Overcoming Spatial and Temporal Barriers to Public Access Defibrillators Via Optimization

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ABSTRACT

BACKGROUND Immediate access to an automated external defibrillator (AED) increases the chance of survival for out-of-hospital cardiac arrest (OHCA). Current deployment usually considers spatial AED access, assuming AEDs are available 24 h a day.

OBJECTIVES The goal of this study was to develop an optimization model for AED deployment, accounting for spatial and temporal accessibility, to evaluate if OHCA coverage would improve compared with deployment based on spatial accessibility alone.

METHODS This study was a retrospective population-based cohort trial using data from the Toronto Regional RescuNET Epistry cardiac arrest database. We identified all nontraumatic public location OHCAs in Toronto, Ontario, Canada (January 2006 through August 2014) and obtained a list of registered AEDs (March 2015) from Toronto Paramedic Services. Coverage loss due to limited temporal access was quantified by comparing the number of OHCAs that occurred within 100 meters of a registered AED (assumed coverage 24 h per day, 7 days per week) with the number that occurred both within 100 meters of a registered AED and when the AED was available (actual coverage). A spatiotemporal optimization model was then developed that determined AED locations to maximize OHCA actual coverage and overcome the reported coverage loss. The coverage gain between the spatiotemporal model and a spatial-only model was computed by using 10-fold cross-validation.

RESULTS A total of 2,440 nontraumatic public OHCAs and 737 registered AED locations were identified. A total of 451 OHCAs were covered by registered AEDs under assumed coverage 24 h per day, 7 days per week, and 354 OHCAs under actual coverage, representing a coverage loss of 21.5% (p < 0.001). Using the spatiotemporal model to optimize AED deployment, a 25.3% relative increase in actual coverage was achieved compared with the spatial-only approach (p < 0.001).

CONCLUSIONS One in 5 OHCAs occurred near an inaccessible AED at the time of the OHCA. Potential AED use was significantly improved with a spatiotemporal optimization model guiding deployment. (J Am Coll Cardiol 2016;68:836–45) © 2016 by the American College of Cardiology Foundation.

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Out-of-hospital cardiac arrest (OHCA) represents a significant public health issue, associated with an estimated 400,000 deaths annually in North America and a <10% survival rate (1,2). Automated external defibrillator (AED) use, coupled with cardiopulmonary resuscitation (CPR), has been shown to increase survival from public location cardiac arrest (3-6).

Despite the substantial amount of financial resources committed to public access defibrillation programs, AED usage in public location OHCA cases remains low (7-9). There are many potential barriers to bystander AED use, including legal liability, awareness, training, technological limitations, and psychological factors (10-12). Another major barrier is the limited availability of AEDs due to building access (11,13-15).

The majority of the research in and guidelines for AED deployment focus on spatial factors with respect to cardiac arrest risk and AED availability. Studies have evaluated cardiac arrest risk according to location type (5,16-23) or optimized deployment of AEDs geographically (24,25), without considering temporal factors. In fact, the well-known American Heart Association guidelines for AED placement have suggested locating an AED where there has been a cardiac arrest every 2 years and, more recently, "in public locations where there is a relatively high likelihood of witnessed cardiac arrest" (26,27). The European Resuscitation Council guidelines are similar (28). AED deployment strategies that only consider spatial factors implicitly assume that AEDs and public locations that house AEDs are available and accessible 24 h a day.

Although cardiac arrest incidence and survival vary substantially according to time of day and day of week (29,30), temporal access has largely been ignored in the literature, with one notable exception (13). In the present article, we present the first mathematical optimization approach for AED deployment that considers both spatial and temporal accessibility. We hypothesized that: 1) OHCA coverage by existing AEDs is significantly overestimated when temporal accessibility is not considered; and 2) optimizing deployment of prospective AEDs, accounting for both spatial and temporal accessibility, can reverse coverage loss and generate a statistically significant increase in OHCA coverage over an approach that only considers spatial accessibility.

METHODS

Toronto has a population of approximately 2.8 million people in an area of about 630.18 km^2.

A single emergency medical service (EMS) primarily serves the city; however, neighboring EMS respond to emergency events if they are close in proximity. Because Toronto has a tiered response system, multiple EMS units and the fire department often respond to a single emergency event.

STUDY DESIGN AND DATA SOURCES. This study was a retrospective population-based cohort trial using data from the Toronto Regional RescuNET cardiac arrest database. Rescu Epistry is compliant with the Resuscitation Outcomes Consortium Epistry-Cardiac Arrest and based on the Strategies for Post Arrest Resuscitation Care methodologies described elsewhere (31,32).

All public location, nontraumatic OHCA episodes in the city of Toronto from January 2006 to August 2014 were included in this study; information for each OHCA entry included demographic characteristics, circumstances of arrest, characteristics of care, and survival outcomes. Public locations included public buildings, places of recreation, industrial facilities, and outdoor public spaces; hospitals and nursing homes were excluded.

A list of registered AEDs was obtained from Toronto EMS as of March 2015. AED registration in Toronto is voluntary but strongly encouraged. The AED dataset contained 912 publicly and privately owned (included with owner consent) AEDs, located at 737 unique addresses. Each entry included the address and location type; most entries included the hours of operation. Missing information was completed by online search, telephone, or in-person visit (Online Appendix).

A dataset of candidate locations for AED placement was collected from June 2014 to January 2015, comprising 4,898 businesses and public points of interest. For each location, the address and hours of operation (if available) were obtained. Data collection was conducted online, by telephone, or by in-person visit.

STATISTICAL ANALYSIS. Two separate analyses were conducted.

Analysis 1: Coverage loss of registered AEDs factoring in temporal availability. We first calculated assumed coverage 24 h per day, 7 days per week. An OHCA is considered covered if it occurred within 100 m (25,26) of an AED regardless of the AED's availability. Second, we calculated actual coverage. An OHCA is considered covered if it occurred both within 100 m of an AED and when the AED was available, based on the location's hours of operation. Locations were considered temporally inaccessible

TABLE 1 Characteristics of Public Cardiac Arrests*				
	Cardiac Arrests			
	Total **(N = 2,440)**	**Daytime†** **(n = 1,252)**	**Evening†** **(n = 840)**	**Night†** **(n = 348)**
Age, yrs	59.0 ± 17.5	60.3 ± 17.9	58.9 ± 16.8	54.6 ± 16.9
Male	58.9 ± 16.7	60.1 ± 17.2	58.7 ± 16.1	55.1 ± 15.7
Female	59.4 ± 20.6	61.1 ± 21.0	60.3 ± 19.5	52.6 ± 20.7
Male	1,979 (81.1)	1021 (81.5)	686 (81.7)	272 (78.2)
Witnessed by bystander	1,142 (46.8)	590 (47.1)	446 (53.1)	106 (30.5)
Received bystander CPR	1,019 (41.8)	533 (42.6)	371 (44.2)	115 (33.0)
Bystander-applied AED	191 (7.8)	96 (7.7)	75 (8.9)	20 (5.8)
Ambulance response interval, min	5.88 (4.68-7.37)	5.75 (4.60-7.20)	5.82 (4.72-7.35)	6.45 (5.17-7.75)
Initial cardiac rhythm				
Shockable‡	868 (35.6)	465 (37.1)	327 (38.9)	76 (21.8)
Not shockable‡	1,504 (61.6)	747 (59.7)	494 (58.8)	263 (75.6)
Survival to discharge	361 (14.8)	196 (15.7)	129 (15.4)	36 (10.3)

Values are mean ± SD, n (%), or median (interquartile range). *Number missing from total: age (n = 79), sex (n = 2), witnessed by bystander (n = 18), received bystander CPR (n = 2), bystander-applied AED (n = 46), arrival interval (n = 2), initial cardiac rhythm (n = 68), and survival (n = 26). †Time periods were defined as follows: daytime, 8:00 AM to 3:59 PM; evening, 4:00 PM to 11:59 PM; and night, 12:00 AM to 7:59 AM. ‡Shockable includes: ventricular fibrillation, ventricular tachycardia, and patients listed as shockable; not shockable includes asystole, pulseless electrical activity, patients listed as not shockable, and patients whose initial rhythm was not obtained because resuscitation was stopped before rhythm analysis by protocol due to obvious signs of death.

AED = automated external defibrillator; CPR = cardiopulmonary resuscitation.

outside their hours of operation. A coverage radius of 100 meters was chosen on the basis of an estimate of the maximum round-trip distance a bystander can transport an AED within 3 min (26,33). Finally, we calculated relative coverage loss: assumed coverage 24 h per day, 7 days per week, minus actual coverage all divided by assumed coverage 24 h per day, 7 days per week. Coverage loss was further analyzed according to different times of day (daytime, 8:00 AM to 3:59 PM; evening, 4:00 PM to 11:59 PM; and night, 12:00 AM to 7:59 AM), days of the week (weekday/weekend), geographic areas (downtown/not downtown), and specific location types. A 95% confidence interval (CI) was computed for the relative coverage loss using a paired proportions approach plus an error propagation step to convert absolute to relative coverage loss (34,35). A chi-square test was also used to test for statistically significant differences in coverage loss compared across disjoint and unpaired categories (time of day, geography, and day of week) of OHCAs, with a 2-tailed value of p < 0.05 being significant.

Analysis 2: Coverage gain of AED locations from a spatiotemporal optimization model. We developed a novel spatiotemporal optimization model for AED placement by augmenting a previous spatial-only optimization model developed by our group (25) to account for temporal information of both OHCA cases and candidate AED locations (Online Appendix). Using a user-defined number of locations (N), our model chose the best locations to place AEDs to maximize OHCA actual coverage by examining historical OHCA data.

The spatiotemporal model and spatial-only model were evaluated on the improvement of actual coverage above a baseline provided by the existing registered AED network in the city. A 10-fold cross-validation method was used to compare the theoretical performance of the spatiotemporal model and spatial-only model in terms of actual coverage on historical OHCA data as follows. The OHCAs that were not already covered by the registered AEDs were randomly divided into 10 disjoint sets of equal sizes, which served as the testing sets for each fold. In each fold, the remaining 90% of the OHCAs comprised the training set; note that in each fold, the training and testing sets are completely disjoint. In addition, the testing sets are disjoint across the folds (i.e., out-of-sample). The training set was used as input to the optimization models to determine the optimal AED locations. The actual coverage of the selected AED locations was assessed by using the testing set OHCAs and then summed over the 10 folds. The totals over the 10 folds were reported for the analysis. By using the testing set OHCAs for the final evaluation of actual coverage, our reported results are out-of-sample. The optimization models were run for each fold increasing by 50 (e.g., N = 50, 100, …, 400).

For each N, relative coverage gain was calculated: actual coverage from the spatiotemporal model minus actual coverage from a spatial-only model divided by actual coverage from the spatial-only model. Overall coverage gain was calculated as the weighted mean of the coverage gain for each N, weighted by the actual coverage values from the spatial-only model. We computed 95% CIs for the overall coverage gain and the coverage gain split by time of day, geography, and day of week (36). Significance in the actual coverage differences was determined by using McNemar's test for each N with a 2-tailed value of p < 0.05 considered significant.

RESULTS

A total of 25,707 nontraumatic OHCAs occurred in Toronto from January 2006 to August 2014. Of these, 2,440 cases occurred in a public setting (Table 1). Of the 25,707 OHCAs, 942 (3.7%) survived to discharge and, of these, 361 occurred in a public setting, corresponding to a survival rate among public OHCAs of 14.8%. Differences in rates of witnessed by bystander (p < 0.001), received bystander CPR (p = 0.001), shockable (p < 0.001), and survival (p = 0.04) were significant across the 3 times of day but not the

difference in bystander-applied AED (p = 0.17). **Table 2** shows the breakdown of the 2,440 included public OHCAs according to time of day, day of week, and geography. The majority of all OHCAs occurred during the evening, night, and weekends (61.0%). **Table 3** shows identical breakdowns for bystander-applied AED. The difference in bystander-applied AED between outside downtown during weekends (6.2%) and downtown during weekdays (11.2%) was statistically significant (p = 0.01).

Of the 737 AED locations, 542 (73.5%) were not open 24 h a day, and 211 (28.6%) were closed on weekends. **Figure 1** illustrates the proportion of time that registered AEDs are available by time of day and day of week.

ANALYSIS 1: COVERAGE LOSS OF REGISTERED AEDs FACTORING IN TEMPORAL AVAILABILITY. **Table 4** summarizes the coverage loss statistics. Of the 2,440 included OHCAs, 451 were covered under assumed coverage of 24 h per day, 7 days per week, whereas 354 were covered under actual coverage, resulting in a relative coverage loss of 21.5% (95% CI: 16.9% to 26.1%). Coverage loss during the evening, night, and weekends was 31.6%, which is when the majority of all OHCAs occurring in public locations (**Table 2**).

Comparable coverage losses were observed in downtown during weekdays (17.2%), downtown during weekends (19.1%), and outside downtown during weekdays (19.0%). In comparison, the coverage loss was more than double outside downtown during weekends (38.8%); these differences were significant (p = 0.04).

Table 5 summarizes the coverage loss experienced by registered AEDs categorized according to their respective location types. Among location types with the most deployed AEDs, the largest coverage losses were observed at schools (39.7%), industrial facilities (39.3%), recreation/sports facilities (37.1%), and offices (35.7%). These 4 location types accounted for 63.9% of AED locations. Transportation facilities experienced no coverage loss while having the largest number of covered OHCAs.

ANALYSIS 2: COVERAGE GAIN OF AED LOCATIONS FROM A SPATIOTEMPORAL OPTIMIZATION MODEL. After the 354 OHCAs covered by the registered AEDs were removed, 2,086 remained for the 10-fold cross-validation optimization analysis.

The overall coverage gain (percent gain in actual coverage) from AED locations determined by using the spatiotemporal model over the spatial-only model was 25.3% (95% CI: 22.9% to 27.6%) (**Figure 2**). As shown in **Figure 3**, the overall coverage gain was statistically significant for all N (p < 0.002). Results

TABLE 2 Public OHCAs

| Time of Day* | Weekday | | Weekend | | Total |
	Downtown	Outside Downtown	Downtown	Outside Downtown	
Daytime	173 (7.1)	778 (31.9)	57 (2.3)	244 (10.0)	1,252 (51.3)
Evening	111 (4.5)	480 (19.7)	46 (1.9)	203 (8.3)	840 (34.4)
Night	54 (2.2)	182 (7.5)	28 (1.1)	84 (3.4)	348 (14.3)
Total	338 (13.9)	1,440 (59.0)	131 (5.4)	531 (21.8)	2,440 (100.0)

Values are n (%). *As defined in **Table 1**.
OHCA = out-of-hospital cardiac arrest.

from **Figure 2** are further broken down for all N according to time of day, day of week, and geography (Online Figures 1 to 7).

An equivalent interpretation of the 25.3% overall coverage gain is that the spatiotemporal model required 32.3% fewer AEDs than the spatial-only model to cover the same number of OHCAs (Online Table 1).
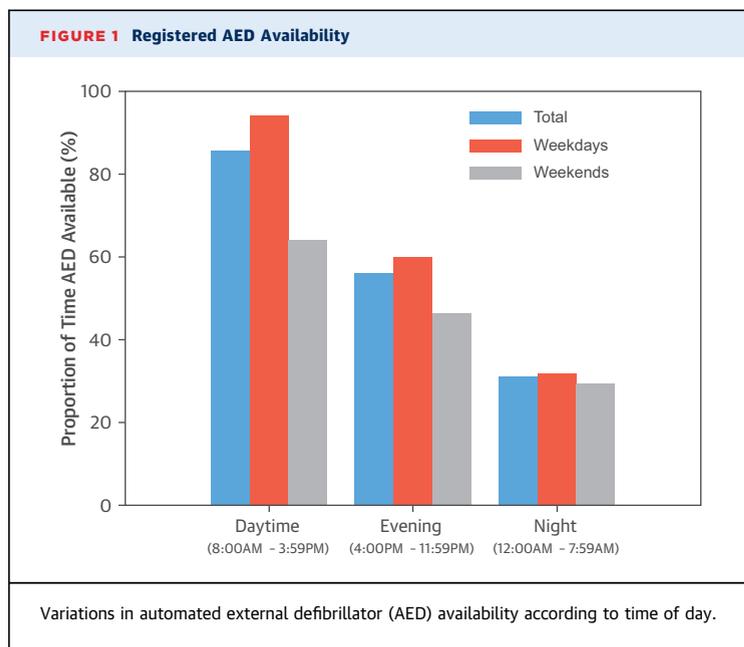
DISCUSSION

The 2 primary, synergistic findings presented in this paper were: 1) a significant proportion of OHCAs occur close to a public AED that is inaccessible at the time of the arrest; and 2) a mathematical model that explicitly accounts for both spatial and temporal accessibility when proposing prospective public AED locations has the potential to significantly increase the likelihood of having an accessible AED nearby during an OHCA event.

ANALYSIS 1: REGISTERED AEDs. A significant loss in OHCA coverage by public AEDs due to limited temporal access was observed across all times of day. The largest loss occurred at night (**Central Illustration**), corresponding to the time period with the lowest percentage of OHCA cases that were witnessed by a bystander, received bystander CPR/AED, and

TABLE 3 Bystander-Applied AED Use on Public OHCAs

| Time of Day* | Bystander-Applied AED Use | | | | |
| | Weekday | | Weekend | | |
	Downtown	Outside Downtown	Downtown	Outside Downtown	Total
Daytime	24 (13.9)	51 (6.6)	6 (10.5)	15 (6.1)	96 (7.7)
Evening	10 (9.0)	43 (9.0)	5 (10.9)	17 (8.4)	75 (8.9)
Night	4 (7.4)	12 (6.6)	3 (10.7)	1 (1.2)	20 (5.7)
Total	38 (11.2)	106 (7.4)	14 (10.7)	33 (6.2)	191 (7.8)

Values are n (%). *As defined in **Table 1**.
Abbreviations as in **Tables 1 and 2**.

FIGURE 1   Registered AED Availability

Variations in automated external defibrillator (AED) availability according to time of day.

survived to discharge. Although coverage loss was significantly different across the 3 times of day, the proportion of cases that received bystander AED was not. It is possible that nighttime OHCAs occurred closer to an available AED or that responding bystanders at night were more willing to apply an AED. The latter possibility highlights the potential for improving survival further by improving AED accessibility at night.

We further examined our results according to geography (downtown/not downtown) and day of week (weekday/weekend). We noted a significant difference in bystander-applied AED between outside downtown during weekends and downtown during weekdays (Table 3). Thus, when considering the subgroups of day of week and geography, the highest bystander-applied AED proportion coincided with the lowest coverage loss (downtown during weekdays), whereas the lowest bystander-applied AED proportion coincided with the highest coverage loss (outside downtown during weekends). These results suggest a potential correlation between AED availability and usage.

In addition, coverage loss in downtown Toronto was similar during weekdays and weekends, unlike the coverage loss outside downtown, which was much greater on weekends. This observation suggests that temporal AED accessibility did not decrease as much during the weekend in downtown as it did outside downtown. Forty years ago, the city adopted a planning principle focused on balancing residential and commercial development in downtown. The

doubling of the downtown population since the mid-1970s has likely played a role in encouraging downtown businesses serving local residents to maintain robust opening hours, mitigating the weekend coverage loss.

A study examined coverage loss due to temporal AED accessibility in Copenhagen, Denmark (13), with a similar significant coverage loss overall as seen in Toronto: 33.5% in Copenhagen and 21.5% in Toronto. Regarding the difference, only 9.1% of AED locations in Copenhagen were open 24 h a day versus 26.5% in Toronto. Certain location types had similar coverage losses, including schools (39.7% in Toronto vs. 40.8% in Copenhagen) and transportation facilities (no coverage loss in either). Offices had a larger coverage loss in Copenhagen than in Toronto, whereas sports/recreation facilities had a smaller coverage loss. A possible explanation for this inversion is a difference in lifestyle and culture: according to an international work–life balance index, assessing 11 topics of well-being, Denmark was ranked first of 38 countries whereas Canada was ranked 24th (37). Because Toronto and Copenhagen have similar OHCA risk at sports/recreation facilities (16,21), the difference in coverage loss might be partially explained by comparatively longer opening hours for offices and shorter opening hours for sports/recreation facilities in Toronto. Overall, these 2 studies suggest that coverage loss due to temporal factors is likely a universal problem, although it may vary according to location type within a city and from city to city for the same location type.

ANALYSIS 2: OPTIMIZATION. Our spatiotemporal model represented 1 possible method to combat the effects of limited temporal accessibility without compromising spatial access when optimizing AED locations. The overall coverage gain demonstrated by our spatiotemporal model when locating prospective AEDs almost exactly offset the coverage loss experienced by the existing registered AED network. Moreover, the coverage gain remained steady as more AEDs were placed (Figure 3), suggesting that the improvement in OHCA coverage is sustainable as the AED network grows, and is not due to the addition of more AEDs but rather to the accounting for temporal accessibility. The greatest coverage gain occurred at night, which is also the time of day when Toronto's existing AED network experienced the greatest loss and when survival was lowest.

The spatiotemporal model's 25.3% coverage gain over the spatial-only model with the same number of AED locations was equivalent to a 32.3% decrease in the number of AED locations required to achieve the

same coverage as the spatial-only model. This equivalence provided 2 different ways to measure the value of temporal information when optimizing AED locations: in terms of improved potential for AED use given constant system resources or lower cost of system implementation/upkeep for the same coverage level. A similar "trade-off curve" between number of deployed AEDs and AED radius was observed previously (24).

The spatiotemporal model can be used as a decision-support tool for stakeholders involved in the strategic placement of public AEDs, including EMS, urban planning departments, or foundations that fund public AEDs. Evaluating AED deployment policies, such as blanket coverage of certain location types, can easily be done. A user may vary the number of prospective AED locations considered (e.g., based on a funding limit) to examine the potential impact on OHCA coverage. Because the model considers both existing AED locations and future AED placements simultaneously, potential redundancies or holes in coverage can be minimized. The model may also serve as an assistive tool for AED relocation by ignoring the existing AEDs when identifying optimal AED locations. Although the model used city-specific information as inputs, it is a general model and translatable to any city. Its practical applicability elsewhere will depend on data availability in the target city. Furthermore, the model is suitable for both small-scale (e.g., neighborhoods, university campuses) as well as large-scale (e.g., city-wide) deployments. Additional applications could include integration with assistive technologies, such as mobile apps or software pertaining to AED placement.

STUDY LIMITATIONS. A tacit assumption is that the historical distribution of OHCAs is representative of the future. Some justification has been provided in the literature (38), and a recent study in progress provides additional evidence for Toronto that the distribution is stable over time (39). In addition, we showed that our spatiotemporal model provides gains in coverage even with variability in OHCA occurrences, which was captured via out-of-sample disjoint testing sets in the 10-fold cross-validation.

AED registration is voluntary in the city of Toronto; thus, our list of registered AEDs likely did not include all AEDs in the city. However, we believe this factor to be a minor limitation in our analysis because it is unlikely a bystander would be able to find and use an unregistered AED in an emergency. Most unregistered AEDs are privately owned and sometimes solely for internal use, and would not be relevant in this study. Also, our numerical results focus on the change in coverage, not the magnitude of coverage; thus, missing AEDs would likely have minimal impact.

Coverage provides a convenient quantitative measure for analysis but ultimately does not equal survival. Although coverage and survival are likely positively correlated, coverage is at best a proxy for

TABLE 4 OHCA Coverage Loss of Registered AEDs

	OHCAs Covered			
	Total (N = 2,440)	Daytime* (n = 1,252)	Evening* (n = 840)	Night* (n = 348)
Total (N = 2,440)				
Assumed 24/7 coverage	451	221	168	62
Actual coverage	354	202	120	32
Coverage loss, %	21.5	8.6	28.6	48.4
Weekdays (n = 1,778)				
Assumed 24/7 coverage	342	176	122	44
Actual coverage	279	166	90	23
Coverage loss, %	18.4	5.7	26.2	47.7
Weekends (n = 662)				
Assumed 24/7 coverage	109	45	46	18
Actual coverage	75	36	30	9
Coverage loss, %	31.2	20.0	34.8	50.0
Downtown (n = 469)				
Assumed 24/7 coverage	158	74	59	25
Actual coverage	130	67	47	16
Coverage loss, %	17.7	9.5	20.3	36.0
Outside downtown (n = 1,971)				
Assumed 24/7 coverage	293	147	109	37
Actual coverage	224	135	73	16
Coverage loss, %	23.6	8.2	33.0	56.8
Weekday				
Downtown (n = 338)				
Assumed 24/7 coverage	116	57	40	19
Actual coverage	96	53	32	11
Coverage loss, %	17.2	7.0	20.0	42.1
Outside downtown (n = 1,440)				
Assumed 24/7 coverage	226	119	82	25
Actual coverage	183	113	58	12
Coverage loss, %	19.0	5.0	29.3	52.0
Weekend				
Downtown (n = 131)				
Assumed 24/7 coverage	42	17	19	6
Actual coverage	34	14	15	5
Coverage loss, %	19.1	17.7	21.1	16.7
Outside downtown (n = 531)				
Assumed 24/7 coverage	67	28	27	12
Actual coverage	41	22	15	4
Coverage loss, %	38.8	21.4	44.4	66.7

Values are n, unless otherwise indicated. The differences between coverage loss during daytime, evening, and nighttime were significant (p < 0.001). The differences remained significant when considering only weekdays (p < 0.001), downtown (p = 0.04), and outside downtown (p < 0.001) but not weekends (p = 0.22). The difference in coverage loss between weekdays (18.4%) and weekends (31.2%) was significant (p = 0.04) but not between downtown (17.7%) and outside downtown (23.6%) (p = 0.30). *As defined in **Table 1**.

24/7 = 24 h per day, 7 days per week; other abbreviations as in **Tables 1 and 2**.

TABLE 5 OHCA Coverage Loss of Registered AEDs According to Location Type

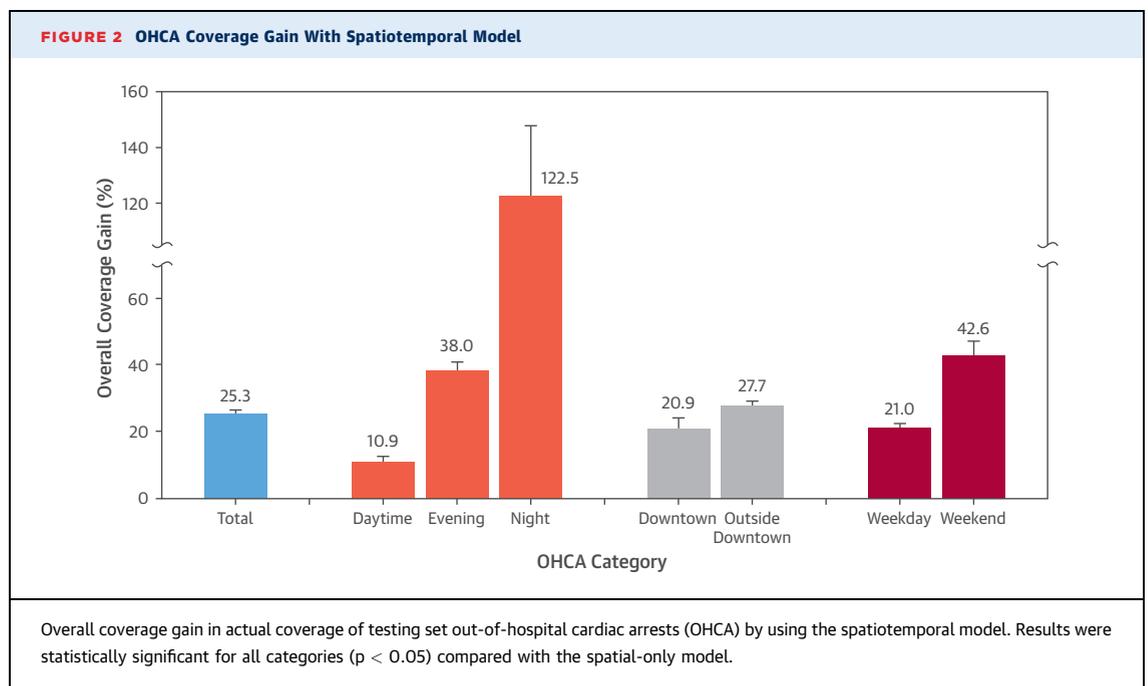|	No. (%) of Locations With an AED	No. of OHCAs Covered		Coverage Loss, %
		Assumed 24/7 Coverage	Actual Coverage	
School	190 (25.8)	68	41	39.7
Recreation/sports facility	165 (22.4)	89	56	37.1
Transportation facility	93 (12.6)	144	144	0
Industrial facility	62 (8.4)	28	17	39.3
Office	54 (7.3)	56	36	35.7
Outdoor seasonal facility	39 (5.3)	8	6	25.0
Law enforcement agency	33 (4.5)	56	39	30.4
Library	25 (3.4)	20	14	30.0
Office building	16 (2.2)	43	37	14.0
Medical facility	15 (2.0)	11	9	18.2
Residences/condominium	13 (1.8)	3	3	0
Emergency services	9 (1.2)	0	0	0
Residence/long-term care or homeless shelters	6 (0.8)	14	14	0
Church	4 (0.5)	1	0	100.0
Community hall	4 (0.5)	2	2	0
Convention facility	3 (0.4)	4	4	0
Entertainment facility	2 (0.3)	2	1	50.0
Shopping center	2 (0.3)	5	2	60.0
Hotel	1 (0.1)	1	1	0
Zoo	1 (0.1)	0	0	0

Abbreviations as in **Tables 1, 2, and 4**.

translate to an increased likelihood of an AED being found and applied in the future.

We used hours of operation to measure temporal availability, but other factors contributing to availability exist beyond hours of operation. For example, employee breaks and tardiness might reduce AED accessibility. In addition, opening hours may vary slightly by season; our analysis used a single snapshot of the hours to represent availability throughout the year.

Our coverage definition did not include the effects of multiple AEDs placed in 1 location or the advantages of closer proximity to the AED within 100 m. The latter issue was addressed in another study (40). AED use and coverage may be higher in these cases because bystanders may be able to locate an AED more rapidly. Doors, walls, and multiple floors were not explicitly modeled. Our spatiotemporal model generated specific locations for prospective AED deployment primarily for the purpose of pinpointing temporally compromised OHCA hotspots that may be addressed with AEDs in nearby, temporally advantaged locations. The model should not be seen as a prescriptive approach to determining specific buildings in which AEDs should be placed because factors such as security, presence of a trained response team, signage, and hours of operation should all be considered in actual deployment decisions. In cities where AED placement decisions are decentralized and most of the suitable locations are private, addressing temporally compromised OHCA hotspots

usage. There has been some effort to relate coverage to AED usage and survival (40), but additional study is required. Coverage gains due to spatiotemporal optimization, all else being equal, should eventually

FIGURE 2 OHCA Coverage Gain With Spatiotemporal Model

Overall coverage gain in actual coverage of testing set out-of-hospital cardiac arrests (OHCA) by using the spatiotemporal model. Results were statistically significant for all categories (p < 0.05) compared with the spatial-only model.
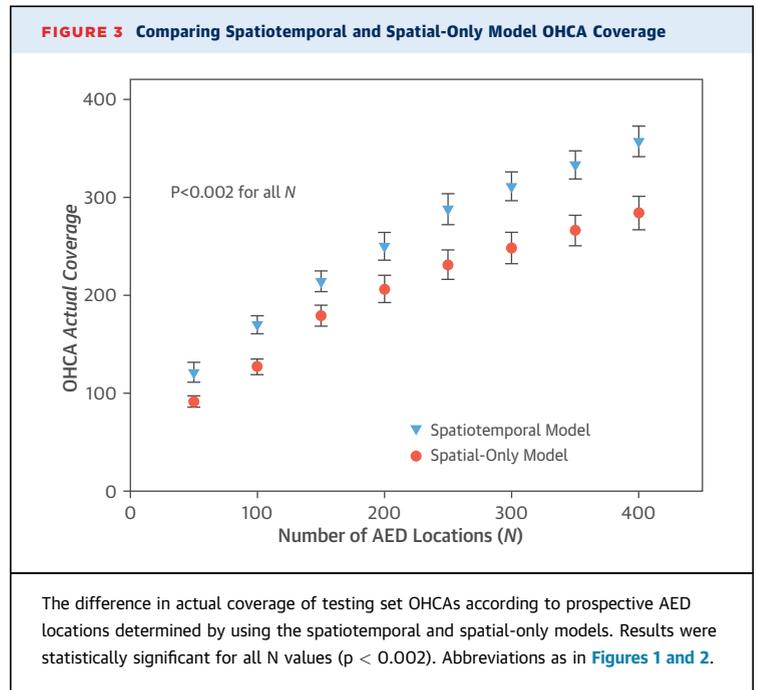
identified by the model will require substantial public-private partnership.

Accessibility is only 1 piece of the larger puzzle in optimizing public defibrillator use and bystander response in an emergency. Other barriers were noted in the Introduction to this paper. There are many synergistic and recent efforts to improve awareness, wayfinding, and EMS integration (41,42).

CONCLUSIONS

Temporal accessibility of public AEDs is critical to both the measurement of true OHCA coverage and the decision on where to locate AEDs. The likelihood of a nearby AED being inaccessible during an OHCA was significant: 1 in 5 OHCAs occurred near an inaccessible AED. According to our computational results, a significant increase in accessibility may be possible if temporal information is properly integrated in AED location decisions. In Toronto, the coverage gain from spatiotemporal optimization was largest at night, which was when the largest loss was experienced by the existing AED network and when survival was lowest. In other words, the potential for spatiotemporal optimization to reverse the effects of limited temporal accessibility was greatest precisely when the need also was greatest. Current evaluation methods may be incorrectly assessing and, thus,

FIGURE 3 Comparing Spatiotemporal and Spatial-Only Model OHCA Coverage

The difference in actual coverage of testing set OHCAs according to prospective AED locations determined by using the spatiotemporal and spatial-only models. Results were statistically significant for all N values (p < 0.002). Abbreviations as in **Figures 1 and 2**.

significantly overestimating OHCA coverage. Including temporal information is a needed change in the way AED placement guidelines are currently designed.

CENTRAL ILLUSTRATION Optimizing Spatiotemporal AED Access: Time Point Comparisons of Registered AEDs

Toronto, Canada
Registered AEDs Accessible at 12:00 pm   Registered AEDs Accessible at 12:00 am

0   2.5   5   7.5   10 km
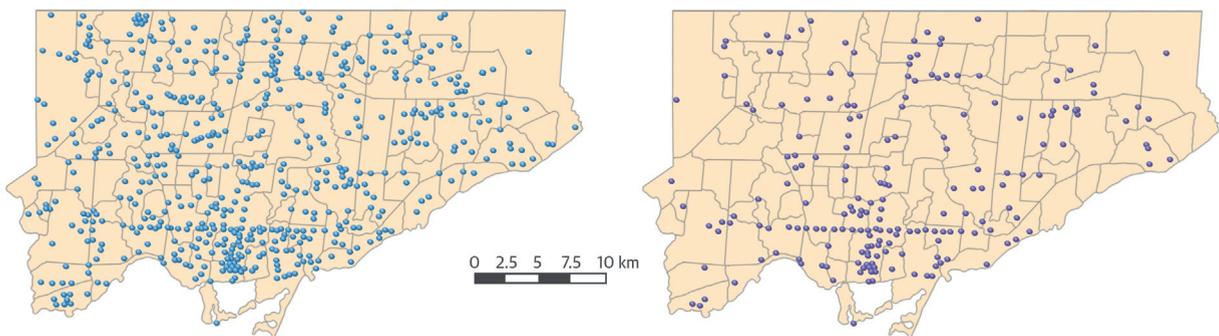
Sun, C.L.F. et al. J Am Coll Cardiol. 2016;68(8):836–45.

Of a total of 737 registered automated external defibrillators (AEDs) in Toronto, Ontario, Canada, 95.9% (707 of 737 AEDs) were available at 12:00 PM, and 30.9% (228 of 737 AEDs) were available at 12:00 AM. The AEDs included in these maps were available at least 5 days of the week at their respective examined times. Potential AED use was significantly improved with a spatiotemporal optimization model guiding deployment, overcoming decreased accessibility in the evening and night.

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PERSPECTIVES

COMPETENCY IN SYSTEMS-BASED PRACTICE: Public defibrillators (AEDs) must be both geographically and temporally accessible to assure optimal availability for individuals experiencing OHCA. Incorporating both temporal and spatial data in determination of optimal AED placement could enhance accessibility for these individuals and improve outcomes. Legislation mandating AED registration with local EMS and 24-7 accessibility to the public would improve access.

TRANSLATIONAL OUTLOOK: Further investigation is needed to identify other factors that contribute to optimal AED placement.

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KEY WORDS automated external defibrillator, cardiac arrest, emergency cardiac care, resuscitation

APPENDIX For an expanded Methods and Results sections as well as figures and tables, please see the online version of this article.