

Prospective Evaluation of Drone-Delivered Automated External Defibrillators for Suspected Out-of-Hospital Cardiac Arrests: A Real-World Observational Study

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Abstract

An innovative method for enhancing bystander defibrillation during out-of-hospital cardiac arrests entails the rapid dispatch and transport of an automated external defibrillator (AED) by drone directly to the location of the suspected arrest. This study evaluated the proportion of cases in which drone delivery of an AED could precede ambulance arrival and determined the median time advantage gained through such drone-assisted deliveries. In this prospective observational investigation, five drones fitted with AEDs were stationed across two designated controlled airspaces in Sweden, encompassing a population of approximately 200,000 residents. These drones were activated concurrently with routine emergency medical services for alerts involving suspected out-of-hospital cardiac arrests and operated autonomously. Dispatches excluded incidents concerning children under 8 years of age, trauma-related events, and arrests observed by emergency medical personnel. Further exclusions applied when air traffic control denied flight permission, weather conditions were unsuitable, no-delivery zones were present, or operations occurred after dark. Information was sourced from dispatch centers, ambulance providers, the Swedish Registry for Cardiopulmonary Resuscitation, and the drone operating team. The main endpoints were the percentage of incidents achieving AED delivery by drone before ambulance arrival and the median time difference (expressed in minutes and seconds) between drone AED delivery and ambulance on-scene arrival. Secondary exploratory measures included the rate of drone-delivered AED attachment before ambulance arrival and the proportion of cases involving defibrillation with a drone-supplied AED when used before ambulance response. From April 21, 2021, to May 31, 2022, 211 suspected out-of-hospital cardiac arrest notifications were issued, resulting in drone deployment for 72 (34%). Successful AED delivery occurred in 58 (81%) of deployed missions; the predominant cause of non-delivery was dispatch center cancellation after determining the event was not a genuine out-of-hospital cardiac arrest. For the 55 cases with complete arrival time data for both drone and ambulance, the drone delivered the AED before ambulance arrival in 37 instances (67%), producing a median time advantage of 3 min and 14 s. Within this subset, 18 (49%) were confirmed true out-of-hospital cardiac arrests, and attachment of the drone-delivered AED occurred in six (33%) of these. Two cases (33%) presented with a shockable initial rhythm and received defibrillation via the drone-delivered AED before ambulance arrival, including one individual who survived to 30 days. The study recorded no adverse events. In 91% of deliveries, the AED was positioned (before final landing) within 15 m of the patient or the relevant building. Drones carrying AEDs, when activated for suspected out-of-hospital cardiac arrests, delivered the devices ahead of ambulance arrival in approximately two-thirds of applicable cases, providing a clinically significant median time saving of over 3 minutes. Such a system may help shorten the delay to AED attachment in the period preceding ambulance response.

Keywords: Out-of-hospital cardiac arrest, Automated external defibrillator, Drone delivery, Bystander defibrillation, Prehospital emergency care, Time to defibrillation

Access this article online

<https://smerpub.com/>

Received: 27 February 2026; Accepted: 04 June 2026

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How to cite this article: Van der Meer E, Jansen L, de Vries B, Claes S. Prospective Evaluation of Drone-Delivered Automated External Defibrillators for Suspected Out-of-Hospital Cardiac Arrests: A Real-World Observational Study. *J Med Sci Interdiscip Res.* 2026;6(1):219-30. <https://doi.org/10.51847/gVN7gRHgRD>

Introduction

Out-of-hospital cardiac arrest constitutes a prevalent and highly lethal condition, carrying a mortality rate nearing 90% [1]. Effective management relies on immediate cardiopulmonary resuscitation (CPR) combined with prompt defibrillation using an automated external

defibrillator (AED) to boost the likelihood of survival [1, 2]. Bystander-initiated interventions delivered within the first 3–5 minutes, before emergency medical services arrive, can elevate survival probabilities to between 50% and 70% [3]. However, both ambulance response times and defibrillation intervals have increased over the last ten years in Sweden [4]. In addition, the large majority of these arrests happen in private households (around 70%), where access to nearby AEDs is frequently limited, and bystander utilization of defibrillators is notably rare [1, 5, 6]. These challenges highlight the pressing requirement for creative solutions aimed at accelerating defibrillation and effectively reaching cardiac arrests that occur in residential environments [7].

Delivering AEDs by drone in response to suspected out-of-hospital cardiac arrests constitutes a novel and highly promising intervention. Several theoretical and mathematical optimization analyses indicate that drone-assisted AED transport can reduce the time required for AED availability compared with traditional ambulance dispatch [8-12]. Earlier research by our group has also shown that deploying AED-equipped drones (AED-drones) to out-of-hospital cardiac arrest events is both practical and safe, with successful placement of the device within 10 m of the arrest site [13]. For drones to meaningfully support earlier defibrillation and better survival, however, they must deliver AEDs not merely before ambulance arrival but with a time saving that carries genuine clinical importance. While a universal definition of clinically relevant time benefit has not been established, we judged that a 3-minute advantage would allow sufficient opportunity for bystanders to retrieve and apply the AED [14, 15]. This judgment reflects the rapid deterioration in survival chances during the first few minutes after collapse in patients experiencing ventricular fibrillation [4].

The primary goal of the current study was to assess whether an AED-drone, activated alongside routine emergency medical services, could deliver an AED before ambulance arrival while providing a clinically meaningful time benefit in suspected out-of-hospital cardiac arrest cases.

Materials and Methods

Study period, design, and setting

This prospective observational investigation was scheduled to run for 11 months, spanning February 1 to December 31, 2021, across the greater Gothenburg

region in Sweden, located within the Västra Götaland area. Five drones were deployed, collectively covering 194.3 km² and serving a population of roughly 200,000 residents, where the annual incidence of out-of-hospital cardiac arrests was approximately 64 per 100,000 inhabitants [16]. The number of drones and the size of the coverage zones were determined by available funding, regulatory approvals, flight permissions, and the overall project timeline.

Västra Götaland utilizes a central emergency call centre (SOS Alarm) to handle national 1-1-2 calls. In addition, a regional medical dispatch centre operated by the local emergency medical services organization (Sjukvårdens Larmcentral) conducts clinical assessments. For suspected out-of-hospital cardiac arrests, two advanced life support ambulances are routinely sent to the location. The fire service and volunteer first responders equipped with mobile positioning are also activated. In the present study, response intervals for drone-delivered AEDs were directly compared with those of ambulances on a case-by-case basis.

The drone operator, Everdrone, designed and managed a fully integrated system comprising five drones housed in dedicated hangars within five distinct zones inside the controlled airspace of Säve Airport (covering Kungälv, Fiskebäck, and Torslanda) and Trollhättan-Vänersborg Airport (covering Trollhättan and Vänersborg). These zones are classified as semi-urban, with historical ambulance response times in 2021 averaging 11 minutes in the Säve Airport airspace and 10 minutes in the Trollhättan-Vänersborg Airport airspace. The Swedish Transport Agency approved the flights before the study began. The controlled airspaces operated on restricted schedules, typically from 0800–2200 h at Säve Airport and 0800–1600 h at Trollhättan-Vänersborg Airport.

The drones employed were adapted versions of the DJI Matrice 600 Pro hexacopter. Each unit featured a maximum operational range of 12 km for the outbound and return journey, a top speed of 60 km/h, and a maximum flight altitude of 65 m. Operations were initially confined to daylight hours within designated administrative boundaries, under clear weather conditions (no precipitation), and wind speeds below 8 m/s. Starting October 21, 2021, software enhancements and integrated lighting on both the drone and AED enabled night-time flights. All drones carried a Schiller FRED Easyport AED (weighing approximately 800 g) secured in a cushioned, lightweight container that incorporated an audible siren activated upon ground

contact. Additional safety features included an emergency parachute and camera-based systems supporting remote monitoring and automated obstacle avoidance.

Drones were intended for dispatch to successive suspected out-of-hospital cardiac arrest incidents arising within the designated zones during periods when the controlled airspace was accessible. All operations adhered strictly to regulations set by the Swedish Transport Agency and the European Aviation Safety Agency (EASA) [17] to minimize risks to ground and air traffic, and required explicit verbal clearance from air traffic control before each launch. Dispatch of AED-drones required satisfaction of two conditions: (1) a 1-1-2 emergency call originating from within one of the study zones (determined by GPS coordinates), and (2) classification of the call by the medical dispatch centre as suspected cardiac arrest or active CPR. When these conditions were met, an automated notification was transmitted to the drone pilot, also referred to as the safety supervisor. Safety supervisors completed roughly 10 days of specialized training with Everdrone and possessed A1/A2/A3 drone operator certification in accordance with EASA standards. Drones were activated for all suspected out-of-hospital cardiac arrests irrespective of anticipated ambulance arrival times. Following activation and air traffic control approval, the drone departed autonomously (under continuous oversight by the safety supervisor) toward the suspected arrest location. Upon reaching the site, the AED was lowered via winch from a height of 30 m to a ground position chosen manually by the pilot. Dispatchers then guided bystanders to the AED when suitable, with decisions made individually based on scene conditions. The AED provided spoken guidance upon activation, supplemented by real-time instructions from the dispatch center. While ambulances followed conventional manual dispatch protocols, drones were triggered automatically according to defined criteria, typically resulting in slightly earlier drone activation than ambulance activation.

Drone pilots received notifications for every suspected out-of-hospital cardiac arrest (including drowning incidents) reported via 1-1-2 calls within the predefined study zones during operational hours of the airports and air traffic control. Exclusions from dispatch applied to cases involving children younger than 8 years, trauma, and arrests witnessed by emergency medical services personnel. Additional exclusion criteria encompassed

denial of flight clearance by air traffic control, adverse meteorological conditions (such as rainfall or winds surpassing 8 m/s), restricted zones (including no-fly areas and buildings exceeding five stories), and periods of darkness (from April 21 to October 20, 2021).

This study focused on evaluating the operational logistics and practicality of an AED drone delivery system rather than individual patient outcomes. Consequently, data were aggregated at the group level, rendering individual patient consent unnecessary. The Swedish Ethical Review Committee approved the study on March 30, 2021 (reference 2020-06906). The study protocol was previously published.

Procedures

Dispatch and arrival time data for ambulances and drones were sourced from the central emergency response coordination body, SOS Alarm. The arrival time for an ambulance was recorded as the point at which the first crew on scene confirmed that their vehicle had reached the designated address. When possible, GPS-based timestamps were included to improve the accuracy of ambulance arrival records. In situations where the drone delivered an AED ahead of the ambulance, the associated 1-1-2 emergency audio recordings were examined more closely to better understand the exchange between the caller and dispatcher. These recordings were obtained from the regional medical dispatch service, Sjukvårdens Larmcentral.

Operational metrics from the drone system, such as prevailing weather, dispatch intervals, air traffic control interactions, flight parameters, travel speed and distance, AED lowering duration, and site-specific observations, were gathered directly by the drone service provider, Everdrone.

Ambulance patient care reports were retrieved from the local emergency medical services in the study districts. These documents supplied information regarding patient demographics (age and sex), incident site, presenting cardiac rhythm, defibrillation performed, use of an attached AED, and initiation of CPR before ambulance arrival. Further details on AED connection, defibrillation success, return of spontaneous circulation, and 30-day survival status were collected from the Swedish Registry for Cardiopulmonary Resuscitation.

Outcomes

The main study endpoints were the proportion of incidents in which an AED-drone successfully delivered

the device before the ambulance reached the scene and the median time interval (in minutes and seconds) between the drone's ground delivery of the AED and the ambulance's arrival at the suspected cardiac arrest location. These measures were assessed only among cases in which both the drone and ambulance were dispatched and arrived at the site. Pre-planned secondary exploratory endpoints included the rate at which drone-delivered AEDs were attached to patients before ambulance arrival and the fraction of cases defibrillated using the drone-supplied AED when it was deployed before ambulance arrival.

The two primary outcomes were evaluated jointly because many early drone deliveries would offer little practical benefit if the time savings were negligible. Although any positive time difference facilitating AED use before ambulance arrival holds value, this investigation defined a minimum 3-minute advantage as clinically meaningful.

Statistical analysis

Temporal intervals are summarised using medians with interquartile ranges, and differences are expressed as Hodges-Lehmann estimates of location shift with associated 95% confidence intervals obtained via paired Wilcoxon signed-rank tests [18]. Categorical variables are reported as absolute numbers and percentages, with group comparisons conducted using McNemar's test. All descriptive statistics were performed employing Microsoft Excel (version 16.62) and R software (version 4.1.3). The trial was prospectively registered at ClinicalTrials.gov (NCT04723368).

Role of the funding source

This research received financial support through grants awarded by the Swedish Heart Lung Foundation. The sponsor played no part in developing the study design, collecting data, analyzing results, interpreting findings, or drafting the report.

Results and Discussion

The investigation was initially intended to start in February 2021 and continue for a full 11 months. Regulatory requirements delayed the launch. To preserve the planned duration, the study end date was extended past December 31, 2021. Drone operations were temporarily halted between January 1 and March 2, 2022, due to the implementation of updated EASA regulations [17] for beyond-visual-line-of-sight flights, which replaced previous national legislation from January 1, 2022. The complete 11-month study period ultimately ran from April 21, 2021, to May 31, 2022.

In the course of the study, 211 suspected out-of-hospital cardiac arrest events were noted in the target regions. Before any drone departure, 139 of these were ruled out for the following reasons: dispatch centre cancellation (19%), adverse weather (26%), insufficient daylight (5%), air traffic control unavailability (22%), technical malfunctions (11%), and prohibited delivery locations (17%). From the 72 missions in which a drone was launched, 14 additional cases were later excluded owing to dispatch cancellation or technical complications (**Figure 1**). Successful AED delivery occurred in 58 (81%) of the 72 launched cases. For two cases involving drone AED delivery, the dispatch centre subsequently canceled the ambulance response because the individuals had already succumbed. In one instance, emergency medical services staff observed the arrest directly. These three cases were removed from the main evaluation, yielding 55 incidents with matched arrival data for both drone and ambulance that formed the basis for primary analyses. The three cases lacking paired timing information showed no consistent patterns distinct from the analyzed group, and their limited count added little value for statistical comparison. Outcome measures did not differ meaningfully between the phases before and after night operations became possible.

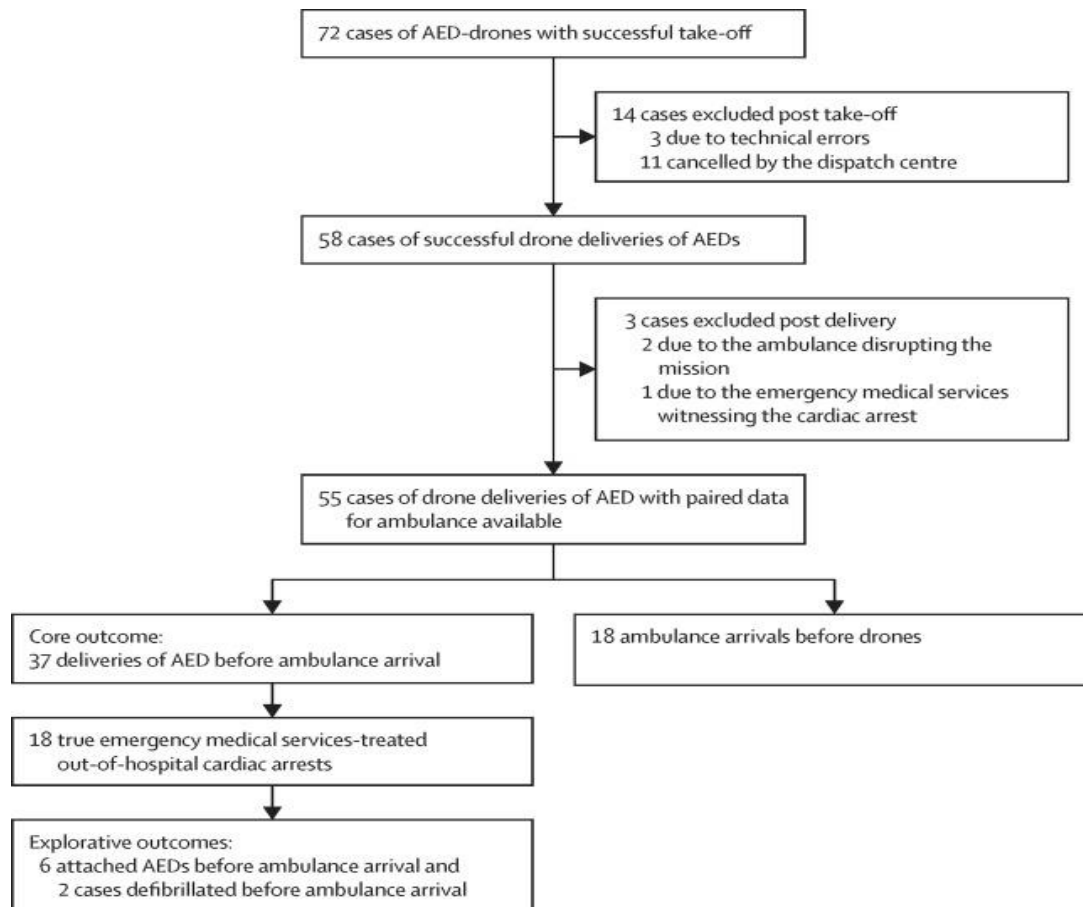


Figure 1. Flowchart of AED-drone flights to suspected out-of-hospital cardiac arrests. Abbreviation: AED = automated external defibrillator.

The drone delivered an AED ahead of ambulance arrival in 37 (67%) of the 55 cases ($P = 0.015$), corresponding to a median time saving of 3 min 14 s (IQR 1 min 42 s–5 min 42 s). In the top quartile of cases benefiting most from earlier drone arrival, the median time advantage reached 7 min 52 s (IQR 6 min 15 s–8 min 41 s). Bystanders successfully attached the drone-delivered

AED at the scene in six patients. Among these, two presented with a shockable rhythm and underwent defibrillation, with one patient surviving to 30 days. Compared with the arrival of fire service first responders, the median time benefit was 4 min 0 s (IQR 2 min 48 s–5 min 8 s). More comprehensive data on response intervals appear in **Table 1** and **Figure 2**.

Table 1. Outcomes of real-life AED deliveries using drones in suspected out-of-hospital cardiac arrests.

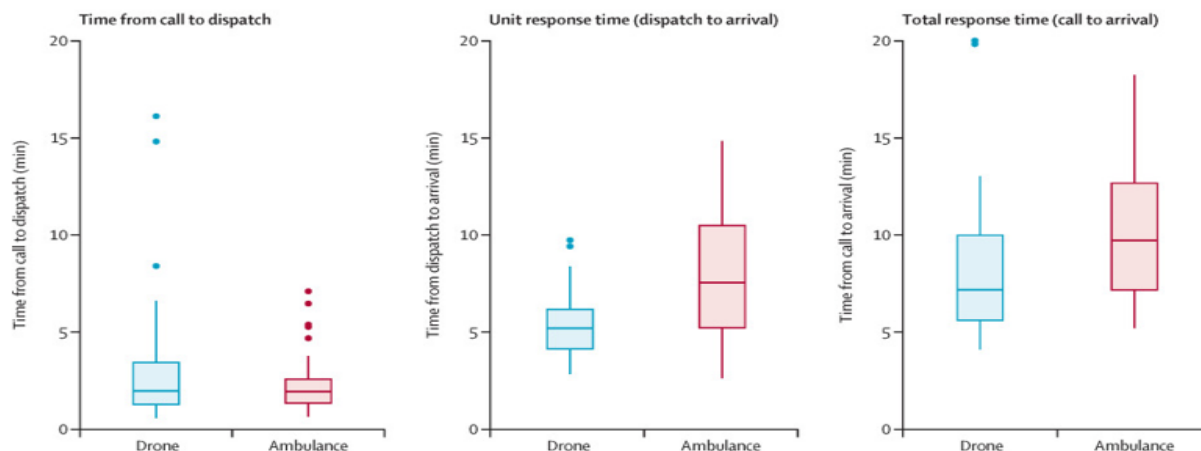
Parameter	Real-world AED drone deliveries (n = 55)	Ambulance response (n = 55)	p Value	Hodges–Lehmann estimated difference
Flight characteristics				
Median travel distance (air or road), km	1.8 (1.1 to 2.5)	4.6 (2.6 to 9.0)	..	..
AED placed within 10 m of the patient or building	35 (64%)	NA	..	..
AED placed within 15 m of the patient or building	50 (91%)	NA	..	..
AED placed within 30 m of the patient or building	55 (100%)	NA	..	..
Mean flight velocity, km/h	48 (43–57)	NA	..	..
Median percentage of flight path over populated regions	35% (27–45)	NA	..	..

Response time metrics				
Median interval from emergency (1-1-2) call* to suspected out-of-hospital cardiac arrest identification at the dispatch center, min:s	01:56 (01:15 to 03:24)	01:56 (01:15 to 03:24)	..	..
Median interval from emergency call to dispatch activation, min:s	01:59 (01:18 to 03:26)	01:57 (01:21 to 02:34)	..	-00:08 (95% CI -00:16 to 00:30)
Median interval between dispatch and drone take-off, min:s	01:20 (01:17 to 01:26)	NA	..	..
Median interval from take-off to AED arrival (response duration), min:s	03:17 (02:38 to 04:38)	NA	..	..
Overall interval from emergency call to AED arrival, min:s	07:11 (05:36 to 09:59)	09:43 (07:10 to 12:40)	..	-01:54 (95% CI -02:58 to -00:50)
Overall interval from dispatch to AED arrival, min:s	05:12 (04:09 to 06:10)	07:14 (05:17 to 10:26)	..	-02:29 (95% CI -03:37 to -01:26)
Primary outcomes				
AED delivered before ambulance arrival	37 (67%)	..	0.015†	..
Median time gained over ambulance when drone arrived first (n = 37), min:s	03:14 (01:42 to 05:42)	..	..	..
Median time gained over ambulance in the highest-benefit quartile (n = 9), min:s	07:52 (06:15 to 08:41)	..	..	..
Median time gained over ambulance in the lowest-benefit quartile (n = 9), min:s	01:06 (00:40 to 01:21)	..	..	..
Exploratory outcomes				
Drone-delivered AED attached before ambulance arrival	6 (11%)	..	<0.0001*	..
Drone-delivered AED attached before ambulance arrival among confirmed cardiac arrests managed by emergency medical services	6/18 (33%)	..	<0.0001*	..
Patients defibrillated using a drone-delivered AED before ambulance arrival	2/18 (11%)	..	<0.0001*	..
AED deliveries performed during darkness	2 (4%)	..	..	..

Data are median (IQR), n (%), or n/N (%), unless otherwise indicated. Differences in time delays are presented as Hodges–Lehmann location shift with 95% CIs extracted from paired Wilcoxon tests. Abbreviations: AED = automated external defibrillator, NA = not applicable.

*Calculated in comparison with the null hypothesis that no drone-delivered AEDs were attached or used (0%).

†Calculated in comparison with cases in which the ambulance arrived first, 18 (33%) of 55



(a)

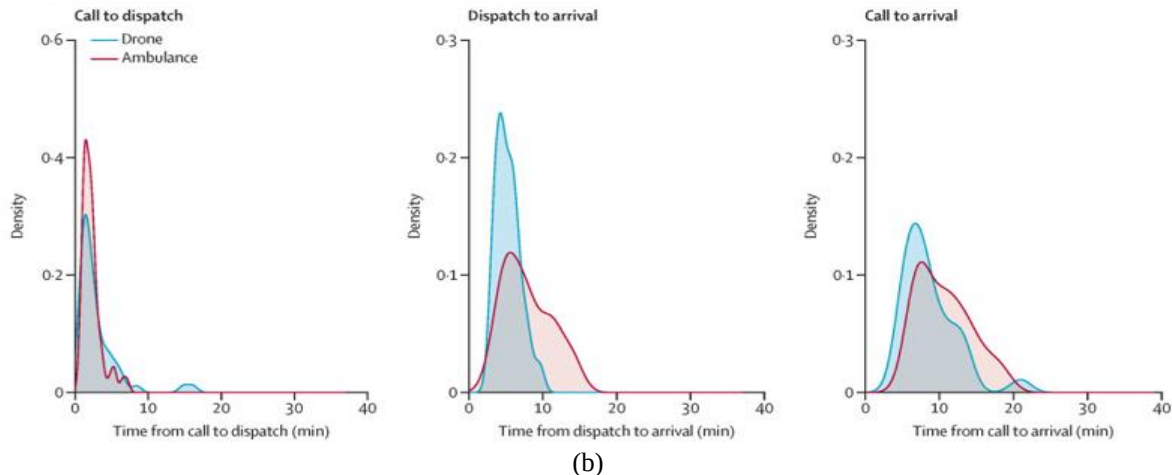


Figure 2. Response times for AED-drones and ambulances. (a) Boxplots of response times for AED-drones and ambulances. From the left: call to dispatch, dispatch to arrival, and call to arrival; (b) Density plots of response times for AED-drones and ambulances. From the left: call to dispatch, dispatch to arrival, and call to arrival. Abbreviation: AED = automated external defibrillator.

Among all 211 suspected alerts examined, 68 cases (32%) were verified as genuine cardiac arrests that received emergency medical treatment but were not witnessed by those services. The other incidents consisted of patients found dead on arrival by ambulance teams (63 [30%]) or individuals experiencing spontaneous circulation with diagnoses unrelated to cardiac arrest (63 [30%]). Emergency medical services witnessed two arrests. Data were incomplete or unavailable in 15 cases (13 due to unreported information from ambulance crews caused by technical problems or oversight, and two where no patient was located at the reported address). Swedish emergency medical services do not routinely document race or ethnicity, so these variables were unavailable.

Of the 58 suspected cases receiving drone AED delivery, 24 (41%) proved to be true non-witnessed cardiac arrests

managed by emergency services, and one additional case was witnessed by such personnel. The median age in this group was 77 years (IQR 69–82), with 11 (46%) of 24 being female and 13 (54%) male. The large majority occurred in homes (20 [83%]), 14 (58%) were bystander-witnessed, and layperson CPR was initiated before ambulance arrival in 20 (83%) patients. In the 37 cases with earlier drone AED delivery, 18 (49%) were confirmed true out-of-hospital cardiac arrests receiving emergency medical treatment. Within this subgroup, six patients (33%) had the drone-delivered AED attached by bystanders before emergency medical services arrived. Multiple bystanders were present at the scene in every instance. Two of the six attached cases (33%) showed a shockable presenting rhythm. Both were defibrillated, and one patient survived to 30 days (**Table 2**) [19].

Table 2. Patient characteristics of ambulance-treated out-of-hospital cardiac arrest cases, by drone delivery of AED

Characteristic	All ambulance-treated out-of-hospital cardiac arrests (n = 68)	Ambulance-treated cases without drone AED delivery (n = 44)	Ambulance-treated cases with drone AED delivery (n = 24)	Ambulance-treated cases where drone arrived first (n = 18)
Median age, years	74 (64–82)	71 (60–81)	77 (69–82)	77 (69–82)
Female patients	19 (28%)	8 (18%)	11 (46%)	7 (39%)
Male patients	49 (72%)	36 (82%)	13 (54%)	11 (61%)
Cardiac arrest at residential location	59 (87%)	39 (89%)	20 (83%)	15 (83%)
Witnessed cardiac arrest	37 (54%)	23 (52%)	14 (58%)	9 (50%)
CPR initiated before ambulance arrival	50 (74%)	30 (68%)	20 (83%)	15 (83%)

AED Applied Before Ambulance Arrival*				
Existing on-site AED	4/58 (7%)	4/43 (9%)	0/15	0/11
AED from first responders or lay responders	5/58 (9%)	4/43 (9%)	1/15 (7%)	1/11 (9%)
Drone-delivered AED	2/58 (3%)†	0/43	2/15 (13%)†	2/11 (18%)†
Initial shockable rhythm	9 (13%)	5 (11%)	4 (17%)	2 (11%)
Defibrillation Before Ambulance Arrival*				
Existing on-site AED	1/58 (2%)	1/43 (2%)	0/15	0/11
AED from first responders or lay responders	3/58 (5%)	3/43 (7%)	0/15	0/11
Drone-delivered AED	1/58 (2%)‡	0/43	1/15 (7%)‡	1/11 (9%)‡
Return of spontaneous circulation upon hospital arrival	20/58 (34%)	14/43 (33%)	6/15 (40%)	4/11 (36%)
Survival beyond 30 days	6/58 (10%)	4/43 (9%)	2/15 (13%)	1/11 (9%)

Data are median (IQR), n (%), or n/N (%). Information was drawn from ambulance patient records and the Swedish Registry for Cardiopulmonary Resuscitation. The term ambulance-treated out-of-hospital cardiac arrest denotes verified cardiac arrest episodes in which ambulance staff performed CPR. AED=automated external defibrillator. CPR=cardiopulmonary resuscitation.

*Information obtained from the Swedish Registry for Cardiopulmonary Resuscitation. Fifteen percent of out-of-hospital cardiac arrests noted in ambulance documentation do not appear in the registry.

†Data on drone-delivered AED attachment are unavailable for four cases.

‡Information regarding defibrillation using a drone-delivered AED is missing for one case.

In the group of incidents where the drone did not succeed in delivering an AED ($n = 153$), 44 (29%) were confirmed as actual out-of-hospital cardiac arrests handled by emergency medical services without bystander or EMS witnessing. Patients in this subgroup had a median age of 71 years (IQR 60–81), including eight (18%) females and 36 (82%) males. The overwhelming majority of these events (39 [89%]) occurred in domestic settings, and bystanders witnessed 23 (52%). An AED was connected in eight (18%) patients, while defibrillation occurred in four (9%) before ambulance arrival. Fourteen (32%) patients regained spontaneous circulation, and four (10%) were alive at 30 days (**Table 2**).

Drones traveled a median flight distance of 1.8 km (IQR: 1.1–2.5), compared with the median ground distance of 4.6 km (IQR: 2.6–9.0) covered by ambulances. The median cruising speed of the drones was 48 km/h (IQR: 43–57). Delivery accuracy was high: the AED landed within 30 m of the suspected arrest location in 100% of missions, within 15 m in 91%, and within 10 m in 64% (**Table 1**).

Throughout the investigation, the study recorded zero adverse events. Every AED operated reliably with no technical failures. After each flight, devices underwent comprehensive checks, including the manufacturer's automatic self-diagnostic routine, battery capacity

verification, and direct inspection of the transport container, enclosure, and screen interface. No AEDs sustained damage at any stage of the missions, and none were positioned at incorrect sites.

This prospective investigation conducted under real-world conditions demonstrates, for the first time to our knowledge, that drones are capable of delivering AEDs to the scene of suspected out-of-hospital cardiac arrests before ambulance arrival in the majority of missions where take-off occurs. The deliveries provided a clinically meaningful time advantage (median 3 min 14 s), enabling bystander attachment of the AED before ambulance arrival in six patients.

AED-equipped drones may serve as a valuable supplement to conventional ambulance services, particularly given evidence from multiple recent reports indicating lengthening ambulance response intervals [4]. The present findings show that the interval from dispatch to scene arrival is shorter and more consistent for drones than for ambulances, whose response times tend to be longer and more variable.

Several key considerations arise when evaluating strategies for providing AEDs before ambulance arrival. While fixed-location AEDs have proven life-saving and support timely defibrillation, they rarely cover the private residences where most out-of-hospital cardiac arrests take place [6, 20, 21]. Despite annual growth in the

number of publicly accessible AEDs, their utilization rate in out-of-hospital cardiac arrest events remains low, ranging from 1.7% to 11.9% [2, 6]. A single operational AED-drone can potentially serve a substantially larger population within a comparable response window than multiple stationary devices. Although some analyses have explored the cost-effectiveness of AED-drones [22], such evaluations are context-dependent across countries, and the real-world economic viability of widespread implementation remains undetermined. Publicly placed AEDs often require ongoing upkeep [23], and one recent study in Denmark found that nearly 20% of public AEDs in the surveyed region were non-functional [24].

In contrast, AED-drone operational status can be monitored more easily. Several modeling studies have concluded that a small fleet of AED-drones could meet defibrillator needs for a large segment of the population [8, 10, 12]. Nevertheless, this approach should be viewed not as a replacement but as an adjunct to existing terrestrial AED networks, with particular relevance for residential settings, especially given that home-based defibrillation initiatives have so far failed to demonstrate survival benefits [25].

In the current study, drones positioned the AED within 15 m of the suspected cardiac arrest location in 91% of deliveries and within 30 m in every case. Earlier research recommends that an AED should be reachable within a 1.5-minute brisk walk, typically interpreted as a 100 m radius around the arrest site [15, 21]. In the United Kingdom, only 5.9% of out-of-hospital cardiac arrest victims have an AED available within 100 m, a figure that drops to 1.6% during night-time hours [21]. Comparable data from Hong Kong indicate availability within 100 m for 11.2% of cases [26]. In comparison, Swedish figures show public AED access within 100 m in just 6.6% of suspected arrests and in only 1.6% when multiple bystanders are present [20]. Thus, drone delivery achieves 100% availability within 30 m, markedly outperforming the inconsistent proximity of public AEDs. This proximity is critical, as shorter distances to the AED can reduce retrieval time, minimize interruptions in chest compressions, and accelerate attachment, all of which may improve survival prospects [3, 27, 28]. Although this study did not directly quantify bystander retrieval time, we consider it realistic to expect retrieval of a drone-delivered AED within approximately 30 seconds in most situations. The observed median time benefit of 3 min 14 s creates a window during which

bystanders can attach the device before ambulance arrival, as occurred in six cases. This is noteworthy because survival probability declines by approximately 7–10% per minute without intervention [3]. Even so, the overall interval from emergency call to AED delivery (median 7 min 11 s) still exceeds the optimal 3–5 minute target, underscoring the need for continued system refinements to shorten the time from collapse to defibrillator application.

The potential life-saving impact of AED-drones differs by setting. Such systems are likely to yield the greatest advantage in semi-urban environments, where cardiac arrest incidence is relatively high, ambulance response times are moderately prolonged, and public AED availability is limited [8, 9, 13]. Rural areas might offer even larger time savings, though lower event rates would result in fewer opportunities for deployment. Urban settings typically feature higher incidence but shorter ambulance response intervals and greater proximity to existing AEDs [8, 29, 30]. The semi-urban zones examined in this study had comparatively brief ambulance response times, yet drones still arrived ahead of ambulances in most instances. Additional research is required to identify optimal drone placement strategies that maximize both clinical effectiveness and cost-efficiency.

AED attachment occurred in relatively few instances compared with cases in which the device was delivered before ambulance arrival (six [16%] of 37). The primary explanation is that only 18 of the cases with earlier drone arrival represented true out-of-hospital cardiac arrests managed by emergency medical services. Consequently, the attachment rate among confirmed treated cardiac arrests reached 33% (six of 18). This left 12 cases (67%) in which a drone-delivered AED could potentially have been used but was not attached. An exploratory review of the 1-1-2 emergency calls for these confirmed cardiac arrests revealed that dispatchers rarely directed bystanders to the AED. Reasons included concerns about causing interruptions in chest compressions when only one bystander was present and the emotional distress of callers. This challenge is not specific to the current investigation. In research by Fredman and colleagues [20], dispatchers mentioned AEDs in merely 4.3% of suitable cases despite the presence of an AED within 100 m and multiple individuals at the scene. In many non-referral cases, dispatchers documented no explicit justification [20]. An accompanying editorial emphasized the necessity for well-defined protocols to

identify available AEDs and determine appropriate moments for dispatcher guidance to bystanders [31]. Additional research is also required on referral strategies for single-bystander scenarios to establish when prioritizing AED retrieval over immediate CPR initiation may be warranted [31]. Previous investigations into public perceptions of drone-delivered AEDs have indicated generally favorable views toward this technology [32], although further evaluation in actual clinical events is warranted.

A substantial proportion of suspected out-of-hospital cardiac arrest alerts were excluded before drone activation, largely for reasons that may become less restrictive with future technological and regulatory progress, such as rainfall, high winds, and restricted airport operating hours under air traffic control. First, the development of autonomous traffic management systems that prioritize emergency medical drones could allow operations beyond current air traffic control schedules and outside controlled airspace. Second, ongoing improvements in drone engineering are expected to incorporate enhanced safety redundancies (including transponders) and support more robust performance in adverse weather, including rain and stronger winds. Moreover, many regions worldwide already employ mobile-phone-based alerting of volunteer first responders for suspected cardiac arrests [33, 34]. Integrating these volunteer responders, who are directed straight to the scene, with AED-equipped drones could offer synergistic benefits by eliminating retrieval delays. First responders could proceed immediately to the arrest location and locate a drone-delivered AED already in place. The present study used automated dispatch of AED-drones triggered by emergency call indexing, enabling faster activation than ambulances and first responders. However, this approach also produced considerable over-triage, as only 68 (32%) of 211 alerts involved genuine cardiac arrests, resulting in several aborted missions. Future research should refine dispatch algorithms for AED-drones. In addition, the experiences of bystanders, emergency medical services crews, and dispatch staff merit further exploration. Finally, applying drones to deliver other critical medical supplies in time-sensitive emergencies rapidly holds considerable promise and deserves dedicated investigation.

This study was conducted in western Sweden, where local conditions such as climate and regulatory frameworks may differ from those in other countries or regions. To improve generalisability, we benchmarked

drone arrival times against ambulance response intervals rather than first-responder response times. Nonetheless, variations in emergency medical services organization across jurisdictions could influence the magnitude of time savings achieved by AED-drones. The current analysis did not evaluate cost-effectiveness, which must be thoroughly assessed before broader adoption. The drones employed had certain technical constraints and could not operate under all environmental conditions (for instance, rainfall, winds exceeding 8 m/s, or near high-rise structures). The impact of these restrictions on the overall findings remains uncertain. Many cases were also excluded because the dispatch centre ultimately determined that no cardiac arrest had occurred.

Conclusion

In summary, AED-equipped drones dispatched by emergency call centers for suspected out-of-hospital cardiac arrests successfully delivered the devices before ambulance arrival in two-thirds of applicable cases, with a clinically significant median time advantage exceeding 3 minutes. This strategy shows promise for reducing the interval to AED attachment before ambulance arrival.

Acknowledgments: None

Conflict of Interest: None

Financial Support: None

Ethics Statement: None

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