Cardiopulmonary Resuscitation in Hypogravity Simulation

Sindujen Sriharan; Gemma Kay; Jimmy C.Y. Lee; Ross D. Pollock; Thais Russomano

BACKGROUND: Limited research exists into extraterrestrial CPR, despite the drive for interplanetary travel. This study investigated whether the terrestrial CPR method can provide quality external chest compressions (ECCs) in line with the 2015 UK resuscitation guidelines during ground-based hypogravity simulation. It also explored whether gender, weight, and fatigue influence CPR quality.

METHODS: There were 21 subjects who performed continuous ECCs for 5 min during ground-based hypogravity simulations of Mars (0.38 G) and the Moon (0.16 G), with Earth's gravity (1 G) as the control. Subjects were unloaded using a body suspension device (BSD). ECC depth and rate, heart rate (HR), ventilation ($\dot{V}_E$), oxygen uptake ($\dot{V}O_2$), and Borg scores were measured.

RESULTS: ECC depth was lower in 0.38 G (42.9 ± 9 mm) and 0.16 G (40.8 ± 9 mm) compared to 1 G and did not meet current resuscitation guidelines. ECC rate was adequate in all gravity conditions. There were no differences in ECC depth and rate when comparing gender or weight. ECC depth trend showed a decrease by min 5 in 0.38 G and by min 2 in 0.16 G. Increases in HR, $\dot{V}_E$, and $\dot{V}O_2$ were observed from CPR min 1 to min 5.

DISCUSSION: The terrestrial method of CPR provides a consistent ECC rate but does not provide adequate ECC depths in simulated hypogravities. The results suggest that a mixed-gender space crew of varying bodyweights may not influence ECC quality. Extraterrestrial-specific CPR guidelines are warranted. With a move to increasing ECC rate, permitting lower ECC depths and substituting rescuers after 1 min in lunar gravity and 4 min in Martian gravity is recommended.

KEYWORDS: extra-terrestrial CPR, hypogravity simulation, body suspension device, gender.

Sriharan S, Kay G, Lee JCY, Pollock RD, Russomano T. *Cardiopulmonary resuscitation in hypogravity simulation.* Aerosp Med Hum Perform. 2021; 92(2):106–112.

The probability of a fatal cardiac event occurring on a space mission is currently rare at approximately 1%.[14] While cardiac arrest has never occurred in a space mission, with our space travel goals becoming more aspirational and interplanetary habitation as the target for the next 10 yr, greater consideration needs to be given to this possibility. Cardiopulmonary resuscitation (CPR) is at the forefront of treating a cardiac arrest, but the effectiveness of the international CPR guidelines used on Earth is poorly understood when applied in microgravity and hypogravity environments.

To improve survival outcome, quality CPR needs to be administered as soon as possible.[28] The effectiveness of CPR is dependent on external chest compression (ECC) depth, ECC rate, adequate chest recoil and a reduction in the interruptions to ECCs with an ECC depth of 50–60 mm and a rate of 100–120 ECCs per min recommended.[21] Differently from the microgravity of space, the presence of a gravitational field in hypogravity environments means that the terrestrial method of CPR might be feasible. The primary challenge with CPR in hypogravity environments, however, is that the reduction in the gravitational strength means adequate quality CPR becomes harder to perform.[13]

Initial studies performed with a body suspension device (BSD) found that quality CPR was possible in hypogravity conditions varying from 0.17 G to 0.7 G, but only in heavier men with others also finding gender differences in CPR quality in microgravity.[7,17] These findings were based on 2005 CPR

From the Centre for Human and Applied Physiological Sciences, King's College London, London, UK.

This manuscript was received for review in July. It was accepted for publication in November 2020.

Address correspondence to: Sindujen Sriharan, King's College London, 4.01 Shepherd's House, Guy's Campus, London, SE1 1UL; sindujen.sriharan@nhs.net.

DOI: https://doi.org/10.3357/AMHP.5733.2021

guidelines requiring a minimum ECC depth of 40 mm, which have now been updated to recommend 50–60 mm.[9] Some studies have suggested that lower overall mass and muscle strength in women rather than gender specifically may be the cause of differences noted in terrestrial 1 G conditions.[8,20] Terrestrially, weight has been shown to play a key role in the ability to perform adequate ECC of adequate depth.[6] Lower weight rescuers have to exert greater force to obtain adequate CPR depth and thus may not be able to consistently reach recommended depths. Furthermore, this could also result in fatigue developing sooner, which has been implicated in the reduction in ECC depth which occurs by 2 min of continuous CPR.[10] Given that future astronaut corps seek to equalize the ratio of men and women, a better understanding of the effects of gender on the ability to perform CPR is required.

It is estimated that the time taken from the start of a cardiac arrest to the initiation of advanced life support (ALS) in a space mission can be up to 4 min.[24] In this time while life support equipment is being retrieved and deployed, quality CPR must be performed to ensure the highest possibility of survival. This is likely to be performed by a single rescuer during this time while other crewmembers are being alerted and retrieving equipment. Therefore, it is also vital we understand the effects of prolonged ECCs and accumulating fatigue on CPR performance in hypogravity conditions.

The primary aim of this study was to determine whether the terrestrial CPR method can provide quality ECCs in line with 2015 Resuscitation Council UK guidelines for 5 min of continuous external chest compression only CPR (CO-CPR).[21] The null hypothesis was that the terrestrial CPR method would be able to provide quality ECCs for 5 mins of CO-CPR in simulated hypogravity conditions. The secondary research objective of this study sought to determine whether specific influential factors affect CPR quality, in particular, gender, weight, and fatigue.

METHODS

Subjects

There were 21 healthy (**Table I**) subjects who participated in this research and provided written informed consent. The study protocol was approved by the King's College London Research Ethics Committee and was performed in accordance with the Declaration of Helsinki. The exclusion criteria for the study were any underlying cardiovascular, respiratory and musculoskeletal issues that would impact a subject's ability to perform CPR.

Table I. Subject Characteristics.

DEMOGRAPHICS	ALL (21)	MEN (11)	WOMEN (10)
Age (years)	28.7 ± 5.7	30.6 ± 5.2	26.5 ± 5.6
Weight (kg)	72.9 ± 16	83.0 ± 8.7***	61.9 ± 15.1
Height (m)	1.71 ± 0.1	1.78 ± 0.1	1.63 ± 0.04
BMI (kg · m^{-2})	24.8 ± 4.5	26.3 ± 3.0	23.15 ± 5.4

Values are mean ± SD. Anthropometric data of subjects. ***Significant difference between men and women subject weight ($P = 0.0008$).

Equipment and Materials

A body suspension device (BSD; Pneumex Unweighting System, Pneumex Inc., Sandpoint, ID, USA) was used to simulate different hypogravity conditions. This BSD was adapted to allow safe unloading of subjects in a kneeling CPR position. The BSD consisted of a steel frame, 2.73 m in height, and a rigid steel bar to which the subjects could be attached which allowed the subject to be unloaded by a pneumatic pressure system (JUN-AIR Deutschland GmbH, Germany). Subjects were fitted in a harness which, from a single point of attachment, was connected to the steel bar. A schematic diagram can be seen in **Fig. 1**.

For simulated Martian (0.38 G) and lunar (0.16 G) simulated gravities, the correct unloading needed was calculated and the pneumatic pressure system adjusted to provide this. To determine the unloading required terrestrial total body weight (TBW) was measured and from this an estimated kneeling weight (KW) was made. This was assumed to be approximately 0.6 of TBW and is the same fraction used in earlier hypogravity CPR studies.[11,23] Using 1 G as Earth's gravitational acceleration (where 1 G is 9.81 m · s^{-2}), the simulated gravitation force (SGF) for Mars and the Moon was used to calculate the simulated hypogravity weight (SHW) in kg. The weight the pneumatic pressure system needed to counter (CW) to unload subjects in the hypogravity environments was calculated using **Eq. 1 and 2**.[7]

$$\mathrm{SHW(kg)} = (\mathrm{TBW} \times 0.6) * \mathrm{SGF} \quad \text{Eq. 1}$$

$$\mathrm{CW(kg)} = \mathrm{KW} - \mathrm{SHW} \quad \text{Eq. 2}$$

The body harness used was the Portwest 2-Point Harness Comfort (Portwest, Ireland). The majority of unloading was through the upper body to minimize restriction of arm and shoulder movement. The metal wiring attached to the steel crossbar of the BSD remained vertical throughout the protocol. This allowed the primary unloading direction and position to stay around the center of mass for each subject. If there was discomfort in the anterior chest due to the harness, a piece of foam was placed underneath these straps to improve comfort.

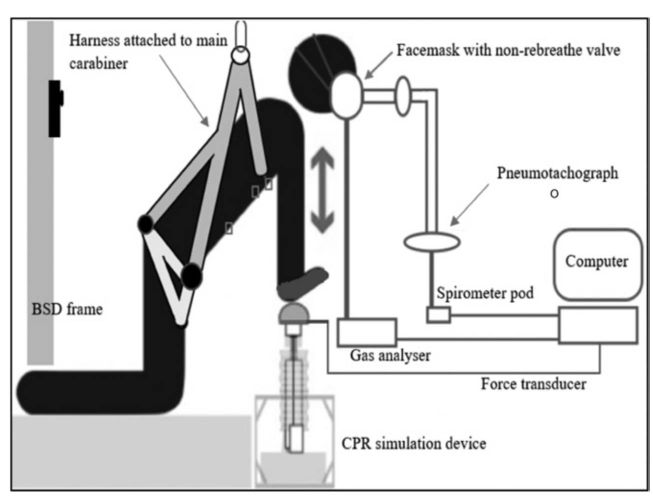

Fig. 1. Schematic diagram depicting a subject performing CPR on the CPR simulator. The 3 small squares on the subject's chest represent ECG electrodes.

A custom-built CPR simulator was used to perform ECCs. This consisted of a sternal cushion pad, on which subjects placed their hands to carry out ECCs, connected to a pneumatic compression system and a spring linear potentiometer. The resistance provided by the CPR simulator was similar to the Laerdal Resusci-Anne manikin of 8–9 kilopounds/cm.[3] Prior to each testing session the linear potentiometer was calibrated relative to known depths of compression and subsequently provided a real-time output of ECC depth.

Subjects wore a facemask (Hans Rudolph Inc., USA) to which a pneumotachograph coupled to a spirometer pod (ML 311, ADInstruments, Australia) were connected. Respiratory gas analysis was performed using a rapid gas analyzer (ML 206-1008, ADInstruments, Oxford, UK) via a probe inserted directly into the spirometer. Continuous 3-lead electrocardiogram (ECG) monitoring (LP22, Life Pulse, HME) was performed to determine the subject's heart rate.

Procedure

Prior to testing, if subjects had no formal CPR training, they were given basic training and familiarization of ECCs by a trained member of the research team. ECCs were performed in three gravity conditions: Earth's gravity (1 G) and simulated Martian (0.38 G) and lunar (0.16 G) gravities. Throughout the experiment period, mean ambient pressure was 760 mmHg and mean room temperature was 20.0 ± 0.7°C.

The order that gravity conditions were performed was randomized using an online random number generator. Subjects were attached to the harness and unloaded to their SHW. The protocol began with subjects staying 5 min at rest, while unloaded at the specific gravity condition, followed by the performance of 5 min continuous ECC. Following CPR, subjects were 'reloaded' to 1 G weight for a period of at least 5 min. This above protocol was repeated for the two remaining conditions.

The 1 G condition was conducted with the subject in the harness without any unloading being provided. Subjects were instructed to perform ECCs in accordance with Resuscitation Council UK 2015 guidelines, which indicate a rate of 100–120 ECCs/min and depth of 50–60 mm. During the initial 20s of CPR, verbal feedback was given by researchers with regards to ECC quality to ensure prolonged audio-visual feedback did not influence results.

Statistical Analysis

All data analysis was conducted using LabChart (LabChart Pro V9, ADInstruments, Oxford, UK). From the depth recording of the linear potentiometer ECC depth was determined for every compression as was the rate of compression. Breath-by-breath tidal volumes (V_T) and respiratory rates (RR) were calculated. From these, minute ventilation ($\dot{V}_E$) was determined. Ventilatory data is reported in BTPS. From the measured O_2, CO_2 and respiratory flow/volume data, oxygen uptake ($\dot{V}O_2$) was calculated. These values were subsequently normalized to each subject's bodyweight to obtain $\dot{V}O_2$ in $ml \cdot kg^{-1} \cdot min^{-1}$. To assess perceived exertion, the subjects were asked to rate this using the Borg rate of perceived exertion (RPE) scale at the end of each CPR bout.[5]

Data are reported as mean ± SD unless otherwise stated. An averaged data value for ECC depth and ECC rate was taken for the 5 min of CPR for each gravity condition. A repeated measures (RM) one-way analysis of variance (ANOVA) with Tukey's post hoc analysis was used to test for statistical significance between conditions. The effect of gender on ECC depth and rate in different gravity conditions were analyzed using a 2-way ANOVA with Sidak's post hoc analysis. ECC depth and rate data was divided into 1-min averages over the 5 min and ECC depth and rate trends were analyzed using a two-way ANOVA with Dunnett's multiple comparisons. Averages of the 1st and 5th min of CPR at each gravity condition were compared for the different physiological workload variables (HR, $\dot{V}_E$, $\dot{V}O_2$) to assess for possible changes over time during the CPR period. Physiological data from CPR min 5 for each gravity condition was also compared This was analyzed using a RM two-way ANOVA with Sidak's post hoc analysis. The Borg scores at the end of CPR for each simulated gravity condition were compared and assessed for statistical significance using the nonparametric Friedman ANOVA test with Dunn's multiple comparison post hoc analysis. Simple linear regression analysis was used to assess for an association between rescuer weight and ECC depth at each gravity condition. The computer software (Graphpad Prism v8.0, San Diego, CA, USA) was used to perform all statistical analysis. Statistical significance was assumed at *P*-values ≤ 0.05.

RESULTS

All subjects (men = 11, women = 10) completed the protocol without incident, and the subject characteristics are summarized in Table I. In 2 subjects an error with the spirometer resulted in no respiratory values being recorded; therefore, respiratory data was analyzed for 19 subjects. In addition, in the final minute of CPR for 1 subject, the gas analyzer stopped recording; therefore the preceding 30 s of end-tidal O_2 and CO_2 (%) values were carried forward.

With regards to the mean ECC depth (± SD) at 1 G, subjects met the 2015 CPR guidelines (Resuscitation Council UK, 2017) with a mean (± SD) ECC depth of 51.2 ± 9.2 mm, but this was not possible at 0.38 G and 0.16 G with ECC depths of 42.9 ± 9.1 mm and 40.8 ± 8.5 mm, respectively (**Fig. 2**). There was a significant effect of gravity condition on ECC depth [$F(1.62, 32.43) = 19.75$, $P < 0.0001$]. Post hoc comparisons indicated that ECC depth for 1 G was higher than the 0.38 G ($P < 0.0001$) and 0.16 G ($P = 0.0002$) conditions. However, ECC depths of 0.38 G and 0.16 G did not differ ($P = 0.442$). ECC rates at all gravity conditions were in line with 2015 guidelines. There was no significant effect of gravity condition on ECC rate [$F(1.71,34.28) = 0.059$, $P = 0.921$].

ECC depth and rate for both genders are depicted in **Fig. 3**, with no difference on ECC depth outcome in any gravity condition [$F(1, 57) = 1.88$, $P = 0.175$]. Both men and women were able to abide by the 2015 guidelines at 1 G. However, at 0.16 G and 0.38 G, the 2015 guidelines were not met for either gender.

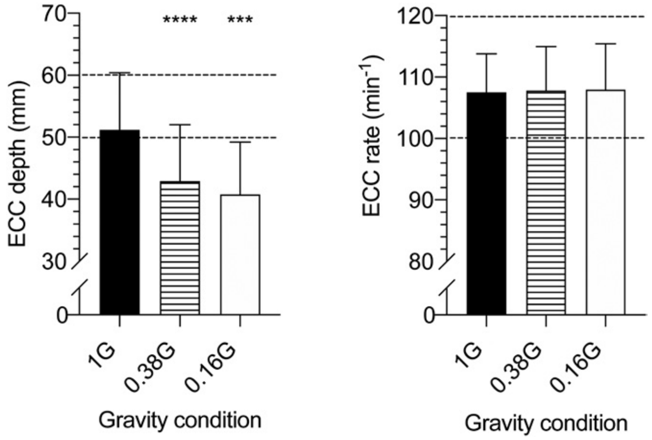

Fig. 2. Mean (± SD) ECC depth and ECC rate at each simulated gravity condition. ***Significantly different from 1 G and 0.38 G ($P < 0.005$); ****significantly different from 1 G and 0.16 G ($P < 0.0005$). Dashed lines represent current recommended 2015 ERC guidelines for ECC depth and ECC rate. 1 G (black bars), 0.38 G (striped bars), 0.16 G (white bars).

ECC rate, for both genders, was in line with Resuscitation Council guidelines in all gravity conditions. There was no significant effect of gender on ECC rate in any gravity condition [$F(1, 57) = 1.37$, $P = 0.247$].

Fig. 4 represents the ECC depths in 1-min means over the 5 min of CPR for each gravity condition. There was a significant effect of time of CPR on ECC depth in each gravity condition [$F(1.94, 116.2) = 12.12$, $P < 0.0001$].

At 1 G, when comparing CPR min 1 to the other minutes, there was a decrease in ECC depth to CPR min 2 and 3 ($P = 0.049$ and $P = 0.015$, respectively). At 0.38 G, ECC depth in CPR min 5 was lower than CPR min 1 ($P = 0.04$). At 0.16 G there was a gradual decrease in ECC depth from CPR min 1 to min 5 ($P = 0.02$). CPR min 2–4 were also lower than CPR min 1 (CPR min 2, $P = 0.02$; CPR min 3, $P = 0.0002$; CPR min 4, $P = 0.004$). Fig. 4 also shows ECC rates over the 5 min of CPR in each gravity condition.

There was a significant finding of time of CPR on ECC rate in each gravity condition [$F(2.35, 140.8) = 2.97$, $P = 0.046$)]. However, on post hoc comparison, there were no differences

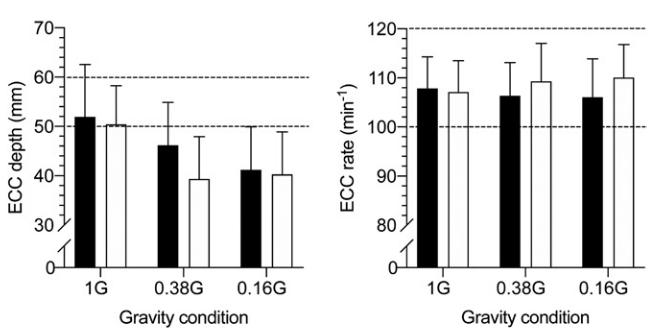

Fig. 3. Mean (± SD) ECC depth and ECC rate at each simulated gravity condition for men ($N = 11$) and women ($N = 10$). Dashed lines represent current recommended 2015 ERC guidelines for ECC depth and ECC rate. Men (black bars), women (white bars).

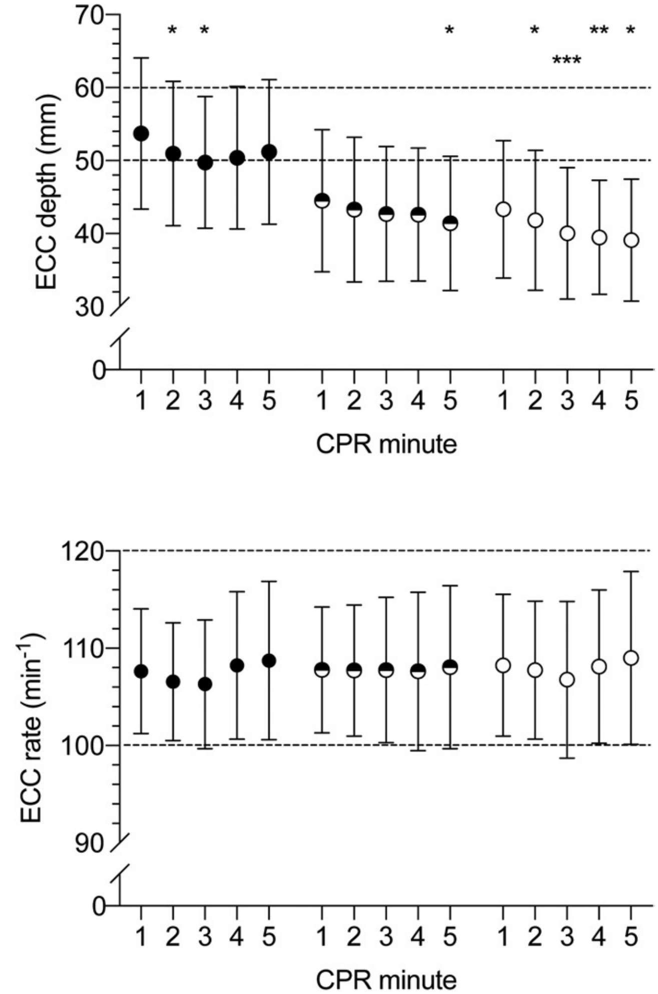

Fig. 4. Mean (± SD) ECC depth (top figure) and ECC rate (bottom figure) over 5 min of CPR at each simulated gravity condition. Dashed lines represent current recommended 2015 ERC guidelines for ECC depth and ECC rate. Each CPR minute has been compared with CPR minute 1 at each gravity condition. *Significant difference ($P < 0.05$); **significant difference ($P < 0.005$); ***significant difference ($P < 0.0005$). 1 G (black circles), 0.38 G (striped circles), 0.16 G (white circles).

found between the time of CPR and ECC rate in each gravity condition.

$\dot{V}_E$, $\dot{V}O_2$, and HR data for CPR min 1 and 5 for each gravity condition are displayed in **Table II**. In all gravity conditions, there was a significant rise from CPR min 1 to min 5 in $\dot{V}_E$ [$F(1, 54) = 111.1$, $P < 0.0001$], $\dot{V}O_2$ [$F(1, 54) = 118.7$, $P < 0.0001$] and HR [$F(1, 60) = 213.1$, $P < 0.0001$].

There was no significant effect of gravity condition on the physiological variables outcome data. $\dot{V}_E$: [$F(2, 54) = 0.369$, $P = 0.693$], $\dot{V}O_2$: [$F(2, 54) = 0.253$, $P = 0.778$], HR: [$F(2, 60) = 0.043$, $P = 0.958$].

Borg scores after CPR were compared in each gravity condition. A difference between groups was found (Friedman statistic of 9.34, $P = 0.009$). Post hoc analysis highlighted that Borg scores were higher at the end of 0.16 G CPR in comparison to 1 G (11.9 ± 2.8 vs. 10.5 ± 2.7, respectively, $P = 0.016$). This was not the case when comparing 1 G to 0.38 G (10.5 ± 2.7 vs. 11.4 ± 2.4,

Table II. Physiological Responses to CPR Over Time in Each Gravity Condition.

	1 G		0.38 G		0.16 G	
CPR minute	**1**	**5**	**1**	**5**	**1**	**5**
HR (bpm)	105 ± 14	112 ± 17***	109 ± 20	113 ± 24*	108 ± 19	113 ± 23**
V_E ($L \cdot min^{-1}$)	20.6 ± 11.7	30.5 ± 14.6***	23.7 ± 10.6	34.1 ± 16.9***	22.9 ± 8.8	33.8 ± 14.6****
Vo_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)	14.4 ± 7.8	21.8 ± 11.0****	16.8 ± 7.2	22.9 ± 9.6***	15.9 ± 6.2	22.4 ± 9.0****

Values are mean ± SD. Physiological variables data from CPR minute 1 to CPR minute 5 in each gravity condition. *Significant difference ($P < 0.05$) between CPR minute 1 and CPR minute 5 for each physiological variable at each gravity condition. ** $P < 0.005$, *** $P < 0.001$, **** $P < 0.0001$.

respectively, $P = 0.316$) nor 0.38 G to 0.16 G (11.4 ± 2.4 vs. 11.9 ± 2.8, respectively, $P = 0.742$).

Simple linear regression was used to determine whether weight was a predictor of CPR depth at each gravity condition. Weight was not shown to be a predictor of CPR depth at 1 G ($r^2 = 0.003$, $P = 0.804$), 0.38 G ($r^2 = 0.089$, $P = 0.188$) and 0.16 G ($r^2 = 0.011$, $P = 0.656$) conditions.

DISCUSSION

The growth of the commercial space industry necessitates that we have evidence-based protocols for medical emergencies in space. The renewed interest of traveling to the Moon and Mars and the potential for cardiac events requires investigation of how to perform CPR in these environments. Currently our understanding of this topic is limited with few studies having investigated CPR quality in light of the most recent CPR guidelines.[21] Our findings have shown that the terrestrial method of CPR does not allow for ECC depths of 50–60 mm in keeping with Resuscitation Council guidelines to be achieved in hypogravity conditions.

Influential Factors

At 1 G, subjects were able to maintain an ECC depth above 50 mm, in keeping with 2015 guidelines. However, ECC depths at Martian and lunar gravities were lower than recommended guidelines (Fig. 2). This illustrates that the terrestrial method of CPR may not be adequate in hypogravity environments. The present results indicate that, due to an effective reduction in a rescuers weight, they are unable to exert the force required to reach depths that were possible in 1 G. This differs from previous findings[23] indicating that effective CPR using the terrestrial method is possible at 0.38 G. However, the ECC time duration of 1.5 min differs from our study and thus fatigue may in part account for this difference. Novel hypogravity CPR techniques including the Mackaill-Russomano (MR) Hypogravity CPR method have been tested which have shown promising results with regards to improving ECC depths, however, further studies with larger sample sizes are warranted.[18]

Importantly, the probability of a return of spontaneous circulation (ROSC) and survival outcomes significantly increases with ECC depths > 40 mm,[25] which greatly increases chances of survival compared to having no intervention.[22] Therefore, as ECC depth was > 40 mm in all conditions currently tested it should be noted that despite compressions outside the target range of 50–60 mm being less effective they may still be clinically important.

Gender itself may not be a direct influential factor to quality CPR. Our study shows no difference between men and women in ECC depth and rate in any gravity condition. These findings are promising as they show that a mixed spaceflight crew consisting of men and women may be at no gender disadvantage when performing CPR. Previous studies have illustrated differences in ECC depths between genders specifically at a lunar gravity.[17] This has been thought secondary to men having a larger total body weight and so having an improved ability to produce sufficient force to obtain ECC depths. However, the average man's weight (83.0 ± 8.7 kg) in our study was larger than the average woman's weight (61.9 ± 15.1 kg), but there were no differences in ECC depth. Similarly, no correlation between rescuer weight and ECC depth was found in the present study. Despite a number of studies linking weight to ECC depth, this study suggests that weight is not the only factor that affects ECC depth and that other factors, such as rescuer strength or experience, may also play a role. While terrestrial studies have noted that lightweight rescuers find it more difficult to reach adequate ECCs, an important consideration in this is the use of nurses who were qualified in basic life support methods and had delivered in-hospital CPR previously.[10] Our study subjects had a wide range of CPR experience; from no experience previously to those who were CPR instructors. CPR experience may have affected our results and could be an important reason why subject weight in this study was not shown to influence ECC depth. Further studies to investigate this area are warranted to see whether higher levels of CPR experience influence ECC quality. This could be a proposed mechanism of improving ECC depth for space crews.

Previous studies exploring CPR in hypogravity and microgravity environments suggest upper body strength exercises and increasing muscle mass as a way of improving CPR quality.[1] Kaminska et al. showed that increased muscle mass may improve ECC depth by up to 7 mm which agrees with this potential strategy.[15] On the other hand, evidence shows that muscle atrophy and deconditioning occur in space despite astronauts exercising for over 2 h a day.[27] Therefore, it may not actually be feasible to add further exercise into this time schedule.

Fatigue and CPR Trend Over Time

In the Martian simulated condition, there was a decrease in ECC depth by the 5th min of CPR indicating that rescuers may be able to sustain ECC depths for up to 4 min, but beyond this their quality will decline. However, during lunar hypogravity simulation, after the first min of CPR, there was a continuous decrease in ECC depth with a reduction of 4.2 mm by the 5th

min suggesting that performing ECCs may be more physically challenging. In support of this, perceived exertion was higher in 0.16 G when compared to 1 G_z. The reduced depth of compression associated with fatigue will compound the impaired ECC depth achieved in lunar and Martian environments leading to inadequate organ perfusion and reduced chances of survival.

As a surrogate of the physical demand associated with performing ECCs, changes in HR, $\dot{V}_E$ and $\dot{V}O_2$ were assessed from CPR min 1 to CPR min 5. An increase in all of these were noted at the end of CPR in each gravity condition. This illustrates that as CPR continues for extended periods, fatigue accumulates. This fatigue manifests as a decreasing ECC depth, as early as 1 min in 0.16 G conditions and 4 min in 0.38 G simulations. This may be due to a significant reduction in effective bodyweight available to produce adequate ECC depth force, most notable at 0.16 G conditions. Therefore, it is pertinent that we create mitigating strategies for allowing CPR quality to be maintained, especially in a 0.16 G environment. Interestingly, the physiological cost was found not to be significantly different between gravity conditions which may also be explained by the decreasing ECC depths seen from 1 G to 0.16 G simulations. As fatigue accumulated earlier in simulated hypogravity, the overall force produced over the 5 min was less and may explain why the overall physiological cost amounted to similar levels at each gravity condition.

It is important to note that this study was done on healthy individuals. One issue for astronauts and space explorers is that $\dot{V}O_{2max}$ is known to decline during spaceflight and slowly return to baseline levels during a 6-mo mission.[19] Upon readaptation to a gravitational field there is a subsequent drop in $\dot{V}O_{2max}$, which can take more than a month to return to baseline levels.[19] Upon reaching hypogravity environments, the space crew is most likely to carry out high intensity activities during this month. The additive effects of microgravity-induced cardiovascular and muscular deconditioning[2] will cause the effort required to perform ECCs to be closer to that of the individual's maximal effort and therefore potentially more fatiguing than currently suggested. This could cause a greater decline in ECC depth quality than reported here.

Consistent with previous studies in hypogravity[17] ECC rate remained between 100 and 120 ECCs/min in all gravity conditions. ECC rate showed a difference over time ($P = 0.046$), yet post hoc analysis did not reveal a specific time effect. This may be due to the large variation of ECC rate between individuals and could potentially reflect insufficient statistical power. Overall, rate was effectively maintained over the 5-min period in all gravity conditions. The fact ECC rate can be maintained in both lunar and Martian environments will improve chances of survival in hypogravity environments.[13]

A novel concept to consider is the introduction of hypogravity-specific CPR guidelines. Extraterrestrial goals for CPR quality are based off terrestrial guidelines. The optimal ECC depth and rate for the highest chance of ROSC and survival are still unknown, yet given the evidence available, current guidelines recommend a depth of 50–60 mm and a rate of 100–120 ECCs/min.[15] What has been noted throughout this study and is evident in the literature,[18,23] is that ECC rate remains within target range in 0.38 G and 0.16 G conditions for 5 min of CO-CPR. This potentially means that ECC rate can be further increased if necessary. A prospective observational study conducted by Kilgannon et al. found that ECC rates between 120-140 ECCs/min were associated with ROSC rates of up to 64% compared to 29% at the current guidance of 100–120 ECCs/min.[16] Future studies are needed to assess whether this is possible, but hypogravity-specific guidelines where rate is further increased to 120–130 ECCs/min and a decrement in ECC depths to $>$ 40 mm is permitted may provide a feasible mitigation strategy for quality CPR to take place in hypogravity environments, despite the issues faced.

It is important to acknowledge the limitations of this study with regards to the equipment and protocol. The BSD is a useful analog to test CPR methods in simulated hypogravity conditions. Yet, a limitation of the system and harness is that the unloading is based on center of mass modeling which is not fully accurate in comparison to the equally distributed decrease in weight seen in hypogravity environments. In addition, the BSD only replicates the weight reduction that occurs in hypogravity conditions, and no other physiological changes that may occur in true hypogravity, such as the changes in chest wall dynamics which may require altered ECC depth parameters.[4,12] Furthermore, a large variability in chest wall compliance exists due to differences in thoracic anterior-posterior diameters, chest elasticity and pre-existing lung pathologies.[26] Therefore, we cannot fully infer from our results that similar depths will be reached on a human chest. The study was also based on a relatively small sample size which may have modified the results that were seen and thus affect reproducibility. The study should be reproduced with a larger sample size to corroborate the current findings.

Upon investigating influential factors, gender and weight do not affect CPR quality in this study. Further studies with larger sample sizes are needed to illustrate what effect CPR experience and lean muscle mass have on CPR quality and outcomes, specifically in hypogravity situations. Fatigue is an important factor which becomes increasingly important as the simulated gravitational field decreases. Interestingly, ECC rate is maintained within the target range in all gravity conditions with no signs of degradation over time.

Given these findings, a mixed gender space crew can provide ECC depths of above 40 mm for up to 4 min in 0.38 G and 1 min in 0.16 G before significant declines. Therefore, if possible, we recommend rescuers being substituted by these time points in each specific hypogravity environment.

In conclusion, a multifaceted approach is needed to address these findings which we believe begins with the introduction of hypogravity-specific CPR guidelines. Hypogravity-specific protocols will ensure that crewmembers and even potential space tourists have the capability to provide quality CPR consistently. CPR using the terrestrial method can be used but future studies should further investigate novel methods to seek improvements in ECC depth.

ACKNOWLEDGMENTS

The authors would like to thank all subjects who volunteered for the study and Lindsey Marjoram for all her technical help and expertise. We are also grateful to Professor Mileva for her ideas and help with producing a working body suspension device. The authors declare they have no conflicts of interest.

Financial Disclosure Statement: The authors have no competing interests to declare.

Authors and affiliations: Sindujen Sriharan, B.M.B.S., Gemma Kay, B.Sc., Jimmy C. Y. Lee, M.B.B.S., Ross D. Pollock, M.Sc., and Thais Russomano, M.D., Centre for Human and Applied Physiological Sciences, King's College London, London, UK; and Jimmy C. Y. Lee, M.B.B.S., Ng Teng Fong General Hospital and Jurong Community Hospital, Singapore.

REFERENCES

1. Baers J, Velho R, Ashcroft A, Rehnberg L, Baptista R, Russomano T. Is weight a pivotal factor for the performance of external chest compressions on Earth and in space. J Exerc Physiol Online. 2016; 19(2):1–16.
2. Barratt MR, Pool S, editors. Principles of clinical medicine for space flight, 1st ed. New York (NY): Springer; 2008:596.
3. Baubin MA, Gilly H, Posch A, Schinnerl A, Kroesen G. Compression characteristics of CPR manikins. Resuscitation. 1995; 30(2):117–126.
4. Bettinelli D, Kays C, Bailliart O, Capderou A, Techoueyres P, et al. Effect of gravity on chest wall mechanics. J Appl Physiol. 2002; 92(2):709–716.
5. Borg GA, Noble B. Perceived exertion. Exerc Sport Sci Rev. 1974; 2(1):131–153.
6. Cornara S, Somaschini A, Baldi E, Contri E, Tonani M, et al. How weight and other anthropometric variables affect CPR quality: A study on lay rescuers. Resuscitation. 2015; 96(Suppl. 1):72.
7. Dalmarco G, Calder A, Falcao F, Azevedo D, Sarker S, et al. Evaluation of external cardiac massage performance during hypogravity simulation. In Conf: IEEE Eng Med. Biol Soc. 2006; 1:2904–2907.
8. Doherty T. The influence of aging and sex on skeletal muscle mass and strength. Curr Opin Clin Nutr Metab Care. 2001; 4(6):503–508.
9. ECC Committee, Subcommittees and Task Forces of the American Heart Association. 2005 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care. Circulation. 2005; 112(24, Suppl.):IV1–IV203.
10. Hasegawa T, Daikoku R, Saito S, Saito Y. Relationship between weight of rescuer and quality of chest compression during cardiopulmonary resuscitation. J Physiol Anthropol. 2014; 33(1):16.
11. Hay J. The Biomechanics of Sports Techniques. 4th ed. Upper Saddle River (NJ): Prentice Hall; 1993:410.
12. Hinkelbein J, Russomano T, Hinkelbein F, Komorowski M. Cardiac arrest during space missions: Specificities and challenges. Trends in Anaesthesia and Critical Care. 2018; 19:6–12.
13. Idris A, Guffey D, Pepe P, Brown P, Brooks C, et al. Chest compression rates and survival following out-ofhospital cardiac arrest. Crit Care Med. 2015; 43(4):840–848.
14. Johnston SL, Marshburn T, Lindgren K. Predicted incidence of evacuation-level illness/injury during space station operation. [Abstract 293]. Proceedings of the 71st Annual Scientific Meeting of the Aerospace Medical Association; May 14–16, 2000; Houston, TX. Aviat Space Environ Med. 2000; 78(3):333.
15. Kaminska H, Wieczorek W, Matusik P, Czyzewski L, Ladny J, et al. Factors influencing high-quality chest compressions during cardiopulmonary resuscitation scenario, according to 2015 American Heart Association Guidelines. Kardiol Pol. 2018; 76(3):642–647.
16. Kilgannon J, Kirchhoff M, Pierce L, Aunchman N, Trzeciak S, Roberts B. Association between chest compression rates and clinical outcomes following in-hospital cardiac arrest at an academic tertiary hospital. Resuscitation. 2017; 110:154–161.
17. Kordi M, Kluge N, Kloeckner M, Russomano T. Gender influence on the performance of chest compressions in simulated hypogravity and microgravity. Aviat Space Environ Med. 2012; 83(7):643–648.
18. Mackaill C, Sponchiado G, Leite A, Dias P, Da Rosa M, et al. A new method for the performance of external chest compressions during hypogravity simulation. Life Sci Space Res (Amst). 2018; 18:72–79.
19. Moore A, Lynn P, Feiveson A. The first 10 years of aerobic exercise responses to long-duration ISS flights. Aerosp Med Hum Perform. 2015; 86(12, Suppl.):A78–A86.
20. Peberdy M, Silver A, Ornato J. Effect of caregiver gender, age, and feedback prompts on chest compression rate and depth. Resuscitation. 2009; 80(10):1169–1174.
21. Resuscitation Council UK. (2017). 2015 Resuscitation Guidelines. Available at: https://www.resus.org.uk/resuscitation-guidelines/ (Accessed: 15/07/2019).
22. Riva G, Ringh M, Jonsson M, Svensson L, Herlitz J, et al. Survival in Out-of-Hospital Cardiac Arrest After Standard Cardiopulmonary Resuscitation or Chest Compressions Only Before Arrival of Emergency Medical Services. Circulation. 2019; 139(23):2600–2609.
23. Russomano T, Baers J, Velho R, Cardoso R, Ashcroft A, et al. A comparison between the 2010 and 2005 basic life support guidelines during simulated hypogravity and microgravity. Extrem Physiol Med. 2013; 2(1):11.
24. Russomano T, Rehnberg L. Extraterrestrial CPR and Its Applications in Terrestrial Medicine. In: Aslanidis T, editor. Resuscitation Aspects. InTech; 2017: 115–148.
25. Stiell IG, Brown S, Christenson J, Cheskes S, Nichol G, et al. What is the role of chest compression depth during out-of-hospital cardiac arrest resuscitation? Crit Care Med. 2012; 40(4):1192–1198.
26. Tomlinson AE, Nysaether J, Kramer-Johansen J, Steen P, Dorph E. Compression force–depth relationship during out-of-hospital cardiopulmonary resuscitation. Resuscitation. 2007; 72(3):364–370.
27. Trappe S, Costill D, Gallagher P, Creer A, Peters J, et al. Exercise in space: human skeletal muscle after 6 months aboard the International Space Station. J Appl Physiol. 2009; 106(4):1159–1168.
28. Wik L, Andreas Steen P, Bircher N. Quality of bystander cardiopulmonary resuscitation influences outcome after prehospital cardiac arrest. Resuscitation. 1994; 28(3):195–203.