Resuscitation 85 (2014) 1330–1336

Contents lists available at ScienceDirect

Resuscitation

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

Clinical Paper

Electrical exposure risk associated with hands-on defibrillation☆

Daniel L. Lemkin[a,*], Michael D. Witting[a], Michael G. Allison[b], Ali Farzad[a], Michael C. Bond[a], Mark A. Lemkin[c]

[a] Department of Emergency Medicine, University of Maryland School of Medicine, Baltimore, MD, United States
[b] Department of Emergency Medicine, University of Maryland Medical Center, Baltimore, MD, United States
[c] Linear Technology, Hayward, CA, United States

ARTICLE INFO

Article history:
Received 9 April 2014
Received in revised form 3 June 2014
Accepted 18 June 2014

Keywords:
Defibrillation
Cardiopulmonary resuscitation
Rescuer

ABSTRACT

Background: The use of hands-on defibrillation (HOD) to reduce interruption of chest compression after cardiac arrest has been suggested as a means of improving resuscitation outcomes. The potential dangers of this strategy in regard to exposing rescuers to electrical energy are still being debated. This study seeks to determine the plausible worst-case energy-transfer scenario that rescuers might encounter while performing routine resuscitative measures.
Methods: Six cadavers were acquired and prepared for defibrillation. A custom instrumentation-amplifier circuit was built to measure differential voltages at various points on the bodies. Several skin preparations were used to determine the effects of contact resistance on our voltage measurements. Resistance and exposure voltage data were acquired for a representative number of anatomic landmarks and were used to map rescuers' voltage exposure. A formula for rescuer-received dose (RRD) was derived to represent the proportion of energy the rescuer could receive from a shock delivered to a patient. We used cadaver measurements to estimate a range of RRD.
Results: Defibrillation resulted in rescuer exposure voltages ranging from 827 V to ~200 V, depending on cadaver and anatomic location. The RRD under the test scenarios ranged from 1 to 8 J, which is in excess of accepted energy exposure levels.
Conclusions: HOD using currently available personal protective equipment and resuscitative procedures poses a risk to rescuers. The process should be considered potentially dangerous until equipment and techniques that will protect rescuers are developed.

1. Introduction

Defibrillators have played an integral role in cardiopulmonary resuscitation (CPR) since the 1950s. They were first demonstrated in 1899 by Prévost and Batelli and first applied to humans in 1947.[1] Defibrillation can correct certain cardiac arrhythmias, the primary one being ventricular fibrillation. When triggered, the defibrillator creates a short burst of electricity that follows a capacitive discharge curve. Modern defibrillators create biphasic discharge curves that compensate for chest wall impedance to lower the total energy used while maintaining efficacy. Rapid and early defibrillation remains a mainstay of treatment for ventricular fibrillation and has been shown to increase survival after cardiac arrest.[2]

High-quality chest compressions also improve survival rates.[2] Brief interruptions in compressions for rhythm and pulse checks have a deleterious effect on patient outcomes.[2] Delays in chest compressions may impair resuscitation outcomes, and high-quality chest compressions are more effective than other advanced interventions.[3–10] By extension, continuous compressions during defibrillation are thought to generate continuous cerebral and coronary perfusion in humans, which maximizes the success of defibrillation.

The resuscitation guidelines issued by the American Heart Association in 2010 sparked interest in delineating the true risks of hands-on defibrillation (HOD) during cardiac arrest.[2] Hoke and associates sought reports of adverse events related to defibrillation and determined that life-threatening events from accidental electric shock during a medical procedure are rare.[11] Lloyd and

☆ A Spanish translated version of the summary of this article appears as Appendix in the final online version at http://dx.doi.org/10.1016/j.resuscitation.2014.06.023.

* Corresponding author at: Department of Emergency Medicine, University of Maryland School of Medicine, 110 South Paca Street, 6th Floor, Suite 200, Baltimore, MD 21201, United States.
E-mail addresses: dlemkin@em.umaryland.edu, mbond@em.umaryland.edu (D.L. Lemkin).

http://dx.doi.org/10.1016/j.resuscitation.2014.06.023
0300-9572/

colleagues set out to measure the voltage experienced by medical care providers engaged in active chest compressions during defibrillation while wearing medical gloves.[7] None of the providers felt a shock. The investigators determined that the average amount of current leaking through a resuscitator's body was below several recommended safety standards. The study was limited by the use of nitrile gloves, which can block the flow of electricity; therefore, the potential danger to providers is still not known if there is a break in the integrity of the gloves, or the provider is not wearing gloves. Worse, recent studies suggest that many gloves lack the dielectric strength necessary to protect rescuers who perform HOD.[12,13]

Current guidelines still recommend withholding chest compressions during defibrillation to prevent the accidental electrocution of rescuers, though recent articles have postulated that the leakage current during defibrillation is low enough to support the idea of HOD[7]; others suggest the conclusions are too far reaching and call for a greater understanding of the risk.[14] However, leakage current does not adequately convey the total risk of defibrillation. Any rescuer in contact with a patient during defibrillation will share a portion of the energy delivered. Energy values greater than 1 J reportedly have the ability to cause ventricular fibrillation.[15] Since total energy delivered, voltage, and the resistance of the patient and rescuer will determine the amount of energy transferred (complete discussion in Supplemental Data: Section 1 [26,27]), we sought to better understand the interplay of these variables on rescuer risk. We introduce the concept of the rescuer-received dose (RRD) of defibrillation as a more accurate measure to describe defibrillation risk. Our specific goal was to determine whether the practice of HOD is safe for rescuers.

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resuscitation.2014.06.023.

2. Methods

2.1. Study design

This is a cross-sectional study of voltage measurements from cadavers during high-voltage defibrillation. Eight cadavers were obtained from the Maryland State Board of Anatomy and were neither frozen nor embalmed. The cadavers' body mass index (BMI) ranged from 12 to 29 kg/m^2. This research protocol was approved by the institutional review board at the University of Maryland School of Medicine.

2.2. Data collection

2.2.1. Resistance measurements

Resistance measurements were taken from eight cadavers and two of the investigators, using a calibrated multi-meter (Fluke Corp., Everett, WA) connected to NovaPlus V2560 (Irving, TX) monitoring electrodes placed 40 cm apart on the chest. A variety of preparations were used to measure resistance differences: intact skin, abraded skin, saline, 1/10 saline (simulating sweat), sterile water, ultrasound gel, and needle probes. The resistances were measured to ensure that the subsequent voltages measured during defibrillation were accurate and not altered by a voltage divider effect. Details of our resistance preparations and measurements are presented in Supplemental Data: Section 2.

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The minimum consistent resistance reading was recorded after a 5 s sampling period. If outliers were recorded, the meter was re-zeroed and another 5 s sampling was obtained. Results were rounded to the nearest significant digit. When unstable measurements were identified, the electrode sites were re-prepped to ensure accurate measurement.

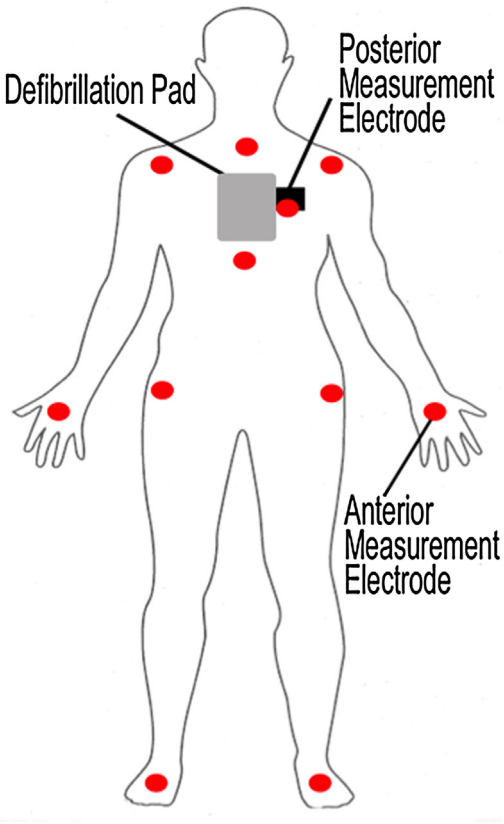

Fig. 1. The red dots denote anatomic sites that the defibrillation voltage measurements were obtained. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

2.2.2. Voltage measurements

Six of the eight cadavers were available for defibrillation and were placed on tables, with care being taken to ensure they were not grounded. Adult defibrillation pads (Physio-Control, Redmond, WA) were applied using standard anterior-to-posterior technique on all cadavers. The posterior electrodes were placed contiguous and lateral to the posterior defibrillation pads. Anterior measurement electrodes were placed at diverse anatomic landmarks as shown in Fig. 1. Measurement electrodes were placed using the abraded skin technique described in Supplemental Data: Section 2. Voltages were acquired at all anatomic sites for each cadaver, and presented in Fig. 2. All voltages were measured with respect to the posterior electrode. Selecting the posterior electrode as a common reference point for all measurements allows easy calculation of voltages between any two anatomic sites and subsequent estimation of electrical hazard for contact between any two anatomic sites.

One of the two inputs of the measurement circuit was connected to the posterior defibrillation pad; the other input was connected anteriorly to each measurement electrode in sequence. An Agilent U1620A 200-MHz oscilloscope (Agilent Technologies, Santa Clara, CA) was connected to the measurement circuit. Probes measured the differential and common-mode voltage at the circuit outputs. The measurement circuit ground and the oscilloscope ground were both connected directly to a grounded outlet.

A Physio-Control Lifepack 20 (Physio-Control, Redmond, WA) defibrillator was charged to 360 J, and the cadaver was defibrillated

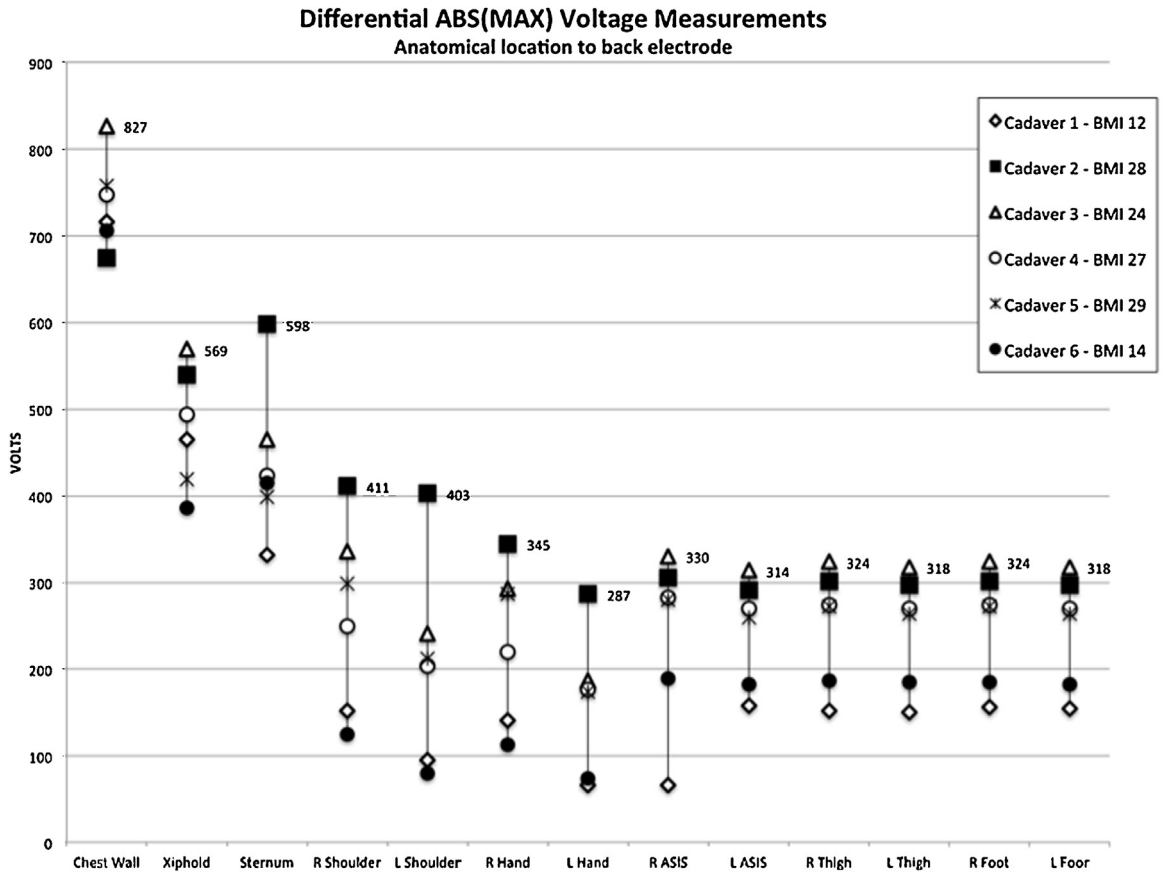

Fig. 2. Differential voltage measurements of the six cadavers at the locations noted. Highest voltages were recorded on the anterior chest wall.

using standard technique. The oscilloscope was configured to trigger on the differential voltage channel. The scope was connected via a USB port to a laptop computer, where both measurement comma-separated values (CSV) and tracing images were saved for each acquisition.

2.3. Data analysis

The energy exposure received by the rescuer can be estimated as a fractional dose of the energy received by the patient under a nominal clinical configuration. We derived a formula for the rescuer-received dose (RRD) to estimate the maximum energy exposure during defibrillation. The formula for the RRD, or $E_{rescuer}$, derived in Supplemental Data: Section 3 [28,29], is as follows:

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$$E_{rescuer} = E_{patient} \cdot \left[\frac{(V_{rescuer}/V_{defib})^2}{(R_{rescuer}/R_{patient})} \right] \quad (1)$$

where E is an energy in joules, V is an electrical potential in volts, and R is a resistence in ohms. Since the RRD is simply a determination of the percentage of the total applied patient dose received by the rescuer, physiologic effects on the rescuer are easily determined by relating the RRD to the published minimum 0.5 to 1 J dose required to cause harm in a healthy individual.[16]

Due to changes in skin resistance at high voltages, the low-voltage (i.e., not during discharge) resistances measured using an ohm meter at the skin surface on cadavers do not reflect the true resistance of rescuers during defibrillation; this phenomenon is known as high-voltage resistance breakdown.[17] To estimate the resistance of rescuers (i.e., $R_{rescuer}$) during transfer of the RRD, we used published resistances, which are accurate under conditions of high voltage (when the voltage is higher than ~200 V). These resistances represent statistical estimates of the skin-contact resistance under a specified applied voltage for 50th and 5th percentiles of the population. These resistances were not measured as part of the experiment as they are present only under high-voltage breakdown conditions which would require a different experimental setup to measure safely and is a different question than the authors intended to address. Instead, we use these published values to provide an estimate of the RRD for a typical population of rescuers by applying this published distribution of population resistances to our measured voltages and derived patient resistances.

$R_{patient}$ is composed of current paths throughout the body yielding an effective, total resistance on the order of 100 Ω as seen at the defibrillator electrodes during discharge (See Supplemental Data: Section 3 for derivation). This is illustrated schematically in Fig. 3 using a resistor network. As the defibrillator current flows through the resistor network, the resistance induces the voltage to drop from V_{defib} at the top electrode to zero volts at the bottom electrode. When a rescuer touches two distinct points on the patient they can have a different potential owing to voltage drops throughout the network. A difference in potential, shown as $V_{rescuer}$ in Fig. 3, induces rescuer current. Rescuer danger occurs when the energy through the rescuer from this current is too high.

Differential voltage measurements were made with an instrumentation amplifier, which measures voltage differences independent of earth ground. The measured voltages represent the differential voltage between the back measurement electrode and the varying anatomic landmark electrode. The difference between

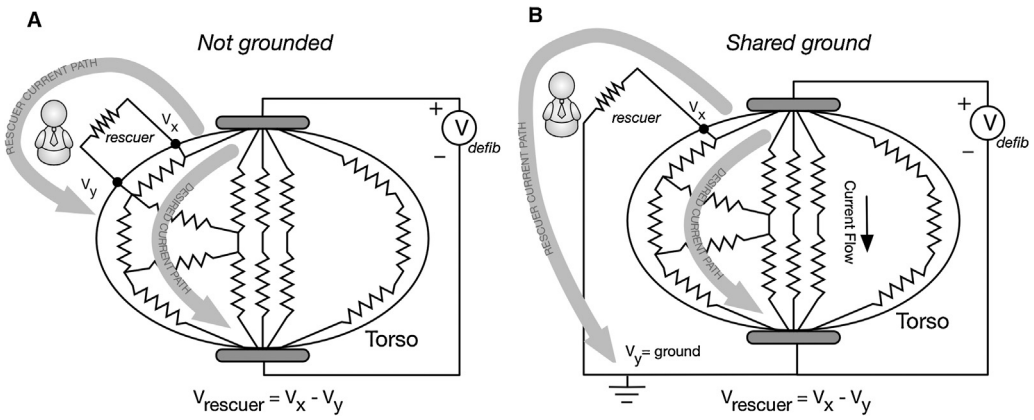

Fig. 3. Patient rescuer circuit. In a non-grounded scenario (A), the defibrillator creates a current path from one electrode to the other. A voltage differential exists between any two points on the patient due to internal resistance pathways. The voltage on the patient drops off precipitously adjacent to the chest electrode. This creates a high differential voltage, which can present a hazard to the rescuer. Under high voltage, skin resistance breaks down and current can flow through these alternative pathways. In the shared ground scenario (B), both current paths terminate at the same point. The voltage of the rescuer pathway equals the full measured V_x. Both scenarios may be hazardous.

any two measured voltages equals the voltage between the two anatomic landmarks.

3. Results

Our skin resistance measurements are presented in Fig. 4. They range from 1.3 kΩ to 25 MΩ, depending on the skin preparation and body type. These measurements reflect resistance in the absence of the voltage breakdown that occurs during defibrillation and do not compensate for the variance in resistance associated with different contact areas (cm^2) of the measurement electrodes versus defibrillation electrodes or hands. The abraded skin measurements ranged from ~1 to 100 kΩ. This range of resistances was deemed adequate to obtain reliable voltage measurements. These issues are more completely discussed in Supplemental Data: Section 2.

Voltage measurements were obtained using the differential voltage output of the measurement circuit. This gave us an accurate measurement of the electrical potential difference that could be used to estimate danger between any two measurement points on the cadaver. The defibrillator used for this study produces a truncated biphasic capacitive discharge curve. The absolute value of the maximum voltage amplitude of the initial phase of the defibrillation was used for calculations. Fig. 2 demonstrates that voltages as high as 827 V were measured at the anterior chest wall.

Voltages at and moving laterally from the top electrode were measured in addition to the voltages at the anatomic landmarks

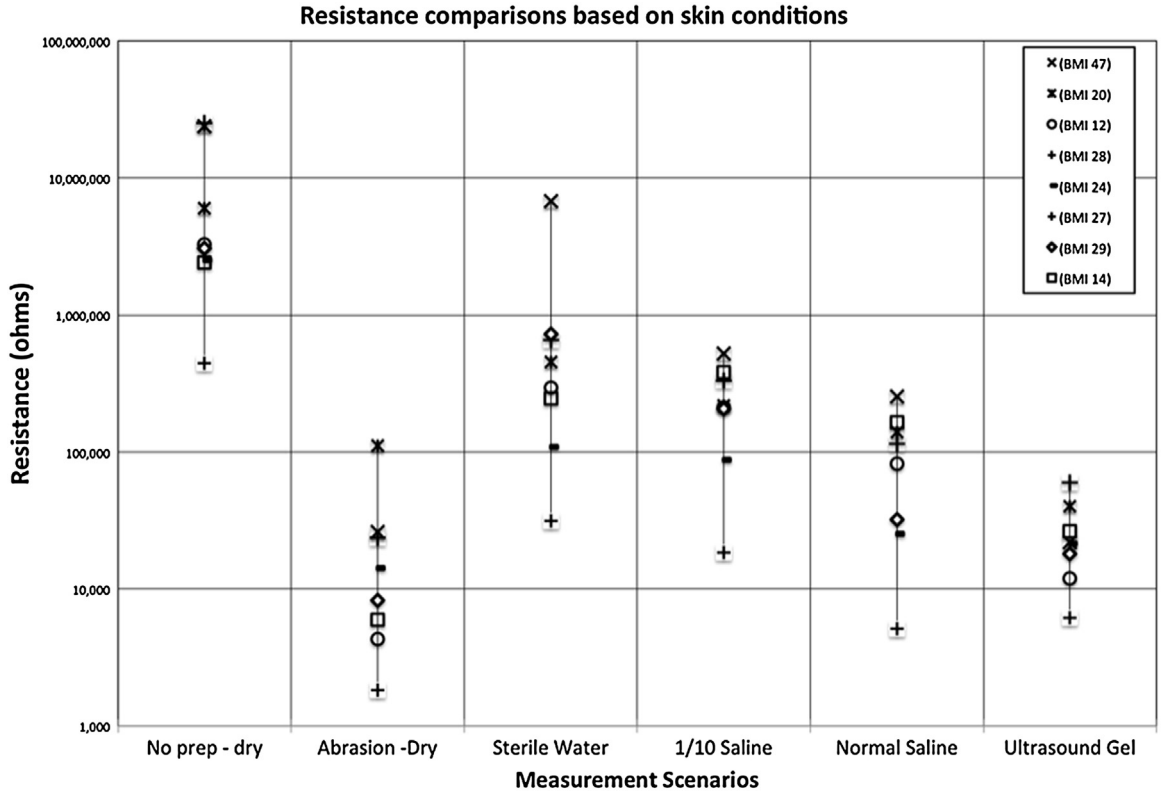

Fig. 4. Measurement of skin resistance in the eight cadavers. Two cadavers (BMI 47 and BMI 20) were used from an earlier procedure lab to obtain passive measurements and were not among the six cadavers used for defibrillation.

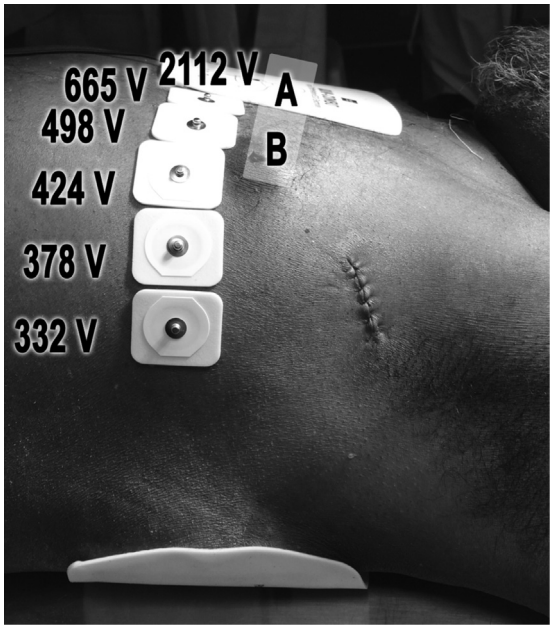

Fig. 5. Measured voltages across the anterior chest wall after a biphasic defibrillation. Voltages dissipate quickly across the anterior chest wall, but the differences in voltage between closely spaced positions are still sufficiently high to pose a risk to the rescuer.

Table 1
Resistance, energy, and voltage values used to determine the rescuer-received dose.

$R_{patient}$	98 Ω	Derived in Supplemental Data: Section 2
$R_{Rescuer}$	Varies from 800 Ω at 200 V to 575 Ω at 1000 V for 5% population values	Published[17]
$E_{patient}$	360 J	Delivered by defibrillator
V_{defib}	2112 V	Measured
$V_{rescuer}$	Varies (see Fig. 2)	Measured

shown in Fig. 1. As shown in Fig. 5, the exposed voltage changes dramatically over a very small distance near the points of application. For example, anatomic landmark measurements for Cadaver 1, the voltage dropped from 717 V to 332 V between 2 points on the anterior chest, a difference of 385 V. Since electrical hazard is a function of the difference in potential, a shock hazard exists even if the only points of contact are both hands on top of the chest (i.e., no backside contact). Thus, a potential hazard exists even if the rescuer is contacting the patient at what *appears* to be a "single point"; the hazard exists because the voltage gradient is very steep, creating a substantial range of voltages under the rescuer's hands.

The values in Table 1 were used to calculate the energy associated with each voltage measurement. Fig. 6 demonstrates that energies in excess of 1 J were present at all measurement points on at least some cadavers, the largest hazard being present at the most likely contact area the chest wall. In the shared ground scenario, such as a rescuer kneeling on wet pavement, touching any part of the body could result in exposure exceeding 1 J, with some

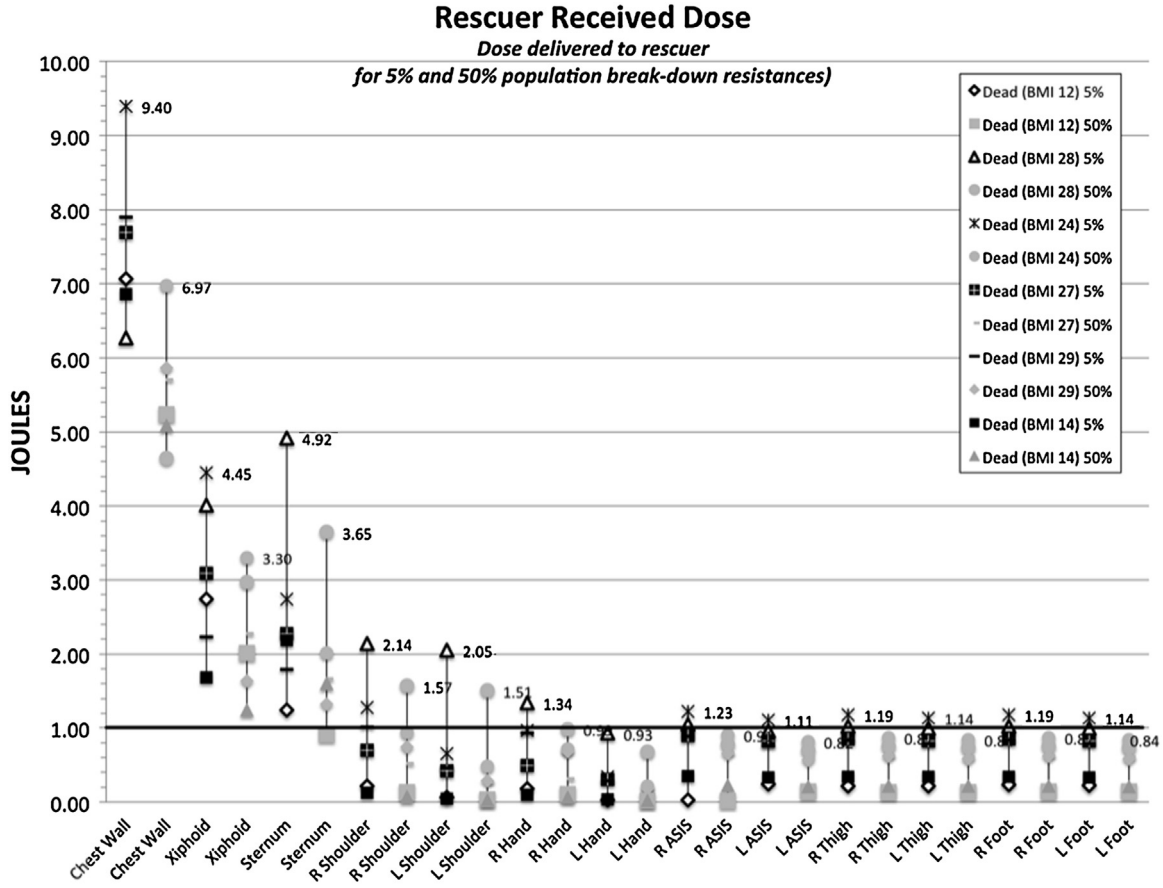

Fig. 6. The rescuer-received dose is noted at the various measurement points using published rescuer skin resistances for both 5% and 50% population thresholds. The horizontal line at 1 J indicates the minimum energy level that is able to cause ventricular fibrillation in a susceptible individual.[15] On the anterior chest wall, where contact would be made with HOD, the energy level is 6–10 times the level needed to cause fibrillation.

exceeding 8 J. Differential voltages also pose a risk, Cadaver 1, with a voltage of 385 V, between two points on the chest wall would receive 1.7 J. Thus, the voltage differences on the chest wall would result in a RRD exceeding 1 J.

4. Discussion

Since publication of the article by Lloyd and colleagues, indicating that the average amount of current leaking through a resuscitator's body while wearing intact nitrile gloves was below several recommended safety standards, anecdotal reports have revealed that HOD is already in use.[7,18,19] Without rigorous investigation of the safety of this practice, rescuers must be aware that they are putting themselves and others at grave risk. Importantly, the potential harm to rescuers is not balanced by a well-established benefit to patients. Although animal studies have suggested improved CPR quality with HOD,[20] we are unaware of any randomized controlled trials in humans that have compared HOD with CPR that uses very brief pauses for defibrillation. While high-quality CPR and minimization of interruptions in compressions are recommended, little is known about the effects of very brief (<5-s) pauses on patient outcomes. During defibrillation, the current is delivered to the patient very rapidly, in about 20 ms. Rescuers should strive to provide continuous compressions while the defibrillator charges, the airway is secured, and other resuscitative efforts take place.[21] Maximizing chest compression fraction (CCF) seems ideal, yet the absolute benefits of HOD have yet to be established.

Two studies of the effect of CCF on return of spontaneous circulation (ROSC) and survival rate show nothing to suggest that pushing the CCF above 80% benefits patients.[22,23] Another study on perishock pauses showed a lower survival rate when compressions were delayed for more than 10 s. We could not find a single study suggesting an increased mortality rate associated with the maximum of 1–5 s it should take to stop and restart compressions after defibrillation.[24] A physiologic argument to avoid pauses in compressions, based on studies in swine, is to avoid the hemodynamic consequences of decreased diastolic blood pressure and cerebral perfusion pressure.[3,25]

The mantra exclaimed by rescuers for decades, "I'm clear, you're clear, everybody's clear!" is one of the few dogmatic and successful examples of procedural guidance that has had almost universal acceptance and adherence. Though there have been no reports of death to medical providers who were accidentally exposed to a defibrillation current, our data show that the use of HOD has the potential to greatly increase the number of providers exposed to the highest voltages (immediately over the anterior pad) when a patient is defibrillated. Therefore, the expansion of the use of HOD will increase the number of risk exposures dramatically, as will the potential for rescuer harm.[11]

5. Limitations

This study is limited by the fact that cadavers were used as proxies for live patients. We attempted to validate this substitution by measuring resistances that are similar to two live investigators. We have shown that at high voltages typical skin and tissue resistance breaks down and does not play a role in the voltage seen. Additionally, our groups of cadavers were lacking in obesity. Obesity tends to increase the resistance of the patient, thus increasing the rescuer-received dose. Thus, our model underestimates the risk when the patient is obese. Our study is also limited by the fact that we only measured the voltages with defibrillation pads place in an anterior–posterior placement, and not in the anterior–lateral placement used by many. The closer placement would result in a shorter current path and lower resistance. However, a rescuer's hands would be positioned between that current path, potentially exposing them to greater energy levels.

6. Conclusions

Recent literature has demonstrated that interruptions in CPR are detrimental to the successful resuscitation of patients.[2] For this reason, some clinicians have embraced the notion of HOD. The lack of reported rescuer injuries resulting from HOD has led many to assume the procedure is safe.

This study demonstrated that under scenarios commonly encountered in a clinical setting, HOD presents a real risk to rescuers. Further, there is no evidence to support that a 5-s pause in compressions has any effect on outcomes. Therefore, it is our conclusion that HOD has real risk with no proven benefit. Further study is needed to identify what procedures, tools, or equipment could adequately mitigate the risks posed to rescuers. These might include insulating gloves that are resistant to tearing and insulated beds and railings that prevent unintentional grounding of the patient, which can defeat the electrical isolation built into the defibrillators.

Until further studies are conducted, we recommend that compressions be performed during the charging of the defibrillator and that rescuers remove their hands during the actual defibrillation. Once the defibrillation is over, compressions should be resumed immediately.

Conflict of interest statement

The authors have no conflicts to disclose.

Acknowledgments

The manuscript was copyedited by Linda J. Kesselring, MS, ELS, the technical editor/writer in the Department of Emergency Medicine at the University of Maryland School of Medicine.

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