mCPR). It reduced efficacy in all positions and increased the slippage rate.

We also found that training novice rescuers on using the NCCD was easy and, following brief instruction, those familiar with CPR were able to use it without difficulty.

We concluded that the NCCD should be used for chest compressions for a diver in cardiac arrest in a diving bell whenever one is available. In its absence, seated knee-to-chest CPR may be a viable option. However, further work would be required before firm recommendations were taken to the industry.

Algorithm development[8]

The next stage of the work was establishing how these methods may be implemented in different diving bell configurations, and how the whole process of diver recovery to the bell, initial assessment, establishing CPR, then subsequently recovering the diver to the support vessel with CPR ongoing, should be protocolised in order to achieve the fastest and most effective order of events. A provisional algorithm, based closely on standard advanced life support (ALS) approaches to resuscitation wherever possible, was drafted based upon experiences during the first phase of the project.

A multi-professional, cross-industry team was then convened in a purpose-built simulation facility, this involved doctors, resuscitation experts, divers, dive supervisors, and industry representatives. An iterative approach was taken to algorithm development throughout the week-long project, with modifications made and tested as required.

The week started with a briefing day, and divers were then trained in the different techniques for manual and mCPR. The algorithm was then discussed in detail, and modifications made based upon the divers' experience of living and working in the hyperbaric setting. Over the following days, different stages of the proposed algorithm were simulated using either the Laerdal Resusci-Anne QCPR or a Ruth Lee manikin, which is weighted and designed for recovery training.

Following these testing and development phases, we performed several full algorithm simulations using live casualties. The setup was such that this involved dive control input and instruction, in addition to the divers in the simulated bell, 'wet-pot' and living accommodation.

The combined output of these work packages is the first algorithm for the recovery and management of a diver in cardiac arrest, developed with collaboration between medical and diving teams. The key recommendations that differ from the standard ALS approach are:

1. Rescue breaths, and early use of an iGel laryngeal mask
We advocate the use of rescue breaths immediately upon identification of a casualty in cardiac arrest. Hypoxia is a more likely cause of cardiac arrest then in other adult medical settings, and establishing effective chest compressions may take some time. Early use of the iGel laryngeal mask supports airway maintenance in an ergonomically challenging setting.

2. Early removal of the hot-water suit
We found that not only did the suit interfere with chest compressions, but it also made application of the NCCD more difficult and time consuming. Removal by cutting of the suit early, whilst the casualty is still in the hoist, was found to add little in the way of time, and brought benefits later with CPR consistency and efficacy.

3. Use of a cervical collar
This was an important addition, and was implemented for head control, rather than because of concern for managing/preventing cervical spine injury. Maintaining the airway even with the iGel laryngeal mask in place, and keeping the head stable, was near-impossible without the additional of the collar. Without it the casualty was also at increased risk of injury. Divers were adept at applying the cervical collar to the casualty whilst they were suspended from the hoist.

4. Use of the NCCD
The NCCD was consistently the most the reliable method for delivering effective chest compressions, and significantly reduced diver fatigue and cognitive load. Early deployment of this device, where available, is therefore strongly advocated. We also found it far simpler to apply with the casualty still in the hoist, rather than in the seat.

An additional advantage of employing the NCCD is that compressions can continue during the extrication of the casualty from the bell to the living accommodation, once the bell is on the surface. Reducing interruptions to effective chest compressions is known to improve outcomes in cardiac arrest.

5. Use seated knee-to-chest compressions if mCPR is not available; consider the Dunoon technique (see below)
No other manual technique for the provision of chest compressions to a seated casualty is supported by efficacy data. Divers found this technique to be deliverable and sustainable with good compression depths achieved.

6. Casualty positioning
The casualty will be managed initially in the bell seat, to enable the second diver to enter the bell (if needed), the bottom hatch to be closed, and the bell to leave bottom. Whilst some evidence exists to support head-up CPR, this is not yet sufficient to advocate its use in preference to supine CPR. As such, if mCPR is in progress (or if the bell floor

permits manual CPR using conventional techniques) then the casualty should be moved to the bell floor during bell ascent.

New CPR technique for the seated casualty[9]

An unexpected outcome of the work was the conception and evaluation of a new technique for delivering chest compressions to a seated casualty. Affectionately referred to within the group as 'the Dunoon technique', this involves delivering chest compressions to the seated casualty with clasped hands in the usual fashion, with the provider either standing or kneeling and bracing themselves against the bell-wall. This was found to be effective and sustainable, and offers a potential alternative to seated knee-to-chest compressions.

ALGORITHM IMPLEMENTATION

This algorithm was developed in collaboration with stakeholder and industry groups and with representation and support from the International Marine Contractors Association (IMCA). It is therefore envisaged that it will be adopted widely across the industry; its implementation will require setting-specific adjustments to account for bell type, size, and design, and it should therefore be woven within companies' Standard Operating Procedures (SOPs).

Whilst a standalone training course for diving bell resuscitations would be ideal, practical and financial constraints render such a venture unlikely to succeed. We therefore suggest that diving bell CPR training forms part of diver and dive medic training courses, with an expectation of simulated practice and regular at-work refresher training to avoid skill fade. The divers involved in the algorithm week felt that this would be a reasonable expectation; they practice and rehearse other critical aspects of their job routinely and felt that critical safety process should be no different.

An exercise in futility?

Cardiac arrest is a condition with a poor prognosis in the best of circumstances, and the diving bell setting presents many additional challenges to its effective management. There are also unavoidable delays associated with casualty extrication from a hyperbaric setting to definitive care or advanced medical intervention. It has therefore been proposed that the provision of CPR, especially in the absence of the ability to deliver defibrillation, may be futile.[10] We refute this suggestion strongly,[11] especially in light of the documented positive outcome from seemingly unrecoverable circumstances in recent years.[4] We suggest that given the oft-reversible aetiologies for cardiac arrest in this setting, and the challenges to early comprehensive medical assessment, it is imperative to provide the best possible care regardless of perceived prognosis. Furthermore, to sit by and do nothing throughout the recovery of bell and casualty to the surface would have unimaginable psychological consequences for fellow divers and friends.

Future research

One of the key research challenges for the field is the development and evaluation of an approach to defibrillation that is safe and suited to the setting. Defibrillation is usually available in the living chambers on board support vessels using one of two methods. One company has a device that is encased in a pressure housing which can operate within the saturation chamber, and requires a stethoscope to hear the commands through the housing, whilst the other option is to hardwire the defibrillator placed outside the living chamber through penetrators to pads on the inside. Both methods require clear protocols and regular drills. There is currently no defibrillation system that can work in a saturation diving bell setting; the pressure and heliox atmosphere are thought likely to impede capacitor function.[12]

Dysrhythmic cardiac arrests have better outcomes than non-shockable arrests in conventional settings, but the current inability to provide timely defibrillation grossly limits the ability to intervene meaningfully for this group of casualties. It is imperative that industry and medical experts collaborate to support the development of a device suited to the diving bell setting.

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