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Defibrillation Success Rates for Electrically-Induced Fibrillation: Hair of the Dog

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ABSTRACT

Accidental electrocutions kill about 1000 individuals annually in the USA alone. There has not been a systematic review or modeling of elapsed time duration defibrillation success rates following electrically-induced VF. With such a model, there may be an opportunity to improve the outcomes for industrial electrocutions and further understand arrest-related-deaths where a TASER® electrical weapon was involved. We searched for MedLine indexed papers dealing with defibrillation success following electrically-induced VF with time durations of 1 minute or greater post VF induction. We found 10 studies covering a total of 191 experiments for defibrillation of electrically-induced VF for post-induction durations out to 16 minutes including 0-9 minutes of pre-shock chest compressions.

The results were fitted to a logistic regression model. Total minutes of VF and use of pre-shock chest compressions were significant predictors of success ($p < .00005$ and $p = .003$ respectively). The number of minutes of chest compressions was not a predictor of success. With no compressions, the 90% confidence of successful defibrillation is reached at 6 minutes and the median time limit for success is 9.5 minutes. However, with pre-shock chest compressions, the modeled data suggest a 90% success rate at 10 minutes and a 50% rate at 14 minutes.

BACKGROUND

In the 1600s an accepted treatment for canine-induced rabies was a *post facto* pseudo-vaccination:

> Let the hair of the mad creature, if it can be had, be laid upon the wound.[1]

Accidental electrocutions kill about 1000 individuals annually in the USA alone.[2] Electrically induced ventricular fibrillation (VF) has a high success rate of electrical conversion. (This is the electrical analog of the unsuccessful "hair-of-the-dog" therapy for rabies.) There is some confusion between the low rates of out-of-hospital cardiac-arrest resuscitations and those with electrically-induced VF. The extremely high rate for successful defibrillation of electrically-induced VF is not widely appreciated. This is largely because ischemically-induced VF is much harder to defibrillate.[3, 4]

Every business day, about 1000 Implantable Cardioverter Defibrillators (ICD) are implanted worldwide and well over 1,000,000 living patients have such devices in them. The majority of these implants involve a cardiac electrophysiologist electrically inducing VF in the patient to test the ICD.[5] With an ICD implant the shock is typically given in 10-20 seconds after the induction of VF and the success rate is 99.98%.[6] Without the knowledge of a nearly 100% success rate for prompt defibrillation, no physician would intentionally electrically induce VF in a patient.

There has not been a systematic review or modeling of delayed defibrillation success following electrically-induced VF. With such a review and model, there may be an opportunity to improve the outcomes for industrial electrocutions. In addition, such an understanding may help in the forensic diagnosis of sudden unexplained deaths where there was an electrical source in physical and temporal proximity to the incident and the presenting rhythm was VF.

METHODS AND RESULTS

We searched for MedLine indexed papers dealing with defibrillation success from electrically-induced VF with elapsed time durations of 1 minute or greater. Successful defibrillation was defined as eventual return of spontaneous circulation (ROSC). This includes the possibilities of multiple defibrillation shocks and post-shock chest-compressions. Studies of intact-chest animals with and without pre-shock chest compressions were included. We found 10 studies covering a total of 191 animal experiments.

Table 1 shows the animal studies that have reported the success of defibrillation (sometimes allowing multiple shocks) for *electrically induced* VF for various post-induction VF durations out to 16 minutes.

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Table 1. Defibrillation success vs. elapsed minutes post *electrically* induced VF.

Study	Year	N	Mins of VF without CC	Mins of Pre-shock CC	Mins Total in VF	N w ROSC	Notes
Yamanouchi[7]	1999	12	1	0	1	12	
Allred[8]	2008	6	7	0	7	6	
Tang[9]	2006	21	7	0	7	18	No CC before 3 shocks
Tang[9]	2006	21	7	0	7	19	CC after failed shock
Niemann[3]	2007	26	7	1	8	24	6 had coronary ligation before induction
Ewy[10]	2007	33	3-6	6-9	12	21	
Xu[11]	2007	7	7	5	12	5	
Wang[12]	2007	10	7	5	12	10	Used Thumper®
Leng[13]	2001	5	12	0	12	1	
Halperin[14]	2010	9	10	3.5	13.5	9	
Hayes[15]	2007	36	8	6	14	13	Ventilated during VF
Leng[13]	2001	5	12	4	16	5	

N is total number of animals studied and "CC" is chest compressions.

The only long-duration canine paper found was that of Leng; all other studies used swine. The univariate dependence of defibrillation success on total VF duration is shown in Figure 1.

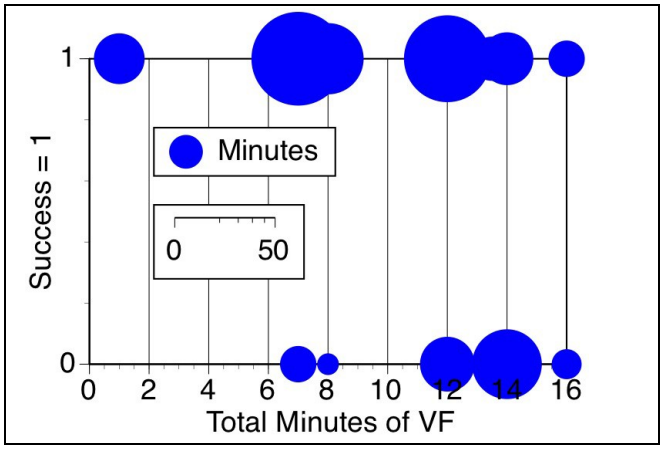

Figure 1. Bubble chart of animal study results. The 0 – 50 scale measures the bubble diameter and the respective number of animals.

The results from Table 1 were fitted to a logistic regression model (Wald's U = .16). Total minutes of VF and the use of pres-shock chest compressions were significant predictors ($p < .00005$ and $p = .003$ respectively). The duration of chest compressions was not a significant multivariate predictor.

These results demonstrate the benefit of pre-shock chest compressions as seen in Figure 2. With no compressions, the 90% confidence of successful defibrillation is reached at 6 minutes and the median time limit for success is 9.5 minutes. However, with pre-shock chest compressions, the modeled data suggest a 90% success rate at 10 minutes and a 50% success rate at 14 minutes.

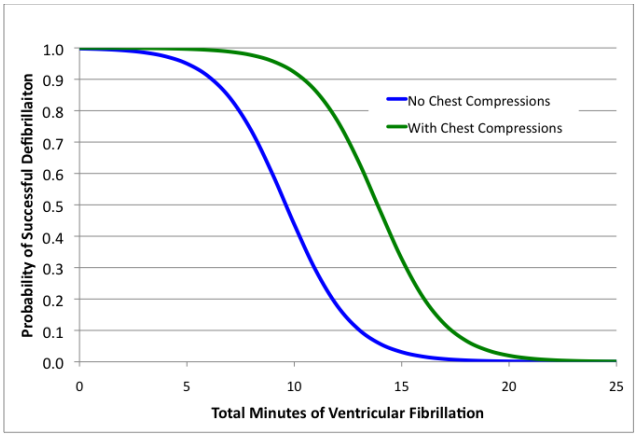

Figure 2. Probability of successful defibrillation from electrically-induced VF. Left curve (blue) is without chest-compressions while right curve (green) is with continuous compressions.

The situation is quite different for someone who has a cardiac arrest from a "heart attack" (myocardial infarction). In this scenario, a coronary artery is occluded and the heart muscle downstream is ischemic. After about 15-30 minutes, the ischemia leads to VF.[3] This is tested in animal models by ligating a coronary artery and waiting for the onset of VF. The relevant studies are shown in **Table 2**.

Table 2. Defibrillation success vs. minutes of *ischemically*-induced VF.

Study	Year	N	Mins without CC	Mins of CC	Mins Total	ROSC
Xu[11]	2007	7	7	5	12	4
Niemann[3]	2007	14	7	1	8	6
Walcott[4]	2002	12	0*	0	0	10

*Defibrillation was attempted immediately

There was insufficient data, in these studies, for any statistically significant modeling. However, it is clear that the defibrillation success results are dramatically different between electrically and ischemically-induced VF. The Niemann success rate for electrically-induced VF was significantly higher than that for ischemically-induced VF in the same study (24/26 vs. 6/14, p = .0006 by chi-square). Note that with ischemically-induced VF there is no duration with a 90% success rate and that at 10 minutes the success rate is < 50%. The Walcott study had 2 failures with shocks given immediately after the appearance of VF.

Human Data (Non-Electrically Induced Cardiac Arrest)

In addition to the differences seen in animals, with ischemia-induced VF, the typical patient has coronary artery disease, which makes it more difficult to perfuse the myocardium with chest compressions. Since it would obviously be unethical to fibrillate humans and monitor them for many minutes, scientific research here is limited to field observation studies. Students in cardiopulmonary resuscitation (CPR) classes are shown a very simplistic illustrative, survival graph that begins with 100% survival and then goes down by 10% per minute. Larsen analyzed 9,245 non-electrically induced, cardiac arrests and showed that this 10% per minute resuscitation degradation graph is extremely inaccurate.[16]

Larsen showed that the best field cardiac arrest survival rate (assuming everything was done instantly) is only 67%. See Table 3. This is largely because about 1/3 of cardiac arrests begin as asystole (flat-line).[17, 18] Also, it is difficult to defibrillate with continuous ischemia as that ischemia often re-induces VF. (Note the dramatic difference vs. the essentially 100% success rate from immediate defibrillation seen with electrically-induced VF). [6] The survival rate goes down 2.3% per minute until CPR is started plus 1.1% per minute until a defibrillation shock is delivered plus 2.1% per minute until Advanced Life Support (ALS) (cardiac drugs, intubation, and oxygen) is initiated. Thus, if there is no CPR or defibrillation the survival rate for field cardiac arrests goes down about 5.5% per minute. Note that this is about ***half*** the 10% per minute overly simplistic illustrative figure used by the American Heart Association (AHA) to encourage responders into quick action. Like many simple rules, the moral lesson is qualitatively, but not quantitatively, correct and the motives are good.

Table 3. Larsen model for death rate from cardiac arrest:

- 33% "ante" due to asystole, ongoing ischemia-VF induction, etc.
- 2.3% per minute until CPR
- 1.1% per minute until a defibrillation shock
- 2.1% per minute until ALS

DISCUSSION

We believe that this is the first review and meta-analysis of the defibrillation success rates for long-duration electrically-induced VF.

There are 2 MedLine-indexed cases of ICD patients being electrocuted. A 75-year man was struck by a lightning side-flash which induced a 200 ms cycle length VF.[19] The second case involved a suicidal electrician that intentionally grabbed onto a 240 VAC source.[20] The ICD detected a rather rapid VF (cycle length 181 ± 42 ms) with several zero-crossings not reflected in the detected cycle lengths. In both cases, the ICD detected the VF and converted it back to sinus rhythm.

The NIOSH (National Institute for Occupational Safety and Health) collects cases of industrial accidents. They have some electrocution cases with enough detail to allow estimates of the delay to defibrillation. Here are 2 such cases.[21]

Case 1. A 30-year-old construction worker was working on a fire escape in a building being renovated. Another worker handed the victim a metal pipe, and he was holding it with both hands when it contacted a nearby high voltage line, completing a path-to-ground. The worker instantly collapsed with this contact. Approximately 4 minutes after he collapsed, the fire department rescue squad arrived and began CPR. Within 6 minutes, a paramedic unit was on the scene providing defibrillation and other ACLS [Advanced Cardiac Life Support] measures. They were able to establish a heartbeat and pulse, but the individual continued to require respiratory support during transport to the hospital. He regained consciousness and was discharged within two weeks. He did have to return for further medical care for burns he received on his hands (current entrance wound) and buttocks (current exit wound).

Comment on Case 1: The standard estimate is that EMS is able to defibrillate within 2 minutes of arrival.[16, 22] Thus there were a total of 12 total minutes of VF including 8 minutes of chest compressions (assuming that the 6 minute delay began after the Rescue Squad arrival). Our model predicts a 77% likelihood of successful resuscitation, which did occur in this case.

Case 2. An 18-year-old male restaurant worker contacted electrical current when he kneeled to plug a portable electric toaster into a 120 VAC floor outlet. After a scream was heard, the victim was found convulsing on the damp floor, with one hand on the plug and the other on the receptacle box. The assistant manager went to the electrical panel, but was unable to locate the appropriate circuit breaker. A coworker attempting to take the victim's pulse received an electrical shock, but was not injured. After telephoning the emergency medical service, the assistant manager returned to the panel and de-energized all of the circuits (3 to 8 minutes after the worker contacted electrical energy). The injured worker was covered with a coat to "keep him warm." After about 5 minutes, another call was placed to the emergency squad, and the assistant manager "yelled" for an off-duty employee who lived in an apartment across the lot, who came and began CPR. The emergency service was on the scene 10 minutes after receiving the first call. ACLS measures were available but the resuscitation was unsuccessful and the worker was pronounced "dead on arrival" at the local hospital.

Comment on Case 2:

3-5 minutes:	Time spent going to electrical panel, taking pulse and making 1st EMS call.
10 minutes:	Time for 1st call to EMS arrival
2 minutes:	Time for EMS to deliver defibrillation shock. [16, 22]
15-17 minutes:	Total time in VF

Our model predicts a likelihood of only 12-33% of successful resuscitation in this case.

The higher defibrillation success rates for longer-duration VF following electrocution are generally not appreciated. Much of this is based on the marginal field results for general cardiac arrests even though those results include a significant number of asystole and PEA cases. There is also a failure to appreciate the difference between electrocution arrests and common cardiac arrests. This is in addition to the confusion caused by the AHA's "10% per minute" leitmotif.

Another theoretical potential source of electrocution risk lies with electrical weapons.[23, 24] In the event of a cardiovascular collapse, during an encounter with law enforcement, rapid initiation of chest compressions can be assumed since law enforcement officers are trained in basic life support. VF is rarely seen in an arrest-related death — with or without electrical weapons — as the arrhythmias are predominantly asystole due to acidosis from excited-delirium syndrome behavior or drug overdoses.[25-27] In the few reported cases of VF, prompt defibrillation attempts were generally unsuccessful.[28] In view of our results, this supports a conclusion that such VF cases were not electrically-induced and hence tends to exculpate the electrical weapon.

Confusion often arises from the possibility of pre-existing lactic acidosis from drug or alcohol abuse, hyperactivity, or struggling. It is sometimes wrongly assumed that lactic acidosis from previous exertion or substances makes successful defibrillation more difficult. However, VF itself causes extracellular myocardial acidosis and thus systemic acidosis may not be that important. [29] In fact, animal studies show that systemic acidosis does not raise the defibrillation threshold (DFT).[30, 31] Alcohol does not raise the DFT in humans.[32]

CONCLUSIONS

Electrically-induced ventricular fibrillation is easier to defibrillate than ischemically-induced VF. Automated defibrillator availability should be stressed for work around industrial electrical sources. A 90% defibrillation success rate is expected for defibrillation attempts within 10 minutes of cardiovascular collapse and a 50% success rate is expected at 14 minutes — assuming some pre-shock chest compressions.

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