Hands-On Defibrillation : An Analysis of Electrical Current Flow Through Rescuers in Direct Contact With Patients During Biphasic External Defibrillation

Michael S. Lloyd, Brian Heeke, Paul F. Walter and Jonathan J. Langberg

The online version of this article, along with updated information and services, is located on the
World Wide Web at:
http://circ.ahajournals.org/content/117/19/2510

Resuscitation Science

Hands-On Defibrillation
An Analysis of Electrical Current Flow Through Rescuers in Direct Contact With Patients During Biphasic External Defibrillation

Michael S. Lloyd, MD; Brian Heeke, BS; Paul F. Walter, MD; Jonathan J. Langberg, MD

Background—Brief interruptions in chest compressions reduce the efficacy of resuscitation from cardiac arrest. Interruptions of this type are inevitable during hands-off periods for shock delivery to treat ventricular tachyarrhythmias. The safety of a rescuer remaining in contact with a patient being shocked with modern defibrillation equipment has not been investigated.

Methods and Results—This study measured the leakage voltage and current through mock rescuers while they were compressing the chests of 43 patients receiving external biphasic shocks. During the shock, the rescuer's gloved hand was pressed onto the skin of the patient's anterior chest. To simulate the worst case of an inadvertent return current pathway, a skin electrode on the rescuers thigh was connected to an electrode on the patient's shoulder. In no cases were shocks perceptible to the rescuer. Peak potential differences between the rescuer's wrist and thigh ranged from 0.28 to 14 V (mean 5.8 ± 5.8 V). The average leakage current flowing through the rescuer's body for each phase of the shock waveform was 283 ± 140 μA (range 18.9 to 907 μA). This was below several recommended safety standards for leakage current.

Conclusions—Rescuers performing chest compressions during biphasic external defibrillation are exposed to low levels of leakage current. The present findings support the feasibility of uninterrupted chest compressions during shock delivery, which may enhance the efficacy of defibrillation and cardiocerebral resuscitation. (***Circulation***. 2008;117: 2510-2514.)

Key Words: defibrillation ■ resuscitation ■ cardiopulmonary resuscitation ■ electrical stimulation

Electrocution of rescuers has been recognized as a hazard of external defibrillation therapy.[1] Historically, shocks were delivered with paddles that had large, rigid, metallic electrodes.[2] Arcing was common owing to inconsistencies in electrode location and contact.[3,4] Variability in the distribution and performance of the conductive gel was also an important cause of stray electrical current. Guidelines have thus mandated "hands-off" periods, whereby rescuers have no contact with the patient or stretcher during shock delivery.

Editorial p 2435
Clinical Perspective p 2514

These hands-off periods pose a challenge to the current strategy of resuscitation for cardiac arrest. The American Heart Association guidelines for the management of cardiac arrest have emphasized the importance of minimizing any interruption in chest compressions during resuscitation.[5] This emphasis is based on the improvements seen with chest compressions before defibrillation and the observation that even small delays in compressions during ventricular tachycardia or fibrillation impair resuscitation outcomes.[6–9]

There have been substantial changes to external defibrillation technology since the inception of resuscitation protocols with hands-off periods. Biphasic shocks and real-time impedance monitoring have reduced peak voltages. Paddles have been replaced in many cardiac arrest settings by conformal, adhesive, pregelled electrodes, which result in better and more consistent electrode-skin coupling. Enhancements of ECG filtering permit rhythm monitoring during chest compression.

With the current state of the art, if certain types of physical contact with the patient were safe during shock delivery, continuous manual compressions might be possible during cardiac arrest. We addressed the feasibility and safety of direct contact with the patient during defibrillation by measuring the voltage and current through volunteers simulating chest compressions on patients receiving external biphasic countershocks.

Methods

The study protocol was approved by the Institutional Review Board at Emory University. Written informed consent was obtained from all patients. The patient population recruited for the present study

Circulation is available at http://circ.ahajournals.org   **DOI: 10.1161/CIRCULATIONAHA.107.763011**
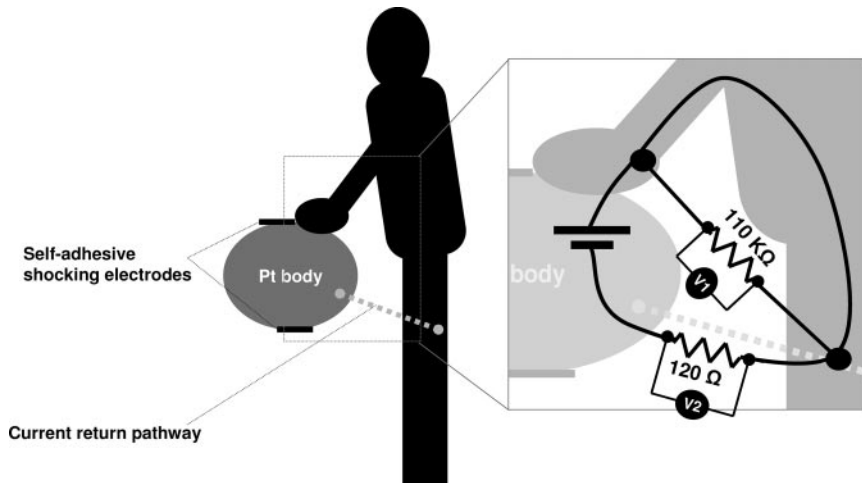
Figure 1. Schematic of rescuer-patient contact during external defibrillation. Volunteers applied ≈20 lb of downward pressure on the bare skin of the patient's lower sternum during shock delivery. Current return pathway indicates a conductive wire that connected the bare skin of the rescuer's thigh to the patient's posterior shoulder. This represents an inadvertent adverse electrical contact. Inset, The "rescuer-patient" circuit is represented by the overlying black line. Known resistances, indicated by resistor symbols, were used in series and parallel to this circuit to measure voltage and current. V1 and V2 indicate the 2 probes used for the recordings across the resistors; Pt, patient.

included those undergoing elective cardioversion for persistent atrial fibrillation or flutter and those undergoing invasive electrophysiology study who were likely to need external cardioversion or defibrillation during the procedure. The external defibrillator used was a Lifepac 12 (Medtronic Corp, Minnesota, Minn), which delivers a truncated exponential biphasic waveform with impedance compensation. The defibrillator power source was a grounded standard mains outlet. Shocking electrodes were self-adhesive (Pad-Pro, Conmed Corp, Utica, NY) and were placed in the anteroposterior position for all patients. After intravenous sedation and the determination by the physician performing the procedure that it was safe to proceed, 1 of 4 healthcare workers (all coinvestigators of the study) simulated manual chest compressions on the patient. A schematic of the rescuer-patient construct is shown in Figure 1. With the coinvestigator wearing polyethylene medical gloves and standing at the right side of the patient's bed, ≈20 pounds of downward force was applied on the lower half of the patient's sternum in the area typical for chest compression. The palm of the investigator performing the chest compressions (termed "rescuer" for the remainder of the text) was in direct contact with the bare skin of the patient's chest adjacent to the anterior shocking electrode. Skin preparation for all electrode attachments included vigorous scrubbing with an alcohol pad and shaving when needed.

To simulate an inadvertent conductive contact between the patient and rescuer, adhesive silver–silver chloride electrodes were placed on the prepared skin of the patient's posterior left shoulder and the prepared skin of the rescuer's anterior thigh (electrode surface area ≈4 cm²; Conmed Corp). This electrical connection simulated an inadvertent skin-to-skin contact between the rescuer and the patient and allowed for a return pathway for leakage current across a rescuer. This connection established a "rescuer-patient circuit" in which the patient being shocked was the voltage source and the rescuer acted as the load. Measurement of the leakage current and voltage across the rescuer was performed by attaching button electrodes to the prepared bare skin of the rescuer's wrist. This electrode and another attached to the rescuer's thigh were connected to a resistor network with a 110-kΩ resistance in parallel with the patient-rescuer circuit and a 120-Ω resistance in series with the circuit (Figure 1, inset). Probes were attached across each of these resistors and connected to a digital dual-channel oscilloscope (Picoscope 2202, Picotech, Cambridgeshire, United Kingdom). Voltages across the resistors were recorded during shock delivery. Transient artifacts were subtracted from the initial 50 μs of the onset, phase change, and termination of the recording. The absolute values of the voltages recorded across the 110-kΩ resistor for each phase of the biphasic waveform were used to derive an average voltage between the rescuer's hand and thigh. The voltage drops across the 120-Ω series resistor were used to determine current flow through the rescuer during both phases of the shock in an analogous fashion. The range, SD, and mean voltage and current were taken for 36 separate

recordings and compared with International Electrotechnical Commission (IEC) 60601-1 and IEC 950 standards for electrical safety.

The authors had full access to and take full responsibility for the integrity of the data. All authors have read and agree to the manuscript as written.

Results

Rescuers were instrumented during 43 hands-on shocks in 39 patients. Four shocks were at 100 J, 27 were at 200 J, and 8 were at 360 J. None of the 43 shocks were perceptible to the rescuers. Seven of the 43 shocks did not produce sufficient leakage current to trigger the oscilloscope, which left 36 suitable for analysis. Representative leakage current and voltage recordings are shown in Figure 2, and summary data are in the Table. The voltage between the rescuer's hand and the return pathway on the thigh was 5.8±5.8 V (range 0.280 to 14.1 V). Leakage current through the rescuer simulating compressions was 283±140 μA (range 18.9 to 907 μA) for each phase of the biphasic waveform. The duration of the defibrillation shocks was ≈15 ms, but this number varied slightly owing to impedance compensation by the defibrillator. With a constant pulse duration of 15 ms for calculations, the mean leakage energy was 24±12 μJ (range 0.07 to 95 μJ). Transthoracic impedances of the patient, as measured by the defibrillator, averaged 60±15 Ω (range 36 to 87 Ω). The mean rescuer circuit impedance, as calculated by dividing the recorded leakage voltage and current, was 22.7 kΩ (range 1.09 to 100 kΩ).

The present data set was compared with several benchmarks of electrical safety (Figure 3). The IEC 950 maximum allowable leakage current for non-handheld equipment is 3500 μA, which is well above the entire range of leakage current values we measured.[10] For handheld equipment, the limit is 750 μA. In a single patient, 1 phase of the biphasic waveform exceeded this value (910 μA). The IEC 60601-1 guidelines for medical equipment are more rigorous owing to potential exposure to patients. Under this standard, the cutoff for enclosures is 500 μA under single-fault conditions, which is greater than the overall mean leakage current in the present study; however, 8 measurements of the 72 phases (36 biphasic shocks) exceeded this cutoff.
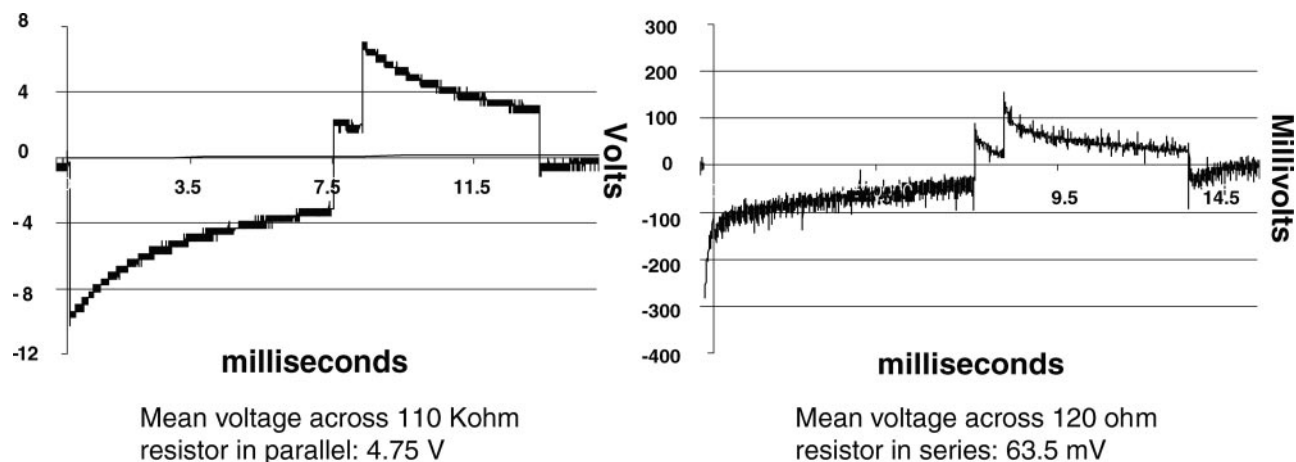
Figure 2. Representative digital recordings during shock delivery. Waveforms closely resembled the truncated exponential biphasic waveform of a defibrillator. Left, Voltage across resistor in parallel, to derive voltage between the 2 points of contact with the patient. Right, Voltage across resistor in series with the rescuer-patient circuit; this value enabled the derivation of the leakage current.

Discussion

The present study was meant to simulate conditions during resuscitation of cardiac arrest victims by medical personnel. We assumed that these rescuers would use gloves as part of standard precautions and would have access to adhesive defibrillation pads. Rescuers in these conditions were exposed to low levels of leakage current and voltage when performing chest compression during delivery of biphasic shocks. This was the case despite the presence of a low-resistance return pathway between the rescuer's leg and the patient's thigh. To the best of our knowledge, these are the first human data to directly address the safety of hands-on defibrillation.

These findings are important because the data demonstrate the safety and feasibility of continuous manual chest compressions throughout the resuscitation cycle. The adverse hemodynamic consequences of delays between chest compression and defibrillation have been clearly demonstrated.[9] Most groups have concluded that defibrillation should occur during and not after chest compressions, but concerns about safety have precluded implementation of such a strategy. To circumvent this, fully automated resuscitation systems have been designed that produce continuous compressions, but the practical use of such devices has been limited in most cardiac arrest scenarios.[11] We have shown that it is possible to perform continuous manual compressions during shock delivery within the constraints of our model. Elimination of delays in compression before defibrillation would also prevent substantial time lags in restoration of adequate coronary perfusion pressure when chest compressions are resumed after a pause.[12] Preventing hands-off periods may improve the quality of chest compressions, which has historically been poor.[13] Shock delivery during chest compressions would potentially increase the likelihood of successful defibrillation by reducing transthoracic impedance.[14] Finally, uninterrupted compressions would represent a protocol simplification and possibly reduce the time to a first shock.

The present data add to prior work examining leakage current from internally delivered defibrillation shocks in animals and humans. Although leakage currents were higher than those obtained from the present models due to much lower load resistances than our directly measured values, the data likewise showed that the overall leakage energy was small.[15,16]

No directly comparable safety standard exists for leakage current in this specific situation. Leakage current standards vary widely depending on the type of equipment and exposure scenario. Values for patients are appropriately much smaller than for occupational exposure.[17,18] Direct intracardiac exposure to very small leakage currents may cause harm.[19] The amount of current needed to cause potential harm is several orders of magnitude higher for external (skin to enclosure) exposure.

We chose to compare our measurements to standards for equipment in the household and in businesses (IEC 950, Underwriters Laboratory 1950) and to those set for medical equipment (IEC 60601-1). These values are obtained by measuring current flow through several paths that incorporate the object of concern, or enclosure. These standards are usually for continuous 60-Hz alternating current and measured with a fixed load simulating that of a human body. In the present study, the patient receiving the shock can be viewed as the voltage source, or enclosure, and the direct thigh-to-shoulder electrical connection between the rescuer and patient can be viewed as a single-fault condition. Although these comparisons are reasonable, the present data

Table.   Measurements From 36 Shocks With Rescuer-Patient Contact During External Defibrillation

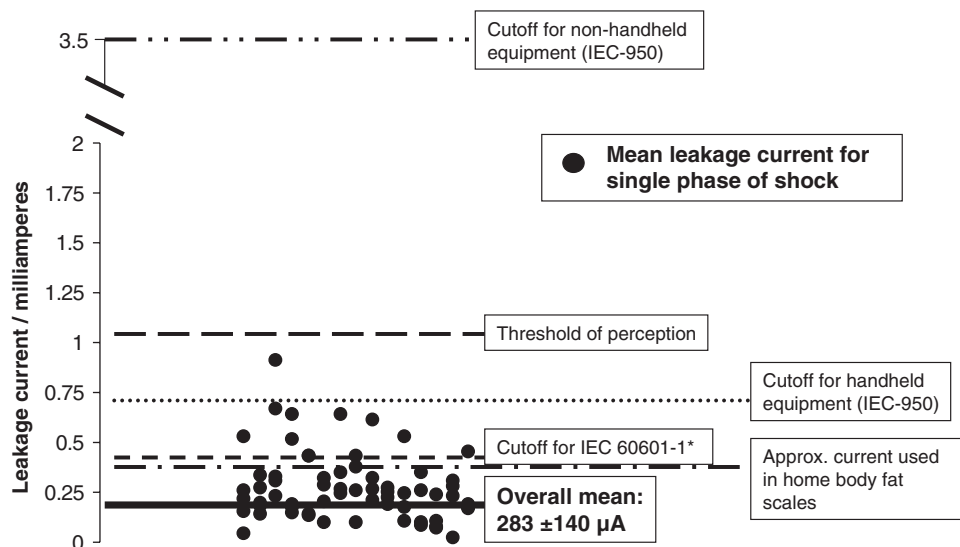|	Mean	SD	Range
Voltage across rescuer, V	5.80	5.77	0.280–14.1
Current through rescuer, μA	283	140	18.9–907
Energy through rescuer, μJ	24	12	0.070–95
Impedance through patient, Ω	60	15	36–87
Impedance through rescuer-patient circuit, Ω	2.27×10^4	1.40×10^4	1.09×10^3 to 1.00×10^5

Figure 3. Average leakage current in 36 trials of hands-on defibrillation in relation to several benchmarks of electrical safety. The data are presented in cluster form as the mean current for each phase of the biphasic shocks. The entire range of data compared favorably with medical and occupational standards. IEC-950 indicates IEC 950, Standards for Household and Business/Occupational Items; IEC 60601-1, IEC 60601-1, Standards for Medical Equipment. *This standard is for single-fault conditions.

differed from these standards because leakage current was recorded directly across rescuers' bodies instead of a simulated load.

The amount of harm that stray electrical energy could cause a human depends mostly on the current but also on voltage, oscillation frequency, current path, and duration of exposure. Safety standards for the latter variables are not well defined. The present study noted a low mean voltage (5.8 V), similar to a single cycle of a 67-Hz alternating current, given the biphasic nature of the waveform. The extremely short duration of exposure (≈15 ms) resulted in low total leakage energy. These variables are far less than what would be seen with accidental contact with an enclosure and further reduce the likelihood of the average 283 μA leakage current posing harm to an individual.

For further perspective on safety, it is useful to compare the average leakage current we measured through rescuers to other, more palpable benchmarks of electrical exposure. The maximum value of leakage current in the present data was below a well-accepted threshold of perception, which agrees with the finding that none of the volunteers were able to sense the shock.[20] The mean leakage current we measured (283 μA) was also below the average amount of current exposure from a home body-fat monitoring scale (500 μA) or that used in cardiac impedance plethysmography.[21]

The ethical considerations involving self-experimentation by the investigators performing manual contact have been considered and elaborated on elsewhere.[22] Because this trial is the first of its kind in its use of human "rescuers" instead of a simulated load for leakage current measurement, only investigators with knowledge and experience of the risks of this type of maneuver participated. This knowledge and experience came from the routine practice of our electrophysiology laboratory, where manual contact comparable to that used in the present study is frequently made with patients being defibrillated to reduce the defibrillation threshold[23] and

avoid dislodgement of intracardiac catheters during ablative procedures. On these grounds, our Institutional Review Board found that informed consent of the rescuers, because they were named investigators of the trial, was implicit in the design and submission of the study itself. Although measurements through investigators themselves introduces potential bias, we believed that it was unethical to use true "volunteers" without knowledge or experience in this arena.

The present study has important limitations. Our rescuer-patient model represents only 1 type of cardiac arrest scenario. Rescuers performed simulated compressions while wearing medical polyethylene gloves. Our measurements do not address bare skin-to-skin contact between the rescuers' hands and the anterior chest of the patient. We also did not examine leakage current using rigid handheld defibrillation paddles. The return pathway between rescuer and patient in the present study is likely to represent a better connection than with inadvertent contact during actual resuscitations. Nonetheless, it is possible that more robust conduction pathways could occur, especially if clothing or bedding is wet. In addition, poorly adherent defibrillating electrodes with resultant arcing could put a hands-on rescuer at risk. The present data, although applicable to a clinically practical construct of resuscitation, cannot be extrapolated beyond the constraints of our model.

Leakage measurements were made with the use of electrodes with an approximate surface area of 4 cm². This could be a source of underestimation. Finally, contact pressure on the anterior chest of the patient was estimated and may have varied between measurements, possibly affecting the amount of leakage energy coupled to the rescuer.

Summary
Uninterrupted manual chest compressions during shock delivery are feasible. Within the constraints of our model, direct manual contact with a patient being defibrillated was associ-

ated with exposure to low levels of electrical current. In many cases of cardiac arrest, these observations would allow for elimination of harmful delays from "all-clear" periods during resuscitation.

References

1. Gibbs W, Eisenberg M, Damon SK. Dangers of defibrillation: injuries to emergency personnel during patient resuscitation. *Am J Emerg Med*. 1990;8:101–104.
2. ECC Committee, Subcommittees, and Task Forces of the American Heart Association. 2005 American Heart Association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care, part 5: electrical therapies: automated external defibrillators, defibrillation, cardioversion, and pacing. *Circulation*. 2005;112(suppl):IV-35–IV-46.
3. Hummel RS III, Ornato JP, Weinberg SM, Clarke AM. Spark-generating properties of electrode gels used during defibrillation: a potential fire hazard. *JAMA*. 1988;260:3021–3024.
4. Theodorou AA, Gutierrez JA, Berg RA. Fire attributable to a defibrillation attempt in a neonate. *Pediatrics*. 2003;112:677–679.
5. ECC Committee, Subcommittees, and Task Forces of the American Heart Association. 2005 American Heart Association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care, part 7.2: management of cardiac arrest. *Circulation*. 2005;112(suppl):IV-58–IV-66.
6. Wik L, Hansen TB, Fylling F, Steen T, Vaagenes P, Auestad BH, Steen PA. Delaying defibrillation to give basic cardiopulmonary resuscitation to patients with out-of-hospital ventricular fibrillation: a randomized trial. *JAMA*. 2003;289:1389–1395.
7. Yu T, Weil MH, Tang W, Sun S, Klouche K, Povoas H, Bisera J. Adverse outcomes of interrupted precordial compression during automated defibrillation. *Circulation*. 2002;106:368–372.
8. Sato Y, Weil MH, Sun S, Tang W, Xie J, Noc M, Bisera J. Adverse effects of interrupting precordial compression during cardiopulmonary resuscitation. *Crit Care Med*. 1997;25:733–736.
9. Steen S, Liao Q, Pierre L, Paskevicius A, Sjoberg T. The critical importance of minimal delay between chest compressions and subsequent defibrillation: a haemodynamic explanation. *Resuscitation*. 2003;58:249–258.
10. Blackburn GE. UL-1950: an IEC-950-based US standard for information technology equipment including electrical business equipment. *IEEE Trans Ind Appl*. 1992;28:228–232.
11. Hallstrom A, Rea TD, Sayre MR, Christenson J, Anton AR, Mosesso VN Jr, Van OL, Olsufka M, Pennington S, White LJ, Yahn S, Husar J, Morris MF, Cobb LA. Manual chest compression vs use of an automated chest compression device during resuscitation following out-of-hospital cardiac arrest: a randomized trial. *JAMA*. 2006;295:2620–2628.
12. Berg RA, Sanders AB, Kern KB, Hilwig RW, Heidenreich JW, Porter ME, Ewy GA. Adverse hemodynamic effects of interrupting chest compressions for rescue breathing during cardiopulmonary resuscitation for ventricular fibrillation cardiac arrest. *Circulation*. 2001;104:2465–2470.
13. Wik L, Kramer-Johansen J, Myklebust H, Sorebo H, Svensson L, Fellows B, Steen PA. Quality of cardiopulmonary resuscitation during out-of-hospital cardiac arrest. *JAMA*. 2005;293:299–304.
14. Kerber RE, Grayzel J, Hoyt R, Marcus M, Kennedy J. Transthoracic resistance in human defibrillation: influence of body weight, chest size, serial shocks, paddle size and paddle contact pressure. *Circulation*. 1981;63:676–682.
15. Niwano S, Kojima J, Inuo K, Saito J, Kashiwa T, Suyama M, Toyoshima T, Aizawa Y, Izumi T. Measurement of body surface energy leakage of defibrillation shock by an implantable cardioverter defibrillator. *Pacing Clin Electrophysiol*. 2002;25:1212–1218.
16. Niwano S, Kitano Y, Moriguchi M, Yoshizawa N, Kashiwa T, Suyama M, Toyoshima T, Izumi T. Leakage of energy to the body surface during defibrillation shock by an implantable cardioverter-defibrillator (ICD) system: experimental evaluation during defibrillation shocks through the right ventricular lead and the subcutaneous active-can in canines. *Jpn Circ J*. 2001;65:219–225.
17. Laks MM, Arzbaecher R, Bailey JJ, Geselowitz DB, Berson AS. Recommendations for safe current limits for electrocardiographs: a statement for healthcare professionals from the Committee on Electrocardiography, American Heart Association. *Circulation*. 1996;93:837–839.
18. Laks MM, Arzbaecher R, Geselowitz D, Bailey JJ, Berson A. Revisiting the question: will relaxing safe current limits for electromedical equipment increase hazards to patients? *Circulation*. 2000;102:823–825.
19. Swerdlow CD, Olson WH, O'Connor ME, Gallik DM, Malkin RA, Laks M. Cardiovascular collapse caused by electrocardiographically silent 60-Hz intracardiac leakage current: implications for electrical safety. *Circulation*. 1999;99:2559–2564.
20. Martinsen OG, Grimnes S, Piltan H. Cutaneous perception of electrical direct current. *ITBM-RBM*. 2004;25:240–243.
21. Summers RL, Shoemaker WC, Peacock WF, Ander DS, Coleman TG. Bench to bedside: electrophysiologic and clinical principles of noninvasive hemodynamic monitoring using impedance cardiography. *Acad Emerg Med*. 2003;10:669–680.
22. Altman LK. *Who Goes First? The Story of Self-Experimentation in Medicine*. 1st ed. Berkeley, Calif: University of California Press; 1998.
23. Dodd TE, Deakin CD, Petley GW, Clewlow F. External defibrillation in the left lateral position: a comparison of manual paddles with self-adhesive pads. *Resuscitation*. 2004;63:283–286.

CLINICAL PERSPECTIVE

During resuscitation from cardiac arrest due to ventricular fibrillation or ventricular tachycardia, "all-clear" or "hands-off" periods are mandated to avoid potential electrocution of rescuers. These hands-off periods interfere with resuscitation, especially given that current strategies emphasize the importance of avoiding any interruption of chest compressions. There have been substantial changes to external defibrillation technology since hands-off precautions were developed. We addressed the feasibility and safety of direct rescuer-patient contact during defibrillation by measuring the voltage and current through mock rescuers simulating chest compressions on patients receiving external biphasic countershocks with adhesive shock electrodes. The main finding of this work was that the leakage current, the key determinant of potential harm to a rescuer, was very low. Within the constraints of our model, uninterrupted manual chest compressions in a patient being defibrillated are associated with exposure to safe, imperceptible levels of electrical current. In many cases of cardiac arrest, these observations would allow for elimination of routine harmful delays during resuscitation and simplify the resuscitation protocol.