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ORIGINAL RESEARCH

CRITICAL CARE AND RESUSCITATION

Combinations of First Responder and Drone Delivery to Achieve 5-Minute AED Deployment in OHCA

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ABSTRACT

BACKGROUND Defibrillation in the critical first minutes of out-of-hospital cardiac arrest (OHCA) can significantly improve survival. However, timely access to automated external defibrillators (AEDs) remains a barrier.

OBJECTIVES The authors estimated the impact of a statewide program for drone-delivered AEDs in North Carolina integrated into emergency medical service and first responder (FR) response for OHCA.

METHODS Using Cardiac Arrest Registry to Enhance Survival registry data, we included 28,292 OHCA patients ≥18 years of age between 1 January 2013 and 31 December 2019 in 48 North Carolina counties. We estimated the improvement in response times (time from 9-1-1 call to AED arrival) achieved by 2 sequential interventions: 1) AEDs for all FRs; and 2) optimized placement of drones to maximize 5-minute AED arrival within each county. Interventions were evaluated with logistic regression models to estimate changes in initial shockable rhythm and survival.

RESULTS Historical county-level median response times were 8.0 minutes (IQR: 7.0-9.0 minutes) with 16.5% of OHCAs having AED arrival times of <5 minutes (IQR: 11.2%-24.3%). Providing all FRs with AEDs improved median response to 7.0 minutes (IQR: 6.2-7.8 minutes) and increased OHCAs with <5-minute AED arrival to 22.3% (IQR: 16.4%-30.9%). Further incorporating optimized drone networks (326 drones across all 48 counties) improved median response to 4.8 minutes (IQR: 4.3-5.2 minutes) and OHCAs with <5-minute AED arrival to 56.3% (IQR: 46.9%-64.2%). Survival rates were estimated to increase by 34% for witnessed OHCAs with estimated drone arrival <5 minutes and ahead of FR and emergency medical service.

CONCLUSIONS Deployment of AEDs by FRs and optimized drone delivery can improve AED arrival times which may lead to improved clinical outcomes. Implementation studies are needed. (JACC Adv 2024;3:101033)

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ABBREVIATIONS AND ACRONYMS

AED = automated external defibrillation

CPR = cardiopulmonary resuscitation

EMS = emergency medical systems

FR = first responders

OHCA = out-of-hospital cardiac arrest

Overall survival following out-of-hospital cardiac arrest (OHCA) cases worked by emergency medical services (EMS) personnel in the U.S. has remained at around 8 to 10% for over 30 years.[1,2] Despite these grim statistics, OHCA is potentially quite responsive to therapy, provided it is administered quickly enough. Immediate cardiopulmonary resuscitation (CPR) and rapid defibrillation within the first few minutes of collapse result in survival rates of 40 to 100%.[3-5] However, observational studies show the rarity of automated external defibrillator (AED) application within the first 5 minutes of OHCA in communities[6] because of how long it takes first responders (FRs) and EMS personnel to get to the victim and the rarity of having an AED available and/or accessible to the bystander 9-1-1 caller.[6-9]

The use of drones to rapidly deliver AEDs has gained recent attention as a potential new approach to treating OHCA. Prospective test operations and mathematical modeling of drone-based AED delivery highlight their promise in reducing time to defibrillation in OHCA.[10-15] To date, limited work has been done in the United States to integrate drone-based AED delivery into the standard of OHCA care.[16,17] North Carolina is ideal for testing drone-AED technology given its ongoing strong focus on improving quality of OHCA care,[7,18] and multidisciplinary role in advancing drone technology and airspace integration in the United States.[19,20] Therefore, we sought to estimate the potential impact of drone-based AED delivery by developing a framework for strategic deployment of AED-carrying drone networks in North Carolina while accounting for existing OHCA response from EMS and improvements in AED deployment from FRs.

METHODS

This study was approved by the institutional review boards at Duke University and the University of Toronto. The requirement for informed consent was waived. Data use agreements were obtained from each EMS agency. A de-identified version of our data is available via request through the CARES Coordinating Center at Emory University.

DATA SOURCE AND STUDY SETTING. We obtained OHCA data from the CARES registry, a voluntary, prospective clinical registry in the U.S. that collects information for all non-traumatic OHCAs where resuscitation was attempted.[21] OHCA case data are collected from participating EMS agencies and receiving hospitals according to the Utstein template[22] and are reviewed for accuracy and completeness by a CARES analyst. We included OHCAs occurring within 48 counties in North Carolina, which have a combined population of 7.5 million (71% of the total state population) and an area of 65,451 km^2 (25,274 mi^2; 47% of the total state area) (Supplemental Table 1). The included counties are diverse in terms of demography and urban/rural make-up (**Table 1**), and primarily utilize a 2-tiered system for OHCA response that consists of fire (and occasionally police) FRs and EMS personnel (EMTs and Paramedics).

STUDY POPULATION AND INTERVENTIONS. We identified all OHCAs recorded in the CARES registry and occurring within the study setting between January 1, 2013, and December 31, 2019. Incidents were excluded if a 9-1-1 responder witnessed the OHCA, the patient was younger than 18 years, there was no recorded EMS on-scene time, or the OHCA occurred within a no-fly zone defined by the Federal Aviation Administration[23] or the Department of Homeland Security[24] data sets as OHCAs in those locations would not be reachable by drones.

We investigated the impact of 2 potential interventions on OHCA response time, which we define as the time interval from 9-1-1 call to the arrival of either an AED or by EMS at the OHCA location. Intervention 1 estimated the impact of providing all FRs with an AED. Although FRs frequently arrive prior to EMS at OHCA incident locations, not all FRs carry AEDs, and the proportion of FRs who carry AEDs in North Carolina is not clear. In our analyses, we

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The authors attest they are in compliance with human studies committees and animal welfare regulations of the authors' institutions and Food and Drug Administration guidelines, including patient consent where appropriate. For more information, visit the Author Center.

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TABLE 1 Patient and Event Characteristics of Included OHCAs and Demographic Characteristics of the Incident Census Tract Stratified by Historical Response Time

	Overall (N = 48)	Q1: Lowest 25% (n = 12)	Q2: Lowest 26%-50% (n = 12)	Q3: Highest 26%-50% (n = 12)	Q4: Highest 25% (n = 12)	*P* Value
Total number of OHCAs	28,292	14,950	6,089	4,433	2,820	-
Number of OHCAs per county	328 (169-750)	823.5 (591-1146)	394 (275-646)	252.5 (169-444)	139 (86-305)	<0.001
Age, y	65 (53-76)	65 (53-76)	66 (54-76)	65 (54-75)	65 (54-75)	0.033
Population density (number/sq mile)	166 (100-303)	379 (254-1085)	166 (142-270)	129 (102-225)	77 (47-116)	<0.001
% rural population per county	51.4 (32.8-73.5)	26.1 (6.6-36.2)	45.3 (30.8-59.2)	66.8 (50.3-78.0)	74.8 (54.0-86.6)	<0.001
Male, %	62.2	62.1	62.9	61.1	62.7	0.276
Public location, %	27.6	30.1	26.1	25.4	21.3	<0.001
Witnessed event, %	50.1	47.6	52.6	51.7	56.0	<0.001
Race, %						
White	68.4	62.9	75.3	73.3	75.1	<0.001
Black/African American	26.7	31.3	21.3	23.0	19.2	<0.001
Asian	0.7	1.0	0.4	0.3	0.2	<0.001
Hispanic/Latino	1.5	1.8	1.2	1.6	0.7	<0.001
Other/unknown[a]	2.7	3.0	1.8	1.8	4.8	<0.001
Initial EMS rhythm, %						
VT/VF	14.5	13.0	15.7	16.6	16.3	<0.001
PEA/asystole	62.7	56.8	66.5	70.6	73.4	<0.001
Unknown shockable rhythm	7.0	7.9	7.9	4.3	4.1	<0.001
Unknown unshockable rhythm	15.8	22.3	9.9	8.5	6.1	<0.001
Treatment prior to EMS, %						
Bystander CPR	47.1	45.9	47.4	51.0	46.5	<0.001
Layperson AED application before EMS	4.4	5.0	4.3	3.5	3.3	<0.001
First responder AED application before EMS	42.8	50.2	41.3	33.8	20.9	<0.001
Defibrillation, %						
Layperson	1.5	1.7	1.5	1.1	0.8	<0.001
First responder	9.6	10.4	10.9	7.5	6.0	<0.001
EMS	23.3	22.1	23.4	24.0	27.8	<0.001

Values are n, median (IQR), or %. *P* values are from Pearson's chi-square test. For all variables <0.1% of the data were missing. Missingness for age is 0.06%, sex 0%, public location 0%, witnessed arrest 0%, race 0%, type of rhythm 0.02%, shockable rhythm 0.02%, bystander CPR 0%, AED applied 0.01%, defibrillation 0.05%. [a]Other/unknown racial groups include American-Indian/Alaskan Native, Native Hawaiian/Pacific Islander, and Unknown.

assumed that a FR who arrived on-scene before EMS carried an AED only if it was recorded that the FR applied an AED in the CARES registry. Intervention 2 estimated the impact of establishing a network of AED-carrying drones in each county in addition to providing all FRs with AEDs.

RESPONSE TIME IMPUTATION. Timestamped data for FR dispatch or arrival on-scene were available for 62.6% of OHCAs in CARES, and CPR and AED application data showed that FRs were on scene for at least 82% of OHCAs. To address missingness with FR response times, based on feedback from multiple EMS agencies, we assumed that FRs were dispatched to every OHCA and imputed missing FR dispatch and on-scene times (Supplemental Methods). This assumption allowed us to derive an ideal scenario for FR deployment in which FRs were always dispatched to OHCAs and provided a more conservative estimate for the impact of drone-delivered AED networks. When computing historical response times, the imputed FR times were only utilized for an OHCA if a FR applied an AED for that OHCA.

The time of call reception by 9-1-1 was missing in 2% of OHCAs. For these cases, the call reception time was assumed to be the time of first vehicle dispatch, minus the median historical 9-1-1 call to first vehicle dispatch interval for the county that OHCA occurred in (Supplemental Methods).

DRONE RESPONSE TIME CALCULATION. Drone response times were calculated using the specifications of the DJI Matrice 600 Pro drone-the top speed was 18 m/s (40 mph), ascent rate was 3 m/s, and descent rate was 2 m/s.[25] We assumed that drones would be dispatched at the first dispatch time and that the drone flight path would be to ascend vertically (to avoid hitting buildings or trees) to a cruising height of 200 ft, fly in the most direct path to the OHCA while avoiding no-fly zones, then descend and land on the ground.[11,26] We assumed a constant 25.2 seconds for a bystander to retrieve the AED after the drone lands, which was the median time from empirical trials conducted in North Carolina.[27] We further assumed that drones would return to base immediately after delivering the AED and would require 30 minutes to be recharged and re-equipped with a new AED.[11] During this period, the drone would not be available for dispatch to a subsequent OHCA. Sensitivity analysis on the AED retrieval time and drone recharge time is provided in the Supplement.

DRONE NETWORK DESIGN. For each county, we developed a separate mathematical optimization model (Supplemental Methods) to determine the optimal number of drones needed and their locations, with the goal of maximizing the proportion of OHCAs with <5-minute AED arrival by drone (5-minute coverage). Drone locations were determined using OHCAs occurring between 2013 and 2018, with the 2019 data kept for out-of-sample evaluation. The candidate base locations considered were all EMS, fire, and police stations within that county. We allowed for a maximum of 3 drones to be placed at any 1 location to be able to respond to simultaneous OHCA from the same drone base. We increased the number of drones placed in each county under the rule that each additional drone must increase 5-minute OHCA coverage by at least 2 percentage points. Sensitivity analyses were conducted with alternate values of 1, 1.5, and 2.5 percentage points. Sensitivity analyses were also conducted by optimizing for 3-minute and 7-minute coverage proportions.

Drone dispatch decisions were made following previously developed decision rules.[28] EMS and FR response times were predicted using linear regression, and the nearest available drone would be dispatched to an OHCA if the drone travel time was predicted to be less than or within a small tolerance of the FR/EMS response time (Supplemental Methods).

STATISTICAL ANALYSIS. For each county, we compared historical OHCA response times to those resulting from the 2 interventions. Each response time distribution was subdivided into the in-sample distribution consisting of OHCAs from 2013 to 2018 on which the drone network was optimized, and the out-of-sample distribution consisting of OHCAs from 2019 to provide a generalizable estimate of the drone network's effectiveness.

To account for differences in FR/EMS system performance across counties, we reported the distribution of the median response times and proportion of 5-minute coverage across the 48 counties and compared the distribution of median response times per county between the historical baseline and those resulting from the 2 interventions. Reductions in the standard deviation of each county's response time distribution were tested with the 1-tailed Levene test. We also determined whether the between-county standard deviation of median response times was lower for either intervention compared to the historical baseline using the 1-tailed Levene test.

We estimated the clinical impact of improved response times on rates of initial shockable rhythm and survival to hospital discharge. First, we stratified OHCAs by whether they were witnessed or unwitnessed, as these subpopulations differ in their associations between response time and survival (Supplemental Methods).[29] For each subpopulation, we used a logistic regression model to predict the likelihood of an initial shockable rhythm. Patients were then subdivided by initial shockable rhythm, and separate logistic regression models predicted survival to hospital discharge.

Models adjusted for age, sex, race, bystander CPR, and location of OHCA. The relationships between response time and the log-odds of shockability and survival were modeled as piecewise linear monotonically decreasing and convex functions, where the slope for each minute was estimated from the data (Supplemental Methods). OHCAs where an FR with an unknown response time or a lay bystander applied an AED were excluded from this analysis as the arrival times of the AEDs were unavailable.

We estimated the clinical impact of the interventions by substituting the improved intervention response times into the logistic regression models while holding all other variables constant. For each patient in each intervention, we used the models to predict the likelihood of: 1) an initial shockable rhythm; 2) survival to hospital discharge given an initial shockable rhythm; and 3) survival to hospital discharge given an initial nonshockable rhythm. These predictions were used to compute and evaluate the interventions on changes in rates of initial shockable rhythm and OHCA survival. Confidence intervals were computed on these values with a nonparametric bootstrap with a sample size of 3,000.

RESULTS

A total of 36,084 OHCAs across the 48 counties were recorded during the study period. After exclusions, 28,292 OHCAs were included in study analyses (Figure 1). Table 1 shows patient and event characteristics of included OHCAs, with stratification of counties by quartiles of historical median response time per county. The median age was 65 (IQR: 53-76) years and 62.2% of patients were male. Black/African American and Hispanic/Latino patients accounted for 26.7% and 1.5% of OHCAs, respectively. Initial shockable rhythm was present in 21.5%, bystander CPR was 47.1%, and AEDs were applied by laypersons or FRs in 4.4% and 42.8% of OHCAs, respectively. Counties with the shortest median response times (quartile 1) had greater numbers of OHCAs, were more likely to have OHCAs occurring in public locations and were more likely to have AEDs applied prior to EMS compared with counties in the upper quartiles.

Within the in-sample (2013-2018) cohort, the historical median county-level response was 8.0 minutes (IQR: 7.0-9.0 minutes) and 5-minute coverage was 16.5% (IQR: 11.2%-24.3%) (Table 2). Under intervention 1, which enhanced all FRs with AEDs, median county-level response was predicted to improve to 7.0 minutes (IQR: 6.2-7.8 minutes) and median 5-minute coverage to 22.3% (IQR: 16.4%-30.9%). With intervention 2, which combined drone-AED networks with FR enhancement, the median county-level response was predicted to further improve to 4.8 minutes (IQR: 4.3-5.2) minutes and median 5-minute coverage to 56.3% (IQR: 46.9%-64.2%). Similar improvements were observed in the out-of-sample (2019) cohort (Supplemental Table 2).

Stratifying counties by historical median response time revealed substantial variation in median response time, with a 3.1-minute difference between the medians of quartile 1 and quartile 4 (6.6 mins vs 9.7 mins; Table 2). Intervention 1 did not significantly reduce the between-county standard deviation of median response times in either the in-sample ($P = 0.10$) or out-of-sample ($P = 0.16$) cohort, while intervention 2 reduced the between-county standard deviation of median response times from 1.4 minutes to 1.0 minute for the in-sample cohort ($P = 0.01$) and 1.8 minutes to 1.1 minutes for the out-of-sample cohort ($P < 0.01$).

Figure 2 shows the historical response time distributions compared to response time distributions for interventions 1 and 2 for each county. While intervention 1 substantially reduced the median response time in many counties, it only reduced within-county standard deviation in less than one-half the counties ($P < 0.05$ for 20 of 48 counties). In contrast, intervention 2 shortened the tail of the response time distributions substantially, reducing within-county standard deviation for most counties ($P < 0.05$ for 43 of 48 of counties) along with further reducing the median response time.

Sensitivity analysis results of 3-minute and 7-minute optimizations and varying the stopping criteria for drone quantities (1, 1.5, 2.5 percentage point coverage per drone) were varied and are shown in Supplemental Tables 3 to 5; the overall trends remained the same.

Figure 3 shows the predicted impact of intervention 2 on initial shockable rhythm and survival to hospital discharge for witnessed OHCAs that would have benefited from the interventions (74% of witnessed OHCAs). For this subpopulation, 62% of patients had a response time of <5 minutes after intervention 2, where compared with historical response, the likelihood of having an initial shockable rhythm with drone AED delivery was predicted to increase from 30.2% to 35.0%, a relative increase of 16% and survival to hospital discharge was predicted to increase from 14.5% to 19.4%, a relative increase of 34%. ORs, CIs, survival curves, and calibration plots

FIGURE 1 Inclusion and Exclusion Criteria in the Drone AED Network Optimization Model

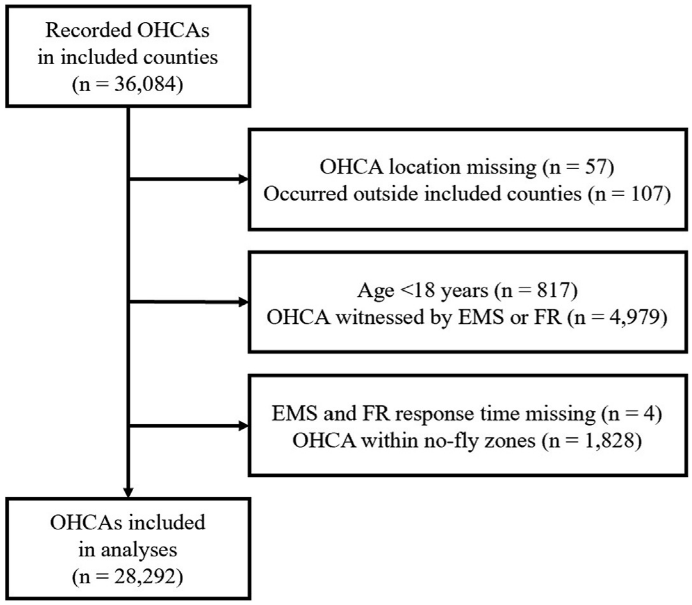
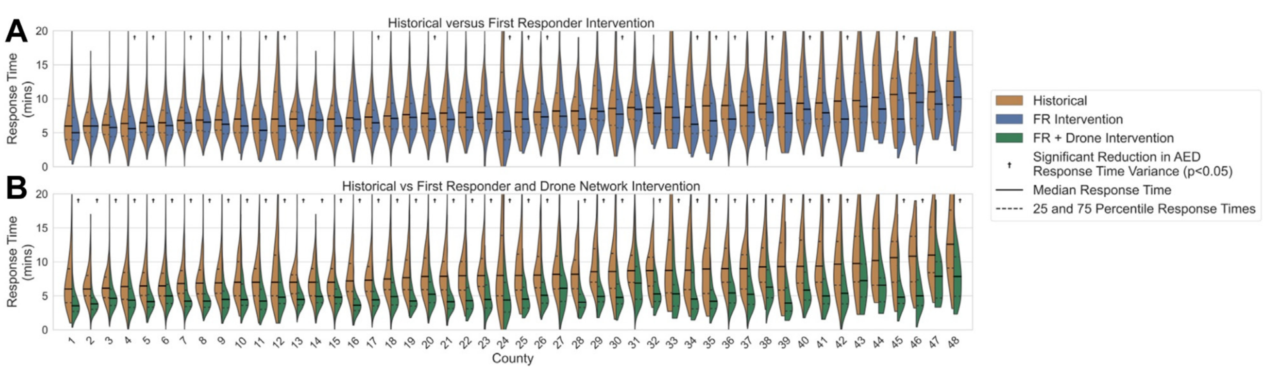


TABLE 2 Median County-Level Data for the 48 North Carolina Counties Participating in the CARES Registry Between 2013 and 2019

		Counties Stratified by Median Historical Response Time				
	All Counties (N = 48)	Q1: Lowest 25% (n = 12)	Q2: Lowest 26%-50% (n = 12)	Q3: Highest 26%-50% (n = 12)	Q4: Highest 25% (n = 12)	*P* Value
Total number of OHCAs	23,650	12,625	5,016	3,412	2,597	-
Number of OHCAs	269.5 (140.8-623.0)	701.5 (488.8-977.8)	329.5 (173.0-544.0)	200.5 (133.5-302.0)	148.0 (86.5-346.2)	<0.001
Historical median response time, min	8.0 (7.0-9.0)	6.6 (6.3-6.9)	7.6 (7.1-7.9)	8.6 (8.2-8.8)	9.7 (9.3-10.7)	<0.001
Historical response times <5 min, %	16.5 (11.2-24.3)	27.0 (23.2-30.4)	16.5 (14.1-21.1)	13.9 (12.1-21.9)	9.2 (7.0-12.0)	<0.001
Call to dispatch time, min	1.6 (1.1-2.0)	1.2 (1.1-1.6)	1.2 (1.0-1.6)	1.8 (1.0-2.0)	2.0 (1.9-2.1)	0.016
Intervention 1: Equipping all first responders with AEDs						
Median response time, min	7.0 (6.2-7.8)	6.0 (5.9-6.3)	7.0 (6.3-7.0)	7.4 (7.0-7.9)	8.2 (7.6-9.0)	<0.001
Response times <5 min, %	22.3 (16.4-30.9)	30.9 (29.1-36.4)	22.0 (18.5-28.6)	20.6 (15.2-28.2)	13.6 (12.7-22.5)	<0.001
OHCAs with improved response, %	28.6 (23.9-37.3)	21.4 (17.7-27.8)	27.5 (24.3-34.9)	27.7 (24.4-35.6)	38.4 (32.5-43.8)	<0.001
Intervention 2: Equipping all first responders with AEDs + drone delivery of AEDs						
Median response time, min	4.8 (4.3-5.2)	4.4 (4.2-4.7)	4.4 (4.2-4.6)	5.0 (4.5-5.3)	5.6 (5.0-6.7)	<0.001
Response times <5 min, %	56.3 (46.9-64.2)	64.4 (59.1-70.6)	63.3 (57.2-64.4)	51.1 (46.6-57.8)	42.2 (35.5-51.4)	<0.001
OHCAs with improved response time after intervention 1, %	66.5 (51.4-75.2)	68.0 (51.9-74.9)	73.8 (59.3-80.1)	66.2 (50.8-71.8)	64.5 (52.1-68.5)	0.823
Median drones placed, n	7.0 (5.0-8.0)	8.0 (6.8-9.2)	8.0 (7.0-8.2)	7.0 (4.0-8.0)	5.5 (4.0-7.0)	0.008

Values are n, median (IQR), or %. Statistics are Based on in-sample 2013-2018 OHCA Data.

FIGURE 2 AED Response Time Distributions by County



Response times are shown for (A) historical vs first responder intervention and (B) first historical vs first responder and drone network intervention. Plots are based on sample 2013 to 2018 OHCA data. Counties are ordered by historical median response time.

of the models used to make these predictions are provided in Supplemental Results (Supplemental Table 6, Supplemental Figures 3 to 7).

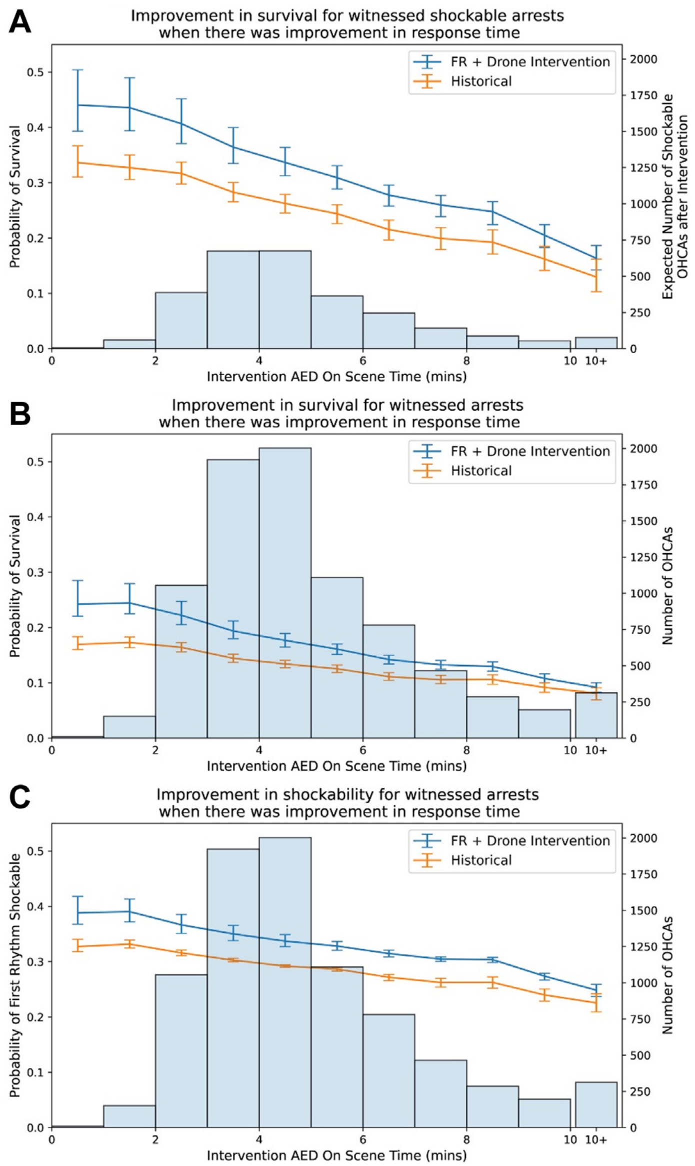
DISCUSSION

We jointly assessed the impact of 2 promising programs for increasing bystander and FR AED application in North Carolina. We estimated that FR AED deployment to all OHCAs would improve the median of county median response times from 8.0 minutes to 7.0 minutes and improve 5-minute coverage from 16.5% to 22.3%. Further including a drone-AED delivery program designed to maximize 5-minute coverage for OHCA would improve response times for a majority (66.5%) of OHCAs, reduce median county-level response time to 4.8 minutes, and provide 5-minute coverage to 56.3% of OHCAs (**Central Illustration**). The expected earlier arrival of our interventions could significantly improve chances of OHCAs with shockable rhythms and survival to discharge for witnessed OHCAs could improve by 31% with AED arrival times at 5 minutes.

Prior studies have demonstrated faster response and defibrillation times with FRs compared with EMS.[30-33] Despite this, only a handful of community-based initiatives have demonstrated improvement in OHCA survival associated with rapid defibrillation.[6,34-39] In a recent implementation study of OHCA community interventions in North Carolina from 2010 to 2013, rates of receiving both bystander CPR and FR defibrillation increased from 14.1% to 23.1% and were associated with a 3.2-fold higher adjusted odds of survival compared with EMS-initiated CPR and defibrillation.[7] Given that FRs are commonly deployed to OHCAs in North Carolina, we believed it was crucial to determine the benefit of a FR system fully equipped to rapidly apply an AED during OHCA. With the FR-based intervention, the median response time decreased in every county (**Figure 2A**), with the magnitude of the improvement generally increasing in counties with longer historical median response times.

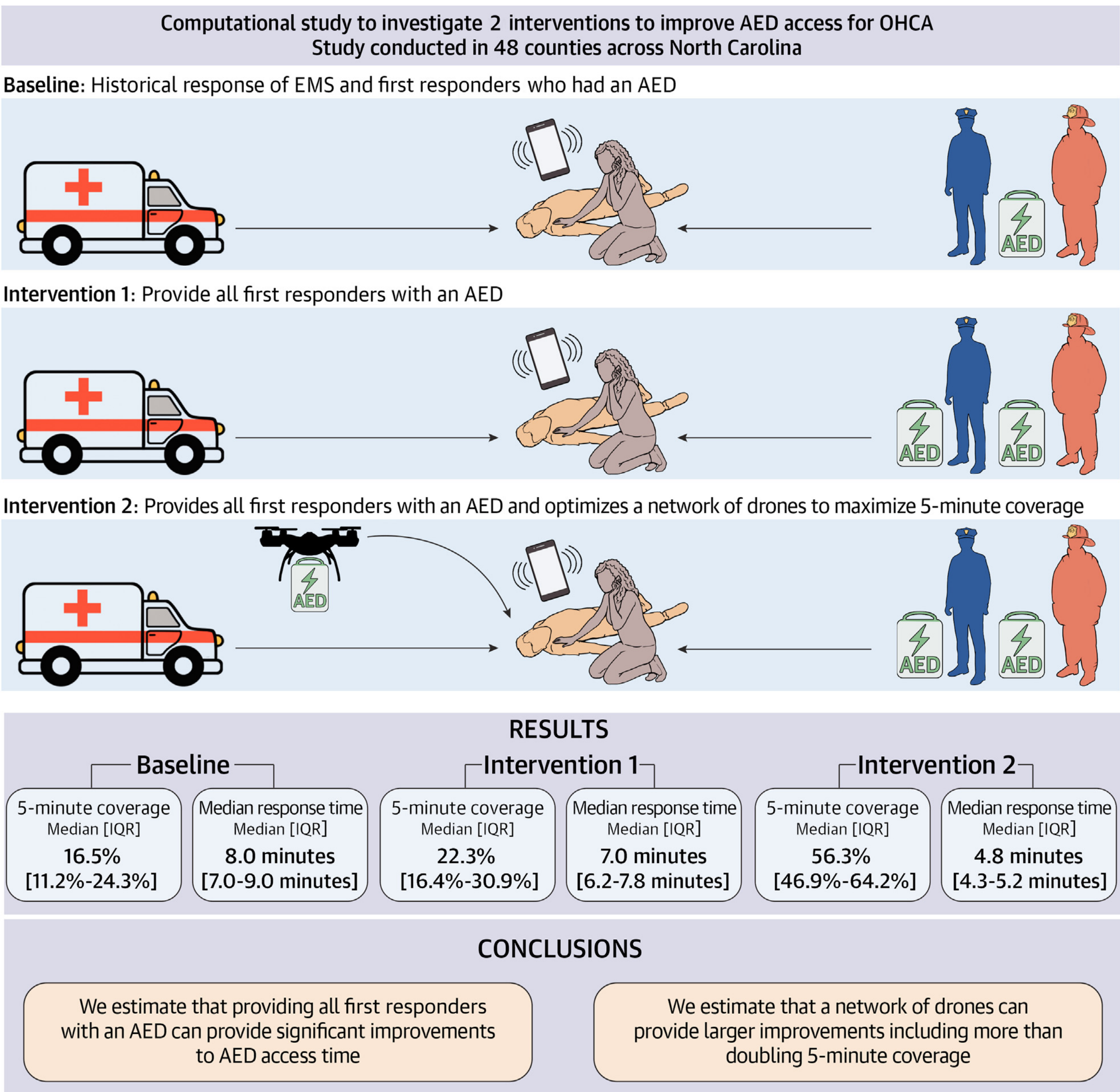
When the drone-based intervention was layered on top of the FR-based intervention, median response times were reduced even further (**Figure 2B**). The drone-based intervention may substantially improve service to those who suffer the longest response times currently, as evidenced by the reduction in standard deviation ($P < 0.05$) for 90% of counties (vs 42% of counties under intervention 1 only) and a shift of the entire response time distributions inward toward the

FIGURE 3 Estimation of the Clinical Impact of Improved Response Times on Rates of Initial Shockable Rhythm and Survival to Hospital Discharge After Intervention 2



Improvement in (A) survival probabilities of shockable witnessed OHCAs, (B) survival probabilities of witnessed OHCAs, and (C) first rhythm shockable probabilities of witnessed OHCAs under intervention 2 where intervention 2 improved the response time. The X-axis shows the time until a drone or FR from intervention 2 delivers an AED on scene. The blue trend line shows the estimated survival or shockability of OHCAs at the corresponding intervention 2 response time. The orange trend line shows the estimated survival/shockability of those same OHCAs when they receive and AED from their historical response time (not the response time on the x-axis). The difference between the 2 lines is the estimated improvement in survival/shockability by moving longer historical response times to the intervention 2 response time shown on the x-axis. Error bands denote 95% CIs. Data used in this figure are provided in Supplemental Tables 7 and 8.

CENTRAL ILLUSTRATION Combinations of First Responder and Drone Delivery to Achieve 5-Minute Automated External Defibrillator Deployment in Out-of-Hospital Cardiac Arrest



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mean. The drone-based intervention substantially outperformed the FR-based intervention because equipping FRs does not change their time to arrival on-scene, while the drone network can be designed and optimized to improve response times.

We presented data on models maximizing 5-minute coverage with a 2-percentage-point coverage improvement threshold, which we believe is a reasonable approach for most counties. The 3-minute coverage model would be more applicable for EMS agencies that already have high rates of 5-minute coverage, while the 7-minute coverage model would be better suited to rural regions with longer response times or those without a budget to pursue lower response time targets. While the 2-percentage point threshold is where many counties start to see diminishing returns (Supplemental Figure 8), this value is arbitrary and would be selected by each EMS agency as they consider budget and intended clinical impact. For drone effectiveness specifications, using a looser threshold such as a 1 or 1.5 percentage-point increase in coverage per drone would further improve response times and coverage but would result in more drones and thus be more expensive to operate.

Our research further builds upon other studies that have demonstrated the impact of drone delivery to significantly improve AED arrival times in other countries.[11,12,15,28,40-43] Our study uniquely first addresses the ability to enhance existing FR systems given their routine arrival ahead of EMS and accounting for their OHCA treatment before estimating treatment with drone-based AED delivery.[11] Furthermore, we iterated on previous optimization models for drone-AED networks, and to the best of our knowledge, we conducted the first study focused on optimizing for 5-minute coverage using historical OHCA data and are the first to integrate dispatch decision making into the planning stage of the drone network. We believe our study presents the first effort to estimate the clinical impact of a proposed drone network while accounting for the potential change in first recorded shockable rhythm that can occur due to an AED arriving on scene earlier due to an intervention.

While we observed substantial improvement with our FR and drone-based interventions, our study highlighted opportunities for improvement in the 9-1-1 call to dispatch time. The national recommendation for time from call transfer and OHCA recognition and dispatch of the first EMS unit is <60 seconds.[44] However, the median county-level call-to-vehicle dispatch time was 1.6 minutes (IQR: 1.1-2.0 minutes) in our study, with the median call-to-vehicle-dispatch time that approached 2.0 minutes for the counties with the longest historical median response times. Improvements in dispatch recognition of OHCA and telephone-CPR in North Carolina would further augment the impact of FR and drone AED delivery programs by reducing AED arrival times.

We estimated that a drone AED delivery program could significantly improve the probability of a patient being in a shockable rhythm upon AED arrival and would improve survival for patients with shockable rhythms. For cases where the drone can arrive between 2 and 4 minutes and ahead of FR and EMS, the survival to discharge for witnessed shockable OHCAs are expected to improve from 29% to 38%. Substantial benefit is maintained on drone arrival between 4 and 6 minutes where survival is expected to improve from 26% to 33%. Despite these estimates, we acknowledge that it is impossible to precisely estimate the impact of drone AED delivery prior to implementation.

STUDY LIMITATIONS. First, our study only included EMS-treated OHCAs from the CARES registry. A drone-AED program would likely be dispatched to suspected and untreated OHCAs, such as those that are obviously dead or have a do-not-resuscitate order. Second, drones may not be able to be dispatched to some OHCAs due to weather conditions or poor visibility (up to 31% of cases in Sweden where winters are long and cold with subzero temperatures).[45] Future weather studies in the United States are needed to determine its impact on drone AED delivery. Third, because we imputed missing dispatch and on-scene times for FRs, some of the response times used in our models include error inherent to imputation methods. Fourth, estimation of clinical impact on shockable rhythm and survival outcomes should be interpreted with caution, as we were not able to include patients with the fastest defibrillation times (those treated by bystanders) as data on time of defibrillation was not available. Fifth, we did not consider the response time of AEDs brought to the scene by a bystander. Additionally, we assumed that whenever a drone-delivered AED arrived on scene it would be retrieved by a bystander and that the time to AED application from either a drone landing or an FR/EMS vehicle arriving on scene was equivalent. This assumption may be an overestimate for real-time AED delivery. Community education programs to increase bystander usage of AEDs will need to be deployed in conjunction with a drone network to maximize drone-delivered AED effectiveness and reach the projected numbers in this study. Sixth, we restricted locations for drone bases to emergency service stations; further improved coverage in a geographic area may have been possible in nonemergency service locations, although literature suggests these differences may be small.[15] Finally, the clinical significance of a drone program may be affected by program setup and range of drone travel, drone logistics technicalities (delays in initiation or return to service, head-wind, airspace conflict, coordinate change, signal transmission during flights, landing conditions, or drone malfunction), weather conditions, time needed to safely deliver an AED, night operations of the program, and bystander willingness to use a drone.

CONCLUSIONS

An optimized drone delivery AED program for OHCA can potentially substantially reduce AED arrival times. A 5-minute coverage for drone AED delivery is estimated to improve the survival of witnessed shockable OHCAs by 34%. Implementation studies of drone AED delivery are needed to confirm effectiveness.

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PERSPECTIVES

COMPETENCY IN PATIENT CARE: In the United States, bystander AED application rates for OHCA are <4%. In our drone optimization research, drone AED delivery combined with universal first responder AED use significantly improved the time it takes to get an AED to the scene of OHCA to <5 minutes and improved rates of AED arrival within 5 minutes by more than 3-fold to 56% in North Carolina.

TRANSLATIONAL OUTLOOK: Implementation studies with real-time drone AED delivery should be prioritized in the United States.

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APPENDIX For supplemental methods, tables, and figures, please see the online version of this paper.