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Potential and Challenges in Airborne Automated External Defibrillator Delivery by Drones in a Mountainous Region

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Abstract: Delivering an automated external defibrillator (AED) to a patient suffering from out-of-hospital cardiac arrest (OHCA) as quickly as possible is a critical task. In this field, airborne drones may help to overcome long response times, especially in mountainous regions where topography and weather pose several challenges for rescuers. Drones are considered a fast option to shorten the time to the first AED shock. This study presents insights into the safety regulations, performance, reliability and public perception of this specific drone-based application. The findings are based on field tests that focused on the operational/logistical benefits and challenges of semi-autonomous drone-based AED delivery to simulated emergency sites in mountainous terrain. The generated results underline the operational and technical feasibility of the proposed system given successful AED delivery in all simulation scenarios. Several challenges remain, such as improvements in terms of the AED pick-up, mobile phone connectivity, tracking of GPS coordinates and weather resistance of the used drone are required. Overall, the study supports paving the way for future trials and real-world implementations of drones into existing emergency response systems.

Keywords: drone technology; delivery; automated external defibrillator; out-of-hospital cardiac arrest; mountainous region

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1. Introduction

Recently, the benefits of drone technology to support emergency operations, including search and rescue missions, telemedicine, public health surveillance and medical supply delivery, have gained academic attention [1,2]. There is evidence of the remarkable speed advantages that come along with the drone delivery of automated external defibrillators (AEDs) when compared to helicopter or ground-based emergency medical service (EMS) [3,4]. Quantitative studies highlight the advantages of drones over traditional means of transport, not only in terms of speed but also cost [5]. Hence, drone-based AED delivery may lead to faster provision of life-saving electric shocks for patients suffering from out-of-hospital cardiac arrest (OHCA). Early usage of an AED and shock delivery improves survival rates and functional outcomes [6–8]. Therefore, this technology may be used for the rapid transportation of AEDs to aid unequipped first responders or laypersons confronted with OHCA patients in the future.

First insights into this potential application were generated by Pulver et al. [9], Boutilier et al. [10], Pulver and Wei [11] and Wankmüller et al. [3]. Most studies reported quantitative methods in the form of optimization modeling and confirmed the advantage of drones in terms of speed and flexibility. By contrasting calculated response times with historical data from EMS services in cities and regions such as Toronto (Canada), Salt Lake County (USA) or South Tyrol (Italy), the authors report a decrease in response times of 6–46 min. The extent of the impact depended on the number of drones used and the remoteness of the considered emergency sites.

However, the authors underlined the need to validate those estimations by empirical tests in real-world settings. This appeal has motivated researchers to initiate several studies that focus on real-world testing of AED drones, primarily in urban areas. Sanfridsson et al. [12] conducted field tests in Western Sweden, where participants experienced a simulated OHCA scenario, including an AED drone that responded to the emergency site. The study mainly focused on the bystanders' experience when handling such a system and summarized that the retrieval of the AED was considered safe and feasible.

A similar study by Claesson et al. [13] presented findings from 18 test flights in a rural region near Stockholm (Sweden). A post-test comparison between measured drone flight times and historical EMS data revealed a remarkable response time reduction. Furthermore, this study did not face any technical or logistical problems of drone-based AED delivery flights. Another paper by Rees et al. [14] illustrated observations from six drone flights to deliver an AED in a rural location in Wales (UK) to laypersons involved in a simulated OHCA event. In total, the study team was able to conduct successful end-to-end flight demonstrations and four parachute payload drops. A further hands-on test was conducted by Cheskes et al. [15], who examined the feasibility of AED drone delivery for rural and remote OHCA patients in Ontario (Canada). Six simulation runs of OHCA events were performed. This study involved trained first responders to cover the timespan until EMS arrival. Overall, the study findings confirmed the feasibility of the proposed drone-based AED delivery and again pointed out the significant response time reduction of the drone compared to the ground EMS (1.8–8 min). Drone-based AED delivery was also analyzed by Baumgarten et al. [16], who performed practical tests in a rural Northeast German region. Community first responders participated in 46 scenario runs to gain knowledge on the feasibility of integrating drones into the chain of survival [17]. Finally, this research group published a drone-based AED delivery, including 29 scenarios of OHCA in a mountainous region. Arrival times of the AED and the overall resuscitation measures were subject to analysis. Moreover, this study included the local emergency call center (ECC) that dispatched the drone after receiving a mock emergency call.

Schierbeck et al. [18] reported findings from an AED drone fully integrated into the existing EMS system in Gothenburg (Sweden). The drone was dispatched to 12 real-life suspected OHCA patients. In total, 11/12 deliveries over a median distance of 3.1 km to a location were successful. To summarize, this pilot study showed that drone-based AED delivery is feasible in real-life scenarios. However, the authors concluded that further improvements in terms of dispatch rate and time benefits are required.

Hence, these first practical tests in urban and rural areas support the feasibility of AED drones. Nevertheless, deeper empirical analyses of drone-based AED deliveries in mountainous settings have not yet taken place. The topographical differences and remoteness of such regions pose certain challenges that are reflected in complex telecommunication, drone communication, flight path obstacles, rapidly changing weather conditions or unknown patient locations. The use of drone technology might be limited by the extension of the necessary infrastructure, like the coverage area of the telephone network, the full integration into the local EMS service or the availability of adequate shelter huts as drone bases. In this regard, the published data highlighted the potential of drones in settings where these conditions were often absent. Therefore, operational and logistical perspectives must be considered to assess its feasibility for real-world implementation.

Consequently, we studied how a drone can deliver an AED to an emergency location within a simulation scenario in mountainous terrain under consideration of different bystander characteristics. From this, we wanted to learn more about the benefits and challenges that occur when inexperienced bystanders or professional paramedics work with an AED drone. To achieve this, we asked the following research questions (RQs):

RQ1: What are the operational/logistical benefits and challenges of drone-based AED delivery to an out-of-hospital cardiac arrest (OHCA) patient in mountainous regions?

RQ2: What are the lessons learned from the field tests to improve the implementation of drone-based AED delivery into existing emergency systems?

To answer the above-described RQs, this study followed a qualitative research approach via observations during field tests of the semi-autonomous drone-based delivery of an AED to simulated OHCA scenarios in a remote area in Carinthia, Austria. In this study, we report the safety and regulatory requirements that need to be overcome in this application, the performance and reliability standards specifically applicable in the transportation of medical devices and the retrieval of those by laypersons or trained EMS personnel. Additionally, we describe technical and human factors that limited the effectiveness of the drone-based AED delivery in mountainous regions. This allows tailored improvements in future applications.

This article continues by thoroughly describing the applied methodology and outlining the scenario setup, including the relevant operational and technical information (Section 2). Finally, Section 3 presents the study findings, and Section 4 discusses the results and the study's limitations. Section 5 concludes the article with an outlook on future research.

2. Materials and Methods

This analysis is part of the TREATED study (Automated external defibrillator delivery by a drone in a rural environment: a practical experience). The setup of the field tests, including simulation scenarios, and the results focused on the successful delivery of an AED to a resuscitation scenario, as well as the quality and timing of resuscitation measures, have been published previously [17]. The field tests served to gather practical insights on the operational/logistical benefits and challenges of delivering an AED to a medical emergency simulation scenario set up in mountainous terrain. This information was used to answer the RQs of the study at hand via quantitative and qualitative SWOT analyses (see Figure 1). In the following, we present insights into the safety and regulatory requirements for drone operations in Austria, information on the field test and the setup of the test scenario, technical data of the drone used and organizational facts on the flight route planning. The study was performed following the rules of the Declaration of Helsinki of 1975, revised in 2013, with institutional review board approval of the local ethics committee of the Medical University of Graz (34-248 ex 21/22, 1054-2022).

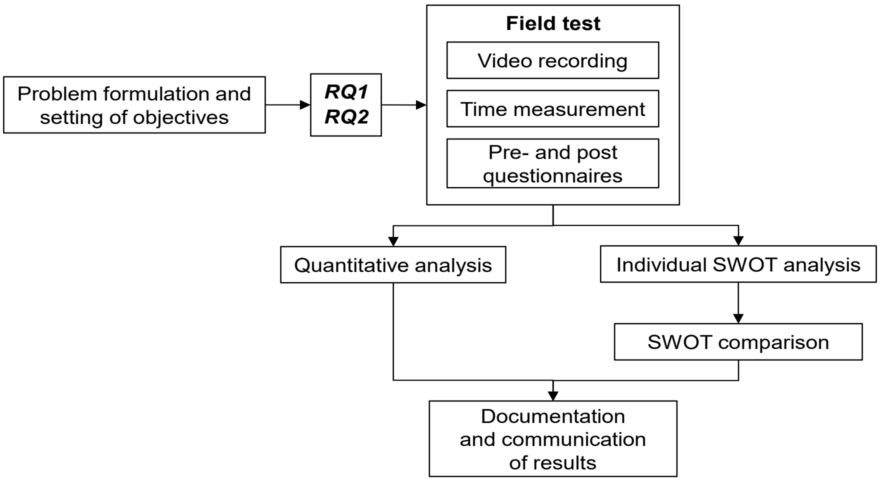

Figure 1. Methodological flowchart of the applied research approach.

2.1. Safety and Regulatory Requirements for Drone Operations in Austria

The specific operations risk assessment (SORA) and concept of operations (ConOps) are crucial for ensuring safe and compliant drone flight operations. Both documents are legally binding and need approval by national authorities when certain risk criteria of a drone operation are present. The responsible authority for civil aviation in Austria is the so-called "Austro Control". Corresponding European standards for both the SORA and ConOps that apply are published by the European Union Aviation Safety Agency (EASA) in the cover regulation to implementing regulation (EU) 2019/947 (Commission Implementing Regulation (EU), 2019) [19,20]. Together, the SORA and ConOps ensure that drone operations are conducted safely, efficiently and in compliance with regulatory requirements. In the development of SORA and ConOps documents as part of the preparatory work for the field tests, we followed the standards and guiding procedures published by the "Austro Control", as described above. The defined and analyzed specific areas and processes of this research project are described in detail below and illustrated in Figure 2.

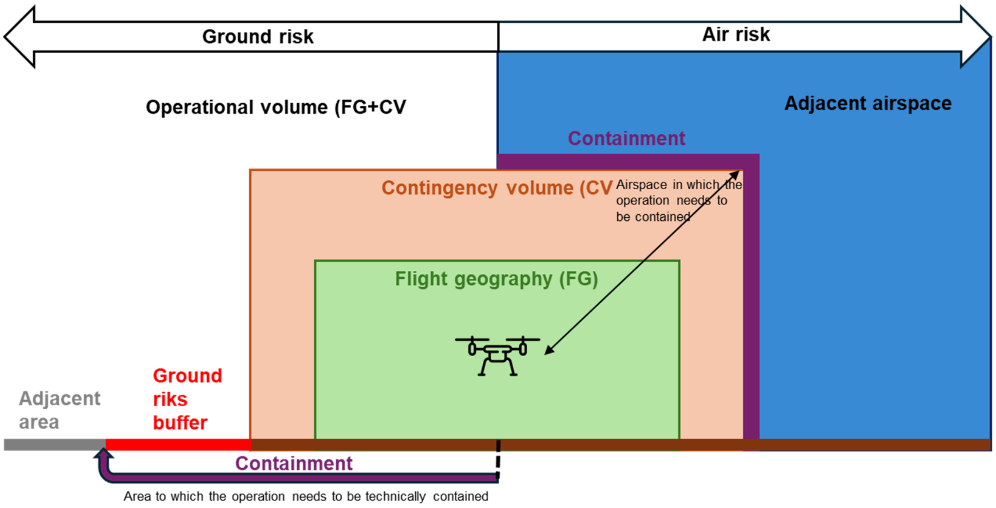

Figure 2. Areas to be defined and analyzed before flight operation. The operation needs to be contained within the flight geography (FG, green) and contingency volume (CV, orange) regarding the airspace to calculated for the air risk. The FG and the CV together make up the operational volume. Concerning the ground risk, those areas are additionally extended by the ground risk buffer (red line) to account for the ground risk. The area needs to be within the area of containment (purple), the adjacent area (grey line) and airspace (blue) may not be used. Based on https://eudroneport.com/de/blog-de/sora-fluggeografie/ (accessed on 9 September 2024).

2.1.1. Specific Operations Risk Assessment (SORA)

The SORA process includes several steps to systematically evaluate and mitigate risks associated with drone operations. These steps are guided by the European Union Aviation Safety Agency [19]. Firstly, it requires defining the operation. This initial step involves providing a detailed description of the planned drone flight, including its specific purpose, the operational area where the flight will take place and the duration of the operation. This step is crucial as it sets the foundation for the subsequent risk assessment and mitigation processes. It ensures that all stakeholders have a clear understanding of the operational context and objectives.

Next, the process involves identifying risks. During this phase, potential hazards to both ground-based entities, such as persons and property on the ground, and air-based entities, such as other aircraft, are thoroughly analyzed. This analysis includes considering various scenarios and conditions that could pose threats during the drone operation. By identifying these risks early on, operators can better prepare and address them. Following the identification of risks, a detailed risk assessment is conducted. This process involves evaluating the probability of each risk occurring and the potential impact it could have on people, property and other airspace users. By quantifying these risks, operators can prioritize them and focus on the most significant threats.

Finally, the process includes a residual risk evaluation. This step assesses the effectiveness of the implemented mitigation measures and determines the remaining level of risk after these measures have been applied. It involves reviewing the mitigation strategies and whether they apply as intended and identifying any residual risks that may still pose a threat. This evaluation helps operators assess overall safety and make adjustments to further reduce risks.

2.1.2. Application of SORA in This Study

The drone flight in this specific study was defined as a beyond-vision-line-of-sight (BVLOS) flight in a sparsely populated environment, for which the drone ground risk class (GRC) was assessed at level 4 (from a 10-point scale, with 10 indicating the highest risk level). Due to low tactical mitigation performance requirements and low associated robustness levels, the air risk class (ARC) (= an index for the risk of a collision with a manned aircraft [18]) was classified as ARC-b. Once the risks have been assessed, the next step is to implement mitigation measures. This involves developing and applying strategies to minimize the identified risks. The goal of this step is to reduce the risks to an acceptable level, ensuring the safety and security of the operation. For ARC-b, several mitigation measures were put in place for the test flights, such as the positioning of visual observers along the flight path and flying below a flight height of 120 m above ground level. Furthermore, the visibility of the drone was ensured by equipping it with a signal red color on the top and bottom of the center body and flashing lights for even better visibility. Additionally, the operation was conducted in coordination with the airport tower in Klagenfurt, Austria, and with first responders (mountain rescue team and police) to ensure safety from airport and helicopter activity.

A re-evaluation taking all risk mitigation measures into consideration resulted in GRC level 2 and ARC-b, resulting in a specific assurance integrity level (SAIL) 2, hence declaring the flight as a low-risk operation.

2.1.3. Concept of Operations (ConOps)

A ConOps is a comprehensive document that outlines the overall strategy and operational plan for a drone flight according to the European Union Aviation Safety Agency [21]. It ensures that all aspects of the mission are clearly defined and understood, including the mission objectives, operational procedures, roles and responsibilities, communication protocols and safety measures. Firstly, the ConOps defines the goals and intended outcomes of the operation, aligning all stakeholders on the expected results. Next, detailed procedures for conducting flights, covering pre-flight preparations, in-flight activities and post-flight tasks are provided. This guarantees the safe and efficient planning and execution of the operations. The ConOps also designates the roles and responsibilities of all personnel involved in the operation, from the drone pilot to the support team, ensuring everyone knows their duties and can perform them effectively. Furthermore, the ConOps outlines procedures to maintain communication between the drone operator, air traffic control and other relevant entities. Finally, the ConOps describes safety protocols and emergency procedures to handle unexpected situations, ensuring the safety of the drone, the operational team and the public.

2.2. Field Test Setup

Applying the above-described principles and requirements, we conducted a series of six field test days in the course of the research project TREATED [17]. The field tests were performed from August to October 2022 at different sites within the mountainous region of Bodental (Carinthia, Austria) during daytime during the week and on weekends. Random passers-by were recruited as participants for the scenarios irrespective of their previous medical experience. Members of the local EMS (Red Cross Austria) were recruited as a second cohort of participants. The group of paramedics included 10 paramedics, who are well trained in terms of basic and advanced medical life support. The age of the paramedics was 26 ± 6 years, 20% were female, and all of them had been confronted with a real-world cardiac arrest situation in their past at least once. The group of laypersons included 19 laypersons with no specific medical education background. The age of the laypersons was 53 ± 15 years, and 37% were female. In each scenario, the participants were confronted with a manikin (Resusci Anne QCPR by the company Laerdal) simulating a person suffering from OHCA. The intention of the scenario was that participants should recognize OHCA, make an emergency call, start basic life support and apply the drone-delivered AED. During the entire scenario, the participants found themselves in the most realistic circumstances with direct contact with the ECC via a mobile phone. The ECC was part of the research project and was expecting calls from these scenarios. Call-takers of the ECC were directed to give instructions on how to perform basic life support and the delivery of the AED by a drone. Members of the research group observed all scenarios and performed structured documentation of all time intervals as well as potential hazards and unexpected issues or situations.

2.3. Drone Communication and GPS Guidance

The GPS coordinates of the bystanders' mobile phones were automatically tracked and forwarded via email by the emergency dispatcher to the drone pilot, as a direct link was not available. Upon receiving the GPS coordinates, the drone pilot processed the incoming data in the flight software to plan the semi-automatic drone flight. Therefore, the drone followed 3–5 waypoints along the shortest flight route and under consideration of a terrain follow function at a height of 80–100 m above ground. Notably, the transferred GPS coordinates had an intentionally chosen deviation of three meters from the original bystander location to avoid close contact between the bystanders and the drone. Aside from using waypoints, the semi-autonomous flight was organized via a mission planner (auto pilot) and satellite communication (satcom). Here, the drone communicates with a laptop and a satcom server.

The drone started under manual control of the pilot in a semi-autonomous flight. Once the flight height was reached, the drone turned to autonomous flight mode and approached the emergency location coordinates. Upon drone arrival at the emergency location coordinates, the drone pilot switched again to manual control to decline the drone by visual control of one study team member. The drone pilot did not see the landing maneuver but received instant information via telephone or radio. The drone descent was stopped when the AED reached a height of approximately one meter above ground to drop it off. Once the drone dropped the AED successfully, it manually ascended to flight height, then switched to autonomous flight mode and returned to the start location.

The drone operator and a spotter monitored the entire flight to check for any technical issues and flight behavior of the drone. The operator was in direct telephone or radio contact with one study team member, who was present at the emergency location. During the entire scenario, the drone pilot was able to step in and take over manual control of the drone at any point in time. In case of communication disruption ("loss of ground control station"—a subsequent action can be set in the settings and adjusted in the mission planner), the drone returns to launch unless the drone operator intervenes and takes over the control of the drone. This so-called secondary communication enables a direct radio link where the pilot overrules the satcom signal and controls the drone manually.

2.4. Technical Specifications of the Drone

An "AIR8 Medium Lifter drone" (4 arms and 8 rotors) by a local drone company AIR6 Systems (Klagenfurt, Austria) was used in the study and had the following technical specifications: weight = 16 kg (including batteries, without payload), maximum take-off weight = 25 kg, operating temperature = −10 to 50 °C, maximum flight time = 60 min, maximum windspeed = 60 km/h, maximum altitude = 4000 m ASL and maximum flight speed = 90 km/h. This drone model is the most robust, can lift the highest payload and has the longest flight duration out of drone models offered by the drone company involved in the tests. The drone was equipped with two first-person view cameras (forward/downward) for operational support. For comparison, the company Zipline operates drones in some countries, including the United States of America, and has developed a drone capable of delivering objects toward a defined landing zone. This company has already gathered experience in delivering payloads for medical purposes [22]. Technical specifications of the AIR8 Medium Lifter drone by Air6Systems located in Klagenfurt, Austria and the Zipline P2 by Zipline located in San Francisco, USA are given in Table 1. Corresponding information stems from official sources by the two companies (see https://www.air6systems.com/ (accessed on 8 September 2024) and https://www.flyzipline.com/technology (accessed on 8 September 2024)).

Table 1. Comparative overview between the used drone and Zipline P2 drone. VTOL = vertical take-off and landing.

	Drone Type	**Number of Rotors**	**Max. Takeoff Weight**	**Max. Flight Range**	**Max. Horizontal Flight Speed**	**Special Features**
AIR8 Medium Lifter Drone	Multi-rotor drone	8	<25 kg	36 km	90 km/h	Terrain follow option, drop-off device option, system tracking option (loss recovery).
Zipline P2	Fixed-wing hybrid VTOL	5	<4 kg	38 km	112 km/h	Delivery droid, predictive weather

2.5. Attachment and Delivery of the AED

The AED model was an AED3 by the company Zoll Medical Austria, weighing 2.5 kg (13.3 × 24.1 × 29.2 cm). It was attached via a 5 m rope at the center of the drone with multiple fixing points to ensure redundancy for safety reasons (see Figure 3). The drop-off mechanism was unarmed during the flight operation and armed only upon drone arrival at the emergency location. After the drone had fully stopped and reached the drop-off height, the drop-off mechanism was armed for release. This method ensures that the bystanders do not come into close contact with the drone, mitigating risks associated with the drone's proximity.

Figure 3. AED hanging on a 5 m rope attached to the drone. Source: The authors.

2.6. Evaluation of User Perception and Acceptance

To learn more about individual user perceptions of the tested drone-based AED delivery, we conducted structured pre- and post-test interviews with the involved participants. Corresponding questions addressed the users' past experience in providing CPR and handling an AED, respectively, and their perception when interacting with a drone delivering an AED as tested in the scenarios. Answers were collected in a digital form using a survey form. Additionally, each of the scenario runs was video recorded to allow for in-depth post-test analysis. To allow for quantitative analysis, multiple time points, as well as the CPR quality, were measured during every scenario. Furthermore, observations of the research group members on site, as well as comments from the participants after the scenarios, were also documented to capture all relevant factors. The pre- and post-test interviews were conducted during the six test days, before and after each test. The pre- and post-test interviews together took up to 5 min for each participant. The validity and reliability of the interviews were guaranteed by using a structured interview guide, detailed documentation and analysis of the collected data and in-depth discussions of findings within the study group.

2.7. Data Collection and Analysis

We assessed our observations and results from the participant interviews through a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis after each field test day [23]. The internal factors thereby relate to aspects that can be influenced by the contributing stakeholders in our study, i.e., the drone manufacturer and the Red Cross Organization, whereas the external factors belong to the project's environment and legal regulations and can, therefore, be not controlled directly by involved stakeholders. After each test day, a separate SWOT analysis was performed to generate the lessons learned on a most granular level and enable ad hoc improvements for follow-up tests. The results from the SWOT analyses were jointly discussed with the study team and summarized in detail.

3. Results

Over six days, 29 emergency scenarios were conducted at four different locations to consider varying topography and changing requirements to operate the entire system. An overview of the individual SWOT findings is given in Table 2.

Table 2. Results from SWOT analyses.

	Strengths	**Weaknesses**
Internal	• Successful delivery of the AED in all 29 test scenarios that underlines the operational as well as logistical feasibility of the proposed system. • Drone-based AED delivery may lead to shorter response times when compared to rescuers on foot and a truck. • Advanced delivery of the AED when hanging on a 5 m rope attached to the drone when compared to a full landing due to safety concerns. • Tracking of the bystander/emergency location (i.e., GPS coordinates) by the emergency call center (ECC) works well with Android mobile phones. • Test participants (i.e., paramedics and laypersons) felt comfortable and safe when working with the AED drone in the scenario. • Improvements in terms of AED pick-up by the bystander after drop-off at the emergency site were discussed due to communication challenges: (1) Acoustic notification by the drone when a safe AED pick-up is possible (2) Call-tacker informs about safe pick-up of the AED	• Relatively slow communication/transmission of emergency site coordinates via Email to the ECC. • Delayed descent flight of the drone at the emergency site due to manual instructions that were given by one person on site via radio to the drone pilot at the starting location. • Communication between the bystander and the ECC call taker was a major concern, as confusion occurred because of imprecise help given to the bystander. • Process document and flowchart illustrating the steps in the drone-based AED delivery should be elaborated to support ECC personnel in providing instructions to the bystander to increase safety and to further accelerate the delivery process. • Mobile phone tracking is not possible for iOS-based mobile phones that can be either country-specific or a technical limitation of the involved ECC.

Table 2. *Cont.*

	Opportunities	Threats
External	• Drone response time may be lower compared to a helicopter from the closest helicopter base to the simulated emergency sites. • Embedding the system in existing emergency response strategies may accelerate response times. • Integration of drones with other technologies, such as advanced GPS systems and real-time data analytics to further enhance the effectiveness of drone-based AED delivery. • Integrate public awareness and education programs to scale drone-delivered medical supply. • Study results can be used to advocate for policy changes and funding allocations to support the integration of drones into emergency response systems.	• Mobile phone connectivity is not always given and depended on the location of the bystander in the field. Under non-connectivity emergency calls cannot be made, which prevents the entire system from being initialized. Network providers need to increase signal coverage for mobile phones to enable emergency calls wherever located in the field. • Strong wind and other external weather factors may hamper the effectiveness of the system, therefore wind/weather parameters and thresholds need to be clearly defined to ensure safety and reliability of the drone-based AED delivery.

The AED was successfully delivered and used in all scenarios at four different sites without any serious adverse events detected. Communication with the local ECC happened in 24 of 29 scenarios, and the call-takers could easily inform participants about the imminent AED delivery by drone. In 5 of 29 scenarios, local phone connection on-site was possible but delayed, which was to be expected in a remote mountainous region in Austria. In these cases, the researchers on scene transmitted the necessary information instead of the call-taker, and the drone delivered the AED to known GPS coordinates in order to be collected in these scenarios. Detailed information on the timing and quality of resuscitation measures has been published elsewhere [17]. Briefly, the median flight time of the drone was 5:20 min to the different locations that were within a range of two kilometers, and the first shock by the AED was delivered after a median time of 12:15 min in the paramedics' group and 14:04 min in the laypersons' group. A direct comparison with the local air ambulance service was not performed because the arrival time compared to the drone is dependent on many more factors, like a suitable landing site and the distance of the scenario location to the base of the helicopter.

3.1. SWOT—Strengths

First and foremost, the delivery of the AED was successful in all 29 scenarios, indicating that the proposed approach is feasible from both an operational and logistical viewpoint. The delivery method of the AED hanging on a rope attached to the drone was preferred over a full landing due to safety concerns. This method ensures that the bystanders do not come into close contact with the drone, mitigating risks associated with the drone's proximity. Additionally, this approach offers time advantages, as a full landing would require time-consuming instructions and coordination efforts of the bystanders. Regarding safety aspects, no serious incidents were observed. During two flights, abnormal drone maneuvers occurred while the drone descended to the drop-off location. This was caused by a disrupted radio/telephone connection between the drone pilot and the spotter, who should inform the drone pilot of the flight height. These situations would not occur in a fully autonomous flight. Typically, during autonomous descending, the drone measures the distance to the ground until it reaches a height between 0.5 and 1 m above ground to drop the AED while hovering at a higher altitude. Future implementations should consider improving the reliability and clarity of the drone's autonomous systems to prevent flight anomalies. Ensuring that the drone can consistently perform precise maneuvers without manual intervention will increase the safety and effectiveness of the AED delivery. Overall, the successful delivery of AEDs in all test scenarios demonstrates the viability of using drones in emergency medical situations.

3.2. SWOT—Weaknesses

Three main concerns can be identified. First, the transfer of emergency site coordinates via email from the ECC to the drone pilot should be accelerated or replaced by alternative mechanisms. The initial plan was for the ECC call-taker to email the coordinates to the drone pilot, who would then input them into the drone software. The coordinates could be tracked in every scenario within 30 s after the emergency call arrived at the ECC. However, the transmission of coordinates via email had a disproportional share in this total time with 9 min, accounting for approximately 50% of the total scenario duration. This time lag needs to be reduced to improve response times and efficiency. In the scenarios, the time to shock was most times longer than 10 min. Reducing the time to shock is critical for a successful application of the AED because, at some point after cardiac arrest, there might not be a shockable rhythm anymore.

The second major concern regarded the communication between the bystanders and the ECC call-takers. Although the call-takers were informed about the scenario and how they should assist the bystanders on the scene, confusion occurred because of imprecise help given to the bystanders. This order of operations is simple: ask the bystanders to check vital signs again and start resuscitation measures, give them information on the arrival of the drone and when the drone is about to arrive, and assist them in handling the AED until a shock is applied and to continue resuscitation measures. If this order is violated, we observed a decline in the quality of the resuscitation measures, ultimately leading to much longer hands-off times. This issue was addressed after the first test series by the implementation of a flowchart to assist ECC personnel in guiding bystanders throughout the entire emergency scenario in the correct order. This flowchart proved to be a valuable tool, highlighting that the active involvement of the ECC is vital for the success of the entire workflow. Bystanders need to be guided meticulously from the moment they recognize OHCA and start CPR to when it is safe to approach the drop-off location of the drone-delivered AED.

Finally, we noticed that it would be beneficial to know under which circumstances it is safe to approach the drop-off location for picking up the AED. Since bystanders can be alone in such a scenario, a clear indicator to pick up the delivered AED is missing. To address this concern, future tests could include acoustic notification by the drone itself (for instance, by attaching a megaphone to the drone) in addition to the call-taker informing the bystanders when it is safe to pick up the AED. Furthermore, the integration of such a notification could enhance the overall efficiency and safety of the operation. For instance, using acoustic signals from the drone can provide immediate and clear instructions to the bystanders, potentially speeding up the AED retrieval process.

3.3. SWOT—Opportunities

Integrating drones into emergency response protocols could revolutionize the way medical aid is delivered, especially in remote or hard-to-reach areas where traditional methods face significant delays. Future work will focus on optimizing the drone's operational capabilities, including improving flight stability and accuracy during AED delivery, enhancing communication systems between the drone, emergency centers and bystanders and developing robust protocols for various emergency scenarios. Additionally, exploring the integration of drones with other technologies, such as advanced GPS systems and real-time data analytics, could further enhance their effectiveness. The positive results from this study can be used to advocate for policy changes and funding allocations to support the integration of drones into emergency response systems. Collaborations with local and national emergency services, healthcare providers and technology developers will be crucial in scaling up the use of drones for medical emergencies. Moreover, public awareness and training programs can be implemented to educate bystanders and emergency personnel on how to interact with drone-delivered medical supplies. This will ensure that the public is well-prepared to utilize such systems effectively and confidently during real emergencies.

3.4. SWOT—Threats

One test day had to be canceled after three scenario runs due to strong wind. Despite the drone's ability to operate in wind speeds up to 60 km/h, a test stop was decided to avoid any additional risks to the study team members and participants. At this point, it was unclear at which wind speed the tested drone operation should be canceled. Ultimately, the responsible drone operator made the decision based on personal experience and after consulting with spotters at the emergency location. While such interruptions can be managed and testing can continue afterward, in a real-world application, unexpected cancellations without clear reasons are not desirable. For future testing, there should be a flight directive that includes maximum wind speeds, threats from thunderstorms and other weather conditions that would necessitate flight cancellation. These parameters need to be clearly defined to ensure safety and reliability. In a final real-world application, the drone should be programmed to autonomously interrupt its operations if internally defined thresholds, such as maximum wind speeds, are exceeded. This removes the need for human reasoning and ensures a standardized response to hazardous conditions. These thresholds must be predefined and rigorously tested to ensure appropriateness for various operational environments. Additionally, we observed that mobile phone connectivity was not always reliable and depended on the location of the bystanders in the field. In cases of non-connectivity, emergency calls cannot be made, which prevents the entire system from being initialized. This is a significant threat to the system's effectiveness, as reliable communication is critical for the timely deployment of drone-delivered AEDs.

4. Discussion

This study aimed to answer two research questions: first, which operational and/or logistical benefits and challenges of drone-based AED delivery to OHCA scenarios in mountainous regions can be identified? The results identified a benefit in time and flexibility in this mountainous region, as already suggested in earlier studies that have been performed in non-mountainous regions [3,4,9–11]. However, this study identified several obstacles that need to be overcome. The discussion includes all identified hazards and their relevance, as well as potential solutions, for further studies on the way to real-world implementation.

4.1. Hazards of a Mountainous Region

In the project considered in this paper, one test day had to be interrupted due to stormy weather conditions. For future testing and real-world application, there should be a flight directive that includes maximum wind speeds, threats from thunderstorms and other weather conditions that would necessitate flight cancellation. These parameters need to be clearly defined to ensure safety and reliability. In a final real-world application, the drone should be programmed to autonomously interrupt its operations if internally defined thresholds, such as maximum wind speeds, are exceeded. This removes the need for human reasoning and ensures a standardized response to hazardous conditions. These thresholds must be predefined and rigorously tested to ensure they are appropriate for various operational environments. Developing and implementing comprehensive flight directives will provide clear guidelines for safe drone operation under various weather conditions. This will not only enhance the safety of the operations but also ensure that the drones can be relied upon in real-world scenarios. Hence, integrating advanced weather monitoring systems within the drone's operational framework will enable real-time assessments and automatic adjustments to flight plans based on current weather conditions. Either the drone is constructed in a way that it can withstand stormy weather conditions or, at least for each region, the historical weather data must be analyzed to identify the probability of disadvantageous flight conditions. A lenient approach might be reasonable because during storms, fewer people will go hiking, and the likelihood of the occurrence of OHCA will be rather low. Of note, wet surroundings are a contraindication for defibrillations; therefore, an AED drone will probably not be dispatched in cases of rainy weather. Future developments should, therefore, focus mainly on wind resistance during the flight and the landing maneuver. Additionally, in drone operations, involved personnel must be adequately trained in handling emergency situations, understanding weather-related risks and making informed decisions based on real-time data. This will improve the overall effectiveness of the system. While the test day cancellation highlighted some operational challenges, it also provided valuable insights into areas that need improvement and finally will help to develop a more reliable and effective drone-based emergency response system.

Another problem of mountainous regions is the coverage area of the telephone network. Enhancing mobile phone connectivity is crucial. This could involve deploying mobile signal boosters in areas with poor reception or working with mobile providers to improve the infrastructure in remote or rural areas. Ensuring robust connectivity is vital for the seamless operation of the emergency response system. Additionally, we observed that mobile phone connectivity was not always reliable and depended on the location of the bystanders in the field. In cases of non-connectivity, emergency calls cannot be made, which prevents the entire system from being initialized. This is a significant threat to the system's effectiveness, as reliable communication is critical for the timely deployment of drone-delivered AEDs. Solving this issue requires collaboration with mobile phone providers to enhance coverage and ensure consistent connectivity in all potential emergency locations. This could involve deploying mobile signal boosters in areas with poor reception or working with mobile providers to improve the infrastructure in remote or rural areas. Ensuring robust connectivity is vital for the seamless operation of the emergency response system. The widespread use of mobile phones leaves little space for alternative communication tools that might work in locations with poor connectivity, like satellite telephones.

4.2. Tracking and Transmission of GPS Coordinates

The tracking of a bystander's location by the ECC was found to work well with Android-based mobile phones, provided there was mobile phone connectivity. However, it was impossible to track locations using iOS-based phones, which is a significant limitation that needs to be addressed in the future. This issue could be either country-specific or a technical limitation of the involved ECC. Accurate caller location information, such as that provided by the Advanced Mobile Location service, is regularly transmitted by both Android and iOS devices, according to the European Emergency Number Association (2020) [24]. Therefore, the inability to track iOS devices indicates a gap in the current system that must be rectified to ensure that all mobile users, regardless of their device, can be accurately located in an emergency. Improving these systems is crucial.

The transmission of GPS coordinates was successful in all cases. Integrating a direct software link would streamline the process, ensuring that critical information reaches the drone pilot almost instantly. This time lag needs to be reduced to improve response times and efficiency. One potential solution is the integration of a dedicated interface that allows a direct link between the ECC and the drone flight planning software. This would eliminate the email intermediary and speed up the process significantly. Future developments should also focus on overcoming the technical limitations that prevent accurate tracking of iOS devices and ensuring that all mobile phone users can benefit from this life-saving technology.

4.3. Integration of the ECC in Drone-Based AED Delivery

Another improvement that was introduced during the test series was the implementation of a flowchart (see Supplementary Materials, Figure S1) to assist ECC personnel in guiding bystanders throughout the entire emergency scenario. This flowchart proved to be a valuable tool, highlighting that the active involvement of the ECC is vital for the success of the entire workflow. Bystanders need to be guided meticulously from the moment they recognize OHCA and start resuscitation measures to when it is safe to approach the drop-off location of the drone-delivered AED. Even professional paramedics require guidance, particularly in managing the drone and picking up the AED.

Furthermore, enhancing the guidance provided to bystanders and paramedics ensures that they can effectively use the AED delivered by the drone, maximizing the chances of successful resuscitation. Providing comprehensive training on handling emergency situations will improve the overall effectiveness of the system. Additionally, ongoing training and updates on new technologies and protocols will keep the team motivated and prepared for any advancements in drone technology and emergency response strategies.

4.4. Autonomous Drone Flights

Future implementations should consider improving the reliability and clarity of the drone's autonomous systems to prevent flight anomalies. Ensuring that the drone can consistently perform precise maneuvers without manual intervention will increase the safety and effectiveness of the AED delivery. To ease the interaction between the drone and the bystanders, clear signs, like colored lights, voice recordings or a loudspeaker attached to the drone that gives instructions at specific time points, could be used. Such signals could remarkably improve the safety and confidence of laypersons being confronted with this aerial vehicle. By refining the delivery methods, enhancing communication protocols and addressing safety concerns, this approach can be further optimized to provide rapid and reliable assistance during cardiac emergencies.

4.5. AED Drop Off

The delivery method of the AED, where it was hung on a rope attached to the drone, was preferred over a full landing due to safety concerns. Compared to other AED drop-off methods, such as parachutes, this approach also offers time advantages, as a full landing would require time-consuming instructions and coordination efforts with the bystanders. However, it is still not clear which proximity of the ground is necessary to drop off medical devices safely for the bystanders and the device itself. The tested AED was working without hazards throughout the test series. In real-world applications, several tests and rigorous safety checks will be needed to exclude technical issues or any damage. Furthermore, a visual and/or acoustic signal from the drone could ensure the safe retrieval of an AED. To address this concern, future tests could include two separate approaches: acoustic notification by the drone itself (for instance, by attaching a micro/megaphone to the drone) or the call-taker informing the bystanders when it is safe to pick up the AED. The latter approach is likely more feasible since the call-taker is already in constant contact with the bystanders throughout the CPR process until the EMS arrival. Furthermore, the integration of these notifications can enhance the overall efficiency and safety of the operation. Acoustic signals from the drone can provide immediate and clear instructions to the bystanders, potentially speeding up the AED retrieval process. On the other hand, relying on the call-taker ensures a personalized and guided approach, which can be reassuring for the bystanders, especially in a high-stress situation.

4.6. Limitations

Several limitations of this study remain. The sample size was rather small, and the (quantitative) results must be interpreted with caution. Also, the participant sample may lack representativeness, as we were not able to include multiple age groups and an adequate gender balance. Random passers-by who declined to participate in our study may have performed better or worse. The paramedics who participated in our study were blinded toward the scenario but should not be considered representative of the general population due to their training. Taking these points together, a generalizability of the (quantitative) results cannot be performed, and studies in the future should consider both aspects. Next, the results from scenarios in which mobile phone connection was interrupted and paramedics had to instruct participants should be viewed critically, as this does not fully correspond to the real-world situation because the paramedics saw what was happening on the scenes in contrast to the call-takers. Nevertheless, observations were worth including in the analysis because the drone flight can be viewed independently of resuscitation. In addition, we did not consider aerial rescue in the scenario, which should be part of future testing, as the parallel presence of drones and helicopters in the same airspace requires standardized operational procedures. Prospective studies may be designed in a way to address these issues before real-world implementation. And finally, at the current stage of testing, we have been primarily focusing on operational as well as logistical challenges and benefits, thereby excluding a deeper analysis of cybersecurity countermeasures and the costs of the drone-based AED delivery system. Further tests should include technicians from drone companies, the ECC and mobile network providers to evaluate the risk of cyberattacks against the AED delivery system and design countermeasures. Also, a comprehensive cost analysis remains a matter for future research. Not only costs for operating the drone itself but also for implementing the system into the existing structure of emergency response centers and setting up drone hubs within landscape infrastructures should be assessed. Additionally, a cost comparison of the system with other means of transport (e.g., helicopters) can be integrated into such an analysis. Notably, the AIR8 Medium Lifter drone used for the tests is not approved by the United States Federal Aviation Administration.

5. Conclusions

This study complements the existing scientific literature by presenting the first findings regarding the practical feasibility of drone-based AED delivery in mountainous regions. Regardless of the obstacles discussed above, the short response times of the drone demonstrate its potential to compete with helicopter rescue services. A detailed analysis of historical helicopter flight times in the test area will provide more insights into this potential and will be the subject of future work. Embedding such a system into existing emergency response strategies offers great opportunities to accelerate response times in critical emergencies.

Recently, a local air rescue organization ÖAMTC initiated a project on medical drone services, where the advantages of drones are considered relevant for wider integration into aerial emergency response. This initiative highlights the growing recognition of drones' capabilities in enhancing emergency response efforts. In this regard, the positive observations within this study support the roll-out of such a system, providing external stakeholders with empirical insights from practical tests. The success of the proposed system in this study not only demonstrates the feasibility and operational efficiency of drone-assisted emergency responses but also paves the way for further advancements in this field. Integrating drones into emergency response protocols could revolutionize the way medical aid is delivered, especially in remote or hard-to-reach areas where traditional methods face significant delays. Future work will focus on optimizing the drone's operational capabilities, including improving flight stability and accuracy during AED delivery, enhancing communication systems between the drone, emergency centers and bystanders and developing robust protocols for various emergency scenarios.

Additionally, exploring the integration of drones with other technologies, such as advanced GPS systems and real-time data analytics, could further enhance their effectiveness. The positive results from this study can be used to advocate for policy changes and funding allocations to support the integration of drones into emergency response systems. Here, a clear definition of no-fly zones and a re-evaluation of current no-fly zones will be necessary. The risk assessment could be streamlined with legal securities and thereby simplify real-world application. It is probably not cost-effective to guarantee AED drone coverage within a drone network of 100%, even in regions with very low incidence rates of OHCA. Epidemiologic research can fill this gap, and policy should encourage the establishment of OHCA registries to identify the most effective places for AED drones [25]. Collaborations with local and national emergency services, healthcare providers and technology developers will be crucial in scaling up the use of drones for medical emergencies. Moreover, public awareness and training programs can be implemented to educate bystanders and emergency personnel on how to interact with drone-delivered medical supplies. This will ensure that the public is well-prepared to utilize such systems effectively and confidently during real emergencies. In conclusion, the proposed drone-based emergency response system has demonstrated substantial promise in reducing response times and improving outcomes in simulated OHCA emergencies. The ongoing and future efforts to refine and integrate this technology into mainstream emergency response frameworks will likely result in significant advancements in emergency medical services, ultimately saving more lives.

With this study, we enrich academia by presenting new knowledge on the application of drones in combination with traditional rescue approaches to enhance the overall performance of medical treatment of critical-care patients. Practitioners can benefit from our results as they provide valuable insights into the performance gains achieved through drone-based AED delivery. Furthermore, rescue organizations can use our framework as guidance for structured drone implementation into existing workflows during critical emergency response missions.

To conclude, the above-described results indicate that the proposed approach is feasible and safe from both an operational and logistical viewpoint. Laypersons, as well as EMS members, felt confident in handling the drone-delivered AED. Several obstacles were identified, and how to incorporate this system into the existing EMS was discussed.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/drones8100525/s1, Figure S1: Flowchart of the scenario setup including the various time samples.

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