

Electrical Dose for Ventricular Defibrillation of Large and Small Animals Using Precordial Electrodes

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ABSTRACT Electrical ventricular defibrillation of heavy subjects (over 100 kg body weight) is uncommon for the human or any animal species. This paper reports trans-chest ventricular defibrillation of subjects ranging in weight from 2.3 to 340 kg using conventional defibrillation current (heavily damped sine wave) of 0.3–30 ms duration. It was found that a body weight-to-electrical-shock strength relationship exists and can be expressed in terms of either electrical energy or peak current. For the duration of current pulse used clinically (3–10 ms), the relationship between energy requirement and body weight is expressed by the equation $U = 0.73 W^{1.62}$, where U is the energy in $W \cdot s$ and W is the body weight in kilograms. The current relationship is $I = 1.87 W^{0.88}$ where I is the peak current in amperes and W is the body weight in kilograms. The energy dose is somewhat more species and weight dependent and ranges from 0.5 to 10 $W \cdot s/kg$ (0.23–4.5 $W \cdot s/lb$). The data obtained indicate that the peak current dose is virtually species and weight independent and is therefore a better indicator than energy for electrical defibrillation with precordial electrodes. In the duration range of 3–10 ms, the electrical dose is very nearly 1 A/kg of body weight (0.45 A/lb).

INTRODUCTION

Until 1970 no reports of successful transthoracic ventricular defibrillation of a human subject weighing over 100 kg were found in a review of the published literature (1); this survey presents the energy vs. body-weight data appearing in all of the published literature dating from 1899 to 1970. Since that review we have located a report (2) which describes the successful defibrillation

of one female subject weighing over 237 lb using 300 $W \cdot s$. We know of one successful defibrillation of a 200 lb human male subject who required multiple 400- $W \cdot s$ countershocks. Defibrillation of heavy subjects may be so commonplace that they are not reported; however, correspondence with numerous cardiologists has revealed that defibrillation of such subjects has been achieved infrequently. Their experience, plus the lack of published data indicate that success must be rare in heavy subjects. A possible explanation for failure to defibrillate such subjects is that existing commercially available defibrillators (400 $W \cdot s$) do not provide an adequate electrical output. There have been four recent reports (3–6) which have documented that virtually all commercially available defibrillators deliver substantially less energy than is indicated by their dial settings. Therefore published values of energy used for defibrillation are higher than those that are actually delivered to the subject. However, it may be unfair to criticize low defibrillator output too strongly because there have been no studies which quantify the electrical "dose" (i.e., energy) needed to defibrillate subjects of widely differing body weights. We have been unable to ascertain why the 400 $W \cdot s$ figure was chosen as the maximum energy for commercially available defibrillators. The study reported herein presents data on the threshold values for delivered energy and peak current necessary to defibrillate mammalian subjects weighing 2.3–340 kg and, in fact, shows that 400 $W \cdot s$ is an inadequate energy for the defibrillation of heavy subjects using precordial electrodes. However it will be shown that many of the presently available 400- $W \cdot s$ defibrillators, which deliver less than this output, can defibrillate heavy subjects if the electrode-subject impedance is reasonably low, indicating that energy may not be the best descriptor for the electrical dose required for defibrillation.

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METHODS

The current waveform employed for ventricular defibrillation is that which is presently used in clinical medicine (1, 3-5, 7) namely a heavily damped sine wave, i.e., a

rounded pulse approximating a half-sinusoid in which the duration in each particular case depends upon the design of the defibrillator and upon the electrode-subject impedance (7). To investigate the importance of the duration

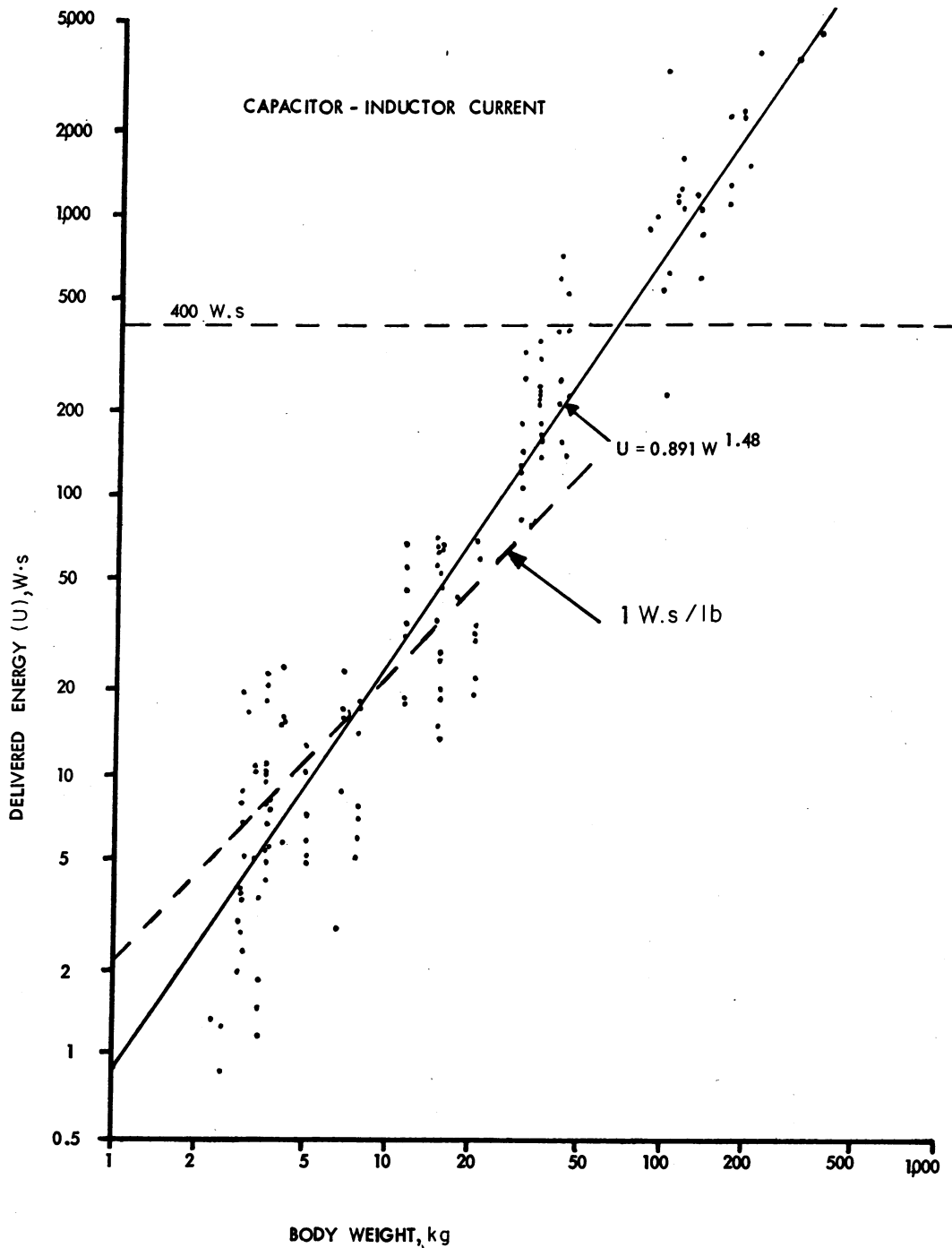


FIGURE 1 Threshold (delivered) energy required to defibrillate subjects of various body weights for all durations (0.3-30 ms). The dashed line represents the energy dose (1 W·s/lb) used by some pediatric cardiologists.

TABLE I
Defibrillation Data

Animal species	Body weight	Delivered energy	Peak current	Pulse duration	Heart weight	Animal Species	Body weight	Delivered energy	Peak current	Pulse duration	Heart weight
	<i>kg</i>	<i>W·s</i>	<i>A</i>	<i>ms</i>	<i>g</i>		<i>kg</i>	<i>W·s</i>	<i>A</i>	<i>ms</i>	<i>g</i>
Rabbit	2.3	1.33	0.8	12.0	5.0			7.03	5.2	12.0	
								10.2	5.2	15.0	
	2.5	0.83	3.0	4.0	5.75			12.6	5.0	30.0	
							6.5	2.8	8.0	1.5	55
	2.8	3.80	4.0	0.3	6.0			8.7	11.0	3.0	
		2.98	6.5	0.8				17.0	10.5	10.0	
		1.94	4.5	1.75				16.0	8.5	15.0	
		2.69	4.6	3.0				23.4	10.5	25.0	
		3.51	4.75	3.5				17.0	6.5	35.0	
		3.74	4.4	5.0			7.5	5.8	7.0	2.5	60
		6.85	5.0	10.0				7.7	7.0	8.0	
		7.90	4.8	17.0				5.0	4.5	12.0	
		19.9	7.0	20.0				6.9	4.5	16.0	
		2.9	2.3	4.8	2.5	6.5		14.0	6.0	25.0	
			5.1	5.2	8.0			18.6	6.8	30.0	
			8.5	5.5	12.0			17.1	6.0	35.0	
			16.9	6.8	25.0						
		3.2	4.96	4.5	10.0	8.0	11	18.5	16.0	2.0	95
								18.3	12.5	5.0	
		3.2	10.4	9.25	3.0	7.6		31.5	15.0	8.0	
			10.5	7.5	8.0			34.4	15.5	11.0	
			10.6	7.0	12.0			45.7	15.5	16.0	
								55.1	15.0	20.0	
		3.5	4.2	8.25	0.75	8.1		66.9	15.5	24.0	
			4.8	6.5	2.0						
			10.9	7.25	8.0		14.5	15.0	14.5	2.5	120
			10.5	7.5	13.0			26.7	16.5	4.0	
		18.7	7.0	20.0			35.5	17.0	8.0		
		23.2	7.0	30.0			53.5	19.5	10.0		
							64.9	19.0	12.0		
	3.4	1.14	4.0	0.7	7.5		63.1	18.0	16.0		
		1.44	3.4	3.0			70.1	18.0	19.0		
		3.6	4.0	8.0			56.1	14.5	24.0		
		1.81	2.1	13.0		15	20.6	16.0	2.5	110	
Dog	3.5	7.8	5.5	0.4	34		13.4	11.5	4.0		
		10.2	11.0	1.0			27.6	13	8.0		
		5.39	7.4	1.5			18.8	11.0	10.0		
		9.27	9.8	2.75			46.6	12.5	12.0		
		10.3	8.8	3.5			65.8	12.5	15		
		5.37	5.6	5.0							
		6.55	7.0	6.0		17	33.2	16.5	7.0	150	
		7.48	6.0	7.0							
		10.5	7.4	10.0		20	22	18.0	2.5	185	
		20.9	8.4	22.0			30	16.0	5.5		
		7.89	4.4	23.0			31	15.0	7.5		
							19	12.0	8.5		
		4.0	15.6	17.0	0.5	48		34	13.0	10.5	
			24.1	10.0	1.5			22	11.0	17.0	
			15.5	13.8	3.5			59	14.0	20.0	
			15.9	7.8	6.0			68	12.5	25.0	
							41	136	50.0	2.0	360
		5.0	5.14	9.0	1.0	42		224	58.0	3.5	
			5.82	6.5	3.0			380	57.0	8.0	
			4.83	5.2	8.0			522	56.0	15.0	

TABLE I—(Continued)

Animal species	Body weight	Delivered energy	Peak current	Pulse duration	Heart weight	Animal species	Body weight	Delivered energy	Peak current	Pulse duration	Heart weight		
	<i>kg</i>	<i>W·s</i>	<i>A</i>	<i>ms</i>	<i>g</i>		<i>kg</i>	<i>W·s</i>	<i>A</i>	<i>ms</i>	<i>g</i>		
Goat	29	179.1	64	1.5	142	Pony	80	594	56	16.5	Horse		
		80.0	40	2.5				94	227	87		4.0	730
		104.0	38	4.0			90		514	70		8.0	
		126.4	44	5.0				104	1,046	130		5.5	524
		123.5	39	5.5			105		1,528	140		8.0	
		325.0	56	7.0				123	846	160		3.5	1,135
		140.5	37	9.0			155		1,003	135		8.0	
	260.7	40	11.0	175	581			85	11.5	1,630			
	33	220.3	72		1.0		139	181	1,082			130	4.0
			211.7	69	1.5				193	2,251		140	7.0
			179.1	63	2.0	340		1,247		100	10.0	3,150	
			211.5	55	4.0			277	2,250	120	8.0		2,460
			242.8	62	4.5	340			2,232	125	8.0	3,150	
			159.7	44	5.0			340	1,474	120	7.0		3,150
			211.4	55	5.5	340			3,687	250	6.5	3,150	
	353.8	62	6.0	340	277		3,463	350	7.0	3,150			
	302.7	57	7.0		340	340	4,535	280	6.8		3,150		
	217.8	65	8.0	340		340	4,535	280	6.8	3,150			
	231.4	49	9.0		340	340	4,535	280	6.8		3,150		
	136.5	32	11.0	340		340	4,535	280	6.8	3,150			
33	163	43	7.0		140	340	4,535	280	6.8		3,150		
		39	153	60						3.5		110	
				258						65			5.5
				208						56			7.5
				384						68			10.0
702	75			11.0									

of the current pulse, the range of durations used for this study (0.3–30 ms) exceeds that presently employed in clinical medicine, which is 3–10 ms. The studies cited above (3–6) revealed that among 13 manufacturers, only two provided defibrillators with durations slightly outside this duration range.

The defibrillator employed was especially constructed for this study (7) and has a maximum energy-storage capacity of 5,000 W·s. The capacitance bank in it allows selection of values ranging from 0.5 to 100 μ F which can be charged from 0 to 10,000 V and the inductance values which can be selected are 0, 11, 29, and 63 mH. The total internal resistance of the defibrillator depends on the inductor used, and is 4.46, 3.81, and 3.31 Ω respectively for the three inductance values available. Both current and voltage-measuring circuits are contained in the defibrillator and the complete operating characteristics are known so that the energy actually delivered¹ to the subject could be calculated. All energy values presented in this report are delivered energy rather than indicated energy.

Rabbits, puppies, dogs, goats, ponies, and horses were studied. The small animals were anesthetized with sodium

¹In any defibrillator, the delivered energy is always less than the stored energy because energy is consumed by the internal resistance of the defibrillator. In a well-designed defibrillator, the internal resistance is low and the delivered energy is very nearly the stored energy.

pentobarbital (30 mg/kg i.v.) and the large animals were anesthetized with a mixture of halothane, nitrous oxide, and oxygen, after anesthesia had first been induced with intravenous glycerol guaiacolate. Arterial blood pressure, lead II electrocardiogram (ECG) and the impedance pneumogram were recorded continuously. In the large animals, the electroencephalogram (EEG) was also recorded as an aid in controlling the depth of anesthesia and evaluating recovery; pH was monitored intermittently to evaluate the acid-base status of the animals and sodium bicarbonate was given as needed to maintain an arterial pH above 7.30. Before each ventricular fibrillation-defibrillation trial, the animals were well ventilated to minimize the effect of hypoxia on defibrillation threshold.

In some of the small animals, ventricular fibrillation was induced by applying 60 Hz current to limb electrodes (8); the remaining small animals and all the large animals were fibrillated by applying 2-ms pulses of 25 V intensity with a frequency of 50 Hz to a catheter passed into the right ventricle via the right jugular vein. Fibrillation was confirmed by a loss of blood pressure and replacement of the QRS-T complex of the ECG by fibrillation waves.

Defibrillation was achieved by applying capacitor-inductor current to soft lead-plate electrodes implanted subcutaneously; this technique was employed to guarantee a stable low-impedance contact. One electrode was located just to the right of the manubrium, the other was over the area of

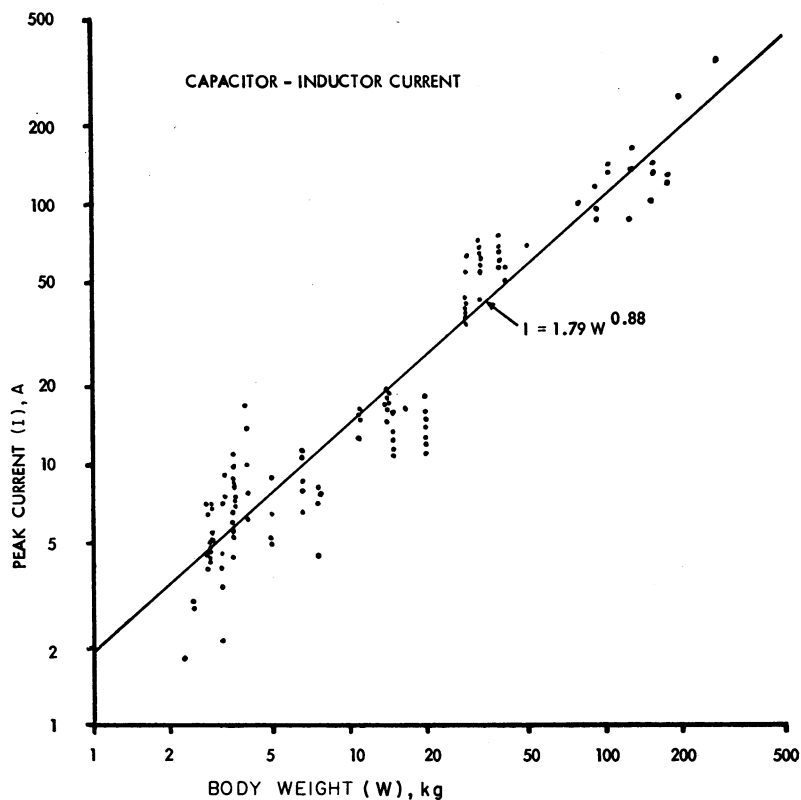


FIGURE 2 Threshold peak current required to defibrillate subjects of various body weights for all durations (0.3–30 ms). The dashed line represents a current dose of 1 A/kg of body weight.

the apex beat of the heart. Defibrillation trials were conducted immediately after the confirmation of fibrillation. The method of defibrillation consisted of choosing a voltage, which was judged to be appropriate for the animal's size, and discharging the capacitor-inductor circuit in the defibrillator through the electrode-animal circuit. When defibrillation was achieved, the animal was allowed to recover before refrillation and a second defibrillation trial with 10% less voltage was attempted. Restoration of the EEG and blood pressure to near control levels were used as signs of recovery. In most cases, arterial pH samples were monitored. Threshold testing was repeated until defibrillation could no longer be achieved. When this occurred, the voltage was increased to a level adequate to defibrillate the ventricles. If the initial defibrillation trial failed, the voltage was similarly increased in increments of 10% until defibrillation occurred. For each duration of current pulse, the lowest voltage and current capable of achieving defibrillation were taken as threshold values. From the voltage, current, duration, and the internal circuit constants of the defibrillator (inductance, capacitance, and resistance), the electrode-subject impedance was calculated and thus, the essential information was available for calculation of the energy actually delivered to each animal (7).

With inductor-capacitor defibrillators the duration of the defibrillating current pulse is a function of inductance and capacitance and subject impedance (7). Various inductance and capacitance combinations were used to obtain a wider range of pulse duration (0.3–30 ms) than is employed in

human defibrillation in order that the full clinical range could be evaluated. Data from a previous study (9) using dogs, had shown that a 3–8 ms duration range requires minimum energy and current.

In all, 35 animals ranging in weight from 2.3 to 340 kg (5–750 lb) were employed. Over 750 fibrillation-defibrillation trials were performed, resulting in the establishment of 144 paired threshold values for delivered energy and current.

RESULTS

Table I presents the threshold-delivered energies and peak currents used to defibrillate all of the animals studied. The values for threshold energy and body weight for the entire duration range (0.3–30 ms) are plotted in Fig. 1; the least-squares line for the data points was found to be $U = 0.891 W^{1.48}$ with a correlation coefficient of 0.945. In this expression, U is the delivered energy in watt-seconds and W is the body weight in kilograms. Similarly, the data points for peak current for the entire duration range (0.3–30 ms) were plotted vs. body weight, and are shown in Fig. 2; the least-squares line for these points is $I = 1.79 W^{0.88}$, with a correlation coefficient of 0.943. In this expression, I is the peak current in amperes and W is the body weight

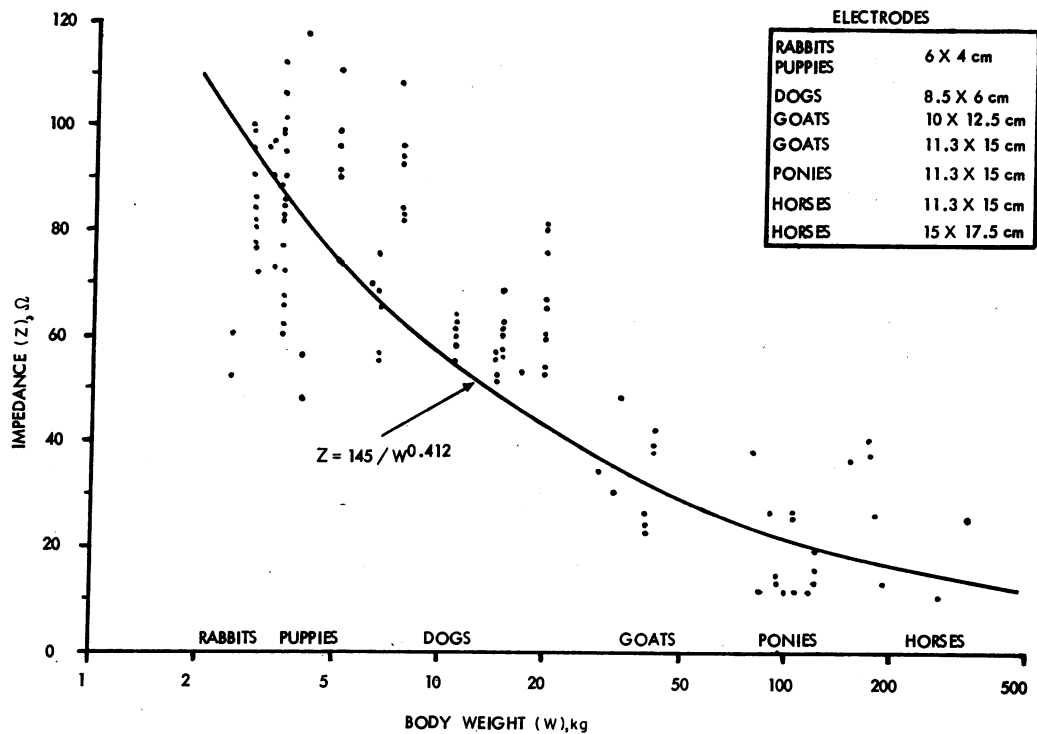


FIGURE 3 Impedance appearing between the terminals of the subcutaneous defibrillating electrodes during passage of the defibrillating current through the animals of various body weights.

in kilograms. The data points shown in Figs. 1 and 2 represent values for all of the durations listed in Table I.

Fig. 3 presents the calculated values for the impedance (Z) appearing between the electrode terminals during passage of the defibrillating current for the various animals. The data points were subjected to a least-squares fit to obtain the following relationship $Z = 145/W^{0.412}$, where Z is the impedance in ohms and W is the body weight in kilograms. The correlation coefficient obtained was 0.865. The size of the electrodes used was dictated by the body weight; the electrode dimensions are shown in Fig. 3 inset.

DISCUSSION

Figs. 1 and 2 indicate that for the entire duration range (0.3–30 ms), there is a direct relationship between threshold energy and peak current vs. body weight, thereby indicating that two dose concepts are identifiable, energy per kilogram and peak current per kilogram. These data also show that it is possible to achieve defibrillation with pulse durations longer and shorter than those presently in clinical medicine (3–10 ms). However before quantification of these two dose concepts and comparing the animal data to man, it is necessary to recognize that the duration of the pulse of defibrillating cur-

rent importantly affects the threshold energy and peak current required for defibrillation (9). To elucidate this point and to minimize the effect of body weight, the energy and peak current values for each species were normalized by division by body weight; these dosage values (energy per kilogram and peak current per kilogram) were then plotted vs. the duration of the current pulse. Fig. 4 and 5 present these normalized data for each animal species.

Inspection of Fig. 4, which shows the curves for the threshold-delivered energy per kilogram for each species plotted vs. the duration of the pulse of current, reveals that there is a slight tendency for the energy required to be a minimum in the region of 2–5 ms. The fact that the curves for the different animals do not lie on top of each other indicates that there is either a species difference or that the energy dose (watt-seconds per kilogram) is larger for heavier animals. Without debating this issue, in the 2–5 ms duration range the energy dose for the lightest animals (rabbits) is 0.5 $W \cdot s/kg$ and for the heaviest animals, it is 10 $W \cdot s/kg$.

Fig. 5, which illustrates the threshold peak current per kilogram of body weight for each species vs. current pulse duration, shows that the threshold peak current per kilogram body weight tends to have a minimum in the

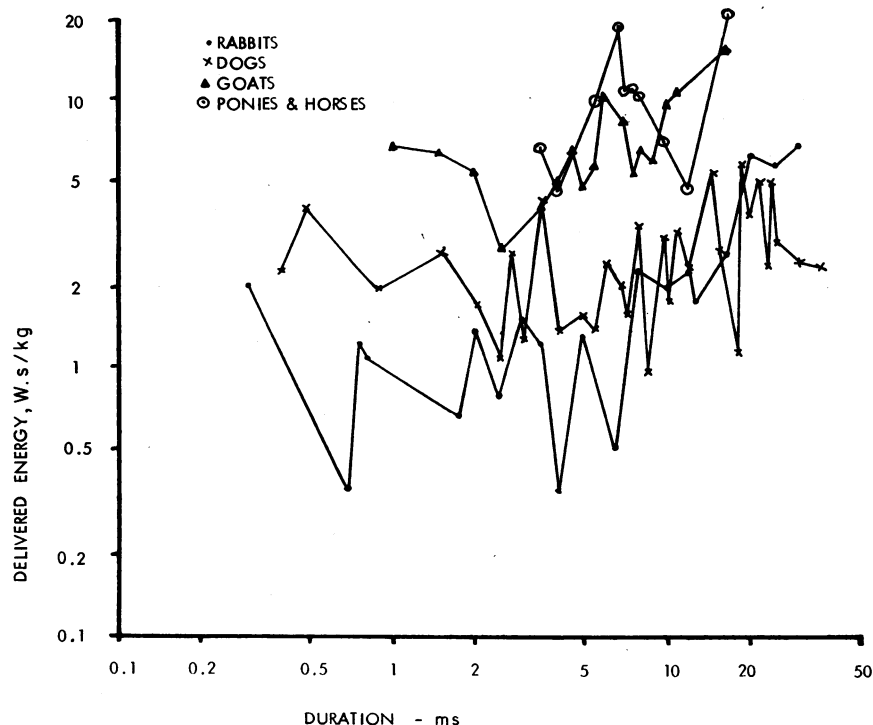


FIGURE 4 Threshold delivered energy per kilogram of body weight vs. duration of defibrillating current for different animal subjects. Note that the curve for each species exhibits a slightly different strength-duration relationship, indicating that this dose concept is relatively species and weight dependent.

range of 5–10 ms. With a pulse in this duration range, the electrical dose required varies between 0.5 and 2.0 A/kg of body weight for the largest and smallest animals. However, more importantly, this illustration shows that the dose criterion of peak current per kilogram of body weight is virtually species and body-weight independent since the curves for the differing species and weights are almost superimposed.

With these animal data in mind, it is useful to relate them to human defibrillation which employs capacitor-inductor discharge current ranging from 3 to 10 ms in duration. Using the energy and peak current data shown in Table I for this range of durations provides the relationship $U = 0.73 W^{1.68}$ for energy and $I = 1.87 W^{0.88}$ for current; the correlation coefficients are 0.967 and 0.968, respectively. In these expressions U is the delivered energy in watt-seconds, I is the peak current in amperes, and W is the body weight in kilograms. Figs. 6A and 6B present both relationships. It must be emphasized that these relationships are for delivered energy and current and for the average subject without known cardiac disease.

With the data in Fig. 6 in view, it is now feasible to relate these animal data to human defibrillation values. From the energy relationship ($U = 0.74 W^{1.62}$) for the

clinical range of pulse durations, it is seen that 472 W·s of energy are required to defibrillate the average 70 kg subject. In view of the fact that 70 kg subjects are routinely defibrillated with existing 400-W·s defibrillators, there is a seeming paradox, particularly in view of the fact that such defibrillators provide less than their indicated energy (3–6). An explanation for the paradox can be found by examining the current requirements ($I = 1.87 W^{0.88}$). For example from this equation, a 70 kg subject requires 78 A and a 100 kg subjects requires 107 A. In other words, the current dose is very nearly 1 A/kg of body weight for adults. Therefore examination of defibrillator output current is in order at this point.

The relationship between energy and peak current is dependent on the design of the defibrillator and the electrode-subject impedance. The capability for current output of present-day defibrillators was measured by Ewy, Fletcher, and Ewy (6). Using the data from his investigation, Fig. 7 was composed to show the peak current that can be delivered to various resistive loads when defibrillator output controls were set to a maximum (400 W·s). Inspection of Fig. 7 reveals that the peak current required for a 70 kg subject can be attained easily if the equivalent electrode-subject resistance is low

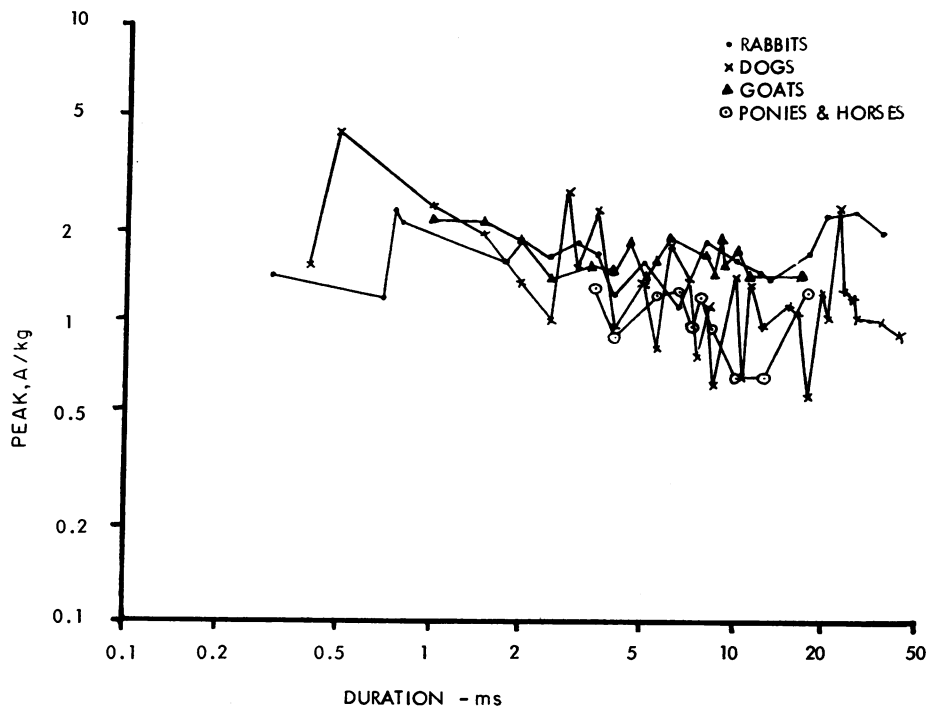


FIGURE 5 Threshold peak current per kilogram of body weight vs. duration of defibrillating current for different animal subjects. Note that the curves for all species measured are almost superimposed, indicating that this dose concept is almost totally species and weight independent.

enough. For the best defibrillator² (no. 6) this current can be attained with a subject resistance as high as 67 Ω . The resistance values for the next best defibrillators (nos. 3 and 7) are 37 and 21 Ω , respectively. The fourth defibrillator tested could not provide this required current.

It is important to note that there are no hard data on the equivalent resistances appearing between the electrode terminals during passage of the defibrillating current. It was for this reason that Fig. 3 was composed to show the practical order of magnitude using electrodes appropriate for the size of a subject. Quite apparent is the fact that with subjects in the weight range of 70 kg, resistance values of 10–40 Ω were obtained. Although, in this study the electrodes were implanted subcutaneously, the values encountered with electrodes applied to the surface of the skin with low-resistivity (10) electrode paste (ca 10 Ω -cm) were found to be only about 10% higher (unpublished data).

It is of some interest to speculate on the relationship of decreasing impedance with increasing animal weight. Two factors underlies this relationship. As heavier animals are encountered, the thorax becomes larger and consequently the electrodes become further apart, thereby increasing the impedance. However, when larger animals

²The numbers correspond to the figure numbers in the paper by Ewy et al.

are encountered, larger electrodes are employed which would result in a decrease in impedance in proportion to electrode area. Thus, on the basis of these two factors, it is not too surprising to encounter a decreasing impedance with increasing subject weight. Fortunately, this is highly desirable because the same defibrillator when set to full output will deliver more current to the heavier subjects who require higher current than the relatively lighter subjects.

Therefore it can be seen that even if existing defibrillators do not deliver their rated energy values, ventricular defibrillation is achievable if the electrode-subject impedance is low enough, indicating that peak current is a better criterion than energy for defining the electrical dose required for ventricular defibrillation. If energy is used to express the dose required, then it can be seen from Figs. 1 and 6A that for children in the pediatric dose of 2.2 W·s/kg. (1 W·s/lb) is consistent with the animal data reported herein. Note that for adult subjects, the energy dose increases to 5–10 W·s/kg of body weight (2.3–4.6 W·s/lb), as shown in Fig. 6A.

If peak current is used to specify the electrical dose for ventricular defibrillation, Fig. 6B presents the current required for different body weights. Note that the current dose is approximately 1 A/kg of body weight. Light subjects require slightly more current and heavy subjects require a current dose which is slightly smaller.

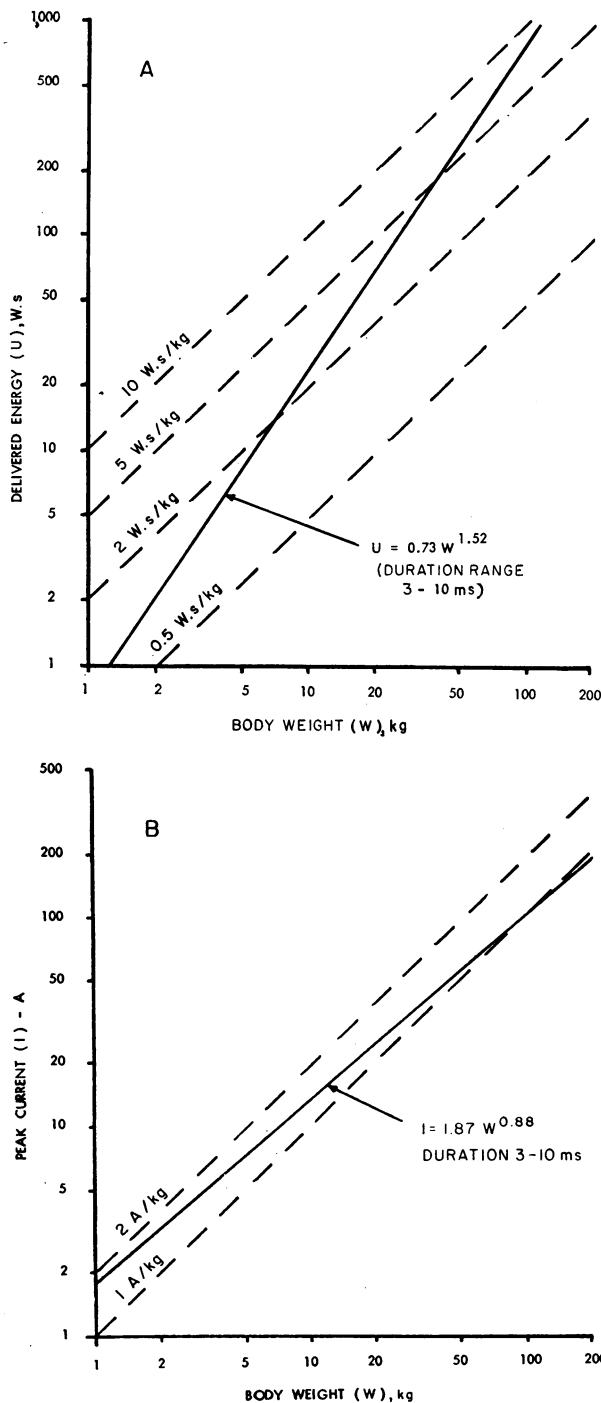


FIGURE 6 Energy (A) and peak current (B) required for defibrillation using the duration of current pulse employed in clinical medicine (3-10 ms).

The fact that disproportionately more energy per kilogram is required to defibrillate the ventricles of large animals than those of small animals is difficult to ex-

plain if successful defibrillation requires that the same current density be achieved within the ventricular myocardium. Delivered energy is proportional to the subject voltage, current and duration of the current pulse. However for the same threshold data point, focusing on current alone disregards the voltage that was needed to obtain the current. Therefore to obtain the same myocardial current density, there appears to be a disproportionate need for voltage with increasing body weight.

It is of some interest to speculate on the effect of animal and heart weight on the requirements for defibrillation as identified in Figs. 4 and 5 which present the energy per kilogram and peak current per kilogram data. Fig. 4 shows that the rabbits required the least energy per gram and Table I shows that for all species, the rabbits had the smallest heart to body weight ratio (about 0.22%). The ponies and horses, with a heart-to-body-weight percentage of about 0.85, required much higher energy per kilogram of body weight. In the case of the current requirement, as shown in Fig. 5, it can be seen that all species and weights required essentially the same current per kilogram of body weight, despite the wide range of heart to body weight percentage (0.22-1.2), indicating again that current is a better descriptor for the electrical dose for ventricular defibrillation.

Beyond the desire to obtain beating ventricles there is,

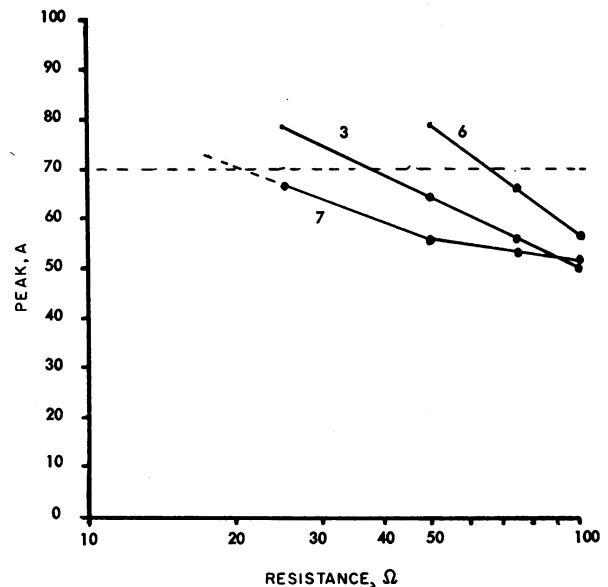


FIGURE 7 Measured output current capabilities of three commercially available defibrillators connected to various resistive loads. None of these defibrillators delivered their rated energy, yet all are capable of providing enough current for the defibrillation of a 70 kg subject using the 1 A/kg criterion providing the electrode-subject resistance is low enough. The numbers in the illustration refer to the numbered figures in the original paper by Ewy et al. (6).

at present, really no agreement on the best criterion for the specification of optimum defibrillation. Mackay and Leeds (11), on the basis of a study of dogs weighing 8-12 kg, showed that electrical energy was the appropriate electrical parameter for indicating the requirement for defibrillation. Others (12-14, 16) have proposed that the current that flows is a better descriptor for the electrical dose required for defibrillation. Without arguing the issue of the superiority of current over energy for specifying the dose for ventricular defibrillation, Fig. 6 shows that for subjects up to about 7 kg, the energy dose is 2 W·s/kg; from 7 to 40 kg the dose ranges from 2 to 5 W·s/kg. Above 40 kg, the dose is 5-10 W·s/kg. The corresponding current dose level is between 1 and 2 A/kg for all weights up to about 100 kg; slightly less current/kg is needed for heavier subjects. The authors wish to emphasize the fact that the data provided herein refer to the presently used capacitor-inductor waveform of current and other current waveforms may require more or less energy and current for defibrillation.

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