Catheter-Mediated Electrical Ablation: The Relation Between Current and Pulse Width on Voltage Breakdown and Shock-wave Generation

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Voltage waveform breakdown is characteristic of barotraumatic shock-wave generation during electrical catheter ablation of cardiac arrhythmias. The purpose of this investigation was to avoid barotrauma by defining, in vitro, the limits of pulse amplitude and pulse width for rectangular constant-current pulses that do not result in voltage breakdown and subsequently to determine what pulsing frequency is safe for use when high-energy trains of pulses are used. Electric pulses were delivered with a variable waveform modulator with a wide dynamic range and bandwidth capable of delivering pulses of 30-10,000-μsec duration with amplitudes of up to 25 A. Cathodal pulses were delivered to a 6F catheter immersed in fresh anticoagulated bovine blood warmed to 37° C to simulate the milieu of a catheter in the chambers of the human heart. The maximum pulse amplitude that could be delivered without incurring voltage waveform breakdown varied inversely with pulse duration. Pulses of 30 μsec broke down at currents above 24 A (2,500 V). Pulses of 10,000-μsec duration broke down at 1 A (250 V). The maximum safely delivered energy for a single pulse was 2.5 J for pulses of 80–120 μsec. Peak power for single pulses was maximum at 50–55 kW with 30–50-μsec pulses. Charge delivery for single pulses was maximized at 9 mC with long, 10,000-μsec duration pulses. To deliver an electrical pulse with energy significantly greater than 2.5 J without incurring voltage breakdown, trains of pulses were delivered where each pulse in the train had previously been shown to be free of voltage breakdown. However, multiple pulses could be delivered without voltage breakdown only when the pulsing repetition interval occurred at critical duty factors, where duty factor is defined as the ratio of pulse width to the time between pulses. For 200-μsec pulses of 5, 10, 15, and 20 A, 200 J could be delivered safely only with duty factors ≤27%, 18%, 15%, and 4%, respectively. This study identifies an inverse relation between pulse width and pulse amplitude because of the phenomenon of voltage waveform breakdown. A critical pulsing duty factor, which is dependent on pulse amplitude and pulse width, is necessary to deliver high energy pulses without voltage breakdown. These considerations should help minimize barotrauma and facilitate more precise methods of catheter ablation. (Circulation Research 1988;63:409–414)
However, current continues to flow to the electrode because of the inertia inherent in inductor-driven defibrillators. This continuing current flow in the face of higher resistance causes a rise in voltage between the bubble-insulated electrode and the surrounding blood. An overvoltage is then generated between electrode and blood as the defibrillator pulse continues to be delivered to the electrode. As the electric field strength increases, more and more electrons enter the bubble that surrounds the electrode until an electron "avalanche" occurs. Eventually, electron density is strong enough to sustain an arc. With sufficient electron density between the electrode and surrounding blood, a flash, or arc, occurs that can result in temperature surges in the bubble as high as 6,000° K.6,8 Such high temperatures result in a very rapidly expanding bubble volume and an extremely rapid change in the thermodynamic state of the gas. The pressure of the shock wave thus generated can be as high as 50,000 atmospheres,6 although it is usually less (10-20 atmospheres).3,4

Because these high-pressure waves can result in cardiac rupture due to barotrauma,1,3-5 alternative forms of energy delivery for catheter-mediated ablation of arrhythmogenic tissue are needed. Given the process responsible for barotrauma with electrical pulses, it is reasonable to assume that electrical pulses of limited amplitude and duration could be generated that would be useful for ablation while avoiding sufficient generation of electrolysis gas to prevent arcing and subsequent shock-wave generation. The first purpose of this investigation, therefore, was to define in vitro the maximum pulse amplitude and pulse width that would avoid shock-wave generation when single rectangular constant current pulses are used. Second, we proposed to use the criteria that enables nonbarotraumatic single-pulse delivery to define, in turn, the limits governing safe delivery of multiple-pulse trains. This would enable higher levels of energy to be delivered than possible with a single pulse.

Materials and Methods

Experimental Methods

Investigation defining the limits of what constitutes safe (no shock wave generated) and unsafe (shock wave generated) rectangular pulses was undertaken in fresh anticoagulated bovine blood maintained at 37°C in a 15 × 15 × 30-cm tank. A 6F copper cable with a hemispherical tip (19 mm² surface area) was used as the cathode and was separated 10 cm from an 8.5-cm diameter stainless steel disk used as the anode. Constant current rectangular cathodal pulses were delivered using a current modulator developed at the University of Washington that functions over a wide dynamic range and bandwidth and is driven by a Wavetek 275 pulse generator.10 A schematic outline of how the current modulator is used to produce electrical pulses is shown in Figure 2. The pulse amplitudes however, current continues to flow to the electrode because of the inertia inherent in inductor-driven defibrillators. This continuing current flow in the face of higher resistance causes a rise in voltage between the bubble-insulated electrode and the surrounding blood. An overvoltage is then generated between electrode and blood as the defibrillator pulse continues to be delivered to the electrode. As the electric field strength increases, more and more electrons enter the bubble that surrounds the electrode until an electron "avalanche" occurs. Eventually, electron density is strong enough to sustain an arc. With sufficient electron density between the electrode and surrounding blood, a flash, or arc, occurs that can result in temperature surges in the bubble as high as 6,000° K.6,8 Such high temperatures result in a very rapidly expanding bubble volume and an extremely rapid change in the thermodynamic state of the gas. The pressure of the shock wave thus generated can be as high as 50,000 atmospheres,6 although it is usually less (10-20 atmospheres).3,4

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investigated ranged between 1 and 25 A. The pulse widths investigated ranged between 20 and 10,000 μsec. Current was recorded with a Tektronix A6303 current probe (Beaverton, Oregon). Voltage was recorded with a 1,000:1 input-to-output ratio resistive-voltage divider. Pulse voltage and current waveform were monitored on two Tektronix 2230 digitizing oscilloscopes that allowed for determination of delivered energy and charge.

**Single Pulses and Voltage Breakdown**

Because of the association between an increase in voltage in the ablation pulse and the physics of shock-wave generation (Figure 1), the acceptable pulse width to avoid barotrauma for any given pulse amplitude was that time during the pulse before the point where voltage rose, that is, where voltage "broke down" (Figure 3). A strength-duration curve for pulses that did not result in shock-wave generation was constructed using the limiting criterion of voltage breakdown. This strength-duration curve is analogous to the strength-duration curves demonstrated in cardiac pacing. However, in the context of this study, and unlike the context of cardiac pacing, the maximum pulse width for any given current defines the pulse parameters that do not result in voltage breakdown. Current, voltage, energy, charge, power, and resistance were plotted as a function of safe pulse duration for single pulses.

**Multiple Pulses and Duty Factor**

After the strength-duration relation for single rectangular pulses was defined, a second series of experiments was undertaken to define safe pulsing limits for trains of rectangular pulses. These trains of pulses were used to achieve higher energy delivery than safely possible with single pulses. The individual pulses that composed the train were those previously determined to be nonbarotraumatic. These multiple-pulse experiments were designed to deliver energies above those possible with single pulses, yet in a time period short enough to be delivered synchronously to a single QRS, that is, in a period of 100 msec. This last criterion was established so that the entire train of pulses could be delivered to a single QRS without extending into the vulnerable repolarization period.

The goal of this phase of the investigation was to deliver trains of pulses yielding a delivered energy of 200 J without incurring voltage breakdown in any of the pulses used in the train. The observed variable controlling the occurrence of voltage breakdown in this instance was duty factor. Duty factor is defined as the ratio of pulse width to the time duration.
Time to Voltage Breakdown at a Function of Current

Time to Voltage Breakdown at a Function of Energy Delivered

Figure 4. Relation between current amplitude and pulse duration before breakdown in voltage waveform with constant current rectangular pulses. High-amplitude pulses in range of 20–25 A could be delivered without risk of barotrauma only at pulse widths of 20–40 μsec. Pulse width could be substantially longer (up to 10,000 μsec) with low amplitude pulses.

Results

For single pulses, the maximum current amplitude that did not result in voltage breakdown was inversely related to pulse width (Figure 4). Pulses of 25 A could only be delivered for 20–40 μsec before sufficient electrolysis gas was generated to result in voltage breakdown. However, when lower amplitude pulses were employed, substantially longer pulse widths could be used safely. The relation between voltage and pulse width was similar with a maximum voltage of 2,500 V at pulse widths of 20–40 μsec (Figure 5).

The relation between delivered energy and pulse width was different. Maximum energy delivery occurred with pulse widths of 80–100 μsec (Figure 6). Maximal allowable current amplitude for these 80–100 μsec pulses was 20–15 A. Even at these pulse widths and currents, however, the largest energy pulse that could be delivered without voltage breakdown was 2.5 J.

The amount of charge that could be delivered safely for any particular pulse width was curvilinearly related to pulse width (Figure 7). A strict linear relation was not present because of the role that diffusion of the electrolysis gas played in uninsulating the electrode. At the longer pulse widths, slightly more charge could be delivered before voltage breakdown occurred because the electrolysis gas dissolved into solution over the relatively long time period of the pulse. Therefore, more charge could be delivered.

The maximum power that could be delivered safely, 50–55 kW (Figure 8), was inversely proportional to pulse width. Power precipitously fell with wider pulse widths because it is the product of voltage and current in a system where resistance remains constant (Figure 9) over the range of pulses used.

For the 200 J, multiple-pulse, variable-amplitude trains, we were able to successfully deliver the train over 100 msec without voltage breakdown in any of the pulses of the train. This nonbarotraumatic pulse train, however, was critically dependent on duty...
factor. An inverse relation was demonstrated between the pulse amplitude and the duty factor: the larger the pulse amplitude used to deliver the 200 J pulse train, the smaller the duty factor needed to be to prevent voltage breakdown (Figure 10). In 200 J trains using 20 A, 200 μsec pulses could only be delivered safely at duty factors of 4%, whereas in 200 J trains using 5 A, 200 μsec pulses could be delivered safely at duty factors of 27%.

Discussion
With use of single rectangular constant-current pulses in a blood medium, we have been able to define the limits of pulse amplitude and pulse width usable for catheter-mediated electrical ablation of cardiac tissue without incurring voltage waveform breakdown and the associated risk of shock-wave generation, barotrauma, and cardiac rupture.

The higher the amplitude of the pulse, the shorter the time period it can be delivered without precipitating the events leading to shock-wave generation. Because of this inverse relation, only a small amount of energy could be delivered without barotrauma when single pulses were used. Energy delivery for single pulses was maximized at 2.5 J when rectangular pulses of 80–100 μsec duration were used. This is a modest energy that is unlikely to be effective for cardiac tissue ablation. Therefore, we investigated the use of a 100-msec train of pulses, sufficient in number to deliver higher energies but also capable of avoiding barotrauma. When the pulsing frequency (i.e., duty factor) was chosen carefully for these trains of pulses, it was indeed possible to deliver up to 200 J during 100 msec without concern for causing barotrauma.

The importance of these findings is the recognition that pulse selection in catheter-ablation procedures should not be arbitrary and based on energy alone. Furthermore, safety, especially in the realm of coronary sinus ablation, remains an ongoing clinical concern with the procedure because of problems related to barotraumatic coronary sinus rupture.1-3 This study also points out that a variety of electrical factors can be emphasized depending on the pulse parameters chosen and the electrical intervention required. For example, even though there is a wide range of "safe" pulses, different "safe" pulses should be chosen to assess the effect of voltage, the effect of charge, or the effect of energy on tissue injury. One might surmise that high-voltage pulses, for instance, could injure cells differently than high-charge pulses. Excessive voltage delivery may kill cells by damaging the dielectric properties of cell membranes11 while excessive...
Charge delivery may injure cells by producing free-radical formation that interferes with numerous cellular-molecular interactions. One might also find that high-voltage pulses cause different amounts of cellular injury than high-charge pulses of equal energy content. The pulsing flexibility afforded by a waveform generator capable of delivering such a broad spectrum of pulses, therefore, may tell us more about the mechanisms of electrical cell death than can be determined with defibrillator or radio-frequency electrical pulses.

References

Key Words • catheter ablation • Wolff-Parkinson-White syndrome • arrhythmias • cardiac surgery
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