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Feasibility of an augmented reality cardiopulmonary resuscitation training system for health care providers

Steve Balian [a], Shaun K. McGovern [a], Benjamin S. Abella [a], Audrey L. Blewer [b], Marion Leary [a,c,*]

[a] Center for Resuscitation Science and Department of Emergency Medicine, University of Pennsylvania, Philadelphia, PA, USA
[b] Department of Family Medicine and Community Health, Duke University, Durham, NC, USA
[c] University of Pennsylvania, School of Nursing, Philadelphia, PA, USA

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ABSTRACT

Aim of the study: Augmented reality (AR) has the potential to offer a novel approach to CPR training that supplements conventional training methods with gamification and a more interactive learning experience. This is done through computer-generated imagery superimposed on users' view of the real environment to simulate interactive training scenarios. We sought to test the feasibility of an AR CPR training system (CPReality) for health care providers (HCPs).

Methods: In this feasibility trial, a CPR training manikin was integrated with a commercial AR device (Microsoft HoloLens) to provide participants with real-time audio-visual feedback via a holographic overlay of blood flow to vital organs dependent on CC quality. In this system, higher quality CC visually improved virtual blood circulation. HCPs performed a 2-minute cycle of hands-only CPR using only the AR system, and CC parameters were recorded. Descriptive data on participants' demographics, CC quality, and satisfaction with the training environment were reported using quantitative and qualitative analysis.

Results: Between 10/2018–11/2018, we enrolled a convenience sample of 51 HCPs. The median age of participants was 31 years (IQR 27–41), 71% (36/51) were female, and 67% (34/51) were registered nurses. CC rates (mean 126 ± 12.9 cpm), depths (median 53 mm, IQR 46–58), and percent with complete recoil (median 80%, IQR 12–100) were consistent with guideline recommendations for good quality CPR. Participants were predominantly satisfied with the system, with 82% perceiving the experience as realistic, 98% recognizing the visualizations as helpful for training, and 94% willing to use the application in future CPR training.

Conclusions: As AR is increasingly applied in the healthcare setting, integration in CPR training offers a novel and promising educational approach. In this convenience sample of trained HCPs, high quality CC delivery was feasible using the AR CPR training system which was received favorably by most participants.

1. Introduction

Efforts directed towards improving in-hospital resuscitation performance, such as early cardiopulmonary resuscitation (CPR) and standardized post-resuscitation care, have been modestly successful, raising in-hospital cardiac arrest (IHCA) survival rates to an estimated 25% in 2017 [1]. Despite clear guidelines for high quality CPR [2, 3], one explanation for the marginal improvement may be health care provider's (HCP) poor adherence to evidence-based CPR performance in clinical practice, in addition to skill decay after initial training [4, 5, 6, 7, 8]. This calls into question the effectiveness of the current CPR certification paradigm, and underpins the importance of innovations in CPR teaching. Numerous investigators have attempted to address this missed opportunity by exploring different educational approaches such as the use of CPR-sensing and feedback devices [9, 10], team debriefing programs [11, 12], high fidelity simulation trainings [13], and refresher training programs [14, 15, 16]; solutions that have had mixed institutional responses and buy-in.

A recent 2018 statement by the American Heart Association (AHA) highlighted the role of immersive technologies and gamified learning in advancing educational strategies in resuscitation by enhancing users' learning experience [17]. Wearable devices, that utilize augmented and virtual reality technology, have already shown promise as a useful training tool in many healthcare training studies with various

* Corresponding author.
E-mail address: mleary@nursing.upenn.edu (M. Leary).

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applications in nasogastric tube placement [18], echocardiography [19], central line placement [20, 21], surgery [22, 23], and pathology [24]. This novel technology allows for high-fidelity simulation and experiential learning by means of holographic visualizations superimposed on what a user sees in the real world. The user's heightened perception of a more realistic scenario potentiates the learning experience, while allowing the user to practice in interactive high-risk situations. The objective of our study was to test the feasibility of an augmented reality (AR) platform for CPR training as a proof-of-concept that overlays an interactive holographic circulatory system next to the physical training manikin during CPR (Fig. 1). We tested the validity of this training system against CPR guidelines and evaluated participants' perception of this educational tool.

2. Methods

2.1. Study design and participants

This was a feasibility study of a novel CPR training tool. Between October and November 2018, we enrolled a convenience sample of HCPs from different specialties and hospitals within one health system, presenting for mandatory Basic Life Support (BLS) and/or Advanced Cardiovascular Life Support (ACLS) recertification training to the health system simulation center. Research staff approached potential participants and asked if they would participate in a short 15-minute AR CPR study prior to the start of their scheduled training session. Enrollment into the study did not impact subsequent BLS or ACLS training and recertification processes.

2.2. Augmented reality system

The AR CPR training application (CPReality) was developed as part of a University of Pennsylvania technology competition in 2017 to create an immersive multi-sensory (audio, visual, tactile) CPR teaching tool. As seen in Fig. 1, it consists of a CPR recording manikin (Laerdal Medical, Wappinger Falls, NY) integrated with a head-mounted commercial AR device (Microsoft Hololens, Microsoft, Redmond WA). As hands-only CPR is performed on the manikin, the system renders recorded quantitative chest compression (CC) data (CC rate, depth, recoil) into an AR holographic image of the circulatory system in front of the study participant. As a form of visual feedback, blood flow to vital organs either increases or decreases based on the actual quality of CC being performed by the subject. If the subject performed CC at a rate outside of the guideline range (100–120 cpm), auditory feedback from the Hololens device, in the form of a heartbeat at 110 bpm, was audible to the subject as a guide. At the end of the CPR cycle, the application also provides participants with a CPR quality score calculated using sensor data and an industry-standard algorithm.

2.3. Study protocol

This protocol was reviewed by the Institutional Review Board at the University of Pennsylvania and granted exemption. Data collection and analysis were compliant with the Health Insurance Portability and Accountability Act of 1996 (HIPAA) regulations. Verbal consent was obtained from HCPs prior to the training session by clinical research coordinators.

Upon verbal consent, data collection was performed in three stages: (1) pre-CPR demographics survey, (2) AR CPR training, (3) post-CPR satisfaction survey. The first survey collected demographic and baseline HCP training information including age, gender, race, healthcare position, number of attended resuscitations per month, and years in training. This was followed by a brief orientation to the Hololens device. As the purpose of the study was feasibility testing of the system for CCs without ventilations, participants then performed a single 2-minute hands-only CPR cycle using the CPReality AR system. Finally, a post-

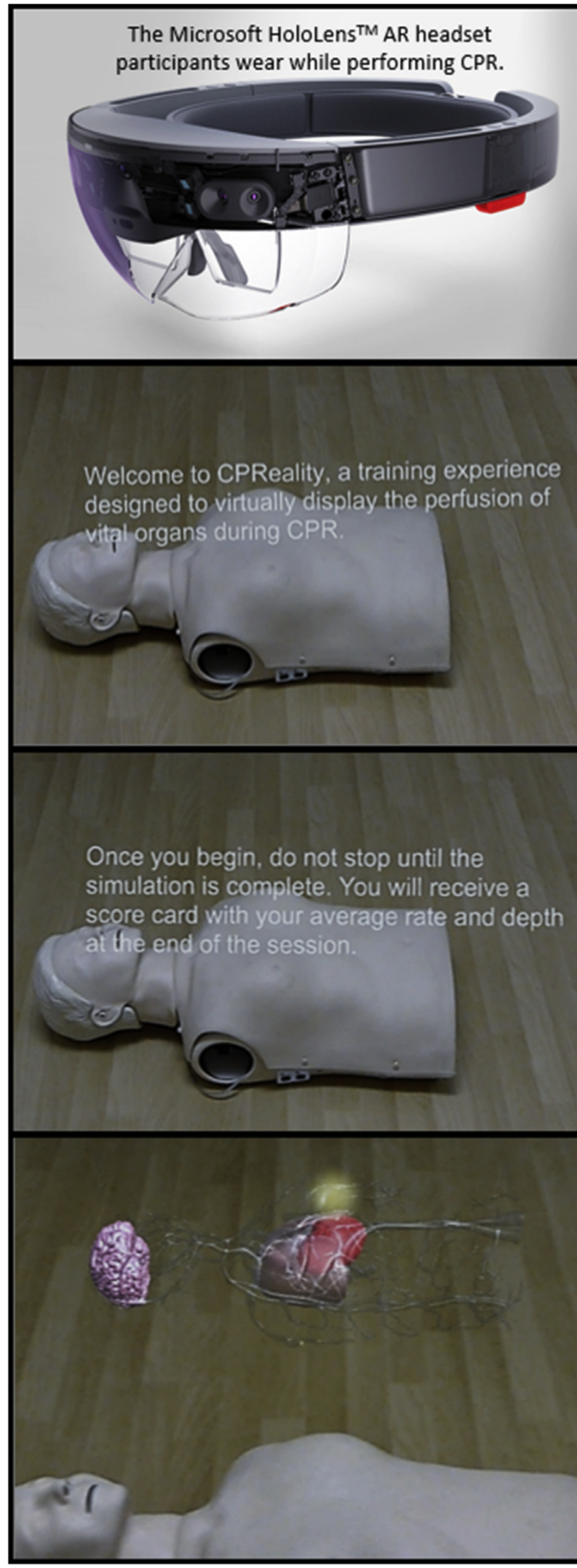

Fig. 1. The CPReality AR CPR training application: Microsoft HoloLens device integrated with a Laerdal CPR feedback manikin displaying the holographic circulatory system.

survey was administered to assess participants' satisfaction with the overall experience and perception of AR technology use in future CPR training applications. The satisfaction survey questions were answered on a four-point Likert scale including the following selections: "strongly agree", "agree", "disagree", and "strongly disagree". Participants were concurrently asked to provide qualitative feedback about the CPReality system in addition to improvement suggestions.

2.4. Data collection

Over a 2-minute cycle, three CC measurements were recorded: mean CC rate in compressions per minute (cpm), mean CC depth in millimeters (mm), and percent of CCs with complete chest recoil (%). CPR quality was analyzed based on the standard AHA guidelines of a CC rate of 100–120 cpm, a depth between 50 and 60 mm, and maximizing full chest recoil [2, 3]. Unidentified data from pre- and post-CPR surveys, initially collected on paper forms, were entered into a REDCap database, an institutionally approved and password protected web application.

2.5. Data analysis

Descriptive statistics were used to summarize participant characteristics, CC parameters, and participant satisfaction survey results. As this was a pilot study on a small HCP population, data was not anticipated to be normally distributed. The Shapiro-Wilk test was however used when applicable, and when the normality assumption was violated, continuous variables were reported as medians with IQR (Q1-Q3) instead of means ±SD. Categorical variables were presented as frequencies and percentages.

Comparative analysis of continuous CPR quality data between HCPs with BLS versus ACLS certification was conducted using the independent samples t-test and Mann-Whitney U tests for parametric and non-parametric data respectively. All statistical tests were 2-sided, and a P-value of <0.05 was statistically significant.

To assess participants' positive and negative observations of the system, qualitative inductive content analysis was performed on free-text responses to open-ended questions [25]. After identification of prevalent topics in responses, related topics were clustered around central ideas using open coding. Higher order categories and headings were generated according to the thematic relationship between codes. Finally, the number of instances of codes falling under different categories were counted to assess the prevalence of raised comments, with certain individual comments addressing more than a single category. Data were managed and analyzed using standard statistical software (IBM SPSS Statistics for Windows, Version 23, Armonk, NY).

3. Results

3.1. Participant demographics

During our enrollment time period, 51 HCPs were enrolled at a centralized simulation and training center, which is part of a multihospital academic health system. Baseline characteristics of participants are presented in Table 1. The median age of participants was 31 years (IQR 27–41), 70.6% (36/51) were female, and 70.6% (36/51) were white. The median years of experience in healthcare was 5 years (IQR 3–15), 66.7% (34/51) were registered nurses, and 60.9% (31/51) of participants participated in at least one resuscitation per month. All participants were at least previously BLS certified (100%), and 66.7% (34/51) had prior ACLS training. Only two participants (4%) had previous experience with the use of AR applications.

3.2. CPR quality

The distributions for mean CC rate, mean CC depth, and percentage of compressions with complete chest recoil per participant after 2 min of hands-only CPR appear in Fig. 2. The mean CC rate was normally distributed; mean CC depth and percent complete recoil were skewed right towards higher depths and percentages, respectively. CC rates and depths were often between the recommended CPR standards by the AHA, with a mean rate of 126 ± 12.9 cpm, and a median depth of 53 mm (IQR 46–58) (Table 2). Among participants, the percentage of compressions with complete recoil was dispersed but with a high median of 80% (IQR 12–100). No comparative data were reported on CPR quality between HCPs with only BLS versus ACLS certification since no significant differences were found.

Table 1
Baseline participant characteristics.

Age (years), median (IQR)	31 (27–41)
Gender (female)	36 (70.6%)
Race (white)	36 (70.6%)
Healthcare experience (years), median (IQR)	5 (3–15)
Healthcare position	
Registered nurse	34 (66.7%)
Physician	8 (15.7%)
Advanced practice registered nurse	2 (3.9%)
Technician	2 (3.9%)
Pharmacy	2 (3.9%)
Other	3 (5.9%)
Resuscitations per month	
0	20 (39.2%)
1	18 (35.3%)
2-3	10 (19.6%)
>4	3 (5.9%)
BLS last certified	
≤1 month	4 (7.8%)
2–6 months	14 (27.5%)
7–12 months	8 (15.7%)
13–24 months	20 (39.2%)
>24 months	5 (9.8%)
ACLS last certified	
2–6 months	6 (11.8%)
7–12 months	3 (5.9%)
13–24 months	21 (41.2%)
>24 months	4 (7.8%)
No Response	5 (9.8%)
Not certified	12 (23.5%)
Used AR device in the past (yes)	2 (3.9%)

IQR, interquartile range; BLS, basic life support; ACLS, advanced cardiac life support; AR, augmented reality.

3.3. Participant satisfaction

The results of the participant satisfaction survey were largely positive (Fig. 3). From the cohort, 92.2% (47/51) of participants agreed or strongly agreed that the device was comfortable to use, with 82.3% (42/51) reporting that the application made the experience more realistic since subjects felt that the patient was in front of them during CPR. A total of 98.1% (50/51) perceived the visualization of blood flow as useful for training, and 94.1% (48/51) expressed a willingness to use the CPReality application in future CPR training.

Participants' open-ended responses were sorted thematically in Table 3, with some comments falling under more than one category when they made reference to more than one feature. Positive responses were largely related to the immersive visualizations and the feedback they provided. The visualizations were described as more realistic, helpful in visualizing the goal of vital organ perfusion, and generally allowing for a better understanding of the effects of high-quality CPR on patients. As for the feedback component, subjects felt that the auditory (heartbeat metronome) and visual cues (increase or decrease in blow flow to vital organs) allowed for appropriate real-time adjustment of compressions, reinforcing the delivery of effective CPR. Improvement suggestions focused mostly on repositioning the blood circulation hologram closer to or directly on the manikin, and the addition of real-time numerical CC statistics (rate and depth) to the HoloLens view as compressions are being

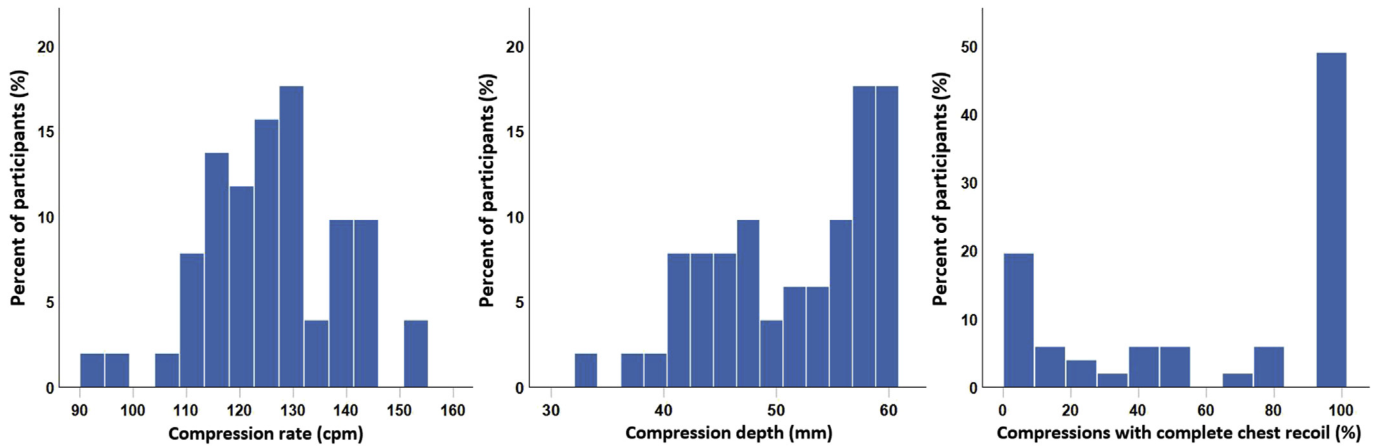

Fig. 2. Frequency histograms of participants' mean CC rate (cpm), mean CC depth (mm), and percent of CC with complete chest recoil (%) after 2 min of CPR.

Table 2
Hands-only CPR performance parameters during AR resuscitation.

CC rate (cpm), mean ± SD	126 ± 12.9
CC depth (mm), median (IQR)	53 (46–58)
CC with complete recoil (%), median (IQR)	80 (12–100)

CC, chest compression; cpm, compressions per minute; SD, standard deviation; mm, millimeters, IQR, interquartile range. When the normality assumption was violated, variables were reported as medians (interquartile range) instead of means ±standard deviation.

delivered (Table 3).

4. Discussion

This is the first US pilot study to develop an AR CPR system and assess its efficacy in a HCP adult resuscitation training setting. In our cohort, we report a mean CC rate of 126 ± 12.9 cpm, a median CC depth of 53 mm (IQR 46–58), and reduced leaning on the chest, as half of the participants delivered more than 80% of compressions with complete chest recoil [2, 3]. In addition, the AR experience was received favorably by most participants, who found the audio-visual feedback from the interactive circulatory system as educational and helpful in guiding effective compression delivery. Accordingly, our guideline-compliant findings in the AR training environment, and positive participant evaluations demonstrate the feasibility of using this multisensory teaching tool in future CPR trainings for HCPs.

The results of this study are consistent with past research that has shown the value of audio-visual feedback [9, 10] and high fidelity simulation trainings [13] in providing timely information for CPR technique correction, while exposing trainees to simulated clinical situations.

However, our work also contextualizes goal-directed hemodynamic resuscitation by incorporating notions of tailored therapy in CPR; this may serve as a more effective educational approach in line with contemporary patient-centered medical care. As participants are able to visualize the effect of CCs on vital organ perfusion, CPR can be titrated to a virtual measure of blood flow, similar to other investigated physiologic markers such as end-tidal CO_2 [26], arterial blood pressure [27], and oxygen content [28]. Similarities may be drawn between the CPReality system and the Brayden illuminating CPR manikin, however AR may offer additional capacity for more vivid and interactive training sessions, besides the greater adaptability of the system to various CPR manikins already in use by various training centers. As may be expected, integrating the proposed technology with standard training manikins will increase costs despite no proven added benefit at this early stage, a question that we aim to address in upcoming randomized controlled

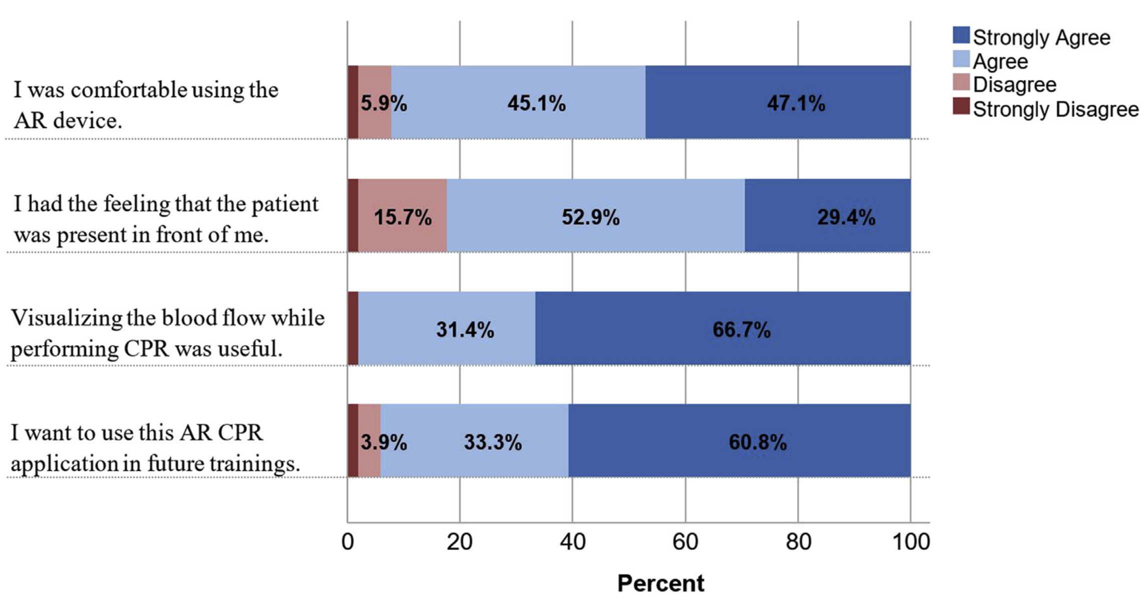

Fig. 3. Likert scale participant evaluation of the CPReality system.

Table 3
Open-ended participant feedback about the CPReality application categorized thematically, N = 51.

		Number of responses
Please tell us what you liked about the augmented reality CPR training application?[a]	Real-time audiovisual feedback: - Allowed appropriate adjustment of CC in real-time - Helped deliver effective CC	35
	Blood flow visualization: - Made experience more realistic - Helped visualize the goal of CC - Helped understand the effect of compressions on perfusing vital organs	24
	Use of technology	3
	Performance scorecard at the end	1
	Nothing	1
	No response	7
What would you change about the augmented reality CPR training application?[a]	Position the blood circulation hologram on top of instead of next to the manikin	12
	Provide users with real-time stats during CC	9
	Sound effect quality or volume	4
	Headset weight and stability	2
	Subject reported dizziness	1
	Nothing	8
	No response	15

CPR, cardiopulmonary resuscitation; CC, chest compression.
[a] Some comments fall under more than one category.

trials and prospective cost-benefit analyses of this integration.

Ultimately, CPReality combines both feedback and simulation training into a single immersive experience, coupled with gaming features that can enhance users' attitudes towards CPR training. Gamified learning, recognized by the AHA as an important area of focus for innovation in future resuscitation education [17], has already been evidenced by several studies to be more engaging, enjoyable, and to increase subjects' knowledge retention and self-efficacy while facilitating practice in team-based scenarios [29, 30, 31]. Interestingly, the AHA recently launched an interactive AR hands-only CPR training application using Google's ARCore platform, which allows users to practice and track their own performance on a virtual person, in any location, and without the need for an instructor [32]. One randomized controlled trial found that the use of AR glasses in Pediatric Advanced Life Support (PALS) showed improved adherence to resuscitation guidelines, with a significant reduction of errors in defibrillation doses by 52.5%, compared to pocket reference cards [33]. Another controlled trial on CPR coaching using Google Glass showed a significant increase in the number of successful defibrillations by 32% [34]. While systematic reviews cannot validate the effects of such learning modules at this early stage [35], these promising results suggest an evolution in healthcare education with a potentially impactful influence on patient outcomes.

Several pilot studies have shown creative implementations of technology-enhanced simulation that highlight valuable new opportunities for HCPs to practice technical skills in a safe environment while maintaining the feeling of a high-risk setting. The stated benefits of fidelity and engagement were recognized as ideal for real-life training by CPR instructors in a recent VR CPR trial in Singapore [29]. Investigators have also shown practical implementations in crisis management training, such as in Advanced Trauma Life Support (ATLS), which requires team-based simulation sessions that are otherwise costly and difficult to coordinate with larger teams [36]. Concurrently, recent work from our team with VR technology was able to examine lay bystander response to a realistic sudden cardiac arrest scenario, capturing data previously beyond the reach of investigators [37]. Other implementations in simulated nasogastric tube or central line placement [18, 20, 21], ultrasound image acquisition [19], and endovascular surgery [38] have also shown promise, and as applications evolve, simulated realities will foreseeably approximate to real clinical practice.

There are several limitations to this study, primarily related to the inherent selection bias in enrolling a convenience sample of experienced HCPs already trained in CPR, a learning effect, and a lack of control for confounders since there was neither a pre-test phase to establish baseline CPR performance, nor a control group against which to compare CC quality outcomes. HCPs who volunteered to participate in our study may conceivably have a higher self-efficacy, an important factor that may positively skew CC parameters in our results. As this was a feasibility study however, limitations on the generalizability of our results and inferences about the effectiveness of AR CPR are expected; we aim to address these limitations in a Phase 2 study comparing the AR system to a CPR feedback device. In addition, as enrollments occurred prior to participants' scheduled BLS and/or ACLS recertification trainings, the duration of the AR simulation was reduced to a single 2-minute cycle to minimize interference with classes; longer durations would have allowed participants for more time to adjust to the environment prior to performance assessment and valuation of the system in the post-CPR survey. Lastly, our reported results on the quality of CPR performed were possibly underestimated since, for most participants, this was their first experience using an AR interface, and only after a short tutorial given by the research coordinators.

5. Conclusions

Overall, the results of this pilot study suggest that AR integration into CPR training may be an effective educational strategy that extends beyond the translation of knowledge and skills, to an inclusive physiology-grounded resuscitation experience in a simulated high-stress environment. As participants generally delivered compressions with adequate rates, depths, and complete chest recoil, the proposed study addresses one of many research questions on technology-enhanced resuscitation education [17], and its possible role in improving HCP's compliance with CPR guidelines. However, given the limitations of this study, further investigations are needed to compare CPReality to traditional CPR training systems.

Declarations

Author contribution statement

Steve Balian: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Shaun K. McGovern: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Benjamin S. Abella: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Audrey L. Blewer: Analyzed and interpreted the data; Wrote the paper.

Marion Leary: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare the following conflict of interests:

Benjamin Abella received research funding from the American Heart Association, National Institutes of Health, Patient Centered Outcomes Research Institute and CR Bard; speaking honoraria from CR Bard and Stryker.

Audrey Blewer was supported through an American Heart Association Mentored Clinical and Population Award and a Doris Duke grant.

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Steve Balian and Shaun McGovern report no conflicts of interest.

Additional information

No additional information is available for this paper.

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