

Keywords: electrocardiograph, protection circuitry, RFI, ESD, EMI, EMS, radio susceptibility, electromagnetic interference, electromagnetic susceptibility

APPLICATION NOTE 5724

LIGHTNING BOLTS, DEFIBRILLATORS, AND PROTECTION CIRCUITRY SAVE LIVES

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Abstract: There have been many studies concerning the safe current levels impressed across the heart. The standards for medical equipment have bounced around, and today safe levels are said to be less than $4\mu\text{A}$ to $10\mu\text{A}$. With lives in the balance, a designer of defibrillators must understand the entire gamut of possible input protection methods and then choose the best defense at a reasonable cost. Victims of sudden cardiac arrest (SCA) can be saved with a small, prompt lightning bolt (defibrillator shock) to the chest.

With lives at stake, the design of medical equipment is very demanding with extremely tight margins. Remember too that it is not uncommon to have several pieces of equipment attached to the patient at the same time. So the total leakage current must remain below the threshold that can harm the patient's heart. This app note discusses several ECG input protection methods including radio susceptibility (RFI), ESD, electromagnetic interference (EMI), electromagnetic susceptibility (EMS), and defibrillator protection.

A similar version of this article appeared July 2014 in [Electronic Design](#).

Introduction

Victims of sudden cardiac arrest (SCA) can be saved with a small, prompt lightning bolt (i.e., a defibrillator shock) to the chest. The shock (3kV to 5kV and 50A) stops the heart from unproductive fluttering (fibrillating) which fails to pump blood to the brain and other organs. This lightning bolt allows the heart to restart orderly pumping of blood. In hospitals it is common to monitor the heart using an electrocardiograph (ECG) with a separate defibrillator. The ECG leads (i.e., electrodes) are on the patient when the defibrillator delivers the shock. With no warning, the ECG must withstand this lightning bolt and continue working properly.

According to the American Heart Association (AHA) nearly 383,000 out-of-hospital sudden cardiac arrests occur annually, and 88 percent of cardiac arrests occur at home. Sadly, less than eight percent of people who suffer cardiac arrest outside the hospital survive.¹ These are sobering statistics. In medical terms a heart attack is much different than an SCA. An SCA has no warning signs; a person just collapses. A heart attack has multiple, generally understood warning signs preceding it.

Without our protective skin a patient's heart is vulnerable to very small currents. In the electrically susceptible patient, moreover, even minute amounts of current ($10\mu\text{A}$) can cause ventricular fibrillation.² Remember that with an ECG and separate defibrillator it is not uncommon to have several pieces of equipment attached to the patient at the same time. Clearly, the total leakage current must remain below the threshold that can harm a human heart.

Defibrillators and Life-Saving Shocks

Many think that a defibrillator restarts the heart, but actually it stops the heart. There is a random beating in the heart called fibrillation, which means the heart is not coordinated and not pumping blood. The defibrillator shocks the heart into inactivity, allowing the normal sinus rhythm to restart.

Figure 1 shows a hospital-style defibrillator and a trained medical technician delivering a life-saving shock for milliseconds. The 3kV to 5kV voltage and 50A current are necessary to penetrate the chest and shock the heart. High voltage and current is necessary because the human body is ~75% salty water. The body conducts the majority of the electricity away, bypassing the heart.



Figure 1. A hospital-style defibrillator with paddles. Note that there is an external electrocardiograph (ECG) or heart monitor on the patient, as evidenced by the white circles (electrodes) and leads (wires) on the chest.

A second type of defibrillator (**Figure 2**) is an automated external defibrillator (AED) designed to be used by a member of the public with minimum training. These disposable electrode patches serve two purposes: first, monitor the heart with an electrocardiograph (ECG); and second, apply the high-voltage shock.

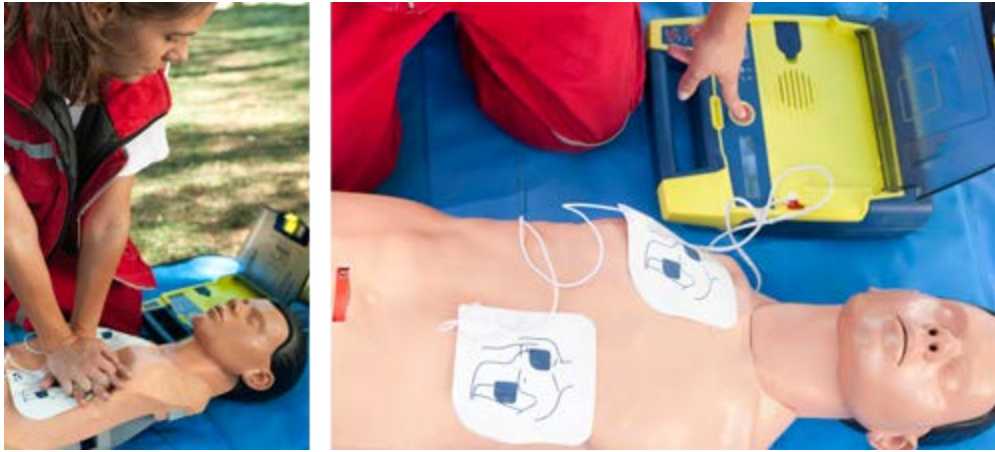


Figure 2. Chest compression CPR (left) circulates blood to deliver oxygen to the brain and other vital organs until the heart can be restarted by the AED (right).

The AED protects its own input from the high voltage and current shock because it knows when it is about to apply the shock. Therefore it can, and does, disconnect the ECG monitor during the shock. The hospital-style defibrillator, however, is often used with a separate ECG or monitor. In this latter situation the ECG or monitor has no advanced warning and must withstand the high-voltage and current of the shock.

Protecting the Defibrillator for ECGs

We learned in Figure 1 that the voltage might be 3kV to 5 kV at 50A. The defibrillator test set in **Figure 3** looks very much like the standard ESD test set⁴. There is, however, an important difference. The ESD test has a capacitor measured in picofarads, but the defibrillator test set is in many microfarads. The extra energy from the defibrillator must, therefore, be dissipated in front of the ECG.

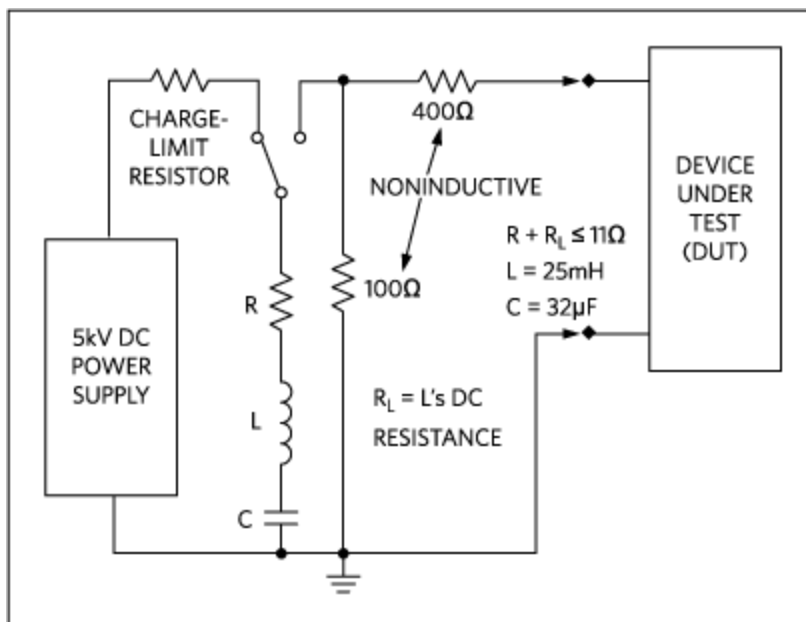


Figure 3. A defibrillator test set (note the large capacitor).

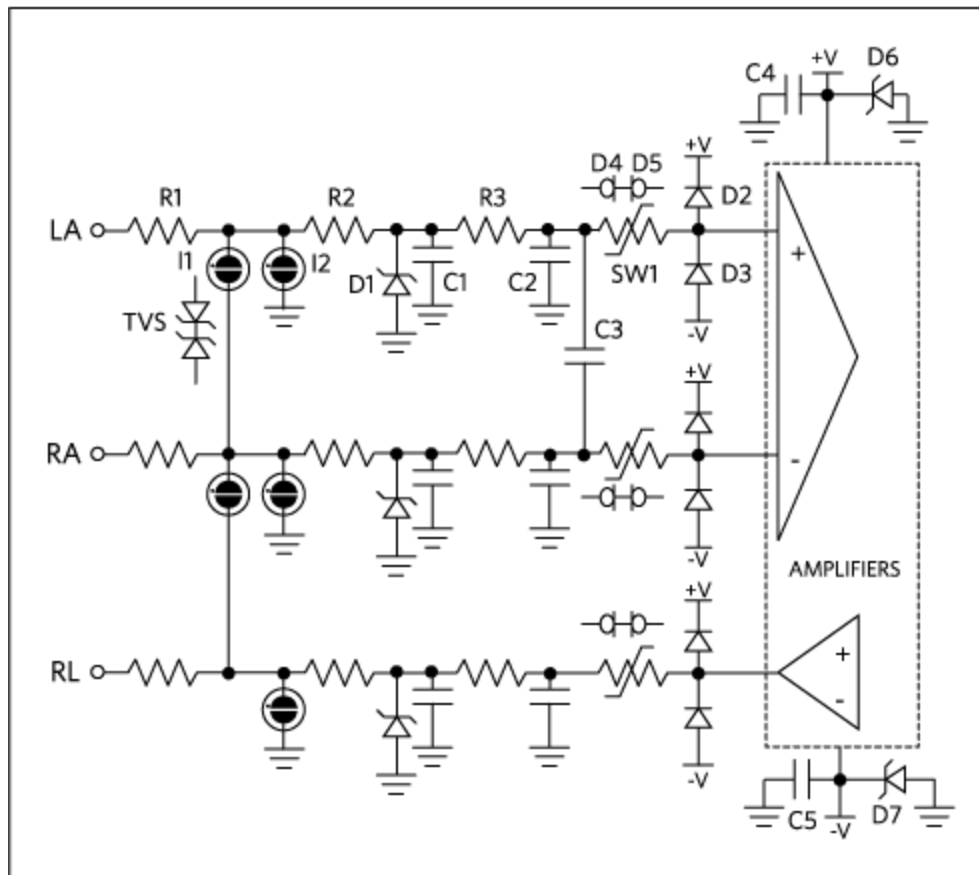


Figure 4. Typical ECG front-end defibrillator protection circuitry. LA = left arm; RA = right arm; RL = right leg.

In **Figure 4** shows a defibrillator's typical protection circuitry for an ECG. For convenience, we labeled the components in the left arm (LA) input circuit at the top. The normal ECG waveforms are on the order of a few (0.5mV to 7mV) millivolts, but the high-voltage defibrillator is in kilovolts and can last 5ms to 20ms—a long time for electronic components to survive such high voltage. Most ECG front-ends like ours in Figure 2 use neon glow lamps such as NE-2 or NE-23 (I1 and I2) for protection. NE-23 has a small radioactive dot inside that provides photons to stabilize the ionization voltage. Alternatives for the neon lamps are gas-discharge arrestor tubes or transient voltage suppressors (TVSs).

Resistor R1 is in the range of 10k to 20k , and can be in the input of the amplifier or built into the cables. It is the series element that limits the current in the neon lamps. Resistors R2 and R3, along with capacitors C1, C2 and C3, form lowpass filters. The D1 diode limits the voltage to a lower level. D1 can be a zener or avalanche diode, a metal-oxide varistor (MOV), or a thyristor surge protector. The D1 capacitance in conjunction with C1 is part of the lowpass filter. Capacitor C2 is the common-mode filter, whereas C3 provides differential filtering. Typically C3 is about 10 times larger than C2. SW1 is a high-voltage signal-line protector: a switch that senses high-voltage, turns off the series switch, and turns on a clamp to reduce the amount of voltage at the amplifier. SW1 can be replaced by a current-limiting diode which looks like a

JFET with the source and drain terminals tied together. Diodes D2 and D3 are ESD-protection diodes that clamp the amplifier input to the power supplies. Notice C4 and zener diode D6 at the top of the amplifiers. They absorb and clamp the positive voltage rail. C5 and D7 do the same for the negative power rail.

“Nothing is perfect.” People have said this for generations, and we can use it here too. This ECG defibrillator protection circuitry involves trade-offs between how well the amplifiers are protected and the frequency response necessary for the ECG to function properly. The capacitance of the protection devices is critical to preserve the wanted heart frequency response.

Repeated defibrillator shocks can degrade the input devices. The neon lamps can become contaminated by the electrode degradation and the defibrillator’s glass envelope can break to allow air and water into the lamp. Consequently, most manufacturers recommend replacing the input protection devices at least annually. In a hospital setting where the ECG and defibrillator are used frequently, they receive more shocks and will degrade even faster.

Now we must consider the effects of radio frequency interference (RFI), electrostatic distortion (ESD), electromagnetic interference (EMI), and susceptibility (EMS) on this protection design.⁴

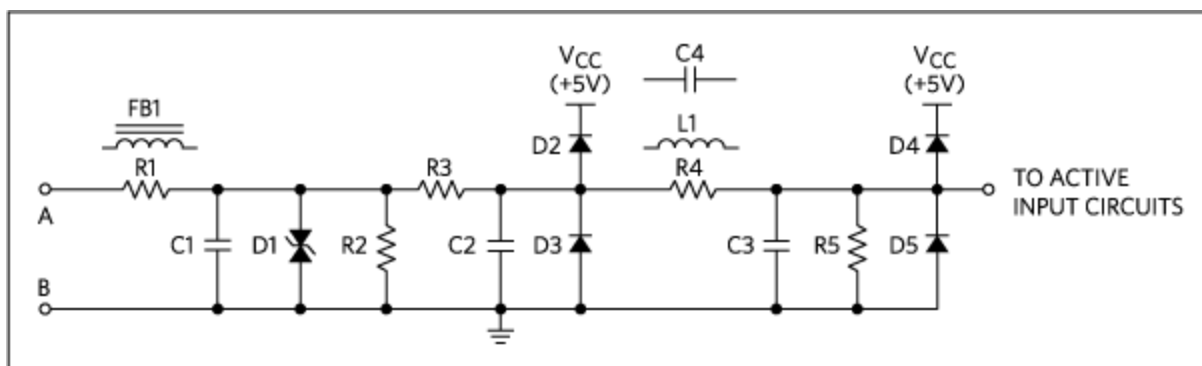


Figure 5. Schematic for protection against unwanted electrical vulnerabilities such as ESD, EMI, EMS, and RFI.

The devices in **Figure 5** fall into three categories:

1. Voltage-limiting devices: gas discharge arrestors, metal-oxide varistors, suppressor diodes, triacs, diacs, and switches
2. Current-limiting devices: fuses, circuit breakers, and thermal cutouts
3. Risetime reducers: resistors, inductors, coils, ferrite beads, and capacitors, all of which slow the risetime of a transient and, thereby, allow time for other protection devices to function.

Capacitors are used with the resistors; ferrite beads, and inductors to act as lowpass filters. This approach controls the anti-alias filtering for the data converter. It slows the ESD risetime by spreading the impulse over time and allows the capacitors to be more effective. The working voltage, equivalent series resistance (ESR), and self-resonance point of each capacitor need to match the application’s frequency and bandwidth. The self-resonance point may mean that several smaller resistors are necessary in parallel to absorb the fast risetime of ESD and a defibrillator shock pulse.

Each of these networks is reciprocal; they protect a system from the outside world and protect the outside

world from any unintentional signal that a device might radiate.

All of these devices can aid the protection circuitry of the ECG. As this is becoming a complex system, it is wise to simulate it. Free and low-cost calculators⁵ and simulators⁶ are available for this task.

The Ultimate Goal Is Patient Protection

There have been many studies concerning the safe current levels impressed across the heart. The standards for medical equipment have bounced around, and today safe levels are said to be less than 4 μ A to 10 μ A. This makes the design of medical equipment very demanding with extremely tight margins. Remember too that it is not uncommon to have several pieces of equipment attached to the patient at the same time. So the total leakage current must remain below the threshold that can harm the patient's heart.

With lives in the balance, a designer of defibrillators must understand the entire gamut of possible input protection methods and then choose the best defense at a reasonable cost. Patients must always be protected which will include proper inspection and calibration of the equipment during the equipments' life time in the medical environment.

References

1. "CPR & Sudden Cardiac Arrest (SCA), Fact Sheet," **American Heart Association**, May 8, 2014, www.heart.org/HEARTORG/CPRAndECC/WhatIsCPR/CPRFactsandStats/CPR-Statistics_UCM_307542_Article.jsp
2. In medical terms, electrical shocks are usually divided into two categories. Macroshock refers to larger currents (typically more than 10mA) flowing through a person. These shocks can cause harm or death. Microshock refers to very small currents (as little as 10 μ A to 50 μ A) and applies only to the electrically susceptible patient, such as an individual who has an internal conduit that is in direct contact with the heart. This conduit can be a pacing wire or a saline-filled central venous or pulmonary artery catheter. In the electrically susceptible patient, even minute amounts of current (10 μ A) can cause ventricular fibrillation. See Barker, Steven J, PhD, MD*; Doyle, D. John, MD, PhD, FRCPC†, "Electrical Safety in the Operating Room: Dry versus Wet," International Anesthesia Research Society, June 2010, http://journals.lww.com/anesthesia-analgesia/Fulltext/2010/06000/Electrical_Safety_in_the_Operating_Room_Dry.1.aspx.
*From the Department of Anesthesiology, University of Arizona College of Medicine, Tucson, Arizona; and †Cleveland Clinic Lerner College of Medicine of Case Western Reserve University, Cleveland, Ohio.
3. Application note 639, "[Maxim Leads the Way in ESD Protection](#)," Figures 2 and 3.
4. Tutorial 4645, "[A Power Engineer: the Super Hero in a Design?](#)" Figure 2.
5. At www.maximintegrated.com/cal see links to Maxim tools and calculators about half way down the page. The links are to analog design calculators for HP50g with a free PC emulator, and a link to an online design and simulator for programmable filters.
6. At www.maximintegrated.com/cal also see links to: Micro-Cap 10 circuit simulator from Spectrum Software (free evaluation version); Solve Elec is a simple circuit simulator (donation software); FilterFree is a filter design program for filters up to three poles (freeware); Kemet[®] Spice Software (freeware); Johanson Technology, JTIsoft[®] (freeware) is comprised of two advanced design simulation software packages, MLCsoft[®] and MLIsot[®], and provides complete S-parameter and

SPICE modeling data on Johanson's line of RF multilayer ceramic capacitors and inductors over the frequency range of 1MHz to 20GHz; AADE Filter Design and Analysis (freeware).

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MAX13206E	2-/4-/6-/8-Channel $\pm 30\text{kV}$ ESD Protectors in μDFN	Free Samples
MAX3205E	Dual, Quad, and Hex High-Speed Differential ESD-Protection ICs	Free Samples
MAX4507	Fault-Protected, High-Voltage Signal-Line Protectors	Free Samples

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