An evaluation of the NUI Compact Chest Compression Device (NCCD), a mechanical CPR device suitable for use in the saturation diving environment

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Abstract
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Introduction: Provision of manual chest compressions in a diving bell using a conventional technique is often impossible, and alternative techniques are poorly evidenced in terms of efficacy and sustainability. The first mechanical cardiopulmonary resuscitation (CPR) device suitable for use in this environment, the NUI Compact Chest Compression Device (NCCD), has recently been designed and manufactured. This study assessed both the efficacy of the device in delivering chest compressions to both prone and seated manikins, and the ability of novice users to apply and operate it.
Methods: Compression efficacy was assessed using a Resusi Anne QCPR intelligent manikin, and the primary outcome was the proportion of compressions delivered to target depth (50–60 mm). The gold standard was that achieved by expert CPR providers delivering manual CPR; the LUCAS 3 mCPR device was a further comparator.
Results: The NCCD delivered 100% of compressions to target depth compared to 98% for the gold standard (interquartile range 1.5%) and 98% for the LUCAS 3 when applied to both supine and seated manikins. The NCCD sometimes became dislodged and had to be reapplied when used with a seated manikin.
Conclusions: The NCCD can deliver chest compressions at target rate and depth to both supine and seated manikins with efficacy equivalent to manual CPR and the LUCAS 3. It can become dislodged when applied to a seated manikin; its design has now been altered to prevent this. New users can be trained in use of the NCCD quickly, but practise is required to ensure effective use.

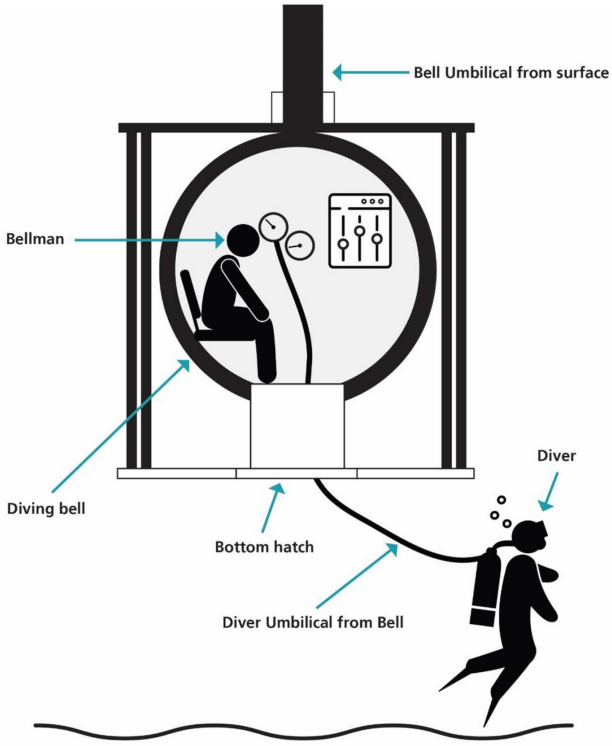
Introduction

Commercial diver deaths historically were predominantly related to trauma or equipment failure, but acute illness now underlies the majority of medical emergencies; this is due to an ageing workforce coupled with improved safety regulations and working conditions.[1]

Management of a sudden cardiac arrest whilst divers are working from the diving bell (Figure 1) is extremely challenging due to space-limited working conditions, a lack of flat surface on which to lie the casualty, the impossibility of immediate medical help, and restrictions on suitable equipment due to the hyperbaric, wet working environment. In addition, extrication times can be prolonged; it may take up to 40 minutes to bring a casualty from the working depth back to the saturation chamber on board the ship, and it may be several days before a casualty can be removed from the chamber and transported to land.

Mechanical cardiopulmonary resuscitation (mCPR) involves the use of a mechanical device to deliver chest compressions to a casualty in cardiac arrest. Whilst outcomes after cardiac arrest management with mCPR are not superior to manual CPR, mCPR has been recommended for situations where provider resource may be lacking, when a prolonged resuscitation is envisaged (to protect against provider fatigue), and in other settings where environmental or situational constraints preclude early initiation of high-quality manual CPR.[2] All of the above conditions are present in the context of a cardiac arrest in a diving bell.

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



There has not been an mCPR device that could be used in this setting due to technical considerations: repeated exposure of the lithium battery and LCD screens to a hyperbaric environment; device size; the impact of the hyperbaric environment on device operation (e.g., a gas-driven device); and the impact of saltwater corrosion. However, the Norwegian company NUI have recently designed and manufactured the NUI Compact Chest Compression Device (NCCD) for use in the saturation diving setting, and specifically in a diving bell.[3] The NCCD (Figure 2) is a gas-driven piston device requiring manual trigger actuation to deliver each compression. The compression is delivered to a fixed depth and then held until the provider releases the trigger. The device is compact, and the piston and device body are held to the chest by a tough fabric strap encircling the casualty and secured by hook-and-loop fastening. The device is driven by gas at 1,000 kPa (10 bar) above ambient gas pressure (readily available in a saturation diving environment from the built-in breathing system) and can work whilst submerged.

Design and space constraints in some diving bells mean that there may be no flat surface on which to manage a casualty, and CPR may therefore need to be delivered with a casualty in a seated position. Manual techniques (e.g., seated knee-to-chest compressions) enable delivery of some effective compressions, but their efficacy does not compare well to conventional CPR in a laboratory environment.[4] Commercial divers also wear a neoprene hot-water suit that may affect the effectiveness of chest compressions if left in-situ. The impact of the seated position and hot-water suit on mCPR chest compression effectiveness have not previously been assessed.

There are no published data on the efficacy of the NCCD. This study evaluated:

1 The efficacy of the NCCD in providing chest compressions in a laboratory setting, compared to manual compressions administered by expert providers, and compared to the LUCAS 3 (Stryker, Kalamazoo, USA), an mCPR device in widespread use in healthcare settings.
2 The efficacy of the NCCD in a seated position, and when administering chest compressions through a (dry) hot-water suit.
3 The ability of new users to apply and use the NCCD after a short familiarisation session.

Methods

SETTING AND EQUIPMENT

Data collection took place in the simulation centre of the Royal Derby Hospital. Chest compression efficacy data were collected using the Laerdal Resuci Anne QCPR manikin. The mCPR devices used were the NUI Compact Chest Compression Device and the LUCAS 3. The hot-water suit was of a type in common industry use.

Figure 2
The NUI Compact Chest Compression Device (NCCD) in use on a manikin

PRIMARY OUTCOME

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

SECONDARY OUTCOMES

Secondary outcome measures included:

1 Depth of compressions
2 Difference between depth of compressions for each device 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 anatomical positioning on the chest
7 The impact of manikin position (supine vs seated) on the above metrics
8 The impact of a hot-water suit on the above metrics
9 Difference between the average depth of compressions for each device in each position/suit configuration, and the same device operated in its ideal working conditions (supine, no suit)
10 Percentage of compressions delivered to target depth by users new to the NCCD
11 Time taken to apply the NCCD by users new to the device
12 Other efficacy metrics as described above when the NCCD was operated by new users

GOLD STANDARD

The notional 'gold standard' was manual chest compressions delivered by expert CPR providers to a supine manikin. These data were collected in another study,[4] but are presented below for ease of comparison.

The study team of expert CPR providers included three emergency medicine consultants, one emergency medicine research fellow, one critical care paramedic/offshore medic, and one emergency medicine charge nurse; all were advanced life support providers or instructors who regularly deliver CPR as part of their professional roles.

DATA COLLECTION

Mechanical chest compression data acquisition

Study team members use the LUCAS 3 in their clinical practice and were familiar with its operation prior to this study. They received a short period (5–10 min) of device familiarisation and training in the use of the NCCD from a NUI representative.

Each mCPR device was applied to the manikin in accordance with the manufacturer's instructions and operated by the study team for a period of two minutes in the following conditions:

» Supine, no suit
» Supine, suit closed (i.e., on and zipped up)

» Supine, suit open (i.e., on but unzipped, such that the device can be applied directly to the front of the manikin)
» Seated (i.e., propped on a chair, back to a wall), no suit
» Seated, suit closed
» Seated, suit open

Application time and new user efficacy data

Twelve volunteer participants (eight nurses and four doctors) were recruited from the Royal Derby Hospital emergency department's staff as a convenience sample. They received the same period of device familiarisation and training as the study team in the use of the NCCD from a NUI representative.

Working in pairs, they were asked to apply the NCCD to a seated manikin and to deliver compressions for a 2-minute period. Volunteer one of each pair delivered compressions in the first attempt.

Time taken until delivery of the first compression was recorded. Following debrief and discussion the pair had a further attempt with volunteer two of each pair delivering compressions. Data from both attempts are reported for each pair.

Results

GOLD STANDARD (CONVENTIONAL CHEST COMPRESSIONS)

The median percentage of conventional chest compressions delivered by the study team to the required depth was 98% (interquartile range [IQR] 1.5%). Further efficacy data can be found in Table 1, and a fuller description of the acquisition of the gold standard data can be found elsewhere.[4]

MECHANICAL CHEST COMPRESSIONS

Data from both the NCCD and the LUCAS in all manikin positions and suit configurations can be seen in Table 2. In a supine position when operated by the study team both the NCCD and the LUCAS delivered compressions to the appropriate depth as well as, or better than, the gold standard in almost all suit configurations; the only supine suit configuration where an mCPR device did not perform equivalently to the gold standard was with the NCCD with an open hot-water suit (NCCD 94%, gold standard 98%).

There are no data for the LUCAS in the seated position because it could not be effectively applied; its mass and centre of gravity caused it to fall from the chest and no compressions could be delivered.

The NCCD became dislodged prior to the completion of the 2-minute compression period in all seated configurations on first attempts; data presented were therefore gathered after adjusting the fitting/application process during repeat attempts.

With a seated manikin and no hot-water suit in place the NCCD delivered 100% of compressions to an appropriate depth with full recoil. It performed inferiorly to the gold standard with the hot-water suit in either the open or closed position.

The mean compression rate with the NCCD in the supine, no hot-water suit configuration was 95 beats per minute (bpm), with only 5% of compressions delivered within the target rate range. The mean rate during all other data collection sessions for the NCCD was within the target range.

The change in mean compression depth for each device, position and suit configuration, when compared to both the gold standard and to that device's 'supine, no suit' configuration, can be seen in Table 3. The presence of a hot-water suit in any configuration had an impact on the depth of compression delivered with the NCCD; the LUCAS was comparatively unaffected.

Volunteer testing

One pair of volunteers were recalled to clinical duty and were unable to perform a second data collection period; their single use of the NCCD is presented with the five other paired data sets in Table 4.

The median percentage of compressions delivered to the target depth with the NCCD by new users was 97% (IQR 37%). The median application time was 61 s, and all pairs showed improvement between their first and second attempts (1st attempt median 67 s, 2nd attempt 45 s).

The median rate of compressions delivered by novice users using the NCCD was 100 bpm (IQR 10).

The percentage of compressions delivered with full recoil varied widely (median 91%, IQR 85%). It was noted that users achieving poor recoil had applied the device tightly which compressed the manikin's chest at baseline, rendering full recoil impossible.

Discussion

In a laboratory setting the NCCD delivered a greater percentage of compressions to target depth and with full recoil than expert providers performing conventional CPR. Whilst further assessment of device performance when operated by saturation divers is required, these early results are encouraging, and suggest that the NCCD may be a suitable device for the delivery of mCPR in a saturation diving setting.

Table 1
Outcomes for conventional chest compressions delivered in the supine position by expert CPR providers for four minutes, without the presence of a hot-water suit; bpm – beats per minute; 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)

Table 2
Outcomes for the NUI compact chest compression device (NCCD) and the LUCAS 3 mechanical CPR device, supine and seated, with a hot-water suit in a variety of configurations; bpm – beats per minute

Device	Manikin position	Hot-water suit position	Compression depth (%)	Recoil (%)	Mean depth (mm)	Rate (%)	Mean rate (bpm)	Position (%)
NCCD	Supine	No suit	100	100	59	5	95	100
NCCD	Supine	Suit closed	100	100	52	98	115	100
NCCD	Supine	Suit open	94	100	51	96	115	100
Lucas	Supine	No suit	98	100	54	98	101	100
Lucas	Supine	Suit closed	100	100	53	94	102	100
Lucas	Supine	Suit open	99	100	56	99	101	100
NCCD	Seated	No suit	100	100	58	98	111	100
NCCD	Seated	Suit closed	0	100	41	99	113	38
NCCD	Seated	Suit open	82	100	51	91	116	2
Lucas	Seated	No suit	–	–	–	–	–	–
Lucas	Seated	Suit closed	–	–	–	–	–	–
Lucas	Seated	Suit open	–	–	–	–	–	–

The NCCD is mechanical but not automatic; it requires manual activation of the piston by a trigger. The proportion of compressions delivered at the target rate was variable, and adherence improved over time. Across all tests the median percentage of compressions delivered at target rate by the study team was 98% (IQR 4%); this is more consistent and accurate than expert providers delivering conventional CPR. The percentage of compressions delivered at an appropriate rate by volunteers, with less exposure to NCCD use than study team members, was more variable; this suggests that a longer period of device familiarisation, together with simulated practice, is required to ensure that compressions are delivered at an appropriate rate by users new to the NCCD. A standardised approach to device training and familiarisation is required.

Resuscitation in a diving bell may have to take place in a fully seated position for at least some of the resuscitation effort, as it may be the only position possible due to space constraints. The NCCD was applied and used effectively in a seated position, with compression depths similar to the gold standard. However, it became loose or dislodged within the 2-minute test period both with and without the presence of a hot water suit, and had to be re-applied to complete data collection.

There is some evidence that head-up CPR, where compressions are delivered with the casualty in the reverse Trendelenburg position, may have a positive impact on outcomes after cardiac arrest.[5] However, it is felt to require a period of 'priming' with the casualty in a supine position in order to be effective; this may not be possible in a diving bell. The efficacy of head-up or seated CPR is not yet well-evidenced, and is possible that the position may reduce cerebral blood flow even during effective chest compressions.

Table 3
Change in mean compression depth compared to gold standard, and to each device baseline (supine, no suit); NCCD – NUI compact chest compression device

Device	Manikin position	Hot-water suit position	Mean compression depth (mm)	Change from gold standard (%)	Change from 'supine, no suit' (%)
NCCD	Supine	No suit	59	7.3	–
NCCD	Supine	Suit closed	52	-5.5	-12
NCCD	Supine	Suit open	51	-7.3	-14
LUCAS	Supine	No suit	54	-1.8	-
LUCAS	Supine	Suit closed	53	-3.6	-2
LUCAS	Supine	Suit open	56	1.8	4
NCCD	Seated	No suit	58	5.5	-2
NCCD	Seated	Suit closed	41	-25.5	-31
NCCD	Seated	Suit open	51	-7.3	-14

Table 4
Efficacy data and application times for the NUI compact chest compression device (NCCD) when operated by emergency department staff/novice device users; bpm – beats per minute; IQR – interquartile range

Team	Member roles	Application time (s)	Depth (%)	Recoil (%)	Rate (%)	Depth (mm)	Rate (bpm)	Position (%)
1	Nurse	67	97	100	65	53	101	100
	Nurse	45	64	100	39	50	99	100
2	Nurse	67	18	87	3	45	131	44
	Nurse	65	0	94	6	47	79	100
3	Nurse	76	97	5	0	53	87	100
	Nurse	61	61	100	9	50	93	100
4	Doctor	80	99	3	19	52	96	100
5	Doctor	55	98	100	56	53	100	100
	Doctor	40	99	0	75	58	103	100
6	Nurse	50	100	91	100	62	109	100
	Nurse	35	99	25	97	56	105	97
Median (IQR)	–	61 (20)	97 (37)	91 (85)	39 (63)	53 (5)	100 (10)	100 (0)

The safe removal of a hot-water suit will take time, and compression delivery during this period will be impossible. Given that reducing the no-flow fraction of a resuscitation is associated with better outcomes,[6,7] it was therefore important to assess the efficacy of the NCCD with the suit still in place; if suit removal could be avoided whilst still delivering effective compressions then this would reduce the no-flow fraction of diver resuscitation. Whilst both the NCCD and the LUCAS delivered effective compressions through the hot-water suit (either open or closed) in a supine position, both had at least one failed attempt where the device came loose or fell off before completion of the 2-minute test period. Applying the device was more difficult, with the suit becoming trapped and interfering with the strap or backboard. The presence of a hot-water suit (either open or closed) also reduced compression depth for the NCCD in both supine and seated positions; the most significant impact was with a closed suit in a seated position where the mean compression depth was reduced by over 30% in comparison to normal operation. Presence of the hot-water suit also impacted the accuracy of device positioning. It is therefore important that in practice the suit is removed, or cut away from the upper body, prior to application of the NCCD.

The median compression depth when the NCCD was applied and operated by new users compared favourably

Figure 3
The NCCD application process showing application of the NCCD with added neck strap (images courtesy of NUI)

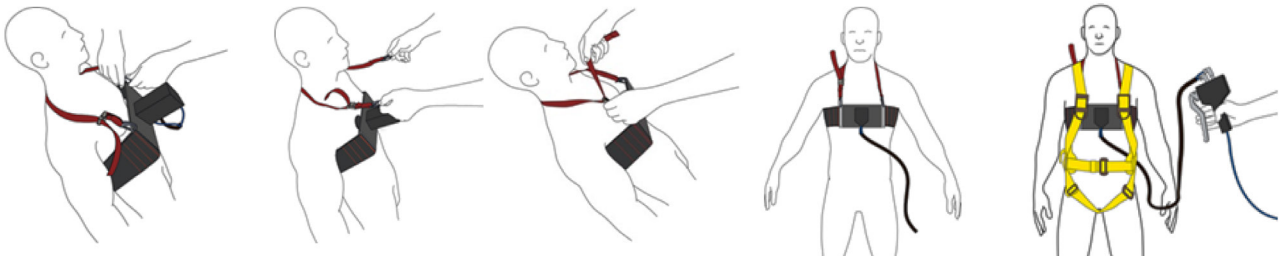
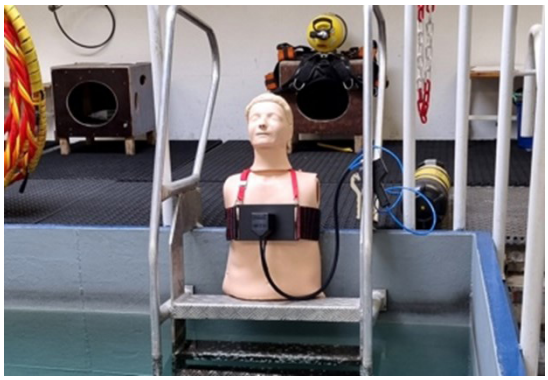


Figure 4
Updated NCCD with neck strap in use on a manikin (image courtesy of NUI)



to the gold standard, but with greater variation between providers compared to when the device was operated by the study team. The device was applied rapidly even by first-time users, and this time decreased with practise; this again highlights the importance of appropriate device training, coupled with the opportunity for simulated practice, prior to any real-world use of the device. It is worth noting that all volunteers were already trained in the delivery of both manual and mechanical CPR using other devices.

DEVICE CONSIDERATIONS

The NCCD requires manual trigger activation to deliver each compression, and its piston will remain extended as long as the trigger is depressed; this has potential safety implications for the patient as the chest could be held in the compressed position indefinitely. The user will need to deliver compressions continuously whilst being mindful of the compression rate. A key benefit of mCPR devices such as the LUCAS 3 is their ability to free up a team member and cognitively offload the team,[2] as they deliver compressions automatically and without user input once applied and started; neither of these benefits is offered by the NCCD.

Whilst the NCCD could be applied effectively in the seated position, it fell off multiple times during testing. This problem is likely to be compounded in a wet environment and with users less familiar with its operation. These findings were fed back to NUI, who have subsequently altered the design to include a neck strap, improving stability in the seated position without impacting the delivery of compressions (Figures 3 and 4). This modified device has not been tested in this study.

Both the group of expert CPR providers and the volunteers received only a short period of device training and familiarisation. Improvements in rate (expert providers), application time (volunteers) and effectiveness of application in a seated position were noted with repeated experience. This highlights the importance of adequate time for device training and familiarisation, together with the need for simulated practice, and is not an unexpected finding.[8]

The various design considerations that allow its use in a saturation diving environment (low profile, light, waterproof, non-electrical) may also render it suitable for use in a variety of non-standard resuscitation settings, including confined spaces, challenging casualty extrications, and other settings which mimic the restrictions present in a diving bell.

STUDY LIMITATIONS

This study reports efficacy metrics from an 'intelligent manikin' and any extrapolation to potential clinical outcomes should be cautious. However, given the relative infrequency of cardiac arrests in saturation diving and the inherent difficulty in performing research in that setting, meaningful clinical data collection is likely to be impossible. The industry is therefore reliant on simulation studies such as this, coupled with extrapolation of data from other settings, to inform best practice.

This small exploratory laboratory study was performed in 'ideal conditions'; further work should involve testing in a simulated, or actual, saturation diving setting, with the mCPR device operated for a longer period of time. Users in this assessment should be equipped authentically for modern saturation diving to evaluate any impact diving equipment may have on the users' ability to operate the device. This work should also explore the efficacy of the device when used by non-expert CPR providers. It should also evaluate the impact of the device on provision of ventilations during CPR. An optimal approach to device

training and familiarisation should be developed, and the rate of skill atrophy should be assessed to inform refresher training requirements.

The NCCD strap was noted to compress the manikin's chest when applied tightly, reducing the ability to record full recoil; it is not clear whether this effect would be present with real casualties.

Conclusions

The NCCD can deliver chest compressions at a rate and depth in line with existing guidelines, and in both a supine and seated position, as effectively as expert CPR providers delivering conventional chest compressions.

The presence of a hot water suit reduced device efficacy and hindered application. A seated casualty position led to the device becoming dislodged, requiring adjustment or re-application; this has led to a modification in device design (incorporation of a neck strap).

New users can apply the device quickly and use it effectively but require device training and familiarisation to use it optimally. It is vital that potential users receive appropriate training and practise prior to using the device in a medical emergency.

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Conflicts of interest and funding

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