Improving 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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CARDIOVASCULAR DISEASE IS THE major cause of death in the United States, resulting in nearly 1 million deaths a year. Nearly half of these deaths (250,000 to 500,000) are sudden and unexpected. Most sudden deaths from cardiac arrest occur outside the hospital, and survival rates have traditionally been poor—only 1% to 5% of these patients are estimated to survive to hospital discharge.4,5 When first-responders arrive early, ventricular tachycardia and ventricular fibrillation are the rhythms they most commonly encounter initially.1,2,7 Most persons experiencing cardiac arrest have no history of severe heart disease, and sudden cardiac death is frequently the first manifestation of cardiovascular disease (FIGURE 1).1,6,7 This has complicated efforts at prevention and has led to a shift in emphasis to improvements in prehospital care.

In an effort to improve prehospital care, the American Heart Association (AHA) has promoted the “Chain of Survival” concept, describing a sequence of interventions (links) that when implemented result in improved survival following sudden cardiac arrest.8 Early defibrillation has emerged as the single most important intervention.7,9-11 There are data from both animal and human studies showing that defibrillation immedi-

See also Patient Page.

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In an effort to overcome these limitations, the AHA has promoted the concept of public access defibrillation (PAD). 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. 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 medical subject headings used were electric countershock, heart arrest, resuscitation, and emergency medical services. Automatic external defibrillator, automated external defibrillator, and public access defibrillation were searched as keywords. All relevant publications were reviewed. Data quality was determined by publication in peer-reviewed literature. In addition, all 5 authors reviewed relevant abstracts and presentations from the official 1999 and 2000 annual meetings of the American College of Cardiology, the AHA, and the North American Society of Pacing and Electrophysiology. Product information was obtained from each AED manufacturer’s official Web site and official specification sheets were provided by each of the manufacturers at our request.

RESULTS
Technology
Automated external defibrillators were developed in the 1970s and first introduced for clinical use in 1979. 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).
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.30-33 Larger electrode pad sizes have been shown to reduce transthoracic impedance and improve defibrillation success rates.34,35

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...
to achieve equivalent or superior defibrillation rates at relatively lower energy levels (<200 J) than the previously used monophasic waveforms.\textsuperscript{36-48} 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.\textsuperscript{23,30,48} Poole et al\textsuperscript{29} 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\textsuperscript{26} achieved a rate of 83%. Ventricular fibrillation was successfully terminated by fewer than 3 shocks in 97% of patients.\textsuperscript{26} Animal studies suggest that these lower energies result in improved postshock myocardial function.\textsuperscript{49,50} 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.\textsuperscript{51-54} 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).\textsuperscript{17,18,55} These 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,\textsuperscript{56-59} 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.\textsuperscript{60,61}

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).\textsuperscript{62-68} Weaver et al\textsuperscript{62} 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\textsuperscript{83} found that survival to hospital discharge in Roy.
**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.  †Shock energy adjusted for impedance. §Includes electrocardiogram monitor and manual capability.

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**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 Location</th>
<th>Manual Defibrillator</th>
<th>AED</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weaver et al17</td>
<td>Seattle, Wash</td>
<td>17 (44/228)</td>
<td>30 (84/276)</td>
</tr>
<tr>
<td>Stults et al16</td>
<td>Iowa</td>
<td>13 (7/53)</td>
<td>17 (6/35)</td>
</tr>
<tr>
<td>Cummins et al15</td>
<td>King County, Wash</td>
<td>23</td>
<td>28</td>
</tr>
</tbody>
</table>

*NS indicates not significant.

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a setting in which a large population is closely monitored. Use of the AED resulted in survival to discharge in 53% (56/105) of patients whose initial rhythm was ventricular fibrillation. Mean time to first defibrillation was only 4.4 (2.9) minutes while mean time for arrival of paramedics was 9.8 (4.3) minutes.

Public Access Defibrillation
How widespread the availability of the AED should be is unknown and whether AEDs should be placed in shopping malls, conventions centers, and large office buildings is largely untested. Becker et al, however, retrospectively looked at the potential benefit of placing AEDs in the higher-incidence sites of cardiac arrest in Seattle and King County, Washington and estimated that 134 cardiac arrest patients would have been provided treatment, with 8 to 32 lives saved over 5 years. The National Heart, Lung, and Blood Institute and the AHA are jointly supporting a multicenter, controlled, prospective clinical trial of PAD that should answer some of these important questions.

In the Hospital
The use of the AED is not limited to prehospital patient care. While cardiac arrest survival rates in the coronary care unit can be as high as 90%, survival outside of these units falls off dramatically. Several minutes can elapse before conventional in-hospital code teams first attempt defibrillation. It has been shown that non–critical care nurses can learn to use the AED and retain the knowledge and skill over time.

The use of the AED has made it possible to reduce time to defibrillation in non–critical care locations and as a result, in-hospital AED programs are increasingly being encouraged. The AED has been used intraoperatively in high-risk patients with success. Advantages of the AED in the operating room included rapid response to ventricular arrhythmia; safe, hands-free operation; and minimal disruption of the surgical procedure.

Cost to the Health Care System
Although based on multiple assumptions of cost and improvements in survival, initial cost-effectiveness analyses have suggested that PAD and first-responder defibrillation are economical in comparison to other common treatments for life-threatening illnesses. Nichol et al estimated that implementation of PAD by laypersons in an urban EMS system was associated with a median cost of $44,000 per additional quality-adjusted life-year saved and that the same program for police use was associated with a median cost of $27,200 per additional quality-adjusted life-year saved, consistent with the cost of other common medical interventions (ie, <$50,000 per quality-adjusted life-year). These data are based on multiple assumptions, 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 Cardiovascular 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.

Barriers to PAD
Physicians and legislators were initially slow to accept the concept of PAD. Recently, however, both state and federal governments have taken a more active role in promoting efforts at reduction 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 regarding lifesaving interventions for individuals who experience cardiac arrest. The success of manufacturers in developing more advanced AEDs has reduced concerns over inappropriate shocks and potential harm of defibrillation by laypersons. These improvements have buoyed the efforts to pass Good Samaritan laws, and currently 45 states have passed legislation protecting laypersons who use an AED in good faith. On May 20, 2000, the president proposed an initiative directing the creation of criteria for the placement of AEDs in federal buildings and on all commercial airlines in an effort to save up to 20,000 lives each year. These initiatives at the state and federal levels are paving the way for more widespread access to defibrillation as legal barriers to PAD, both perceived and real, are slowly eliminated.

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></td>
<td></td>
<td>First Responder</td>
<td>Paramedic/EMT</td>
</tr>
<tr>
<td>Mosesso et al,17</td>
<td>Allegheny County, Pa</td>
<td>26 (12/46)</td>
<td>3 (1/29)</td>
</tr>
<tr>
<td>Weaver et al,17</td>
<td>Seattle, Wash</td>
<td>30 (84/276)</td>
<td>19 (44/220)</td>
</tr>
<tr>
<td>Shuster et al,16</td>
<td>Hamilton, Ontario</td>
<td>5.7 (8/140)</td>
<td>2.7 (4/147)</td>
</tr>
<tr>
<td>White et al,15</td>
<td>Rochester, Minn</td>
<td>43 (41/84)</td>
<td>43 (23/53)</td>
</tr>
<tr>
<td>Weaver et al,17</td>
<td>Seattle, Wash</td>
<td>30 (26/87)</td>
<td>28 (105/370)</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.
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.

Author Contributions: Study concept and design: Marenco, Wang, Link, Estes. Acquisition of data: Marenco, Homoud. Analysis and interpretation of data: Marenco, Wang, Link, Homoud. Drafting of the manuscript: Marenco, Wang. Critical revision of the manuscript for important intellectual content: Marenco, Wang, Link, Homoud, Estes. Statistical expertise: Marenco, Link, Homoud. Administrative, technical, or material support: Marenco. Study supervision: Marenco, Wang, Link, Homoud, Estes.

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AUTOMATED EXTERNAL DEFIBRILLATORS