DEFIBRILLATION THRESHOLDS WITH MULTIPLE PULSES AND ANGULAR LEADS

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ABSTRACT--Multiple pulse defibrillation using angular electrode leads was studied as opposed to single shock defibrillation. After an experimental series in dogs and by comparison with previously reported results using single pulses, it was found that the latter requires high current levels potentially harmful to the myocardium. Multiple shocks appear as valid alternative to decrease voltage, current, and power. Energy is distributed over a longer time and, thus, its effects are minimized. Besides, with multiple shocks, power is drastically reduced. The search to reduce the electrical parameters in implantable defibrillators should be oriented toward a decrease in power rather than in energy. Impedance measurements of the defibrillatory path are useful to dose the shock and so avoiding excessive currents.

INTRODUCTION

A defibrillating shock may produce functional and morphological myocardial damage. Traditionally, a single discharge has been used and, in spite of technological improvements, defibrillatory electric levels have not decreased very much. Even nowadays, a considerable amount of energy is applied. Trying to lower it and, consequently, to lower any possible postdefibrillatory injury, efforts have been invested in studying different pulse waveforms, such as rectangular, trapezoidal, sinusoidal, exponential (capacitive), damped sinusoidal and biphasic shocks. This fact, along with the development of the automatic implantable defibrillator [Mirowski et al, 1980], spurred the search for alternative procedures in an attempt to reduce the defibrillating electrical parameters.

Thus, the objective of this communication was to compare different defibrillation procedures which make use of multiple shocks, via either one or more electrode leads, in relationship to single pulse techniques.

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METHODS AND MATERIALS

Multiple Pulse Defibrillation

Wiggers, in 1940, first proposed the concept that multiple shocks might be more effective than a single shock in arresting fibrillation. However, it took many years before the idea was further advanced. The following classification can be suggested:

1. Temporal Hypothesis. Kugelberg [1968] stated that a "shock should consist of two pulses with a pulse duration and a pulse interval adjusted so that those cells excitable at the first moment and defibrillated by the first pulse will be refractory to the second. The latter pulse should then be timed in such a way that it defibrillates the cells which were refractory to the first pulse but which have now become excitable. At the end of the second pulse all cells should thus be depolarized. By stimulation of all cells in their excitable phase, a defibrillation with a minimum of energy ought to be expected." In canine hearts connected to a heart-lung machine, he reported successful defibrillation in 85% of the cases with a pulse duration of 20 ms, an interval of 100 ms, an amplitude of 40 V and an energy of 2 J. In forty one patients who had open-heart surgery, successful defibrillation was achieved in the third attempt on the average with a pulse duration of 30 ms, a pulse interval of 100 ms, a mean amplitude of 50 V and a mean energy of 2.4 J.

2. Homogeneous Current Density Hypothesis. Jones et al [1985] reasoned that, when a shock is applied across a single pair of electrodes, two regions are generated between them: One of high current density (near the electrodes) and another one of low current density (in the central part). The former may produce injury while the latter may not be enough to depolarize the fibers. They proposed two orthogonal shocks via two pairs of electrodes (alternate lead orientation and twin pulse delivery) in order to obtain a more homogeneous current density. These authors used 5 ms trapezoidal pulses separated by 1 ms and found a reduction in energy requirements with a significant improvement in the defibrillation success.

3. Spatial Hypothesis. Bardou et al [1986], in turn, proposed stimulating the cardiac fibers along their longitudinal axis because depolarization is easier than following a transverse direction. However, myocardial fiber bundles are rather complex in orientation and no single axis collects at once all of them. According to these authors, two sequential orthogonal shocks might compensate for this geometrical difficulty. The second

discharge would depolarize those fibers which, by geometry, are "invisible" to the first one. In practice, this procedure is similar to that brought forward by Jones et al [1985], however, the hypothesis is different. Bardou et al [1986] used damped sinusoids of 4 ms (measured to half amplitude) separated by 100 ms and reported, in dogs, a 64% energy reduction with respect to single shock defibrillation.

4. Angular-Temporal Hypothesis. Taking into account the above-mentioned hypotheses, we developed a fourth trying to combine their advantages: Four rectangular pulses A1, B1, A2 and B2 are applied through two angular electrode leads (pair A and pair B). The first pulse A1 is applied via pair A and the second pulse B1 via pair B with a delay exactly equal to the pulse duration t_1. After a long interval t_2, the third and fourth pulses, A2 and B2, are delivered through pairs A and B, respectively, with the same delay t_1 as before (Figure 1). If the electrode leads are orthogonal, we are implementing Bardou's concept. Simultaneously, since two sequential pulses are applied via each pair of electrodes, Kugelberg's idea is also realized. Besides, the intervals between A1-B1 and A2-B2 are minimized, thus verifying Jones et al's twinning pulse proposal.

Equipment

A laboratory equipment [DANTE, after Defibrillation: ANgular-TEmporal, Puglisi et al, 1988] was constructed in order to implement any of the hypothesis (or modes) previously described. These modes will be called K (after Kugelberg) and JB (after Jones/Bardou). The equipment has three stimulators, an impedance meter (at 12 kHz and 315 uA rms), an A/D converter, and a relay array. These modules are controlled by a computer (INTELLEC SERIES II). The actual values for voltage, pulse duration, pulse interval and choice of defibrillation mode are indicated by the operator via keyboard. After the shock, the computer gives as a print out the delivered current, current per gram of ventricle and energy. The equipment can supply variable rectangular pulses up to 220 V, in steps of 10 V, at a maximum current of 2.6 A. Pulse duration can be changed from 2 to 20 ms, in steps of 1 ms, and the interval between A1 and A2 (or B1 and B2) can be varied from 2 to 200 ms, also in steps of 1 ms. The impedance meter range goes from 40 to 400 ohms with a maximum error of 5%.

Experimental Protocol

An experimental series was carried out with 9 dogs (average weight=12 kg, SD=6, range 7-22). Blood pressure and ECG were connected to a polygraph recorder (GOULD 2600S). After midsternal thoracotomy, three pairs of electrodes were sewn to the intact pericardium, in 5 animals (Group G1) along approximately orthogonal axes (anterior-posterior, base-apex, and left-right). In the remaining 4 instead (Group G2), the second pair was positioned along the right base-left apex axis and the third was affixed roughly following the left base-right apex line (Figure 2).

The two pairs offering minimum impedance (to ensure maximum current) were selected by the computer as leads A and B to apply the defibrillating pulses (Figure 1). Electrodes were round patches of flexible copper mesh. Two sets were constructed (7 and 12 cm^2) to be fitted to ventricular size. Fibrillation was triggered with a train of rectangular pulses (GRASS S88 stimulator). The defibrillating mode (K, JB or DANTE) was chosen at random. If defibrillation was successful, the electric dose (in A/kg) was decreased by 20% for the next time the mode was selected. If defibrillation failed, a second discharge with a 20% dose increase was attempted. If it failed again, a back up conventional damped sinusoidal shock was delivered (Savino et al, 1977). The latter dose was to be the dose for the next time the mode was selected. The interval between fibrillatory episodes was never shorter than 5 min (to permit recovery) and, in no case, fibrillation was allowed to last more than 2 min. In three animals, arterial blood samples were tested every half hour for pH, P_{O2} and P_{CO2} with a CORNING 161 analyzer.

Delivered Power

We calculated the applied power making a distinction between pulse power, P_p, and mean power of the total discharge, P_{md}, that is, when a sequence of pulses was administered. The power of a rectangular pulse is simply the product of the voltage, U, across times the current, I, through the myocardial path. For a sequence of two pulses (as for example A1 and A2, in Figure 1), the mean power delivered by the total discharge is given by,

$$P_{md2} = 2\ U\ I\ [t_1/(2t_1 + t_2)] \qquad (1)$$

while, for a sequence of four pulses (as for example A1, B1, A2 and B2, in Figure 1), and irrespective of the different generators or electrode pairs), the mean power is described by,

$$P_{md4} = 4\ U\ I\ [t_1/(3t_1 + t_2)] \qquad (2)$$

showing in both cases that t_2, when much longer than t_1, may reduce significantly the total power absorbed by the myocardium.

RESULTS

Table 1 summarizes the numerical results obtained for each group and for all the population using the three defibrillation modes. Each value represents the overall average for the group with its standard deviation SD. Letters ND and NS stand, respectively, for "number of discharges" and "number of successful discharges". The last row in each group is the ratio between the two previous values. As expected, it is about 50% because threshold values were sought i.e., by definition, a threshold is a value with 50% probability of success.

In Group G1 and with method K, current and energy were highest (2.1 A and 7.6 J, respectively) as compared to the values produced by methods JB and DANTE. For Group G2, instead, current showed relatively small differences between methods. DANTE yielded the highest energy level (7.2 J) and JB the lowest (3.0 J). Considering both groups pooled together, the highest current belonged to method K (1.8 A) and the lowest energy was yielded by mode JB (3.9 J). For DANTE, current scaled to ventricular weight was lowest in Groups G1 and (G1+G2) but not in Group G2.

The mean power delivered by the total discharge, however, showed striking differences when method JB is compared either with K or with DANTE. The reason is the very short interval t_2 employed by JB (see equations 1 and 2). As expected, in all cases the single pulse delivered power was higher than the mean power.

DISCUSSION

The first question to consider is whether the multiple pulse defibrillation (either with method K, JB or DANTE) is better than the traditional single pulse procedure. One way of evaluating them is by comparing thresholds. However, this leads to the old question of the electrical parameter to be used, that is, voltage, current or energy. Another possibility is to measure the efficacy of defibrillation, i.e., for a given electrical value to determine which method yields the highest percentage of successful defibrillations. Once again, we must select one of the electrical parameters.

Using data from Armayor et al [1979] for defibrillation with simple capacitor discharge in canine hearts via transventricular paddles (30 cm^2), the following average thresholds values can be offered for comparison: peak voltage=277 V, peak current=10.7 A, peak current to heart weight=0.09 A/g, energy=2.83 J, power=815 W (taking 2 time constants as duration of the shock).

For multiple pulses (Table 1), all the values of voltage and current are considerably lower than those given above. Energy, instead, is lowest for the capacitor discharge (2.83 J versus a range of 3.0 to 7.6 J) irrespective of the group, meaning that the electrode lead did not have any apparent influence. As a consequence, we can state that defibrillation discharges of more than one pulse require higher energies but lower currents. However, Jones et al [1985, 1988] reached an opposite conclusion. Current density distribution may have played a role in this discrepancy.

If high currents are responsible of electrophysiological injury (and we think they are), then any multiple pulse defibrillation is less harmful than a single pulse shock, even though the delivered energy of the former is, or may be, greater than that of the latter. The important difference lies in the fact that a multiple pulse discharge energy is distributed over a longer time. Thus, power would appear as a suitable parameter. From the values of Armayor et al [1979], we obtained an average power of 815 W, much higher than any of the mean power values reported in Table 1 for multiple pulses. Besides, the latter mean values are always lower than the single pulse values delivered per pulse (see equations 1 and 2).

It can be stated that peak current would be the best electrical parameter to assess defibrillation thresholds and efficacy of defibrillation methods. Moreover, a multiple pulse discharge applies the required energy keeping a beneficial low peak current. Nontheless, when discharges of different duration are to be compared, power would appear as a good parameter to assess the defibrillatory act. The search to reduce the electrical parameters in implantable defibrillators should be oriented toward a decrease in delivered power rather than in energy.

The number of measurements we have are still insufficient to obtain valid conclusions regarding the best multiple pulse defibrillating method.

In conclusion: (1) Single pulse shocks administer current and voltage values above the required levels to revert fibrillation. (2) Multiple shocks appear as valid alternative to decrease the electrical parameters (voltage, current and power), with equal or increasing energy, but always distributed over a longer period. (3) Impedance measurement of the defibrillatory path is useful to dose the electric discharge and so avoiding excessive currents.

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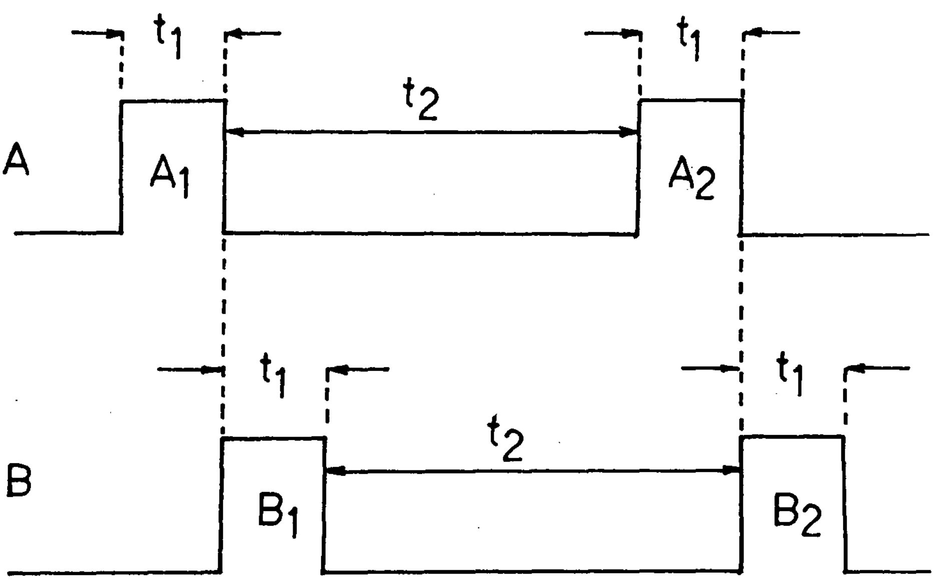

FIGURE 1. Angular-Temporal Defibrillating Discharge. Pulses Ai and Bi are generated by the stimulators and are delivered, respectively, via leads A and B (see text).

TABLE 1 - AVERAGE DEFIBRILLATION VALUES

GROUP G1 (5 dogs)	**K**	**JB**	**DANTE**
VOLTAGE (V)	160(35)	152(39)	118(38)
CURRENT (A)	2.1 (0.3)	1.5(0.36)	1.19 (0.34)
AMPERES/GRAM	0.032 (0.012)	0.025 (0.011)	0.021 (0.011)
ENERGY (J)	7.6 (1.3)	4.6 (1.5)	5.8 (2.8)
PULSE POWER (W)	337(88)	245(89)	157(80)
MEAN POWER (W)	63(10)	230(75)	48(21)
ND	31	49	106
NS	14	21	39
NS/ND (%)	45	43	37
GROUP G2 (4 dogs)	**K**	**JB**	**DANTE**
VOLTAGE (V)	129(29)	108(25)	110(27)
CURRENT (A)	1.3 (0.5)	1.2(0.56)	1.51(0.7)
AMPERES/GRAM	0.015 (0.009)	0.015(0.006)	0.017 (0.004)
ENERGY (J)	3.5 (1.7)	3.0 (1.7)	7.2 (4.5)
PULSE POWER (W)	175(85)	181(121)	200 (127)
MEAN POWER (W)	29(14)	150(85)	55(34)
ND	13	30	57
NS	8	15	25
NS/ND (%)	61	50	44
GROUPS (G1+G2) (9 dogs)	**K**	**JB**	**DANTE**
VOLTAGE (V)	148(35)	133(40)	115(34)
CURRENT (A)	1.8 (0.5)	1.4(0.51)	1.3(0.56)
AMPERES/GRAM	0.026 (0.014)	0.021 (0.011)	0.02 (0.01)
ENERGY (J)	6.1(2.5)	3.9(1.7)	6.4(3.6)
PULSE POWER (W)	278(116)	218(108)	156 (80)
MEAN POWER (W)	50(21)	195(85)	49(28)
ND	44	79	163
NS	22	36	64
NS/ND (%)	50	45	40

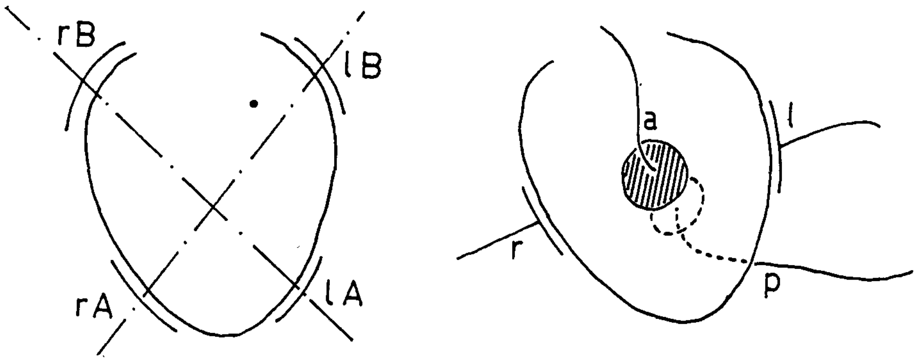

FIG 2. Defibrillating Leads. Left: G1, minimum impedance, right base-left apex (rB-lA) and left base-right apex (lB-rA). Right: G2, minimum impedance, anterior-posterior (a-p) and left-right (l-r).