Body Surface Potentials During Discharge of the Implantable Cardioverter Defibrillator

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Body Surface Potentials During ICD Discharge. ***Introduction:*** **Little is known about the hazard for persons in contact with patients experiencing a high-voltage discharge of their implantable cardioverter defibrillator (ICD). Compared to epicardial systems, this risk may be increased with transvenous electrode systems and particularly in active can configurations.**

Methods and Results: **In 23 patients with a transvenous active can ICD system, body surface potentials V_S and current through an external resistance were measured during 35 discharges. V_S was detected using skin electrodes positioned over the left subpectorally implanted pulse generator [C], apex of the heart [A], and the right pectoral region [RP]. Mean V_S during discharges without an external shunt resistance ranged between 13 and 63.8 V [C to A] and 12.5 to 47.3 V [C to RP] (ICD peak stored/output voltage V_{cap} = 183 to 606 V, n = 20). Mean current flow [C to A] was 8.2 to 46.8 mA (V_{cap} = 288 to 633 V, n = 10) and 42 to 120.7 mA (V_{cap} = 447 to 579 V, n = 5) across a resistance of 1,696 and 797 Ω, respectively.**

Conclusion: **During high-output shocks, a considerable potential difference is present on the body surface of ICD patients that, according to the literature, may induce a single cardiac response in a bystander. Analogous to spontaneous extrasystoles, there is only a minimal chance of triggering a tachyarrhythmia by this stimulated extra beat. Direct induction of ventricular fibrillation is unlikely, since reported fibrillation threshold values are much higher than the observed magnitudes of current and voltage.** *(J Cardiovasc Electrophysiol, Vol. 9, pp. 491-497, May 1998)*

body surface potentials, DC shock, implantable cardioverter defibrillator

Introduction

Malignant ventricular tachyarrhythmias are increasingly treated using the implantable cardioverter defibrillator (ICD), which effectively detects and terminates ventricular tachyarrhythmias.[1-4] Due to lower perioperative morbidity and mortality,[4,5] nonthoracotomy transvenous lead systems (NTVL) have replaced epicardial systems and the development of a single-lead unipolar transvenous active can (NTVL-AC) system facilitates the implant procedure.[6]

With epicardial electrodes, little current will flow at sites remote from the heart since the anode and cathode directly cover the heart with an insulation surface (e.g., silicon) on the pericardial site. In contrast, with the NTVL and especially the NTVL-AC systems, the anode and cathode are closer to the body surface, thus raising more concern about possible unwanted effects toward a bystander in contact with a patient experiencing a high-voltage ICD discharge. Depending on the magnitude of the electrical force, possible adverse events include immediate direct (e.g., stimulation of skeletal and myocardial tissue inducing single and repetitive responses) and indirect effects due to a startle reaction.[7-17]

Stimulated by questions from patients and their relatives, as well as from the emergency and nursing staff, about the potential risk of tachyarrhythmia induction in a bystander, we investigated the body surface potentials V_S and current I driven by V_S across a shunt resistance during shocks in patients scheduled for the then routine predischarge testing of their NTVL-AC systems.

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Methods

Patients

The study population consisted of 23 patients (20 men and 3 women; 57.7 ± 12.6 years; 170.8 ± 6.1 cm; 76 ± 10.2 kg; 1.88 ± 1.32 m^2 body surface area) who had undergone ICD implantation for malignant ventricular tachyarrhythmias. Coronary artery disease was present in 16 and dilated cardiomyopathy in the remaining 7 patients with an ejection fraction of 32.8% ± 13.5%. Fourteen patients were in New York Heart Association (NYHA) failure Class II and 9 patients were in NYHA Class III.

ICD Systems

The following active can devices were implanted: Medtronic (Minneapolis, MN, USA) PCD 7219C (n = 2), 7220C (n = 9), 7221CX (n = 3); and Ventritex (Sunnyvale, CA, USA) Cadet V-115AC (n = 3) and Contour V-145AC (n = 6). The NTVL-AC system was completed by combining these ICDs with a single transvenous defibrillation lead placed in the apex of the right ventricle, namely, the Medtronic 6936-65 (n = 1), 6936-75 (n = 2), and 6932-75 (n = 1), and Ventritex TVL RV-02 (n = 9). The Medtronic devices use a capacitor of 120 μF to deliver a biphasic impulse with a 65% fixed tilt in both the positive and negative phase of the discharge. Initially, the right ventricular defibrillation coil is used as the cathode and the can as the anode. Polarity is subsequently switched and the leading voltage of the second phase (P2) equals the trailing voltage of the first phase (P1). In this device, only stored energy is programmable. In contrast, the Ventritex devices use two capacitors of 300 μF in series (equivalent to a capacitance of 150 μF) during P1 and a single 300-μF capacitor during P2. Consequently, the leading-edge voltage of P2 is half the trailing-edge voltage of P1. It requires programming of a stored peak voltage and impulse duration (set to 8 msec each for P1 and P2 throughout this study). Another characteristic of the Ventritex devices is that the right ventricular defibrillation electrode serves as the anode during P1.

Predischarge Testing

All studies were performed during routine predischarge testing after obtaining informed consent. First, a noninvasive electrophysiologic study was done with programmed right ventricular stimulation over the implanted ICD system. If ventricular tachycardia (VT) or fibrillation (VF) was not induced, either a T wave shock or burst stimulation was applied. By this means, a total of 35 episodes of VT/VF were induced in the 23 patients (range 1 to 4 episodes per patient, median 1) and treated by a biphasic high-voltage discharge of the devices. During VT, these shocks occurred after failure of antitachycardia pacing. Twenty-five shocks were delivered with the Medtronic NTVL-AC systems using a programmed stored energy in the range of 2 to 24 J (according to a conversion table,[18] this corresponds to a peak output voltage of 183 to 633 V) and 10 shocks using the Ventritex devices with a programmed peak stored voltage of 350 to 600 V. Total impedance measured by the ICD systems during the 35 discharges was 51 ± 5 Ω.

Measurements

During 20 of the 35 high-voltage discharges, V_S values were measured using a digital oscilloscope (model 5027, series 200044, Enertec/Schlumberger, Paris, France) with electrodes (Blue Sensor® disposable electrodes type QR-50-5, Medicotest GmbH, Andernach, Germany) positioned on the skin directly over the active ICD can [C], apex of the heart [A], and the right pectoral region [RP]. These radiolucent self-adhesive electrodes are routinely used for ECG monitoring during electrophysiologic studies at our institution and consist of a nickel-plated brass stud and carbon fiber conduction wire, and use a water-based wet gel for electric skin contact with a total resistance of about R_{blue} = 348 Ω (mean value of 10 in vitro measurements with no pressure applied, range 282 to 375 Ω; increasing contact pressure decreased this value to 160 to 265 Ω with a mean of 190 Ω due to redistribution of the contact gel). No special cleaning of the skin was done before placing the electrodes. Potential differences were recorded between [C] and [A] as well as from [C] to [RP]. From these recordings, leading and trailing voltages of P1 (V_{Sp1} and V_{Se2}) and P2 (V_{Sp2} and V_{Se2}) were measured. Considering the absolute values of these parameters, the mean value of V_S operative during the biphasic discharge was estimated by simply calculating mean $V_S = \frac{1}{4} * [V_{Sp1} + V_{Se1} + V_{Sp2} + V_{Se2})$, which slightly overestimates the true value due to the exponential voltage decay.

In the remaining 15 shocks, a shunt resistance R of 1,000 Ω (n = 10) or 100 Ω (n = 5) was placed between the two nickel-plated brass studs of the skin electrodes placed at [C] and [A] in order to measure the current I driven by V_S. The total resistance R_{total} such offered to V_S consists of a series of three resistances and equals twice the resistance of the skin electrodes R_{blue} (348 Ω) plus the value of the shunt resistance R. Current flow through R_{total} equals the current flow through the shunt resistance R and thus can be determined from the voltage drop V across R using Ohm's law I = V/R, with I_{p1}, I_{e1}, I_{p2}, and I_{e2} being peak and end current flow during P1 and P2, respectively. V_S across R_{total} can be estimated from these recordings again using Ohm's law, with R_{total} being 1,696 Ω and 796 Ω for R = 1,000 Ω and 100 Ω, respectively.

Statistics

Linear regression analysis was performed using the statistical software package SPSS®, Version 7.5.2 (SPSS, Inc., Chicago, IL, USA).

Results

Representative examples of oscilloscopic potential recordings (with the electrodes placed between the active ICD can and apex of the heart) during three discharges are shown in Figure 1. They illustrate the two different waveforms, the dependence of V_S on the magnitude of the internal shock, and the effect of the shunt resistance R. Panel A shows a recording in a patient with a Ventritex device. It illustrates the initial positive (P1) and subsequent negative deflection (P2) since the right ventricular electrode functions as the anode at the beginning of the discharge, and the expected voltage decay during the shock reflecting the biphasic trapezoidal discharge of the ICD. Stored peak voltage V_{cap} was 450 V with an impulse duration of 2*8 msec. Potential recordings during shocks from a Medtronic device are shown in panels B and C, which cover two discharges in the same patient with different settings. In contrast to panel A, the initial phase P1 shows a negative deflection according to the design of the system. During discharge with a programmed stored energy of 5 J (peak output voltage V_{cap} = 288 V, Fig. 1B), the voltage decays from initially 50.5 V (S_{p1}) to 6.7 V (S_{e2}), with an impulse duration of 13.7 msec. Figure 1C shows the recording after a shunt resistance R = 1,000 Ω had been placed. Here, much less voltage is recorded (17.9 to 2.3 V) by the oscilloscope, and the resulting current across R (as well as across R_{total}, see above) can be calculated to be 17.9 to 2.3 mA (I_{p1} to I_{e2}). It should be noted that oscilloscopic potential recordings shown in Figures 1A and 1B directly represent the body surface potentials V_S since the input impedance of the oscilloscope (~10^7 Ω) is very high compared to R_{blue}. In contrast, the potentials shown in Figure 1C only show the voltage drop across R, which, as explained, is smaller than the actual V_S.

Table 1 lists data regarding V_S (measured directly by the oscilloscope with no R placed, i.e., R = ∞, and calculated according to Ohm's law with R_{total} assumed to be 1,696 Ω and 796 Ω for R = 1,000 Ω and 100 Ω, respectively) and I from all 35 discharges showing the magnitude of body surface potential recordings and current flow. Figure 2 illustrates the general relationship between peak stored/output voltage V_{cap} and the mean V_S. Based on the basic law of excitation (stating the relationship between current strength and impulse duration to induce a response[19]), mean V_S is the most likely determinant of stimulatory effects. For pooled analysis of the high-voltage discharges with both NTVL-AC systems used, stored energy was converted into peak output voltage[18] in the Medtronic devices and served together with the programmable stored voltage value in the Ventritex devices, as the independent variable V_{cap}. To estimate the effects of shocks with various intensities that could not be tested in this study, linear regression analysis was performed forcing the regression line through the origin, since an ICD output of 0 V will not yield any surface potentials.

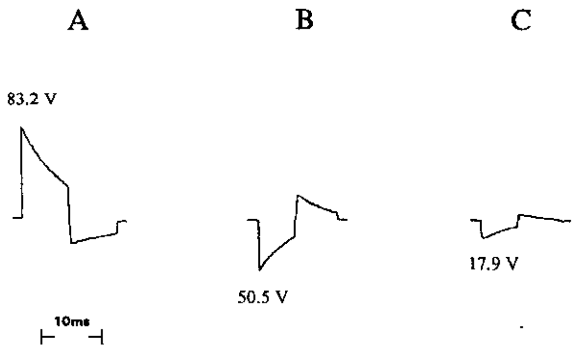

Figure 1. *Potential recordings during three biphasic discharges. Electrodes were placed on the skin near the active ICD can and apex of the heart. (A) Body surface potential V_S during a discharge of 2*8 msec duration and V_{cap} = 450 V (Ventritex waveform). (B) Body surface potential V_S during a discharge with V_{cap} = 288 V (stored energy 5 J) and 65% tilt (Medtronic waveform). (C) In the same patient as shown in panel B, a shunt resistance R = 1,000 Ω was introduced. Voltage drop across R is shown during a discharge with the same strength as in panel B. Numbers indicate the maximum potential observed by the oscilloscope in each recording. See text for further explanation.*

TABLE 1

Potentials on the Body Surface Between the Left Subpectorally Implanted Active ICD Can and Apex of the Heart as well as the Right Pectoral Region During 35 ICD Discharges

	Can–Apex	Can–Apex	Can–Apex	Can–Right Pectoral
R [Ω]	∞	1,000	100	∞
R_{total} [Ω]	∞	1,696	796	∞
No. of Discharges	20	10	5	20
V_{cap} [V]	183–606	288–633	447–579	183–606
V_{Spl} [V]	27.6–120	30.4–167.6	76.8–207.2	26–94
V_{Se2} [V]	4.4–22	3.9–23.9	10.6–28.7	3.6–17
Mean V_s [V]	13–63.8	13.9–79.4	33.4–96.1	12.5–47.3
I_{pl} [mA]	NA	17.9–98.8	96.5–260.3	NA
I_{e2} [mA]	NA	2.3–14.1	13.3–36.1	NA
Mean I [mA]	NA	8.2–46.8	42–120.7	NA

Listed are the ranges of programmed peak stored/output voltages (V_{cap}), body surface potentials V_s and current flows I at the beginning (V_{spl}, I_{pl}), and end (V_{Se2}, I_{e2}) of the individual discharges as well as the mean values of V_s and I during the shocks. NA = not applicable, since shunt resistance R = ∞. R_{total} = R + 2 * skin electrode resistance. See text for further explanation.

Analyzing only the 20 shocks with direct measurement of V_S (i.e., no shunt resistance placed), adjusted R^2 values of 0.977 (V_{Spl}), 0.969 (mean V_S), and 0.929 (V_{Se2}), all $P < 0.05$, showed a reasonably good description of the data by a simple linear model with a slope of 0.183, 0.089, and 0.03, respectively. Pooled analysis of all 35 shocks yielded equivalent results with adjusted R^2 values of 0.918 (V_{Spl}), 0.914 (mean V_S), and 0.884 (V_{Se2}), all $P < 0.05$, and a slope of 0.205, 0.094, and 0.029, respectively.

Granted the limited data available, height and body weight as well as the derived variable body surface area were not found to be related to the amount of voltage shunted to the skin (V_S/V_{cap}).

Discussion

The main finding of this study is that a considerable potential difference can be detected on the body surface of patients during discharges of transvenous active can ICD systems. In order to estimate the potential danger a bystander might be subjected to, these data are interpreted in the context of the available information in the literature about the effects of electricity in man with focus on possible cardiac stimulation.

The cardiac stimulatory effects of an external current source with a finite capacitance and a given internal resistance depend on the operating voltage, resistance, amperage, type of current, the current pathway through the body, the impulse duration, and the surface area of contact. Although many of these variables are not actually known during an accidental contact, the following considerations may illustrate the effects to be expected due to the observed magnitude of body surface potentials.

Although resistance of biological tissues is dependent on factors such as species, measurement setup, and tissue geometry (e.g., degree of anisotropy in heart muscle), it is known that the resistance of human tissue increases in the following order: nerve, blood vessel, muscle, skin, tendon, fat, and bone.[12,20] For the current to reach the heart of a bystander, it must pass the skin twice, at the entry and exit points of the circuit, in both the ICD patient and the person making the incidental contact. Therefore, skin resistance may be the most important variable determining current flow secondary to the external power source, namely the

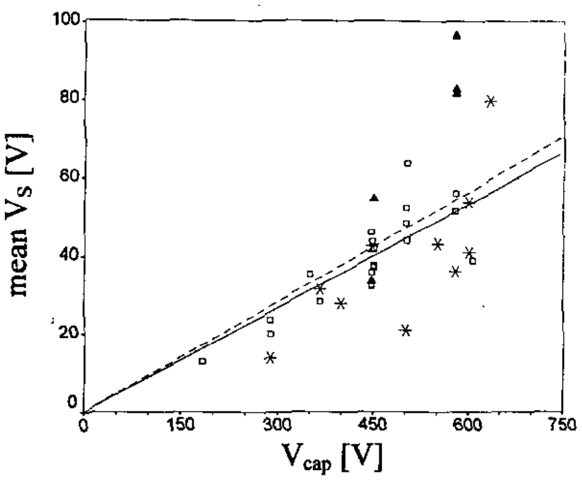

Figure 2. *Calculated (n = 15) or directly measured (n = 20) mean body surface potentials V_S (C to A) versus peak stored/output voltage V_{cap} during all 35 ICD discharges. Shunt resistance R was ∞ (□), 1,000 Ω (*), and 100 Ω (▲), respectively. Also, the corresponding linear regression lines for the 20 shocks with no R (—) and all 35 discharges (--) are plotted. See text for further explanation.*

ICD capacitance. Skin resistance varies due to thickness, moisture, cleanliness, area of contact, pressure applied, and the magnitude[21,22] and duration of the impulse, and it may be as high as 100,000 Ω for dry skin.[13] Because of the wide range of possible contact resistances, current for a given voltage can vary from near zero, when the contact resistance is high, to maximum, where only body resistance is important. Usually, the human trunk has an internal resistance of about 500 Ω,[8,13] and a current pathway across the two arms, the two legs, or arm to leg will have a minimal resistance of 1,000 Ω.[8,10,13,23] The wide range of possible resistances offered to an external current source also may be illustrated by impedance values of about 74 Ω observed during high current (18 to 40 A) transthoracic defibrillation[24] and 1,500 to 7,000 Ω (mean ± SD: 2,460 ± 1,600 Ω) during transthoracic pacing,[25] and the fact that during current flow, contact resistance may initially be very high with a subsequent decrease. Based on this information, a shunt resistance R = 1,000 Ω (with R_{total} offered to V_S then being between 1,564 to 1,750 Ω, with a mean of 1,696 Ω) was chosen in this study in order to represent a likely low resistance value that a bystander might offer to V_S. In addition, a value of R = 100 Ω (with R_{total} being between 664 and 850 Ω with a mean of 796 Ω) was used to gain further insight into the pathophysiologic consequences of V_S and I. Since values for R_{total} are dependent on R_{blue}, these impedance values are to be taken as estimates realizing the wide range of possible values for R_{blue} (see Methods section). By this means, it could be observed that body surface potentials V_S are dependent on the magnitude of the internal shock delivered and that V_S is generated by a current source with a significant capacitance allowing a considerable I to flow during the total impulse duration. Relating V_{Sp1} to peak stored/output voltage V_{cap}, linear regression analysis yields that 18.3% of the potential difference V_{cap} is to be expected on the body surface. This value decreased to 8.9% and 3% looking at mean V_S and V_{Se2}, respectively.

Mean V_S during the discharges with a duration of 13 to 16 msec was measured to be between 13 to 63.8 V (V_{cap}: 183 to 606 V) with no R, and 13 to 96.1 V (V_{cap}: 183 to 633 V) looking at all 35 discharges including the 15 discharges with R = 1,000 Ω and 100 Ω (Table 1). Calculating V_S depending on the voltage drop across the shunt resistance R requires the acceptance of the mean in vitro measurement as a likely value of R_{blue}, acknowledging the described variation of individual values of R_{blue}. Based on the 20 discharges without R, it may be inferred from the measured V_S that the magnitude of mean current flow across an impedance value of 1,696 Ω is between 7.7 and 37.6 mA. These values are in good agreement with the actually measured mean current flows after placement of R = 1,000 Ω (yielding a mean R_{total} = 1,696 Ω). The same holds for the data with R = 100 Ω (mean R_{total} = 796 Ω). The magnitude of current observed in this study will most likely reflect a maximum possible current flow, since the real value of R_{total} under normal conditions will be ≥ 1,000 Ω, with values as high as 100,000 Ω.[13]

The biphasic waveform of V_S and resultant I is essentially comparable to a single cycle of 60-Hz alternating voltage and current flow. The various immediate effects of 60-Hz alternating current applied to the skin depend, beside individual differences such as body weight, on the pathway, which determines the amount of current flowing through the tissue it will affect. For the heart, this phenomenon was realized as early as 1932, when Kouwenhoven et al.[26] found that for a pathway parallel to a dog' s body axis (right foreleg to the two hindlegs), about 9% to 10% of the total body current flows through the heart, and this proportion was further reduced to approximately 3% when current was applied in the transverse direction (foreleg to foreleg). During an incidental body contact between a bystander and a patient experiencing an ICD discharge, the most likely current pathway will be from hand to hand. Representative 60-Hz threshold levels for such a pathway are given by Bridges[9] to be I ≥ 0.5 mA (perception), I ≥ 6 mA (involuntary reactions), and as the current is further increased, the probability of VF induction increases with a threshold of about I ≥ 30 mA for shocks longer than 1 second and a threshold of about I ≥ 500 mA for impulse durations < 100 msec. For the impulse durations of ICD discharges (13 to 16 msec), a value of about 300 mA may be considered a likely threshold for the induction of VF,[9] thus the values observed in this study are well below this threshold.

Although no values are given for the threshold of inducing a single or repetitive ventricular response, according to Reilly[15] this excitation threshold is about 1% of the value inducing VF. Therefore, it may be inferred that a value as low as 3 mA can trigger a single ventricular response, which certainly is within the range of observed current flows in this study. The ability of V_S and I to induce such a single extrastimulus, especially during high-output shocks, is supported further by the experience with conventional transcutaneous pacing where excitation thresholds have been reported to be as low as 30 mA–10 msec[27] in children and 20 mA–40 msec (mainly between 40 to 70 mA)[28] and between 50 to 200 mA (15 to 100 V) using an impulse with a short duration of 2 to 3 msec.[29] The proarrhythmic effect of such a single ventricular extrastimulus is comparable to a single extrasystole, which is observed very often in a Holter recording without further sequelae. Still, there may be a minimal risk of triggering a tachyarrhythmia, especially in the presence of preexisting heart disease and the induction of a ventricular response during the vulnerable period of the cardiac cycle. For this reason, it is advisable for rescue personnel to wear gloves when performing cardiopulmonary resuscitation on ICD patients, which will reduce any possible risk.

Another clinical situation of interest is transthoracic defibrillation where a bystander is touching the patient. To our knowledge, body surface potentials have never been measured in this setting. Nevertheless, the necessary voltage values for effective transthoracic defibrillation have been reported to be in the range of 1,531 to 1,693 V and 1,902 to 4,271 V for truncated biphasic and damped sine wave monophasic shocks, respectively.[30] Depending on the contact points in relation to the external defibrillator pads, in such a setting a bystander might be subjected to voltage values much higher than during internal defibrillation. Therefore, this seems to be a more dangerous scenario for inadvertent tachyarrhythmia induction in a person making incidental contact.

Limitations

Looking into a worst case scenario with a minimum contact resistance of 1,000 Ω and a maximum stored voltage V_{cap} = 750 V, our measurements have to be extrapolated. Shocks of such high magnitude were not analyzed in this study, since all episodes were done for clinical reasons during routine predischarge testing. As such, we tested energy/voltage settings for VF therapy being lower than the maximum ICD output allowing a safety margin to be added for final programming at discharge. Thus, our data may be extrapolated using the described linear regression analysis, yielding a mean current flow of 66.75 mA. This value still is only a fraction of the current considered necessary to possibly directly induce ventricular tachyarrhythmias. Realizing the impossibility to cover every situation that might occur during an incidental contact between a bystander and an ICD patient receiving an internal high-voltage shock, these data may reassure patient's relatives and medical staff[31] about the lack of direct tachyarrhythmic risk attributed to V_S and the resulting I.

In conclusion, a considerable potential difference can be detected on the body surface during discharges of NTVL-AC systems. During high-output shocks, a single cardiac stimulation may eventually occur in an accompanying person incidentally in contact with a patient experiencing an ICD discharge. The risk of triggering a sustained arrhythmia by this stimulated extra beat is minimal but not zero, as may be inferred from the experience with spontaneously occurring extrasystoles. Thus, the overall tachyarrhythmic risk to a bystander associated with V_S and I is very low.

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