Scaling Current and Energy with Body Weight:
Requirements for the Transthoracic Ventricular
Defibrillation of Calves as They Grow from 50 to 150 Kg

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SUMMARY To test the hypothesis that the effectiveness of a shock in achieving ventricular defibrillation is relatively independent of body weight if electrode diameter is proportional to the one-third power and current is proportional to the two-thirds power of weight, we studied defibrillation rates in 10 calves as they increased in weight. At 50 kg, each calf was subjected to 20 fibrillation-defibrillation episodes using 10.3-cm diameter electrodes and 32-amp, 4-msec rectangular pulses for defibrillation. Two days after the original study, each calf underwent 20 additional episodes involving 44-amp pulses. With the specified scaling of electrode diameter and pulse amplitude, the two studies were repeated at weight intervals of 25 kg as the animals grew. Six calves survived. In the study that started with 32-amp pulses, first-shock success values of 28%, 49%, 66%, 51% and 23% were found in the six surviving calves at 50, 75, 100, 125 and 150 kg, respectively. The corresponding values were 92%, 96%, 93%, 94% and 91% in the study that started with 44-amp pulses. While the results of the 32-amp study fail to support our initial hypothesis, those obtained in the 44-amp current study appear compatible with the hypothesis.

Theoretical Considerations

We assume an idealized situation in which each linear dimension of the larger subject is \( \alpha \) times that of the smaller subject (fig. 1). The diameter of the chest electrodes used with the larger subject is \( \alpha \) times the diameter of the electrodes used with the smaller subject and the electrodes are positioned similarly on the two subjects. The physical density and electrical conductivity at each point within the larger subject is the same as at the corresponding point within the smaller subject. Homogeneity is not postulated; both physical density and electrical conductivity are assumed to vary with spatial position.

To realize the conditions outlined in the previous paragraph, the diameter (d') in meters of the electrodes used with the larger subject must be related to the diameter (d) of the electrodes used in the smaller subject by

\[
d' = \left( \frac{m'}{m} \right)^{1/3} d
\]

where \( m' \) is the weight (more technically, the mass) in kilograms of the larger subject and \( m \) is the weight of the smaller subject. If, in addition, the instantaneous current (I') in amperes into the larger subject is adjusted so it relates to the instantaneous current (I) into the smaller subject by the relationship

\[
I' = \left( \frac{m'}{m} \right)^{2/3} I
\]

the instantaneous current density vectors at corresponding points within the myocardium and elsewhere within the two subjects will be everywhere identical. Furthermore, if \( V \) and \( V' \) are the instantaneous potential differences in volts between the two chest electrodes, \( R \) and \( R' \) are the electrode-to-

CAN THE PARAMETERS of a transthoracic shock be scaled to achieve substantially equivalent results in defibrillating subjects of widely different weights? If so, how should the scaling be carried out? These questions are important as we strive to improve techniques for adequate defibrillation using shocks that have the least potential for harm and to reconcile the apparently divergent viewpoints of different investigators.1-7

In an earlier paper, an analytical scaling procedure was derived for transforming transthoracic defibrillation experience with one size subject of a given species to a different size subject of the same species.8 This procedure is based on an idealized physical model and the assumption that the heart's response to electroshock is a function of the current-density vector within the myocardium. Accordingly, we could, for example, formally transform experimental data from extensive experiments in medium-sized dogs9-12 to apply to a hypothetical 100-kg dog.8 We have used such transformed data to compare the results in studies conducted in dogs with results in studies involving 100-kg calves.13 In this paper we summarize our analytical procedure and describe an experimental study in which the validity of our procedure was tested in calves as they grew through the 50 to 150 kg range.

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electrode resistances in ohms, and \( U \) and \( U' \) are the delivered energy levels in joules in the smaller and larger subjects, respectively, then

\[
V' = \left( \frac{m'}{m} \right)^{1/3} V \quad (3)
\]

\[
R' = \left( \frac{m'}{m} \right)^{-1/3} R \quad (4)
\]

and

\[
U' = \left( \frac{m'}{m} \right) U \quad (5)
\]

when equations 1 and 2 are satisfied. The derivation of equations 1-5, using the approach from the reference cited, is sketched in the appendix of the present paper.

If — and this is by no means certain, a priori — equality of the current density vector at corresponding points within the myocardiums of subjects of different sizes also implies the same cardiac response in terms of defibrillation effectiveness, post-defibrillation electrocardiographic findings, and cardiac injury, equations 1-5 are a simple way to scale and transform defibrillation data or experience observed at one body weight (m) to apply to another body weight (m'). In the transformation of data shown in tabular or graphical form, time, general waveform shape and indices of cardiac response are invariant, while electrode diameter, current, voltage, resistance and delivered energy are modified as given by equations 1-5.

**Methods**

**Equipment**

An ultra high-energy hydrogen thyratron/silicon-controlled rectifier research defibrillator\(^{13,14}\) was used to supply a 1-second, 60-Hz shock for inducing fibrillation, the 4-msec, rectangular waveform being evaluated, and a highly effective follow-up shock to salvage the calf if the waveform being studied failed to defibrillate. Current and voltage waveforms of the shock being evaluated, whose droop never exceeded 2.6%, were displayed on a Tektronix model 5031 dual-beam storage oscilloscope. From values observed at the midpoints of the waveforms, the chest resistance and delivered energy associated with each shock were calculated as the ratio of voltage to current and the product of voltage, current and pulse width, respectively. We used a Hewlett-Packard model 130-C oscilloscope to display and a Sanborn model 500 electrocardiograph to record the lead II ECG of the calves.

**Procedure**

Our overall investigation consisted of two similar but essentially independent studies interlaced in time. For simplicity of presentation, we shall discuss one of these studies in some detail and then indicate how the two studies were related in time.

In our first study, the effectiveness of shocks was evaluated as our calves reached weights of 50, 75, 100, 125 and 150 kg. At each weight, we selected values of electrode diameter, pulse current and pulse duration that we anticipated would be about 50% successful in terminating ventricular fibrillation. We did this by first selecting 13.0-cm diameter electrodes and a 50-amp, 4-msec shock for calves at the 100-kg level because in an extensive previous study involving 100-kg calves, such electrodes and shock yielded successful defibrillation in 62 of 120 (52%) of the episodes.\(^{18}\) The values of electrode diameter and pulse current for the other body weights were then scaled by means of equations 1 and 2. For example, if \( d \) and \( I \) are the electrode diameter and pulse current to be used with 100-kg calves and \( d' \) and \( I' \) are the electrode diameter and pulse current to be used with 150-kg calves, we have from equations 1 and 2 that \( d' = (150/100)^{1/3} \cdot 13.0 = 14.9 \) cm and \( I' = (150/100)^{1/3} \cdot 50 = 66 \) amp. Electrode diameters and pulse currents for specified body weights are tabulated in table 1. In practice, we were always able to study the individual calves when they were within ±5% of the weight values specified in the first column of table 1. The term “nominal body weight,” as used in the table and text, signifies a weight such that each calf was studied when it was within ±5% of the weight value stated.

Each of 10 calves, at a nominal weight of 50 kg, was
anesthetized with 110 mg/kg glyceryl guaiacolate and 4.4 mg/kg thiopental sodium injected intravenously, intubated, and maintained with methoxyflurane in 50% N₂O and 50% O₂. Stainless steel chest electrodes, 10.3 cm in diameter, were covered with Redux paste and held in place by rubber straps. One electrode was positioned on the left chest over the apex of the heart and the other electrode was positioned on the right chest centered approximately over the fifth interspace. The calf was restrained in right lateral recumbency.

After preparation as outlined above, ventricular fibrillation was induced through the chest electrodes with a low-voltage shock and verified with the monitoring oscilloscope. After 30 seconds of fibrillation, a 32-amp, 4-msec rectangular wave shock was applied via the chest electrodes. If defibrillation was achieved, the episode was tabulated as a success and the resulting ECG was recorded for 2.5 minutes. The ECG was later evaluated by one of us without prior knowledge of the experimental conditions under which it was recorded. If defibrillation was not achieved with the 32-amp, 4-msec shock, a shock of known high effectiveness, applied via the chest electrodes, was used to defibrillate the calf, the episode was tabulated as a failure, and the resulting ECG was not recorded. In either event, the procedure was repeated with not less than 3 minutes between the start of successive episodes. After 20 fibrillation-defibrillation episodes, the animal was returned to its stall to recover from anesthesia.

Except for changes in the diameter of the chest electrodes to conform with equation 1 and changes in the pulse current to conform with equation 2 (see table 1), the procedure described above was repeated on each calf at nominal weight levels of 75, 100, 125 and 150 kg.

The second study, which used the same calves and was interlaced in time with our first study, differed from the first study only in that the pulse current at each weight level was increased to values that we anticipated would be about 90% successful in terminating ventricular fibrillation (based upon our scaling hypothesis and a previous study in 100-kg calves in which 70-amp, 4-msec shocks yielded successful defibrillation in 109 of 120 (91%) of the episodes). As shown in table 1, at the initial 50-kg weight level, the second study involves a 44-amp, 4-msec shock. Each calf was used in a given portion of the second study on the second or third day after its use in the corresponding portion of the first study.

### Results

Of the 10 calves originally entered into our program, one died unexpectedly in its stall 31 days after being studied at the 75-kg level, a second died after the sixteenth episode during an experimental session at the 100-kg level with 50-amp pulses, and two more died after the eighteenth and nineteenth episodes, respectively, during studies at the 125-kg level with 58-amp pulses. Thus, there were 200, 200, 176, 157 and 120 fibrillation-defibrillation episodes in study 1, and 200, 200, 160, 120 and 120 fibrillation-defibrillation episodes in study 2 at nominal weight levels of 50, 75, 100, 125 and 150 kg, respectively. Of the total of 1653 episodes, 453 involved the four calves that died. Necropsies, including gross and microscopic examinations of the heart, performed at the Univer-

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**Table 1. Defibrillation Data**

<table>
<thead>
<tr>
<th>Nominal body weight (kg)</th>
<th>Electrode diameter (cm)</th>
<th>Current (amp)</th>
<th>Actual body weight (kg)</th>
<th>Potential difference (V)</th>
<th>Chest resistance (ohms)</th>
<th>Delivered energy (J)</th>
<th>Number of successful defibrillations</th>
<th>Time required for return of ventricular complex (sec)</th>
<th>Time required to return to normal sinus rhythm (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First study</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>10.3</td>
<td>32</td>
<td>51 ± 1</td>
<td>839 ± 64</td>
<td>26.2 ± 2.1</td>
<td>108 ± 8</td>
<td>34</td>
<td>3.4 ± 1.1</td>
<td>3.4 ± 1.7</td>
</tr>
<tr>
<td>75</td>
<td>11.8</td>
<td>41</td>
<td>76 ± 1</td>
<td>927 ± 57</td>
<td>22.6 ± 1.6</td>
<td>152 ± 10</td>
<td>59</td>
<td>5.0 ± 2.1</td>
<td>5.3 ± 2.2</td>
</tr>
<tr>
<td>100</td>
<td>13.0</td>
<td>50</td>
<td>103 ± 2</td>
<td>1009 ± 63</td>
<td>20.1 ± 1.3</td>
<td>203 ± 14</td>
<td>79</td>
<td>3.0 ± 1.5</td>
<td>3.1 ± 1.5</td>
</tr>
<tr>
<td>125</td>
<td>14.0</td>
<td>58</td>
<td>127 ± 1</td>
<td>1132 ± 83</td>
<td>19.4 ± 1.5</td>
<td>265 ± 21</td>
<td>61</td>
<td>4.1 ± 2.3</td>
<td>4.5 ± 2.6</td>
</tr>
<tr>
<td>150</td>
<td>14.9</td>
<td>66</td>
<td>151 ± 3</td>
<td>1233 ± 102</td>
<td>18.6 ± 1.7</td>
<td>327 ± 28</td>
<td>27</td>
<td>7.2 ± 7.8</td>
<td>7.4 ± 7.7</td>
</tr>
<tr>
<td>Second study</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>10.3</td>
<td>44</td>
<td>51 ± 1</td>
<td>838 ± 42</td>
<td>19.1 ± 1.0</td>
<td>147 ± 8</td>
<td>112</td>
<td>9.4 ± 7.9</td>
<td>20.7 ± 8.5</td>
</tr>
<tr>
<td>75</td>
<td>11.8</td>
<td>58</td>
<td>75 ± 2</td>
<td>990 ± 68</td>
<td>17.1 ± 1.2</td>
<td>229 ± 17</td>
<td>115</td>
<td>8.3 ± 7.7</td>
<td>30.0 ± 23.1</td>
</tr>
<tr>
<td>100</td>
<td>13.0</td>
<td>70</td>
<td>102 ± 2</td>
<td>1109 ± 122</td>
<td>15.8 ± 1.8</td>
<td>310 ± 35</td>
<td>111</td>
<td>4.5 ± 4.5</td>
<td>25.6 ± 15.7</td>
</tr>
<tr>
<td>125</td>
<td>14.0</td>
<td>81</td>
<td>127 ± 4</td>
<td>1244 ± 121</td>
<td>15.4 ± 1.5</td>
<td>402 ± 39</td>
<td>113</td>
<td>6.2 ± 6.0</td>
<td>27.7 ± 17.3</td>
</tr>
<tr>
<td>150</td>
<td>14.9</td>
<td>92</td>
<td>149 ± 5</td>
<td>1274 ± 71</td>
<td>13.9 ± 0.9</td>
<td>469 ± 27</td>
<td>109</td>
<td>7.2 ± 6.9</td>
<td>38.7 ± 27.8</td>
</tr>
</tbody>
</table>

Entries for actual body weight are based upon six calves. Entries for potential difference, chest resistance and delivered energy are based upon 120 episodes. Entries for the times required for the return of a ventricular complex and for a return of normal sinus rhythm in the ECG are based upon the number of successful defibrillations.

All of these values are mean ± sd.
sity of Missouri Veterinary Medical Post-Mortem Laboratory, revealed scattered myocardial necrosis in one calf, numerous ecchymotic hemorrhages on the epicardium in a second calf, and considerable edema between individual muscle fibers and between muscle bundles of the ventricle in a third calf, which died during an experimental procedure. No relevant cardiac changes or cause of death were ascertained for the calf that died unexpectedly.

Six calves survived both studies to be eventually transferred out of our program in apparently healthy condition. For these calves, the time interval between the initial fibrillation-defibrillation session in the first study (at approximately 50 kg) and the final session in the second study (at approximately 10 kg) ranged from 131–230 days (mean 180 days). The relevant results obtained from the studies conducted with these six calves are summarized in table 1. Because at each of the 10 unique weight-electrode-current conditions listed, each of six calves was involved in 20 fibrillation-defibrillation episodes, every line of data in table 1 is based upon 120 fibrillation-defibrillation episodes and the complete table covers 1200 such episodes.

An analysis of the data from the nonsurvivors indicates that their inclusion in the data base would make relatively little difference in the results, and a more straightforward presentation of our findings is possible if we focus primarily upon data from the six calves that survived.

In figures 2–4, mean values of electrode-to-electrode voltage, chest resistance and delivered energy as functions of mean values of calf weight are plotted on log-log coordinates. The straight lines and the associated equations represent the best least-squares fits to the data represented by the solid dots. To give some indication of the episode-to-episode variation, vertical bars (±SD) are placed around each of the indicated data points in figures 3 and 4. To avoid overlap and confusing clutter, these bars are omitted in figure 2. The coefficients of determination (measurement of goodness of fit) for the equations are 0.97 and 0.99 for studies 1 and 2 in figure 2, 0.98 and 0.97 for studies 1 and 2 in figure 3, and 0.99 and 1.00 for studies 1 and 2 in figure 4.

In figure 3, the line of chest resistance vs calf weight for study 2 is essentially parallel to, but appreciably below, the line for study 1. At each weight level, the average chest resistance in study 2 is significantly \( p < 0.005 \) less than the corresponding resistance in study 1. An analysis of data from a study involving defibrillation in 100-kg calves indicated comparatively little variation in average chest resistance with current amplitude (for pulse currents 50–70 amp), but a considerable decrease in chest resistance with the number of episodes.15 We believe that this anomaly may be attributed to an apparent increase in tissue conductivity induced by repeated episodes of electroshock; that is, the line for study 2 is probably below that for study 1 because of the time sequence in which the two studies were conducted. Presumably, interchanging the time sequence would approximately interchange the position of the lines, and interlacing the studies on an episode-by-episode basis would generate closely spaced lines positioned immediately between the lines shown in figure 3. While this shift in apparent tissue conductivity also serves to influence somewhat the positions of the voltage vs weight and delivered energy vs weight lines in figures 2 and 4, our ability to draw valid inferences from the two studies, each considered alone, is not adversely affected.

Equality between the exponents in the equations in

![Figure 2](image1.png)

**Figure 2.** Relationships between mean electrode-to-electrode voltage and mean weight for six calves that survived both studies.

![Figure 3](image2.png)

**Figure 3.** Relationships between mean chest resistance and mean weight for six calves that survived both studies. Vertical bars represent ± SD.
figures 2–4 and the corresponding exponents in equations 3–5 is a necessary, although not sufficient, condition for our calves to satisfy the anatomical or physical assumptions associated with our idealized model. Since the discrepancies between the corresponding exponents are relatively small, we interpret our data to mean that conditions within our calves may approximate the assumptions associated with our model and, consequently, that the current density vector at corresponding points within the myocardium of a calf may remain relatively constant with increasing body weight when electrode diameter and current amplitude are scaled according to equations 1 and 2.

In study 1, the overall mean percent success level (43%) in achieving defibrillation is lower than the initially anticipated level (52%). Furthermore, as shown by the lower curve of figure 5, the percent success level varies considerably with body weight, and three of the points on the curve are significantly \( p < 0.01 \) different from the grand mean of 43%. Of the six individual curves of percent success vs body weight (fig. 6), five have the same general shape as the summary curve in figure 5 (that is, percent success increases, peaks, and then decreases with increasing body weight). In addition, each of these curves has one or more points which differ significantly \( p < 0.01 \) from the mean percent success levels for the individual calves. For the current levels used in study 1, these results do not support our hypothesis that the effectiveness of defibrillation is substantially independent of body weight when electrode diameter and current amplitude are scaled according to equations 1 and 2.

In study 2, the overall mean percent success level (93%) in achieving defibrillation is quite close to the initially anticipated level (91%). As shown by the upper curve of figure 5, the percent success level is substantially independent of body weight, with no point being significantly \( p > 0.2 \) different from the grand mean of 93%. The individual curves of percent success vs body weight, as sketched in figure 7, appear to lack any common mode of variation of percent success with body weight. Three of the six curves have single points that differ significantly \( p < 0.01 \) from the mean percent success levels for the individual calves. Points on the other three curves do not vary significantly \( p > 0.01 \) from the mean percent success level for the individual calves. For the current levels used in study 2, we interpret these results as tending to support our hypothesis that the effectiveness of defibrillation is substantially independent of body weight when equations 1 and 2 are satisfied.

Parenthetically, the composite percent success data from both the six surviving and four nonsurviving calves (study 1: 50 kg — 44%; 75 kg — 53%; 100 kg — 62%; 125 kg — 52%; 150 kg — 23%; and study 2: 50 kg — 96%; 75 kg — 95%; 100 kg — 87%; 125 kg — 94%; 150 kg — 91%) suggest a study 1 curve with somewhat less variation and a study 2 curve with somewhat more variation than in the curves shown in figure 5.

The post-defibrillation ECG in the calf is frequently characterized by extended periods in which electrical activity is absent or in which only p waves are present. Even longer periods are often required in the calf for the ECG to return to normal sinus rhythm (NSR) after a successful defibrillatory shock. In a previous study in 100-kg calves, we found that for 4-msec rectangular wave shocks, the mean durations required for a return of a ventricular complex and for a return to NSR in the ECG after a successful defibrillatory shock increased considerably with increasing amplitude of pulse current and thus, also, with increasing myocardial current density.18

The mean time for the return of a ventricular complex as a function of body weight is plotted in figure 8 for both study 1 and study 2. Calculated from data tabulated in table 1, the grand mean time for the return of a ventricular complex after all of the successful defibrillatory episodes in study 1 is 4.2 seconds; the corresponding grand mean time for the episodes of study 2 is 7.1 seconds. The grand mean time for a return of a ventricular complex of 4.2 seconds falls within 1 SD of each data point in study 1 (fig. 8, table 1). Similarly, the grand mean time for a return of a ventricular complex of 7.1 seconds falls within 1 SD of each data point in study 2.

The mean time for the return of NSR as a function of body weight is plotted in figure 9 for both study 1 and study 2. In study 1, the grand mean time for the return of NSR is 4.4 seconds; in study 2, the grand mean time for the return of NSR is 28.5 seconds. The grand mean time for the return of NSR of 4.4 seconds falls within 1 SD of each data point in study 1. Likewise, the grand mean time for a return of NSR of 28.5 seconds falls within 1 SD range of each data point in study 2.

For the two electrocardiographic parameters con-
considered, we interpret our results from both studies to generally support the hypothesis that the electrocardiographic findings in the immediate postdefibrillation period are substantially independent of body weight when electrode diameter is scaled to the one-third power and pulse current is scaled to the two-thirds power of body weight.

Discussion

The shape of the percent successful defibrillation vs body weight curve for study 1 (fig. 5) and the discrepancies between the curve and the straight horizontal line which we hypothesized should have resulted from our study suggest that there may be a mechanism that makes defibrillation easier in the middle portion and/or more difficult in the lower and upper portions of the weight range than indicated by our model. Causes appear to fit into two categories. First, the assumption of approximate anatomical similitude as the calf grows with a resultant weight-independent, current-density vector distribution within the myocardium may be in error. While the approximate agreement between the exponents in the equations in figures 2–4 and the exponents in the corresponding theoretical equations is a necessary condition for anatomical similitude, it is not, as has previously been noted, a sufficient condition. Growth within an animal could seriously violate the similitude hypothesis, yet still yield approximate equality for the corresponding exponents. Second, the assumption that the equality of the current-density vector at all corresponding points

Consider the figure 5. It illustrates the relationships between percent success of ventricular defibrillation and mean weight for six calves that survived both studies.

Figure 5. Relationships between percent success of ventricular defibrillation and mean weight for six calves that survived both studies.

Consider the figure 6. It presents condensed percent success-weight curves for the six surviving calves. Study 1.

Figure 6. Condensed percent success-weight curves for the six surviving calves. Study 1.
within the myocardium will result in the same response to electroshock as the heart grows may be in error. For example, it is quite possible that other factors such as age and heart size may also influence the response of our calves to electroshock. While experiments could be designed to elicit more information, our data do not permit us to identify or categorize the actual causes for the discrepancies between the theoretical hypothesis and experimental results.

In view of the shape of the percent success vs weight curve in study 1, would we have expected the corresponding curve for study 2 to be as straight and horizontal as it appears to be in figure 5? The answer is closely associated with the results in 100-kg calves in an earlier study, in which we found that the percent success in achieving defibrillation with 4-msec rectangular pulses varies quite rapidly with current amplitude for success levels of 20–80%, but very slowly with current amplitude for success levels of 90–93%. That is, in the range of 90–93%, the percent success in achieving defibrillation is quite insensitive to modest changes in pulse current, and also to modest changes in the myocardial current-density level. If the considerable variation in percent success with body weight shown in study 1 is the result of discrepancies between actual myocardial current density and the weight-independent myocardial current density

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**Figure 7.** Condensed percent success-weight curves for the six surviving calves. Study 2.

**Figure 8.** Relationships between mean time interval required for return of a ventricular complex after a successful defibrillatory shock and mean weight for six calves that survived both studies.
hypothesized in our model, we would expect the same percentage discrepancies in the myocardial current density in study 2. However, because of the insensitivity of percent success in achieving defibrillation to modest changes in myocardial current density when the percent success is 90–93%, we would expect little variation in percent success with body weight. There is no experimental evidence whether the same type of argument could explain the results in study 2 if the variations present in the curve for study 1 were primarily attributable to changes in age or heart size or both.

The energy prescription or dosage for the defibrillation of human patients is often expressed as the number of joules per kilogram of body weight to be supplied or as a fixed number of joules that is independent of body weight. The experimental data we report were collected under conditions which corresponded very nearly to the joules per kilogram of body weight type of dose specification. This can be verified by observing that the data tabulated in table 1 yield a mean dose of 2.1 J/kg and a range of 2.0–2.2 J/kg for study 1 and a mean of 3.1 J/kg and a range of 2.9–3.2 J/kg for study 2. Further verification is furnished by the equations in figure 4, which indicate exponents fairly near unity and, consequently, a nearly proportional relationship between delivered energy and body weight. More fundamentally, the proportional relationship between delivered energy and body weight (see Appendix) is a consequence of the model we have chosen. Using this type of prescription terminology, the curve for study 1 in figure 5 tells us, for example, that despite a dose level of about 2.1 J/kg at all weight levels, the percent success achieved varies widely with body weight; the curve for study 2, on the other hand, indicates that with a dose level of about 3.1 J/kg, the success achieved is about 93% and almost independent of body weight.

References

Appendix
Consider an idealized situation as outlined in the first paragraph under "Theoretical Considerations" and suggested by the sketch in figure 1. When a potential difference is applied to the two electrodes on the chest of the smaller subject, the current will distribute itself to satisfy the necessary boundary conditions and the condition that the divergence of the current-density vector is zero. If we assume that the instantaneous current-density vector within the larger subject is the same as at the corresponding point within the smaller subject, it, too, will satisfy the necessary boundary and continuity conditions. Furthermore, the instantaneous electric field vector (E) at any point within the larger subject will be the same as at the corresponding point within the smaller subject.
If \( \vec{f} \) and \( \vec{f}' \) represent corresponding vector displacements and \( \vec{s} \) and \( \vec{s}' \) represent corresponding vector surface areas in the smaller and larger subjects, respectively, then

\[
\vec{f}' = \alpha \vec{f}
\]

(6)

and

\[
\vec{s}' = \alpha^2 \vec{s}.
\]

(7)

The instantaneous potential difference \( (V') \) between the two electrodes in the larger subject is given by the line integral

\[
V' = \int E \cdot d\vec{f}'.
\]

(8)

Substituting the value of \( \vec{f} \) from equation 6 into equation 3 yields

\[
V' = \int E \cdot d\vec{f} = \alpha \int E \cdot d\vec{f}
\]

(9)

where the line integral is now between the electrodes on the smaller subject. But the potential difference between the electrodes on the smaller subject is given by

\[
V = \int E \cdot d\vec{f}.
\]

(10)

Thus, from equations 9 and 10,

\[
V' = \alpha V.
\]

(11)

The current \( (I') \) flowing into the larger subject from one of the chest electrodes is given by the surface integral

\[
I' = \int \int \vec{J} \cdot d\vec{s}'.
\]

(12)

where \( \vec{J} \) is the current-density vector within the subject and the integration is carried out over the surface of one of the electrodes in contact with the chest of the larger subject. Substituting the value of \( \vec{s}' \) from equation 7 into equation 12 yields

\[
I' = \int \int \vec{J} \cdot d\vec{s} = \alpha^2 \int \int \vec{J} \cdot d\vec{s}
\]

(13)

where the surface integration is now over the surface of an electrode in contact with the chest of the smaller subject. But the current into the smaller subject is given by

\[
I = \int \int \vec{J} \cdot d\vec{s}.
\]

(14)

Thus, from equations 13 and 14,

\[
I' = \alpha^2 I.
\]

(15)

Using a simple volume integration procedure, it can be shown that the mass of the larger subject is related to the mass of the smaller subject by

\[
m' = \alpha^3 m
\]

(16)

which can be rewritten as

\[
\alpha = \left( \frac{m'}{m} \right)^{1/3}
\]

(17)

Equation 1 in the main text follows immediately from the condition that the diameter of the chest electrodes for the larger subject is \( \alpha \) times the diameter of the electrodes used with the smaller subject and from equation 17. The substitution of the value of \( \alpha \) from equation 17 into equations 15 and 11 yields equations 2 and 3, respectively. Furthermore, if equation 2 is satisfied, the uniqueness theorem confirms our assumption about the relationship between the current-density vectors in the two subjects. The division of both sides of equation 3 by the corresponding sides of equation 2 yields equation 4. The multiplication of both sides of equation 2 by the corresponding sides of equation 3 indicates that the instantaneous power delivered to the larger subject is \( (m'/m) \) times that delivered to the smaller subject. Since the total delivered energy is the time integral of instantaneous power, the energies are similarly related and the validity of equation 5 is established.
Scaling current and energy with body weight: requirements for the transthoracic ventricular defibrillation of calves as they grow from 50 to 150 kg.

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