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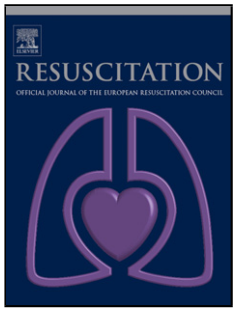

Delivery of Automated External Defibrillators via Drones in Simulated Cardiac Arrest: Users' Experiences and the Human-Drone Interaction

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ABSTRACT

Background

Survival after out-of-hospital cardiac arrest (OHCA) in the United States is approximately 10%. Automatic external defibrillators (AEDs) are effective when applied early, yet public access AEDs are used in <2% of OHCAs. AEDs are often challenging for bystanders to locate and are rarely available in homes, where 70% of OHCAs occur. Drones have the potential to deliver AEDs to bystanders efficiently; however, little is known about the human-drone interface in AED delivery.

Objectives

To describe user experiences with AED-equipped drones in a feasibility study of simulated OHCA in a community setting.

Methods

We simulated an OHCA in a series of trials with age-group/sex-matched participant pairs, with one participant randomized to search for a public access AED and the other to call a mock 9-1-1 telephone

number that initiated the dispatch of an AED-equipped drone. We investigated user experience of 17 of the 35 drone recipient participants via semi-structured qualitative interviews and analyzed audio-recordings for key aspects of user experience.

Results

Drone recipient participants reported largely positive experiences, highlighting that this delivery method enabled them to stay with the victim and continue cardiopulmonary resuscitation. Concerns were few but included drone arrival timing and direction as well as bystander safety. Participants provided suggestions for improvements in the AED-equipped drone design and delivery procedures.

Conclusion

Participants reported positive experiences interacting with an AED-equipped drone for a simulated OHCA in a community setting. Early findings suggest a role for drone-delivered AEDs to improve bystander AED use and improve outcomes for OHCA victims.

ABBREVIATIONS

AED, automatic external defibrillator;
CPR, cardiopulmonary resuscitation;
EMS, emergency medical services;
OHCA, out-of-hospital cardiac arrest;
UAV, unmanned aerial vehicle;
UNC, University of North Carolina at Chapel Hill.

Keywords: automated external defibrillator, cardiac arrest, drone

INTRODUCTION

The majority (73%) of the 475,000 sudden cardiac arrests in the United States (US) each year occur outside of the hospital.[1,2] After an out-of-hospital cardiac arrest (OHCA), survival to hospital discharge in

the United States (US) is 10.6%, and survival with good neurological function is 8.6%.[1] When a bystander applies an automatic external defibrillator (AED) to a victim of OHCA prior to ambulance arrival, the chance of survival is nearly doubled.[3] However, the likelihood of survival decreases by 10% for every minute without defibrillation and cardiopulmonary resuscitation (CPR), underscoring the critical need for timely intervention.[1,4,5] OHCA survival rates can reach up to 50% when active citizen CPR training programs are coordinated with enhanced access to AEDs.[6] Barriers remain, however, to public access AED use for OHCA. Poor knowledge and awareness of AED location, lack of AED accessibility, unwillingness to use AEDs in an emergency, inadequate distribution, and lack of maintenance of public AEDs all contribute to suboptimal AED use in the out-of-hospital setting.[7,8]

Unmanned aerial vehicles (UAV), or drones, equipped with AEDs are a potentially promising strategy to augment emergency medical services (EMS) and increase access to early defibrillation for OHCA.[9-12] In drone-assisted AED delivery, when a bystander activates an emergency response system ("9-1-1" in the US), the dispatcher could deploy AED-equipped drones in conjunction with EMS for suspected OHCA events where response times may be prolonged (e.g., remote areas, traffic delays). While prior studies have investigated the theoretical benefit of drone-delivered AEDs using mathematical models, [13,14] few have assessed the feasibility of drone-delivered AEDs in community settings.[15] In particular, little is known about bystanders' perceptions of interacting with drones equipped with AEDs.[16] Here we report on participant experiences interacting with an AED-equipped drone at the scene of a simulated OHCA.

METHODS

Between March and June 2019, we conducted 35 OHCA simulation trials in five distinct zones outdoors across the University of North Carolina-Chapel Hill (UNC) campus.[17] Each trial included a life-sized manikin (Laderal Resusci Anne) as the OHCA victim, accompanied by two participants, paired by sex and age (18-34, 35-49, 50-65 years). We randomized participants either to call a mock 9-1-1 telecommunicator who initiated the autonomous flight of a drone modified to carry a standard AED

(Philips HeartStart Onsite, weight 3.3 lbs. with case) or to conduct a ground search for a fixed AED. A comparison of AED delivery times has been published.[17] When the participant called mock 9-1-1 telephone number, he or she was instructed by the telecommunicator to initiate CPR and to instruct the second participant to search for an AED. We conducted seven trials in each of five zones on campus. Zones varied by environmental challenges to drone navigation, challenges to pedestrian AED acquisition, and number of fixed AEDs. Drone launch site locations varied and were not visible from the event site.

We recruited participants from the campus community through email listserv solicitation and a web-based recruitment platform. Inclusion criteria specified that participants 1) be between 18-65 years of age, 2) have self-reported ability to jog for 2 minutes, 3) have no history of cardiovascular disease or other medical history that would exclude moderate physical activity for 2-3 minutes, or complaints of non-traumatic chest pain or anginal equivalent symptoms (arm, shoulder, jaw pain, shortness of breath, syncope), and 4) be fluent in English. Participants were excluded if they 1) had cognitive impairment resulting in difficulty understanding and providing written consent or 2) declined to consent. Drone dispatch and landing sites were approved by UNC Public Safety and Police. The mock 9-1-1 dispatcher, staffed by a research team member, followed a local EMS OHCA response script, modified to prepare the caller for the AED delivery by drone (**Appendix A**). Research staff surveyed all study participants before and after each trial. Pre-trial surveys focused on participants' previous experience with drones, confidence and comfort level with drone interactions, knowledge and confidences about AEDs and their location on campus, and safety concerns with drones. Post-trial surveys focused on participants' impressions about either interacting with the drone or their experience searching for an AED. Findings from these brief surveys have been published.[17] Seventeen participants randomized to interact with the drone (drone recipient) were asked to complete an approximately 15-30 minute, semi-structured post-trial interview. Interviewees were selected based on interviewer availability and a desired interviewee sample diverse in age and sex. A qualitative researcher (MG) on our team conducted the semi-structured interviews, with questions focused on the participant's experience interacting with the AED-equipped drone in simulated OHCA (**Appendix A**). Interviewees were asked to share their experiences participating in the simulation,

their concerns about the simulation and interacting with the drone, and ways to improve the drone design and the overall AED delivery via drone process. Interviews were audio-recorded, and the interviewer took additional written notes. The interviewer, later, listened to the audio recordings of each interview and recorded detailed notes, including select illustrative quotes, comparing the detailed notes to the initial interview notes to identify any missing information. The interviewer analyzed the detailed notes, organizing the information thematically according to key questions of interest. A second team member (AJ) reviewed the complete interview notes and independently noted themes, which were consistent with those identified by the primary analyst.

The UNC institutional review board approved the trial protocol and consent forms. We worked closely with UNC Public Safety and Police to ensure the safety of pedestrians in the event simulation areas on campus and to adhere to existing UNC Drone Policy regulations and guidelines.

RESULTS

We conducted 35 trials, 18 with female pairs and 17 with male pairs. These included 15, 11 and 9 trials across three age strata (18-34, 35-49, and 50-65 years), respectively. In seven of the 35 trials, only one participant was present and performed both roles as a caller and seeker sequentially. We conducted semi-structured qualitative interviews with 17 of the 35 participants that served in the drone-recipient role (**Table 1**). Analysis of the interviews focused on four key thematic domains: (1) general feelings about the drone and simulation; (2) perceived benefits of drone delivery system; (3) concerns and suggestions to improve user experience; and (4) potential of use of AED drones in real-life situations of OHCA (**Table 2**).

1. General Feelings

Participants generally reported positive feedback about their experiences interacting with the drone. Many described feeling excited and intrigued, said that the drone experience was fun or cool, or reported that the entire experience was positive in general. One participant shared, “It was thrilling to see

this non-manned machine in the sky that was descending with life-saving equipment, that's pretty cool." Another summed up the experience saying, "I would say the cool factor is definitely there."

Despite the overall positive feedback, some participants conveyed neutral or indifferent feelings towards interacting with the drone, and a few reported negative feelings associated with particular aspects of the simulation. Some described having a sense of uncertainty or anxiety about the timing or direction of the drone's arrival or landing, such as whether it would land close enough (or too close), or how they would remove the attached AED. One participant explained:

> *"It was just that period of time between not knowing exactly what to look for, being able to hear something and not see it, and not knowing what direction it was going to be coming from. That was kind of the weird uncertainty. Once I saw it, fine."*

Others reported feeling frustrated when they had difficulty removing the AED, hearing the mock 9-1-1 operator, or performing CPR. One participant shared:

> *"There was anxiety, there was panic there, because you start running through what the person on the phone told you about actually unlatching and getting an AED, and I didn't ask them to repeat it so felt stupid for not asking…you're judging yourself on whether you're doing this properly."*

2. Perceived Benefits

Most participants thought AED delivery by drone was an interesting and innovative concept. As one shared:

> *"You think of drones negatively, either just as an annoying recreational thing or consumer thing to deliver things…. So the thought of a drone doing something to help people, to save lives or whatever, seemed really interesting to me."*

Participants highlighted key benefits of AED delivery by drone, including 1) an efficient way to get an AED to OHCA victims, and 2) the ability to deliver AEDs to remote areas. Some felt relief and comfort of having lifesaving equipment delivered to a victim. The following quote reflected this:

"*When the drone finally arrived and landed, the feeling of relief I had after that period of*

uncertainty…and just being like, ok, this is the thing that can make a difference in saving this person's life. It's here now."

Many noted the advantage of being able to stay with the victim and continuing CPR, instead of leaving to find an AED. One participant said the most difficult part *"would be walking away from someone who has arrested because I would have to feel like I could find a defibrillator really fast, or it's not worth it, or CPR is better."* Another stated:

"You don't want to leave your friend when they've collapsed. You want to stay and see if you can help. Or you could ask someone else to go but then you don't know if they are competent, do they know the area. So, feeling like they know where I am and they're going to be able to bring this thing to me is a good feeling."

3. Concerns and Suggestions for Improvement

Participants discussed concerns and made several recommendations that could facilitate the human-drone interaction.

Attributes of Drone Arrival and Landing

A number of interviewees expressed concerns related to being unclear about the drone's location when arriving or not knowing where it would land. Several participants suggested the AED-equipped drone emit a noise (i.e., siren or beep) to indicate its location, or be voice-activated to alert people of its arrival and when it is safe to approach. Others suggested ways to make the drone stand out more, such as adding reflective tape or lights. They suggested that the drone land close (but not too close) to the caller, to avoid needing to step over or around a victim to retrieve an AED, and to decrease the time to defibrillation.

Removal of AED from the Drone

Several participants suggested strategies to improve AED access and decrease release time. Some had difficulty removing the Velcro straps that secured the AED to the drone and recommended alterations, including brightly-colored straps and the addition of labels (e.g., arrow pointing to edge of

straps, or "pull here"). Others felt the AED and Velcro straps could be more accessible if located on the side of the drone instead of underneath.

Drone Safety

Participants voiced few concerns, overall, for their safety or that of others regarding drone-delivered AEDs. Few expressed safety concerns related to direct interaction with the drone. Some were concerned about the drone's ability to land effectively and safely in a crowded area. One participant was concerned the propellers could start up again and cause injury while reaching for the AED or that the drone might land too close by. *"What if the propellers started again? That's the one part I was like really nervous [about] … things malfunction all the time."* Some participants suggested adding protective features to the drone such as propeller guards, or propellers that tilt upwards or fold and retract after landing.

Interaction with the Mock 9-1-1 Telecommunicator

Participants expressed a need for clearer instructions from the 9-1-1 call operator. Some desired more information about what the drone would look and sound like, what direction it would be coming from, where it would land, or what to expect once it landed. In contrast, one participant felt that extensive operator instructions contributed to them doubting their ability to remove the AED from the drone.

Several participants felt that the 9-1-1 call operator could provide better instructions for caring for the victim and performing CPR, including demonstrating the rhythm to use for compressions, and clarifying that they should continue compressions until the drone lands and propellers have stopped. A couple participants noted that it might be helpful for the operator to provide instructions throughout the process (e.g., while doing CPR) rather than only at the beginning.

CPR and AED Use

Many of the concerns participants shared were regarding CPR and defibrillation, rather than about drone delivery. As one participant shared, *"I was just grateful it was a mannequin, otherwise I probably would have hurt someone*." Another stated, "*If once I opened the AED up and instructions were not clear, I would be worried that maybe I was doing it wrong.*" The benefit of a drone bringing the AED

to the site as opposed to having to leave the scene to search was reflected again in the context of general concerns. Individuals did not want to leave the "patient" for long, were concerned that difficulty in AED removal might contribute to a lapse in CPR or were unsure about when to stop CPR to retrieve the AED delivered by drone. One participant stated:

> *"The most uncomfortable part was standing over the victim on the ground and not knowing what to do"….I was anxious about continuing those chest compressions…when's the last moment I should stop and go retrieve the AED [from the drone]?"*

4. Real Life Application

Participants overwhelmingly said they would use the drone-delivered AED in real life. As one participant stated, *"I would use it in a heartbeat*." Some expressed concerns about it in real life, including drone arrival time, landing in crowded areas, issues with bystanders, flights at night or in poor weather, and worries about the drone's ability to find the OHCA site. Some participants noted the benefit of having a partner in the simulation and hoped for the same should they encounter an OHCA in real life.

DISCUSSION

In this community-based OHCA simulation study, we found participants were overwhelmingly positive about their interactions with an AED-equipped drone. Many felt relieved and comforted in having life-saving equipment directly delivered, enabling them to stay with the victim and continue CPR. A few expressed concerns surrounding technical aspects of the AED-drone delivery system, including potential safety issues related to moving propellers. All expressed willingness to use an AED drone in a real-life OHCA.

To our knowledge, our study is the first in the US to examine the human-drone interaction in the context of a drone-delivered AED. Sanfridsson et al. conducted a small-scale (N=8) OHCA simulation study in Sweden to determine bystanders' experiences with an AED drone.[16] Similar to our findings, participants generally felt positive, expressed relief at receiving an AED via drone and felt AED delivery

via drone was feasible and safe. Also similar to our study, some participants in the Sanfridsson et al. study expressed more concern with defibrillation than interacting with the drone-delivery mechanism. While in the Sanfidsson et al. study all participants felt that support from the emergency response communicator was helpful,[16] in our study some felt that the mock 9-1-1 call operator was helpful, yet others felt operator instructions were unclear or had a hard time hearing instructions. Sanfridsson et al.'s participants specified use of their mobile phones to be technically challenging, especially in a time-sensitive simulated situation,[16] while none of the participants in our study reported difficulty using their personal cell phones aside from some having difficulty hearing the telecommunicator. Differences in our findings may reflect the older age of the Sanfridsson et al. study population (ages 73-80 years). Although our study population was larger and included a wider age range, it was drawn from university faculty, students and staff rather than the general population.

Participants in our simulation study provided valuable suggestions to enhance the overall human-drone interaction. Several participants suggested strategies to improve AED access and decrease time to defibrillation, including improved labeling, signage, and sounds. Others highlighted ways that the 9-1-1 script and communication could be better tailored for the drone-delivery system.

Findings from this study also highlight that while participants overwhelmingly felt comfortable interacting with drones for the purposes of responding to an OHCA event, some felt uncomfortable or unsure about using the AED itself and/or performing CPR. Although our protocol did not require study participants to apply and operate the AED on the study manikins, several noted concern about whether they were equipped to use an AED in a real OHCA situation. Similarly, even though study participants conducted CPR on manikins in our study, some were concerned about hurting an OHCA victim in real life. These findings are line with prior studies that have found that despite wide-spread efforts to increase the placement of public access AEDs, many remain uncomfortable with the correct way to use AEDs[16,18,19] and uncertain in the correct way to initiate CPR.[20] Together, these results underscore the need for increased public education and community training on these life-saving interventions.

Limitations

Our study was limited to a small sample of participants all affiliated with a university setting. Participants, therefore, may not reflect the general population. While informative, it is difficult to know how participants might feel or respond in a true OHCA event. Our simulation study was controlled, both in study design and in execution on the campus during daylight hours and in good weather, and limited to simulations conducted outdoors due to campus and Federal Aviation Administration regulations. Experiences may differ in simulations conducted indoors, which is where the majority of OHCA occur. The perceived benefits expressed by the participants in our study, notably the ability to stay next to a victim while waiting for an AED delivery by drone, would change in the setting of an indoor OHCA. Bystanders, if alone, would need to leave the victim's side to search and retrieve the AED outside, which could add time to defibrillation. Additionally, our trials were in an AED-rich campus setting, which may impact participants' responses to some of the questions. In a setting with no public access AEDs and a drone being the only way to defibrillate a victim before EMS arrives, participants' thoughts, fears and concerns may have a different focus. Future studies of participants' experiences interacting with AED-equipped drones in real cases of OHCA need to be explored.

Conclusion

Overall, participants reported a positive experience interacting with an AED-equipped drone responding to a simulated OHCA, and all reported a willingness to use the system in a real-life OHCA emergency. AED drone delivery systems can be further improved to enhance both the user experience and delivery process by addressing the concerns noted by participants and considering their suggestions. Despite our study being a simulation, participants' discomfort with performing CPR and using an AED persists, while their perceptions about interacting with the drone itself were positive overall. Findings from this study can inform the design of larger-scale studies both in terms of the AED-equipped drone design and 9-1-1 communication protocol. Future studies should seek to demonstrate user acceptability of AED-equipped drones among lay bystanders in a diverse, representative population and in both rural and urban settings

and using both indoor and outdoor event sites. We need to examine the potential role of 9-1-1 telecommunicators which may include, but not be limited to, providing information about the drone's approaching direction, where it would land, and what bystanders can expect, especially in the setting of indoor OHCA.

Credit author statement
Each author made substantial contributions to the revised manuscript and has approved the final version of the revised manuscript prior to submission to Resuscitation.

Jessica Zègre-Hemsey conceived of the idea and led the project.
Mary Grewe led the qualitative data analysis and helped write that part of the manuscript.
Anna Johnson helped draft the tables and sections of the manuscript; she reviewed and helped with revisions.
Evan Arnold contributed and reviewed the manuscript and revisions.
Chris Cunningham helped draft and contribute to the manuscript development and revisions.
Brittany Bogle reviewed drafts and make contributions to revisions.
Wayne Rosamond helped draft, review, and contribute to all parts of the manuscript.

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Conflict of interest statement

All authors report no conflicts of interest.

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TABLES

Table 1. Characteristics of interviewees (n=17) compared to those of all participants that interacted with a drone (n=35).

	Male	**Female**	**TOTAL**
All drone recipients			
18-34 years	7 (20%)	7 (20%)	14 (40%)
35-49 years	5 (14%)	6 (17%)	11 (31%)
50-65 years	6 (17%)	4 (11%)	10 (29%)
Total	**18 (51%)**	**17 (49%)**	**35 (100%)**
Interviewees			
18-34 years	5 (29%)	2 (12%)	7 (41%)
35-49 years	3 (18%)	2 (12%)	5 (29%)
50-65 years	3 (18%)	2 (12%)	5 (29%)
Total	**11 (65%)**	**6 (35%)**	**17 (100%)**

Table 2. Key thematic domains of interviews with participants and example quotes.

Domain	**Example quote(s)**
Feelings about Drone and Simulation	"It was thrilling to see this non-manned machine descending with life-saving equipment." "When drone arrived and landed…feeling of relief after a period of uncertainty"
Perceived Benefits of Drone Delivery System	"The thought of drone doing something to help people like save lives seemed really interesting." "Feeling like they know where I am and they're going to be able to bring this thing to me is a good feeling." "I just thought it was really a great idea…just to bring an AED right to the spot, I mean it's just so efficient, it seems so effective and quick, like a lifesaving maneuver, faster than an ambulance."
Concerns and Suggestions for Improvement	"What if the propellers started again?" "I wish somebody said the Velcro attaches at the top"
AED Drone Delivery in Real Life	"I would use it in a heartbeat"