Resuscitation 131 (2018) 101–107

Contents lists available at ScienceDirect

Resuscitation

journal homepage: www.elsevier.com/locate/resuscitation

Clinical paper

Spatiotemporal AED optimization is generalizable☆

Christopher L.F. Sun[a], Lena Karlsson[b,c], Christian Torp-Pedersen[d], Laurie J. Morrison[e,f], Fredrik Folke[b,c], Timothy C.Y. Chan[a,e,*]

[a] Department of Mechanical and Industrial Engineering, University of Toronto, Toronto, Canada
[b] Department of Cardiology, Copenhagen University Hospital Gentofte, Copenhagen, Denmark
[c] Emergency Medical Services Copenhagen, University of Copenhagen, Denmark
[d] Department of Cardiology and Epidemiology/Biostatistics, Aalborg University Hospital, Aalborg, Denmark
[e] Rescu, Li Ka Shing Knowledge Institute, St. Michael's Hospital, Toronto, Canada
[f] Division of Emergency Medicine, Department of Medicine, University of Toronto, Toronto, Canada

A R T I C L E I N F O

Keywords:
Resuscitation
Cardiac arrest
Public access defibrillation
Automated external defibrillator

A B S T R A C T

Aims: Mathematical optimization of automated external defibrillator (AED) placements has the potential to improve out-of-hospital cardiac arrest (OHCA) coverage and reverse the negative effects of limited AED accessibility. However, the generalizability of optimization approaches has not yet been investigated. Our goal is to examine the performance and generalizability of a spatiotemporal AED placement optimization methodology, initially developed for Toronto, Canada, to the new study setting of Copenhagen, Denmark.

Methods: We identified all public OHCAs (1994–2016) and all registered AEDs (2016) in Copenhagen, Denmark. We calculated the coverage loss associated with limited temporal accessibility of registered AEDs, and used a spatiotemporal optimization model to quantify the potential coverage gain of optimized AED deployment. Coverage gain of spatiotemporal deployment over a spatial-only solution was quantified through 10-fold cross-validation. Statistical testing was performed using χ^2 and McNemar's tests.

Results: We found 2149 public OHCAs and 1573 registered AED locations. Coverage loss was found to be 24.4% (1104 OHCAs covered under assumed 24/7 coverage, and 835 OHCAs under actual coverage). The coverage gain from using the spatiotemporal model over a spatial-only approach was 15.3%. Temporal and geographical trends in coverage gain were similar to Toronto.

Conclusions: Without modification, a previously developed spatiotemporal AED optimization approach was applied to Copenhagen, resulting in similar OHCA coverage findings as Toronto, despite large geographic and cultural differences between the two cities. In addition to reinforcing the importance of temporal accessibility of AEDs, these similarities demonstrate the generalizability of optimization approaches to improve AED placement and accessibility.

Introduction

Out-of-hospital cardiac arrest (OHCA) affects over 700,000 people a year in North America and Europe [1,2]. Survival from OHCA decreases rapidly for every minute delay in treatment [3]. Treatment options include cardiopulmonary resuscitation (CPR) and defibrillation. In particular, publicly located automated external defibrillators (AEDs) can be used by bystanders to reduce the delay to defibrillation for OHCA victims [3–6]. Consequently, much effort has focused on implementing public access defibrillator (PAD) programs and developing guidelines for strategic AED placement, which recommend AEDs be placed in high-risk areas and be easily reachable within a few minutes [7,8]. Prior research has focused on quantifying OHCA risk in different location types in cities worldwide, demonstrating generalizability of many of the findings [3,6,9–14]. For example, transportation and recreation facilities have been established in multiple studies as high-risk areas that can benefit from AED placement [3,6,9,15]. In practice, AEDs may be positioned based on local or political decisions, resulting in paradoxical placement in low risk areas [9,16].

For an AED to be used it needs to be accessible. Previous research has shown that in North America and Europe, inaccessible AEDs can significantly decrease OHCA coverage [17], in particular by over 50%

☆ A Spanish translated version of the abstract of this article appears as Appendix in the final online version at https://doi.org/10.1016/j.resuscitation.2018.08.012.

* Corresponding author at: Department of Mechanical & Industrial Engineering, University of Toronto, 5 King's College Rd. – Office: MC315, Toronto, Ontario, M5S 3G8, Canada.

E-mail address: tcychan@mie.utoronto.ca (T.C.Y. Chan).

https://doi.org/10.1016/j.resuscitation.2018.08.012
Received 23 May 2018; Received in revised form 21 July 2018; Accepted 8 August 2018
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during the weekends, evening, and night times [18]. To better guide AED placement and temporal AED accessibility, current research has focused on mathematical optimization of AED placements [17,19–23]. Studies from Toronto, Canada, suggest that optimizing AED locations can outperform population-guided strategies [19], reverse the negative effects of limited temporal availability [17], and be cost-effective [22]. However, unlike the findings on OHCA risk in different location types, it is currently unclear whether the optimization methodologies and results are generalizable. Establishing generalizability is particularly important since the potential financial benefits of optimization strategies can be realized through more efficient PAD programs, many of which have low utilization despite widespread and costly AED deployment [24].

The current paper presents the first study to determine generalizability of previous optimization research for AED placement. In particular, we use the methodology from the spatiotemporal optimization study from Toronto, Canada [17], and apply it to a new study setting of Copenhagen, Denmark. We perform two analyses using Copenhagen data: 1) quantify the temporal availabilities and OHCA coverage of existing registered AEDs, and 2) measure the improvement in AED accessibility and OHCA coverage from spatiotemporal optimization of AED locations. Copenhagen and Toronto are contrasting in size, population, city structure, existing AED networks, and working hours [9,17,25–31]. Given these differences, establishing generalizability to Copenhagen suggests that optimization will be effective in other settings as well.

Methods

Study setting

Central Copenhagen has a population of roughly 600,000 and spans approximately 97 square km [30]. The Copenhagen Emergency Medical Service (EMS) system is a two-tiered system, which consists of ambulances staffed by paramedics providing basic life support, and mobile emergency care units (MECUs) staffed by physicians providing advanced life support. Both EMS tiers are deployed simultaneously by the Emergency Medical Dispatch Centers (EMDCs) during a cardiac arrest.

Study design and data sources

This was a retrospective, registry-based study using data on OHCA documented by the Copenhagen MECUs physicians. The study population included all public location OHCAs of presumed cardiac cause in the city of Copenhagen, Denmark, from 1994 to 2016. Data abstraction on the historical OHCAs included the Utstein predictors of outcome, specifically demographic characteristics, circumstances of arrest and characteristics of care, and the primary outcome of survival. Information regarding bystander witnessed collapse, bystander CPR, and bystander defibrillation before EMS arrival was available during 2008–2016. Public locations were defined as areas accessible to the general public and included outdoor locations, public transportation sites, schools, outpatient clinics, commercial and civic buildings, and exclude hospitals.

All publicly available AEDs registered with the Danish AED Network (https://hjertestarter.dk/) by the end of 2016 in central Copenhagen were included. The registry is managed by a private foundation and contains detailed information on AED location, temporal availability and date of registration. The AEDs in this registry are linked directly with Copenhagen EMS to allow dispatchers to identify the closest available AEDs for lay responders to obtain and use in the case of an OHCA. AED registration information is confirmed by network staff members prior to including the AED location in the registry [25]. By the end of 2016, there were 1573 registered publicly available AEDs in central Copenhagen (262.2 AEDs per 100,000 inhabitants).

A dataset of candidate locations to examine for potential AED placement in Copenhagen, composed of 2138 businesses and public points of interest, was collected from January to March 2017. Candidate locations were selected based on common and popular buildings because of our focus on public OHCAs and were equivalent counterparts to locations selected in Toronto, Canada [17]. The exact location and hours of operations was collected by Viamap©, a private cooperation, as well as through online resources and data extraction from websites.

Analysis 1: temporal availability and coverage loss of registered AEDs

We calculated OHCA coverage based on two definitions. First, we calculated *assumed 24/7 coverage*, where an OHCA was considered covered if it occurred within 100 m of an AED. Second, we calculated *actual coverage*, where an OHCA was considered covered if it occurred within 100 m of an AED and when the AED was available at the time of the OHCA. Locations housing an AED were defined as temporally inaccessible when they are closed according to their hours of operation. The 100 m coverage radius was selected as an approximation of the maximum round trip distance a bystander could travel to retrieve and setup an AED within 3 min [7,8,19].

Using the coverage definitions, we then calculated *coverage loss*, which was defined as *assumed 24/7 coverage* minus *actual coverage*, and then divided by *assumed 24/7 coverage*. *Coverage loss* was examined for different times of day (daytime, 8:00 A.M.–3:59 P.M.; evening, 4:00 P.M.–11:59 P.M.; night, 12:00 A.M.–7:59 A.M.), days of the week (weekday and weekend), geographic areas (city center and outside city center), and by location types where the registered AEDs were placed. The 95% confidence intervals (CI) were calculated for the *coverage loss* using an error propagation and paired proportions approach to change absolute to *coverage loss* CIs. To test for statistical significance in coverage loss across the disjoint and unpaired categories (time of day, day of week, and geography), a chi-squared test was used, where a 2-tailed value of $P < 0.05$ was considered significant.

Analysis 2: spatiotemporal optimization of AED placements

We used a previously developed spatiotemporal optimization model [17], which accounts for both spatial and temporal information of OHCA events and candidate AED locations, to choose the optimal locations to place AEDs and maximize OHCA coverage based on historical OHCA incidence. The model, applied to the Copenhagen data, was unmodified from its initial development in Toronto. The spatiotemporal model used the following inputs: 1) addresses and hours of operation of existing registered AED locations, 2) locations and times of historical OHCAs, 3) addresses and hours of operation of candidate AED locations, and 4) a user-specified model parameter N, which determines the number of candidate locations where AEDs are to be placed. The model outputted the N selected locations that together maximized *actual coverage* of historical OHCAs, along with the total number of OHCAs covered.

The spatiotemporal optimization model was compared to a spatial-only optimization model [19], which works similarly to the spatiotemporal model, but does not consider the time of the OHCAs and the hours of operation of the candidate AED locations. The two models were evaluated on the improvement in *actual coverage* on top of the baseline coverage provided by existing registered AEDs (model input #1) of historical OHCAs in Copenhagen. To ensure the comparison of the two models is based on out-of-sample data, we used a 10-fold cross validation approach in which the OHCAs not covered by the existing registered AEDs were divided randomly into 10 disjoint sets of approximately equal size. In each fold, one set was used as a testing set, while the remaining nine sets were used as the training set. The testing sets across each fold were disjoint.

For each fold, the optimization models used the training sets as the historical OHCA data (model input #2) to select the optimal AED locations from the candidate AED locations (model input #3). The optimal locations determined by the spatiotemporal and spatial-only models were then evaluated on *actual coverage* using that fold's testing set. This process was carried out for all 10 folds, producing *actual coverage* values for each of the 10 testing sets. The results reported in this study represent the totals over the 10 folds. The models were run for values of N (model input #4), ranging from 50 to 200 in increments of 50 for each fold (i.e. $N = 50, 100, 150, 200$).

The *coverage gain* was calculated for each N and was defined as the *actual coverage* from the spatiotemporal model minus *actual coverage* from the spatial-only model, and then divided all by *actual coverage* from the spatial-only model. *Overall coverage gain* was calculated by taking the weighted mean of the *coverage gain* for each N, weighted by the *actual coverage* values from the spatial-only model. The 95% CIs were computed for the *overall coverage gain*, as well as for the *coverage gain* broken down by time of day, day of week, and geography. The difference in *actual coverage* between the two models was determined to be significant using McNemar's test for each N, where a 2-tailed value of $P < 0.05$ was considered significant.

Results

There were 2149 public OHCAs of presumed cardiac cause in Copenhagen, Denmark between 1994–2016 (Table 1). A total of 653 public non EMS-witnessed OHCAs occurred between 2008–2016 where bystander response information was readily available. There was no significant difference in rates between pre-specified time of day intervals for received bystander CPR ($P = 0.37$), received bystander defibrillation ($P = 0.79$) arrests, and 30-day survival ($P = 0.12$). Bystander-witnessed rates were significantly associated with different time intervals ($P = 0.002$).

Public OHCA incidence (1994–2016) by time of day, day of week, and geography is shown in Online Table 1. Online Table 2shows a similar categorization for arrests that received bystander defibrillation (2008–2016). The majority of registered AEDs, 1243 of 1573 (79.0%), were not available 24/7, and 997 (63.4%) were unavailable on weekends. The availabilities of these AEDs by time interval and day of week as compared to previously published Toronto AED availabilities [17] are shown in Fig. 1(A, B). AEDs availabilities are much greater during

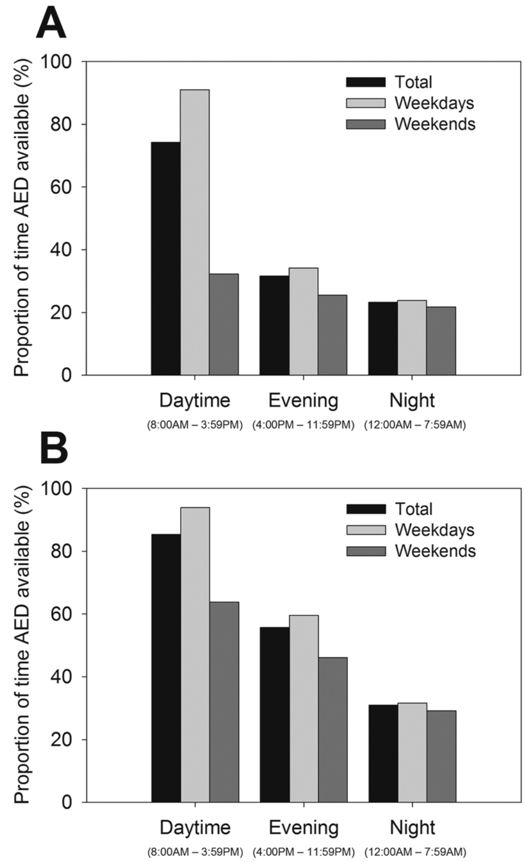

Fig. 1. Accessibility of registered AEDs. AED accessibility by time of day, day of week and geography. AED accessibility over times of day for A: Copenhagen (N = 1573), B: Toronto (N = 737).
Fig. 1B: Reprinted from The Journal of the American College of Cardiology, Vol. 68 No. 8, Sun CLF, Demirtas D, Brooks SC, Morrison LJ, Chan TCY, Overcoming Spatial and Temporal Barriers to Public Access Defibrillators Via Optimization, Pages 836-45, 2016, with permission from Elsevier.

Table 1
Baseline Characteristics of Public OHCAs in Copenhagen.

OHCA from 1994 to 2016[a]	Total (n = 2149)	Daytime (8:00A.M.–3:59P.M.) (n = 1148)	Evening (4:00PM. –11:59P.M.) (n = 714)	Night (12:00A.M.–7:59A.M.) (n = 287)
Median age, y (IQR)	63 (51–75)	66 (54–77)	62 (49–74)	55 (44–69)
Men	61 (50–72)	62 (52–74)	61 (48–70)	54 (43–66)
Women	74 (59-82)	76 (65–83)	72 (55–81)	67 (47–81)
Male sex, n (%)	1608 (75.6)	844 (74.8)	539 (75.5)	225 (79.2)
Median response time, min (IQR)[b]	5 (3–6)	5 (3–6)	5 (3–6)	5 (4–7)
Shockable initial heart rhythm, n (%)	829 (38.6)	492 (42.9)	268 (37.5)	69 (24.0)
OHCA from 2008 to 2016[c]	**Total (n = 653)**	**Daytime (8:00A.M.–3:59P.M.) (n = 354)**	**Evening (4:00P.M.–11:59P.M.) (n = 201)**	**Night (12:00A.M.–7:59A.M.) (n = 98)**
Bystander-witnessed arrest, n (%)	438 (69.9)	255 (76.6)	131 (66.5)	52 (53.6)
Received bystander CPR, n (%)	440 (70.4)	242 (72.7)	138 (70.4)	60 (62.5)
Received bystander defibrillation, n (%)	94 (14.6)	53 (15.2)	29 (14.5)	12 (12.5)
30-day survival, n (%)	193 (32.4)	112 (34.5)	61 (33.3)	20 (23.0)

EMS = emergency medical service; CPR = cardiopulmonary resuscitation; OHCA = out-of-hospital cardiac arrest.
[a] Number of missing for variables available and described from 1994 to 2016: age (n = 45), sex (n = 22), and response time (n = 16). A total of 2087 of 2149 OHCAs were complete for all variables.
[b] Time interval from the dispatch of the EMS to vehicle arrival at scene".
[c] The following variables were only available for cardiac arrests from 2008 through 2016 and includes only known non EMS-witnessed arrests: n = 71 OHCA excluded due to EMS-witnessed arrests; n = 4 OHCA excluded due to missing information on EMS-witnessed status. Number of missing: bystander-witnessed arrest (n = 26), bystander CPR (n = 28), bystander defibrillation (n = 8). 30-day survival: n = 58 OHCAs excluded due to invalid personal identification number. A total of 562 of 653 OHCAs were complete for all variables.

Table 2
Summary of OHCA coverage loss of registered AEDs.
Right side (Toronto) of Table 2: Reprinted from The Journal of the American College of Cardiology, Vol. 68 No. 8, Sun CLF, Demirtas D, Brooks SC, Morrison LJ, Chan TCY, Overcoming Spatial and Temporal Barriers to Public Access Defibrillators Via Optimization, Pages 836–45, 2016, with permission from Elsevier.

		Copenhagen				Toronto				
		Total (n = 2149)	Daytime (8:00A.M.–3:59P.M.) (n = 1148)	Evening (4:00P.M.–11:59P.M.) (n = 714)	Night (12:00A.M.–7:59A.M.) (n = 287)	Total (n = 2440)	Daytime (8:00A.M.–3:59P.M.) (n = 1252)	Evening (4:00PM–11:59P.M.) (n = 840)	Night (12:00A.M.–7:59A.M.) (n = 348)	
Total	*Assumed 24/7 coverage*	1104	575	377	152	451	221	168	62	**Total**
(n = 2149)	*Actual coverage*	835	510	242	83	354	202	120	32	**(n = 2440)**
	Coverage loss (%)	**24.4**	**11.3**	**35.8**	**45.4**	**21.5**	**8.6**	**28.6**	**48.4**	
Weekday	*Assumed 24/7 coverage*	840	442	301	97	342	176	122	44	**Weekdays**
(n = 1610)	*Actual coverage*	682	428	198	56	279	166	90	23	**(n = 1778)**
	Coverage loss (%)	**18.8**	**3.2**	**34.2**	**42.3**	**18.4**	**5.7**	**26.2**	**47.7**	
Weekend	*Assumed 24/7 coverage*	264	133	76	55	109	45	46	18	**Weekends**
(n = 539)	*Actual coverage*	153	82	44	27	75	36	30	9	**(n = 662)**
	Coverage loss (%)	**42.0**	**38.3**	**42.1**	**50.9**	**31.2**	**20.0**	**34.8**	**50.0**	
City Center	*Assumed 24/7 coverage*	280	151	88	41	158	74	59	25	**Downtown (n = 469)**
(n = 349)	*Actual coverage*	225	141	59	25	130	67	47	16	
	Coverage loss (%)	**19.6**	**6.6**	**33.0**	**39.0**	**17.7**	**9.5**	**20.3**	**36.0**	
Outside City Center	*Assumed 24/7 coverage*	824	424	289	111	293	147	109	37	**Outside Downtown (n = 1971)**
(n = 1800)	*Actual coverage*	610	369	183	58	224	135	73	16	
	Coverage loss (%)	**26.0**	**13.0**	**36.7**	**47.7**	**23.6**	**8.2**	**33.0**	**56.8**	

the weekdays compared to weekends in Copenhagen.

Analysis 1: temporal availability and coverage loss of registered AEDs

The registered AEDs covered 1104 OHCAs (51.3%) under *assumed 24/7 coverage* and 835 (38.9%) under *actual coverage*, corresponding to a *coverage loss* of 24.4% of the 2149 public OHCAs included in the study. The coverage losses by time of day and geography, compared across cities are shown in Table 2. Overall coverage loss during the daytime, evening, and night was significant ($P < 0.001$). The differences in coverage loss across time of days was also significant for Weekdays ($P < 0.001$), City Center ($P < 0.001$), and Outside City Center ($P < 0.001$) splits, but not for weekends ($P = 0.284$). Overall coverage loss during the weekend and weekday ($P < 0.001$) as well as city center and outside city center ($P < 0.05$), were both significantly different. City center and outside city center definitions are equivalent to Toronto's downtown and not downtown categories in Table 2. The majority of all OHCAs occurred during the weekends, evenings, and night and experienced a coverage loss of 38%.

Coverage loss due to AED inaccessibility during the weekend in the city center (36.7%) and outside city center (43.6%) was more than double that of the weekday city center (15.0%) and outside city center counterparts (20.2%) and all differences were significant ($P < 0.001$) (Online Table 3).

The coverage loss categorized by AED location type is show in Online Table 4. Companies and office buildings accounted for the most registered AEDs as well as providing access for most of the OHCAs covered under both *assumed 24/7 coverage* and *actual coverage*. Four of the top five location types with the most registered AEDs, accounted for 62.8% of all deployed AEDs, and had a coverage loss exceeding 40% based on actual coverage. Coverage loss was minimal for both transportation facilities (0.9%) and residential settings (4.7%).

Analysis 2: spatiotemporal optimization of AED placements

The 835 OHCAs covered by the registered AEDs were excluded from the analysis; the remaining 1314 OHCAs were used in the 10-fold cross validation analysis.

Fig. 2 shows the *coverage gain* from the AED placements selected by the spatiotemporal over the spatial-only model split by time of day, day of week and geography. The *overall coverage gain* was 15.3% (95% CI: 12.7%–17.9%). The coverage gain in AED accessibility was statistically significant for all categories ($P < 0.05$) except for Copenhagen – City Center. The difference in *actual coverage* values were statistically significant ($P < 0.005$) for all N (Fig. 3). Additional placement of AEDs above $N = 200$ does not provide an increase in coverage because all of the historical OHCAs that are within range of the candidate locations are covered by this point. The coverage values for each N for each OHCA category split are shown in the Appendix (Online Figs. 1–7). The 15.3% coverage gain was determined to be equivalent to a 21.2% gain in efficiency of AED placements. That is, when using the spatiotemporal model to optimize AED placements, 21.2% fewer AEDs are required to reach the same level of coverage as the spatial-only model (Online Table 5).

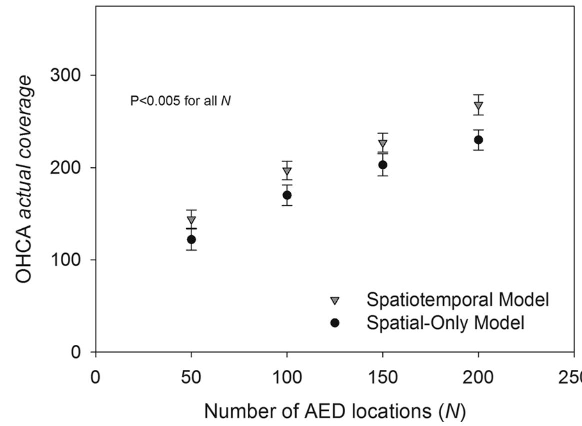

Fig. 3. Comparing Actual AED accessibility for OHCA based on coverage values of the spatiotemporal and spatial-only model in Copenhagen. The *actual coverage* of testing set OHCAs from registered AED locations selected by the spatiotemporal and spatial-only models.

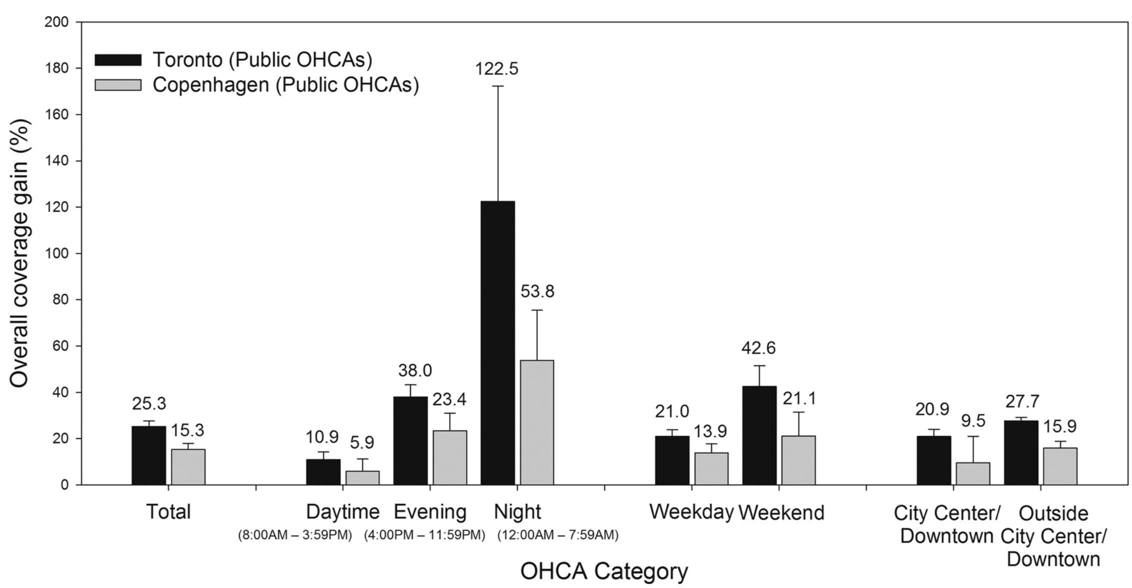

Fig. 2. OHCA coverage gain using the spatiotemporal model. AED accessibility for OHCA as defined as coverage gains in *actual coverage* of the testing set OHCAs when using the spatiotemporal model over the spatial-only model. The coverage gains were calculated as the weighted mean of the coverage gain for each N, weighted by the *actual coverage* values of the spatial-only model.

Toronto data in Fig. 2: Reprinted from The Journal of the American College of Cardiology, Vol. 68 No. 8, Sun CLF, Demirtas D, Brooks SC, Morrison LJ, Chan TCY, Overcoming Spatial and Temporal Barriers to Public Access Defibrillators Via Optimization, Pages 836-45, 2016, with permission from Elsevier.

Discussion

This study offers support for the generalizability of mathematical optimization approaches for AED placement. Similar to findings from a previous study in Toronto [17], a spatiotemporal optimization model was able to identify AED placements in Copenhagen that could reverse the coverage loss associated with limited temporal availabilities of existing AEDs. In Toronto, a coverage loss of 21.5% was observed, which could be offset by a coverage gain of 25.3% through spatiotemporal optimization. In comparison, a coverage loss of 24.4% was observed in Copenhagen, while spatiotemporal optimization generated a coverage gain of 15.3%. Despite significant differences between the cities, including Copenhagen's smaller total population [27,30,31], higher population density [27,30,31], city structure [28,31], demographic consisting of fewer individuals of differing ethnic origins [30–32], larger AED network size [17], and shorter working hours [26,29], the similar coverage loss/gain trends reinforce the finding that temporal accessibility is a critical and potentially widespread issue that should be considered for AED placement guidelines and that may be addressed through spatiotemporal optimization.

Although the OHCA coverage gains in Copenhagen followed the same trend seen in Toronto, the magnitude of the gains was lower. One factor could be that our model optimizes placements on top of the already existing registered AED network. If an AED network is already well-designed and provides high OHCA coverage, there is less opportunity for the spatiotemporal model to increase coverage. For example, the number of AEDs deployed in Copenhagen has increased 15-fold from 6 to 92 AEDs/100,000 inhabitants from 2007 to 2011 [25] and is at 262.2 AEDs/100,000 inhabitants as of 2016, reducing coverage loss due to limited temporal availability from 33.5% in 2011 to 24.4% in 2016 [18]. Limited temporal availabilities of candidate AED locations might also reduce the coverage gain. For example, 62.1% of Copenhagen buildings containing AEDs were closed on weekend, compared to 28.6% in Toronto. Furthermore, there was generally more consistency in opening hours of candidate locations in Copenhagen. As a result, optimization for spatial coverage would be similar to optimization for spatiotemporal coverage, resulting in less of an advantage for the spatiotemporal optimization model.

Nevertheless, a 15.3% coverage gain represents a significant opportunity for improvement given the high coverage loss overall in Copenhagen. Copenhagen, due to its high bystander intervention rate, which is fairly stable across all times of day, may be better positioned to realize the benefits of improved AED accessibility associated with the coverage gain. In general, a combination of a willing bystander population, strong dispatch-assisted bystander support, and strategies to help retrieve nearby AEDs are needed to capture the coverage gains projected through spatiotemporal optimization.

Significant costs and inefficient use of resources is a critical issue confronting many PAD programs [16,24,33]. Studies have noted that the cost-effectiveness of PAD programs hinge on the frequency of AED use [34,35]. Optimization may be able to improve cost-effectiveness of PAD programs by identifying optimal locations to place AEDs. Equivalently, as our efficiency analysis suggests, optimization can help PAD programs achieve comparable coverage levels with fewer resources.

Although the spatiotemporal optimization approach is general, applying it to other cities may require a varying level of effort depending on data availability and completeness, including historical OHCA data, locations and availabilities of existing AEDs, and candidate locations for AEDs. We also note that even with detailed data regarding OHCAs and AEDs, there may be additional factors, such as registered AEDs with expired batteries or pads, that impact the true availability of AEDs.

Improving AED placement through optimization is only one of the many ways to contribute towards improving bystander defibrillation and OHCA survival. Increasing the rate of bystander intervention, reducing the delay to bystander response [36], or improving access to AEDs either through placements that facilitate 24/7 availability or innovations that deliver an AED to the patient side [21] are all important factors that may substantially increase the chances of early defibrillation and ultimately survival.

Conclusion

Optimization of AED placements is a promising approach to support PAD program development, improve OHCA coverage and AED usage, and improve utilization of scarce and costly resources. This study is the first to validate the potential gains due to optimization in a new study setting (Copenhagen) from the one in which the model was initially developed (Toronto). This finding suggests that the benefits of optimizing AED placements can be generalized to new settings to improve OHCA response and PAD programs worldwide.

Conflict of interest

None.

Acknowledgements

This work was supported by the Danish foundation TrygFonden with no commercial interest in the field of cardiac arrest. The authors acknowledge the Danish AED Network (http://www.hjertestarter.dk) for sharing information on the automated external defibrillators registered in their network and to the EMS personnel that report and support the Danish OHCA database.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.resuscitation.2018.08.012.

References

[1] Mozaffarian D, Benjamin EJ, Go AS, Arnett DK, Blaha MJ, Cushman M, et al. Heart disease and stroke statistics—2015 update: a report from the American Heart Association. Circulation 2015;131:e29–322.
[2] Grasner JT, Lefering R, Koster RW, Masterson S, Bottiger BW, Herlitz J, et al. EuReCa ONE-27 Nations, ONE Europe, ONE Registry: a prospective one month analysis of out-of-hospital cardiac arrest outcomes in 27 countries in Europe. Resuscitation 2016;105:188–95.
[3] Valenzuela TD, Roe DJ, Nichol G, Clark LL, Spaite DW, Hardman RG. Outcomes of rapid defibrillation by security officers after cardiac arrest in casinos. N Engl J Med 2000;343:1206–9.
[4] Weisfeldt ML, Sitlani CM, Ornato JP, Rea T, Aufderheide TP, Davis D, et al. Survival after application of automatic external defibrillators before arrival of the emergency medical system: evaluation in the Resuscitation Outcomes Consortium population of 21 million. J Am Coll Cardiol 2010;55:1713–20.
[5] Becker L, Eisenberg M, Fahrenbruch C, Cobb L. Public locations of cardiac arrest: implications for public access defibrillation. Circulation 1998;97:2106–9.
[6] Caffrey SL, Willoughby PJ, Pepe PE, Becker LB. Public use of automated external defibrillators. N Engl J Med 2002;347:1242–7.
[7] Neumar RW, Shuster M, Callaway CW, Gent LM, Atkins DL, Bhanji F, et al. Part 1: executive summary: 2015 American Heart Association Guidelines update for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation 2015;132:S315–67.
[8] Monsieurs KG, Nolan JP, Bossaert LL, Greif R, Maconochie IK, Nikolaou NI, et al. European Resuscitation Council guidelines for resuscitation 2015: section 1. Executive summary. Resuscitation 2015;95:1–80.
[9] Folke F, Lippert FK, Nielsen SL, Gislason GH, Hansen ML, Schramm TK, et al. Location of cardiac arrest in a city center: strategic placement of automated external defibrillators in public locations. Circulation 2009;120:510–7.
[10] Muraoka H, Ohishi Y, Hazui H, Negoro N, Murai M, Kawakami M, et al. Location of out-of-hospital cardiac arrests in Takatsuki City: where should automated external defibrillator be placed. Circ J 2006;70:827–31.
[11] Sun CL, Brooks SC, Morrison LJ, Chan TC. Ranking businesses and municipal locations by spatiotemporal cardiac arrest risk to guide public defibrillator placement. Circulation 2017;135:1104–19.
[12] Gratton M, Lindholm DJ, Campbell JP. Public-access defibrillation: where do we place the AEDs? Prehosp Emerg Care 1999;3:303–5.
[13] Page RL, Joglar JA, Kowal RC, Zagrodzky JD, Nelson LL, Ramaswamy K, et al. Use of automated external defibrillators by a U.S. airline. N Engl J Med 2000;343:1210–6.

[14] Lee M, Demirtas D, Buick JE, Feldman MJ, Cheskes S, Morrison LJ, et al. Increased cardiac arrest survival and bystander intervention in enclosed pedestrian walkway systems. Resuscitation 2017;118:1–7.
[15] Brooks SC, Hsu JH, Tang SK, Jeyakumar R, Chan TC. Determining risk for out-of-hospital cardiac arrest by location type in a Canadian urban setting to guide future public access defibrillator placement. Ann Emerg Med 2013;61:530–8. e2.
[16] Fleischhackl R, Roessler B, Domanovits H, Singer F, Fleischhackl S, Foitik G, et al. Results from Austria's nationwide public access defibrillation (ANPAD) programme collected over 2 years. Resuscitation 2008;77:195–200.
[17] Sun CLF, Demirtas D, Brooks SC, Morrison LJ, Chan TCY. Overcoming spatial and temporal barriers to public access defibrillators via optimization. J Am Coll Cardiol 2016;68:836–45.
[18] Hansen CM, Wissenberg M, Weeke P, Ruwald MH, Lamberts M, Lippert FK, et al. Automated external defibrillators inaccessible to more than half of nearby cardiac arrests in public locations during evening, nighttime, and weekends. Circulation 2013;128:2224–31.
[19] Chan TC, Li H, Lebovic G, Tang SK, Chan JY, Cheng HC, et al. Identifying locations for public access defibrillators using mathematical optimization. Circulation 2013;127:1801–9.
[20] Siddiq AA, Brooks SC, Chan TC. Modeling the impact of public access defibrillator range on public location cardiac arrest coverage. Resuscitation 2013;84:904–9.
[21] Boutilier JJ, Brooks SC, Janmohamed A, Byers A, Buick JE, Zhan C, et al. Optimizing a drone network to deliver automated external defibrillators. Circulation 2017;135:2454.
[22] Chan TCY, Demirtas D, Kwon RH. Optimizing the deployment of public access defibrillators. Manage Sci 2016;62:3617–35.
[23] Chan TCY, Shen Z-JM, Siddiq A. Robust defibrillator deployment under cardiac arrest location uncertainty via row-and-column generation. Oper Res 2018;66:358–79.
[24] Kitamura T, Kiyohara K, Sakai T, Matsuyama T, Hatakeyama T, Shimamoto T, et al. Public-access defibrillation and out-of-hospital cardiac arrest in Japan. N Engl J Med 2016;375:1649–59.
[25] Hansen CM, Lippert FK, Wissenberg M, Weeke P, Zinckernagel L, Ruwald MH, et al. Temporal trends in coverage of historical cardiac arrests using a volunteer-based network of automated external defibrillators accessible to laypersons and emergency dispatch centers. Circulation 2014;130:1859–67.
[26] OECD. OECD better life index: work-life balance. 2018.
[27] City Population. Copenhagen (Denmark): city districts – population statistics, charts and map. 2018.
[28] Copernicus. Urban atlas 2012. 2012http://land.copernicus.eu/local/urban-atlas/urban-atlas-2012/view.
[29] UBS. Open data – prices earnings. 2015https://www.ubs.com/microsites/prices-earnings/open-data.html.
[30] Statistics Denmark. Statistics Denmark. 2018http://www.statbank.dk/statbank5a/default.asp?w=1366.
[31] City of Toronto. Open data. 2018https://www.toronto.ca/city-government/data-research-maps/open-data/.
[32] Becker LB, Han BH, Meyer PM, Wright FA, Rhodes KV, Smith DW, et al. Racial differences in the incidence of cardiac arrest and subsequent survival. The CPR Chicago Project. N Engl J Med 1993;329:600–6.
[33] Hansen SM, Hansen CM, Folke F, Rajan S, Kragholm K, Ejlskov L, et al. Bystander defibrillation for out-of-Hospital cardiac arrest in public vs residential locations. JAMA Cardiol 2017;2:507–14.
[34] Cram P, Vijan S, Fendrick AM. Cost-effectiveness of automated external defibrillator deployment in selected public locations. J Gen Intern Med 2003;18:745–54.
[35] Moran PS, Teljeur C, Masterson S, O'Neill M, Harrington P, Ryan M. Cost-effectiveness of a national public access defibrillation programme. Resuscitation 2015;91:48–55.
[36] Ringh M, Rosenqvist M, Hollenberg J, Jonsson M, Fredman D, Nordberg P, et al. Mobile-phone dispatch of laypersons for CPR in out-of-hospital cardiac arrest. N Engl J Med 2015;372:2316–25.