Improve Survival From Sudden Cardiac Arrest
The Role of the Automated External Defibrillator

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Context Sudden cardiac death is a major public health problem in the United States, and improving survival after out-of-hospital cardiac arrest has been the subject of intense study. Early defibrillation has been shown to be critical to improving survival. Use of automated external defibrillators (AEDs) has become an important component of emergency medical systems, and recent advances in AED technology have allowed expansion of AED use to nontraditional first responders and the lay public.

Objectives To examine advancements in AED technology, review the impact of AEDs on time to defibrillation and survival, and explore the future role of AEDs in the effort to improve survival following sudden cardiac arrest.

Data Sources MEDLINE was searched for articles from 1966 through December 2000 (Medical Subject Headings: electric countershock, heart arrest, resuscitation, emergency medical services; keywords: automatic external defibrillator, automated external defibrillator, public access defibrillation). Reference lists of relevant articles, news releases, and product information from manufacturers were also reviewed.

Study Selection Initial MEDLINE search produced 4816 articles, from which 101 articles were selected for referencing based on having been published in a peer-reviewed journal and on relevance to the subject of the manuscript as determined by all 5 authors.

Data Extraction All studies were critically reviewed for relevance, accuracy, and quality of data and study design by all authors.

Data Synthesis Recent advances in AED technology and design have resulted in marked simplification of AED operation, improvements in accuracy and effectiveness, and reductions in cost. Use of AEDs by first responders and laypersons has reduced time to defibrillation and improved survival from sudden cardiac arrest in several communities. Initial studies of the cost-effectiveness of AED use in comparison with other commonly used treatments are favorable.

Conclusion The AED represents an efficient method of delivering defibrillation to persons experiencing out-of-hospital cardiac arrest and its use by both traditional and nontraditional first responders appears to be safe and effective. The rapidly expanding role of AEDs in traditional emergency medical systems is supported by the literature, and initial studies of public access to defibrillation offer hope that further improvements in survival after sudden cardiac death can be achieved.

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AUTOMATED EXTERNAL DEFIBRILLATORS

Figure 1. Incidence of Sudden Death From Cardiac Arrest

A. Sudden death incidence and total events for various population pools, showing inverse relationship between risk and total number of events. Note that the horizontal axis for the incidence graph is not linear. B. Comparison of sudden death rates in a high-risk subgroup of patients with cardiovascular disease after a major cardiovascular event with a low-risk subgroup of patients with cardiovascular disease but free of a major event. After 18 months, the curves become parallel indicating that the presence of a prior major cardiovascular event as a risk factor for future cardiac arrest becomes limited with time. EF indicates ejection fraction; VT, ventricular tachycardia; VF, ventricular fibrillation; MI, myocardial infarction; and CV, cardiovascular. Reproduced with permission.9

Figure 2. Rates of Survival to Hospital Discharge

Rates given for 4 years of consecutive patients (1112) initially discovered in ventricular fibrillation. Response times are known for 942 cases. Both witnessed and un-witnessed cases in this 4-year period are considered. The average (SD) response time for first emergency unit was 3.0 (1.5) minutes and for paramedics was 6.5 (3.2) minutes after dispatch. VF indicates ventricular fibrillation. Reproduced with permission.9

concept of public access defibrillation (PAD).20,21 This concept promotes the expansion of the role of defibrillation to both minimally trained first-responders (police officers, firefighters, security guards, flight attendants) and to trained laypersons who witness an arrest. It also promotes the placement of automated external defibrillators (AEDs) in such areas as airports, convention centers, sporting arenas, casinos, shopping malls, and large office buildings. Some have envisioned a future where the AED is as commonplace as the fire extinguisher.2 One of the keys to making PAD feasible has been advances in technology over the past 2 decades that have made AED use by nonmedical personnel safe and effective. Although there is growing literature to suggest that PAD is greatly improving survival from sudden cardiac arrest, many questions remain. We will examine the important advances in AED technology over the past 2 decades, review the existing literature on the effectiveness of the AED, and explore the future role of the AED in our effort to improve survival from sudden cardiac arrest.

METHODS

We used MEDLINE to identify all English-language publications on AEDs from 1966 to December 2000. The medi-

RESULTS Technology

Automated external defibrillators were developed in the 1970s and first introduced for clinical use in 1979.22,23 The AED is a lightweight portable device containing a battery, capacitors, and circuitry designed to analyze cardiac rhythm and inform the operator whether a shock is indicated. Information is transmitted to the device by electrode pads used for both monitoring and shock therapy (Figure 3). Manu-
facturers were challenged to develop an AED so reliable and easy to use that fears of misuse and inappropriate shocks would be unfounded. Reductions in size, weight, cost, and maintenance were also essential if PAD were to be logistically and economically feasible. Several advances in AED technology over the past decade have been instrumental in the effort to achieve these goals.

Ease of Use
Laypersons trained to use an AED may go months or years without witnessing an arrest or operating an AED. Operation of an AED, therefore, needs to be nearly intuitive for timely delivery of therapy. Several important changes have resulted in marked simplification of AED use. Self-adhesive electrode pads are provided with diagrams on how to apply them (Figure 3). Once activated, AEDs have voice and text prompts to guide the user through the few simple steps. An arrhythmia analysis algorithm automatically interprets the rhythm and either recommends countershock, to be given by the push of a button, or no countershock. The device immediately reevaluates the rhythm and determines whether to recommend an additional shock. Cardiac rhythms are automatically recorded for review. These simplifications in AED operation have resulted in a marked reduction in defibrillation times and have minimized the need for retraining. A study examining the use of the AED in out-of-hospital cardiac arrests showed that trained first responders had an average time from power-on to first defibrillation of only 25 seconds.24 One recent study of mock cardiac arrest showed that mean time to defibrillation from arrival at the scene was only 90 seconds for a group of untrained sixth-grade students and 67 seconds for trained EMTs and paramedics.25

Arrhythmia Analysis Algorithms
Taking advantage of innovations in computer technology and detection algorithm design in the 1980s and 1990s, manufacturers have developed arrhythmia analysis algorithms that can interpret complex cardiac rhythms and deliver appropriate therapy with impressive accuracy (Figure 4). In 1997, the AHA Subcommittee on AED Safety and Efficacy recommended specific performance goals for arrhythmia analysis algorithms. Current AEDs have consistently exceeded these goals.23 Several studies have demonstrated 100% sensitivity and specificity for the detection of ventricular fibrillation.24,26-29

Energy Delivery and Storage
External defibrillation requires the delivery of energy, in the form of current, to the myocardium. This process has been made more efficient through the use of impedance-based defibrillation, larger electrode pad sizes, and biphasic waveforms. Impedance-based defibrillation refers to the adjustment of shock waveform features or shock energy based on patient impedance (resistance). Because defibrillation thresholds vary substantially from patient to patient, this feature results in a more efficient use of energy.30,31 Larger electrode pad sizes have been shown to reduce transthoracic impedance and improve defibrillation success rates.32,33

Early AEDs and most external defibrillators used monophasic waveforms, in which current is delivered to the patient in a single direction (polarity). Two conventional monophasic waveforms exist: damped sinusoidal, in which a high peak current is delivered with the current returning to zero gradually; and truncated exponential, in which current returns to zero instantaneously after delivery of the selected energy. More recently, biphasic waveforms, in which the direction of current flow is reversed part way through the pulse (Figure 5), have been used extensively in implantable cardiac defibrillators (ICDs) and found

Figure 3. Automated External Defibrillator With Attached Electrode Pads

AED indicates automated external defibrillator; ECG, electrocardiogram.
to achieve equivalent or superior defibrillation rates at relatively lower energy levels (<200 J) than the previously used monophasic waveforms. While direct comparison of biphasic with monophasic waveforms in the out-of-hospital setting are lacking, evidence that lower energy shocks using biphasic waveforms have comparative efficacy and are safe and clinically effective has led some AED manufacturers to use a fixed 150-J shock energy.

Poole et al demonstrated a first-shock defibrillation rate of 89% using low-energy (150 J) biphasic waveforms in patients with out-of-hospital cardiac arrest found to be in ventricular fibrillation, while Gliner et al achieved a rate of 83%. Ventricular fibrillation was successfully terminated by fewer than 3 shocks in 97% of patients. Animal studies suggest that these lower energies result in improved postshock myocardial function. Such data have resulted in biphasic waveforms becoming the most common waveform offered in AEDs, and the manufacturers of standard external defibrillators have begun to market biphasic waveform devices as well.

Nonrechargeable lithium-based batteries that can last up to 5 years without requiring service are rapidly replacing larger lead and nickel cadmium batteries as the energy source for the AED. At present, most devices automatically perform self-tests on a daily or weekly basis, alerting users when service is required. Such innovations in energy delivery and storage have led to marked reductions in maintenance requirements and reductions in both the size and cost ($3000-$4500 each) of AEDs (TABLE 1).

**Use of the AED Within the Traditional EMS System**

Several studies have demonstrated that EMTs and paramedics can safely and effectively use manual external defibrillators. Subsequent studies of AED use by these trained personnel demonstrated that the AED was equally safe and effective and suggested a possible survival advantage over use with the manual external defibrillator (TABLE 2). The data, along with improved portability and ease of use of the AED, have led to AEDs becoming standard equipment in many EMSs. Several communities have documented improved survival with the addition of EMT defibrillation using the AED while 2 meta-analyses have demonstrated that defibrillation by basic life support providers reduced the relative risk of death for persons experiencing out-of-hospital cardiac arrest who are in ventricular fibrillation.

In an effort to further reduce time to defibrillation and in response to evidence demonstrating the safety and ease of use of the AED, many communities expanded the role of defibrillation to trained first-responders (eg, police officers and firefighters) who often arrive at the scene of an arrest before paramedics. Studies of the use of the AED by such personnel have shown dramatically reduced time to defibrillation and enhanced survival in select communities (TABLE 3). Weaver et al showed that firefighters could deliver defibrillation with an AED 5 minutes earlier than paramedics could with a standard defibrillator. A study by White et al found that survival to hospital discharge in Rochester...
estcase, Minn, was increased from 26% to 58% when patients in ventricular fibrillation were defibrillated by police. Mosseso et al* showed that police use of the AED in Allegheny County, Pennsylvania, decreased time to defibrillation and was an independent predictor of survival to hospital discharge.

Despite these impressive results, several studies indirectly point out the inability of early defibrillation alone to overcome other deficiencies in the chain of survival. Kellermann et al69 showed that the impact on survival of adding first responder defibrillation to a fast-response urban EMS system was small despite a reduction in time to defibrillation. Low rates of bystander CPR (12%) were felt likely to have contributed to poor survival rates in this study. Sweeney et al70 also showed that the addition of AEDs to their EMS system in North Carolina failed to improve survival rates. Bystander CPR was impressively frequent, but delays in calling for EMS support and long call-processing times were noted. A large study by Stiell et al,71 involving more than 19 different communities in Ontario in which survival rates had previously been low (2.5%), showed implementation of a rapid defibrillation program to be an effective and inexpensive approach to improving out-of-hospital cardiac arrest survival.71,72 Much of the benefit to survival in this study, however, came from patients unlikely to benefit from early defibrillation—those initially found with pulseless electrical activity and asystole—suggesting that shorter response times and early CPR were important determinants of improved survival.73 A meta-analysis by Nichol et al74 concluded that while early defibrillation had the greatest relative impact on survival, increased rates of bystander CPR and the presence of advanced cardiac life support–capable EMSs are also important determinants of survival. In summary, while each component of the chain of survival remains critical to improved survival, the AED is a vital addition to an EMS and a powerful tool in the effort to reduce time to defibrillation and improve survival from sudden cardiac death.

Outside the Traditional EMS System

Because the majority of cardiac arrests occur at home, several studies have examined the use of AEDs by family members of high-risk patients.75,76 Although these studies demonstrated the feasibility of training laypersons (eg, family members) to use an AED, researchers had difficulty with patient recruitment and obtained disappointing results. There is mounting evidence for the efficacy of ICDs in patients at increased risk for sudden cardiac death.77-79 This has limited enthusiasm for the placement of AEDs in the home of high-risk patients and primarily limited the role of the AED in the home to high-risk patients who either refuse an ICD or have a contraindication to ICD placement. However, these studies used earlier-generation AEDs and, given the lower costs and ease of use of the current devices, further study with the newer technology is warranted.

In 1991, Quantas Airlines initiated a program using AEDs on overseas flights and at major terminals. Quantas documented 46 cardiac arrests in a 64-month period in which long-term survival from arrests was 26%, comparable with the most effective prehospital emergency services.80 In data from American Airlines over a 2-year period, the AED was used on 200 patients. Of those with ventricular fibrillation, 6 of 15 (40%) were shocked and survived to hospital discharge with full neurologic and functional recovery. Specificity and sensitivity for ventricular fibrillation were 100%.81 Based on these experiences, several US and international airlines have installed AEDs or are planning to do so.82,83

Valenzuela et al84 looked at use of the AED by security personnel in casinos,

Table 1. Automated External Defibrillators

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Battery Type</th>
<th>Waveform (Shock Energy, Joules)</th>
<th>Weight, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agilent Technologies, Seattle, Wash</td>
<td>Heartstream FR2</td>
<td>Lithium</td>
<td>Nonescalation biphasic (150)*</td>
<td>2.1</td>
</tr>
<tr>
<td>Medtronic Physiocontrol, Redmond, Va</td>
<td>Lifepak 500</td>
<td>Lithium or lead-acid</td>
<td>Escalating biphasic or monophasic (200, 300, 360)</td>
<td>3.2</td>
</tr>
<tr>
<td>Survivalink, Minneapolis, Minn</td>
<td>FirstSave</td>
<td>Lithium</td>
<td>Escalating biphasic or monophasic (140-360)†</td>
<td>3.4</td>
</tr>
<tr>
<td>Laerdal Medical, Wappingers Falls, NY</td>
<td>Heartstart FR</td>
<td>Lithium</td>
<td>Nonescalating biphasic (150)*</td>
<td>2.1</td>
</tr>
<tr>
<td>Medical Research Laboratories, Buffalo Grove, Ill</td>
<td>AEDefibrillator</td>
<td>Lithium</td>
<td>Escalating biphasic or monophasic</td>
<td>2.1</td>
</tr>
<tr>
<td>Zoll Medical Corporation, Burlington, Mass§</td>
<td>Zoll M Series</td>
<td>Lead-acid</td>
<td>Monophasic (200, 300, 260) or biphasic (120, 150, 200)</td>
<td>5.2</td>
</tr>
</tbody>
</table>

*Shock waveform adjusted for impedance.
†Awaiting approval from the Food and Drug Administration.
§Includes electrocardiogram monitor and manual capability.

Table 2. Comparison of Survival Rates From Out-of-Hospital Cardiac Arrest After Defibrillation With an Automated External Defibrillator (AED) vs a Manual Defibrillator*

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Manual Defibrillator</th>
<th>AED</th>
<th>Survival, % (No.)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weaver et al77</td>
<td>Seattle, Wash</td>
<td>17 (44/228)</td>
<td>30 (84/276)</td>
<td></td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Stults et al85</td>
<td>Iowa</td>
<td>13 (7/53)</td>
<td>17 (6/35)</td>
<td></td>
<td>&gt;.75</td>
</tr>
<tr>
<td>Cummins et al86</td>
<td>King County, Wash</td>
<td>23</td>
<td>28</td>
<td></td>
<td>NS</td>
</tr>
</tbody>
</table>

*NS indicates not significant.
that should answer some of these im-
trolled, prospective clinical trial of PAD
jointly supporting a multicenter, con-
over 5 years. The National Heart, Lung,
vided treatment, with 8 to 32 lives saved
arrest patients would have been pro-
in the higher-incidence sites of cardiac
estimated that 134 cardiac
arrest in Seattle and King County, Wash-
in the potential benefit of placing AEDs
at the National Heart, Lung, and Blood Institute and the AHA are
s that PAD and first-
lished with caution. Prospective
ents of cost and improvements in sur-
success of manufacturers in devel-
ong more advanced AEDs has re-
ducing concerns over inappropriate
shocks and potential harm of defibril-
tions for life-threatening ill-
nesses.98,99 Nichol et al99 estimated that
plementation of PAD by laypersons
in an urban EMS system was associ-
ated with a median cost of $44000 per
additional quality-adjusted life-year
and that the same program for
police use was associated with a
median cost of $27000 per additional
quality-adjusted life-year saved, con-
sistent with the cost of other common
medical interventions (ie, <$50000
per quality-adjusted life-year). These
data are based on multiple assump-
tions, including the cost to implement
a PAD program and the survival rate
from cardiac arrest, and must be
evaluated with caution. Prospective
randomized trials are needed to better
answer these questions. The AHA
Guidelines 2000 for Cardiopulmonary
Resuscitation and Emergency Cardio-
vascular Care currently call for PAD
programs in areas where response
times of fewer than 5 minutes, from
EMS call to countershock, cannot be
reliably achieved, and in areas where
there exists a reasonable probability of
at least 1 AED use in 5 years.86

Barriers to PAD
Physicians and legislators were ini-
tially slow to accept the concept of PAD. Recently, however, both state and fed-
eral governments have taken a more
active role in promoting efforts at re-
duction of sudden cardiac death. In
1997 the 106th Congress passed the
Cardiac Arrest Survivor Act of 1997,
amending the Public Health Service Act
to establish at the National Heart, Lung,
and Blood Institute a program regard-
ing lifesaving interventions for indi-
viduals who experience cardiac arrest.
The success of manufacturers in devel-
oping more advanced AEDs has re-
duced concerns over inappropriate
shocks and potential harm of defibril-

Table 3. Comparison of First-Responder Defibrillation With Paramedic/EMT Defibrillation

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Survival, % (No.)</th>
<th>Call-to-Shock Time, min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mossesso et al*</td>
<td>Allegheny County, Pa</td>
<td>26 (12/46)</td>
<td>8.7</td>
</tr>
<tr>
<td>Weaver et al†</td>
<td>Seattle, Wash</td>
<td>30 (84/276)</td>
<td>8.7</td>
</tr>
<tr>
<td>Shuster et al†</td>
<td>Hamilton, Ontario</td>
<td>5.7 (8/140)</td>
<td>5.6</td>
</tr>
<tr>
<td>White et al††</td>
<td>Rochester, Minn</td>
<td>48 (11/84)</td>
<td>6.3</td>
</tr>
<tr>
<td>Weaver et al†‡</td>
<td>Seattle, Wash</td>
<td>30 (26/87)</td>
<td>8.8</td>
</tr>
</tbody>
</table>

*EMT indicates emergency medical technician; CPR, cardiopulmonary resuscitation; and NS, not significant.
†Subset of patients who had prolonged paramedic response times or in whom initiation of CPR did not demonstrate significant improvement in survival.
‡Subset of patients who had prolonged paramedic response times or in whom initiation of CPR did not demonstrate significant improvement in survival.
CONCLUSION

Sudden cardiac death remains a major public health issue. Animal and human data demonstrate that early defibrillation improves survival, and that reductions in time to defibrillation can increase survival following sudden cardiac arrest. However, there are limitations to how quickly the EMSs can respond in many communities, particularly in rural and urban centers. The AED represents a major advance in the effort to achieve early defibrillation and further improve survival following out-of-hospital sudden cardiac arrest. By responding to the challenge to develop an AED that is more accurate, lightweight, affordable, and easy to use, AED manufacturers have helped make public access to defibrillation feasible. With help from the state and federal governments, manufacturers have helped overcome many of the obstacles to AED implementation. Automated external defibrillators are quickly becoming an integral part of the EMS and their presence in the community is increasing at a rapid rate. Additional studies are needed to determine how widespread the deployment of these lifesaving devices should be, provide more data on the cost-effectiveness of PAD, and further define the role of the AED in children and infants.

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