Drone delivery of automated external defibrillators compared with ambulance arrival in real-life suspected out-of-hospital cardiac arrests: a prospective observational study in Sweden

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Summary

Background A novel approach to improve bystander defibrillation for out-of-hospital cardiac arrests is to dispatch and deliver an automated external defibrillator (AED) directly to the suspected cardiac arrest location by drone. The aim of this study was to investigate how often a drone could deliver an AED before ambulance arrival and to measure the median time benefit achieved by drone deliveries.

Methods In this prospective observational study, five AED-equipped drones were placed within two separate controlled airspaces in Sweden, covering approximately 200 000 inhabitants. Drones were dispatched in addition to standard emergency medical services for suspected out-of-hospital cardiac arrests and flight was autonomous. Alerts concerning children younger than 8 years, trauma, and emergency medical services-witnessed cases were not included. Exclusion criteria were air traffic control non-approval of flight, unfavourable weather conditions, no-delivery zones, and darkness. Data were collected from the dispatch centres, ambulance organisations, Swedish Registry for Cardiopulmonary Resuscitation, and the drone operator. Core outcomes were the percentage of cases for which an AED was delivered by a drone before ambulance arrival, and the median time difference (minutes and seconds) between AED delivery by drone and ambulance arrival. Explorative outcomes were percentage of attached drone-delivered AEDs before ambulance arrival and the percentage of cases defibrillated by a drone-delivered AED when it was used before ambulance arrival.

Findings During the study period (from April 21, 2021 to May 31, 2022), 211 suspected out-of-hospital cardiac arrest alerts occurred, and in 72 (34%) of those a drone was deployed. Among those, an AED was successfully delivered in 58 (81%) cases, and the major reason for non-delivery was cancellation by dispatch centre because the case was not an out-of-hospital cardiac arrest. In cases for which arrival times for both drone and ambulance were available (n=55), AED delivery by drone occurred before ambulance arrival in 37 cases (67%), with a median time benefit of 3 min and 14 s. Among these cases, 18 (49%) were true out-of-hospital cardiac arrests and a drone-delivered AED was attached in six cases (33%). Two (33%) had a shockable first rhythm and were defibrillated by a drone-delivered AED before ambulance arrival, with one person achieving 30-day survival. No adverse events occurred. AED delivery (not landing) was made within 15 m from the patient or building in 91% of the cases.

Interpretation AED-equipped drones dispatched in cases of suspected out-of-hospital cardiac arrests delivered AEDs before ambulance arrival in two thirds of cases, with a clinically relevant median time benefit of more than 3 min. This intervention could potentially decrease time to attachment of an AED, before ambulance arrival.

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See **Comment** page e849

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Introduction

Out-of-hospital cardiac arrest is a common and life-threatening occurrence, with a mortality rate of approximately 90%.[1] Treatment by means of cardiopulmonary resuscitation (CPR) and early defibrillation with an automated external defibrillator (AED) is essential for increasing chances of survival.[1,2] If these treatments are given by a bystander within the first 3–5 min and before the arrival of emergency medical services, survival could be as high as 50–70%.[3] However, ambulance response times and times to defibrillation have both increased over the past decade in Sweden.[4] Furthermore, the majority of out-of-hospital cardiac arrests occur in private homes (approximately 70%), where distances to the nearest AED are often long and the rate of bystanders using defibrillators is extremely low.[1,5,6] Accordingly, there is an urgent need for novel initiatives to shorten the time to defibrillation as well as to reach

Research in context

Evidence before this study

Survival in cases of out-of-hospital cardiac arrest is low globally; only 10% of people survive despite efforts made to increase bystander cardiopulmonary resuscitation and availability of automated external defibrillators (AEDs). During the past decade, the idea of drones delivering AEDs has arisen and several studies on this subject have been done. We searched the PubMed database from database inception using the terms "drones", "AED", and "OHCA". The search was made on Jan 27, 2023, and included articles published in English. We found 29 articles. Many of the studies have been focused on using computer models to investigate the theoretical time benefit of AED delivery achieved using AED-equipped drones (AED-drones) compared with emergency medical services. Other studies have been aimed at testing the feasibility of using drones to deliver AEDs by carrying out such deliveries to simulated out-of-hospital cardiac arrest locations. All studies have suggested that AED delivery by drones is feasible, with the theoretical potential to decrease the time to AED use compared with emergency medical services. Only one study highlighted concerns for the real-life feasibility of flying AED-drones to cases of suspected out-of-hospital cardiac arrest in parallel with emergency medical services. This proof-of-concept study showed that the use of AED-drones is feasible in real-life situations. However, whether or not drones can consistently deliver AEDs before ambulance arrival remains unknown.

Added value of this study

To our knowledge, this study is the first one focused on drone-AED delivery times compared with ambulance-response times. We found that in cases in which a drone delivered an AED, the delivery occurred before ambulance arrival in two-thirds of cases, with a median time benefit of 3 min and 14 s. This time benefit made it possible for bystanders to attach the drone-delivered AED to the patients before ambulance arrival in six cases. This study provides evidence to help answer the question if drones have the potential to deliver AEDs before ambulance arrival.

Implications of all the available evidence

The results of this study, combined with all evidence from theoretical and simulated studies in other parts of the world, suggest that the use of AED-drones is a promising novel method of AED delivery that has the potential to increase the use of AEDs before the arrival of emergency medical services. Little is still known about the optimal routines at dispatch centres, and efforts should be focused on increasing the attachment rate of drone-delivered AEDs.

out-of-hospital cardiac arrests occurring in private homes.[7]

A novel and very promising strategy is to deliver AEDs by drone in cases of suspected out-of-hospital cardiac arrests. Several theoretical and mathematical optimisation studies of AED delivery by drones have shown a potential to shorten the time to AED delivery compared with standard ambulance responses.[8–12] Additionally, we have previously documented that dispatch of AED-equipped drones (AED-drones) to cases of out-of-hospital cardiac arrests is both feasible and safe, with successful AED delivery within 10 m of the out-of-hospital cardiac arrest location.[13] However, for drones to contribute to earlier defibrillation and improved survival, AEDs should be delivered not only before ambulance arrival, but also with a clinically relevant time benefit. There is no standard definition for such a time benefit, and we estimated that a benefit of 3 min would be sufficient to enable bystanders to retrieve and use an AED.[14,15] This estimation was made because the chance of survival decreases rapidly the first few minutes after a cardiac arrest in ventricular fibrillation patients.[4]

The aim of this study was to investigate if an AED-drone, dispatched in addition to standard emergency medical services procedures, can deliver an AED before ambulance arrival, with a clinically relevant time benefit in real-life cases of suspected out-of-hospital cardiac arrests.

Methods

Study period, design, and setting

We planned to conduct this prospective observational study over 11 months, from Feb 1 to Dec 31, 2021, in the greater Gothenburg area of Sweden, which lies in the Västra Götaland region. Five drones were used, and together they covered an area of 194·3 km² with approximately 200 000 inhabitants, and an incidence rate of out-of-hospital cardiac arrests of about 64 per 100 000 inhabitants per year.[16] The number of drones and drone areas were chosen on the basis of funding, flight permits, regulatory aspects, and time frame.

Västra Götaland has a primary service answering point for emergency 1-1-2 calls: the national dispatch organisation SOS Alarm. Additionally, there is a regional emergency medical dispatch centre run by the local emergency medical services organisation for medical assessment, Sjukvårdens Larmcentral. In cases of suspected out-of-hospital cardiac arrests, two ambulances are dispatched to the scene, each equipped with advanced life support capability. Additionally, both the fire department and volunteer mobile-positioned first responders are dispatched. In this study, delay times of drone-delivered AEDs were compared with delay times of ambulances in each case.

The drone operator Everdrone developed the fully integrated drone system and operated five drones placed in hangars (from which they were dispatched) in five different study areas within the controlled airspaces of

Säve Airport (Kungälv, Fiskebäck, and Torslanda) and Trollhättan-Vänersborg Airport (Trollhättan and Vänersborg). The study areas are considered semi-urban areas and historical ambulance response times from 2021 were 11 min for areas in the controlled airspace of Säve airport and 10 min for areas in Trollhättan-Vänersborg Airport. Flight permission was received from The Swedish Transport Agency before the study was initiated. The controlled airspaces had limited hours of activity, usually 0800–2200 h for Säve airport and 0800–1600 h for Trollhättan-Vänersborg Airport (appendix p 2).

The drones used in this study were modified DJI Matrice 600 Pro hexacopter drones (appendix p 9). They have a predefined maximum range of 12 km outbound and return, a maximum velocity of 60 km/h and an operating altitude of up to 65 m during flight. Flights were restricted to operations within the administrative areas in daylight (initially), in clear skies (non-rain) and in winds less than 8 m/s since the drones could not fly in those conditions. From Oct 21, 2021, a software update and additional lighting integrated to both the drone and the AED made flights in darkness possible. All drones were equipped with a Schiller FRED Easyport AED (weight approximately 800 g) and placed in a padded lightweight basket, which also included a siren that was activated when the AED touched the ground (appendix p 9). Additionally, the drone had an emergency parachute and camera systems for remote surveillance and automatic collision avoidance.

Drones were planned to be dispatched to consecutive suspected out-of-hospital cardiac arrest cases that occurred in the study areas during the study period at times when the controlled airspace was open. All missions were executed in compliance with The Swedish Transport Agency and European Aviation Safety Agency (EASA) regulations[17] to mitigate ground and air risks and with verbal approval from air traffic control before each flight. For AED-drones to be dispatched, two criteria were to be met: (1) an emergency 1-1-2 call occurring within one of the study areas (based on GPS coordinates), and (2) the call had to be indexed by the emergency medical dispatch centre as either suspected cardiac arrest or ongoing CPR. If those criteria were met, an automatic alert was sent to the drone pilot. The drone pilot is also called the safety supervisor and is described further in the appendix (p 3). The safety supervisors had undergone approximately 10 days of company-specific training at Everdrone and hold an A1/A2/A3 drone licence according to EASA regulations. Drones were dispatched to suspected out-of-hospital cardiac arrests regardless of expected ambulance response time. When alerted, the drone could take off (after verbal approval from air traffic control) and fly autonomously (with surveillance by the drone pilot) to the location of the suspected cardiac arrest. On arrival, the AED was winched down by the drone pilot from an altitude of 30 m to a manually selected spot on the ground (appendix pp 2–3). When delivered, dispatchers referred bystanders to the AED if appropriate (the decision was made by the dispatcher on a case-by-case approach depending on the conditions at the scene). The AED gives verbal instructions to bystanders when turned on, accompanied by instructions from the dispatcher at the dispatch centre. Ambulances were dispatched manually, following a standard procedure, and drones were automatically dispatched based on the aforementioned criteria, resulting in drones being usually dispatched a few seconds earlier than were the ambulances.

See Online for appendix

Drone pilots were alerted in all suspected out-of-hospital cardiac arrests during 1-1-2 calls (including drowning) within the prespecified study areas during airport and air traffic control hours of operation. Alerts concerning children younger than 8 years, trauma, and emergency medical services-witnessed cases were not included. Exclusion criteria were air traffic control non-approval of flight, unfavourable weather conditions (rain and winds exceeding a median of 8 m/s), no-delivery zones such as no-fly zones and high-rise buildings (>5 storeys), and darkness (between April 21 and Oct 20, 2021).

This study aimed to describe the logistics and feasibility of a system of AED-delivery by drones and was not focused on individual patients. Data were reported at the group level and therefore no patient consent was required. This study was approved by the Swedish Ethical Review Committee (March 30, 2021, reference 2020–06906). The study protocol has previously been published.

For the **study protocol** see https://clinicaltrials.gov/ct2/show/NCT04723368?term=drone&cond=ohca&draw=2&rank=1

Procedures

Delay times for dispatch and delivery regarding both ambulances and drones were collected from the primary service answering point organisation, SOS Alarm. Ambulance arrival time was defined as when the crew of the first ambulance on scene reported arrival with the vehicle at the target location. When available, arrival time based on GPS location for ambulances was added to increase precision. The 1-1-2 calls in cases for which the drone had delivered an AED before ambulance arrival were listened to in order to obtain better understanding of the interaction between caller and dispatcher during the emergency call. Audio files were retrieved from the emergency medical dispatch centre Sjukvårdens Larmcentral.

Flight data on drone system performance (weather conditions, dispatch delay times, contact with air traffic control, flight information, drone velocity, travel distance, AED-drop time, and characteristics on site) were collected from the drone operator Everdrone.

Ambulance charts were collected from the ambulance services in each area. From these, information on age, sex, location, first rhythm, defibrillation, attached AED,

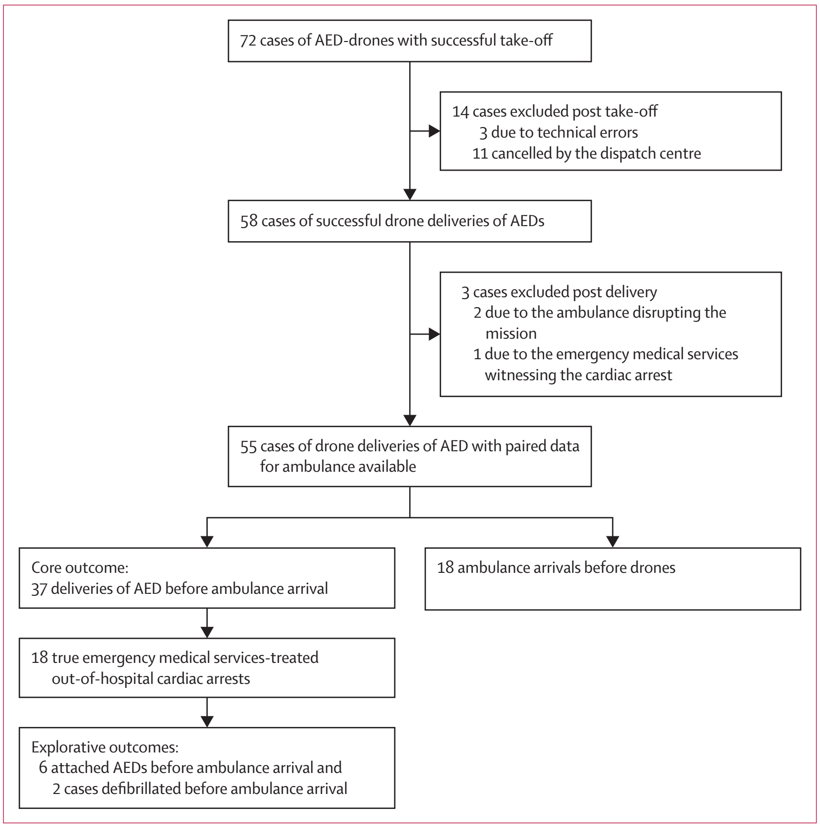

Figure 1: **Flowchart of AED-drone flights to suspected out-of-hospital cardiac arrests**
AED=automated external defibrillator.

and CPR before ambulance arrival was gathered. Data on AED attachment, defibrillation, return of spontaneous circulation, and 30-day survival were obtained from the Swedish Registry for Cardiopulmonary Resuscitation.

Outcomes

Core outcomes were the percentage of cases in which an AED was delivered by an AED-drone before ambulance arrival and the median time difference (minutes and seconds) between AED delivery on the ground by the drone and ambulance vehicle arrival at the location of the suspected out-of-hospital cardiac arrest. Outcome data were calculated in cases for which both a drone and an ambulance were dispatched and arrived on site. Explorative prespecified outcomes were the percentage of attached drone-delivered AEDs before ambulance arrival and the percentage of cases defibrillated by a drone-delivered AED when it was used before ambulance arrival.

A combination of the two core outcomes was used, since a high proportion of AED deliveries by drone before ambulance arrival is probably of less value if the time benefit is small. Although any time benefit that makes AED attachment and usage before ambulance arrival is beneficial, in this study, a time benefit of at least 3 min was considered to be of clinical relevance.

Statistical analysis

Time delays are presented as medians with IQRs, and differences are presented as Hodges-Lehmann location shift with 95% CIs extracted from paired Wilcoxon tests.[18] Categorial variables are presented as counts and proportions, and differences were analysed using McNemar's test. Descriptive analysis was carried out using Microsoft Excel (version 16.62) and R (version 4.1.3). The study is registered at ClinicalTrials.gov (NCT04723368).

Role of the funding source

Grants were received from the Swedish Heart Lung Foundation. The funder had no role in the study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Initially, we planned to begin an 11-month study in February, 2021. However, the start was delayed for regulatory reasons. To reach the goal of an 11-month study period, the end date of the study (Dec 31, 2021) was postponed. Owing to a shift from national legislation approved by The Swedish Transportation Board to EASA regulations[17] valid from Jan 1, 2022, for beyond-visual-line-of-sight flights, there was a pause in operations between Jan 1 and March 2, 2022, when no flights were executed. The 11-month study was eventually conducted between April 4, 2021 and May 31, 2022.

During the study period, 211 suspected out-of-hospital cardiac arrests were documented within the study areas, of which 139 cases were excluded before take-off because of cancellation from the dispatch centre (19%), bad weather conditions (26%), darkness (5%), air traffic control closure (22%), technical issues (11%), and no delivery zones (17%; appendix p 7). Of the remaining 72 cases, where a drone was deployed, an additional 14 were excluded due to cancellation from the dispatch centre, and technical reasons (figure 1; appendix p 7). An AED was delivered in 58 (81%) of the 72 cases. In two of the cases for which a drone had delivered an AED, the dispatch centre cancelled the ambulance missions because the patients had died, and in one case the cardiac arrest was witnessed by the emergency medical services. These three cases were thus excluded from further analysis, resulting in a total of 55 cases for which arrival times for both drone and ambulance were available included in the final analyses. The three cases without paired data showed no systematic differences compared with the paired data and this low number makes statistical analysis less valuable. We did not detect any differences in the outcomes between the period before and after flights in darkness were possible.

In a total of 37 (67%) of 55 cases, a drone delivered an AED before ambulance arrival (p=0·015), with a median time benefit of 3 min 14 s (IQR 1 min 42 s–5 min 42 s). Within the most beneficial quartile of cases in which the drone arrived first on scene, the median time benefit was

	AED-drone real-life deliveries (n=55)	Ambulance (n=55)	p value	Difference in Hodges–Lehmann estimate
Flights				
Median distance to location (flown or driven), km	1·8 (1·1 to 2·5)	4·6 (2·6 to 9·0)	..	..
AED delivery within 10 m of building or patient	35 (64%)	NA	..	..
AED delivery within 15 m of building or patient	50 (91%)	NA	..	..
AED delivery within 30 m of building or patient	55 (100%)	NA	..	..
Average in-flight speed, km/h	48 (43–57)	NA	..	..
Median proportion of flight distance above populated areas	35% (27–45)	NA	..	..
Time delays				
Median time from 1-1-2-call* to indexing of suspected out-of-hospital cardiac arrest at emergency medical dispatch centre, min:s	01:56 (01:15 to 03:24)	01:56 (01:15 to 03:24)	..	..
Median time from 1-1-2-call to dispatch, 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 time from dispatch to take-off, min:s	01:20 (01:17 to 01:26)	NA	..	..
Median time from take-off to AED-delivery, min:s (response time)	03:17 (02:38 to 04:38)	NA	..	..
Total time from 1-1-2-call to AED delivery, 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)
Total time from dispatch to AED delivery, 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)
Core outcomes				
Delivery of AEDs before ambulance arrival	37 (67%)	..	0·015†	..
Median time benefit compared with ambulance when drone arrived first (n=37), min:s	03:14 (01:42 to 05:42)	..	..	..
Median time benefit compared with ambulance when drone first within the most beneficial quartile (n=9), min:s	07:52 (06:15 to 08:41)	..	..	..
Median time benefit compared with ambulance when drone first within the least beneficial quartile (n=9), min:s	01:06 (00:40 to 01:21)	..	..	..
Explorative endpoints				
Drone-delivered AED attached before ambulance arrival	6 (11%)	..	<0·0001*	..
Drone-delivered AEDs attached before ambulance arrival among real cardiac arrests treated by emergency medical services	6/18 (33%)	..	<0·0001*	..
Defibrillated by drone-delivered AED before ambulance arrival	2/18 (11%)	..	<0·0001*	..
AED deliveries in 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. 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 ambulance arrived first, 18 (33%) of 55.

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

7 min 52 s (IQR 6 min 15 s–8 min 41 s). In six patients, a drone-delivered AED was attached by a bystander on site and, among them, two patients had shockable rhythm and were defibrillated; one of these patients survived beyond 30 days. Time benefit compared with fire first responders was a median of 4 min 0 s (IQR 2 min 48 s–5 min 8 s). Further details and information on time delays are presented in table 1 and figure 2.

Of the 211 alerts of suspected out-of-hospital cardiac arrests included in the study, a total of 68 cases (32%) were identified as true emergency services-treated but non-emergency services-witnessed cardiac arrests (appendix p 8). The remaining cases were patients assessed by the ambulance crew as either dead on arrival (63 [30%]), or patients with spontaneous circulation and with conditions other than out-of-hospital cardiac arrest (63 [30%]). In two cases the cardiac arrest was witnessed by the emergency medical services. In the remaining 15 cases, data were missing or incomplete (13 because the ambulance crew did not report data in those cases, due to technical issues or human error), or no patient was present when the ambulance arrived (n=2). Data on race and ethnicity were unavailable because such data is not reported by emergency medical service systems in Sweden.

Of the 58 cases of suspected out-of-hospital cardiac arrest where the drone delivered an AED, 24 (41%) were true cardiac arrests not witnessed by emergency services, and one case was witnessed by emergency services. The

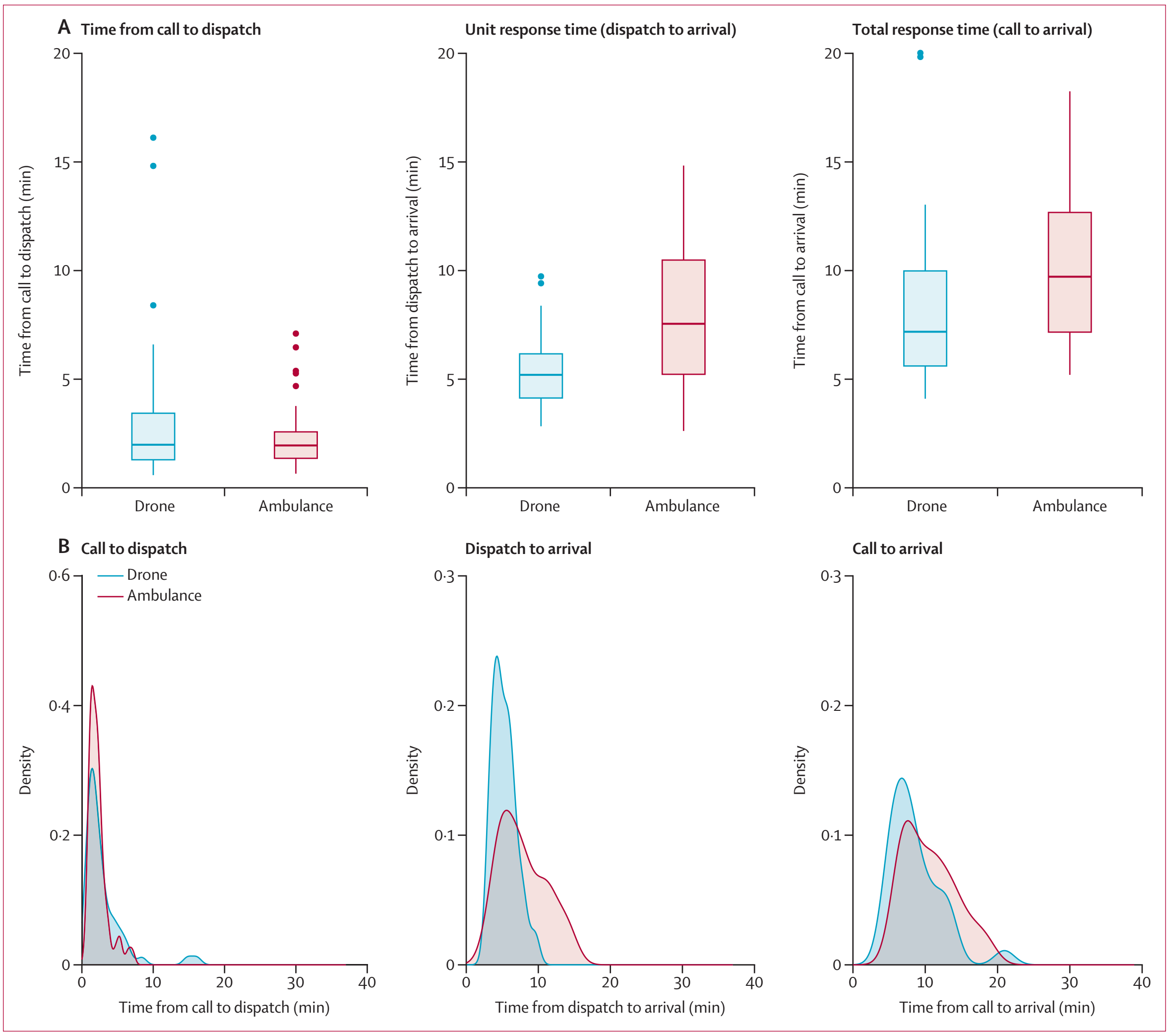

Figure 2: **Response times for AED-drones and ambulances**
(A) Boxplots of response times for AED-drones and ambulances. From the left, call to dispatch, dispatch to arrival, and call to arrival. (B) Density plots of response times for AED-drones and ambulances. From the left, call to dispatch, dispatch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

median age was 77 years (IQR 69–82), 11 (46%) of the 24 were female and 13 (54%) were male, 20 (83%) were residential, 14 (58%) were witnessed, and 20 (83%) of the patients received lay responder CPR before ambulance arrival. Of the 37 cases where the drone delivered an AED before ambulance arrival, 18 (49%) were true out-of-hospital cardiac arrests treated by emergency medical services and, among these, six patients (33%) had a drone-delivered AED attached before emergency medical services arrival (appendix p 6). In all these cases, there was more than one on-site bystander. Two of the six patients who had a drone-delivered AED attached had shockable first rhythm (33%). Both patients were defibrillated, and one of them survived to 30 days (table 2).[19]

Of all cases for which the drone did not deliver an AED (n=153), 44 (29%) were true out-of-hospital cardiac arrests treated by but not witnessed by emergency medical services. The median age was 71 years (IQR 60–81), eight (18%) were female and 36 (82%) were male, 39 (89%) occurred in residential locations, and 23 (52%) were witnessed. In total, eight (18%) of the patients had an AED attached, and four (9%) were defibrillated before ambulance arrival. Return of spontaneous circulation was achieved in 14 (32%) patients, and four (10%) survived beyond 30 days (table 2).

The drones flew a median of 1·8 km (IQR 1·1–2·5), and the corresponding median driving distance for the ambulances was 4·6 km (2·6–9·0). The drones flew at an average cruising speed of 48 km/h in median (IQR 43–57). AEDs were delivered within 30 m of the location of the suspected cardiac arrest in all cases, within 15 m in 91% of cases, and within 10 m in 64% of cases (table 1).

	Ambulance-treated out-of-hospital cardiac arrests (n=68)	Ambulance-treated out-of-hospital cardiac arrests (when drone did not deliver an AED; n=44)	Ambulance-treated out-of-hospital cardiac arrests (in cases with a drone-delivered AED; n=24)	Ambulance-treated out-of-hospital cardiac arrests (when drone arrived first; n=18)
Age, years	74 (64–82)	71 (60–81)	77 (69–82)	77 (69–82)
Females	19 (28%)	8 (18%)	11 (46%)	7 (39%)
Males	49 (72%)	36 (82%)	13 (54%)	11 (61%)
Residential location	59 (87%)	39 (89%)	20 (83%)	15 (83%)
Witnessed	37 (54%)	23 (52%)	14 (58%)	9 (50%)
CPR before ambulance arrival	50 (74%)	30 (68%)	20 (83%)	15 (83%)
AEDs attached before ambulance arrival*				
On-site AEDs	4/58 (7%)	4/43 (9%)	0/15	0/11
First responders' and lay responders' AEDs	5/58 (9%)	4/43 (9%)	1/15 (7%)	1/11 (9%)
Drone AEDs	2/58 (3%)†	0/43	2/15 (13%)†	2/11 (18%)†
Shockable first rhythm	9 (13%)	5 (11%)	4 (17%)	2 (11%)
Defibrillated before ambulance arrival*				
On-site AEDs	1/58 (2%)	1/43 (2%)	0/15	0/11
First responders' and lay responders' AEDs	3/58 (5%)	3/43 (7%)	0/15	0/11
Drone AEDs	1/58 (2%)‡	0/43	1/15 (7%)‡	1/11 (9%)‡
Return of spontaneous circulation at hospital arrival	20/58 (34%)	14/43 (33%)	6/15 (40%)	4/11 (36%)
Survival past 30 days	6/58 (10%)	4/43 (9%)	2/15 (13%)	1/11 (9%)

Data are median (IQR), n (%), or n/N (%). Data collected from ambulance charts and The Swedish Registry of Cardiopulmonary Resuscitation. Ambulance-treated out-of-hospital cardiac arrest means true cardiac arrest where ambulance personnel performed CPR. AED=automated external defibrillator. CPR=cardiopulmonary resuscitation. *Data from The Swedish Registry of Cardiopulmonary Resuscitation. 15% of all out-of-hospital cardiac arrests identified in ambulance charts are missing in the registry. †Four cases of drone-delivered AED attachment missing. ‡One case of defibrillation by drone-delivered AED missing.

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

During the study period no adverse events occurred. There was no AED malfunction, and all AEDs were tested for functionality after each mission, including AED self-test and sufficient battery level as well as manual inspection of basket, housing, and display. There were no incidents of AED damage or non-functionality during or after the alert, and no AEDs were delivered to inappropriate spots.

Discussion

In this prospective real-life study, to our knowledge, we have shown for the first time that AEDs can be delivered by drones to the site of a suspected out-of-hospital cardiac arrest before the arrival of an ambulance, in most cases in which a drone takes off. The delivery was made with a clinically important time benefit (median, 3 min 14 s), which made AED attachment before ambulance arrival possible in six patients.

AED-drones might be an important complement to ambulances, given that in several recent studies, ambulance response times have been shown to be increasing.[4] In this study, we have shown that the time from dispatch to arrival is shorter and varies less for drones, whereas the response time for ambulances is longer and shows greater variation than for drones.

There are several important aspects to consider when assessing the methodologies of delivering AEDs before ambulance arrival. Although stationary AEDs are life-saving and facilitate early defibrillation, residential areas where most out-of-hospital cardiac arrests occur are not usually covered by stationary AEDs.[6,20,21] Even though the number of publicly available AEDs is increasing every year, they are used in only 1·7–11·9% of all out-of-hospital cardiac arrest cases.[2,6] One AED-equipped drone, when able to take off, could cover a larger proportion of the population within a similar timeframe compared with several stationary AEDs. Although there are studies on cost-effectiveness of AED-drones,[22] circumstances vary between countries and, on a universal level, the cost-effectiveness of implementing AED-drones in real life remains unknown. Public, stationary AEDs regularly require maintenance,[23] and a recent Danish study showed that almost 20% of all the public AEDs in the study area were not functional.[24] The functionality of AED-drones is easy to monitor, and many investigators studying AED-equipped drones have concluded that only a few AED-drones could cover the AED requirement for a large part of the population.[8,10,12] Nevertheless, we believe that this novel method should not be seen as a substitute, but rather as a complement to existing ground-based AEDs—an intervention perhaps more focused on residential areas, especially since home defibrillation programmes have not yet shown effect on survival.[25]

The AEDs in this study were delivered by drones within 15 m of the location of the suspected out-of-hospital cardiac arrest in 91% of cases and within 30 m in all cases. Previous evidence suggests that an AED should be available within a 1·5-min brisk walk, which commonly has been translated to 100 m from an out-of-hospital cardiac arrest.[15,21] In the UK, only 5·9% of people who have had an out-of-hospital cardiac arrest have an AED available within 100 m and, at night, the number decreases to 1·6%.[21] Data from Hong Kong showed that 11·2% of people who have had an out-of-hospital cardiac arrest had an AED within 100 m.[26] Swedish data showed that a public AED was available within 100 m of suspected out-of-hospital cardiac arrests in only 6·6% of cases, and an AED was available within a 100 m with more than one bystander present in only 1·6% of cases.[20] Therefore, compared with 100% availability within 30 m for drone-delivered AEDs, public AEDs are much less accessible due to their variable proximities. This finding is important because the closer the AED is located to the patient, the higher potential for short retrieval time, hands-off time (time when no CPR is performed), and time to attachment of an AED, which in turn has the potential to increase the chance of survival.[3,27,28] Although bystander AED retrieval time was not measured here, we believe that retrieval of a drone-delivered AED within an estimated 30 s is feasible in most cases. The time benefit (median 3 min 14 s) achieved by using drones to deliver AEDs could open a time window in which bystanders have time to attach an AED before ambulance arrival, which was seen in six of our cases. This is clinically important because chance of survival decreases by roughly 7–10% each minute without treatment.[3] However, even with a time benefit of this magnitude, time delay from call to delivery of an AED is still longer than the desirable 3–5 min (in our report the time delay was a median of 7 min and 11 s) and further improvements of the system are needed to decrease time from out-of-hospital cardiac arrest to attachment of AED.

The life-saving potential of AED-drones varies between locations, and drones could, in theory, provide the most benefit in semi-urban areas, due to the relatively high incidence of out-of-hospital cardiac arrests, relatively long ambulance response times, and low accessibility of public AEDs.[8,9,13] In rural areas the time benefit might be even greater than in semi-urban areas. However, a low incidence of out-of-hospital cardiac arrests leads to fewer cases in which AED-drones can be used. In urban locations the incidence is higher, but ambulance response times are usually shorter than ambulance response times in rural and semi-urban areas. Additionally, in urban areas there is often one or more accessible AEDs in close proximity.[8,29,30] The areas used in this study are considered semi-urban areas and, despite the fairly short ambulance response times, the drones were faster than the ambulances in most cases. Further studies on optimal locations of drones are needed to further optimise the system and cost-effectiveness.

AEDs were attached in only a few cases compared with the number of cases where the AED was delivered before ambulance arrival (six [16%] of 37). The main reason was that only 18 cases in which the drone arrived first were true out-of-hospital cardiac arrests that were treated by emergency medical services. The attachment rate was therefore 33% (six of 18) in out-of-hospital cardiac arrest cases that were treated by emergency medical services. This resulted in 12 cases (67%) where a drone-delivered AED could have been attached but was not. An explorative audit of emergency 1-1-2 calls for out-of-hospital cardiac arrest cases that were treated by emergency medical services showed that dispatchers seldom mentioned AEDs, for reasons including fear of introducing hands-off intervals in cases of a single bystander, and distraught bystanders. This is not a problem unique to this study. In data published by Fredman and colleagues,[20] dispatchers referred to AEDs in only 4·3% of cases, although an AED was within 100 m, and there was more than one person at the scene. In many cases of non-referral, no reason for the non-referral was found.[20] An editorial on the aforementioned study states that robust protocols on both how to identify available AEDs and when to refer the callers to get them are needed.[31] Moreover, studies on referral in cases of single bystanders need to be done to decide if there are circumstances when a dispatcher should prioritise retrieval of an AED before the start of CPR.[31] Earlier studies on bystanders' experiences of drone delivery of AED have shown positive attitudes towards potential drone usage from the public,[32] but this area needs to be further studied in real-life situations.

Many suspected out-of-hospital cardiac arrest cases were excluded before deployment, mostly due to factors that could possibly be overcome in coming years; for example, rain, wind, and limited opening hours at airports with air traffic control. Firstly, an unsupervised traffic management system, in which emergency-medicine drones are prioritised, could mean that drones could operate outside of air traffic control hours and outside of controlled airspace. Secondly, advancements of drone technology in the future will facilitate redundancy of safety systems such as transponders, as well as enable faster and more accurate operations, including missions in rain and windy conditions. Furthermore, mobile-phone dispatch of volunteer responders to suspected out-of-hospital cardiac arrest cases is used in many areas around the world[33,34] and we believe that there might be potential in combining volunteer mobile-phone first responders dispatched directly to the site of the cardiac arrest with AED-equipped drones providing early delivery of an AED at the scene. This might eliminate AED retrieval time and thereby shorten response times, as dispatched first responders run straight to the location of the cardiac arrest and find a drone-delivered AED at the address. In this study, automated dispatch of AED-drones was used (based on indexing of the emergency call), which resulted in a faster dispatch of drones than with ambulances and first responders. However, it also led to over-triage of calls (only 68 [32%] of 211 calls concerned true out-of-hospital cardiac arrest) and missions that had to be cancelled during flight.

In future studies, optimal routines regarding dispatch of AED-drones should be evaluated. Experiences of bystanders, as well as emergency medical services and dispatch personnel should be further assessed. Finally, use of drones to deliver other medical equipment in time-sensitive emergency situations might have live-saving potential and should be further studied.

This study was performed in western Sweden, and conditions (eg, weather conditions) as well as regulatory requirements might vary compared with other countries and areas. To make the study more generalisable, AED-drone arrival times were compared with ambulance response times (not first responders). However, emergency medical services system configuration varies between countries, which could affect the time benefit achieved by AED-drones. Cost-effectiveness was not investigated in this study and must be considered before implementation of a drone system. Drones used in the study had several technical limitations and could not respond in all conditions or situations (for example rain, wind >8 m/s, and high-rise buildings), and we do not know how these limitations affected the results. Furthermore, many cases were excluded due to cancellation by the dispatch centre (no cardiac arrest).

AED-equipped drones alerted by the dispatch centre in cases of suspected out-of-hospital cardiac arrests delivered AEDs before ambulance arrival in two-thirds of cases, with a clinically relevant median time benefit of more than 3 min. This intervention could potentially decrease time to attachment of an AED, before ambulance arrival.

Contributors

Data curation, investigation, and project administration were done by SS and AC. SS, AC, and MJ performed the formal analysis. Methodology was performed by SS, AN, LS, and AC. Figures were created by SS and MJ. Conceptualisation was done by LS, MR, PN, JH, SF, FF, and AC. The original manuscript draft was written by SS, and all authors reviewed and edited the manuscript. PL helped with resources in terms of contacts at the dispatch centre and ambulances (for data collection and project administration and implementation). AC was responsible for funding acquisitions. AC and MJ have verified the underlying data. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Declaration of interests

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Data sharing

Data will be available with publication on request to the authors (proposals can be directed to sofia.schierbeck@ki.se). Data will be shared with researchers who provide a methodologically sound proposal. Data that will be shared are de-identified data on response times, drone flights, and characteristics of patients who had a cardiac arrest.

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