

Ventricular Fibrillation and the Use of Automated External Defibrillators on Children

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ABSTRACT

The use of automated external defibrillators (AEDs) has been advocated in recent years as a part of the chain of survival to improve outcomes for adult cardiac arrest victims. When AEDs first entered the market, they were not tested for pediatric usage and rhythm interpretation. In addition, the presumption was that children do not experience ventricular fibrillation, so they would not benefit from use of AEDs. Recent literature has shown that children do experience ventricular fibrillation, and this rhythm has a better outcome than do other cardiac arrest rhythms. At the same time, the arrhythmia software on AEDs has become more extensive and validated for children, and attenuation devices have become available to downregulate the energy delivered by AEDs to allow their use in children. Pediatricians are now being asked whether AED programs should be implemented, and where they are being implemented, pediatricians are being asked to provide guidance on the use of AEDs in children. As AED programs expand, pediatricians must advocate on behalf of children so that their needs are accounted for in these programs. For pediatricians to be able to provide guidance and ensure that children are included in AED programs, it is important for pediatricians to know how AEDs work, be up-to-date on the literature regarding pediatric fibrillation and energy delivery, and understand the role of AEDs as life-saving interventions for children.

INTRODUCTION

Early defibrillation has been shown to be the most effective treatment for adult out-of-hospital cardiac arrest caused by ventricular fibrillation (VF).^{1,2} The likelihood of survival decreases by approximately 7% to 10% with each minute of delay to defibrillation after cardiac arrest. Strategies to decrease the time to defibrillation that have been shown to be effective include the use of an automated external defibrillator (AED) by emergency medical services (EMS) personnel and nonmedical lay people.³⁻⁶ AEDs represent a significant breakthrough for adult out-of-hospital cardiac arrest.³ For adults, when combined with effective cardiopulmonary resuscitation (CPR), the use of early defibrillation has been shown to produce the highest rates of survival.²

For children, the use of defibrillation traditionally has been downplayed with a focus on early airway and ventilatory assistance, because available data showed that asystole was the predominant rhythm and that VF rarely occurred.⁷ Although not the most common rhythm, VF does occur in children. In addition, the chance of surviving after VF is greater than that for other nonperfusing rhythms, which

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The guidance in this report does not indicate an exclusive course of treatment or serve as a standard of medical care. Variations, taking into account individual circumstances, may be appropriate.

Key Words

automated external defibrillator, ventricular fibrillation, emergency medical services, cardiac resuscitation, school emergency care

Abbreviations

VF—ventricular fibrillation
AED—automated external defibrillator
EMS—emergency medical services
CPR—cardiopulmonary resuscitation
PEA—pulseless electrical activity
VT—ventricular tachycardia
ALS—advanced life support
DFT—defibrillation threshold
ED₅₀—median effective dose
TD₅₀—median toxic dose
LD₅₀—median lethal dose
LV—left ventricular
LOE—level of evidence

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makes timely treatment of VF a priority for pediatric resuscitation.⁸ As a result, many current guidelines, including those of the International Liaison Committee on Resuscitation,⁹ the American Heart Association,¹⁰ and the National Association of EMS Physicians,¹¹ now advocate for AED use on children to analyze rhythms and provide early defibrillation in cases of VF.

To be effective and safe for children, an AED must achieve several goals. First, it must capture the patient's rhythm from surface electrodes and then use a computer algorithm to determine if a shock is indicated. For an AED to be used on children, it must have the capability to determine shockable rhythms, but more importantly, it must accurately determine when not to deliver a shock. When the correct rhythm is identified, the AED must be capable of delivering a shock with sufficient energy to convert the rhythm to a perfusing rhythm without causing damage to the myocardium. In the past, published data related to the effective energy for defibrillation or safety of different energy levels and waveforms for children were lacking. In previous reviews, the only source of data regarding energy levels was a single retrospective study from 1976, which showed, on average, that 2 J/kg treated VF in many children and, if it failed, that 4 J/kg was usually effective. As a result, AEDs were recommended for use only on older children and adults.⁹ Fortunately, AED technology has improved dramatically in recent years, and additional research has been conducted and demonstrated that AEDs are safe for use on younger children. In addition, although there are fewer data available for infants and young children than for adults and older children, there are studies that have shown AED safety and efficacy for infants and young children. Finally, pediatric-capable AEDs have been approved by the US Food and Drug Administration not only for use on young children but also on infants of all ages. AEDs are now capable of recognizing pediatric shockable rhythms, and some are programmed to decrease the delivered energy on the basis of a fixed reduction, chest wall impedance, or a combination of the two, which makes them suitable for pediatric patients.

CARDIAC ARREST PHYSIOLOGY

Children and adults have anatomic differences that may be significant in pediatric defibrillation. Children's hearts are smaller than those of adults. A critical mass of myocardial tissue is required to sustain fibrillation.¹² This could be one of the reasons why VF is less prevalent in the pediatric population than it is in adults.¹³

Pediatric and adult patients also have some important physiologic differences. Children have higher cardiac output per kilogram of body weight than adults, but because oxygen demand is high in children, oxygen reserves are limited. Cardiopulmonary deterioration can occur whenever oxygen delivery is compromised or when oxygen demand is increased above oxygen supply.

Children have higher heart rates and lower stroke volumes than adult patients.

In children, sinus tachycardia is the normal response to stress, because infants and children increase their cardiac output by increasing their heart rate rather than stroke volume. Normal heart rates for neonates have been reported to range from 100 to 180 beats per minute. In addition, detecting a carotid pulse in infants may be more difficult than it is in adults because of their shorter, chubbier necks.

Adults and children also have biochemical differences, which may be relevant to the toxicity of defibrillation shocks. Newborn infants have substantially less myocardial catecholamine than adults.¹⁴ It is believed that the biochemical effects of catecholamines on oxygen consumption and use may have a role in causing myocardial damage.¹⁵ Thus, it may be expected that newborn infants would have a higher tolerance for high-energy defibrillation doses than adults.

CARDIAC ARREST EPIDEMIOLOGY

Children suffer fewer cardiac emergencies than adults. One estimate indicates that sudden cardiac death is one tenth as common in children as it is in adults and that it occurs in only 1 to 2 per 100 000 children annually.¹⁶ However, the death of a child is an enormous emotional and social loss and has a community-wide impact. Because of their life expectancy, the number of years of life lost as a result of pediatric cardiac arrests may rival that for all adult arrests.¹³ Survival and neurologic outcomes are better for pediatric patients whose initial recorded rhythm is VF, compared with other causes of pediatric cardiac arrest.¹⁷

In a 6-year retrospective population-based review of pulseless, nonbreathing patients younger than 20 years, Mogayzel et al⁸ compared the causes and outcomes for patients whose initial rhythms were VF with those whose initial rhythms were asystole or pulseless electrical activity (PEA). Of the 157 patients included in the study, VF was the initial rhythm of 19%, excluding patients younger than 6 months who died as a result of sudden infant death syndrome. The study reported that, in the witnessed arrests, a significant percentage of the patients were found to be in VF as the initial rhythm on arrival of EMS. In addition, it was reported that the age of the patient did not alter the percentage of patients with VF. The percentage of cardiac arrest patients found in VF was approximately the same for 0- to 4-year-olds as it was for 15- to 19-year-olds (17% vs 19%, respectively). The first responders identified the initial rhythm of only 44% of the patients. A majority of the patients in this study (16 of 29 children) who initially were in VF did not receive defibrillation by the first responder, because protocol and available equipment required the proce-

cedure to be performed by an EMS professional. These 16 children may have benefited from AED use.

Young and Seidel's comprehensive review of pediatric CPR¹⁷ included articles that were published over a 27-year period from 1970 through 1997, representing 44 studies and involving a total of 3094 patients. Of the 1407 patients in cardiac arrest, approximately half were younger than 1 year. Of the patients for whom initial electrocardiography was performed, 10% were in VF or pulseless ventricular tachycardia (VT), and 73% had either asystole or PEA. Only 5% of the patients with cardiac arrest whose initial recorded rhythm was asystole survived to discharge, compared with 30% of the patients in VF/VT. Because of the lack of consistency in definitions, inclusion criteria, and outcome measures, the authors of this review urged the use of pediatric Utstein-style definitions, which represents an internationally accepted standard method of collecting and reporting respiratory and cardiac arrest and resuscitation data to minimize variations in definitions and outcome measures in future pediatric resuscitation studies.¹⁸ They also noted that the survival rate for pediatric victims of sudden cardiac arrest had not improved in the last decade. Despite the low incidence of VF in this population, there was a dramatic difference in survival for patients with VF compared with other rhythms in cardiac arrest. Patients in asystole rarely respond to treatment. Because VF may precede asystole, resulting in a short "window of opportunity" for defibrillation, the authors suggested a dramatic change in pediatric resuscitation protocols and emphasized early defibrillation. Furthermore, the studies included in this review may have underestimated the true existence of VF in the pediatric patient. Because AEDs were not authorized for use on children, rhythms were determined only on arrival by advanced life support (ALS) providers. This protocol may have allowed undetected VF at the time of arrival of the first responder to degenerate to asystole by the time an ALS provider had arrived to perform a rhythm analysis.

In a recent retrospective study, Smith et al¹⁹ reported VF rates of 7.6% for children 1 to 7 years of age and 27.0% for children 8 to 18 years of age, with an overall incidence of VF of 17.6%; VF was most associated with age of 8 to 18 years, witnessed arrest, and cardiac etiology. The authors found survival rates of 31.3% for those with VF and 10.7% for those with all other rhythms, which provided further support for VF being a rhythm that has a better outcome. The lower incidence of VF in children 1 to 7 years of age, compared with those 8 to 18 years of age, may not reflect the actual incidence of VF in younger children, as was the case in the Young and Seidel study¹⁷ described previously. Because AEDs were not authorized for use on children during much of the study period, rhythms were determined only on arrival of ALS providers.

ACCURACY OF RHYTHM DETERMINATION

It is an overall safety goal for AED algorithms to be highly specific in the presence of nonshockable rhythms. Because of higher-than-normal heart rates in infants and young children, AEDs that advise shocks primarily on the basis of heart rate would not be appropriate for use with pediatric patients. This is of even greater importance for a public-access defibrillation program in that most lay people are taught not to check the patient's pulse before application of an AED but to rely on the device's recognition of a shockable rhythm. The anatomic and physiologic differences between adults and children summarized previously underscore the importance of this requirement. Because many high-rate rhythms in children may be associated with a pulse, it is important that an AED for use on children be designed so that shocks are not advised for such rhythms. For rhythms for which there is not general agreement regarding whether a shock is warranted and for which there may be an associated pulse (intermediate rhythms), the AED should be designed such that shocks are not advised. The American Heart Association defines intermediate rhythms as "rhythms for which the benefits of defibrillation are limited or uncertain."²⁰ For these rhythms, the therapeutic benefit of a shock is uncertain, and the victim may be exposed to some risk if a shock is delivered.

Studies of AED rhythm detection in children generally have reported good accuracy.²¹⁻²⁵ In 1 study, rhythms from patients in PICUs with ages ranging from 5 days to 7.5 years were recorded.^{21,22} Rhythms were digitized and annotated by 3 reviewers and then read into several AEDs. The AED-analysis results were then compared with those of the reviewers. The study found that the specificity of the AEDs for pediatric tachycardias was not 100%, which suggests that modifications to AED algorithms might be needed to accommodate pediatric patients.

Atkins et al²⁶ compared rhythms obtained by using an AED with those obtained by using a standard electrocardiography device and then digitally analyzed both the sensitivity and specificity of the AED software in identifying pediatric VF. In this study, 696 five-second rhythm strips were analyzed. The AED was found to have a specificity of 100% for nonshockable rhythms and sensitivity of 96% for detecting VF. The authors demonstrated that AEDs have a low risk of providing an inappropriate shock and that the AED correctly identified shockable rhythms, which makes their software algorithm safe and effective for children.

In 1 of the only studies of out-of-hospital AED use on children younger than 16 years, AEDs were found to be highly accurate, with 100% specificity and 88% sensitivity.²⁶ The AEDs used in this study included multiple parameters in their analysis algorithms (the criteria on which these AEDs will advise a shock includes more

than just heart rate and amplitude). Although sensitivity was excellent at 88%, this result does present some missed opportunities and room for improvement. More important, however, was the 100% specificity, which indicates that under no circumstances was a patient defibrillated incorrectly. The authors of an AED manufacturer's study of its patient-analysis system collected 233 rhythm strips from 71 pediatric patients younger than 12 years and showed similar results, with 100% specificity and sensitivity for VF and 81.8% for VT.²³ The study supported the feasibility of using a single AED algorithm for both adults and children.

In a case report that described the use of an AED on a patient younger than 8 years, the AED correctly detected VF and advised a shock, which defibrillated the VF successfully, and then the device correctly detected the resulting nonshockable rhythm and advised that no shock was required. Importantly, there was no detectable cardiac damage from the defibrillation.²⁷

A recent observational study by Atkins and Jorgenson²⁸ of pediatric-attenuated pads used to reduce the energy delivered by some AEDs showed that for patients younger than 10 years, the 8 VF rhythms were identified correctly, as were the 10 nonshockable rhythms.

AED ENERGY AND WAVEFORM SAFETY AND EFFICACY

Defibrillation involves delivery of current through the chest and to the heart to depolarize myocardial cells and eliminate VF. In addition to recognizing a shockable rhythm, an AED must deliver the electrical energy that will have the greatest potential for conversion to a perfusing rhythm while minimizing the potential for harm. The currently accepted prehospital approach for manual defibrillation is 2 J/kg initially, followed by 4 J/kg. The energy range for current AEDs is between 150 and 360 J, depending on type of waveform and model.

Modern defibrillators are classified according to 2 types of waveforms: monophasic and biphasic. Monophasic waveform defibrillators were introduced first, but biphasic waveforms are used in almost all the AEDs and manual defibrillators that are available today. Energy levels vary according to type of device. No specific waveform (either monophasic or biphasic) is consistently associated with a higher rate of return of spontaneous circulation or improved rates of survival to hospital discharge after cardiac arrest. Monophasic waveforms deliver current of 1 polarity. Monophasic waveforms can be categorized further by the rate at which the current pulse decreases to 0. The monophasic damped sinusoidal waveform returns to zero gradually, whereas the monophasic truncated exponential waveform current is abruptly returned to baseline 0 current flow. Few monophasic waveform defibrillators are being manufactured, but many are still in use. Most of these defibrillators use monophasic damped sinusoidal waveforms. Biphasic AED models primarily come in 2 types of waveforms: truncated exponential and rectilinear.

Both of these waveforms are fairly prevalent in available biphasic defibrillators.

In 1976, Gutgesell et al²⁹ reported the results of a retrospective chart review of pediatric cardiac arrests that was performed to determine if their institution's guidelines for defibrillation energy dose in pediatric patients was effective. Twenty-seven children were included, with weights ranging from 2.1 to 50.0 kg and ages ranging from 3 days to 15 years. In these children, 71 defibrillation attempts were made by using monophasic wave technology. The authors found that 91% of the shocks with an energy dose of 2 J/kg \pm 10 J were effective, whereas the 2 shocks below this level were ineffective, and all but 1 of the 12 shocks above this level were effective. The single higher-energy shock that was ineffective was only 13 J higher than the 2 J/kg dosage guideline, and the child previously had received an unsuccessful initial shock at a lower level (1.9 J/kg). A third shock at 60 J (3.8 J/kg) was successful for this patient. All shocks above 2 J/kg were at least as effective as shocks of 2 J/kg \pm 10 J, and the study included 1 shock at more than 7 J/kg.²⁸

Before the study reported by Gutgesell et al, the recommendations for initial defibrillation energies of children ranged from 60 to 200 J.^{30,31} Afterward, this study was the basis for the pediatric defibrillation recommendations of 2 J/kg, followed by 4 J/kg, for children. It is important to note that the study by Gutgesell et al was not designed to establish a defibrillation threshold (DFT)-based dose for children; rather, it confirmed the guidelines for effective defibrillation that the investigators had already established on the basis of their previous animal studies. In addition, this study established neither dose safety ranges nor the risk/benefit of this or any other dosing strategy. Although Gutgesell et al acknowledged that the damage threshold is much higher, they decided to keep the 2 J/kg initial and 4 J/kg subsequent shocks protocol, because it was easy to remember and seemed to be successful in most cases. This single retrospective case series, in which a monophasic waveform was used, has served as the basis for most guidelines for pediatric defibrillation, including extrapolation without evidence to biphasic waveform energy settings.

Mogayzel et al⁸ found similar results, reporting that 93% of the 29 patients in their study whose initial rhythm was VF were defibrillated with 2 to 4 J/kg as the initial dose and 4 J/kg for subsequent shocks. Seventeen percent of the patients with VF were discharged with no or mild disability, compared with only 2% of patients whose initial rhythm was asystole or PEA. The authors found that VF was the only variable associated with a good outcome in this population and that patients whose initial rhythms were VF had a survival rate that approached that of adults.

Atkins et al²⁶ recently studied out-of-hospital AED use on patients younger than 16 years. In total, the AEDs

performed 67 analyses, and there were 25 episodes of VF. Three of the 7 patients who received shocks survived and were discharged from the hospital, with AEDs having delivered either 200 or 360 J. Two of the patients with VF did not receive shocks, because they were younger than 12 years and/or weighed less than 90 kg, and the dose would have exceeded the 4 J/kg recommended dose; both patients died.

Successful use of an AED in a younger child has been reported.²⁷ In this case, a 3-year-old child received a 9 J/kg dose delivered by his mother using a 150-J biphasic AED. The child was awake and crying with a heart rate of 120 beats per minute when the EMS team arrived 10 minutes after his defibrillation.²⁷ The child was defibrillated successfully with 1 shock. The child's creatinine kinase and troponin concentrations were within the reference ranges after his resuscitation, which indicated no clinically significant damage. A postmarket observational study of pediatric-attenuated pads by Atkins and Jorgenson²⁸ has shown that using these pads with a certain AED and a fixed biphasic energy of 50 J resulted in successful termination of 8 cases of VF.

The harmful effects of defibrillation cannot ethically be induced deliberately in human subjects; therefore, it is not possible to determine the dose-response curves for toxic and lethal energies in humans. As a result, appropriate energy dosing for defibrillation and energy dosing that might cause injury must be extrapolated from animal models.

Determination of the DFT for a waveform typically requires delivery of multiple shocks to each subject in a controlled setting, which makes the study in a human population extremely difficult; the difficulty of studying effectiveness of external defibrillation shocks in human pediatric subjects is compounded by the lower incidence of pediatric cardiac arrest. One study across a wide variety of animal species showed that the energy dose required for defibrillation was somewhat weight dependent and ranges from 0.5 to 10 J/kg.³² Although external defibrillation-effectiveness data are too limited to draw any definitive conclusions, this study suggests that the DFT for most patients who weigh up to 50 kg is likely close to 2 J/kg. Other studies in animals and humans have shown that repeated high-energy shocks with a 360-J monophasic damped sine waveform might cause significant damage.^{33,34} One study found that animals that received a single high-energy shock sustained little damage, but animals that received multiple shocks had significant cardiac injury and acute pump failure.³⁵ The authors emphasized the need to optimize first-shock effectiveness.

A clinical study also has shown that initial shocks that were too low (below the DFT) caused an increase in the energy requirement for subsequent shocks to defibrillate.³⁶ This report emphasizes the importance of first-shock effectiveness and casts doubt on the philosophy of

starting with a low or moderate energy level with the intent to increase if needed for subsequent shocks. These reports also provide a possible explanation for the single unsuccessful shock that was more than 2 J/kg in the pediatric patient in the Gutgesell et al study.²⁹ This patient initially received a shock that was less than 2 J/kg. In addition, these data suggest that an initial dose somewhat higher than the current recommendations may be warranted for pediatric patients.

In 1980, Babbs et al³⁷ published therapeutic indices for effective, damaging, and lethal doses of defibrillation energy using monophasic wave technology on the basis of studies that involved more than 100 dogs. The delivered energies ranged from 1 to 512 J/kg. They found that it took 5 times more energy to produce detectable histologic damage than was required for effective defibrillation. The ED₅₀ (defined as the energy at which 50% of the animals were defibrillated successfully) was 1.5 J/kg. The TD₅₀ (defined as the energy at which 50% of the animals had detectable myocardial damage) was 30 J/kg. The LD₅₀ (the 50% lethal dose for the population) was 470 J/kg. The ED₅₀ curve was significantly steeper than the TD₅₀ and LD₅₀ curves, showing that the toxic and lethal effects were more variable in the study population. The authors concluded that the "fear of inducing damage should not be a dominant factor in determining defibrillation dose. Instead, effectiveness should be the major criterion."

Gaba and Talner¹⁵ studied monophasic wave defibrillation safety in 21 newborn pigs that ranged from 2 to 18 days of age and weighed 0.95 to 4.7 kg. Some animals that were shocked with doses greater than 150 J/kg had substantial myocardial damage, but this effect was not seen in animals that were shocked at lower energy levels. The dose-response curves established by this study are nonlinear and exponential, as seen in other studies. However, the authors noted that substantially more energy was needed to cause myocardial damage in newborn piglets when compared with results reported in previous investigations of adult dogs. These results suggest that in humans, newborns are more tolerant of high-energy doses than adults, and Gaba and Talner hypothesized that the intrinsic structural and physiologic differences between the newborn and adult myocardium could account for the differences observed.

Several studies have shown that biphasic waveforms cause less damage than monophasic waveforms, and these effects seem to be independent of energy.³⁸⁻⁴⁰ One study found that the use of biphasic waveforms was associated with significantly better postresuscitation myocardial function than monophasic waveforms, even with the same high energies and capacitance typically used for monophasic defibrillation.⁴¹ These studies demonstrated the safety of pediatric defibrillation shocks, even at energy doses significantly higher than the cur-

rently recommended 4 J/kg and especially when the number of shocks delivered is minimized.

Several recent studies have addressed the question of energy dosage by using a biphasic AED and the benefit of biphasic versus monophasic waveforms. In a study of piglets, Clark et al⁴² showed that biphasic waveforms proved superior to monophasic waveforms and at lower energies in both infant and young-animal models. Although the exact energy needed for humans cannot be extrapolated from this study, the benefit of biphasic waveforms was shown. In 2002, Killingsworth et al⁴³ published results from a piglet study that was aimed at determining the DFT for biphasic truncated exponential waveform shocks. They found that the DFT with pediatric patches was 2.4 ± 0.81 vs 2.1 ± 0.65 J using adult patches. Also of note, initially after the shock, they found an increased drop in left ventricular (LV) function with increasing energy dosage compared with baseline, but by 60 seconds, there was no difference in LV function with increasing energy dosage. The importance of this study was that it determined a 2.3 J/kg DFT but also that higher dosages, even up to 360 J, produced only transient ST segment and hemodynamic changes. This led the authors to conclude that AED dosages of 50 to 100 J would be appropriate for a child weighing up to 25 kg, but using an AED with a higher energy would not pose a risk to a child or even an infant.

Additional studies have evaluated the use of adult AEDs on animal models of children and have compared attenuated adult AEDs versus nonattenuated adult AEDs. A study by Berg et al⁴⁴ in 2003 compared a single escalating energy sequence (50, 75, and 86 J) of an attenuated adult-dose biphasic shock, nonattenuated adult-dose biphasic shock, and weight-based monophasic shock for piglets with prolonged VF. The attenuated and monophasic dosages were delivered via pediatric pads and the nonattenuated dose was delivered via adult pads. The best outcome in terms of 24-hour survival and neurologic function, as well as a lesser decrease in LV end-diastolic function, was found with the attenuated adult-dosage AED. In addition, the study indicated that the adult biphasic AED, although not as good as the attenuated dosage, was superior in outcome and LV ejection fraction to the weight-based monophasic AED. In another study, Berg et al⁴⁵ showed that escalating attenuated adult-dosage biphasic shocks are more effective and have fewer adverse outcomes than standard escalating adult-dosage biphasic shocks. Although the attenuated dosage was more effective and had fewer adverse effects on the myocardium, the adult escalating-dosage biphasic shocks also were effective in terminating VF in this piglet model of pediatric VF. Berg et al⁴⁶ have also shown that attenuated adult-dosage biphasic shocks are at least as effective, if not more effective and safe, than weight-based monophasic shocks in a piglet model. A study by Tang et al⁴⁷ showed that a single attenuated

adult-dosage biphasic energy dosage (50 J) was effective in terminating VF in piglets that ranged in weight from 3.8 to 25.0 kg. In addition to the effective termination of VF, even when applied to piglets that weighed only 3.8 kg (comparable with an infant), this energy dosage resulted in a return to normal for both hemodynamic and myocardial function, indicating the safety of the attenuated adult-dosage technique, even in models of newborn infants.

The animal data indicate that there is a wide margin between effective and toxic doses,³⁷ especially in neonates.¹⁵ Other studies⁴¹⁻⁴⁶ have shown also that although pediatric-attenuated shocks are ideal, including in the treatment of infants, nonattenuated adult-dosage biphasic shocks still are highly effective and relatively safe, even for a newborn infant.

Because of the prohibition of energy doses higher than the 4 J/kg dose in the past, many children have not received timely shocks for VF,⁸ even when shocks were advised by AEDs.²⁶ It is unknown how many children may have died awaiting defibrillation while receiving lower, recommended energy doses. All available data indicate that traditional and even very high defibrillation doses from AEDs designed for adults are effective and safe in this population and fall below the TD₅₀ and LD₅₀ levels.

INTERNATIONAL AND NATIONAL GUIDELINES

Several international and national guidelines have included evaluations of the literature on AED use on children as the basis on which recommendations have been formed. A recent international review of resuscitation science and a subsequent consensus on science and treatment recommendations referenced 8 levels of evidence (LOE) to provide the basis of the strength of evidence behind the conclusions made the following statement⁹:

Many but not all AED algorithms have been shown to be sensitive and specific for recognizing shockable arrhythmias in children. A standard AED ("adult" AED with adult pad-cable system) can be used for children older than about 8 years of age and weighing more than about 25 kg. Many manufacturers now provide a method for attenuating the energy delivered to make the AED suitable for smaller children (eg, use of a pad-cable system or an AED with a key or switch to select a smaller dose).

The consensus-on-science statement added (LOE represents levels of evidence of the studies used as defined by the AHA):

The ideal energy dose for safe and effective defibrillation for children is unknown. Extrapolation from adult data and pediatric animal studies suggests that biphasic shocks are at least as effective as monophasic shocks and produce less postshock myocardial dysfunction. One LOE 5 and one LOE 6 study show that an initial monophasic or biphasic shock dose of 2 J/kg generally

terminates pediatric VF. Two pediatric case series (LOE 5) report that doses 4 J/kg (up to 9 J/kg) have effectively defibrillated children under 12 years of age, with negligible adverse effects. In 5 animal studies (LOE 6) large (per kilogram) energy doses caused less myocardial damage in young hearts than in adult hearts. In 3 animal studies (LOE 6) and 1 small pediatric case series (LOE 5) a 50 J biphasic dose delivered through a pediatric pad/cable system terminated VF and resulted in survival. One piglet (13–26 kg) study (LOE 6) showed that pediatric biphasic AED shocks (50/75/86 J) terminated VF and caused less myocardial injury and better outcome than adult AED biphasic shocks (200/300/360 J).

As a result of this scientific review, the following treatment recommendation was made:

The treatment of choice for pediatric VF/pulseless VT is prompt defibrillation, although the optimum dose is unknown. For automated defibrillation, we recommend an initial pediatric attenuated dose for children 1 to 8 years of age and up to about 25 kg (55 pounds) and 127 cm (50 inches) in length. There is insufficient information to recommend for or against the use of an AED in infants <1 year of age. A variable dose manual defibrillator or an AED able to recognize pediatric shockable rhythms and equipped with dose attenuation are preferred; if such a defibrillator is not available, a standard AED with standard electrode pads may be used. A standard AED (without a dose attenuator) should be used for children > 25 kg (about 8 years of age) and older adolescent and adult victims.

On the basis of the aforementioned consensus-on-science and treatment recommendations and after an evaluation by its Pediatric Advanced Life Support Committee, the American Heart Association made the following recommendations¹⁰:

Many AEDs have high specificity in recognizing pediatric shockable rhythms, and some are equipped to decrease the delivered energy to make it suitable for children 1 to 8 years of age. Since the publication of the ECC [Emergency Cardiovascular Care] Guidelines 2000, data has shown that AEDs can be safely and effectively used in children 1 to 8 years of age. However, there is insufficient data to make a recommendation for or against using an AED in infants < 1 year of age. In systems and institutions that care for children and have an AED program, it is recommended that the AED have both a high specificity in recognizing pediatric shockable rhythms and a pediatric dose-attenuating system to reduce the dose delivered by the device. In an emergency, if an AED with a pediatric attenuating system is not available, use a standard AED. Turn the AED on, follow the AED prompts, and resume chest compressions immediately after the shock. Minimize interruptions in chest compressions.

Last, the National Association of EMS Physicians also reviewed the evidence that supports the use of AEDs on children and made the following recommendations¹¹:

Strategies for treatment of pediatric arrest should focus on shortening the intervals from collapse to recognition

of ventricular fibrillation and to defibrillation. Data on the correct energy for defibrillation of children is limited. Animal studies suggest the immature heart is less susceptible to energy related damage than the adult heart and that there is a wide therapeutic range of defibrillation energy dose. Although using a fixed energy AED in some children may have the potential for harm, not treating ventricular fibrillation has the potential for even greater harm, death of the child. As such, defibrillation should not be withheld based on weight and size criteria alone. Systems should attempt to provide defibrillation to children suffering ventricular fibrillation in the time-liest fashion possible. Strategies may include: manual defibrillation, AEDs designed for defibrillation of young children, and standard AEDs used in children with appropriate protocols and medical oversight.

AED DESIGN CONSIDERATIONS

One factor that has delayed professional organization recommendations and protocol development that advocate AED use for young children and infants has been the need to simplify resuscitation training of the lay public.⁴⁸ This would necessitate a device designed to detect and analyze the rhythms in children accurately while not requiring dose-energy adjustments on the basis of the weight of the patient or allowing for energy-dose adjustment for children to apply across large age ranges with a minor and easy-to-teach modification. Some have postulated that any age-specific cutoff, although arbitrary but allowing simplicity, outweighs the need for strict adherence to dosing recommendations. Studies have shown that keeping resuscitation instructions simple provides for improved skill mastery and retention.^{49–51} The more complex the teaching sequence or message, the less likely it is that the rescuer will remember what to do and successfully complete the task. Because lay responders or first responders with limited training in arrhythmia recognition use AEDs, it is important to keep the user interface simple. This principle must be applied to pediatric AEDs as well as adult AEDs. Adding complexity to the AED user interface to accommodate pediatric defibrillation could result in opportunities for error in both adult and pediatric defibrillation. Therefore, any enhancement to allow treatment of pediatric patients with the AED must be as simple as possible while not compromising adult care. If this goal cannot be achieved in certain situations, it may be more appropriate to allow existing adult AEDs to be used on children.

IMPLEMENTATION OF A LAY RESCUER AED PROGRAM IN SCHOOLS WITH A DOCUMENTED NEED

The implementation of an AED program in schools has become a point of major discussion in recent years. Despite this growing interest in the use of AEDs on children, as recommended in a recent American Academy of Pediatrics–endorsed policy statement from the American Heart Association,⁵² lay rescuer and emer-

gency preparedness programs should be directed at the complete planning and response to cardiac arrest and other life-threatening conditions rather than focused on a single piece of equipment. The policy-statement recommendations were to establish a comprehensive emergency response plan, which would include the following key elements:

1. Effective and efficient communication throughout the school campus: Establish a rapid communication system that links all parts of the school campus, including outdoor facilities and practice fields, to the EMS system. Establish protocols to clarify when the EMS system and other emergency contact people should be called. Determine the time required for EMS response to any location on campus and establish a method to efficiently direct EMS personnel to any location on campus. Create a list of important contact people and telephone numbers with a protocol to indicate when each person should be called. Include names of experts to help with postevent support.
2. Coordinated and practiced response plan: Develop a response plan for all medical emergencies in consultation with the school nurse, the school or school athletic team physicians, athletic trainers, and the local EMS agency as appropriate. EMS and emergency dispatchers (911 centers) should be made aware of the type of rescue equipment available at the school and its location. Practice the response sequence at the beginning of each school year and periodically throughout the year and evaluate and modify it as needed.
3. Risk reduction: Prevent injuries through safety precautions in classrooms and on the playground. Identify students, faculty, and staff with medical conditions that place them at risk for development of life-threatening conditions and train and equip personnel to provide the appropriate response for those conditions.
4. Training and equipment for first aid and CPR: Ensure that a sufficient number of teachers are trained as CPR and first aid instructors. Train school staff and graduating high school students for CPR. Teachers and staff trained for first aid should, at a minimum, be equipped and able to give first aid for the following life-threatening emergencies until EMS rescuers arrive:
 - a. severe breathing problems including asthma, choking, and anaphylaxis (severe allergic reaction);
 - b. chest pain and heart attack;
 - c. diabetes and low blood sugar;
 - d. stroke;

- e. seizure;
 - f. shock;
 - g. bleeding;
 - h. head and spine injury;
 - i. broken bones;
 - j. burns;
 - k. sudden cardiac arrest;
 - l. temperature-related emergencies (heatstroke and hypothermia); and
 - m. poisoning.
5. Implementation of a lay rescuer AED program in schools with an established need: If the school determines that a lay rescuer AED program is needed, school administrators and medical personnel should include the AED program in the school medical emergency response plan and practice and evaluate response to sudden cardiac arrest with the AED. EMS and 911 centers should be notified of the specific type of AED and the exact location of the AED on the school grounds. Rescuers who are unfamiliar with the school can call 911 and receive instructions from 911 dispatchers to find and use the AED. AED programs should have the following elements:
 - a. medical/health care provider oversight;
 - b. appropriate training of anticipated rescuers in CPR and use of the AED;
 - c. coordination with the EMS system;
 - d. appropriate device maintenance; and
 - e. an ongoing quality improvement program.

As was discussed in the aforementioned policy statement and has been shown through several studies, the AED may be part of a school emergency response program but should be implemented only as part of a comprehensive program as described, with appropriate oversight, and based on determination of need. To determine the need for an AED program at any location, the policy statement recommended consideration of lay rescuer AED program implementation in locations with at least 1 of the following characteristics:

1. The frequency of cardiac arrest events is such that there is a reasonable probability of AED use within 5 years of rescuer training and AED placement. This probability is calculated on the basis of 1 cardiac arrest known to have occurred at the site within the last 5 years, or the probability can be estimated on the basis of population demographics.
2. There are children attending the school or adults working at the school who are thought to be at high risk for sudden cardiac arrest (eg, children with conditions such as congenital heart disease and a history

of abnormal heart rhythms, children with long QT syndrome, children with cardiomyopathy, adults or children who have had heart transplants, adults with a history of heart disease).

3. An EMS call-to-shock interval of less than 5 minutes cannot be reliably achieved with conventional EMS services and a collapse-to-shock interval of less than 5 minutes can be reliably achieved (in >90% of cases) by training and equipping laypersons to function as first responders by recognizing cardiac arrest, telephoning 911 (or other appropriate emergency response number), starting CPR, and attaching/operating an AED.

When funds are limited but there remains a desire to establish some AED school programs, priority should be given to establishing programs in large schools, schools used for community gatherings, schools at the greatest distance from EMS response, and schools that are attended by the largest number of adolescents and adults (eg, high schools and trade schools).

The 5 key components of an AED program are:

1. medical/health care provider oversight;
2. appropriate training of anticipated rescuers in CPR and use of the AED;
3. coordination with the EMS system;
4. appropriate device maintenance; and
5. an ongoing quality improvement program to monitor training and evaluate response with each use of the device.

If an AED program is established at the school, the AED should be placed in a central location that is accessible at all times and ideally no more than a 1- to 1 1/2-minute walk from any location. The device should be secure and located near a telephone (eg, near the school office, library, or gymnasium) so that a rescuer can activate the EMS system and get the AED at the same time. The EMS system should be notified of the establishment of the AED program and the emergency medical dispatcher should know the specific type of AED at the school and where it is located. Several staff members should be trained in both CPR and use of the AED.

Recent federal legislation provides guidance for AED programs in schools. HR 389/Pub L No. 108–41 enabled the creation of an information clearinghouse with funds from the AED program in the Public Health Security and Bioterrorism Response Act (Pub L No. 107–188). The new law allows creation of a national resource center to provide schools with information and technical guidance to set up AED programs, giving schools access to the appropriate training, fund-raising techniques, and other logistics required to make such programs successful. The national resource center is modeled after Project ADAM,

a joint venture between the Children's Hospital of Wisconsin and David Ellis, a friend of the project's namesake, Adam Lemel, who collapsed and died during a high school basketball game. Senate Bill 231 is a companion measure.

CONCLUSIONS

Although the incidence of VF in the pediatric population is low, there is a need for developing strategies to provide early defibrillation to patients younger than 8 years. This may include the need for an AED suitable for use on pediatric patients. Because of the limited nature of effective energy-dose data, EMS systems, medical directors, and pediatric researchers should make efforts to gather information regarding pediatric uses of their devices and report it by using the pediatric Utstein style, which represents an internationally accepted standard method of collecting and reporting respiratory and cardiac arrest and resuscitation data. In addition, because the literature suggests that some emergency responders may fear using AEDs on children, EMS and physician leaders should work with professional organizations, community organizations, and researchers to educate both first responders and community members regarding the benefits of early pediatric defibrillation and the use of available varieties of AEDs.

Current pediatric protocols and guidelines recommend energy doses of 2 to 4 J/kg for defibrillation of children. These recommendations evolved from limited data that focused on the likelihood of effectiveness without consideration for therapeutic window determination or analysis of potential toxicity. In addition, these dose recommendations were made on the basis of data from defibrillation with monophasic damped sine waveforms and without impedance compensation, which makes their extrapolation to current monophasic and biphasic technology unreliable. The existing data on the relationship between size or weight and impedance in children are poor, which indicates that weight-based dosing may be of limited value in pediatric defibrillation.

The most important safety feature of an AED is specificity. As long as there is a very high level of assurance that shocks will be advised only for appropriate rhythms in the pediatric population, then the risk of myocardial damage from defibrillation likely is significantly less than the risk of not delivering a shock (probable death). However, the potentially toxic effects of delivering too much energy must be minimized whenever possible. Data extrapolated from animal models support the use of adult-energy AEDs even in smaller pediatric patients.

In the future, technology probably will provide for the development of a "1-size-fits-all" version of an AED. While that technology is being developed, an AED in use today ideally should have both a high specificity in recognizing pediatric shockable rhythms and a pediatric dose-attenuating system to reduce the dose delivered for

children younger than 8 years, including infants. Several AEDs that are currently on the market have such pediatric-attenuating devices that have been approved by the Food and Drug Administration for both children and infants. These same devices have the specificity needed to recognize shockable rhythms in children and infants. As such, these systems are the preferred treatment for both children and infants. However, if an AED with a pediatric-attenuating system is not available, the responder should use a standard AED rather than delay the delivery of a potentially life-saving intervention.

The message for the public and EMS systems is that the existence of VF in children and infants needs to be recognized, and effective methods to treat VF need to be used as early as possible to improve the chance of survival for children and infants after sudden cardiac arrest. In addition, this possibly life-saving therapy should not be withheld purely on the basis of absolute weight and size issues. In locations where AEDs are currently deployed, the acquisition and deployment of models that have the ability to provide an attenuated adult dosage to treat children and infants should be encouraged. In the absence of these attenuated-dose devices, rescuers need to be aware that they should still provide care to infants and children with a nonattenuated adult-dosage device, because the potential for benefit far outweighs the risk. The key is to pursue a long-term goal of providing devices that will allow rapid defibrillation for adult and pediatric patients. This can be accomplished through deploying devices that treat children without compromising adult care, having approaches that minimize device training issues, and optimizing the use of limited financial and personnel resources.

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