Original articles

Delivering manual cardiopulmonary resuscitation (CPR) in a diving bell: an analysis of head-to-chest and knee-to-chest compression techniques

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Abstract
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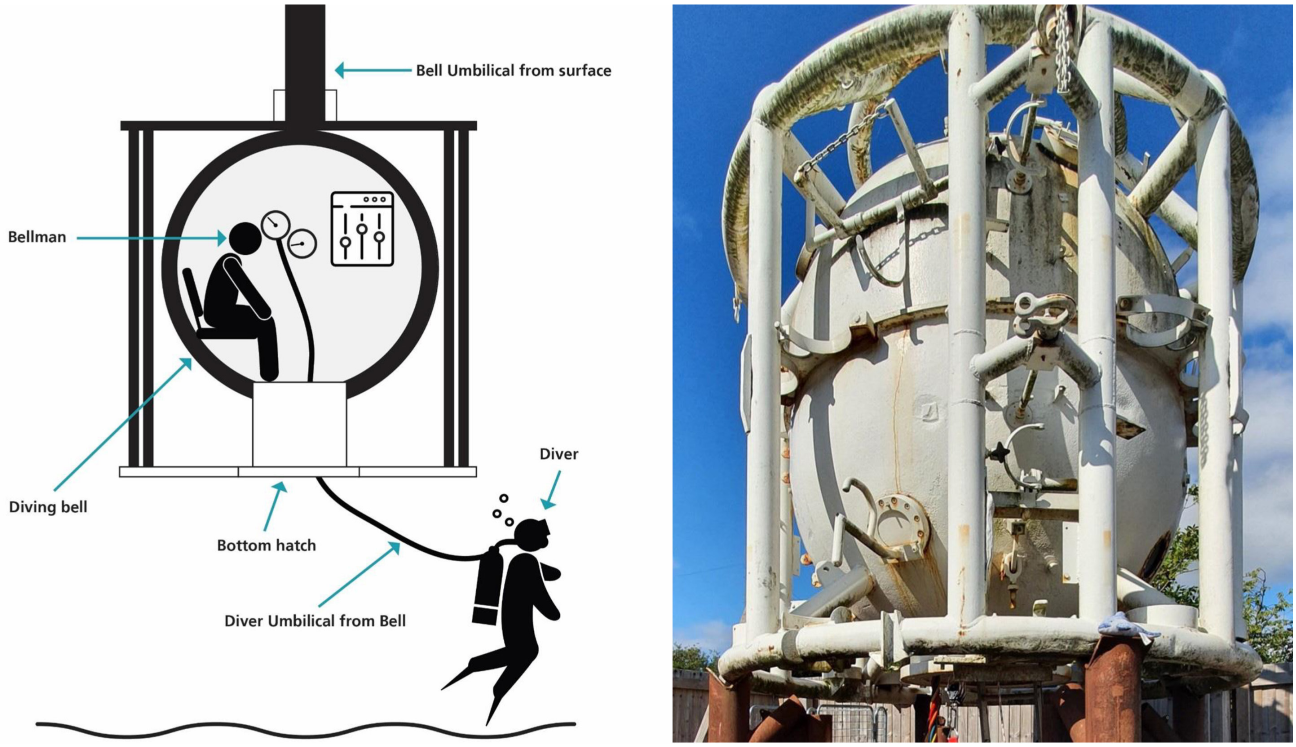
Introduction: Chest compression often cannot be administered using conventional techniques in a diving bell. Multiple alternative techniques are taught, including head-to-chest and both prone and seated knee-to-chest compressions, but there are no supporting efficacy data. This study evaluated the efficacy, safety and sustainability of these techniques.
Methods: Chest compressions were delivered by a team of expert cardiopulmonary resuscitation (CPR) providers. The primary outcome was proportion of chest compressions delivered to target depth compared to conventional CPR. Techniques found to be safe and potentially effective by the study team were further trialled by 20 emergency department staff members.
Results: Expert providers delivered a median of 98% (interquartile range [IQR] 1.5%) of chest compressions to the target depth using conventional CPR. Only 32% (IQR 60.8%) of head-to-chest compressions were delivered to depth; evaluation of the technique was abandoned due to adverse effects. No study team member could register sustained compression outputs using prone knee-to-chest compressions. Seated knee-to-chest were delivered to depth 12% (IQR 49%) of the time; some compression providers delivered > 90% of compressions to depth.
Conclusions: Head-to-chest compressions have limited efficacy and cause harm to providers; they should not be taught or used. Prone knee-to-chest compressions are ineffective. Seated knee-to-chest compressions have poor overall efficacy but some providers deliver them well. Further research is required to establish whether this technique is feasible, effective and sustainable in a diving bell setting, and whether it can be taught and improved with practise.

Introduction

There are many potential causes of acute illness in a saturation diver, including equipment and gas supply problems, trauma, and environmental issues. Although commercial divers are typically viewed as a healthy population, they are ageing; a large proportion are over the age of 45 and a significant number are 60 and over. Cardiac arrest can occur at any age and for a multitude of reasons, with medical causes becoming increasingly common with increasing age.[1] Sudden cardiac arrest is also more common in the male population that forms the vast majority of commercial divers.[2] Observations from recreational diving suggest that the majority of incidents are cardiac in origin, with some correlation with age.[3] There have also been well-publicised cardiac arrests in a saturation environment in recent years.[4,5]

Diving bells (Figure 1) are spherical containers with an internal diameter of 1.5–2.5 m which transport 2–4 divers and their personal equipment. Space inside the diving bell is extremely limited. Divers exit the bell to work, returning to the bell when it is time to return to the ship. One diver remains in the bell during the dive to monitor progress and undertake safety-related activities. Divers remain in a hyperbaric environment for continuous periods of up to a month before decompressing. The decompression process takes several days, with its duration governed by the depth

Figure 1
Diving bell schematic (left) and exterior appearance of a real diving bell



to which divers were compressed and the company's specific diving tables. Decompressing too quickly leads to harm, including decompression illness, which can be fatal.[6]

Effective management of a cardiac arrest in the diving bell environment is extremely challenging, with many factors affecting the provision of basic life support (BLS). The bell is small, and many have insufficient room in which to lie a casualty flat on the floor (Figure 2); some bell floors have protrusions rendering them unsuitable for casualty management. This has led to the development of techniques for the provision of BLS to a casualty in a seated or semi-recumbent position; these techniques include head-to-chest compressions, seated knee-to-chest compressions[7] and prone knee-to-chest compressions.[8] Whilst these techniques are taught on a variety of courses, no evidence informing their effectiveness or sustainability has been identified.

Early defibrillation, a mainstay of conventional cardiac arrest management, is not possible in a diving bell; there are currently no devices able to withstand the operating conditions. Defibrillation is possible within the saturation chamber on the ship but extricating a casualty from the seabed to the ship can take up to 40 minutes. In the absence of effective CPR during extrication, ongoing treatment in the chamber is likely to be futile.

Effective chest compressions are defined in current guidelines as delivered to a depth of at least 5 cm and not more than 6 cm, at a rate of 100–120 beats per minute (bpm),[9] whilst allowing effective recoil and keeping non-compression time to a minimum is vital.[10,11]

This study evaluated the efficacy, safety, and sustainability of three alternative chest compression techniques, in comparison to conventional manual chest compressions, when performed by a team of expert CPR providers.

Methods

TEAM

The team of expert CPR providers included three emergency medicine consultants, one emergency medicine research fellow, one critical care paramedic (and offshore medic) and one emergency medicine charge nurse; all were advanced life support providers or instructors and deliver CPR on a regular basis as part of their professional role.

The study team also included a diver medical technician (an active commercial diver), an offshore medic without extended life support training, and an anaesthetic nurse. All had received basic life support training and would be expected to deliver life support when needed in their professional roles, but none had ever delivered CPR outside of a simulated setting.

Figure 2
Diving bell interior with a simulated victim requiring resuscitation in the sitting position

SETTING AND EQUIPMENT

Data collection took place in the simulation centre of the Royal Derby Hospital. Chest compression efficacy data were captured using the Laerdal Resusci Anne QCPR manikin; this manikin has been used in multiple evaluations of CPR efficacy.[12–14]

OBJECTIVE

To assess the efficacy of existing techniques for providing chest compressions to a casualty in a diving bell environment. The techniques evaluated were head-to-chest compressions, seated knee-to-chest compressions, and prone knee-to-chest compressions.

PRIMARY OUTCOME

The primary outcome measure was the percentage of compressions delivered to target depth (50–60 mm).

SECONDARY OUTCOMES

The following secondary outcomes were recorded.

1. Depth of compressions
2. Difference between depth of compressions for each technique and the gold standard
3. Proportion of compressions with full recoil
4. Proportion of compressions delivered at target rate (100–120 bpm)
5. Rate of compressions
6. Proportion of compressions delivered with correct chest position
7. Sustainability of compressions
8. Adverse events reported by providers during the delivery of chest compressions

GOLD STANDARD

The 'gold standard' comparator was conventional manual chest compressions delivered by expert CPR providers.

DATA COLLECTION

Gold standard data acquisition

The team of expert CPR providers were allowed to familiarise themselves with the manikin and its outputs. Following a rest period, each provider then delivered chest compressions with the manikin supine on a trolley at an appropriate height.

Head-to-chest compressions

The manikin was placed in a seated position on a chair against a wall to simulate the conditions found in a diving bell environment (Figure 3). Head-to-chest compressions were delivered by all members of the study team for a 2-minute period (or until exhaustion).

Seated knee-to-chest compressions

The manikin was placed in the same seated position as for head-to-chest compressions (Figure 3). Knee-to-chest compressions were delivered by all members of the study team for a 2-minute period (or until exhaustion).

Prone knee-to-chest compressions

The manikin was placed face down across a seated provider's knee, with the knee placed in the centre of the chest (Figure 3). Hands were placed on the manikin's back, and compressions delivered by either lifting the knee, pushing down on the manikin's back, or both. Compressions were delivered by all members of the study team for a 2-minute period (or until exhaustion).

STOPPING CRITERIA

Testing of a chest compression technique was abandoned if no provider could deliver effective compressions for at least 30 seconds, or if provider harms (e.g., injury) related to the delivery of compressions were identified.

FURTHER EVALUATION

Techniques for which compression data could be effectively gathered were then evaluated further using a group of up to 20 emergency department doctor and nurse volunteers (different individuals for each technique), all of whom were trained in the provision of basic life support and who were expected to deliver chest compressions as part of their professional role. Each provider again delivered

Figure 3
Head-to-chest CPR (left); seated knee-to-chest CPR (middle); prone knee-to-chest CPR (right)

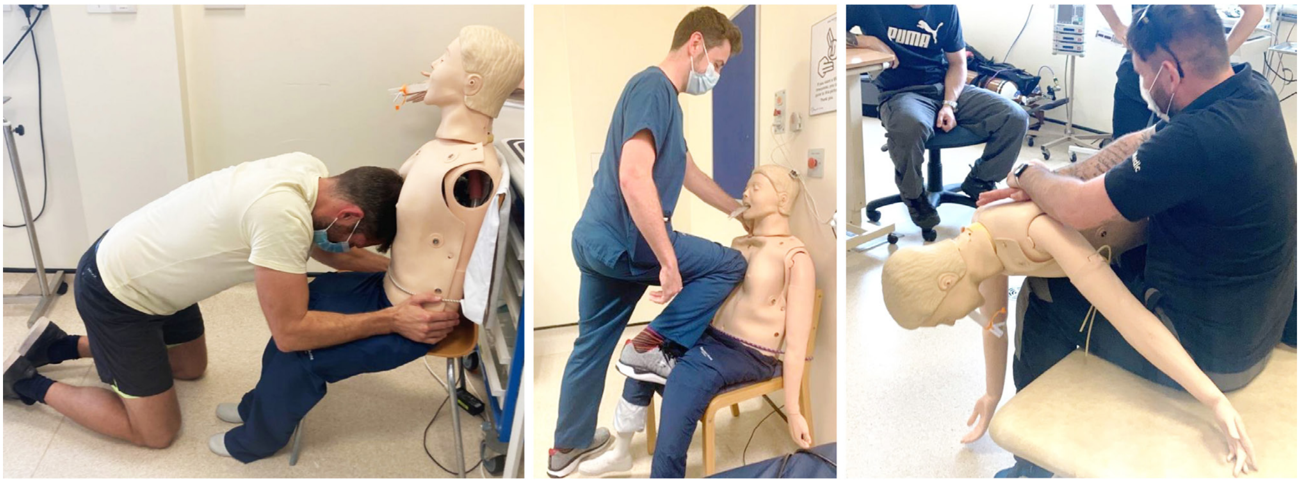


Table 1
Outcomes for conventional chest compressions delivered by expert CPR providers (compression-only); IQR – interquartile range

Provider number	Compression depth (%)	Recoil (%)	Mean depth (mm)	Rate (%)	Mean rate (bpm)	Position (%)
1	99	98	56	99	111	51
2	98	98	54	81	117	100
3	99	98	61	95	112	71
4	98	53	58	64	120	100
5	97	65	54	89	117	100
6	84	99	51	97	116	100
Median (IQR)	98 (2)	98 (25)	55 (4)	92 (14)	117 (4)	100 (22)

chest compressions for 2 minutes (or until exhaustion); no volunteer delivered more than one technique to avoid fatigue.

ADVERSE EVENTS

Any discomfort or injuries sustained during the delivery of chest compressions were recorded.

SUSTAINABILITY

If a provider ceased compressions prior to completion of the planned time period then their total time was recorded. At the end of each data collection period each provider was asked their opinion on whether the technique could be sustained for a period of 40 minutes; this interval represents the theoretical maximum time between commencing CPR in a diving bell and offloading a casualty onto the ship.

DATA ANALYSIS

Study team data were compared to volunteer data using the Mann-Whitney U test; if no significant difference was identified between the groups then pooled data are presented.

Results

GOLD STANDARD (CONVENTIONAL CHEST COMPRESSIONS)

The median percentage of compressions delivered to depth was 98%, interquartile range (IQR) 1.5%. Further efficacy data can be found in Table 1.

HEAD-TO-CHEST COMPRESSIONS – STUDY TEAM

Efficacy data for this technique can be seen in Table 2. Two study team members could not complete the planned 2-minute period of head-to-chest compressions, and no study team member felt that head-to-chest compressions would be sustainable for 40 minutes. All but one provider reported side effects, including headache and neck pain, from head-to-chest compressions.

HEAD-TO-CHEST COMPRESSIONS – FURTHER EVALUATION

The median percentage of compressions delivered to the required depth (study team and volunteer) was 32% (IQR

Table 2
Outcomes for head-to-chest compressions delivered in the seated position for up to two minutes, compression only; sustainability assessed by each provider; *emergency department staff volunteer; bpm – beats per minute; IQR – interquartile range

Provider number	Compression depth (%)	Recoil (%)	Mean depth (mm)	Rate (%)	Mean rate (bpm)	Position (%)	Adverse effects	Sustainable for 40 min?
1	80	57	55	94	102	100	Head pain	No (1 min 50 s)
2	64	60	51	98	115	100	Head pain	No
3	10	97	40	7	94	100	Head pain	No
4	7	60	44	99	113	100	Head pain	No
5	46	21	48	100	111	100	Headache	No
6	70	51	51	96	107	100	Headache	No
7	0	80	35	30	124	100	–	No
8	18	7	45	74	101	86	Head pain	No
9	78	66	55	99	109	100	Head pain, felt unwell	No (1 min 22 s)
10*	5	99	44	0	84	100	Head and neck pain	No
Median (IQR)	32 (61)	60 (24)	47 (58)	95 (7)	108 (11)	100 (0)	–	–

60.8%). The change in median compression depth compared to the gold standard was -14.5% (8 mm). Further efficacy data can be found in Table 2.

The combination of poor efficacy findings and adverse effects meant that only a single member of emergency department staff was recruited before further evaluation was abandoned on safety grounds.

SEATED KNEE-TO-CHEST COMPRESSIONS – STUDY TEAM

Two study team members could not complete the planned 2-minute period of seated knee-to-chest compressions, and only one study team member felt that seated knee-to-chest compressions would be sustainable for 40 minutes. No study team members reported adverse effects from delivering seated knee-to-chest compressions.

The median percentage of compressions delivered to the required depth was 15% (IQR 42%). The change in median compression depth compared to the gold standard was -21.8% (12 mm). Further efficacy data can be found in Table 3.

SEATED KNEE-TO-CHEST COMPRESSIONS – FURTHER EVALUATION

Twenty members of emergency department staff delivered seated knee-to-chest compressions; two were unable to complete the full 2-minute compression period. The median percentage of compressions delivered to the required depth was 7.5% (IQR 51.3%). The change in median compression depth compared to the gold standard was -25.5% (14 mm). Further efficacy data can be found in Table 4.

One provider felt that seated knee-to-chest compressions could be sustained for 40 minutes, with a further 13 stating it might be sustainable; multiple participants observed that the opportunity to swap providers every few minutes would improve its sustainability. The remaining six providers felt that seated knee-to-chest compressions could not be sustained for 40 minutes regardless of the ability to swap providers.

There was no significant difference between the proportion of compressions to depth using seated knee-to-chest delivered by the study team and that delivered by emergency department staff volunteers ($P = 0.45$); the median proportion of compressions to depth in pooled data was 12% (IQR 49%). The change in median compression depth for pooled data when compared to the gold standard was -25.5% (14 mm).

PRONE KNEE-TO-CHEST COMPRESSIONS

Prone knee-to-chest compressions could not be delivered by any study team member to a sufficient depth to register a sustained output from the manikin. There are therefore no efficacy data to present; no further evaluation was performed.

Discussion

This study represents the first evaluation of the three alternative chest compression techniques widely taught and employed in the commercial diving industry. None of the

Table 3
Outcomes for seated knee-to-chest compressions delivered in the seated position by study team members for up to two minutes, compression only; sustainability assessed by each provider; bpm – beats per minute; IQR – interquartile range

Provider number	Compression depth (%)	Recoil (%)	Mean depth (mm)	Rate (%)	Mean rate (bpm)	Position (%)	Adverse effects	Sustainable for 40 min?
1	48	67	49	4	95	100	No	No (44s)
2	34	80	47	99	106	100	No	No
3	3	58	39	89	112	100	No	No
4	6	53	41	69	110	82	No	No (18s)
5	0	60	37	99	110	100	No	Yes
6	98	25	60	100	107	100	No	No
7	12	97	41	84	117	100	No	No
8	15	63	43	94	105	100	No	No
9	92	46	58	91	114	100	No	No
Median (IQR)	15 (42)	60 (14)	43 (14)	91 (15)	110 (6)	100 (0)	–	–

Table 4
Outcomes for seated knee-to-chest compressions delivered in the seated position by emergency department staff for up to two minutes, compression only; sustainability assessed by each provider; bpm – beats per minute; F – female; IQR – interquartile range; M – male

Volunteer	Sex	Profession	Depth (%)	Recoil (%)	Depth (mm)	Rate (%)	Rate (bpm)	Position (%)	Adverse effects	Sustainable for 40 min?
1	F	Nurse	1	100	38	19	93	100	No	Yes
2	M	Doctor	99	100	60	89	103	100	Knee pain	Maybe
3	F	Nurse	0	100	40	89	120	100	No	Maybe
4	M	Doctor	19	100	45	92	116	100	Calf pain	No
5	F	Nurse	1	100	39	95	108	100	No	No (56 s)
6	F	Doctor	59	100	52	84	99	100	Back pain	Maybe
7	F	Doctor	97	95	59	30	96	100	Knee pain	No (1 min 30 s)
8	F	Doctor	0	89	37	0	90	100	Knee pain	Maybe
9	M	Paramedic	0	100	29	96	104	100	Hip pain	Maybe
10	M	Doctor	50	87	49	100	108	100	No	Maybe
11	M	Paramedic	97	70	52	38	99	100	Hip pain	Maybe
12	F	Nurse	10	100	45	0	84	100	Hip pain	Maybe
13	F	Doctor	49	77	49	97	107	100	No	No
14	M	Nurse	58	100	49	97	107	100	Leg pain	Maybe
15	M	Doctor	12	81	41	62	102	100	No	No
16	F	Nurse	0	100	34	35	92	100	Leg pain	Maybe
17	M	Doctor	3	100	41	98	116	100	Knee pain	Maybe
18	M	Doctor	5	99	39	82	103	100	No	No
19	M	Doctor	1	100	36	71	101	100	No	Maybe
20	M	Doctor	0	100	29	83	103	100	No	Maybe
Median (IQR)	–	–	8 (51)	100 (7)	41 (11)	84 (58)	103 (9)	100 (0)	–	–

techniques have efficacy comparable to conventional chest compressions and none were perceived to be sustainable for a prolonged period. However, given that environmental limitations frequently prohibit the use of conventional chest compressions, alternative techniques are undoubtedly necessary if a casualty is to be given a meaningful chance of recovery from cardiac arrest. At least one recent incident has shown that neurologically intact survival is possible after a prolonged period with low cerebral oxygen delivery in the hyperbaric environment.[5] In the absence of defibrillator availability, high quality CPR is therefore the mainstay of treatment and essential to maintain cerebral and coronary blood flow.[11] Whilst neurologically intact survival after prolonged CPR is frequently perceived to be unlikely, consciousness and awareness during high quality CPR have been demonstrated, highlighting the value of effective CPR in optimising outcomes.[15]

Head-to-chest compressions were found to have an unacceptably high incidence of adverse events, with almost all providers reporting head and/or neck pain; this is even more concerning given the short study period (two minutes). The only study-team member who did not report an adverse event (Provider 7) was also the only member who failed to deliver any compressions to an adequate depth (mean 35 mm). Conversely, the two providers unable to complete the full 2-minute test period were those with the highest percentage of compressions delivered to an appropriate depth. This suggests that delivering effective compressions is not sustainable and is likely to be associated with adverse events.

The seated knee-to-chest compression data are more nuanced. The median compression depth from the pooled data (12%) suggests that this technique is ineffective; this was unaffected by provider gender (of relevance given most commercial divers are male). However, two providers delivered 98% of compressions to depth and five providers delivered 90%; conversely, many providers delivered none of their compressions to target depth. The reason for this variation is not yet established by this study, but may well be related to technique or biomechanical issues.

The perceived sustainability of seated knee-to-chest compressions was variable. Four providers (two study team members and two volunteers) were unable to complete two minutes of compressions, whilst four were able to deliver compressions of comparable depth to expert conventional CPR for the full 2-minute period. Multiple providers felt that seated knee-to-chest compressions could potentially be sustained for 40 minutes, especially if alternating of providers was possible. It is well-known that even conventional resuscitation techniques in a hospital environment are extremely tiring, and that provider-effectiveness decreases after as little as two minutes of delivering chest compressions.[16] Real-world assessment of seated knee-to-chest compression sustainability is needed.

Resuscitating a casualty in a seated position in a diving bell is undertaken through necessity, and the effectiveness of head-up CPR is not yet well-evidenced. It has been suggested that in some settings head-up CPR achieves improved cerebral blood flow compared to conventional CPR, but that this improvement requires a period of supine chest compressions first; the latter would not always be possible in a diving bell setting.[17]

No provider was able to administer prone knee-to-chest compressions effectively. Correct positioning of the casualty on the rescuer's knee was difficult, even with a manikin weighing considerably less than a diver and unencumbered by the supplemental equipment, water and cognitive load that would be associated with a real emergency.

This study has not considered mechanical CPR, a technique commonly used in clinical settings to reduce provider cognitive load and fatigue, and shown to be non-inferior to conventional chest compression.[18] The authors are only aware of one device that can be used in a saturation environment (the NUI compact chest compression device);[19] the efficacy of this device is presented elsewhere in this issue.[20] However, it will not be universally available across the industry due to varying safety standards and financial constraints, and mechanical failures are always a possibility; techniques for providing manual chest compressions in a diving bell environment are therefore still required.

Across the pooled study participants (and with exceptions discussed above), seated knee-to-chest CPR efficacy data are poor. However, in the absence of an alternative method for manual compression delivery, and without the availability of a mechanical CPR device, the only remaining alternative would be to forego chest compressions altogether. Given the close working relationships between divers, the lack of immediately available medical help, and the prolonged extrication time in an enclosed space, it is hard to envisage that bystanders would not wish to attempt resuscitation; not being able to do so would likely increase the likelihood of psychological consequences. We must therefore develop and teach the best possible techniques given the context and environmental constraints, both to optimise outcomes in casualties and to reduce the likelihood of second victim syndrome.[21]

LIMITATIONS

This is a laboratory study of chest compressions using an intelligent manikin; it is impossible to predict whether the efficacy findings seen in this study would translate to clinical effectiveness. Despite efforts to simulate appropriate casualty positioning, it is likely that the environmental limitations of a diving bell would affect the biomechanics of delivering compressions to a casualty.

Time off the chest to deliver ventilations would be necessary during the provision of compressions to a casualty, and this time may vary between techniques; this variation has not been assessed in this study, and pauses in chest compressions are known to be associated with poor resuscitation outcomes.[22]

Resuscitation in a diving bell would present myriad challenges in addition to those experienced by those providing chest compressions in this study, including (but not limited to): lack of familiarity with techniques; presence of extraneous equipment; wet conditions; stress and cognitive load; the need to resuscitate a colleague; physical fatigue due to recent manual labour; and the need to focus both on the management of the casualty and on bringing the bell to the surface safely. As such, positive data should be considered exploratory, rather than as evidence of likely technique effectiveness in a real-world setting. Nonetheless, given the relative infrequency of cardiac arrests in this environment coupled with the challenges of delivering clinical research on this topic, it is extremely unlikely that clinical outcome trial data will ever be available.

Finally, the absolute nature of target ranges does not translate perfectly to clinical practice. A provider delivering every compression to 49 mm is deemed to have delivered 0% of compressions to depth by the intelligent manikin; it is debatable whether delivering these compressions 1 mm deeper translates to meaningful clinical impact.

Conclusion

Head-to-chest compressions have limited efficacy and are unsafe for providers; they should no longer be taught or used. Prone knee-to-chest compressions are ineffective and the technique should be abandoned.

Further research is required to establish the feasibility, effectiveness, and sustainability of seated knee-to-chest compressions in a diving bell environment, and to incorporate them into an algorithm for the management of a casualty in a saturation diving setting. It must be established whether the provision of effective seated knee-to-chest compressions is a teachable and reproducible skill. Caution should be applied to the teaching and implementation of seated knee-to-chest compressions until further data concerning optimum techniques in a diving bell setting are available.

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