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Ventricular Fibrillation Threshold vs Alternating Current Shock Duration

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Abstract: Introduction: International basic safety limits for utility-frequency electrical currents have long been set by the International Electrotechnical Commission 60479-1 standard. These were inspired by a linear-section plot proposed by Biegelmeier in 1980 with current given as a function of the shock duration. This famous plot has contributed to safe electrical circuit design internationally and has properly earned significant amount of respect over its 35 years of life. However, some possible areas for improvement have been suggested.

Methods: We searched for all animal studies of ventricular fibrillation threshold versus duration that used a forelimb to hindlimb connection that had at least 3 durations tested. We found 6 such studies and they were then used to calculate a new C3 curve after normalizing the data.

Results: A rational function model fit the animal data with r^2 =.96. Such a correlation calculation tends to underweight the smaller values, so we also correlated the log threshold values and this had a correlation of r^2=.94.

Conclusion: Existing ventricular fibrillation threshold current versus duration data can be fitted with a simple rational function. This can provide a useful update to IEC 60479-1.

I. INTRODUCTION

International basic safety limits for utility-frequency electrical currents have long been set by IEC (International Electrotechnical Commission). These limits were inspired by a linear-section plot proposed by Biegelmeier in 1980 with current given as a function of the shock duration as seen in Figure 1.[1]

The linear-section "b" curve lower line for a "non-fibrillating" current had 500 mA_{rms} for a short shock (defined as 10 ms for this paper) and 50 mA_{rms} for a long shock (defined as 10 seconds for this paper). Biegelmeier's upper "a" line was for a 50% risk of VF (ventricular fibrillation) had 1800 mA_{rms} for a short shock and 100 mA_{rms} for a long shock.

In addition, an intermediate line (C2) was added to give an intermediate 5% risk of VF. The IEC 60479-1 That curve was then rounded and rotated to give the present version as seen in IEC 60479-1 (Their fig. 20) and our Figure 2.[2]

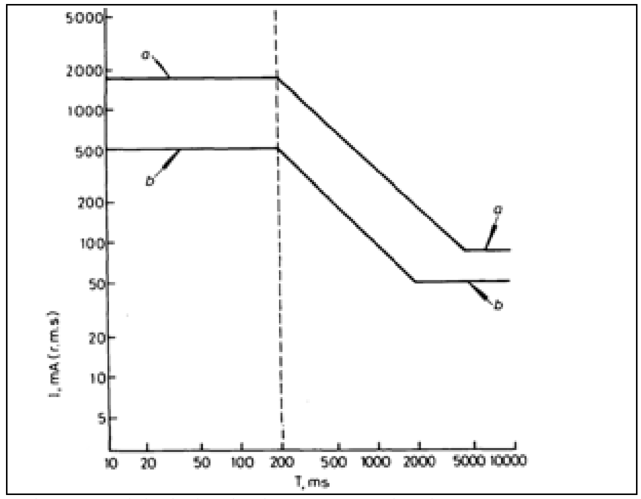

Figure 1. Original Biegelmeier current vs. duration curve.

International basic safety limits for utility-frequency electrical currents are based on the line for a "generally considered safe" current (now called the "C1" line) had 500 mA_{rms} for a short shock and a current level appearing to be 35-40 mA_{rms} for a long shock. We say "appearing to be" as the standard never gave a table for these values but rather presented curves which were open to interpretation and copying errors. The upper line for a 50% risk of VF (ventricular fibrillation) (now called the "C3" line) had a current level appearing to be 1500-1600 mA_{rms} for a short shock and 80 mA_{rms} for a long shock.

IEC 60479-1 also has non-cardiac lines "a" (startle-reaction) and "b" (let-go immobilization) which are not relevant to this paper. *Nor are they related to Biegelmeier's "a" and "b" curves.* Note that the C1 long-shock (10 s) current was reduced from 50 mA (Biegelmeier's proposal) to below 40 mA and has served as a

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guideline for countless residual current limiters installed around the world which trip at 30 mA_{rms} within 200 ms.

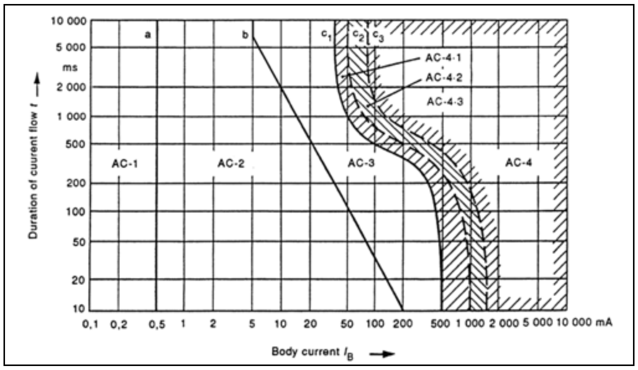

Figure 2. IEC 60479-1 Fig 20 giving the effects of current vs. duration.

This famous plot has contributed to safe electrical circuit design internationally and has properly earned significant respect over its 35 years of life. However, some possible areas for improvement have been suggested:

The rotated orientation of the curves makes them difficult to understand for novices that are not familiar with them. This might limit the use of these curves for non-specialists. For the specialized group of RCD designers, the independent variable is trip time and the dependent variable is current.

There is no formula provided for the curves and this means that interpretation and reproduction is sometimes subjective. Part of the problem is that one cannot write functions for the vertical parts of the curves.

The safety ratio between the long-shock safe level of about 40 mA and the VF "probable" level of about 80 mA is only 2:1. Due to the human variability, this small ratio has been questioned. It is also not supported by the Kouwenhoven and Ferris animal data as they support a ratio closer to 4:1.[3, 4]

The short-shock VF probable level of 1.5 A RMS implies a VF threshold (VFT) of 13.5 mC which is significantly less than the 10 ms DC pulse VF limit of 30 mC in the proposed update to IEC 60479-2. Note that the 30 mC threshold is based on human data using damped RLC shocks so there was no "anodal-break" induction possibility.[5, 6]

We decided to collect all available relevant animal data to refine Fig 20. Of IEC 60479-1 and address the above issues.

II. METHODS

We elected to set the C1 long-duration (10 s) level at 40 mA due to the decades of acceptance near this level and the large number of RCDs that have been sold and designed to 75% of this level. We also decided to maintain the curved "knee" current vs. duration relations implemented by Biegelmeier. We then searched for all animal studies of VFT versus duration that used a forelimb to hindlimb connection that had at least 3 durations tested. This was then used to calculate a new C3 curve.

A. Raw Data

We found 6 studies of VFT vs. duration (D) based on animal experiments using forelimb-to-hindlimb connections with at least 3 durations as shown in

Table 1 and Figure 3. Note: all are for 50/60 Hz AC.

Table 1. VFT Studies Evaluated

Author	Year	Animal	Wgt (kg)	HR (BPM)	n	D_{min} (ms)	VFT ave (A)	D_{max} (s)	VFT ave (A)
Ferris[3]	1936	sheep	56	132	87	30	2.82	3	0.248
Kouwenhoven[4]	1959	dog	8-16	200	34?	17	1.2	5	0.052
Koeppen[7]	1961	?	?	?	?	320	0.85	1	0.14
Osypka[8]	1963	swine	30-60	?	5	180	2.2	1.2	0.31
Geddes[9]	1973	dog	5-12	?	5	200	0.2	5	0.025
Jacobsen[10]	1975	swine	20	?	?	10	3.7	5.2	0.206

We also found 2 studies of VFT vs. duration using direct contact to the heart. [11, 12] They were useful for verifying the curved "knee" of VFT vs duration but were not used further as they had very large ratios of VFT between short and long durations. Biegelmeier had been in contact with participants in the Ferris and Kowenhoven studies and published their data in greater detail than the original papers so we used that as our final source.[13]

We were unable to locate the Koeppen paper and took his data from the Osypka thesis.[8] The Geddes and Jacobsen data were presented graphically and these were digitized using the Adobe measurement tool. The Osypka thesis presented data credited to Dalziel but we were able to verify that this was actually the Kouwenhoven data re-analyzed by Dalziel.

B. Normalization of Data

Both Geddes and Kouwenhoven used small dogs and had relatively low VFTs. Their VFT values were scaled up by 5x and 1.5x. Due to possible methodology differences, Jacobsen had relatively higher VFTs; these were scaled down by 0.75x. Koeppen's values were scaled up by 2x. This brings the end points together and the results are shown in Figure 4.

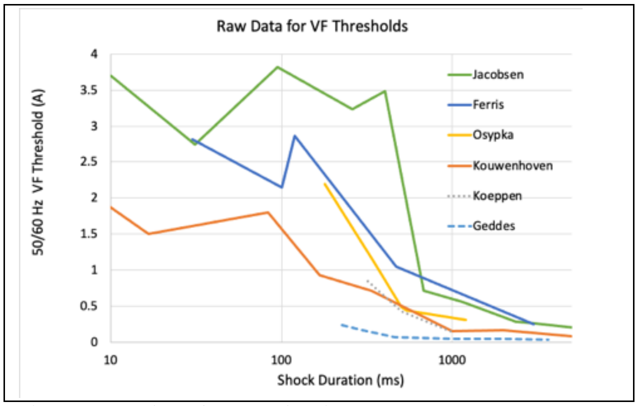

Figure 3. Raw data of VFT vs durations.

Biegelmeier and Ferris stressed the importance of the species heart rate in determining the location of the transition part of the VFT vs duration curves.[1, 3] Dogs tend to have very high heart rates under anesthesia while they have consistent average heart rates of 50-110 BPM (beats per minute) under normal conditions.[14] Kouwenhoven reported an average dog heart rate of 200 BPM. Biegelmeier, after analyzing Kouwenhoven's raw stated that the average heart rate was 182 BPM. The durations for the Kouwenhoven and Geddes dog studies were thus scaled by 2x.

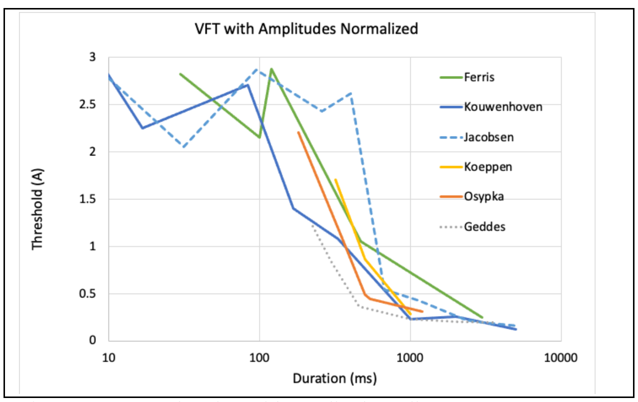

Figure 4. VFT vs duration with amplitude scaling.

While Jacobsen did not disclose his average heart rate, his transition duration was clearly longer than that of the other swine and sheep studies, so his durations were scaled down by 0.75x. This provides a transition region close to what Biegelmeier determined. This brings the central portion of the data together and the results are shown in Figure 5.

C. Curve Fitting

Some effort was expended to find a good fit to the data that was also easy to express and explain. After numerous models were tried, the classic "Witch of Agnesi" stood out as the best as shown in Figure 6.[15]

$$VFT = \frac{1}{1 + d^2}$$

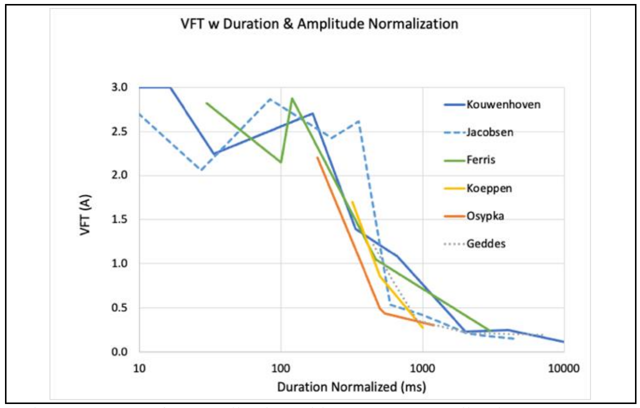

Figure 5. VFT after amplitude and heart rate normalization.

Note that this is a rough approximation of the common logistic formula regularly used in statistics.

$$y = \frac{1}{1 + e^x}$$

The "Witch" was appropriately scaled by the VFT_{max}, "transition" duration (d_t) for the VFT_{ave}, and VFT_{min}.

$$VFT = \frac{VFT_{max} - VFT_{min}}{1 + \left(\frac{d}{d_t}\right)^2} + VFT_{min}$$

where:

VFT_{max} = 3 A

VFT_{min} = 0.12 A

d_t = 300 ms

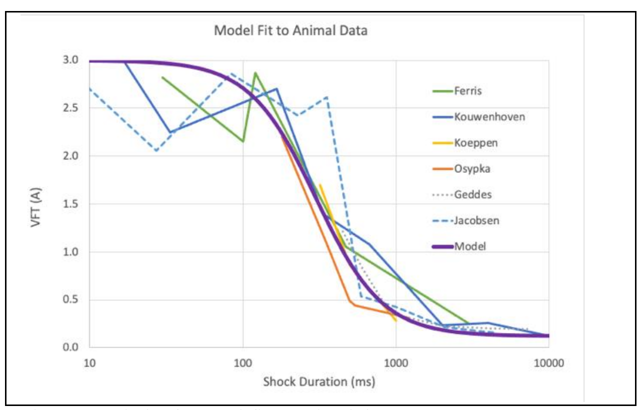

Figure 6. Witch of Agnesi fit to animal data.

III. RESULTS

A. Accuracy of Fit

The model fit the animal data quite well with r^2 = .96 which is impressive considering the spread of the animal data. This is depicted in Figure 7. Such a correlation calculation tends to underweight the smaller values, so we also correlated the log-log values as shown in Figure 8. This had a correlation of r^2=.94.

The above analysis suggests a C3 line of 120 mA_{rms} at 10 seconds. This is higher than the present C3 value of 80 mA_{rms}. However, that 80 mA_{rms} value was questionable as it was only 2x the “low-risk” value of 40 mA_{rms}.

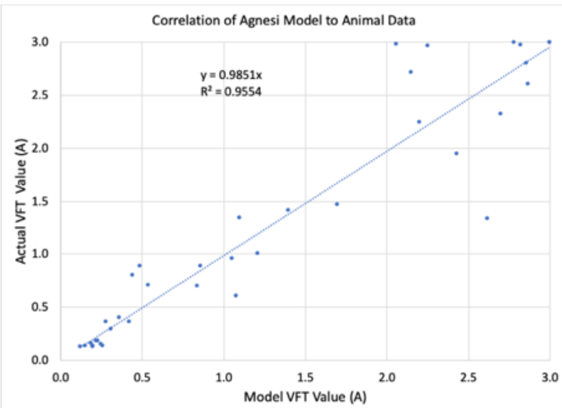

Figure 7. Model correlation to animal VFT data.

B. Determination of the C1 Line

Having already elected to set the long duration C1 one line at 40 mA_{rms}, the question was then if a simple proportion of 3:1 for the C1 line was consistent with animal data for the long *and* short shock VFT’s.

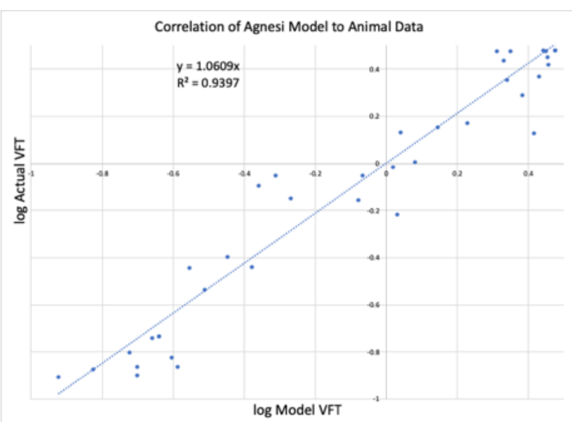

Figure 8. Correlation of log model values to log animal data.

Dalziel performed a statistical analysis of the Kouwenhoven dog and Ferris sheep data as shown in Table 2.[16] The average ratio between the median VFT and the 0.5 %ile was 3.71x which strongly contradicts the present low ratio of 2:1. The present C1 level for 10 s (at 40 mA) is assumed by present residual-current detectors (which are set at 75% of this level) and appears to be consistent with existing animal data for the probabilistic VF threshold. The C2 level of 80 mA_{rms} was then chosen as the midpoint. The result is shown in Figure 9.

Table 2. Dalziel Statistical Analysis of Kouwenhoven Dog & Ferris Sheep Data

Model	Duration (ms)	Median (mA)	5 %ile (mA)	0.5 %ile (mA)	Ratios	
		C3	C2	C1	C3/C1	C2/C1
dog	8.3	2070	1200	650	3.18	1.85
dog	16.7	1450	1050	800	1.81	1.31
dog	83.3	1800	800	240	7.50	3.33
dog	333	740	400	200	3.70	2.00
dog	1000	150	90	50	3.00	1.80
dog	2000	150	85	50	3.00	1.70
dog	5000	83	45	25	3.32	1.80
sheep	30	2480	1800	1400	1.77	1.29
sheep	100	2200	1200	600	3.67	2.00
sheep	120	3400	1500	400	8.50	3.75
sheep	470	1080	600	350	3.09	1.71
sheep	3000	240	165	120	2.00	1.38
				Average	3.71	1.97
				StDev	1.80	0.64
				Median	3.14	1.80

In Figure 10, the proposed new curves are overlaid on the existing curves. It will be seen that the long duration (10 s) safe level is consistent, the “dangerous” curve (C3) is now 3 times (vs 2:1) that of the safe curve and the short duration (10 ms) levels are matching those of the new IEC 60479-2 limits.

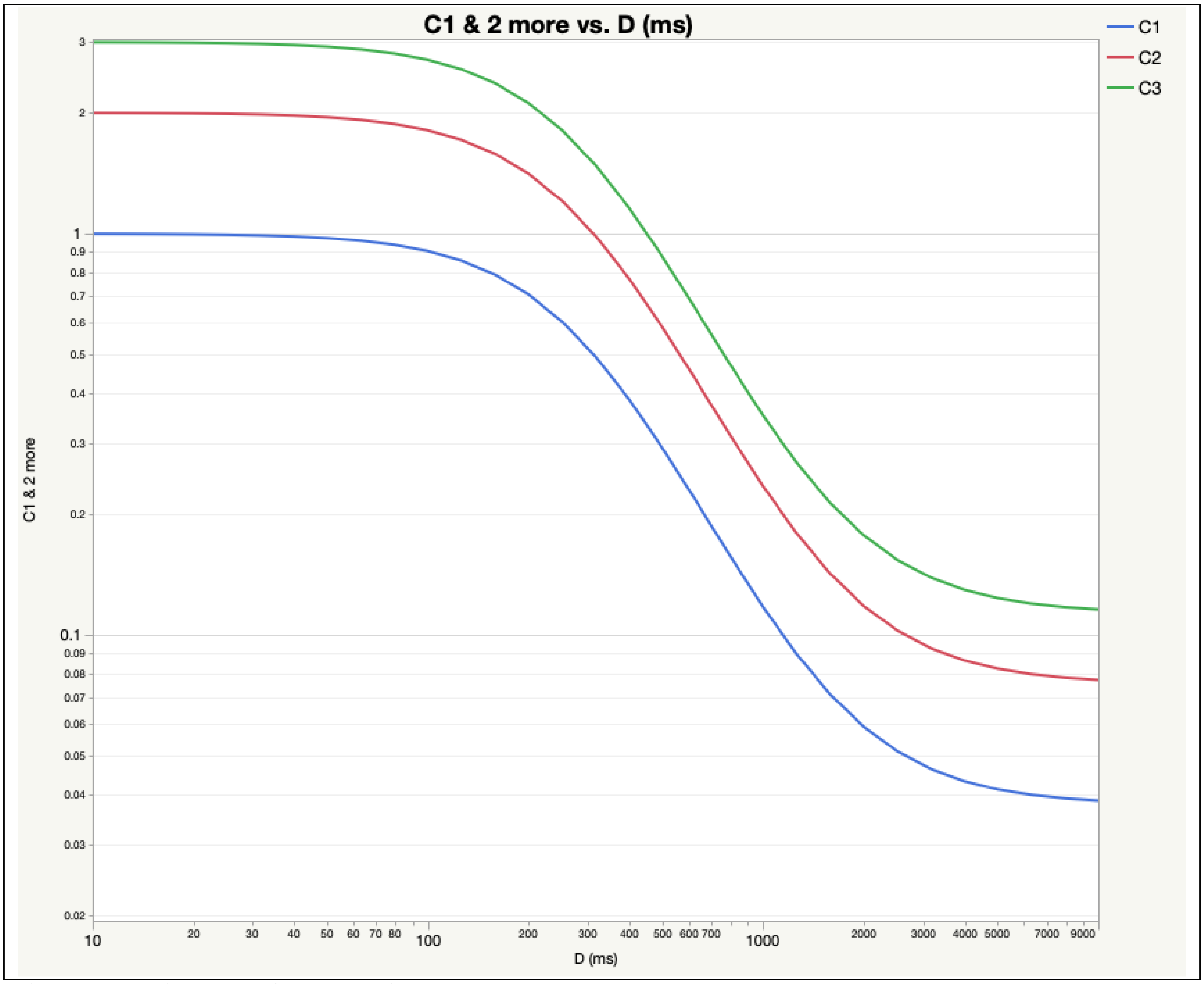

Figure 9. Proposed new curves for C1, C2, and C3.

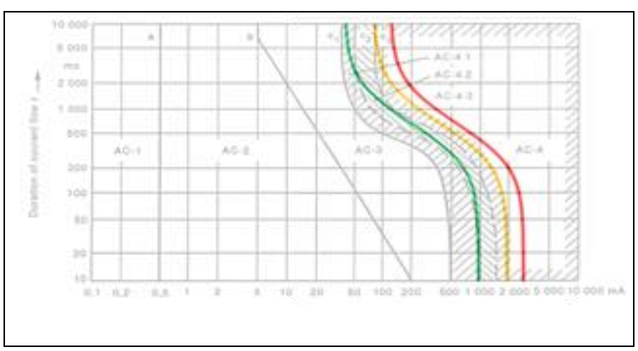

Figure 10. Proposed new curves overlaid on existing curves.

IV. DISCUSSION

The transition or "knee" is centered at about the cardiac cycle for heart rates of 60-120 BPM. This raises the obvious question of whether or not there should be different curves for different heart rates of resting or excited and exercising people. The Ferris data teaches us 2 things. (1) For a given fixed heart rate, the knee is narrow giving a steep drop. (2) For *all* his sheep, the knee was much wider, due to the variability of the heart rate between individual sheep. It is a reasonable assumption that Biegelmeier recognized that not all humans have the same heart rate and hence provided a wider knee versus an arbitrary steep transition.

Is there a statistical meaning of low, medium and high risk for the C1, C2, and C3 lines based on these animal experiments? Biegelmeier suggested that the lines indicated a VF risk of "safe," 5%, and 50% respectively.[17] We do not take a position on the accuracy of this interpretation.

Another important question is the meaning of a short shock of utility frequency. In Figure 11 we have 15 ms sine and cosine waves of 50 Hz. For a 10 ms sine wave, the interpretation is very simple; it is essentially a DC pulse and the VF threshold should just closely match the 10 ms DC pulse threshold from IEC 60479-2.

However, what if the 10 ms partial wave is not a simple half-sine but rather a "biphasic" or a partial cosine wave? Luckily, Green studied both of what he called "zero start" and "peak start" waves with his dog VF studies.[20] His dogs #54 and #56 were tested with both waveforms and thus we have strong pair-wise comparisons. As seen in Figure 12, the VF thresholds for a 10 ms half-sine was about 1.1 A and the VF threshold for a 10 ms half-cosine was about 2.5 A.

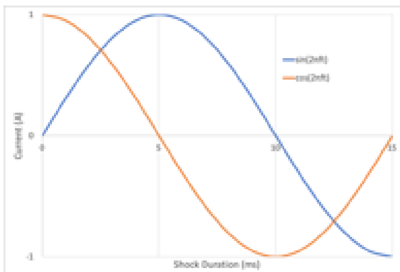

Figure 11. Short cosine and sine wave currents.

Thus, it appears that there is some cancellation effect and the thresholds for a biphasic partial wave (cosine) are larger than those for a simple monophasic half-sine wave. Hence, the thresholds proposed are conservative enough to cover both situations. In other words, a ≤ 10 ms utility-frequency partial-sine wave shock can be considered a DC pulse for purposes of VF safety.

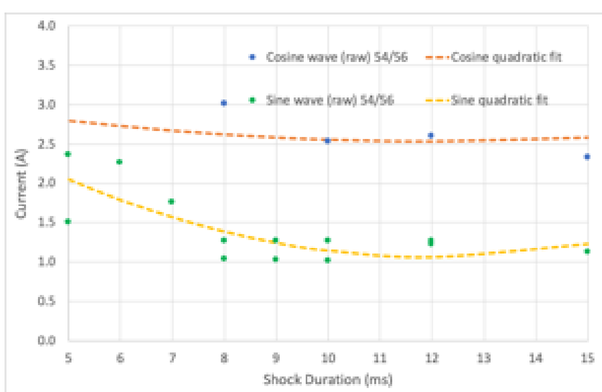

Figure 12. Ventricular fibrillation thresholds for Green's dogs 54 & 56

Unfortunately, the IEC AC requirements are written in terms of RMS current which confuses heating with stimulation capability. For example, the 10 ms C1 level is 500 mA for both AC and DC. For the DC pulse, this sets a charge threshold of 5 mC. For a sine-wave current of: I = Asinωt, the RMS AC current is A÷√2. The average current is given, for a single positive phase by:

$$I_{ave} = \frac{1}{\pi}\int_0^{\pi} Asint\,dt$$

$$= \frac{A}{\pi}[-cos\pi + cos0] = \frac{2A}{\pi}$$

So the ratio between the RMS and average current is:

$$\frac{I_{RMS}}{I_{ave}} = \frac{A}{\sqrt{2}} \div \frac{2A}{\pi} = \frac{\pi}{2^{3/2}} = 1.111$$

And thus 500 mA_{RMS} sets an *average* current threshold of 450 mA giving a *charge* threshold of 4.5 mC. Rather than complicate the standard by moving away from RMS current, we recommend allowing this 11% discrepancy to remain.

V. LIMITATIONS

The scaling of the animal studies is partially subjective. The fit, of durations < 100 ms, is good for the data of Ferris and Kouwenhoven. In Figure 5, it appears a little high (10-25%) for the Jacobsen data but the Jacobsen data were scaled by 75% to make them fit into the other animal studies. An Occam's razor argument can be made that the simplest fit should be chosen in the absence of more extensive data. We also note that the animal data were used to find the shape of the transition region between short and long shocks and thus the absolute values are not necessarily critical.

While the fit is good above 100 ms, the curve appears to possibly slightly overestimate the data below 100 ms., i.e the data predicted by the curve might be higher than the experimental values. However, there are theoretical reasons to believe that the VF threshold should actually briefly rise in the region between 10 and 100 ms due to the less efficient charging of the heart during the vulnerable period. Thus, the flatline ends up being a compromise between theory and the limited animal data.

VI. CONCLUSIONS

Existing ventricular fibrillation threshold current vs. duration data can be well-fit with a simple rational function. This can provide a useful update to IEC 60479-1.

VII. DISCLAIMER

This paper represents the work of the authors alone and is not, at present, reflective of the official position of the IEC technical committee 64 which is responsible for the 60479-1 standard.

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