0090-6689/88/281-285/$02.00/0
MEDICAL INSTRUMENTATION
Vol. 22, No. 6

Comparison of Effectiveness of Relay-Switched, One-Cycle Quasisinusoidal Waveform with Critically Damped Sinusoid Waveform in Transthoracic Defibrillation of 100-Kilogram Calves

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Studies of 240 transthoracic fibrillation-defibrillation episodes in calves of 91–108 kg are reported. The waveform in 120 of the episodes was a one-cycle, quasisinusoidal waveform having peak currents of 64 and −32 A and half-cycle durations of 4 and 6 ms. The episodes were interlaced with 120 others involving critically damped sinusoid waveforms having a 70.2-A peak current at 1.1 ms to peak. Applied after 30 s of fibrillation, the biphasic shock (201 J of delivered energy) was successful on the initial attempt in 106 of 120 episodes (88%), and the uniphasic shock (206 J) was successful in only 44 of 120 episodes (37%). The biphasic waveform, producible by a simple relay-armature shift in a passive circuit, yielded significantly better results ($p < 0.001$) and should be evaluated clinically.

A general belief is that ventricular fibrillation in patients with potential for survival can usually be reversed by electric shock from widely used defibrillators delivering a uniphasic or near-uniphasic waveform. Interest in the development of improved devices continues, however, partially because the patient load is so large.

Experimental evidence indicates that 1) both symmetric and asymmetric biphasic rectangular waveforms are superior to uniphasic rectangular waveforms[1–3]; 2) both symmetric and asymmetric biphasic, truncated exponential waveforms are superior to uniphasic, truncated exponential waveforms[4–6]; and 3) a variety of biphasic waveforms considerably out perform the critically damped, uniphasic shock in transthoracic defibrillation in the 100-kg-calf model.[7] Uniphasic or near-uniphasic defibrillators continue to be dominant in the clinical environment.

In this article, we use a circuit having the topology described by Negovsky *et al.*[8] that can deliver biphasic waveforms reasonably close to the asymmetric biphasic waveforms we have found to be so successful. The waveform can be generated by a relay-armature shift in a passive circuit instead of with high-current electronic devices such as silicon-controlled rectifiers (SCRs).

METHODS

Apparatus

The defibrillator used in this research is a modified version of one that can provide ultrahigh-energy, uniphasic/biphasic, rectangular/truncated exponential waveforms. That defibrillator, previously described,[9] uses hydrogen thyratron/SCR switching. The modifications involved replacing two of three electronically controlled pulse generators with electromechanical relays and passive circuits for generating the waveforms to be tested. The operator could easily select the fibrillatory shock, the critically damped uniphasic waveform, the quasisinusoidal biphasic waveform, or an electronically generated uniphasic rectangular backup waveform of almost any desired pulse width or pulse amplitude by front-panel controls.

Circuits used in generating the quasisinusoidal biphasic and critically damped uniphasic waveforms are shown in Figures 1 and 2, respectively. In both circuits, the calf chest resistance (average value of some 20 Ω with the 13-cm diameter electrodes employed) was trimmed with a variable resistance in such a way that the combined trimmer and calf resistance remained substantially invariant at 25 Ω from animal to animal and from episode to episode, thus permitting any shifts in delivered energy attributable to changes in electrode-skin interface resistance to be absorbed in the interface region rather than in the regions of both the heart and the interface.

The component values and initial voltage on the capacitor used in the circuit of Figure 1 were derived by one of us (D.Y.) so as to (a) yield a current waveform similar to a biphasic rectangular waveform that had been found to be effective in an earlier study,[3] (b) be practical, component-wise, to scale and implement in apparatus designed for use on humans, (c) be appropriately scaled for use with the 20-Ω resistance presented by the chest of the calf, and (d) deliver about 200 J to the subject. The waveform of current, as shown in Figure 3, had a maximum amplitude of 64 A and a minimum amplitude of −32 A; the half-cycle durations were approximately

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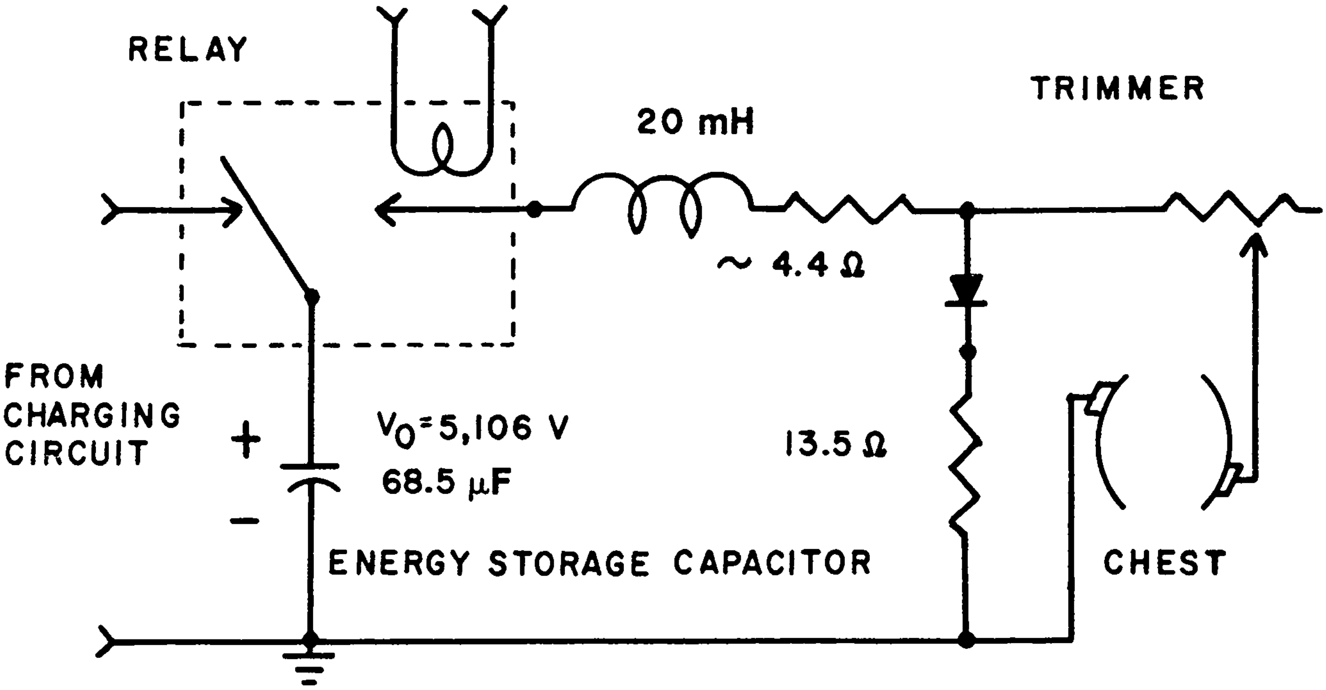

Figure 1. Circuit for generating biphasic waveform.

4–6 ms, respectively. That this waveform will deliver 200 J to a 20-Ω chest can be demonstrated easily by graphic integration of the corresponding current-squared curve, and multiplication by 20 Ω.

The component values and initial capacitor voltage of the circuit of Figure 2 were derived so as to deliver some 200 J to a 20-Ω chest; the critically damped sinusoid would peak at 70.2 A in 1.1 ms, as shown in Figure 4. That this waveform will deliver 200 J to a 20-Ω chest follows analytically from a simple manipulation of the current equation for critically damped waveforms using the specified values of peak current and time required to reach the peak current. In both circuits, the resistance shown in series with the inductive element was primarily that of the inductor.

A double-throw, electromechanical relay was used in the circuit of Figure 1 to prevent shunting by the charging circuit, which would occur when the storage capacitor reversed its polarity during discharge. Because polarity reversal does not occur in the circuit shown in Figure 2, a single-throw relay was adequate.

The initial polarity of the capacitors differs in the two circuits, but this is compensated by the connections to the chest electrodes—with the result that in both the uniphasic shock and in the leading portion of the biphasic shock, the lower left electrode was positive with respect to the upper right electrode on the chest.

Procedure

Anesthesia was induced with 110 mg of glyceryl guaiacolate/kg and 4.4 mg of thiopental sodium/kg injected intravenously. The calf was intubated and then maintained in anesthesia with methoxyflurane in 50% N_2O and 50% O_2. Fibrillation was induced with a 1-s, 60-Hz, 100-V (rms) shock applied through the chest electrodes; after 30 s, one of the two waveforms being studied was applied.

If defibrillation was accomplished on the *first* attempt, the episode was recorded as a success, and the lead II electrocardiogram was observed on an oscilloscope and recorded for 2½ min. Otherwise, the episode was recorded as a failure, and a shock of known high effectiveness was used to salvage the animal. With not less than 3 min between the start of successive episodes, the procedure was repeated—but with the other waveform being evaluated. In a given session, animals were carried through not more than 20 episodes (10 episodes involving one of the waveforms interlaced with 10 involving the other). The waveforms of both current and voltage of the shocks being studied were observed on a dual-beam storage oscilloscope (model 5113, Tektronix, Beaverton, Oregon). The chest resistance associated with each biphasic shock was calculated as the mean of the voltage-to-current ratios at the positive and negative peaks. The chest resistance to each uniphasic shock was calculated as the ratio of the peak voltage to peak current. For both waveforms, and to the extent that the current waveforms were maintained invariant, the actual delivered energy in joules in any episode was given by the calculated resistance for the episode divided by 20 and multiplied by 200. The mean delivered energy was calculated from the mean resistance by the same procedure.

In addition to the alternating of the waveforms being

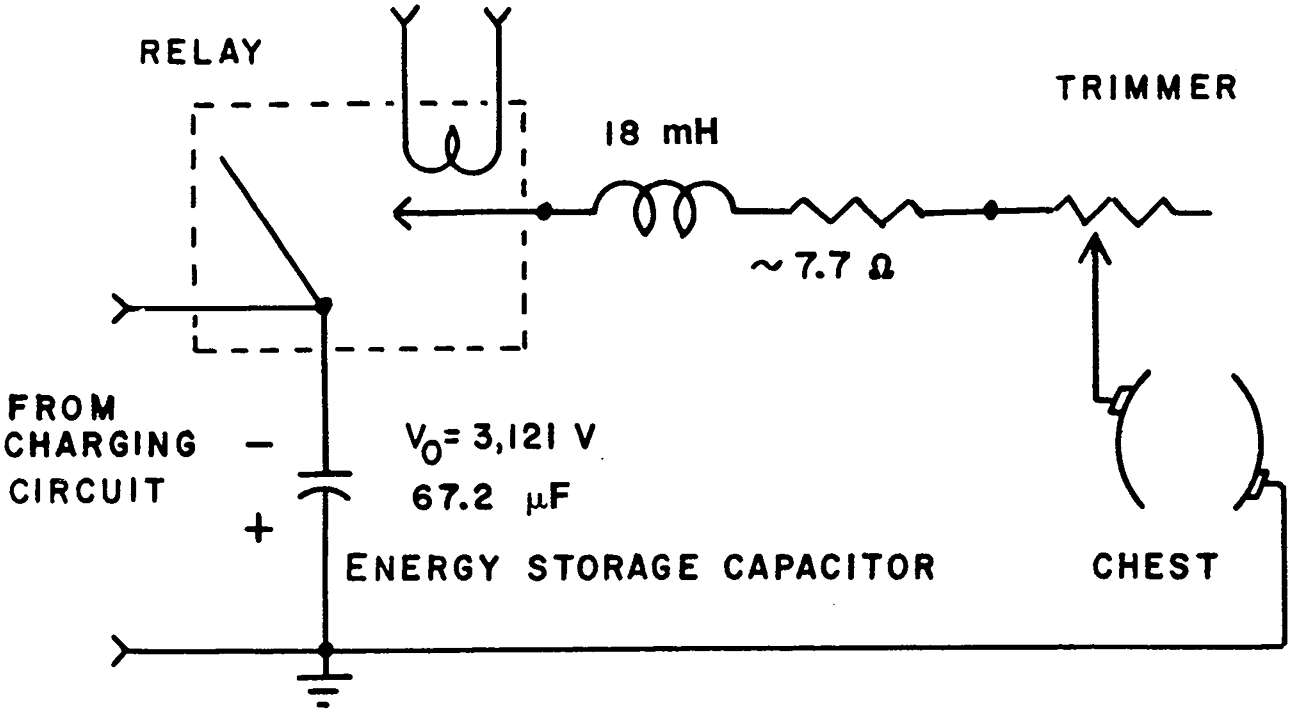

Figure 2. Circuit for generating uniphasic waveform.

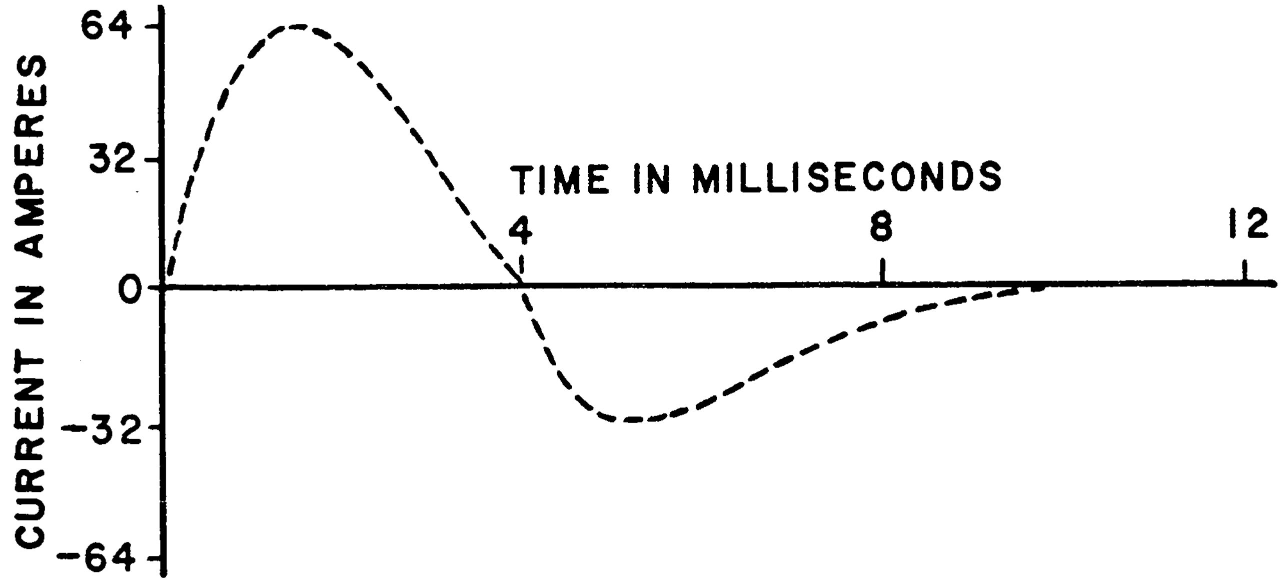

Figure 3. Quasisinusoidal biphasic waveform.

evaluated in successive episodes as described above, the initial episode in animals as they were successively entered into the study alternated between the two waveforms. With no animal being carried through more than 20 episodes with a particular waveform (nor more than 40 episodes in total), the sessions were ordinarily repeated with at least one day between sessions. A total of 7 calves of 91–108 kg were used in the 240-episode study.

RESULTS

In 120 episodes with each waveform, our study yielded chest resistances of 20.1 ± 3.5 Ω (mean ± SD) with the biphasic waveform and 20.6 ± 3.1 Ω with the uniphasic one. The biphasic shock generated by the circuit of Figure 1 and sketched in Figure 3 was successful in 106 of 120 episodes (88%) at an average delivered energy of 201 J. The uniphasic shock generated by the circuit of Figure

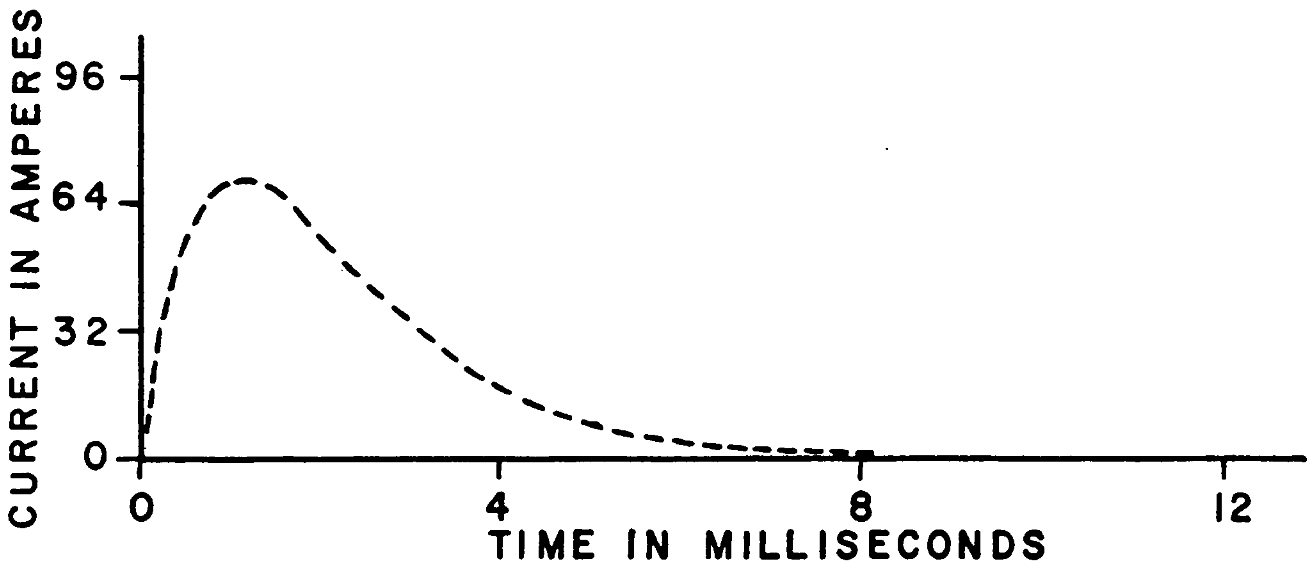

Figure 4. Critically damped uniphasic waveform.

2 and shown in Figure 4 yielded 44 successes in 120 episodes (37%) at an average delivered energy of 206 J. The difference is large, and an unpaired χ^2 test shows it is significant ($p < 0.001$).

In terms of the electrocardiographic findings, 2.8 ± 1.1 s (mean ± SD) were required for the appearance of the first ventricular complex following a successful biphasic shock, and 6.8 ± 4.2 s were required after a successful uniphasic shock. An unpaired Student's *t* test showed that this difference is significant ($p < 0.05$). Similarly, 4.3 ± 2.8 s were needed for the return of normal sinus rhythm after the biphasic shock, compared with 12.0 ± 6.8 s after the uniphasic shock ($p < 0.05$). Thus, the electrocardiographic disturbances caused by successful shocks were significantly less severe with biphasic than with uniphasic waveforms.

DISCUSSION

The results of this study are seen as further confirmation of what seems to be a general superiority of biphasic over uniphasic waveforms in the defibrillation of calves. A series of studies in cultured chicken-embryo myocardial cells by Jones *et al.*[10-12] have furnished some hypotheses for the superiority of biphasic shocks and can be broadly interpreted as compatible with our previous results with a biphasic waveform applied to calves, thus suggesting that the findings in calves may extend to other species.

Although the simplicity of relay switching for generating biphasic waveforms may be attractive in many applications, a shortcoming of the biphasic circuit of Figure 1 is the power loss and consequent loss of efficiency associated with the shunt consisting of the series combination of the diode and 13.5-Ω resistor. For example, with essentially the same delivered energy, the stored energy is 2.73 times as large in the biphasic circuit of Figure 1 as in the uniphasic circuit of Figure 2. We anticipate that the efficiency of the circuit of Figure 1 would also compare poorly with that of a defibrillator circuit using SCRs or similar switches in providing biphasic defibrillation.

CONCLUSION

The significantly better defibrillation results in calves with the relay-generated biphasic waveform of Figure 1 compared with the uniphasic waveform of Figure 2 support the conclusion that clinical trials should be performed to see if the results from the calf model translate to human patients.

This work was supported by a grant from the Physio Control Corporation and was presented in part at the 23rd Annual Meeting of the Association for the Advancement of Medical Instrumentation, Washington, D.C., May 14–18, 1988.

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