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Review

Current summary of the evidence in drone-based emergency medical services care

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Abstract

Interventions for many medical emergencies including cardiac arrests, strokes, drug overdoses, seizures, and trauma, are critically time-dependent, with faster intervention leading to improved patient outcomes. Consequently, a major focus of emergency medical services (EMS) systems and prehospital medicine has been improving the time until medical intervention in these time-sensitive emergencies, often by reducing the time required to deliver critical medical supplies to the scene of the emergency. Medical indications for using unmanned aerial vehicles, or drones, are rapidly expanding, including the delivery of time-sensitive medical supplies. To date, the drone-based delivery of a variety of time-critical medical supplies has been evaluated, generating promising data suggesting that drones can improve the time interval to intervention through the rapid delivery of automatic external defibrillators (AEDs), naloxone, antiepileptics, and blood products. Furthermore, the improvement in the time until intervention offered by drones in out-of-hospital emergencies is likely to improve patient outcomes in time-dependent medical emergencies. However, barriers and knowledge gaps remain that must be addressed. Further research demonstrating functionality in real-world scenarios, as well as research that integrates drones into the existing EMS structure will be necessary before drones can reach their full potential. The primary aim of this review is to summarize the current evidence in drone-based Emergency Medical Services Care to help identify future research directions.

Keywords: Drone, Emergency Medical Services, Cardiac arrest, Automated external defibrillators, Unmanned Aerial Vehicles, Out-of-hospital cardiac arrests, Defibrillation, EMS, Naloxone, Anti-Epileptics, Prehospital medicine

Patient outcomes in many emergent clinical conditions – such as cardiac arrests, strokes, myocardial infarctions, drug overdoses, seizures, and trauma – are linked to how quickly medical interventions can be delivered. Improving the treatment of the most time-sensitive conditions has been a key focus of emergency medical services (EMS) systems and prehospital medicine over the past 50 years. One of the most significant developments in this regard was the widespread implementation of automated external defibrillators (AEDs) in the 1980s, which allowed prehospital providers to effectively defibrillate patients in cardiac arrest.[1] Likewise, the development of autoinjectors by the military allowed for the introduction of the EpiPen, which has been the cornerstone of prehospital anaphylaxis treatment since it was introduced in 1987.[2–4] A more recent and similarly impactful development is the proliferation of intranasal naloxone, which is effective in treating patients suffering an acute opioid overdose.

The effectiveness—and urgency—of these treatments is so high that, in many cases, they are distributed within the community in hopes that they can be administered by a bystander prior to EMS arrival (i.e., public access AEDs, home EpiPens, and over-the-counter naloxone). However, the benefits of such efforts have been inconsistent, and their widespread community staging is often prohibitively expensive.[5] Consequently, the rate-limiting step in treatment of these time-sensitive emergencies remains, in most cases, the speed with which medical responders can arrive on-scene.

Unfortunately, public demand for EMS services in the US has risen dramatically over the past 10+ years, while EMS system funding, CMS reimbursement, and number of providers have not kept

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pace with costs.[6–8] Furthermore, the COVID-19 pandemic has compounded staffing shortages and prolonged response times for EMS both in the US and globally.[9–11] Despite the expansion of communities' needs over time and specifically during this global healthcare crisis, EMS systems' ability to quickly respond to time-sensitive emergencies has declined.

One promising technology currently being studied to improve access to effective prehospital medicine is the use of Unmanned Aerial Vehicles (UAVs), or drones. Drones are pilotless robotic devices capable of flying autonomously using pre-set programming or through remote control modalities. Over recent years, drone use and accessibility has rapidly expanded within the civilian and commercial spheres, from the entertainment industry to agriculture.[12] Due to increased speed, lack of reliance on traffic patterns, and relative immunity to staffing shortages, drones offer the potential to reliably serve as a bridge between the onset of a medical emergency and EMS arrival.[13]

Prior reviews have reinforced the potential for drones to improve medical services.[14,15,15–18] Clinicians and emergency responders have advocated for and investigated drones as mechanisms to deliver critical medical equipment or therapies to the scene of an emergency while offering the ability to gather and transmit information from an emergency scene to remote medical teams. The potential applications of drones in EMS are vast and the literature is evolving yet underdeveloped, resulting in significant opportunities for future research to impact patient outcomes. Here we examine the current literature on potential drone uses in EMS and establish future directions for research. Most of the research has focused on the delivery of AEDs while literature concerning the delivery of other emergency supplies such as naloxone, anti-epileptics, and blood products is more limited but growing.

Box 1: Summary of search strategy and paper selection

We searched PubMed (MEDLINE), Embase and Web of Science databases using the following keywords combined with the Boolean operators "AND" and "OR" as appropriate: "drone," "unmanned aerial vehicle," "emergency medical services," "EMS," "emergency treatment," "emergency medical dispatch," "emergency," "emergencies," "out-of-hospital," "prehospital,". We also manually reviewed the bibliography of the identified articles and performed additional targeted searching in Google Scholar, Access Medicine, and CINAHL. The last literature search was performed on April 11, 2022.

Drones for AED delivery

Out-of-hospital cardiac arrest (OHCA) is considered by many to be the most time-sensitive medical emergency.[19–22] In the United States, there are an estimated 350,000 OHCA annually, with a survival rate (<10%) that has remained essentially unchanged for the past three decades.[19–22] Increased early AED use is associated with variable, yet significant, increases in survival rates and more productive life-years in patients with a shockable initial rhythm [ventricular tachycardia (VT) or ventricular fibrillation (VF)].[16,17,9] Prompt intervention increases likelihood of a more favorable outcome. In OHCA patients defibrillated within 2 min, nearly 60% survived, compared to 13.2% for patients defibrillated within 10 min.[23]

AED devices used in OHCA are typically brought by first responders or are public-access defibrillators (PAD). The use of a PAD can double the chance of OHCA survival.[24,25,] Despite this, these AEDs are only used by bystanders in $\sim$ 5% of out-of-hospital cardiac arrests in the US.[26] The cause of this low use rate appears to be multifactorial, including accessibility issues and ease of locating the PAD.[27] Creative alternate mechanisms to increase bystander AED use include the use of drones to deliver AEDs to the site of an OHCA. Here we examine the current literature on potential drone uses for AED delivery in OHCA response.

Theoretical impact of drone networks utilizing mathematical modeling/computer simulations

For maximal efficiency, drones would need to be automatically deployed through the EMS network following a 9-1-1 call from predetermined locations specifically chosen to optimize regional coverage. Such optimization involves mathematical and geographic analysis of areas with prolonged EMS response times to determine the most appropriate number and location of drone bases. These mathematical models can then estimate the effect of the identified base stations on the time to delivery of AEDs and other medical equipment.

Computer-simulated networks of drone bases have been shown to theoretically enable significant improvements in AED response times over large geographic areas. A mathematical optimization model utilizing AED-equipped drone docking stations suggested that such a network could double the region's OHCA survival rate compared to previously published survival data for North Carolina.[28–30] Using modeling techniques such as geographic information system (GIS), optimal drone networks were created and demonstrated improved response times compared to EMS in Canada, The United States, Sweden, France, and South Korea.[22,31–38] There are obvious situations in which drones would not improve the delivery time of an AED relative to EMS AED delivery, such as if an OHCA occurred immediately adjacent to an EMS base station. In Ontario, machine based learning analyzed 3,573 suspected OHCA and demonstrated the ability to delineate the OHCA in which drones would have a time benefit from those situations in which it would not.[36] When used to create and optimize drone networks for OHCA response, GIS modeling suggests that optimally located drones could result in robust improvements in the time to AED delivery while providing broader geographic AED coverage than traditional ground EMS. Limitations to GIS modeling do exist, including their inability to accurately account for the subtle complexities in EMS systems, such as field triage decisions.[39] However, GIS modeling has previously demonstrated promising results in reducing EMS response time.

Financial analysis

While costs for novel technologies, such as drones are difficult to predict, efforts to assess this cost have been made in several studies. The cost-effectiveness of drones for the delivery of AEDs was evaluated in Germany, via a location-allocation analysis. It was estimated that a drone network that covered 80% of the difficult-to-reach areas would require 800 drones and save an additional 1,477 life-years at a cost of approximately €18 million per year.[40] In another financial modeling study in Italy, it was estimated that 96 drones were able to cover an area of 2,800 square km to provide a time to intervention of just 4.5 min at a cost of approximately €300,000.[41] It was estimated that the cost of drone use in North Carolina was $3,143 to $13,501 per quality-adjusted life year, based on the number of drones and associated survivors, well under the $50,000 per quality-adjusted life year typical benchmark of cost-effectiveness.[29,42] Although still in early testing and simulation phase, emerging technologies such as 3D printed drones, such as the drone developed by *Gino et al.,* for AED transport, could potentially lower total system costs even further.[43]

Time saving compared to ground

Many studies of simulated OHCA have compared the time to drone AED delivery versus ground EMS AED delivery and suggest that drones may improve AED delivery times to the scene of an OHCA. One study in Sweden found that drones traveling 70 km/hr arrived earlier than ground EMS in all OHCA cases, with a median reduction in response time of 16 min and 39 s.[44] In another Canadian simulation study, drones and traditional EMS were dispatched simultaneously from the same location to a simulated cardiac arrest; the drone, traveling 80 km/h, arrived at the scene between 2.1 to 4.4 min faster than EMS.[45,46] When drones were dispatched from a location specifically selected to optimize drone delivery coverage, the drone arrived on the scene and resulted in AED application 6–7 min earlier than the traditionally dispatched EMS crew. Similarly, drones were either launched from the same base as EMS, a remote EMS base, or an optimal location chosen via computer modeling. The AED-delivery drone arrived faster in all three scenarios, with the time savings ranging from 1.8 to 8 min. Not surprisingly, the optimized drone location facilitated the fastest AED delivery.[45,46] Similarly, in a recent study by Baumgarten *et al.* drones were dispatched from five drone bases to a simulated OHCA in Germany, with a time to defibrillation varying from approximately 6 min to 15.5 min, depending on the distance traveled to the scene from the drone launch site, a considerable improvement compared to the average EMS time to defibrillation of 19.5 in 2019.[47,48] Because the majority of studies demonstrating the time saving nature of drones are simulation-based, which may over-exaggerate any time benefit, more real-world studies are needed to account for other variables, such as delays due to air traffic control and dispatching.

Though the majority of time saving studies are simulations, there is one recently published study describing the prospective real-world use of drones to deliver AEDs to the scene of 12 actual OHCA cases.[49] In this study, the drone successfully delivered the AED in 92% of OHCA cases and arrived faster than traditional ground EMS in 64% of those cases. This reduced median delivery time by nearly-2 min. None of the AEDs were applied to patients prior to EMS arrival, and there were no adverse events. Although not as robust a time savings as demonstrated in simulations, this study proves the feasibility of real-world application of drone delivery and paves the way for future real-world trials.[49] Furthermore, in a recently reported major milestone for drone-based delivery of AEDs, a drone-delivered AED was used to deliver a shock before the arrival of ambulance personnel.[50] To our knowledge, this is first ever real-world use of a drone-delivered AED.

Time saving compared to public-access AEDs

There is minimal literature directly comparing drone-based AED delivery to the utilization of public access AEDs. In one such study, bystanders in 35 OHCA simulations were tasked to either search for a nearby PAD or to call 9-1-1, who would dispatch an AED-equipped drone. A drone delivered an AED within 5 min in 71% of the trials, compared to just 51% of the ground searches for a PAD, suggesting that drone AED delivery is faster than bystanders searching for PADs and would likely improve outcomes for OHCA.[51,52]

Bystander experiences with a drone-delivered AED

The impact of the delivery of an AED by drone is highly dependent on bystanders at the scene who must approach the drone and retrieve the device. In OHCA simulation studies, it took 15–39.7 s to deliver the AED to the patient following drone arrival, suggesting that bystander-drone interactions were not the rate-limiting step in an OHCA with drone AED delivery.[47,51,52] Bystanders reported the ability to stay by the victim while a drone delivers the necessary medical equipment, whereas they had to leave the patient when using a public-access AED. Few participants articulated safety concerns such as the possibility of drone accidents.[22,53,54]

They did express a desire for clearer instructions from the dispatcher regarding what to expect with the arrival of the drone and suggested drones be equipped with automated signaling to announce their arrival. They also made suggestions regarding clearer labeling of the drone to ease removal of the AED, along with improved dispatcher instruction on how to access the AED and perform CPR. Such observations of drone-bystander interactions are being used to impact drone design, including the integration of drone-based video feeds to augment dispatcher-assisted CPR.[55,56] Further work into bystanders' interactions with the method of AED delivery is necessary to optimize the drone-bystander user experience.

Although these studies have their limitations, the current evidence suggests that bystander interactions with drones are positive and unlikely to be a major hindrance to drone-based delivery of AEDs. Upon review of the published medical literature, we found no studies demonstrating significantly problematic bystander-drone interactions.

Stakeholders' opinions regarding a drone-delivered AED

In addition to the abilities and attitudes of simulated bystanders, research has also evaluated the opinions of key stakeholders regarding the development of drone-based EMS care for out-of-hospital cardiac arrest. In North Carolina, healthcare and EMS providers along with members of government and the aviation industry all vocalized broad support for drone-based AED delivery as they felt it would reduce response times and enhance access.[57] While uniformly supported, areas of concern included operationalization of the system, privacy and safety issues, legal and regulatory requirements, financial liabilities, public buy-in, and the need for research on the cost-effectiveness of a drone network. They additionally noted that the development of a drone AED network would require identifying viable funding from private and public entities and learning from existing drone models in other industries.[57]

Drone-based delivery of other emergency supplies

The drone-based delivery of other emergency medical supplies is less well-studied, though feasibility and simulation studies suggest drones could offer similar improvements in time to access these critical materials.

Naloxone

The rapid administration of naloxone can reverse a potentially fatal opioid overdose, which in its intranasal (IN) form, can be easily administered by a bystander.[58] Although the prescription of home IN naloxone to at-risk patients has increased over the past decade,[59] recent data suggest that less than five percent of overdose victims receive bystander-administered naloxone,[60] likely attributable to inadequate naloxone access. There remains a critical need to improve naloxone availability on the scene of otherwise often-fatal opioid overdoses, especially in rural settings.[61] Preliminary studies suggest drone-based delivery of naloxone would be a feasible and faster method compared to historical ground EMS response times,[62–64] and that drone technology may be able to assist with prompt bystander administration.[62]

Similar to the AED drone literature described above, Ye *et al.* developed a geospatial network model to investigate the potential for drones to improve the delivery time of naloxone in Durham County, North Carolina, an area with an average ground EMS response time to overdose scenes of 10 min and 46 s. Their analysis determined that four drone launch bases could optimally cover 64.2% of the county and reduce response times by 4 min and 38 s compared to traditional EMS response.[64] Subsequently, Tukel *et al.* also showed significantly faster IN naloxone drone delivery time compared to historical EMS data using a simulation study of 50 drone flights in Detroit, Michigan.[63] Flight trials were planned using locations of previous EMS calls for overdoses or suspected overdoses, creating a realistic simulation of destinations and allowing for direct comparison to historical EMS ground response for those locations. Drone response times were drastically faster than ground ambulance at all distances measured, with a mean difference ranging from 189 to 255 s.[63] A study by Ornato *et al.* achieved similar findings in Richmond, Virginia, demonstrating naloxone could be delivered by drone and administered by a bystander within 2 min of initial 9-1-1 contact.[62] This was further facilitated using remote audio communication where a 9-1-1 operator provided verbal instructions on how to locate the drone and administer the naloxone. While a small subset of participants reported difficulty with naloxone administration, all attempts were ultimately successful. Notably, 97% of participants stated they felt confident they could administer the medication again in the future.[62]

We identified no published feasibility studies where a drone-delivered naloxone system has been used to respond to real-world overdose cases.

Anti-epileptics

It is well-established that prolonged seizures or status epilepticus demands prompt treatment, as the likelihood that a seizure will spontaneously terminate decreases with prolonged time to therapy.[65] Longer seizure duration and refractory status epilepticus are associated with higher mortality and morbidity.[66] A greater than 10-minute delay in benzodiazepine treatment from onset of pediatric status epilepticus has been associated with higher frequency of death, increased need for continuous infusions of anti-epileptic medications, longer seizure duration, and more unstable vital signs.[67] In the case of a seizure lasting longer than 5 min, prehospital administration of benzodiazepines reduces the duration of the seizure and the likelihood of recurrence.[68,69] Many seizures occur outside of a hospital setting, where prompt treatment has several challenges. Administration of benzodiazepines by family and bystanders has historically been hindered by route of administration as, until recently, the only FDA-approved medication utilized a rectal route of administration.[70–72] While the development of alternative administration routes and formulations[73–79] has begun to mitigate these concerns, lack of access to benzodiazepines in the out-of-hospital setting, similarly to AEDs and naloxone, remains a barrier.

Geospatial modeling in the Republic of Guinea investigated the feasibility and potential benefits of drone-based delivery of anti-epileptics for out-of-hospital status epilepticus.[80] This setting was chosen given current challenges with accessing anti-epileptics and other medical supplies due to widespread poverty, poor transportation infrastructure, and limited access to public and private transport. Mateen *et al.* evaluated drone-based delivery time to 27 public access points (e.g., pharmacies, mosques, gas stations) throughout the country using four drones. Their analyses showed an overall 80% reduction in time to intervention compared to ground transportation.[80] Specifically, their modeling demonstrated that drones could access eight of these access points within 5 min of dispatch, 20 within 10 min, and 24 within 15 min, compared to ground transportation, which could reach only two of these points within 10 min and five within 15 min.

There are no other published studies describing drone delivery of antiepileptics, either simulation or real-world. Preliminary theoretical work by Mateen *et al.* shows the potential impact of drone-based delivery of anti-epileptics, especially in under-resourced and/or rural areas with poor infrastructure.[80] Previously described simulation studies of drone-delivered naloxone may indirectly support the use of drone-based delivery of anti-epileptics given their similarities in payload size. Importantly, the delivery by drone of anti-epileptic medications may be limited by the logistics of distributing controlled substances, such as benzodiazepines.

Epinephrine

Anaphylaxis is yet another time critical emergency which may rapidly progress to death if not appropriately treated with epinephrine.[81] Consequently, epinephrine auto-injectors are also a time-critical medical intervention that may be delivered by drones. However, research to-date on the delivery of epinephrine auto-injectors by drone is limited. Auto-injectors for anaphylaxis have been found to be stable through drone transport conditions and feasibility may be indirectly supported through work on naloxone and anti-epileptic transport.[82] However, further research regarding the delivery of epinephrine by drone is necessary.

Other

To our knowledge, there are also no other peer-reviewed studies or case reports describing drone delivery of other critical medications for bystander use, such as inhaled bronchodilators for asthma, glucagon autoinjectors or buccal dextrose gel for hypoglycemia or tourniquets for arterial hemorrhage. Research in these areas is warranted.

Emergent blood products

Another potential area within EMS where drones could be utilized would be the augmentation of paramedic-based care through the transport of rare interventions that are typically under-utilized in the prehospital setting due to logistical constraints, such as blood for trauma. Blood products, including red blood cells (RBCs), platelets, and plasma, can be safely transported without evidence of deleterious changes via drones equipped with a cooler and temperature monitoring technology. However, there are no published studies looking at drone-based delivery of blood to a prehospital scene for use by trained personnel and further research in this area is needed.[83–88]

Drone-based interfacility delivery of blood products has been investigated to address shortages of blood among hospitals, particularly in rural settings or in times of increased blood demand. The feasibility and potential time savings of drone-based blood delivery has been studied in rural Rwanda and Borneo, in urban North America, and to remote islands in Japan.[89–93]

In rural Rwanda, ground transportation has historically been unable to deliver blood products effectively and promptly to remote areas due to numerous difficulties including topography, limited transportation infrastructure, and the short half-life of many medical products.[90,91] In 2016, Zipline International and the Rwandan government developed a system in which drones were dispatched from two central bases to 21 different healthcare facilities located up to 80 km away with reported delivery times ranging from five to 45 min for emergency orders and within 3 h for non-emergent orders.[94] Since its inception, this system has seen significant improvements in both delivery times and rates of blood product waste. A recent study in Borneo investigating the feasibility of a similar system found that drone delivery of blood is more cost effective than traditional ground-based transport model.[92,95]

Recent work by Homier *et al.* investigated potential benefits of the drone-based interfacility delivery of blood products in an urban setting in the context of a simulated mass casualty incident, where there is increased stress on blood supplies and disruptions in ground transportation. Over nine runs of simultaneous drone- and ground-based transportation of simulated blood products from blood centers to two trauma centers, drone transport time was significantly shorter than ground transportation (average of 17 and 29 min respectively). This difference was even greater during times of increased ground traffic congestion, when ground transportation time increased to over twice that of the average drone delivery time. No adverse events or safety concerns occurred during any of these trials and drones equipped with appropriate technology ensured the simulated blood products remained within acceptable temperature ranges throughout transport.[96]

Blood delivery to remote islands presents another suite of challenges, as infrastructure and population density are often not sufficient to support the local storage of blood products. In one recent Japanese study, blood samples were carried by drone from Tokyo to Sasebo, approximately 1,000 km away, to simulate flight to a remote outlying island. The investigators found that samples remained viable with adequate temperature control during flight and no evidence of hemolysis on arrival.[93]

One of the most significant limitations of drone-based delivery of blood products is drone payload capacity, particularly in comparison to that of a ground ambulance. For instance, Zipline cites payload weight limitation of 1.3 kg or two units of blood per drone.[90] This limitation would be most problematic in situations of high blood product demand.

Non-medical limitations of drones

Admittedly, there are a variety of non-medical barriers to EMS drone implementation whose full analysis is beyond the scope of this review. Within the United States, Federal Aviation Administration (FAA) regulations, security concerns, funding streams, and costs and requirements related to licensure, training, and insurance, will need to be addressed prior to widespread adaptation into existing EMS systems. Additionally, intra-state transport and dispensing of medications may be open to regulation by state boards of pharmacy or the Federal Drug Administration (FDA).

Conclusions

Prehospital medical indications for using drones are rapidly increasing and are poised to significantly impact out-of-hospital emergencies. Drones offer an exciting possibility to reduce the time-to-intervention and improve patient outcomes for time-dependent medical emergencies that are beyond the rapid arrival of traditional EMS. However, significant research remains before drones are likely to realize their full potential and achieve widespread adoption, including further research demonstrating functionality in real-world scenarios and guidance on how to operationalize broad integration into the EMS system.

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Nathan B. Roberts: Conceptualization, Writing – original draft, Writing – review & editing. **Emily Ager:** Conceptualization, Writing – original draft, Writing – review & editing. **Thomas Leith:** Conceptualization, Writing – original draft, Writing – review & editing. **Isabel Lott:** Conceptualization, Writing – original draft, Writing – review & editing. **Marlee Mason-Maready:** Conceptualization, Writing – original draft, Writing – review & editing. **Tyler Nix:** Conceptualization, Writing – original draft. **Adam Gottula:** Writing – review & editing. **Nathaniel Hunt:** Conceptualization, Writing – review & editing, Supervision. **Christine Brent:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision.

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