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Drones reduce the time to defibrillation in a highly visited non-urban area: A randomized simulation-based trial

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A B S T R A C T

Introduction: Out-of-hospital cardiac arrest (OHCA) has a high global incidence and mortality rate, with early defibrillation significantly improving survival. Our aim was to assess the feasibility of autonomous drone delivery of automated external defibrillators (AED) in a non-urban area with physical barriers and compare the time to defibrillate (TTD) with bystander retrieval from a public access defibrillator (PAD) point and helicopter emergency medical services (HEMS) physician performed defibrillation.
Methods: This randomized simulation-based trial with a cross-over design included bystanders performing AED retrievals either delivered by automated drone flight or on foot from a PAD point, and simulated HEMS interventions. The primary outcome was the time to defibrillation, with secondary outcomes comparing workload, perceived physical effort, and ease of use.
Results: Thirty-six simulations were performed. Drone-delivered AED intervention had a significantly shorter TTD [2.2 (95 % CI 2.0–2.3) min] compared to PAD retrieval [12.4 (95 % CI 10.4–14.4) min] and HEMS [18.2 (95 % CI 17.1–19.2) min].
The self-reported physical effort on a visual analogue scale for drone-delivered AED was significantly lower versus PAD [2.5 (1 – 22) mm vs. 81 (65–99) mm, $p = 0.02$]. The overall mean workload measured by NASA-TLX was also significantly lower for drone delivery compared to PAD [4.3 (1.2–11.7) vs. 11.9 (5.5–14.5), $p = 0.018$].
Conclusion: The use of drones for automated AED delivery in a non-urban area with physical barriers is feasible and leads to a shorter time to defibrillation. Drone-delivered AEDs also involve a lower workload and perceived physical effort than AED retrieval on foot.

1. Introduction

Out-of-hospital cardiac arrest (OHCA) has a global average incidence of 55 per 100.000 and a high mortality of around 90 % [1,2]. Early recognition of OHCA, early activation of emergency response, high quality bystander basic life support (BLS) and early defibrillation are critical components of the adult Out-of-Hospital Chain-of-Survival [3]. Defibrillation by bystander by automated external defibrillator (AED) within the first 3–5 min before the arrival of emergency medical services (EMS) can increase survival to as high as 50–70 % [4] if they can be effectively directed to a nearby public access defibrillator (PAD) [5]. However, bystander use of PAD during OHCA is poor, at 2 % to 3 % [6].

Increasing the proportion of AED applied on adult individuals with OHCA before the EMS arrives to >20 % is one of the first two American Heart Association Emergency Cardiovascular Care (AHA ECC) Committee 2030 Impact Goals (Merchant et al. 2024).

OHCA cases in rural areas are associated with a reduced likelihood of 0.39 to receive bystander AED usage versus OHCA cases in urban areas

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due to limited availability [8]. Highly visited mountainous areas such as the Austrian Alps reported that cardiopulmonary resuscitation (CPR) is initiated in less than 20 % of cases, and all survivors received immediate BLS and AED treatment [9]. Response times in such areas with ground vehicles or helicopter emergency medical services (HEMS) can be delayed due to physical barriers, long distances, and dynamic weather conditions [10,11].

Mathematical models for drone placement confirmed the ability of drones to deliver an AED ahead of traditional EMS [12]. Drones have delivered an AED through automated flight and shortened the time to defibrillation (TTD) in urban areas [13] and were piloted to deliver medical equipment and establish telemedical communication in non-urban areas with physical barriers (i.e., not accessible by ambulance) [14]. It is not known whether drones are capable of fully autonomous delivery of an AED in non-urban areas with physical barriers and different weather conditions to the location of the alert, without support of a pilot. It is also not known if bystanders can provide timely defibrillation using PAD retrieval on foot in this setting and to what distance from a PAD it would be quicker for a bystander to retrieve an AED on foot than wait for drone delivery.

The objective of this study was to examine the feasibility of integrating drone delivered AEDs with automated flights into a 911-response system in a highly visited non-urban area already covered by PAD, and determine the TTD comparing drone delivery of AED to bystanders using PAD and to HEMS, the golden standard in remote and mountainous areas. Our hypothesis was that drone delivery of AEDs is feasible and results in a faster TTD at different locations in a non-urban area with physical barriers. We evaluated the physical effort, challenges in practical handling and the workload experienced by bystanders comparing drone delivery of AED versus retrieving an AED on foot from a PAD point.

2. Methods

2.1. Design and study setting

This is a randomized controlled trial with a cross-over design that compared three methods of delivery and application of an AED or manual defibrillator, reported according to the CONSORT guidelines (Fig. 1). The Ethics Committee for Clinical Trials and Testing of the Autonomous Province of Bolzano, Italy, approved the study with protocol number 67–2023. We conducted the trial under the principles of the Declaration of Helsinki.

Twelve bystanders performed two AED retrievals and applications in random order, one delivered by drone (primary intervention), one retrieved on foot from a PAD point (secondary intervention) at six randomly assigned locations in the study area. The drone take-off point and the PAD were at the same location (Fig. 2). Two physicians performed a simulated ground approach from a HEMS landing zone or winch target depending on the terrain at each location in random order (control arm). The primary outcome was a comparison between the primary intervention and the control arm in terms of TTD. Secondary outcomes were a comparison between the primary and secondary intervention regarding TTD, perceived workload, physical effort, and ease of use.

The trial took place in the Fanes-Senes-Braies natural park (South Tyrol, Italy), a site with over 17,000 visitors per day in high season that frequent a circular 4 km hiking path [15]. The area is located at an elevation of 1,496 m and around 33 km from the nearest HEMS base of Bressanone, Italy. We randomly chose six locations around the lake where witnessed cardiac arrest scenarios were simulated, located 50 m – 1,600 m on foot away from the drone take-off and PAD point (Fig. 2). All scenarios presented with a shockable rhythm. The trial took place in Autumn 2023 and was scheduled independently of weather forecast.

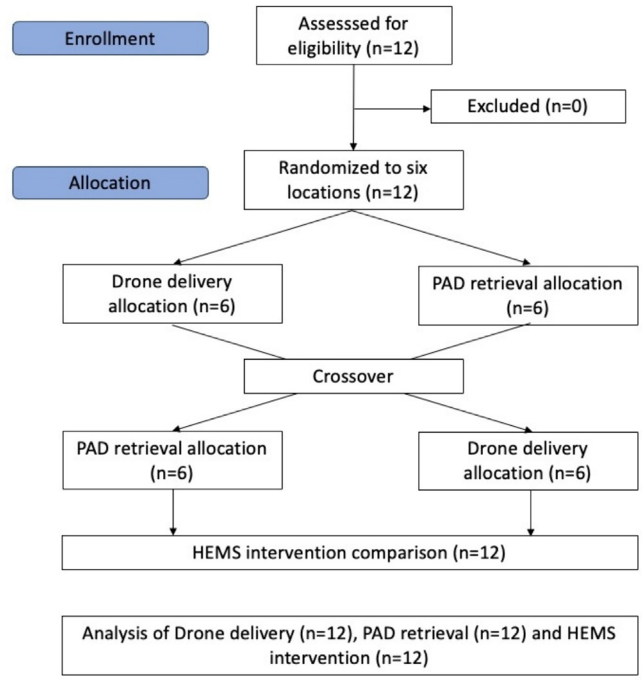

Fig. 1. Study design with enrolment and allocation of participants demonstrating the crossover design of bystander involvement with both drone delivery of the automated external defibrillator (AED) and public access defibrillator (PAD) on foot compared to helicopter emergency medical services (HEMS) intervention.

2.2. Participants

Twelve healthy (ASA 1) adult volunteers with a valid BLS certification were recruited to assure similar baseline level of AED operation skills. Age younger than 18 years and ASA >1 were exclusion criteria. The bystanders witnessed a simulated OHCA of a training manikin positioned at a randomly assigned location twice. They were asked to perform a safety check and make an emergency call to 911, during which they were directed, randomly and without prior notice, to either wait for a drone delivering an AED at their location or directed to retrieve an AED on foot. The bystander was instructed by the dispatch center not to be involved in performing BLS until the AED was on site and a study collaborator performed BLS on the manikin during the retrieval process. During each AED retrieval on foot the bystander covered between 100 m to 3200 m with up to 150 m of ascent. TTD was calculated as the time elapsed from when the bystander concluded the 911 call until the shock was administered. For the HEMS arm two licensed physicians were recruited using the same inclusion criteria. They performed a simulated HEMS intervention after landing or winch operation, depending on the terrain. The prospective time recorded on the ground consisted of the physician reaching the patient carrying equipment, attaching the defibrillator pads of a monitor on demo mode and initiating a manual defibrillation. The TTD in the HEMS arm consisted of the prospective data recorded in this simulation, added to activation and flight times modelled from local historical data from the nearest helicopter base in Bressanone, Italy (Supplemental table S1). Each location was assessed for suitability for landing or winch approach and the times were adjusted for this.

Before starting the study, all participants were made familiar with the AED, monitor, and the sticker pads and rated their baseline depression, anxiety and stress symptoms using the Depression Anxiety Stress Scale (DASS-21) [16]. After each AED application participants rated their perceived workload on a visual analogue scale (VAS) using the National Aeronautics and Space Administration Task Load Index (NASA-TLX) [17] that includes six subscales ranging from 0 to 20

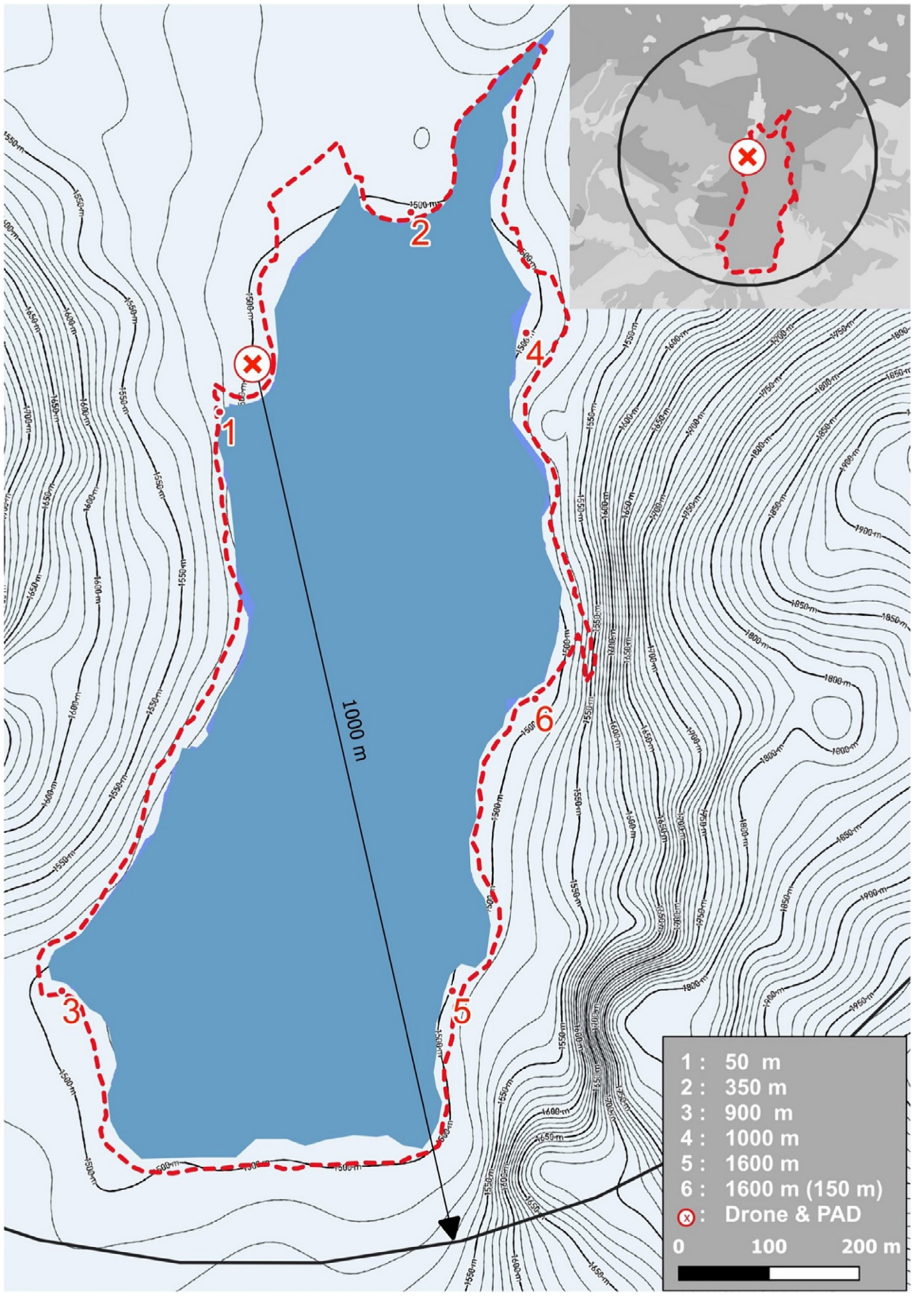

Fig. 2. Study area depicting the lake, hiking path (red dashed line), drone take off point and public access defibrillation (PAD) retrieval point (X), and location 1–6 of simulated out-of-hospital cardiac arrest (OHCA) including one way walking distances from X with altitude difference in brackets. A range of 1000 m flight distance is shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Supplemental table S2): Mental Demand, Physical Demand, Temporal Demand, Effort, Frustration (ranging from “Low” to “High”), and Performance (ranging from “Good” to “Poor”). Participants also marked their perceived physical effort and their level of practical handling challenge by placing a mark on a 100 mm horizontal line on a VAS labelled with the extremes of low level of effort or challenge and high levels of effort and challenge [18].

2.3. Materials

The drone model Q4X (MAVTech, Italy) performed automated flight plans drawn up in Mission Planner (ArduPilot, NY) based on the reported coordinate position of the distress call under the supervision of a stand-by pilot and was equipped with a custom bracket to carry a polystyrene box containing the AED. The drone was able to release the box autonomously upon reaching the specified GPS location. The box was equipped with a self-opening parachute to brake descent and contained a trainer Fred Easyport AED (Schiller, Switzerland) with trainer sticker pads. As soon as the AED was unpacked, its operation was guided by conventional pre-recorded voice commands. The manikin used in the scenarios was a Resusci Anne QCPR torso (Laerdal, Norway). The HEMS physician was equipped with a HEMS medical backpack Model Viper 44 (Rock Snake, Austria) and a Corpuls3 monitor defibrillator (Corpuls, Germany), with a total weight of 18.6 kg.

2.4. Statistical analysis

A linear mixed model (LMM) was used to analyze the effect of the method of delivery, the location, and the interaction of the method of delivery with the location on TTD. A linear regression for each method of delivery was performed to analyze the effect of the walking distance on TTD. Wilcoxon signed ranks test was used to compare NASA-TLX and VAS parameters between drone and PAD. Multiple comparisons were adjusted by means of Holm–Bonferroni correction. Normal distribution was assessed by means of Shapiro–Wilk test and normal Q-Q plots. Data were reported as mean ± standard deviation if they were normally distributed, otherwise as median (range). Estimated means of the LMM were reported as mean (95 % confidence interval). SPSS version 29 (IBM Corp., Armonk, NY, USA) was used for statistical analysis and $p < 0.05$ (two-sided) was considered statistically significant.

3. Results

Thirty-six simulations were performed (Table 1). At the baseline evaluation anxiety (DASS-21 > 7) and depression (DASS-21 > 9) were absent in all study participants and one participant experienced mild stress (DASS-21 > 14) (Supplemental table S3). All drone flights and automated AED box drops ($n = 12$) were successful without constraints in weather conditions or technical difficulties, as well as all PAD retrieval and HEMS simulations.

TTD was shorter in the drone-delivered AED intervention [2.2 (95 % CI 2.0–2.3) min] in comparison to PAD [12.4 (95 % CI 10.4–14.4) min] and HEMS [18.2 (95 % CI 17.1–19.2) min]. There was an effect of the method of delivery ($p < 0.001$), of the location ($p < 0.001$) and of the interaction of the method of delivery with the location ($p < 0.001$) on TTD (Fig. 3). The mean distance the drone package landed from the bystander was 4.2 (3.6–4.7) m. When comparing drone delivery of AED to bystanders using PAD, the TTD was shorter when PAD was located only within 140 m from the simulated OHCA (location 1 vs. location 2–6; Fig. 3). When comparing bystanders using PAD to HEMS, the TTD was shorter when PAD was located within 1381 m from the simulated OHCA (location 1–4 vs. location 5–6).

In all cases the AED pads were placed correctly ($n = 36$). The physical effort rated on a VAS scale by bystanders was significantly lower for the drone delivered AED intervention compared using PAD [2.5 [1 - 22] mm vs. 81 (65–99) mm, $p = 0.02$], whereas the practical handling challenge was rated similar [4 (0−33) mm vs. 7.5 (0–25) mm, $p = 1.0$] (Table 2). The overall mean workload measured with the NASA-TLX was significantly lower for the drone delivered AED intervention [4.3 (1.2–11.7)] on a twenty point scale, compared to bystander using PAD [11.9 (5.5–14.5)] ($p = 0.018$); four of the six subscales (physical demand, temporal demand, effort and frustration) of the NASA-TLX were also rated lower by bystander receiving AED by a drone (Table 2).

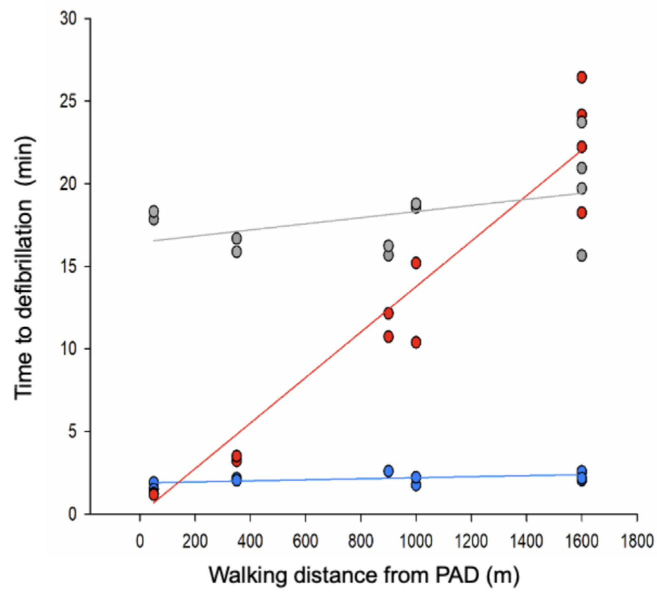

Fig. 3. Relationship between time to defibrillation and one way walking distance from public access defibrillation (PAD); lines are calculated by means of linear regression. Blue colour indicates drone delivery, red colour indicates PAD and grey colour indicates helicopter emergency medical service. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

This study demonstrates that the use of drones for automated AED delivery to a bystander at the site of an OHCA in a non-urban area with physical barriers is feasible and leads to a shorter TTD compared to a bystander using PAD and HEMS physician performed defibrillation. The TTD was independent by OHCA when AED was delivered by drones, whereas AED retrieval on foot depended on the distance the OHCA occurred from the PAD. The handling of a drone delivered AED involved a lower workload and perceived physical effort than retrieval of an AED on foot.

Our study shows a clinically relevant reduction in TTD in drone delivery of AED compared to bystanders using PAD and helicopter emergency medical services. Previous studies evaluating automated drone delivery of AED's have also demonstrated significant time reduction versus conventional EMS response in urban areas in which the delivery occurred before ambulance arrival in two-thirds of cases, with a median time reduction of 3 min and 14 s [13] and in another setting with 16 min and

Table 1
Time to defibrillation (TTD) by means of helicopter emergency medical service (HEMS), drone delivery and public access defibrillation (PAD) per location and participant/HEMS team. BMI, body mass index; F, female; ID, identification; M, male; SD, standard deviation.

Location	HEMS		Bystanders						
	HEMS physician	TTD HEMS (min)	Sex	Age (years)	BMI	Drone flying distance (m)	TTD drone (min)	Walking distance from PAD, one way (m)	TTD PAD (min)
1	A	17.9	F	34	30.8	70	1.9	50	1.3
1	B	18.3	M	36	22.4	70	1.5	50	1.2
2	A	16.7	M	33	23.1	260	2.2	350	3.2
2	B	15.9	M	42	27.8	260	2.0	350	3.5
3	A	15.7	M	22	22.0	750	2.6	900	10.7
3	B	16.2	M	36	26.9	750	2.6	900	12.2
4	A	18.6	M	48	32.1	300	1.8	1000	15.2
4	B	18.8	M	29	23.8	300	2.2	1000	10.4
5	A	21.0	F	21	22.9	750	2.5	1600	24.2
5	B	23.7	M	53	26.3	750	2.6	1600	22.2
6	A	15.7	M	42	23.1	500	2.0	1600	18.3
6	B	19.7	M	29	24.9	500	2.2	1600	26.5
mean ± SD		18.2 ± 2.4		35.4 ± 9.7	25.5 ± 3.3	438 ± 264	2.2 ± 0.4	917 ± 605	12.4 ± 9.0

Table 2
Comparison between drone and public automated external defibrillator (PAD) of National Aeronautics and Space Administration Task Load Index (NASA-TLX) parameters on a scale of 0–20 and visual analogue scale (VAS) of physical effort and practical handling on a scale of 0–100. Wilcoxon signed ranks test was used and *p*-values were adjusted by means of Holm-Bonferroni method. Values are reported as median (range).

Test	Parameter	Drone	PAD	*P*-value
VAS	Physical effort	2.5 (1–22)	81 (65–99)	0.020
	Practical handling	4 (0–33)	7.5 (0–25)	1.000
NASA-TLX	Overall mean workload	4.3 (1.2–11.7)	11.9 (5.5–14.5)	0.018
	Mental demand	5 (1–16)	5 (1–14)	1.000
	Physical demand	3 (1–12)	16.5 (4–20)	0.023
	Temporal demand	5.5 (1–20)	17 (3–20)	0.032
	Effort	2.5 (1–16)	9 (2–20)	0.020
	Frustration	2.5 (1–6)	15 (1–19)	0.038
	Performance	2 (1–13)	7 (1–19)	0.135

39 s [19]. A recent trial piloting local drone delivery of AEDs within a range of under 400 m led to a TTD of 3 min and 53 s with no comparison arm [20]. In our trial set in a non-urban area with physical barriers (i.e., not accessible to ambulance) we found a TTD by bystander of maximum 2 min and 36 s in all drone delivered simulations in the entire study area, which would likely lead to a clinically relevant improvement in survival. Previous research demonstrated that defibrillation by bystander within 3 min can increase survival to as high as 74 % in OHCA patients presenting with a shockable rhythm [4]. The time reduction in our trial was larger than in most previous trials due to the increased distance that decrease the efficacy of both bystanders using PAD and HEMS response. Specifically, the TTD by bystander using PAD depends on its distance from the OHCA. When an OHCA occurs at a distance less than 140 m from a PAD and a bystander was instructed to retrieve the AED on foot this led to a shorter TTD compared to drone delivery. To be effective, GPS data of the bystander must be shared with the dispatch center automatically during the distress call, for a drone to deliver an AED at the site of an OHCA through an automated flight, which is not the international standard. International regulatory authorities have however adopted measures to ensure mobile devices and network providers can provide caller location based on hybrid means of cell phone tower triangulation and sharing of device GPS data [21,22]. Automated deployment of drones in the prehospital care chain requires ad hoc clearance to use the shared airspace. In a recent pilot project in Sweden this clearance was provided by local air traffic control of a nearby airport [13].

Handling an AED delivered by drone is perceived to have a lower overall workload compared to using PAD. Specifically, bystanders rated themselves to be comparably challenged in practical handling and rated less physical effort than retrieving and handling an AED from a PAD. This confirms the findings of a Norwegian study examining the bystanders' experiences of retrieving an AED delivered by a drone, which showed that retrieval of the AED was perceived safe and feasible [23]. A recent study confirmed that bystanders can deliver a defibrillation from an AED delivered by drone in a box in a time effective way and were able to largely maintain CPR quality according to the AHA guidelines [20].

PAD can be the quickest way to initiate treatment also in a remote area, depending on the physical barriers that can increase the time to cover the distance between the OHCA location and the PAD. However, as high quality BLS is also required it would only be possible in case of multiple bystanders as the retrieving bystander is required to leave the scene. Previous experiences showed that in only 1.6 % of cases an AED was available within a 100 m with more than one bystander present [24]. The bystander also needs to be reliably informed of the location of the PAD and directed there effectively over instructions with the phone operator or via GPS based application on a smartphone [5]. Bystander retrieval of PAD was considered a comparable technical handling challenge as AED reception by drone but required significantly higher physical effort. Our bystanders covered the retrieval with an average speed of around 9 km/h, which is faster than in a previously documented study in Sweden in which an average speed of 8.3 km/h was recorded of phone dispatched lay responders measured with GPS [25]. This might be explained by the straightforward navigation around the lake, even though the paths were unpaved, the lack of crowding and crossings, and possibly the fitness level and uneven sex distribution of our participants with an average age of 36 years and an average body mass index of 25.5.

Even though HEMS physician provided manual defibrillation in our study was associated with a longer time compared to PAD and AED delivery by drone, the high level of essential ongoing care and transport provided is required in the management of OHCA [26]. Advanced life support (ALS) is typically performed by physicians or paramedics and focuses on advanced airway procedures, administration of cardioactive medication and diagnosis as well as treatment of reversible causes [27]. Bystander care cannot replace this treatment, regardless of the modality of delivery of an AED. However, survival is highly dependent on bystander BLS with early defibrillation when indicated [28]. Increasing bystander effectiveness through early availability of an AED improves the chain of survival of OHCA patients, but still requires physician or paramedic dispatch. In our study area, HEMS intervention was associated with a late start of potential treatment by defibrillation of more than 18 min, which is linked with a poor prognosis [29]. Therefore, OHCA's that occur in non-urban areas likely benefit more from the introduction of a drone delivered AED than urban areas, especially if visitor numbers are high. Epidemiological data of cardiac arrest incidence combined with geographical information system analysis is required to identify which areas benefit most [12,30,31]. Popular remote and mountainous areas, such as national parks, natural reserves, or ski resorts, with many visitors of increasing age, performing recreational physical activities in cold and moderate to high altitude environments, potentially suffer from an increased incidence of cardiovascular events [11]. In this study we selected a geographical area with a high theoretical yield due to a combination of high visitor numbers and large potential time gains due to its remoteness. We believe more real-life studies at theoretical geographical hotspots can validate efficacy. However, high-quality data on cardiac arrest incidence and locations are required to determine these hotspots. Furthermore, full implementation in the prehospital care chain and timely procedures for flight approval in shared airspace are necessary for ad hoc activations.

4.1. Limitations

The simulated scenario might not reflect the diverse conditions and stressors experienced in actual use. We simulated that the HEMS crew always started from the helicopter base in Bressanone, Italy but they might in some cases be airborne or elsewhere for operational reasons. Furthermore, we set our field trial in autumn, excluding the possibility of a frozen lake. Our study dates were fixed in advance and not adjusted for weather forecasts to stay within the operational limits of the drone or helicopter. Additionally, the small sample size and overrepresentation of male participants of bystanders and physicians may limit the generalizability of the results. We chose to include BLS certified bystanders only; their performance may be superior to the general population in both intervention arms. The geographical area with its specific elevation and terrain chosen for the study, while representative of a non-urban, high-visitor location, may not encompass all the challenges faced in other remote or rural areas.

5. Conclusions

This study demonstrates that the use of drones for automated AED delivery to a bystander at the site of an OHCA in a highly visited non-urban area with physical barriers is feasible and leads to a shorter TTD compared to bystanders using PAD and HEMS physician performed defibrillation. Drone-delivered AEDs demand less overall workload and perceived physical effort compared to AED retrieval on foot by bystanders. The effectiveness of automated drone delivery of AEDs for OHCA will depend on their integration into the prehospital care chain, with their potential benefits being greater in highly visited non-urban areas where conventional response times are delayed and PAD coverage is limited.

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CRediT authorship contribution statement

Michiel J. van Veelen: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Giovanni Vinetti:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation. **Tomas Dal Cappello:** Writing – review & editing, Visualization, Methodology, Funding acquisition, Data curation, Conceptualization, Writing – original draft. **Frederik Eisendle:** Writing – review & editing, Methodology, Data curation. **Abraham Mejia-Aguilar:** Writing – review & editing, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Riccardo Parin:** Writing – review & editing, Methodology, Data curation. **Rosmarie Oberhammer:** Writing – review & editing, Resources, Methodology, Investigation, Data curation, Conceptualization. **Marika Falla:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giacomo Strapazzon:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Writing – original draft.

Data availability

The datasets collected and analyzed in the current study are available from the corresponding author on reasonable request.

Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ajem.2024.09.036.

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