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Simulation and education

Automated external defibrillator delivery by drone in mountainous regions to support basic life support – A simulation study

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Abstract

Background: Out-of-hospital cardiac arrest (OHCA) is associated with poor survival rates. Factors that may enable survival include cardiopulmonary resuscitation (CPR) initiated by bystanders and early use of an automated external defibrillator (AED). This explorative simulation study was conceptualized to test the feasibility of a semi-autonomously operating drone that delivers an AED to a remote emergency location and its bystander-use.

Methods: Ten paramedics and nineteen laypersons were confronted with a manikin simulating an OHCA as single bystanders within a field test located in a mountainous region between Austria and Slovenia. The scenario included a mock-call to the local emergency response center that dispatched a drone towards the caller's GPS coordinates and supported the ongoing CPR. The outcomes were the successful delivery of the AED, the time to the first shock, hands-off times, and the overall performance of the CPR.

Results: The AED was delivered by drone and used in all 29 scenarios without serious adverse events. The flight time of the drone was in median 5:20 (range: 1:35–8:19) minutes. The paramedics delivered the first shock after a mean of 12:15 ± 2:03 min and hands-off times were 50 ± 22 s. The laypersons delivered the first shock after 14:04 ± 2:10 min and hands-off times were 2:11 ± 0:39 min. All participants felt confident in the handling of the delivered AED.

Conclusion: The delivery and usage of an AED via a semi-autonomously flying drone in a remote region is feasible. This approach can lead to early administration of shocks.

Keywords: Out-of-hospital cardiac arrest, Automated external defibrillator, Cardiopulmonary resuscitation, Drone, Mountainous region

Introduction

Medical emergencies such as sudden cardiac arrest (SCA) require immediate treatment. Given the time criticality of SCA and considering potential long emergency medical service (EMS) response times, basic life support performed by a fast-reacting bystander is essential for the survival of the patient. Here, early defibrillation with an automated external defibrillator (AED) is associated with higher survival rates.[1,2] The availability of corresponding devices is relatively high in urban areas and AEDs can be frequently found in governmental buildings, shopping malls, airports, or train stations. However, in rural and mountainous regions a comparable dense network of publicly available AEDs is inexistent.[3–5] Professional help may arrive via helicopters or per local first responders; nevertheless, timely interventions are hard to realize. A novel approach to overcome those issues is to deploy drones in the delivery of AEDs to SCA victims. The latest drone types have relatively high flight range (up to 100 km) and can carry a payload of approximately 25 kg.[6] Several theoretical studies highlight the advantages in terms of faster

Abbreviations: AED, automated external defibrillator, BVLOS, beyond-vision-line-of-sight, CPR, cardiopulmonary resuscitation, EMS, emergency medical services, GPS, global positioning system, OHCA, out-of-hospital cardiac arrest, SCA, sudden cardiac arrest

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response times, minimized risk exposure for rescue personnel, and lower costs of drones over traditional means of transport in urban and rural areas.[7–9] In the theoretical setting of an out-of-hospital cardiac arrest (OHCA), drones may deliver an AED towards an emergency location.[10–15] Practical tests in simulated response settings support this idea.[16–20] In Gothenburg (Sweden), AED drones have already been implemented in the local EMS system since 2020 as part of a prospective study.[21] However, no comparable data is available for mountainous regions. The topographical differences and remoteness of such regions pose certain logistical and operational difficulties that make final real-world implementation a challenging task. This study was conceptualized to test the feasibility of a semi-autonomously operating drone that delivers an AED to a remote emergency location and its bystander-use during basic life support in a simulation-based scenario. The primary aim was to demonstrate that early administration of shocks is possible, secondarily that hands-off times remain short, and quality of cardiopulmonary resuscitation (CPR) can be maintained throughout such a scenario.

Methods

Study overview

The study was approved by the Ethics Committee of the Medical University of Graz (Austria; 34-248ex21/22) and permission for beyond-vision-line-of-sight (BVLOS) drone flight was granted by the Austrian air navigation service provider Austro Control. The test location Bodental is situated in southern Carinthia (Austria) close to the border to Slovenia. It is a remote hiking area that is representative for mountainous regions and rough terrains. As illustrated in Fig. 1, four spots were chosen as test locations to simulate different environmental situations. These locations were meadows within woods suitable for an AED drop by drone and BVLOS for the drone pilot. Participants of the scenario were paramedics from an EMS located in the city of Klagenfurt (Austria) that were not informed previously about the AED delivery by drone and recruited during regular training sessions. They were regarded as optimal bystanders with expectable good performance. For real-world data acquisition, laypersons who went out hiking in the test area were randomly invited to participate in the study. To demonstrating the feasibility of an AED-delivery by drone in rough terrain, we initially aimed for 30 scenario runs. All participants gave written informed consent to participate in this study.

Technical data: drone, aviation tools, used AED, and CPR manikin

An "AIR8 Medium Lifter drone" by the local drone company AIR6 Systems (Klagenfurt, Austria) was used (Fig. 2). This octocopter drone is designed for medium payload up to 10 kg and for operational flight altitudes up to 4,000 m above sea level. The maximal horizontal flight speed accounts to 90 km per hour. The drone moves satellite-guided and is capable of full-autonomous flights following three to five waypoints along the optimal flight route under consideration of a terrain follow function towards GPS coordinates. A flight distance of 100 m above ground was set to avoid collisions with trees and other obstacles. Due to safety purposes, the drone was only operated to a maximum wind speed of 30 km per hour. The AED was attached to the drone via a long rope. The drone pilot could manually drop off the rope that was carrying the AED. The AED model was a Zoll AED3 (Zoll Medical Österreich, Vienna, Austria).

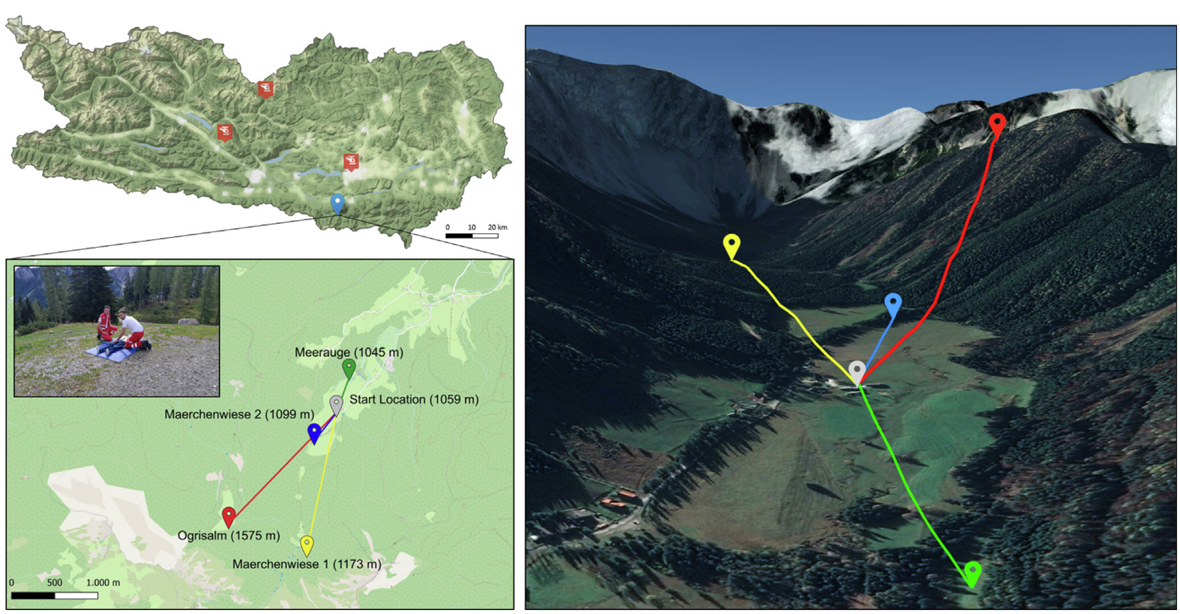

Fig. 1 – Map of the test area showing the four test spots and the drone start location (including meters above sea level). Top left: Austrian State Carinthia based on leaflet provider stamen (Stamen Design, San Francisco, California, USA) using "Stamen Maps -Terrain Background"[31] and processed via software package RStudio (Posit PBC, Boston, Massachusetts, USA). Bottom left: zoom to the test region with the four scenario locations based on the open-source software OpenStreetMap[32] and processed via the open-source GIS software QGIS 3.22.11 "Białowieża"[33] (green line: "Meerauge", red line: "Ogrisalm", blue line: "Märchenwiese 2", yellow line: "Märchenwiese 1"). The right side shows the topography of the region including the four flight routes based on Google Earth Pro 7.3.6.[34]

Fig. 2 – Left: drone on the starting place before takeoff. Middle: Drone hovering before dropping off the AED. Right: CPR manikin and scenario location.

A “Resusci Anne QCPR” (Laerdal, Stavanger, Norway) was used as CPR manikin during the tests. According to current guidelines, a chest compression depth of 50–60 mm and frequency of 100–120 compressions per minute were assumed to be acceptable.[22] Mouth-to-mouth ventilation was assumed to be adequate if at least 50% of all required ventilation maneuvers were performed with volumes higher than 350 mm. Two study members evaluated the CPR quality independently and confirmed quantitative measures of the CPR manikin.

Scenario setup

All study participants were confronted with a manikin simulating SCA with no further information. In the scenario, the assumption was made that no other persons were in the surroundings (single rescuer). Prior to the scenario start, participants received an unlocked smartphone (Samsung Galaxy A5). The only advice given to participants was to make an emergency call dialing the real emergency number if necessary. The emergency call center operated by the Austrian Red Cross was aware of the OHCA scenario and responded in the same way that they would have done for a real-world emergency call. The caller´s GPS coordinates were tracked automatically and forwarded via email to the drone pilot, who was blinded to the scenario location and was located near the open field where the drone was placed. Then the drone pilot initiated the semi-autonomously BVLOS drone flight towards these GPS coordinates and planned to land the AED three meters away for safety reasons. After arrival, the drone was manually controlled to descent and stopped when the AED reached a height of approximately one meter above ground to drop it off. In parallel, the emergency call taker supported the participants throughout the scenario, informed them upon the arrival of the drone, and gave instructions how to use the AED. After the administration of the second shock, the scenario was successfully completed. In case of a disconnection of the emergency call due to poor mobile phone network coverage in the test area, an experienced paramedic on-site gave advice and informed the participant about the drone arrival. In this case, the drone started after 4 min towards the GPS coordinates of the location.

All participants were interviewed before and after the scenario. The questions are displayed in Table 1 and asked for the participants’ knowledge on CPR algorithms, previous usage of AEDs, witnessed or performed CPR measures, and safety concerns about interacting with the drone. All scenarios were video recorded. Various timepoints, as described in Fig. 3, and CPR quality were subject of analysis. The timepoints were manually measured and cross-checked with corresponding video documentation.

Data management and quantitative analysis

Data were documented in a manual process on case report forms. Further data processing was performed with Microsoft Excel (Microsoft, Redmont, Washington, USA) and the statistics software RStudio (Posit PBC, Boston, Massachusetts, USA). Continuous variables with normal distribution were expressed as mean ± standard deviation or as medians [interquartile range] if non-normally distributed. Categorical variables were shown as percentages. Tests for normal distribution of variables included Kolmogorov-Smirnov- and Shapiro-Wilk-test, and visual inspection of kurtosis and skewness. In this feasibility study, in-depth statistical group comparison was not performed (i.e., paramedics vs. laypersons). We still report the results for laypersons and paramedics separately for a simple comparison between “optimal” (paramedics) and “real-world” (laypersons) bystanders to show how untrained bystanders perform as single rescuers in such a scenario and how an optimal performance could look like.

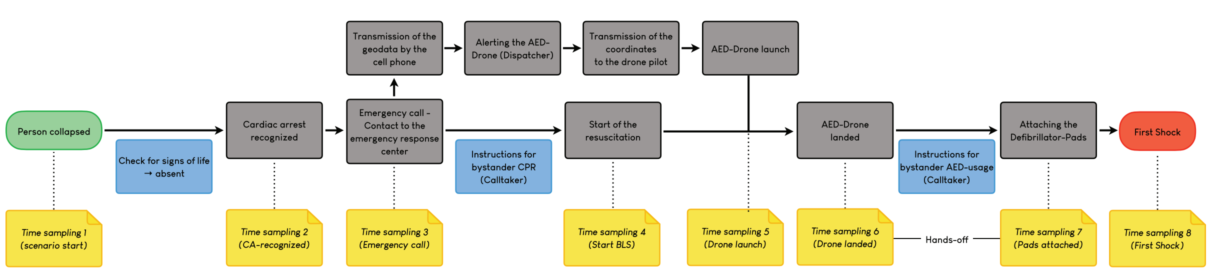

Fig. 3 – Flow chart of the scenario including all measured timepoints.

Results

In total, 29 persons (ten paramedics and nineteen laypersons) participated in the study on 5 days in late summer and early autumn of 2022. Each participant underwent a full scenario, and the drone successfully delivered the AED in all 29 scenario runs. The total scenario length (median: 16; range 12–20 min) differed due to different emergency locations and an unexpected long delay in the transmission of GPS coordinates via email. The median flight time of the drone was 5:20 (range 1:35–8:19) minutes. Rainy weather and wind speeds above the predefined safety limits forced the termination of one test day in the afternoon hours. Fig. 4 shows important markers of the CPR quality and measured time frames. Other aspects of the participants, the CPR measures, and the pre- and post-trial interview are displayed in Table 1.

Paramedics

The age of paramedics was 26 ± 6 years, 20% were female, and all of them were confronted with a cardiac arrest situation in their past at least once. They realized the cardiac arrest after a median of 18 [14–28] seconds and successfully called the emergency number without notable time delay. The resuscitation measures were initialized in parallel to the emergency call. 60% reached an ideal depth and frequency of the chest compressions, while 30% compressed the chest more than 60 mm and one paramedic with a frequency of over 120/min. 50% performed a sufficient mouth-to-mouth ventilation. The emergency calls were terminated by all paramedics stating that no further assistance by the call-taker is required. In this group, the drone dropped the AED after a mean of 10:52 ± 2:06 min. Hands-off times to place the defibrillation electrodes were in mean 50 ± 22 s. The first shock was delivered after a mean of 12:15 ± 2:03 min. All paramedics continued the resuscitation measures until the end of the scenario.

Laypersons

The age of laypersons was 53 ± 15 years and 37% were female. In the pre-trial interviews, only 37% reported to have knowledge about resuscitation algorithms, 42% of them received an AED training in their past, 16% used a real AED, and 21% performed or observed CPR measures at least once in their life. The laypersons realized the cardiac arrest after a median of 39 [20–62] seconds. Almost half of the laypersons called the emergency number before identifying the cardiac arrest. All laypersons started chest compressions, 58% compressed the chest more than 50 mm, one person compressed the chest more than 60 mm, and 53% reached a compression frequency of more than 100 per minute. Overall, 26% reached an ideal depth and frequency of the chest compressions and 68% managed to perform sufficient mouth-to-mouth ventilation. In five scenarios,

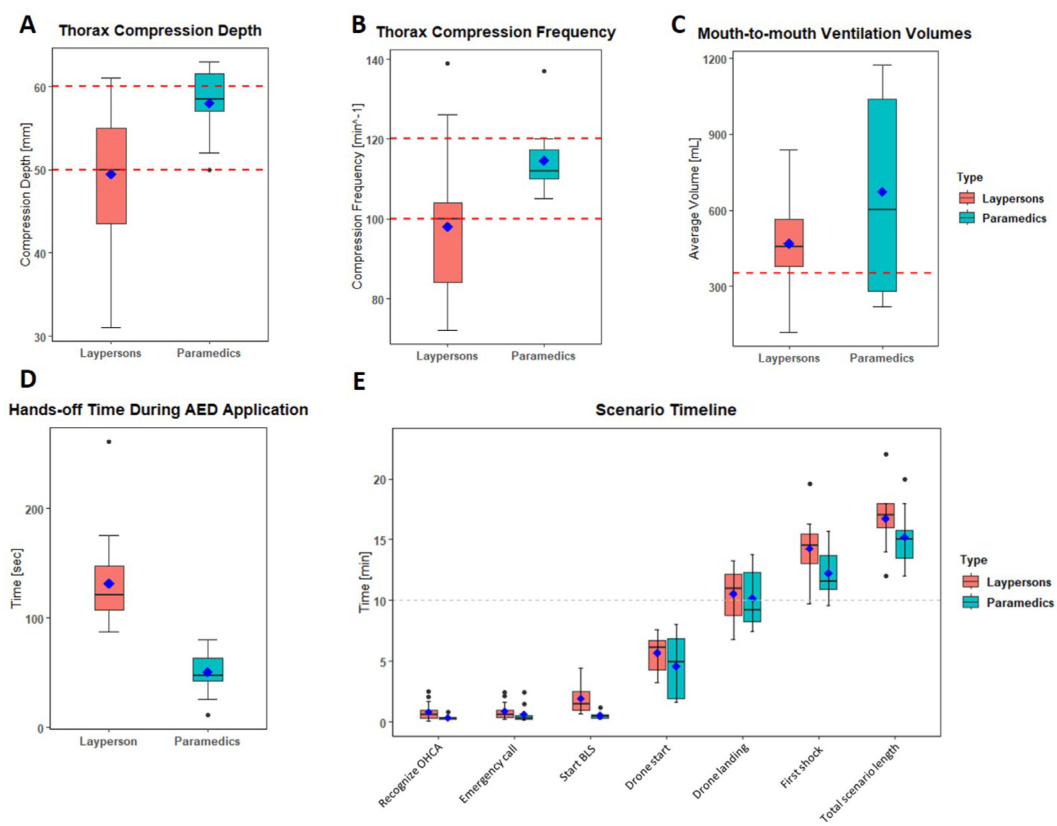

Fig. 4 – Evaluation of the quality of the CPR measures and timing of the scenario. Red boxplots are data from laypersons (n = 19) and blue boxplots are data from paramedics (n = 10). A: Chest compression depth, red lines indicate the optimal compression depth. B: Chest compression frequency, red lines indicate optimal compression frequencies. C: mouth-to-mouth ventilation, red line indicates volumes larger than 350 mm. D: hands-off times during the AED application. E: Scenario timeline (only data shown from 14 laypersons were included due to loss of mobile phone connection).

Table 1 – Qualitative and quantitative evaluation of the CPR and pre- and post-trial interview.

	Paramedics (n = 10)	Laypersons (n = 19)
Emergency call performed [%]	100	100
Started chest compressions [%]	100	100
Correct position of chest compressions [% of time]	83	81
Adequate depth of chest compressions [%]	70	53
Average depth of chest compressions [mm]; *median [IQR]*	58 [55–62]	50 [43–55]
Adequate rate of chest compressions [%]	90	53
Average rate of chest compressions [min^{-1}]; *median [IQR]*	112 [109–118]	100 [81–104]
Adequate depth and rate of chest compressions [%]	60	26
Adequate ventilation performed [%]	50	68
Average volumes if ventilation was performed [mL]; *median [IQR]*	603 [262–1043]	457 [358–579]
Adequate ventilation and chest compressions [%]	40	26
Time from scenario start to emergency call [s]; *median [IQR]*	21 [15–48]	39 [23–70]
Time from emergency call to drone start [s]; *median [IQR]*	297 [112–421]	370 [246–410]
Flight time of the drone [s]; *median [IQR]*	356 [293–427]	307 [290–337]
Time from AED delivery to first shock [s]; *median [IQR]*	79 [66–97]	140 [127–196]
Time from AED delivery to get it to the manikin [s]; *median [IQR]*	15 [10–19]	14 [10–20]
Average hands-off times for AED use [s]; *mean ± SD*	50 ± 22	131 ± 39
Total time to first shock	735 ± 123	844 ± 130
Continuation of CPR measures after first shock [%]	100	100
Adequate support via emergency call taker [%]	0 *	86
Total scenario length [s]; *median [IQR]*	900 [780–990]	1020 [960–1080]
Pre-trial questions		
Age of the participants [years]; *mean ± SD*	26 ± 6	53 ± 15
I know the resuscitation algorithms for laypersons [%]	100	37
I feel comfortable to handle a cardiac arrest as a bystander [%]	100	68
I used a training AED at least once in my life [%]	100	42
I used a real AED at least once in my life [%]	90	16
I once witnessed or performed CPR measures [%]	100	21
In general, I can handle unknown situations [%]	100	63
Post-trial questions		
I felt safe in my actions during the scenario [%]	100	90
I received enough support and information from the emergency call taker [%]	50	100
I felt comfortable when the drone approached on scene [%]	90	95
I could get to the AED without problems [%]	100	100
I felt myself at risk when the drone approached on scene [%]	20**	0
I think a drone is useful in such a scenario	100	100

Data are presented as mean ± standard deviation (SD) if normally distributed, otherwise as median [interquartile range (IQR)].

*All paramedics terminated the phone call after receiving the information of the AED delivery via drone.

** In one case, the drone landed accidentally before dropping off the AED due to a loss of communication during the landing phase of the scenario and in another case the drone kept hovering at a height of 20 m for the same reason.

the telephone connection was interrupted leading to on-site support by an experienced paramedic. In the other 14 scenarios, the communication between the laypersons and the emergency call taker was maintained throughout the entire scenario. The drone dropped the AED after a mean of 10:54 ± 1:56 min. Hands-off times to place the defibrillation electrodes were 2:11 ± 0:39 min. The first shock was delivered after a mean of 14:04 ± 2:10 min. All laypersons continued basic life support until the end of the scenario.

Safety aspects

No serious safety-related incidents occurred. In two test scenarios the AED drop-off was delayed due to a loss of communication via radio and telephone between the observers on stage and the drone pilot, both events happened in the paramedic group. In one scenario the drone kept hovering 20 m above ground. In another case, the drone landed on the ground unintentionally. These circumstances added a time delay of 4 and 5 min until the communication with the drone pilot could be reconnected; nevertheless, the scenario could be finished as intended in both cases. In the post-trial interview, 93% of all participants reported to feel safe when the drone approached the scene.

Discussion

This study demonstrates the feasibility of an AED delivery via drone in a mountainous region. Paramedics kept hands-off times short. Laypersons had longer hands-off times, which highlights the importance of knowing basic life support measures.

In an emergency located in a mountainous region, help by helicopters may arrive late and cause significant time delay or not at all in case of unavailability or bad weather on the way. For example, the air ambulance in Val Venosta, a region in South Tyrol (Italy) had response times between 17 and 48 min to arrive on scene in the year 2018.[7] In line with these data, the air ambulance of the Austrian State Tyrol reported in 46% of all missions a preclinical time of more than 90 min between 2011 and 2013,[23] suggesting remarkable response times. A large observational study from Korea showed that OHCA cases that occurred in mountainous regions had worse prognosis compared to cases that happened in other locations.[24] This is reflected by mortality data according to the Austrian Board of Mountain Safety in the timeframe between 2005 and 2015, where 781 OHCA events occurred in the Austrian Alps with very low rates of survival.[4] A single drone cannot cover a broad area; therefore, the implementation of an AED drone network seems to be highly beneficial. Corresponding regions need to be identified first via an evaluation of historical OHCA events with long EMS arrival times, as shown exemplary by Schierbeck et al. for Sweden.[14] Optimal locations could be skiing or small but popular hiking resorts without EMS services.[25] Beside an AED, a rescue network of drones could include a variety of bystander-usable emergency equipment like an epinephrine autoinjector for the treatment of anaphylactic reactions or a tourniquet for the treatment of severe bleeding. Considering further technical advancements, drones may fly completely autonomously with a pilot being a backup. Important aspects regarding flight safety, legal issues, identification of possible landing sites, risk of air collisions with other drones, helicopters, or birds have recently been discussed by Baumgarten et al.[16] While day- and nighttime does not matter to a full-autonomously flying drone, weather conditions may be a clear limitation for all air-rescue systems. In misty conditions without rain or heavy snow, a drone may still fly autonomously while a helicopter is often grounded. Rainy or wet conditions are a contraindication for any defibrillation; therefore, the drone should not even start its flight in a real-world emergency under such circumstances. Windy conditions may also prohibit the drone from flying. Therefore, current weather data of a region must be available for a rational use of a drone network.

The time to first shock of approximately 12–14 min in this study implies that for a promising outcome sufficient CPR is necessary to even reach the point of a shockable rhythm. If CPR is performed adequately, a shockable rhythm may be defibrillated, potentially gaining time until advanced life support teams arrive. However, laypersons provided adequate chest compression frequencies and depth in only 26% of the scenarios. This is expectable because most did not recently attend a training program. The low rate of adequate mouth-to-mouth ventilation in the paramedic group must be viewed from a similar perspective since mouth-to-mouth ventilation is practically never performed or trained in EMS systems. In a German study, paramedics did not reach optimal results during CPR either.[26] A Norwegian study compared the effectiveness of training duration with CPR measures and found that more intense training is associated with improved CPR quality.[27] The same is true for the mouth-to-mouth ventilation, where training programs can enhance the effectiveness.[28]

Most participants in this study felt comfortable when the drone arrived on scene. This high acceptance rate is in line with other AED drone studies.[16,18,29] Two paramedics felt at risk due to abnormal landing maneuvers, that should not occur in a full-autonomous flight. With modern drone technologies, an autonomously flying drone can measure the distance to the ground and decline a distance, where the AED is between 0.5 and 1 m above ground and then drop the AED while the drone itself hovers at a higher altitude (as demonstrated in Fig. 2).

Some limitations of this study must be addressed. First, the drone was placed on an open field and was started without additional procedures. A permanently installed drone must be protected from environmental exposure by some sort of hangar. Available infrastructure that already exists in remote regions such as buildings of ski lodges, inns or fire stations could serve as a platform. Second, there was no direct communication between the drone and the emergency call taker. Enabling such communication would probably lead to less time delay compared to the applied approach of sending GPS coordinates via email to the drone pilot. Third, the mobile phone network coverage is potentially poor in many mountainous regions. An emergency call is necessary to initiate the rescue chain. We could not establish a communication with the emergency call center in five scenarios, which would primarily pose a problem to make an emergency call and may prolong hands off times as well as prevent the drone to deliver an AED leading to worse prognosis for a SCA victim. GPS coordinates of the incident location can be produced via tracking of the callers' smartphone and currently, at least in Austria, this is only possible for android-based smartphones. Fourth, dropping off the AED from one meter height might damage the AED and lead to a loss-of-function. And fifth, in our test most certainly a selection bias is present, therefore the evaluation of the CPR measures and timely interventions must be viewed critically. The paramedics were randomly invited to participate in the simulation scenario during the regular training sessions; therefore, their performance provides information on what timeframes can be possible with regular training. However, laypersons hiking in this region who declined to participate in our study may have performed worse.[30]

Conclusion

The delivery and usage of an AED via a semi-autonomously flying drone in mountainous regions is feasible and can lead to early administration of shocks. The acceptance rate of the drone-delivered AED was high among participants. Our study also highlights the need for permanent CPR training to increase the efficiency of basic life support.

CRediT authorship contribution statement

Philip Fischer: Conceptualization, Investigation, Data curation, Visualization, Writing – review & editing. **Ursula Rohrer:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision, Funding acquisition. **Patrick Nürnberger:** Methodology, Investigation, Validation, Writing – review & editing. **Martin Manninger:** Conceptualization, Writing – review & editing, Funding acquisition. **Daniel Scherr:** Resources, Writing – review & editing, Funding acquisition. **Dirk von Lewinski:** Resources, Writing – review & editing, Supervision. **Andreas Zirlik:** Resources, Writing – review & editing, Supervision. **Christian Wankmüller:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – review & editing. **Ewald Kolesnik:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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