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Clinical paper

Novel relocation methods for automatic external defibrillator improve out-of-hospital cardiac arrest coverage under limited resources[☆]

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ABSTRACT

Background: Mathematical optimisation models have recently been applied to identify ideal Automatic External Defibrillator (AED) locations that maximise coverage of Out of Hospital Cardiac Arrest (OHCA). However, these fixed location models cannot relocate existing AEDs in a flexible way, and have nearly exclusively been applied to urban regions. We developed a flexible location model for AEDs, compared its performance to existing fixed location and population models, and explored how these perform across urban and rural regions.
Methods: Optimisation techniques were applied to AED deployment and OHCA coverage was assessed. A total of 2802 geolocated OHCAs occurred in Canton Ticino, Switzerland, from January 1st 2005 to December 31st 2015.
Results: There were 719 AEDs in Canton Ticino. 635 (23%) OHCA events occurred within 100 m of an AED, with 306 (31%) in urban, and 329 (18%) in rural areas. Median distance from OHCA events to the nearest AED was 224 m (168 m urban vs. 269 m rural). Flexible location models performed better than fixed location and population models, with the cost to deploy 20 new AEDs instead relocating 171 existing AEDs to new locations, improving OHCA coverage to 38%, compared to 26% using fixed models, and 24% with the population based model.
Conclusions: Optimisation models for AEDs placement are superior to population models and should be strongly considered by communities when selecting areas for AED deployment. Compared to other models, flexible location models increase overall OHCA coverage, and decreases the distance to nearby AEDs, even in rural areas, while saving significant financial resources.

Introduction

The American Heart Association (AHA) and the European Resuscitation Council (ERC) recommend the placement of public Automated External Defibrillators (AEDs) in areas in which a cardiac arrest has occurred every 2 and 5 years, respectively [1,2]. Accordingly, great effort and research has been devoted to identify high-risk out-of-hospital cardiac arrest (OHCA) locations and building types to place AEDs [3]. This approach is justified by the evidence that national PAD programs involving widespread deployment of static AEDs are unlikely to be cost-effective [4].

Mathematical optimisation of AED deployment may best serve this scope. This approach has been recently developed in urban areas [5–8], where they identify AED locations that maximise the number of OHCA events covered within a specified distance of an AED, typically set to 100 m [5]. However, these methods assume existing AEDs are fixed and cannot be moved, and additionally have not been tested in rural regions. This highlights a need to develop new AED deployment models

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that consider the possibility to relocate AEDs and assess the performance of existing and new models for rural and urban areas. Assessing AED placement performance in both rural and urban areas that include homes is of particular importance for two reasons. Firstly, publicly occurring OHCAs only make up a small fraction of all OHCAs [9], with approximately 70% of OHCA events occurring in home or private buildings, where AED access is normally poor. Secondly, because the development of smartphone applications has allowed for lay responders trained in CPR and AED use, can improve AED access in public and private locations [10,11].

This manuscript focuses on three objectives: (1) Evaluate current OHCA coverage provided from AEDs (2). Evaluate and compare population models, and fixed location deployment models in urban and rural areas, and (3). Evaluate and compare the fixed location models to a novel, cost saving flexible location model, in urban and rural areas.

Methods

We conducted a retrospective observational study of all OHCA episodes occurring in Canton Ticino, Switzerland from January 1st, 2005 to December 31st, 2015. The population is approximately 346,539 (as of 2013), covering 2812 km^2 of land with geographic features such as mountains, valleys, and lakes [12], with a population density of 123.23 per km^2.

Data sources

A cardiac arrest registry capturing all cardiac arrest cases was established on 1st of January 2002, with audited data entered from 1 January 2005 [13]. Prior to April 2nd 2009, OHCA events were manually geolocated based on the address provided; all subsequent OHCAs were automatically geolocated. Every AED in Canton Ticino is registered and owned by Fondazione Ticino Cuore, which lends AEDs to those institutions, corporates and individuals seeking AED installation. Each AED's coordinates, exact position in the building (floor, room, etc.), and availability ("public AED" is available 24/7, 365 days a year vs. "private AED" − which has some time limitations if in a non- public structure) are on record. OHCA events were broken into urban and rural locations, with urban defined as municipalities with a population over 7000 and a population density over 200 per km2. There are 6 urban municipalities and 125 rural municipalities.

Data are collected and stored following Good Clinical Practice Guidelines and the relevant legislation governing the use of patient data. The investigation complied with the Declaration of Helsinki's principles for physicians engaged in biomedical research involving human subjects. The Queensland University of Technology Human Research Ethics Committee assessed this research as meeting the conditions for exemption from HREC review and approval in accordance with section 5.1.22 of the Australian National Statement on Ethical Conduct in Human Research. The study was conducted in Switzerland. The study matched the guidelines and legislation in the country. The Federal Ethics Committee waived the need for informed consent to collect data in a cantonal OHCA registry.

Potential locations for new AEDs

Potential locations for new AEDs were sourced using data provided by the Federal Statistical Office, Federal Register of Buildings and Dwellings. The data contained information on 118,476 buildings, that is every residential, industrial, commercial, or public building in Ticino, including GPS co-ordinates, municipality, and the number of floors, apartments, and separate rooms.

Analysis 1: determining OHCA coverage

Distance between each OHCA and AED was calculated by computing pairwise haversine distances, and the closest AED to each OHCA event recorded. An OHCA is covered if an AED is within 100 m, and coverage was calculated as the proportion of OHCA events covered.

Analysis 2: evaluating and comparing fixed location and population models

The fixed location model is based on the Maximal Covering Location Problem, [5,14] and identifies a given number (N) of AED locations that maximize the number of historical cardiac arrests covered within 100m. This model assumes existing registered AEDs cannot be moved, and is referred to as the "fixed location model".

A population model was used to compare a "common sense" approach to the fixed location model. Here, AED locations are chosen with high population. This model does not use information about OHCA occurrences, instead following the formulation below, where nbuilding is the number of floors in a building, nmunicipality is the total number of floors in all buildings in a municipality, and popmunicipality the population of the municipality

$$\text{score} = \frac{n_{\text{building}}}{n_{\text{municipality}}}\text{pop}_{\text{municipality}}$$

Each building gets a score, a rank is calculated, and the top N locations are chosen. Other approaches were explored, changing the number of rooms and apartments in a building and municipality, and also changing nmunicipality and popmunicipality to n_{canton} and pop_{canton}. Of these, we used the population model which provided best OHCA coverage.

A 2 × 2 contingency table was created to compare OHCA coverage in the fixed location model and the population model. Here the main diagonal counts the number of cardiac arrests covered by each model, and the off diagonals count those cardiac arrests covered by one and not the other. The McNemar test of paired comparisons was then performed for each value of N, to determine whether there were significantly more OHCA events covered in the optimisation or population based approach [15].

Analysis 3: evaluating and comparing the flexible location model to the fixed location model

The fixed location model does not allow for existing AEDs to be relocated, thus we developed a new, flexible location model that allows for relocation of existing AEDs, referred to as the "flexible location model". This model uses information about the cost of installation and relocation of an AED to determine whether it could achieve better coverage by relocating an AED, or installing a new one. This model assumes that relocation cost is independent of geographic distance between source and destination positions. As before, potential AED locations were selected from the building dataset. Instead of the number of new AEDs we limit the maximum cost, C, so C = 60,000 Euro is the equivalent cost of installing 10 new AEDs costing 6000 Euro. This approach also takes into account AED relocation costs of 700 Euro, calculated based upon material costs, and the number of working hours (200 Euro/hour) to remove and reposition an AED. So, instead of installing 10 new AEDs, it may do a mixture of new installations, and relocation of existing AEDs. The flexible location and fixed location models are compared using the McNemar test. We also assess how many AEDs are installed and relocated at each price point.

Cross validation in OHCA data

To avoid an inflated coverage score, we assessed the optimisation and population models with 5-fold cross validation for each value of N (20, 40, 60, 80, 100), or the equivalent cost, 120,000, 240,000, 360,000, 480,000, 600,000 Euro. Additionally, we specify a coverage distance of 100m, as done in Chan et al. [5]. To perform five-fold cross-validation, we randomly split the OHCA data into 5 non-overlapping groups (folds) and label OHCA observations 1–5. Folds were not forced to have matching characteristics, but were explored to ensure groups were represented appropriately. The first fold was treated as a test set, and the optimisation model for placing AEDs is applied to the remaining four folds (training set). Using AEDs placed by this training set, we determined OHCA coverage in the test set. This process was repeated for all 5 folds as test set, ensuring coverage was obtained for each OHCA entry without relying on information from that entry. The coverage results were then summed across test sets and coverage is calculated. We assess test and training coverage and evaluate how coverage varies over urban and rural areas.

Software

The R statistical programming language (version 3.3.3), and additional R packages were used to perform data preparation and analysis [16]. These R packages are listed in the supplementary materials (Part C).

Results

Determining OHCA coverage

From 2005–2015, 2802 OHCAs occurred in Ticino. Demographic characteristics of OHCA and location are shown in Table 1; the majority of OHCA events occurred in rural areas and homes. There were 719 AEDs placed throughout Ticino, with 253 in urban areas vs. 466 in rural areas. There are 329 AEDs in public locations (80 urban, and 249 rural), which were available 24 h/365 days, and 390 AEDs in locations with more limited availability (173 urban and 217 rural).

All AEDs provided 23% coverage of all OHCA events, and Public AEDs 15%, with coverage being significantly higher in urban compared to rural areas for all AEDs and for Public AEDs (Table 2). For all AEDs and OHCA events, the median distance from an OHCA to the closest AED was 224 m (IQR 110 m − 420). Rural areas had significantly larger distances compared to urban areas for all both all AEDs and public AEDs (Table 2).

Evaluating and comparing optimisation and population methods

Test set coverage of the fixed location model indicated expected coverage of OHCA events in Ticino to range between 26% and 35% when placing 20–100 new AEDs, respectively, with results varying for urban and rural areas, (Fig. 1A). Very similar improvements in coverage were observed when using only public AEDs with coverage being 26%, and 34%, (Supplementary Fig. 1A). OHCA coverage for the population model ranged from 24% to 27%. Substantially less coverage was observed for the population model when considering only Public AEDs, with coverage ranging from 16% to 20% (Supplementary Fig. 1A).

Table 1
Demographic characteristics of the 2802 out-of-hospital cardiac arrests occurred in Canton Ticino from January 1st 2005 until December 31st, 2015.

Characteristic	
Average Age(± SD)	71.9 ± 13.9
Male Age	69.8 ± 13.9
Female Age	76.7 ± 12.8
Male sex, n(%)	1922(68.6)
Locations of cardiac arrest	
Urban Areas, n(%)	1001 (35.7)
Rural Areas, n(%)	1801 (64.3)
Home Urban/Rural	707/1265
Street Urban/Rural	92/184
Public building Urban/Rural	68/122
Other Urban/Rural	57/113
Elderly Home Urban/Rural	44/39
Sport & Free time Urban/Rural	10/46
Work Urban/Rural	23/31
School Urban/Rural	0/1
Not Identified Urban/Rural	2/15

Table 2
The 25th, 50th, and 75th percentiles of the distance from OHCA to the nearest AED for All AEDs, Public AEDs only and the coverage for urban and rural areas. Test scores comparing the distances and coverage for urban and rural are also shown. * = Kolmogorov-Smirnov Test, § = paired proportions test.

Type	All	Public	All
	(25th, 50th, 75th)	(25th, 50th, 75th)	(% OHCA covered)
Urban	90 m, 168 m, 278m	135 m, 263 m, 434 m	31%
Rural	127 m, 269 m, 511 m	175 m, 359 m, 721 m	18%
Test	*D = 0.242 $p < .001$	*D = 0.2 $p < .001$	§χ = 54.855 $p < .001$

When placing 20–100 AEDs, distances from OHCA to nearest AED for the fixed location model were less than the population model for all AEDs and public AEDs (Table 3).

OHCA coverage was significantly higher in the fixed location model over the population model for all values of N, with odds ratios always greater than 1 ($p \leq .01$, McNemar test, Supplementary Fig. 2A). Very similar coverage results were obtained when running the models using only Public AEDs (Supplementary Fig. 2C).

Evaluating and comparing the flexible location method to the fixed-location method

Spending 120,000 Euro (cost of 20 AEDs), relocated 171 AEDs, and covered 38% of OHCAs. Spending 600,000 Euro (cost of 100 AEDs) relocated 604 AEDs, installed 29, and covered 50% of OHCAs (Fig. 1A; Table 4). OHCA coverage was significantly higher in the flexible location model compared to the fixed location model for all budget points ($p \leq .001$, McNemar Test, Supplementary Fig. 2B).

Median distance for the flexible location model were better than fixed location and population model (Table 3). The flexible location model had significantly higher coverage than the fixed location ($p \leq .001$), the size of the effect ameliorates as more AEDs are added (Supplementary Fig. 2B).

The flexible location model did not relocate additional AEDs when moving from 80 to 100 AEDs (480,000 Euro to 600,000 Euro), and had to install and purchase new AEDs to continue to improve coverage (Table 4). Similar results were observed when optimising models for public AEDs only, as no more AEDs were relocated by the flexible location model at 40 (240,000 Euro), rather than 80 (480,000 Euro) (Table 4).

Discussion

We applied models for AED deployment in urban areas covering OHCAs occurring in public areas, significantly expanding current knowledge by including home and private locations. Furthermore, we demonstrated for the first time that optimisation models (fixed location and flexible location) can significantly improve OHCA coverage also in rural areas, majorly reducing distances between OHCA victims and their nearest AED in some cases by over 100m. Finally, the AED flexible location model is a novel method that can save significant financial resources, while substantially improving coverage and reducing distance from OHCA to AEDs.

Optimisation is effective in urban and rural areas

Even though PAD programs are found to be associated with improved survival rates [2,20], only a small percentage of OHCA victims have an AED applied before EMS arrival [21,22]. Many factors may contribute to the low usage rate of AEDs, including lack of public

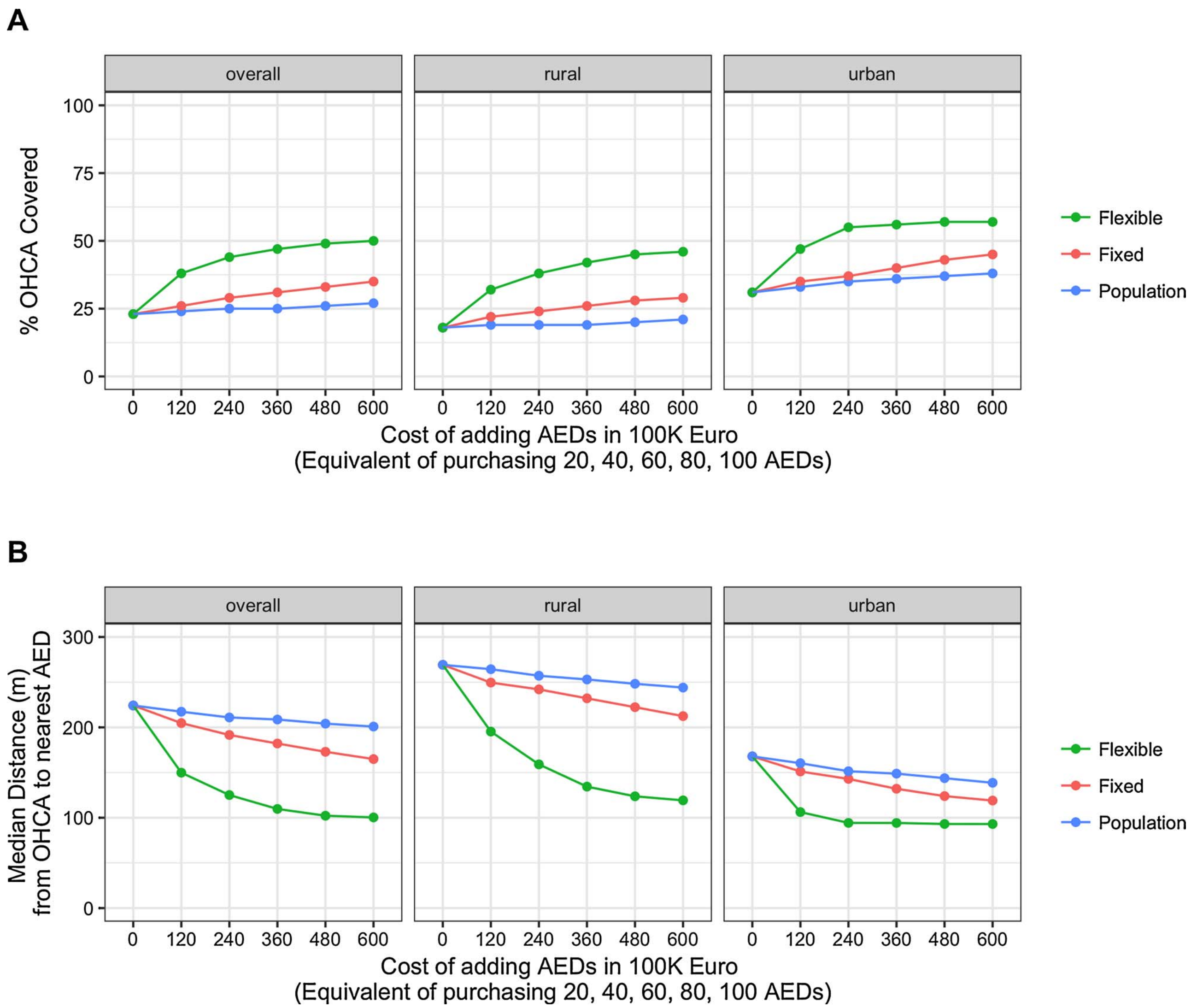

Fig. 1. Panel A shows OHCA test set coverage for flexible location, fixed location, and population models. Panel B shows the median distance from OHCA events to the nearest AED for flexible location, fixed location, and population models. All results use the test set coverage and distances, and are split by the overall area, and rural and urban areas.

Table 3
The 25th, 50th, and 75th percentiles of the distance from OHCA to the nearest AED and the percentage of OHCA events covered for the population model, fixed location model, and flexible location model, tabulated against placing 20 AEDs or 100 AEDs for all AEDs or just public AEDs.

Terms	Population	Fixed	Flexible
	(25th, 50th, 75th)	(25th, 50th, 75th)	(25th, 50th, 75th)
	(% Coverage)	(% Coverage)	(% Coverage)
All 20	105 m, 217 m, 415 m 23.59%	97 m, 205 m, 401 m 26.40%	82 m, 150 m, 334 m 37.54%
All 100	94 m, 201 m, 399 m 27.01%	84 m, 165 m, 345 m 34.51%	73 m, 100 m, 232 m 49.85%
Public 20	147 m, 299 m, 587 m 16.05%	99 m, 208 m, 409 m 26.41%	89 m, 211 m, 541 m 31.62%
Public 100	118 m, 254 m, 550 m 20.34%	84 m, 170 m, 361 m 34.51%	83 m, 156 m, 418 m 38.47

Table 4
The number of AEDs relocated, and purchased installed at each price point.

Total Cost	All Number Relocated	All Number Purchased	Public Number Relocated	Public Number Purchased
120,000 Euro	171	0	171	0
240,000 Euro	342	0	293	5
360,000 Euro	514	0	294	25
480,000 Euro	603	9	293	45
600,000 Euro	604	29	293	65

awareness, lack of bystander willingness, and lack of data-driven guidance in choosing AED locations. The AHA/ERC recommends public AEDs are deployed where there has been an OHCA every 2 years, or in public locations with high likelihood of witnessed cardiac arrest [1,2]. Recently, several spatial and spatiotemporal mathematical models have been developed [6,7], which demonstrate better performance than empiric or population-based models for placement of public AEDs. Their approach may be better suited for those organizations that have already extensively implemented AHA/ERC recommendations. Our research reflected similar findings, the fixed location model improved OHCA coverage as AEDs were placed, and the population model improved very little. In Canton Ticino, current OHCA coverage was 23%, with higher coverage in urban areas (31%) and lower coverage in rural areas (18%). The OHCA coverage for urban area in Ticino was already much higher than the 23% recently reported for Toronto area by Chan et al. [5]. Our flexible location model results showed that an equivalent deployment of 100 new AEDs would relocate 633 AEDs, which in urban areas increased coverage to 50%, and decreased median distance from 168 m to 93m, a reduction of 75 m, a 45% improvement. In rural areas, coverage increased to 46%, and decreased median distance from 270 m to 119m, a reduction of 151 m, a 56% improvement.

In contrast to previous studies [5–8], our findings show for the first time that optimization models (fixed and flexible models) perform well in both rural and urban areas. Rural areas still pose significant optimization issues due to the geographical challenges to cover small villages in valleys and mountains. Across all models, rural areas had lower OHCA coverage than urban areas (11–17 percentage points), and fixed and flexible location models always improved coverage over population models (2–23 percentage points).

Optimisation considering an efficient lay responder network

All previous studies on spatial or spatiotemporal optimization strategies have exclusively targeted OHCAs occurring in public locations; such OHCAs typically represent 20–30% of all OHCAs [5,7,8,17]. In contrast, our study considered all OHCAs occurring in the Canton Ticino because lay responders are part of the first responder network, and are involved in the treatment of OHCA cases. Lay responders are alerted via mobile applications, and requested to start CPR or to deploy/use an AED [10,11,18]. Thus, reducing the distance a lay responder needs to walk/run by about 100 m has the potential to save close to a minute in response time, meaning faster treatment and a higher survival rate.

As in other cases [9], two-thirds of all OHCAs occur at home where on-site AEDs are rarely available; usually these events are associated with lower rates of early initiated CPR and worse outcomes. Zijlstra et al. [19] reported that in notifying AED location via SMS to lay persons, AEDs were used before EMS arrival in 23% of all OHCAs in residential areas. Geolocation of victims, first responders, and the nearest AED provides strong motivation to optimize placement of public AEDs and include home and private locations in optimisation models.

Performance of flexible location model under budgetary constraints

The relocation approach as described by Chan et al. [8] considered removal of all existing AEDs, and then to optimally relocate them. Directly modelling optimal AED relocation allows for observation of coverage change as more AEDs are relocated, and avoiding cases where already optimally located AEDs are unnecessarily relocated. We also allow for budgetary constraints, and provide great potential for efficient and economic AED placement. For example, the cost of 20 AEDs can instead be used to relocate 171 AEDS, improving coverage to 38%, saving over 900,000 Euro (171 − 20 = 151 6,000 Euro). The cost of 100 AEDs would install 633 AEDs, relocate 604 AEDs, and purchase 29 new AEDs, increasing coverage to 50%, and save over 3,000,000 Euro (633 − 100 = 533 6000 Euro). Comparatively, the equivalent cost of 20 or 100 AEDs improves coverage from 26% to 35%. This cost saving strategy is in line with previous work by Moran et al. [4] who indicated that widespread deployment of AEDs are not yet cost-effective. This model can be used as a decision- support tool for stakeholders involved in the strategic placement of public AEDs, including communities and national regulators.

Fig. 2 displays existing AED locations, and the optimally placed AEDs from the fixed location and flexible location model in Locarno, a municipality of Ticino, when providing the costs to place 20 AEDs. Note that there is one additional AED for the fixed location model (Panel A), and 15 for the flexible location model (Panel B). This demonstrates that the flexible location model provides many more optimally placed AED locations. Several AEDs which had not provided coverage are also indicated to be removed. In panel B a cluster of 3 AEDs in the center all provide similar coverage, two are relocated to cover additional OHCA events. Finally, rural areas present a challenging environment to provide OHCA coverage with public AEDs, and may require enormous financial investment − even after flexible AED location strategies. In our region, the median distance to a PAD/AED was relatively short (359 m) but the 95%CI indicates a distance of 721 m. Even the median distance may take up to 5–6 min to be covered, a timeframe where the value of early defibrillation and initiation of CPR is becoming modest. Outside Canton Ticino, there are more geographically sparse jurisdictions which suggests that different AED deployment strategies should be implemented, in some case the use of AEDs in every remote home, and in others a more novel approach, such as the use of drone delivery [23,24].

Limitations

We implicitly assume that the distribution of past cardiac arrests is representative of the future, as in previous research [5,8], based on evidence that historical OHCA event locations are representative of future events [25]. We have addressed these concerns using cross- validation to account for year-to-year variability, as each fold contains a random sample from each year, meaning estimated coverage is based on samples not dependent on year.

We considered the optimisation problem using distances calculated by haversines formula only. However, given the small AED coverage distance of 100m, and the significant reduction in the median distance achieved with the flexible location model, it is unlikely that harversine and walking distance should be significantly different. Additionally, as harversine distance is used for all models compared, the relative merits of models are not affected by the choice of metric. Furthermore, it is not clear whether walking distance accurately describes AED lay responder behaviour. A better approach would be to enter in the model the real distance obtained from the smartphone application developed in Ticino, which can physically track individual response behaviour and the distance that they travelled. This is an area of future development, which requires data not currently available. Future models could also consider cases where the closest AED is assigned when there is more than one suitable AED within 100 m.

The definition of urban and rural areas varies across regions and countries. Furthermore, urban structures undergo change over time due to creeping urbanization and the growing importance of ever-larger functional spaces. This makes it necessary to undertake a frequent, thorough revision of the existing definition of urban areas. We arbitrarily stated that urban was defined as municipalities with a population over 7000 and a population density over 200 per km^2, which could be appropriate in the Swiss context (total population in 2016: 8,400,000; total area: 41,205 Km^2). However, this definition is certainly different from UK or from the one recently proposed by European Commission [26]. In the UK, where it is defined as rural if they fall outside of settlements with more than 10,000 resident population [27], and in Europe it is distinguished in densely, intermediate and thinly populated areas [26]. This means the performance of these models may be different in different regions, and so researchers should be sure to take the definition of urban and rural areas for their region into consideration when interpreting their results.

The fixed and flexible location models outlined in this paper provide evidence based decisions for AED placements. However, actual locations and relocations of AEDs will need to screened. We did not model AED coverage in highrise buildings, and we expect that this has minimal effect, as Ticino has very few highrise buildings, unlike cities such as Toronto. Highrise buildings could easily be addressed by placing AEDs in elevators, as suggested in Chan et al. [8]. Additionally, optimal AED placement does not mean optimal AEDs use. This problem is less relevant in Ticino, due to the development of a smartphone application which provides precise AED locations.

Conclusions

Optimisation models for AED placement are superior to population

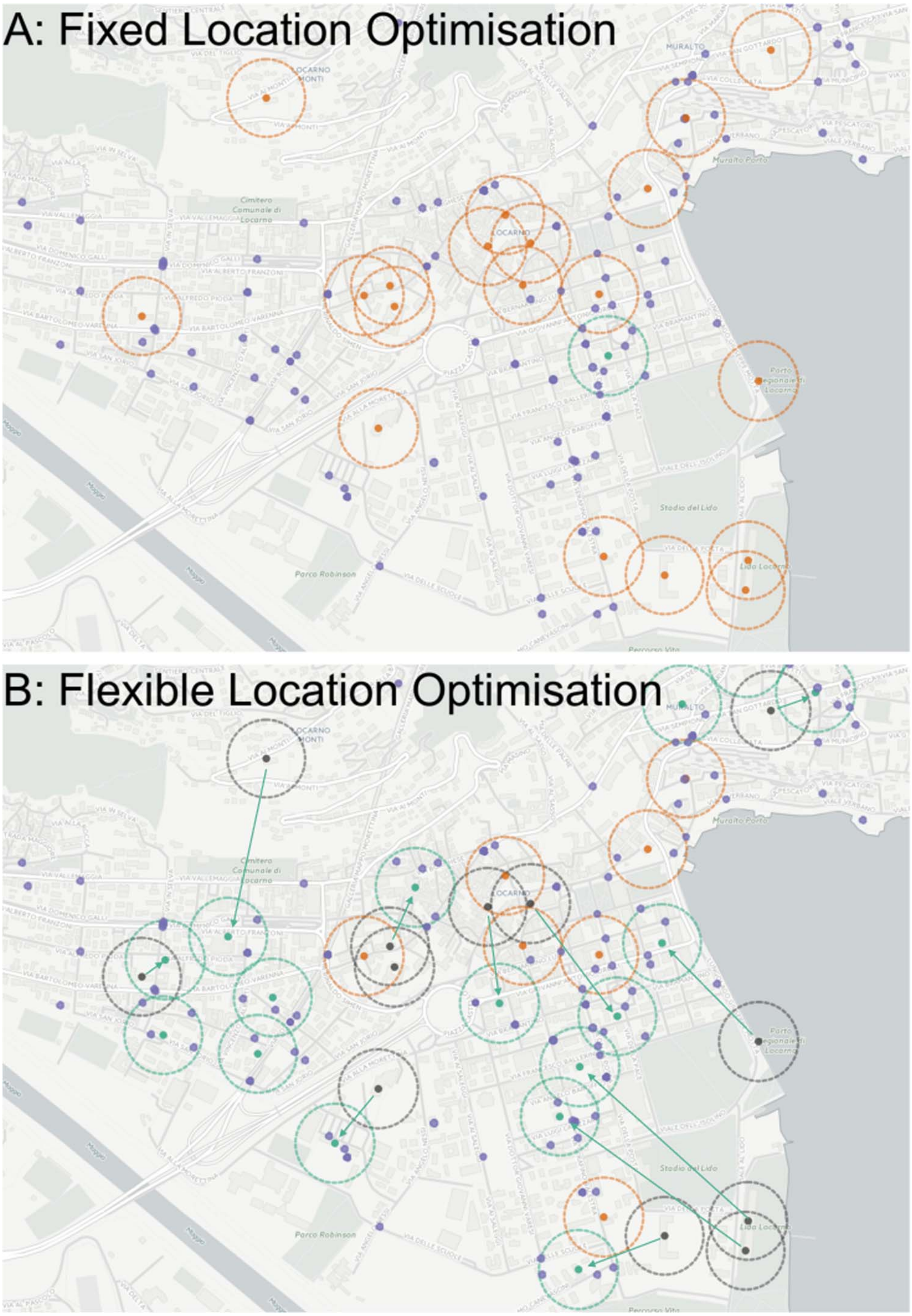

Fig. 2. Geographical display of current AED locations (Orange), OHCA event locations (Purple), suggested optimal locations (Green), and Existing AED locations suggested to be removed for relocation, (Black) in Locarno, Ticino for the cost of placing 20 AEDs. Dotted line shows a 100 m radius around the AEDs, which indicates coverage. Panel A shows AEDs placed with the fixed location model. Here one AED is placed, providing good coverage. Note there are some existing AEDs which provide no coverage. Panel B shows the existing AEDs suggested for relocation in black, and other suggested AEDs in green. The AEDs selected to be removed are those existing AEDs which did not provide any coverage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

models. Rural areas are the most challenging to be covered by public AEDs, having much worse OHCA coverage than urban areas. Appropriate OHCA coverage in rural areas may require large financial investment, and thus we strongly suggest the implementation of different AED deployment strategies. Finally, compared to other methods, flexible location models increase overall OHCA coverage even in rural areas, decrease the distance to nearby AEDs, all whilst saving significant financial resources.

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None.

Conflict of interest statement

The authors of the manuscript, "Novel relocation methods for automatic external defibrillator improve out-of-hospital cardiac arrest coverage under limited resources", (Nicholas John Tierney, Antonietta Mira, H. Jost Reinhold, Martin Weiser Ph.D, Roman Burkart, Claudio Benvenuti, Angelo Auricchio) Hereby declare that there is no conflict of interest to report.

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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.2018.01.055.

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