RESUSCITATION 138 (2019) 250–258

Available online at www.sciencedirect.com

Resuscitation

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

Clinical paper

Cost-effectiveness of public automated external defibrillators

Lars W. Andersen[a,b,*], Mathias J. Holmberg[a,b], Asger Granfeldt[c], Lyndon P. James[d], Lisa Caulley[e,f,g]

[a] Research Center for Emergency Medicine, Department of Clinical Medicine, Aarhus University Hospital, Aarhus, Denmark
[b] Center for Resuscitation Science, Department of Emergency Medicine, Beth Israel Deaconess Medical Center, Boston, MA, USA
[c] Department of Intensive Care Medicine, Aarhus University Hospital, Aarhus, Denmark
[d] Center for Health Decision Science, Harvard T. H. Chan School of Public Health, Boston, MA, USA
[e] Department of Otolaryngology-Head and Neck Surgery, University of Ottawa, The Ottawa Hospital, Ottawa, ON, Canada
[f] Ottawa Hospital Research Institute, Ottawa, ON, Canada
[g] Department of Epidemiology, Erasmus MC, Rotterdam, The Netherlands

Abstract

Background: Despite a consistent association with improved outcomes, public automated external defibrillators (AEDs) are rarely used in out-of-hospital cardiac arrest. One of the barriers towards increased use might be cost-effectiveness.

Methods: We compared the cost-effectiveness of public AEDs to no AEDs for out-of-hospital cardiac arrest in the United States over a life-time horizon. The analysis assumed a societal perspective and results are presented as costs per quality-adjusted life year (QALY). Model inputs were based on reviews of the literature. For the base case, we modelled an annual cardiac arrest incidence per AED of 20%. A probabilistic sensitivity analysis was conducted to account for joint parameter uncertainty.

Results: The no AED strategy resulted in 1.63 QALYs at a cost of $28,964. The AED strategy yielded an additional 0.26 QALYs for an incremental increase in cost of $13,793 per individual. The AED strategy yielded an incremental cost-effectiveness ratio of $53,797 per QALY gained. The yearly incidence of cardiac arrests occurring in the presence of an AED had minimal effect on the incremental cost-effectiveness ratio except at very low incidences. In several sensitivity analyses across a plausible range of health care and societal estimates, the AED strategy remained cost-effective. In the probabilistic sensitivity analysis, the AED strategy was cost-effective in 43%, 85%, and 91% of the scenarios at a willingness-to-pay threshold of $50,000, $100,000, and $150,000 per QALY gained, respectively.

Conclusion: Public AEDs are a cost-effective public health intervention in the United States. These findings support widespread dissemination of public AEDs.

Keywords: Cardiac arrest, Cardiopulmonary resuscitation, Public, Automated external defibrillators, Cost-effectiveness analysis, Public health, United States

* Corresponding author at: Research Center for Emergency Medicine, Department of Clinical Medicine, Aarhus University Hospital, Palle Juul Jensens Boulevard 99, Bygning J, Plan 1, 8200 Aarhus N, Denmark.
E-mail address: lwandersen@clin.au.dk (L.W. Andersen).

https://doi.org/10.1016/j.resuscitation.2019.03.029
Received 10 January 2019; Received in revised form 11 March 2019; Accepted 20 March 2019

Introduction

Out-of-hospital cardiac arrest is estimated to occur in 350,000 individuals in the United States each year and outcomes remain poor with only 11% surviving to hospital discharge.[1] Observational studies in both out-of-hospital and in-hospital cardiac arrest have found that early defibrillation, in patients with an initial shockable rhythm, is associated with improved outcomes.[2,3] Automated external defibrillators (AEDs) are designed to allow bystanders to perform early defibrillation in patients with out-of-hospital cardiac arrest. A randomized trial[4] and a number of observational studies[5–7] have found that bystander AED use is associated with improved clinical outcomes. Bystander training in cardiopulmonary resuscitation and the use of AEDs are therefore recommended by both European and American cardiac arrest guidelines.[8,9]

Despite these recommendations, AEDs are often not used during out-of-hospital cardiac arrest. In a recent study from the United States, an AED was only applied in 11% of public out-of-hospital cardiac arrests.[7] Based on estimates from this recent study, approximately 4000 additional lives could be saved each year in the United States if AEDs were used in all public out-of-hospital cardiac arrests (see Supplemental Appendix).[7] There are multiple potential reasons for the low use of AEDs, including a lack of adequate bystander training, awareness, and willingness to use an AED and the costs of acquiring and maintaining an AED.[10,11] Despite the evidence indicating a positive effect of AED use[4–7], it is unknown whether AEDs are cost-effective as a public health intervention.[12] Multiple factors could potentially limit the cost-effectiveness of AEDs. First, out-of-hospital cardiac arrest at a given location is relatively rare. Second, AEDs are only effective when a shockable rhythm is present (which occurs in approximately half the patients).[5,7] Third, acquiring an AED and training large numbers of potential bystanders are relatively expensive endeavors. Fourth, despite being present, AEDs are often not used.[10] These, and other considerations, have resulted in the European Resuscitation Council only recommending AED placement in settings with a relatively high risk of out-of-cardiac arrest (at least 1 every 5 years) while the American Heart Association guidelines recommend AED placement in communities with people "at risk" of out-of-hospital cardiac arrest.[8,9]

The objective of this study was to evaluate the contemporary cost-effectiveness of public AEDs in the United States, to inform guidelines as well as local and national public health initiatives.

Methods

Overview

The population of interest was patients with a public out-of-hospital cardiac arrest in the United States without emergency medicine service personnel present at the time of cardiac arrest. We compared the cost-effectiveness of public AEDs ("AED strategy") to no public AEDs ("No AED strategy"). Both strategies included standard of care, which we assumed included bystander cardiopulmonary resuscitation.

The base case analysis assumed a societal perspective and accounted for lifetime costs and health outcomes measured in quality-adjusted life years (QALYs). A secondary analysis was performed from a health care sector perspective (see Supplemental Appendix).[13]

All costs and effects were discounted at a rate of 3% per year.[13] Results are presented as costs per QALY gained. According to the most recent American Heart Association classification of medical strategies of high and intermediate level of value, which are generally consistent with recommendations from the World Health Organization, we used a willingness-to-pay threshold of $150,000 per QALY gained to signify the ratio below which an intervention would be considered cost-effective.[14–16] Analyses were performed in TreeAge Pro 2018 Suite (TreeAge Software Inc., Williamstown, MA, USA).

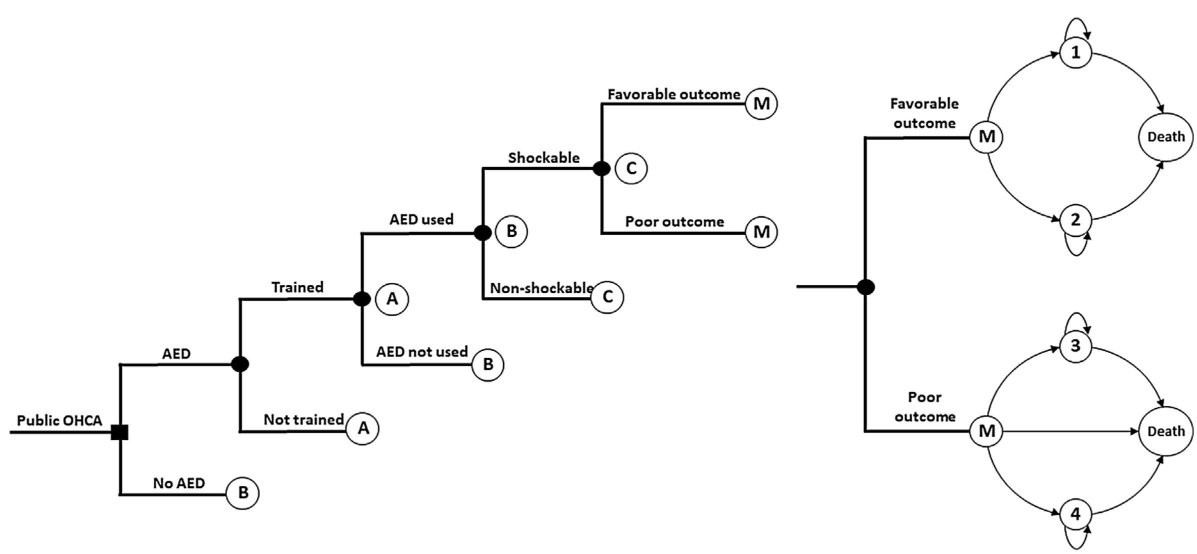

Fig. 1 – Schematic overview of the model.
The letters A, B and C represents clones of the tree structure (left). M signifies a Markov model and the numbers in the Markov model (right) corresponds to CPC scores. In the Markov model, individuals can either stay within the same CPC category or transition to death. "Trained" refers to whether a bystander trained in AED use was present. "Shockable" and "Non-shockable" refers to the initial rhythm of the cardiac arrest.
OHCA denotes out-of-hospital cardiac arrest, AED automated external defibrillator, and CPC cerebral performance category.

Table 1 – Overview of estimates used in the model.

Variable		Base case estimate	Empirical 95%CI	Distribution[a,b]	Key reference(s)[c]
Miscellaneous					
Incidence of cardiac arrest per year (%)		20[d]	–	–	9
AED use when present (%)	Bystander trained	50	–	Triangular (25–75)	30
	Bystander not trained	10	–	Triangular (0–20)	See Appendix
Proportion shockable (%)	No AED group	48	46, 50	Beta	7
	AED group	53	51, 55	Beta	7
Short-term outcomes					
Favorable functional outcome[e] in the no AED group (%)	Shockable	34	33, 35	Beta	7
	Non-shockable	7	7, 8	Beta	7
Risk ratio for favorable functional outcome in the AED group[e,f]	Shockable	1.52	1.18, 1.95	Lognormal	7
	Non-shockable	1	–	–	5,7
CPC score at hospital discharge		See eTable 10	See eTable 10	Beta	7
Long-term outcomes					
Post-discharge yearly mortality stratified by CPC (%) — the first year[g]		1: 9 2: 23 3: 36 4: 72	1: 7, 11 2: 18, 29 3: 27, 47 4: 58, 84	Beta	20
Post-discharge yearly mortality stratified by CPC (%) — subsequent years[g]		1: 5 2: 8 3: 9 4: 5	1: 3, 7 2: 5, 12 3: 4, 18 4: 0, 23	Beta	20
Utilities stratified by CPC[h]		1: 0.77 2: 0.49 3: 0.32 4: 0	–	Empirical[i]	23
Costs per cardiac arrest ($)					
Yearly cost of an AED[j]		255[k]	–	Triangular (±30%)	See Appendix
Bystander AED training		19,286[l]	–	Triangular (±30%)[m]	See Appendix
Emergency department costs		2643	–	Triangular (±30%)	31
Hospital costs stratified by discharge CPC		1: 89,027 2: 100,469 3 + 4: 130,846 5: 37,262	–	Empirical[n]	32
Costs after hospital discharge stratified by discharge CPC — first year		1: 24,857 2: 46,276 3: 83,356 4: 13,918	–	Triangular (±30%)	33
Costs after hospital discharge — subsequent years		5761	–	Triangular (±30%)	34

AED denotes automated external defibrillator and CPC Cerebral Performance Category.

[a] Distributions used for probabilistic sensitivity analyses. When no numbers are presented, the distribution was based on the empirical distribution as expressed by the 95% confidence intervals.

[b] See text and Supplemental Appendix for additional details on sensitivity analyses.

[c] The key references are listed here. Additional discussion and references are provided in the Supplemental Appendix.

[d] Corresponding to one cardiac arrest per AED every five years.

[e] Defined as a CPC score of 1 or 2 at hospital discharge.

[f] Comparing the use of an AED to no use of an AED.

[g] Sensitivity analyses were performed where AED use resulted in a lower post-discharge mortality compared to no AED use. See Supplemental Appendix for additional details.

[h] 0.10 were deducted for the first year after the cardiac arrest.

[i] See eFig. 5 in the Supplemental Appendix.

[j] Includes use and maintenance.

[k] Calculated based on a base case incidence of 0.20 out-of-hospital cardiac arrests per AED per year. Corresponds to a per AED cost of $1275. See Supplemental Appendix for additional details.

[l] Calculated based on approximately 9% of the United States population being trained in AED use each year and 15$ per bystander trained. See Supplemental Appendix for additional details.

[m] Distributions modelled around the per bystander cost (i.e. 15$, see Supplemental Appendix).

[n] See eFig. 9 in the Supplemental Appendix.

Model

The decision analytic model combined a decision tree of initial treatment, and a Markov model for post-discharge survival according to functional status at hospital discharge (Fig. 1). The model had a one-year cycle length and was terminated after 50 years.

The analysis evaluated outcomes of out-of-hospital cardiac arrest with an AED present, as compared to outcomes without an AED present. The probability of an AED being used is related to bystander training[10], so we modelled that an AED would be used more often if a bystander trained in AED use was present when compared to a bystander not trained in AED use. Short-term outcomes (i.e. survival and functional status at hospital discharge) were stratified according to the initial cardiac rhythm (shockable vs. non-shockable) and AED use (used vs. not used). Long-term outcomes (i.e. after hospital discharge) were stratified in five health states according to functional status at hospital discharge as assessed by the Cerebral Performance Category (CPC) score, which is commonly used in cardiac arrest research.[17] A CPC score of 1 represents good cerebral performance, 2 represents moderate cerebral disability, 3 represents severe cerebral disability, 4 represents coma or a vegetative state, and 5 represents death.[18]

Model inputs were based on de novo reviews of the literature, previous published systematic reviews[5,10,19], and a recently published observational study on the association between AED use and outcomes in public out-of-hospital cardiac arrest in the United States.[7] Model inputs are provided in Table 1 and described briefly below. Additional details, including a rationale for the estimates used as well as supplementary references, can be found in the Supplemental Appendix (including eTables 1–13 and eFigs. 1–10).

Probability of clinical events

For the base case, we modeled an annual cardiac arrest incidence of 20% per AED (i.e. on average, one cardiac arrest every 5 years).[9] Approximately half of all public out-of-hospital cardiac arrests have an initial shockable rhythm.[7] Since AED use might facilitate earlier rhythm analysis, and the proportion of patients with a shockable rhythm decreases over time, this proportion was modelled as slightly higher in the AED group (see Supplemental Appendix for details). Short-term outcomes (i.e. outcomes at hospital discharge) were based on a recent observational study which used a difference-in-difference approach to estimate the causal effect of AED use in public out-of-hospital cardiac arrest patients with an initial shockable rhythm.[7] This study found that AED use was associated with an approximate 50% relative increase in survival to hospital discharge with a favorable functional outcome (CPC score 1 or 2).[7] It was assumed that there would be no effect of AED use in those with a non-shockable rhythm.[5,7] Long-term outcomes (i.e. after hospital discharge) were obtained from Phelps et al. and stratified by discharge functional status as measured by the CPC score.[20] For the base case, it was assumed that survival after hospital discharge was dependent on the discharge CPC score, and not on the initial rhythm or use of an AED.

Costs

All costs are presented in 2017 United States dollars ($). When needed, costs were adjusted using the Consumer Price Index for Medical Care Services.[21] All costs were modelled as costs per cardiac arrest, e.g. costs of bystander training and AED acquisition and maintenance were modeled as the average cost per cardiac arrest (see Supplemental Appendix). As such, the incidence of cardiac arrest around a specific AED was included as an integral part of the cost of the AED with a higher incidence resulting in a lower per cardiac arrest AED cost.

Quality of life

Post-discharge quality of life was quantified using utilities (a value from 0 to 1 with higher values indicating a better quality of life).[22] Utilities were obtained from Stiell et al.[23] and stratified according to functional outcome (i.e. CPC score) at hospital discharge. Given that quality of life might be lower during the first year after cardiac arrest,[24] a value of 0.10 was deducted from the utility values during the first year.

Sensitivity analyses

We conducted a number of secondary and sensitivity analyses to explore the robustness of our findings and to guide public health initiatives in various settings. For example, in one-way sensitivity analyses we varied the incidence of cardiac arrest in the vicinity of an AED, the short- and long-term effects of AED use, and the use of an AED when present. We also performed a probabilistic sensitivity analysis with 150,000 iterations to account for multivariable uncertainty. See Supplemental Appendix for additional details.

Results

Main results

In the base case analysis, the no AED strategy resulted in 1.63 QALYs at a cost of $28,964. The AED strategy yielded an additional 0.26 QALYs for an increase in cost of $13,793 per individual over their remaining lifetime (Table 2). From the societal perspective, at a cost-effectiveness threshold of $150,000 per QALY, the AED strategy was cost-effective with an incremental cost-effectiveness ratio (ICER) of $53,797 per QALY gained (Table 2).

The AED strategy was cost-effective from a health care sector perspective, at an ICER of $13,700 per QALY gained (Table 2).

The AED strategy resulted in a 1-year and 5-year survival of 21.6% and 17.2%, respectively. The corresponding values for the no AED strategy were 19.0% and 15.1%. Survival curves are presented in eFigure 11. The distributions of CPC scores are illustrated in eTable 14.

Incidence of cardiac arrest

The yearly incidence of cardiac arrests occurring in the presence of an AED had minimal effect on the ICER except at very low incidences (Fig. 2). For an incidence as low as 1% (i.e. one cardiac arrest per AED every hundredth year), the ICER was $101,040 per QALY gained (Table 3).

AED effectiveness

The results were sensitive to the favorable effect of an AED in patients with a shockable rhythm, i.e. the increased chance of survival to hospital discharge with a favorable functional outcome (Fig. 3). However, even when it was assumed that there were no other favorable effects of the AED (see Supplemental Appendix), the AED strategy remained cost-effective at substantially lower effects than the one used for the base case (risk ratio of 1.52). For example, for a risk

Table 2 – Main results.

Strategy	Cost ($)	Incremental cost ($)	Effectiveness (QALYs)	Incremental effectiveness (QALYs)	Incremental cost-effectiveness ratio ($ per QALY gained)
Societal perspective					
No AED	28,964	–	1.63	–	–
AED	42,757	13,793	1.88	0.26	53,797
Health care sector perspective[a]					
No AED	28,964	–	1.63	–	–
AED	32,477	3,513	1.88	0.26	13,700

AED denotes automated external defibrillator and QALY quality adjusted life year.
[a] Health care sector costs were similar to societal costs except that the costs of the AED and bystander training were not included (see Supplemental Appendix). Therefore, only the costs in the AED strategy group changed.

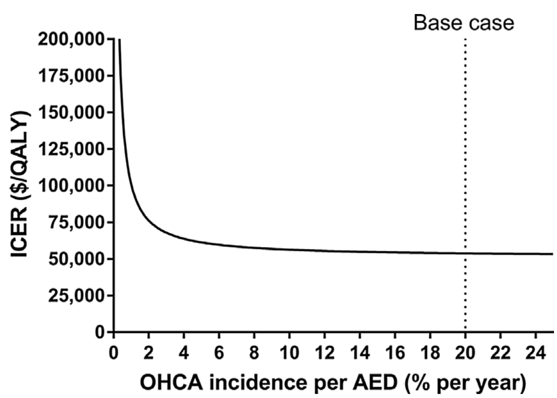

Fig. 2 – Relationship between the yearly cardiac arrest incidence per AED and the ICER.
One-way sensitivity analysis of the yearly incidence of cardiac arrest in the vicinity of an AED (x-axis) and the ICER (y-axis). The vertical dotted line represents the yearly incidence in the base case scenario (20%).
ICER denotes incremental cost effectiveness ratio, QALY quality-adjusted life year, OHCA out-of-hospital cardiac arrest, and AED automated external defibrillator.

ratio of 1.30 (i.e. a 30% increased chance of a favorable functional outcome), the ICER was $108,038 per QALY gained. The ICER remained below the willingness-to-pay threshold after accounting for the potential (negative or positive) effect of AEDs in patients with a non-shockable rhythm, and potential favorable long-term effects (i.e. post-discharge) in those with a shockable rhythm (eFig. 12).

AED and bystander costs

The cost of the AED only had a marginal impact on the ICER. For example, when the yearly cost of an AED was tripled, the ICER increased to $58,770 per QALY gained (eFig. 13).

The ICER increased with increasing costs of training bystanders (eFig. 14). For example, if the per bystander costs were doubled ($30), the ICER was $91,408 per QALY gained. Similarly, if training retention intervals were reduced, the ICER increased e.g., if training retention only lasted a half year, the ICER was $87,610 per QALY gained (eFig. 14).

Hospital and post-discharge costs

Hospital costs and post-discharge costs according to each CPC score had limited impact on the ICER (eFigure 15, 16, and 17). While the ICER was sensitive to a combined increase in all post-discharge costs (eFigure 18), even at a large combined increase in costs, the AED strategy remained cost-effective. For example, when all post-discharge costs were increased to 300% of the base case value, the ICER was $101,949 per QALY gained.

Additional sensitivity analyses

Additional one-way sensitivity analyses are presented in Table 3 and eFigs. 19–25. The ICER was sensitive to the proportion of the population that were trained in AED use, the proportion of bystanders using the AED, as well as the proportion of patients with survival to hospital discharge with a favorable functional outcome within the no AED strategy (i.e. baseline survival), but consistently remained below $150,000 per QALY gained across the range of estimates. It was only in isolated scenarios that the ICER exceeded the willingness-to-pay threshold: (1) the scenario of one bystander present when the incidence of cardiac arrest per AED per year was very low (1%); and (2) when baseline favorable functional outcome in the no AED strategy was very low (10%) for shockable out-of-hospital cardiac arrest ($155,603 and $158,736 per QALY gained, respectively).

Accounting for age-related increases in post-discharge mortality did not meaningfully change the results (see model survival curves in eFig. 26). For the analysis assuming no disease-specific mortality

Table 3 – Overview of one-way sensitivity analyses.

Parameter[a]	Examples				Figure
	Low value	High value	Low value ICER ($/QALY)	High value ICER ($/QALY)	
Incidence (%)	1	100	101,040	51,808	2
AED effectiveness					
AED effect — shockable					
Other estimates at base case (RR)	1.2	2.0	96,250	36,375	3
No other favorable effects (RR)	1.2	2.0	154,962	42,343	3
AED effect — non-shockable (RR)	0.5	2.0	60,105	45,315	e12A
AED long-term effect —shockable (HR)	0.5	1.0	29,657	53,797	e12B
AED and bystander costs					
Yearly cost of an AED ($)	50	1000	51,789	61,062	e13
Cost per bystander trained ($)	5	45	28,724	129,018	e14A
Training retained (years)	0.25	10	102,351	36,129	e14B
Hospital costs					
Emergency department costs ($)	1,000	6,000	53,758	53,878	e15A
Hospital costs — CPC 1 ($)	50,000	200,000	51,686	59,801	e15B
Hospital costs — CPC 2 ($)	50,000	200,000	53,579	54,227	e15C
Hospital costs — CPC 3 and 4 ($)	75,000	300,000	53,875	53,563	e15D
Hospital costs — CPC 5 ($)	20,000	80,000	53,886	53,578	e15E
Post-discharge costs					
1st year — CPC 1 ($)	10,000	75,000	52,993	56,510	e16A
1st year — CPC 2 ($)	20,000	150,000	53,684	54,245	e16B
1st year — CPC 3 ($)	40,000	250,000	53,822	53,700	e16C
1st year — CPC 4 ($)	5,000	40,000	53,804	53,776	e16D
Subsequent years — CPC 1 ($)	2,500	15,000	49,839	65,010	e17A
Subsequent years — CPC 2 ($)	2,500	15,000	53,600	54,357	e17B
Subsequent years — CPC 3 ($)	2,500	15,000	53,818	53,739	e17C
Subsequent years — CPC 4 ($)	2,500	15,000	53,815	53,748	e17D
All post-discharge costs (% of base-case)	50	300	41,759	101,949	e18
Additional sensitivity analyses					
Population trained per year (%)	1	45	28,780	120,279	e19
AED use by untrained bystander (%)	0	50	63,653	36,111	e20A
AED use by trained bystander (%)	10	100	125,752	35,943	e20B
Number of bystanders present	1	5	78,847	45,560	e21
Shockable rhythm — AED strategy (%)	48	70	63,834	37,741	e22
Favorable outcome — no AED strategy					
Shockable (%)	10	50	158,736	40,649	e23A
Non-shockable (%)	1	20	52,832	56,067	e23B
Mortality after year one — CPC 1 (%)	2	20	39,230	124,270	e24A
Quality of life — CPC 1 (utilities)	0.50	1	81,796	41,652	e24B
Discount rate (%)	0	10	38,827	89,841	e25A
Stages (years)	5	100	144,175	53,013	e25B

ICER denotes incremental cost-effectiveness analysis, QALY quality-adjusted life year, AED automated external defibrillator, RR risk ratio, HR hazard ratio, and CPC cerebral performance category.

[a] For base-case values, see Table 1.

after 5 years, the ICER was $48,139 per QALY gained. For the analysis assuming a constant disease-specific mortality the ICER was $61,139.

Probabilistic sensitivity analysis

When accounting for parameter uncertainty, the AED strategy was cost-effective in 43%, 85%, and 91% of the scenarios at a willingness-to-pay threshold of $50,000, $100,000, and $150,000 per QALY gained, respectively (eFigs. 27 and 28). The results of the expected value of perfect information analysis are presented in eFig. 29.

Discussion

In this cost-effectiveness analysis, we found that public AEDs were cost-effective at a commonly accepted societal willingness-to-pay threshold and in several sensitivity analyses across a plausible range of health care and societal estimates. While the majority of previous cost-effectiveness analyses on AEDs for out-of-hospital cardiac arrest were performed more than 10 years ago and largely focused on select settings (eTable 15)[5], the current analysis provides a contemporary estimate to guide current and future public health initiatives and inform guidelines.

One of the main drivers of cost in our analysis was the cost of bystander training. This reflects that a large number of bystanders need to be trained per cardiac arrest and that retraining at certain intervals are currently necessary. Consequently, decreasing costs related to bystander training could have a major positive impact on the incremental cost-effectiveness ratio. While it is challenging to meaningfully lower the cost of individual bystander training, an increased use of public AEDs by non-trained bystanders could have a similar effect. Ongoing efforts, such as dispatcher-assisted use of AEDs, might achieve this.[10] Similarly, recruiting more (trained and non-trained) bystanders to the scene of a cardiac arrest, the goal of recent mobile application initiatives[10], would also increase the chance of AED use at a likely small incremental cost.[10]

We selected a societal perspective for the base case analysis as multiple stakeholders (for example, private companies, non-profit organizations, or public initiatives) may potentially incur the costs related to AEDs. A societal perspective provides an upper bound for this ICER as this perspective includes all relevant societal costs. As AEDs were cost-effective in the societal perspective, they will therefore also be cost-effective from the perspective of other stakeholders.

The results should be interpreted in the context of some considerations. First, only one randomized trial performed from 2000 to 2003 has assessed public AEDs.[4] We therefore used estimates from observational studies to inform our analysis. While observational studies are prone to bias, our main measure of AED effectiveness was obtained from a large contemporary observational study (data from 2013 to 2016) which used a difference-in-difference approach to minimize bias.[7] Under the assumptions of the difference-in-difference model, this approach accounts for both measured and unmeasured confounders and therefore provides a valid estimate of the treatment effect.[7] Of note, the treatment effect used from this study is smaller (i.e. closer to one) compared to a meta-analysis of observational studies, another recent observational study, and the aforementioned randomized trial (see Supplemental Appendix).[4–6] Furthermore, in sensitivity analyses, public AEDs remained cost-effective even at lower estimates of the AED treatment effect (Fig. 3). Second, the incremental cost-effectiveness ratio of AEDs was just above the traditional willingness-to-pay threshold of $50,000 per QALY gained. However, multiple stakeholders, including the American Heart Association and the World Health Organization, support a higher threshold of up to $150,000 in the United States.[14–16] Ultimately, local, regional, and national stakeholders will determine whether AEDs are cost-effective at a socially acceptable threshold in their specific settings. Third, our population of interest included public out-of-hospital cardiac arrests in the United States. We chose to focus on public cardiac arrest since AEDs are very rarely used in non-public out-of-hospital cardiac arrests.[25,26] Given that non-public out-of-hospital cardiac arrests are rare at any given location, more often have a non-shockable rhythm, and have low baseline survival[27,28], it is unlikely that our findings directly translate to this setting, where the ICER might be substantially larger. The model was primarily informed by estimates from the United States, but the effects of AEDs are presumably independent of country. Since the United States generally have higher health care related costs[29], our conclusions are likely generalizable to other high-income countries. Whether AEDs are cost-effective in low- and middle-income countries remain unknown. Lastly, the cost-effectiveness of public AEDs might vary depending on the specific public setting (e.g. shopping mall, sport facility, street corner) given the potential variation in demographics of patients with cardiac arrest at these locations. As detailed data is not available for specific locations, we did not limit our analysis by

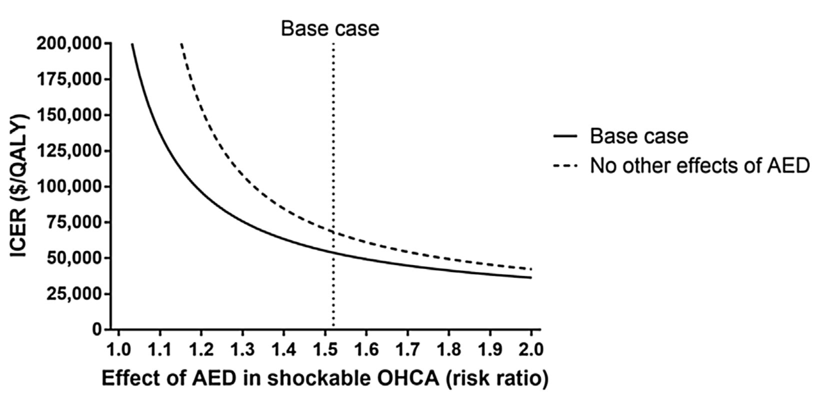

Fig. 3 – Relationship between the effect of an AED in those with a shockable rhythm and the ICER.
One-way sensitivity analyses of the relationship between the effect of an AED in those with a shockable rhythm (x-axis) and the ICER (y-axis). The effect is quantified by the RR indicating the risk (i.e. proportion) of a favorable functional outcome when an AED is used divided by the risk of the same outcome when an AED is not used. An RR of 1.0 corresponds to no direct effect on this outcome from AED use. The solid line represents the analysis when all other variables are at their base case values. The dotted line represents the analysis when other beneficial effects of an AED (i.e. more shockable rhythms and different distribution of CPC scores, see Supplemental Appendix) are nullified (i.e. the same between groups). In this analysis, a RR of 1.0 truly represents no effect at all of AED use. The vertical dotted line represents the effect used in the base case scenario (RR = 1.52).
ICER denotes incremental cost-effectiveness ratio, QALY quality-adjusted life year, AED automated external defibrillator, OHCA out-of-hospital cardiac arrest, and RR risk ratio.

the geographic location of the cardiac arrests and instead conducted numerous sensitivity analysis to confirm the robustness of our results.

In conclusion, we found that public AEDs are a cost-effective public health intervention in the United States. These findings support widespread dissemination of public AEDs.

Funding

This study was partly funded by TrygFonden, a non-profit Danish foundation, which provided salary support for Lars W. Andersen. No other specific funding was available.

Conflict of interest

The authors have no conflicts of interests.

Acknowledgements

We thank Yuanyuan Tang, Ph.D. and Paul Chan, M.D., M.Sc., Guillaume Geri, M.D., Ph.D. and Thomas D. Rea, M.D., M.P.H., and My-Linh Tran and Ian Stiell, M.D., M.Sc. for providing original data/results from their respective studies.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resuscitation.2019.03.029.

REFERENCES

1. Benjamin EJ, Blaha MJ, Chiuve SE, et al. Heart disease and stroke statistics-2017 update: a report from the American Heart Association. Circulation 2017;135:e146–603.
2. 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.
3. Chan PS, Krumholz HM, Nichol G, Nallamothu BK. American Heart Association national registry of cardiopulmonary resuscitation I. Delayed time to defibrillation after in-hospital cardiac arrest. N Engl J Med 2008;358:9–17.
4. Hallstrom AP, Ornato JP, Weisfeldt M, et al. Public-access defibrillation and survival after out-of-hospital cardiac arrest. N Engl J Med 2004;351:637–46.
5. Holmberg MJ, Vognsen M, Andersen MS, Donnino MW, Andersen LW. Bystander automated external defibrillator use and clinical outcomes after out-of-hospital cardiac arrest: a systematic review and meta-analysis. Resuscitation 2017;120:77–87.
6. Pollack RA, Brown SP, Rea T, et al. Impact of bystander automated external defibrillator use on survival and functional outcomes in shockable observed public cardiac arrests. Circulation 2018;137:2104–13.
7. Andersen LW, Holmberg MJ, Granfeldt A, et al. Neighborhood characteristics, bystander automated external defibrillator use, and patient outcomes in public out-of-hospital cardiac arrest. Resuscitation 2018;126:72–9.
8. Kronick SL, Kurz MC, Lin S, et al. Part 4: systems of care and continuous quality improvement: 2015 American Heart Association guidelines update for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation 2015;132:S397–413.
9. Perkins GD, Handley AJ, Koster RW, et al. European Resuscitation Council guidelines for resuscitation 2015: section 2. Adult basic life support and automated external defibrillation. Resuscitation 2015;95:81–99.
10. Smith CM, Lim Choi Keung SN, Khan MO, et al. Barriers and facilitators to public access defibrillation in out-of-hospital cardiac arrest: a systematic review. Eur Heart J Qual Care Clin Outcomes 2017;3:264–73.
11. Ringh M, Hollenberg J, Palsgaard-Moeller T, et al. The challenges and possibilities of public access defibrillation. J Intern Med 2018;283:238–56.
12. Kleinman ME, Perkins GD, Bhanji F, et al. ILCOR scientific knowledge gaps and clinical research priorities for cardiopulmonary resuscitation and emergency cardiovascular care: a consensus statement. Circulation 2018;137:e802–19.
13. Sanders GD, Neumann PJ, Basu A, et al. Recommendations for conduct, methodological practices, and reporting of cost-effectiveness analyses: second panel on cost-effectiveness in health and medicine. JAMA 2016;316:1093–103.
14. Anderson JL, Heidenreich PA, Barnett PG, et al. ACC/AHA statement on cost/value methodology in clinical practice guidelines and performance measures: a report of the American College of Cardiology/American Heart Association Task Force on Performance Measures and Task Force on Practice Guidelines. J Am Coll Cardiol 2014;63:2304–22.
15. World Health Organization, In: Tan-Torres Edejer T, Baltussen R, Adam T, Hutubessy R, Acharya A, Evans DB, editors. Making choices in health: WHO guide to cost-effectiveness analysis. .
16. Neumann PJ, Cohen JT, Weinstein MC. Updating cost-effectiveness—the curious resilience of the $50,000-per-QALY threshold. N Engl J Med 2014;371:796–7.
17. Perkins GD, Jacobs IG, Nadkarni VM, et al. Cardiac arrest and cardiopulmonary resuscitation outcome reports: update of the Utstein Resuscitation Registry Templates for Out-of-Hospital Cardiac Arrest: a statement for healthcare professionals from a task force of the International Liaison Committee on Resuscitation (American Heart Association, European Resuscitation Council, Australian and New Zealand Council on Resuscitation, Heart and Stroke Foundation of Canada, InterAmerican Heart Foundation, Resuscitation Council of Southern Africa, Resuscitation Council of Asia); and the American Heart Association Emergency Cardiovascular Care Committee and the Council on Cardiopulmonary, Critical Care, Perioperative and Resuscitation. Circulation 2015;132:1286–300.
18. Jennett B, Bond M. Assessment of outcome after severe brain damage. Lancet 1975;1:480–4.
19. Haywood KL, Pearson N, Morrison LJ, Castren M, Lilja G, Perkins GD. Assessing health-related quality of life (HRQoL) in survivors of out-of-hospital cardiac arrest: A systematic review of patient-reported outcome measures. Resuscitation 2018;123:22–37.
20. Phelps R, Dumas F, Maynard C, Silver J, Rea T. Cerebral Performance Category and long-term prognosis following out-of-hospital cardiac arrest. Crit Care Med 2013;41:1252–7.
21. U.S. Department of Labor — Bureau of Labour Statistics. Databases, tables & calculators by subject. 2018.
22. Hunink MGM, Weinstein MC, Wittenberg E, et al. Decision making in health and medicine: integrating evidence and values. 2nd ed. Cambridge University Press; 2014.
23. Stiell IG, Nesbitt LP, Nichol G, et al. Comparison of the cerebral performance category score and the health utilities index for survivors of cardiac arrest. Ann Emerg Med 2009;53:241–8.
24. Raina KD, Callaway C, Rittenberger JC, Holm MB. Neurological and functional status following cardiac arrest: method and tool utility. Resuscitation 2008;79:249–56.
25. Berdowski J, Blom MT, Bardai A, Tan HL, Tijssen JG, Koster RW. Impact of onsite or dispatched automated external defibrillator use on survival after out-of-hospital cardiac arrest. Circulation 2011;124:2225–32.

26. Hansen SM, Hansen CM, Folke F, et al. Bystander defibrillation for out-of-hospital cardiac arrest in public vs residential locations. JAMA Cardiol 2017;2:507–14.
27. Weisfeldt ML, Everson-Stewart S, Sitlani C, et al. Ventricular tachyarrhythmias after cardiac arrest in public versus at home. N Engl J Med 2011;364:313–21.
28. Folke F, Gislason GH, Lippert FK, et al. Differences between out-of-hospital cardiac arrest in residential and public locations and implications for public-access defibrillation. Circulation 2010;122:623–30.
29. Papanicolas I, Woskie LR, Jha AK. Health care spending in the united states and other high-income countries. JAMA 2018;319:1024–39.
30. Hedges JR, Sehra R, Van Zile JW, et al. Automated external defibrillator program does not impair cardiopulmonary resuscitation initiation in the public access defibrillation trial. Acad Emerg Med 2006;13:659–65.
31. Nichol G, Huszti E, Birnbaum A, et al. Cost-effectiveness of lay responder defibrillation for out-of-hospital cardiac arrest. Ann Emerg Med 200954: 226–235.e1-e2.
32. Geri G, Fahrenbruch C, Meischke H, et al. Effects of bystander CPR following out-of-hospital cardiac arrest on hospital costs and long-term survival. Resuscitation 2017;115:129–34.
33. Perman SM, Stanton E, Soar J, et al. Location of in-hospital cardiac arrest in the United States-variability in event rate and outcomes. J Am Heart Assoc. 20165:.
34. Weiss JP, Saynina O, McDonald KM, McClellan MB, Hlatky MA. Effectiveness and cost-effectiveness of implantable cardioverter defibrillators in the treatment of ventricular arrhythmias among medicare beneficiaries. Am J Med 2002;112:519–27.