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The Case for Drone-assisted Emergency Response to Cardiac Arrest:

An Optimized Statewide Deployment Approach

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Abstract

BACKGROUND—Despite evidence linking rapid defibrillation to out-of-hospital cardiac arrest (OHCA) survival, bystander use of automatic external defibrillators (AEDs) remains low, due in part to AED placement and accessibility. AED-equipped drones may improve time-to-defibrillation, yet the benefits and costs are unknown.

METHODS—We designed drone deployment networks for the state of North Carolina using mathematical optimization models to select drone stations from existing infrastructure by specifying the number of stations and the targeted AED arrival time. Expected outcomes were evaluated over the drone's lifespan (4 years). We estimated the following parameters: proportion of OHCAs within a targeted AED delivery time, bystander utilization of AEDs, survival/neurological status, and incremental cost per quality-adjusted life year (QALY).

RESULTS—Statewide, 16,503 adults aged 18 or older were expected to experience OHCA with an attempted resuscitation over 4 years. Compared to no drone network, all proposed drone networks were expected to improve survival outcomes. For example, assuming 46% of OHCAs have bystanders willing to use an AED, a 500-drone network decreased the median time of defibrillator arrival from 7.7 to 2.7 minutes compared to no drone network. Expected survival rates doubled (24.5% versus 12.3%), resulting in an additional 30,267 QALYs ($858/incremental QALY). If just 4.5% of OHCAs had willing bystanders, 13.8% of victims would have survived. Sensitivity analysis demonstrated that an AED drone network remained cost-effective over a wide range of assumptions.

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CONCLUSI0NS—With proper integration into existing systems, large-scale networks for drone AED delivery have the potential to substantially improve OHCA survival rates while remaining cost-effective. Public health researchers should consider advocating for feasibility studies and policy development surrounding drones.

The American Heart Association Emergency Cardiovascular Care Committee aims to double out-of-hospital cardiac arrest (OHCA) survival rates to 15.5% by 2020 [1]. However, recent estimates suggest insufficient progress toward this goal. Of the estimated 395,000 adults who annually experience OHCA in the United States, only 6% survive to hospital discharge and this number remains unchanged over the past 30 years [2–4].

OHCA victims are more likely to survive and have a favorable neurological status when they receive early defibrillation [2, 5–8]. A recent study found that OHCA survival rates increased with shorter time-to-defibrillation—13.2% survived if defibrillated greater than 10 minutes after arrest, but 59.1% of those defibrillated within 2 minutes survived [9]. However, reducing time-to-defibrillation presents a major challenge, as timely access is influenced by a complex set of conditions including: emergency response arrival; modest witness rates; proximity of automatic external defibrillators (AEDs); and a bystander’s ability to locate and willingness to use an AED [10, 11]. These barriers help explain why bystanders defibrillate only 2% of OHCAs prior to emergency medical service (EMS) arrival [4, 12]. Accordingly, the Institute of Medicine advocates for developing innovative technologies to increase bystander AED use [13].

A recent feasibility study in Sweden demonstrated a significantly faster delivery of AEDs by drones than estimated EMS arrival times [14]. A network of autonomous flight AED-equipped drones—housed in *drone docking stations* where they are protected, charged, and then dispatched by a central system—may be a novel system for the quick delivery of AEDs to bystanders over a large region. The purpose of our study was to design a statewide network of drone docking stations within North Carolina. We developed mathematical models to optimize the selection of docking station locations and compared the expected costs and patient outcomes of each strategy to those if no drones were purchased. North Carolina is an opportune place for examining statewide OHCA response initiatives as it is the 9th most populated US state (population ~10 million) characterized by both urban and rural regions over various terrains, with over 10,000 deaths attributable to coronary heart disease annually [15]. Furthermore, designing a drone-enabled medical device delivery infrastructure aligns with the state’s goal of accelerating drone integration into airspace and public service through policy development, economic development, and technological advancement of the modern air transportation system.

Methods

Geographical Units

We assessed the access to an AED within a target time for each census block group in North Carolina. Block groups are the smallest geographical unit designated by the US Census and partition each county into areas with between 600 and 3,000 people [16]. A block group was considered "covered" if the expected time until arrival of an AED to its population center by either a drone or EMS was within a specified target time.

Estimating the Incidence and Location of OHCAs

We estimated age- sex- and race-adjusted incidence of OHCA in each North Carolina census block group (N = 6,155) [16] using incidence of OHCA events where resuscitation was attempted as reported from the Cardiac Arrest Registry to Enhance Survival (CARES) registry [17]. However, CARES reported 2009 total population by region but not strata-specific populations in that publication [17]. Thus, we retrieved 2009 US Census estimates for each of the regions published, stratified by age group, sex, and race, and summed across all regions for each strata to arrive at strata-specific population denominators for the CARES regions. Then, we calculated the incidence rate for each stratum using the CARES-published estimated OHCA incidence [17] as the numerator and our population estimate as the denominator. These rates were applied to 2010 populations for each census block group and confirmed to approximate to published estimates.

Locations of Candidate Docking Stations and Emergency Response Stations

We considered fire stations, EMS stations, first responder stations, and post offices to serve as *candidate docking stations*. Because North Carolina only mandates that ambulances be equipped with an AED (North Carolina College of Emergency Physicians Standards for EMS Equipment, unpublished material, 2009), we further defined stations capable of ambulance dispatch as emergency response stations. We included all United States Geological Survey (USGS) "ambulance station" facilities, as well as first responder and fire stations that we conservatively assumed were able to dispatch ambulances or vehicles equipped with AEDs if the responder or fire station site name contained "rescue," "EMS," "emergency," "medical," or "response." The geolocations of both candidate docking stations and emergency response stations were identified from the USGS National Structures Dataset, which classifies key structures nationwide for disaster and emergency planning [18].

Emergency Responder Response Times

We geocoded every emergency response station and block group population centroid within North Carolina. We determined emergency responder response time to the population-based centroid of each block group as follows: first, the great-circle distance was calculated between all emergency response stations and the centroid. Using these calculations, next the 2 emergency response stations closest to the centroid were identified. Next, we retrieved the average real-road travel time in traffic from MapQuest Application Program Interface (https://developer.mapquest.com) between the centroid and each of these 2 emergency response stations. Finally, we estimated the emergency responder response time using shorter of the 2 travel times.

Drone Specifications

We designed drone deployment networks for small autonomous drones having the following specifications: 40 mph maximum speed when carrying a 4.8 lb. AED; a 12-mile maximum round-trip distance per charge; and returns to its departure docking station [19, 20]. For each candidate docking station, flight times were calculated (via great-circle distance) to each block group centroid. However, the described specifications limit drones to block groups within a 9-minute travel radius from docking station. Therefore, only block groups with < 9-minute flight times were considered within a docking station's service area.

Designing the Drone Deployment Network

Integer linear programming decision models were formulated to optimally select docking stations from candidate locations. Models were programmed in Python 2.7 and solved using Gurobi 6.5.1 [21].

The models designed a network with a maximum of D docking stations. Candidate locations were valued by the total annual expected person-minutes of delay in AED delivery that would be avoided if selected and were further prioritized if an AED would be within the targeted delivery time. The model selects locations to minimize the statewide number of person-minutes until AED arrival. We separately designed networks consisting of up to $D =$ 50, 200, 500, or 750 docking stations and examined AED delivery targets of 5, 6, 7, or 8 minutes. We also designed a network where there was no limit on the number of docking stations that could be selected, where the objective was to select the minimum number of candidate docking stations such that the maximum number of at-risk OHCA victims would be within the specified target time (5, 6, 7, or 8 minutes) to defibrillator delivery by either a drone or emergency responder.

Framework for Assessing Network Effectiveness

We developed a conceptual framework at the block group level to evaluate the effectiveness of each network design. The key assumptions used in our models are documented in Table 1. Of particular note, we relied on data from 2 publications [2, 9] to derive our estimates for rates of defibrillation by bystanders, first responders, or EMS, as well our estimates of survival and neurological outcome probabilities as a function of AED application time. We also assumed that drones and responders are dispatched without assumptions on whether the OHCA victim had a shockable rhythm, and that this would be unknown until either EMS made a decision to not apply an AED (eg, in cases where the victim was discovered in a state of decomposition) or until an AED was applied and the AED algorithms determined not shockable (eg, asystole). However, the probability of survival at the time of AED application or EMS arrival incorporates the probability of an OHCA victim having a shockable rhythm.

We modeled OHCA outcomes as follows. Emergency responders and drones were assumed to be notified of the event location at the same time, and emergency responders had a 1.5-minute delay between notification and dispatch. We assumed that 2.2% of OHCAs in each census block group would receive defibrillation prior to the first arrival of either drone or emergency responder [2]. For these cases, the time to application was estimated as the median point between 0 and the time of either drone or first responder arrival (for which estimates will be described shortly). Of the remaining OHCA events, we estimated the time to AED application based on shorter of the nearest drone travel time and the first responder/EMS travel time, and that time was used to assign a probability of survival and neurological outcome. The travel times were calculated as described earlier. For example, if a drone was estimated to arrive in 3 minutes, and the nearest emergency responder was estimated to arrive in 6 minutes, the drone would arrive first (at 3 minutes) and 45.7% of these OHCAs would have a willing bystander to use the AED from the drone [2]. In this example, the OHCAs did not have a willing witness wait 6 minutes for an emergency responder to arrive, and overall 66.8% of OHCAs did not have AEDs applied at all [2]. The probabilities of survival to hospital discharge and favorable neurological outcomes were modeled as a function of time to defibrillation using published estimates, which are also displayed in Table 1 [9]. Thus, we estimated that individuals within that census block group had a 38.5% probability of survival and 91.1% probability of favorable neurological outcome (if they survived) if the AED from the drone was applied, and a 33.1% survival probability and 93.8% favorable neurological outcome probability (if they survived) if the emergency responder applied the AED. For those individuals with no AED applied we assumed a survival rate of 2.4% and favorable neurological outcome rate of 79.8% (of survivors).

We conservatively assumed that only bystanders applying cardiopulmonary resuscitation (45.7% of OHCAs) [2] would be willing to use a drone-deployed AED and examined the sensitivity of our outcomes by varying the assumed proportion of these bystanders who are willing to use a drone-delivered AED.

Quality-adjusted life years (QALYs) were assigned to survivors according to neurological status. QALYs are commonly used in health economic analyses to assess how future quality and quantity of life is impacted by a health event or status [22]. A QALY is an estimate of the quality of life compared to a year of perfect health. For example, in our study, we assign a QALY of 0.85 and 0.2 for every year of life for survivors of OHCA with favorable and unfavorable neurological outcomes respectively [23]. We assumed an expected lifespan was 11.4 years [24]. QALYs are discounted to the current time period when costs are incurred to reflect that individuals prefer good health now rather than in the future. These discounted QALYs were then added together. We used a discount rate of 3% for QALYs. All costs of drone and maintenance were discounted to the year of drone purchase using a 3% discount rate. The cost per QALY was calculated by dividing the discounted cost by the discounted QALY for each scenario.

Evaluating Costs and Outcomes for Each Network Design

We evaluated the 5 networks (where the number of docking stations was limited to 50, 200, 500, 750, and unlimited) designed with the most aggressive target time for AED delivery (5 minutes). A drone capable of carrying an AED and its drone docking station was estimated to cost $15,000 after discussions with drone experts, and annual maintenance was an estimated 20% of the purchase price [20, 25]. Over a planned 4-year lifespan of the drone [20, 25], we evaluated: (1) OHCAs receiving AEDs, and whether by bystander prior to drone or emergency responder arrival, upon drone arrival, or upon emergency responder arrival; (2) survivors; (3) whether survivors had favorable or unfavorable neurological outcomes; (4) discounted QALYs; (5) net present cost, discounted to the date of purchase using a 3% rate; (6) costs per survivor and per incremental QALY as compared to not using drones.

We further estimated the proportion of OHCAs expected to have an AED delivered within the target time and the median time until delivery for every network design.

Results

We estimated that 16,503 OHCAs occur among 9.5 million North Carolinians over a 4-year drone lifespan. While North Carolina has 2,297 fire, ambulance, and first responder stations, just 761 of these stations were classified as first responder stations using our criteria [18]. In North Carolina, there were a total of 3,138 fire, ambulance, police stations, and post offices that served as candidate sites for drone docking stations [18].

OHCA incidence varied widely by block group, from 0.0 to 15.8 per 4 years (see Figure 1). Only 26.2% of OHCAs were within 5 minutes of emergency response stations (see Figure 1 and Table 2). However, as the limit on the docking stations increases, the resulting network designs are expected to deliver AEDs within 5 minutes to a larger portion of the state; 50 docking stations puts 50.0% of OHCAs within 5 minutes, but the percentage grows to 96.5% when the number of stations that can be selected by the model is unconstrained and results in 1,015 stations selected (see Table 2). The remaining 3.5% are not within 5 minutes of an emergency responder or candidate docking station. Maps displaying the locations of docking stations necessary to reach the maximal number of block groups for each target time are in Figure 2.

Expected costs and outcomes for 5-minute networks, assuming that 50% of bystanders who initiate CPR would be willing to use a drone-delivered AED if it arrives before an emergency responder, are presented in Table 2. A network with 50 stations has a 4-year cost of $1.3 million, whereas a 1,015-station network would cost $26.5 million over the same period. Total bystander use of AEDs increases with the number of docking stations. For example, AEDs are applied to 31.1% of OHCA victims in the status quo (eg, no drones). However, 34.4% of OHCA victims are expected to have an AED used on them even if we assume that just 50% of bystanders who initiate CPR are willing to use a drone-delivered AED if it arrives before an emergency response vehicle. While this increase (34.4% versus 31.1%) may appear modest, it corresponds to 531 additional OHCAs receiving defibrillation over 4 years and a substantial reduction in median time to defibrillation (7.7 versus 2.1 minutes). These factors contribute to 334 additional survivors (311 with favorable neurological outcomes) who have 2,543 discounted QALYs remaining. Thus, a $23.5 million drone network of 1,015 stations with 4-year cost of $23.5 million only costs an estimated $10,438 per incremental QALY.

Patient outcomes improve and relative costs decrease if more bystanders use drone-delivered AEDs before emergency responder arrival. If 100% of all bystanders performing CPR (45.7% of OHCAs) also use an AED if it is delivered by drone prior to emergency responder arrival, the survival rate is expected to more than double (27.7%) in a 5-minute network design with 1,015 stations (see Table 2). Additionally, 60% of OHCAs receive defibrillation, of which 71.3% are bystander-applied. The subsequent estimated cost is just $1,376 per incremental QALY

For a fixed number of docking stations, network designs with a more relaxed (larger) target time for AED delivery covered more victims within the target time, but the median time to AED arrival was similar (see Figure 3). For example, 200 docking stations put 68.5% of OHCAs within 5 minutes and 87.1% within 8 minutes of an AED, but the median time to arrival was 3.6 minutes and 3.8 minutes for the 5- and 8-minute network respectively. However, implementing any of the drone deployment network designs was expected to improve the median time to AED arrival; even just 200 docking stations across North Carolina reduced the median to approximately 3.7 minutes compared to 7.7 minutes if there was no drone network.

Discussion

Rapid defibrillation of individuals experiencing sudden cardiac arrest is associated with an increased likelihood of survival, favorable neurological outcomes, and increased quality of life [13]. However, OHCA victims in remote areas suffer worse outcomes than those in densely populated regions because dispatched responders equipped with AEDs often cannot quickly reach them [26]. OHCA victims who receive a rapid response with defibrillation in the first few minutes following arrest are hypothesized to have a higher likelihood of survival because the electrical ventricular fibrillation phase dissipates to a circulatory phase after 4 minutes [8, 27–29, 30, 31]. We estimate that only 23% of OHCAs occur within 5 minutes of a first responder station, highlighting the need for an innovative approach to reach many victims who are otherwise unlikely to receive defibrillation while still likely presenting with a shockable rhythm [32, 33]. Deploying AED-equipped drones to bystanders may radically increase access to timely defibrillation [14].

We have demonstrated that drone-delivered AEDs according to an optimized statewide drone deployment network could substantially improve survival and neurological outcomes at a justifiable expense. Under a very modest assumption that AED-delivered drones are used by 10% of bystanders performing CPR (<4.5% of all cases), the cost per incremental QALY of a statewide program targeting a 5-minute delivery ranged from $3,143 (50 drones, 80 additional survivors/4 years) to $13,501 (1,015 drones, 258 additional survivors/4 years), and costs decreased as bystander participation or target AED delivery time were relaxed. The $50,000 per QALY ratio is a common, yet conservative benchmark for assessing the cost-effectiveness of an intervention [34]. Under our models, situating docking stations with a 5-minute delivery goal remains cost-effective even if costs were 4 times higher, QALYs per survivor were a quarter of what we estimated, or total survivors due to the application of drone-delivered AEDs were only one quarter of what we used to assess the value of our placement strategies. Why do these strategies appear to be cost-effective across a spectrum of uncertainty? Unlike many medical interventions, drone-delivered AEDs benefit from economies of scale: potentially many cardiac arrest victims over a large geographical area can be served by a single drone throughout its relatively short lifespan.

To our knowledge, we are the first to design statewide drone deployment networks and estimate the population-level shift in expected survival, favorable outcomes, and QALYs lived because of AED-equipped drones. Designing drone networks for an entire state, rather than leaving it to local governing bodies, is advantageous for several reasons. First, complex modifications to relevant laws and emergency protocols are likely to occur at the state level. Second, investment decisions and funding for drone networks are most likely to come from the state. Finally, state-level coordination of drone networks reduces the likelihood of disparate or overlapping placement of drone docking stations. However, determining the optimal locations of drone docking stations across a state is naturally more complex than for a smaller region, such as a city or county. Mathematical programming offers a systematic methodology for optimizing these decisions. We leveraged well-established mathematical programming coverage models [35] to select docking station locations in order to maximally reduce the minutes of delay to defibrillation, given a specified target time and limit on number of drone docking stations.

A primary limitation of our study is that results of our models are driven by data inputs obtained from prior studies [2, 9], rather than event-level OHCA data such as from CARES and governmental infrastructure databases. Therefore, they are subject to imprecision and bias in those studies and programs. While we attempted to include all first responder and EMS locations by querying the USGS data-base, it is possible that we missed some locations. If some locations were missed, our results would reflect a lower bound on responder locations, so our results would therefore be conservative in terms of response time and number of drones needed for adequate coverage. We made several assumptions that may not be realistic due to a lack of estimates that we could derive with confidence from prior studies. For example, we assumed that bystanders and trained responders would have the same rate of accurate placement and time-to-placement. Several studies suggest that EMTs are slightly faster and more accurate than untrained bystanders [36, 37], but we could not find a consensus to use as an estimate for this difference. Nevertheless, our sensitivity analysis of the proportion of bystanders accurately using the AED demonstrated that our results were robust to placement accuracy, and drone delivery target times of 5–8 minutes were sill cost-effective, demonstrating that a delay in AED delivery (and by extension the application time) did not impact the cost-effectiveness of this intervention. Our analysis also did not consider the precise placement of publicly accessible AEDs, since AED databases are not publicly accessible for the state of North Carolina. While we did assume that 2.2% of OHCA victims received defibrillation prior to emergency responder arrival, including lay responders who used a publicly accessible AED, we also assumed that this probability was equal regardless of where the victim was geographically located. It is likely that the availability of AEDs varies by type of location (public or at home) and also by the geography (eg, rural, urban, suburban), and this information will need to be explored before real decisions about drone placement for AED delivery can be made. Perhaps the greatest uncertainty lies within our estimates of expected years lived after survival and the corresponding QALYs. Nevertheless, our conclusions regarding the cost-effectiveness of our strategies are robust to uncertainty from these limitations, and the use of our conceptual model allows a curious reader to approximate how outcomes vary as assumptions are manipulated. Furthermore, drone technologies are rapidly evolving, and we anticipate that competition and technological advancements will soon produce additional drones capable of carrying heavy payloads at even lower costs over longer distances than we used in our analysis. We finally acknowledge that logistical, legal, and technological facets of AED drone delivery must be refined prior to operationalizing any regional or statewide strategy. Research in this area is dynamic, with growing interest among academic, private, and government sectors.

The North Carolina Department of Emergency Management has integrated drones into surveying and mapping operations since 2015 and multiple local public safety agencies have active drone programs, utilizing best practices shared through the North Carolina Department of Transportation and the Next Generation Air Transportation Consortium. These programs are examining challenges facing broad, autonomous establishment of drone networks in the United States. Our study is providing Emergency Management with new applications and is furthering interest in statewide implementation of technology. Future research is needed to examine feasibility, acceptability, and security of drones in community settings, which will require demonstrations to assess not only the logistical but also human-machine interaction barriers, such as the psychological and intellectual barriers to use of drone-delivered AEDs. Additional considerations include airspace access restrictions, cost, legal barriers, aircraft ownership, insurance requirements, and implications for public policy.

Drones are likely to continue to be integrated into many aspects of daily life, including retail delivery, food production, and recreational activities. Stakeholders in acute health care research should consider advocating for the early adoption of drones to improve public health. Our study provides important quantitative data useful in the strategic development of a statewide network of AED-equipped drones. It demonstrates the potential for substantially improving cardiac arrest survival and neurological outcomes with estimates of the associated financial investment. We envision a future where drone networks are strategically designed to rapidly deliver AEDs and other life-saving technology to large and diverse geographic regions.

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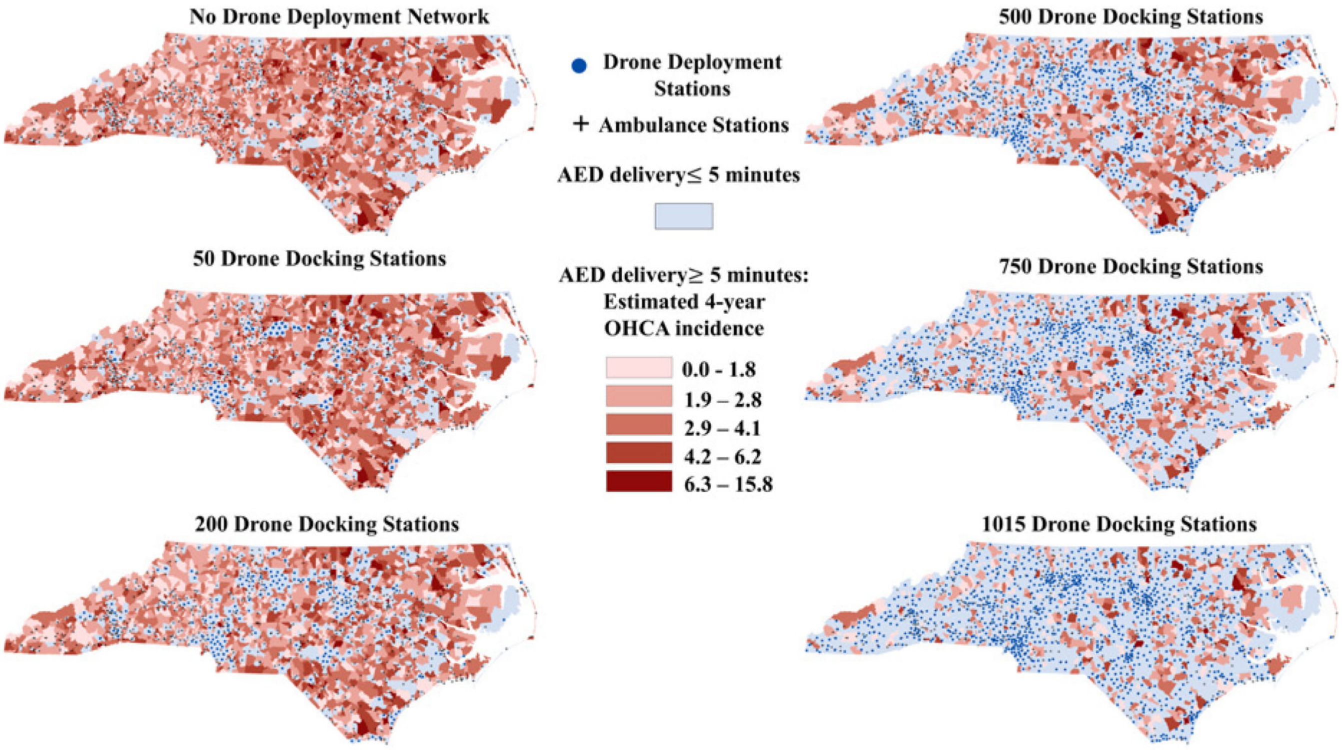

FIGURE 1.

North Carolina Census Block Groups Expected to Have an AED Delivered in ≤ 5 Minutes or ≥ 5 Minutes When there is No Drone Deployment Network and For Networks with Limits of 50, 200, 500, 750, and 1015 Docking Stations

Note. OHCA incidence rates are only shown for census block groups that have an expected AED arrival time ≥ 5 minutes.

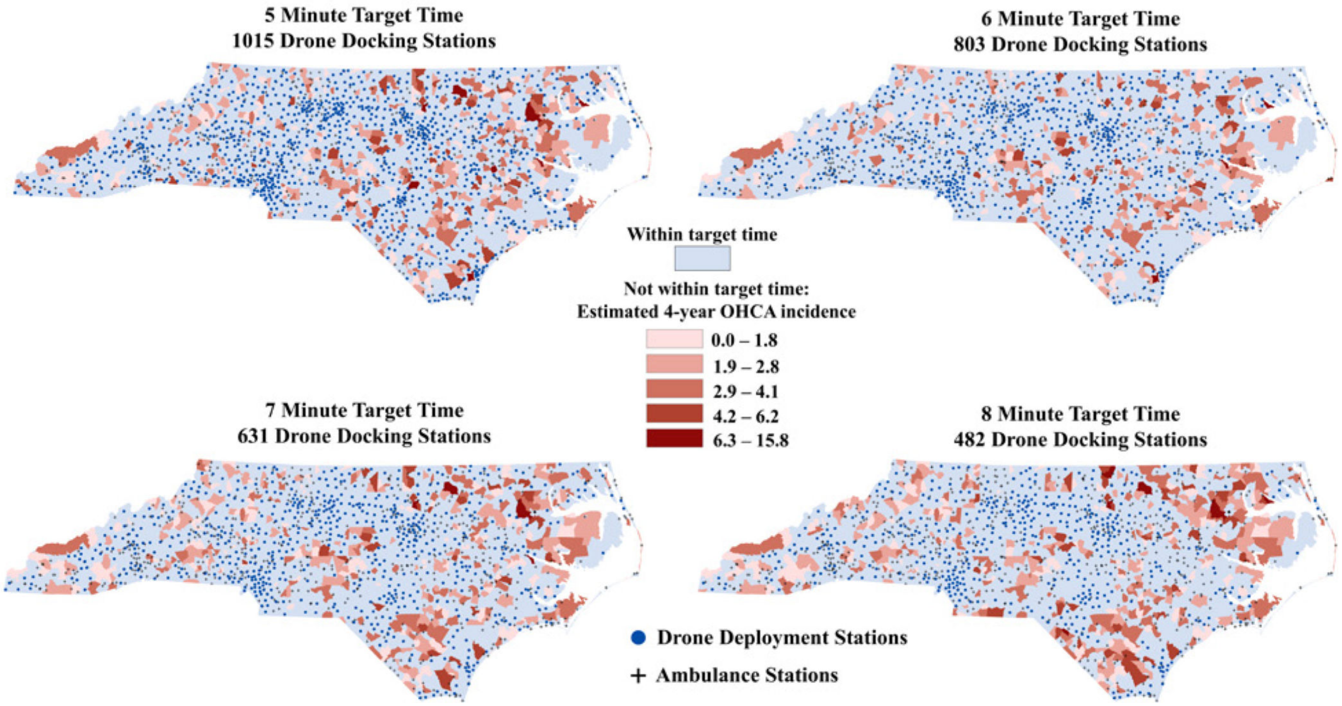

FIGURE 2.

North Carolina Census Block Groups Expected to Have an AED Delivered ≤ Specified Target Time ≥ Target Time for the Maximum Number of Drone Docking Stations Necessary to Cover Block Groups within the Specified Target Time

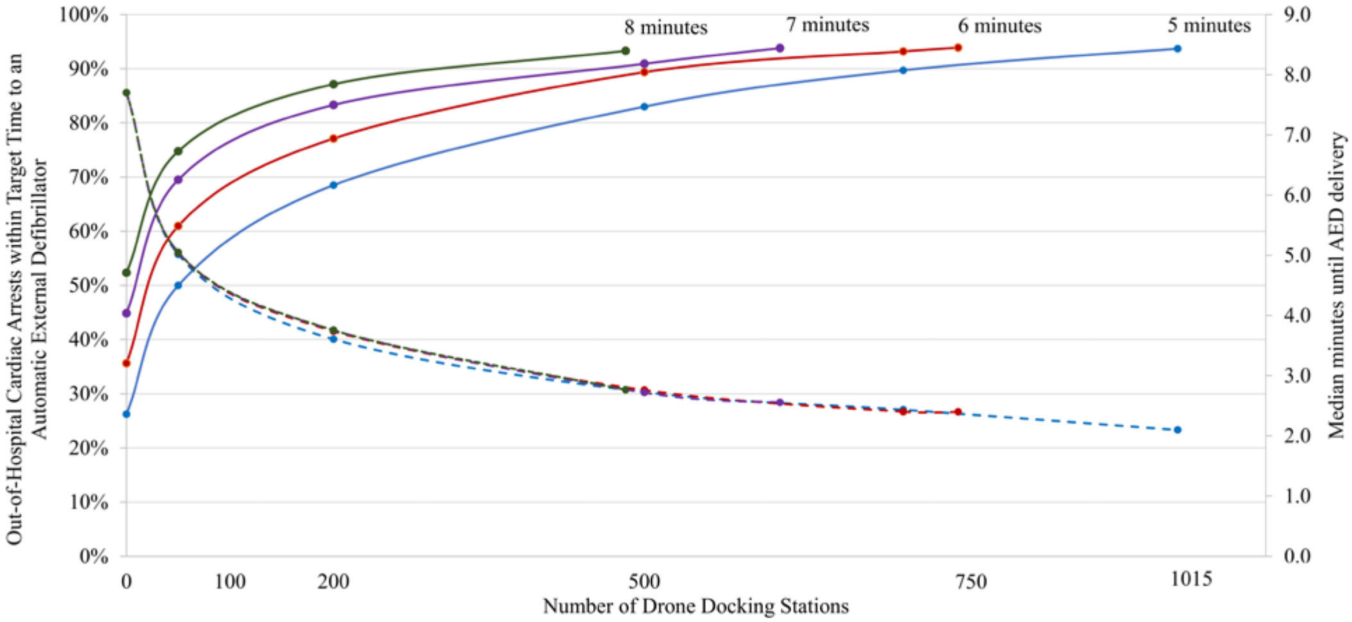

FIGURE 3.

Percentage of Out-of-Hospital Cardiac Arrests (Left Y-Axis, Solid Lines) and Median Minutes until AED Delivery (Right Y-Axis, Dashed Lines) According to Network Design Specifications

TABLE 1.

Parameter Estimates Used in Model and References

Parameter	Value
OHCA Defibrillation	
Time between 911 call and dispatch	1.5 minutes
% OHCAs first defibrillated prior to emergency responder/drone arrival	2.2%[1]
% OHCAs first defibrillated upon first responder/EMS arrival	31.0%[1]
% OHCAs not defibrillated	66.8%[1]
% OHCAs with willing bystanders to perform CPR (used to represent percent who would have a bystander use an AED if drone-delivered)	45.7%[1]
% OHCAs that get first defibrillated by dispatched responder | not defibrillated prior to responder/drone arrival	29.5%[1]
Probability of survival to hospital discharge | defibrillation time is…	
<2 minutes	59.1%[2]
2 to 5 minutes	38.5%[2]
5–9 minutes	33.1%[2]
>10 minutes	13.2%[2]
Probability of survival to hospital discharge | not defibrillated	2.4%[2]
Probability of favorable neurological outcome | survive and defibrillation time is …	
<2 minutes	92.3%[2]
2 to 5 minutes	91.1%[2]
5–9 minutes	93.8%[2]
>10 minutes	89.9%[2]
Probability of favorable neurological outcome | not defibrillated	79.6%[1]
Drone Assumptions	
Drone purchase price	$15,000[8]
Annual maintenance cost	20% of drone purchase[2,3]

Parameter	Value
Drone lifespan	4 years[3,4]
Discount rate for cost analysis	3%
Speed	40 mph[4,5]
Maximum round trip distance	12 miles[4,5]
Quality of Life Assumptions	
Mean life expectancy | survive OHCA	11.4 years[6]
1 Quality-Adjusted Year favorable neurological status	0.85[7]
1 Quality-Adjusted Year |unfavorable neurological status	0.20[7]
Discount rate for cost analysis	3%

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TABLE 2.

Costs and Expected Patient Outcomes over 4-year Lifespan of Drones for Drone Networks with 5-minute Target Times to AED Delivery*

Maximum Number of Docking Stations Per Network	**No Drones**	**50**	**200**	**500**	**750**	**Unlimited**
Number of docking stations selected	-	50	200	500	750	1015
Cost (%) over 4-year drone lifespan	$0	$1,307,565	$5,230,259	$13,075,648	$19,613,471	$26,543,565
OHCA incidence, per 4 years	16,503	16,503	16,503	16,503	16,503	16,503
OHCAs, per 4 years, <5 minutes from AED delivery, No. (%)	4340/16,503 (26.3%)	8252/16,503 (50.0%)	11305/16,503 (68.5%)	13697/16,503 (83.0%)	14803/16,503 (89.7%)	15463/16,503 (93.7%)
Median (interquartile range) minutes to first AED delivery	7.7 (4.9–11.3)	5.0 (3.2–8.3)	3.6 (2.3–6)	2.7 (1.7–4.2)	2.4 (1.5–3.6)	2.1 (1.3–3.2)
AED Use % (N)						
Total AEDs used on OHCA victims, No. (%)	5139/16,503 (31.1%)	45300/16,503 (32.1%)	5433/16,503 (32.9%)	5546/16,503 (33.6%)	5594/16,503 (33.9%)	5670/16,503 (34.4%)
Applied by bystander, No. (% of all AEDs used)	363/5139 (7.6%)	589/5300 (11.1%)	776/5433 (14.3%)	935/5546 (16.9%)	1003/5594 (17.9%)	1110/5670 (9.6%)
Applied prior to drone or emergence responder arrival, No. (% of all AEDs used by bystanders)	363/363 (100%)	363/589 (61.6%)	363/776 (46.8%)	39.2/935 (38.8%)	363/1003 (36.2%)	363/1110 (32.7%)
Applied using drone-delivered AED, No. (% of all AEDs used by bystanders)	0/363 (0%)	226/589 (38.4%)	413/776 (53.2%)	572/935 (61.2%)	640/1003 (63.8%)	747/1110 (67.3%)
AED applied by emergency responder, No. (% of all AEDs used)	4776/5139 (92.9%)	4711/5300 (88.9%)	4657/5433 (85.7%)	4611/5546 (83.1%)	4591/5594 (82.1%)	4560/5670 (80.4%)
No AED applied, No. (% of all OHCA victims)	11364/16503 (68.9%)	11203/16503 (67.9%)	11071/16503 (67.1%)	10958/16503 (66.4%)	10910/16503 (66.1%)	10833/16503 (65.6%)
Outcomes						
Survivors, per 4 years, No. (%)	2038/16503 (12.3%)	2126/16503 (12.9%)	2202/16503 (13.3%)	2272/16503 (13.8%)	2306/16503 (14.0%)	2372/16503 (14.4%)
Survivors with favorable neurological status, No. (% of survivors)	1815/2038 (89.1%)	1898/2126 (89.3%)	1968/2202 (89.4%)	2033/2272 (89.5%)	2065/2306 (89.5%)	2126/2372 (89.6%)
Expected discounted quality-adjusted life years	15,021	15,696	16,269	16,805	17,062	17,564
Cost per quality-adjusted life years gained (compared to “No Drones”)	$0	$1,937	$4,190	$7,329	$9,610	$10,438
Cost per additional survivor (compared to “No Drones”)	-	$14,752	$31,905	$55,792	$73,160	$76,495

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[*] Estimates assume that 50% of bystanders initiating CPR are willing to apply a drone-delivered AED if delivered prior to emergency responder arrival.