

# The Response of Intact Guinea Pigs to AC Leakage Currents

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## Abstract

*There was a difference in the standard for leakage current in the US and Europe. This difference existed largely because there was very little data on AC stimulation of the heart in situ. In this study, we examine AC stimulation of the intact guinea pig. Nine male guinea pigs were anesthetized with isoflurane, intubated and monitored with the lead II ECG and optical plethysmograph. For AC stimulation, a stainless steel electrode was used. The return electrode was applied to the right rear paw. Five seconds of AC stimuli at various frequencies was used. The minimum VF threshold in these animals was found to be  $558 \pm 314 \mu\text{A}$  at 100 Hz. Frequencies both below (20 Hz:  $1584 \pm 753 \mu\text{A}$ ) and above (160 Hz:  $1355 \pm 1007 \mu\text{A}$ ) were found to be significantly different from 100 Hz (20 Hz:  $p=0.0017$  and 100 Hz:  $p=0.0085$ ). By contrast the minimum current required to have any effect on the heart only increased with frequency from 10 Hz ( $119 \pm 53 \mu\text{A}$ ), to 160 Hz ( $183 \pm 50 \mu\text{A}$ ,  $p < 0.0001$ ).*

## 1. Introduction

In 1993 the American standard for leakage current through the heart under a single-fault condition was set at 10  $\mu\text{A}$  rms [1], [2]. However the European standard was 50  $\mu\text{A}$  rms [2], [3]. Both these standards were based on estimates of the ability of 60 Hz AC current to induce ventricular fibrillation (VF) [4]. This was logical, considering that VF causes systemic blood pressure collapse, leading to morbidity and death. In 1999 Swerdlow, Malkin and their colleagues showed that systemic pressure collapse can result from 60 Hz AC leakage currents ( $84 \pm 27 \mu\text{A}$  rms) far below those required to induce VF ( $278 \pm 226 \mu\text{A}$ ) in 32 closed-chest humans [5]. This was followed by an editorial in Circulation [6] concluding that the endpoint in electrical safety monitoring should be systemic hypotension with ventricular tachycardia (not VF) and that the standard for allowable current must be 10  $\mu\text{A}$ . In other words, it is important to know the minimum amount of AC current required to cause systemic hypotension, not the amount of current required to induce VF, the focus of all previous

work. Such a large difference in leakage current standards existed largely because there was very little data on AC stimulation of the heart in situ. Even today there is very little data on AC stimulation of the heart in situ. In this study we examine AC stimulation of the intact guinea pig.

Specifically, the objectives of this research were to establish the frequency dependence of the AC stimulation effect and VF threshold.

## 2. Materials and methods

Nine retired male guinea pigs, weighing 910-1258 g were used. Anesthesia was induced using 4% isoflurane with oxygen at 1 liter/minute in an induction box for approximately fifteen minutes (Surgivet Anesco – Isotec 4). An endotracheal tube was inserted and continuous positive pressure ventilation was maintained (Ventilator/SAR-830/P). The standard lead II electrocardiograph (NDM corporation, Ohio), optical plethysmograph (CSI, inc) and rectal thermocouple (Harvard Apparatus) were used to continuously monitor the electrocardiogram, oxygen saturation (SpO<sub>2</sub>) and rectal temperature of the guinea pig. A stainless steel wire (0.18 mm in diameter, of length 10 cm), insulated with Teflon was used for AC stimulation. Two mm of one end was exposed and bent in half to form a hook. The other end was exposed to make electrical connections. A 10 ml syringe and 22 gauge needle were used to insert the wire into the heart. The syringe was filled with saline and the stainless steel wire was passed through the needle into the syringe in such a manner that the hooked end pointed out. The needle along with the wire was advanced through the sixth intercostal space into the heart. The syringe was used to aspirate blood to ensure that the electrode was in the heart. Then the needle and syringe were withdrawn leaving the electrode hooked into the heart. The return electrode was applied to the right rear paw. For defibrillation, two stainless steel electrodes, twelve millimeters in diameter were inserted subcutaneously at opposing aspects of the thorax, one of them corresponding to the point of maximal impulse.

A computer driven, analog stimulus isolator (A-M systems, model 2200) produced the AC stimulus. Each stimulus consisted of 5 seconds [5], [7], [8] of sinusoidal

AC without DC ( $<1\mu\text{A}$ ). AC stimuli were started at 25  $\mu\text{A}$ , then increased in steps of 25  $\mu\text{A}$  till 500  $\mu\text{A}$ , then in steps of 50  $\mu\text{A}$  till 1000  $\mu\text{A}$  and then in steps of 100  $\mu\text{A}$  till 3000  $\mu\text{A}$ . If four consecutive effects were seen then the next reading was taken at 1000  $\mu\text{A}$ . If VF was observed during this time then the readings were stopped for that frequency. The AC stimulation frequencies were 10, 20, 40, 60, 80, 100, 120 and 160 Hz. A computer-driven amplifier (Bipolar Operational Source/Sink, Electronic Measurements) was used to deliver the defibrillation shock. The data was stored in the form of the electrocardiogram and plethysmogram for each stimulus given.

When the variance of the plethysmogram during either of the last two seconds of stimulation was less than 30% greater or smaller than the variance of the plethysmogram of the first second, two seconds before stimulus began, the episode was defined as normal. When the variance of the plethysmogram during either of the last two seconds of stimulation was more than 30% greater or smaller than the variance of the plethysmogram of the first second, two seconds before stimulus began, then the stimulus was considered to have an effect on the heart's mechanical activity. When the variance of the plethysmogram during the two seconds following the end of the stimulus was less than 10% of the variance of the plethysmogram of the first second, two seconds before the stimulus began, the stimulus was considered to have caused a ventricular fibrillation. The effect threshold was defined as the lowest current strength at which an effect was seen for a particular frequency. The lowest current strength to cause VF for a particular frequency was defined as the VF threshold.

### 3. Results

The mean effect threshold for each frequency was determined from the nine studies. The minimum effect threshold was seen at 10 Hz ( $119 \pm 53 \mu\text{A}$ ). Paired t-tests were used to compare this minimum effect threshold at 10 Hz with the mean effect thresholds at the remaining frequencies. The tests showed that the effect threshold increased with frequency from 10 Hz upwards (160 Hz:  $183 \pm 50 \mu\text{A}$ ,  $p < 0.0001$ ).

The mean VF threshold for each frequency was determined from the nine studies. Unlike the effect threshold the minimum VF threshold in these animals was found to be  $558 \pm 314 \mu\text{A}$  at 100 Hz. Paired t-tests were used to compare this minimum effect threshold at 100 Hz with the mean effect thresholds at the remaining frequencies. Frequencies both below (20 Hz:  $1584 \pm 753 \mu\text{A}$ ) and above (160 Hz:  $1355 \pm 1007 \mu\text{A}$ ) were found to be significantly different from 100 Hz ( $p = 0.0017$  and  $p = 0.0085$  for 20 Hz and 160 Hz respectively).

### 4. Discussions

The normal heart is said to be susceptible to electrical stimulation only during the vulnerable period. Based on this, the effect and VF threshold patterns for various frequencies should follow a similar pattern. However, our studies show that effect and VF thresholds have a different dependence on the frequency of the stimulating current. This indicates that in addition to the theory of the vulnerable period, there exists at least one additional mechanism for VF to occur.

The work by Malkin and Hoffmeister on the frequency dependence of the effect and VF threshold shows that the effect threshold increases as the frequency of AC stimuli is increased, whereas the VF threshold has a minimum at 40 Hz [8]. Edward Vigmond et al. showed that the effect threshold increased as the frequency of the AC stimuli is increased [9]. Our results for the effect threshold agree. However, for the VF threshold frequency dependence, the minimum threshold in our study was observed at 100 Hz.

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