

# Common-Mode Rejection: How It Relates to ECG Subsystems and the Techniques Used to Provide Superior Performance

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## IDEA IN BRIEF

*The techniques described in this article for optimizing common-mode rejection in ECG subsystems have been proven over time to result in excellent diagnostic performance, while keeping patient and operator safety requirements at the forefront.*

Depending on the application for the ECG subsystem, there are clinical situations where the CMR (common-mode rejection) must be very high. The AAMI (Association for the Advancement of Medical Instrumentation) specifies a test methodology with typical electrode impedance imbalances and offsets that must be met. Other standards, such as IEC, UL, and medical directives from various countries, also have various tests for common-mode rejection.

This article describes human body impedance mismatch, electrode and cable design, protection circuitry, usage of right leg drive, and other considerations that affect common-mode rejection and proposes various ways to enhance CMR in ECG subsystems.

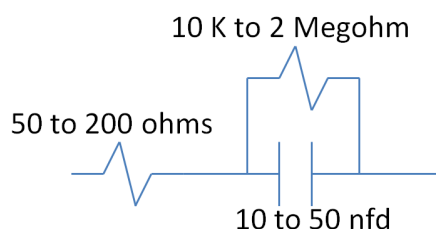


Figure 1. Human Tissue → Electrolyte → Electrode Model

## COMMON-MODE REJECTION, SAFETY, AND RFI

Multiple design trade-offs must be made to optimize common-mode rejection in ECG systems.

Evaluating these trade-offs starts with safety. Most standards indicate that 10  $\mu\text{A}$  rms from dc to 1.00 kHz is the upper limit for “normal condition” operation of the ECG system. For “single fault conditions” some standards allow an increase to 50  $\mu\text{A}$  rms, but currents as low as 35  $\mu\text{A}$  rms can compromise the myocardium. 10  $\mu\text{A}$  rms is recommended for “single fault conditions.” (See reference 1.)

AC mains leakage current must be limited to this maximum level. Various standards measure source and sink currents between electrodes, electrodes tied together, and with the electrodes energized with ac mains relative to earth ground.

Since standards and specific country directives change with time, the designer is encouraged to stay current with latest releases to ensure continued compliance with safety standards, including maximum source and sink currents allowed, as a function of frequency, for the human subject and the test methodologies used to ensure compliance.

In addition, the ECG subsystem must be protected from a defibrillator pulse (bi-phasic or unipolar) so current limit circuitry is added between the in-amp (instrumentation amplifier) to protect the circuitry. ESD (electrostatic discharge) protection circuitry is also required.

### Essential Performance

In addition to the safety requirements, the ECG subsystem must be able to provide what IEC 60601-1-1 and derivatives describe as “essential performance” during electrosurgical procedures and other harsh environments where nearby RFI (radio frequency interference) can be high. This would include environments such as aircraft, radar, trains, and ships.

### Sources of Common-Mode Signals

The source of a common-mode voltage is typically the ac mains frequency of 50 Hz or 60 Hz with line voltages as high as 264 VAC rms. Nontypical environments such as European trains that run off 16.666 Hz can also be a source of common-mode input.

### Common-Mode Model of the Human Body and Other Circuit Paths of the ECG Subsystem

In Figure 2, the common-mode signal is coupled through the “human torso,” from the surface of the skin through the

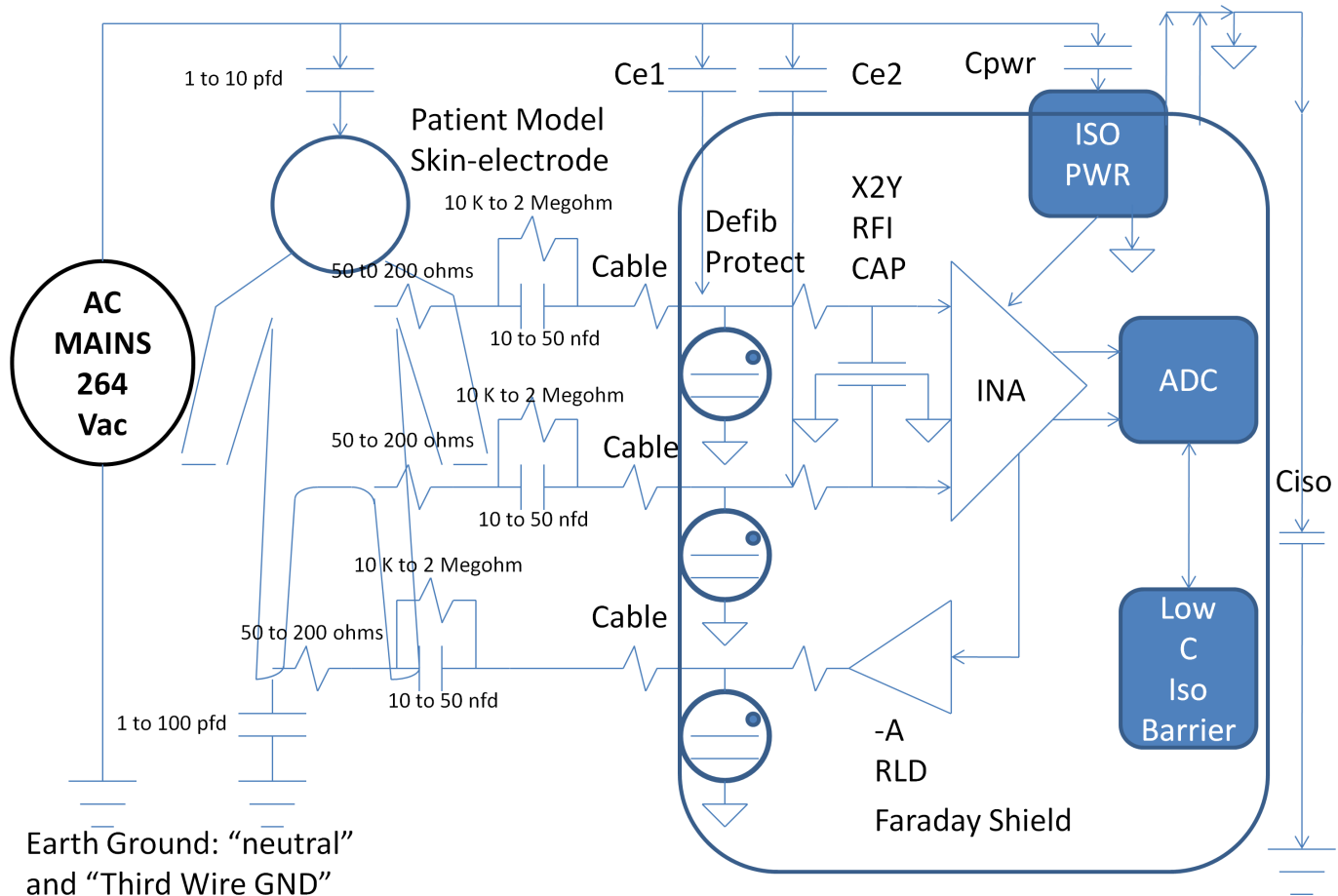


Figure 2. Block Diagram of ECG Subsystem.

electrolyte, the electrode, to the ECG electrode wire, through the defibrillator protection circuitry, the RFI input filtering, and in-amp to earth ground through capacitance between isolated ground and earth ground. Figure 1 presents an impedance model of the ECG electrode and its interface to the surface of the skin. The ac mains may also be coupled into the ECG “front end” through the ECG cable, the input protection circuitry from external transients such as a defibrillator pulse, and direct coupling through the isolated power supply. Potential RFI rectification on the in-amp input can also create issues with the in-amp common-mode rejection.

#### Common-Mode to Differential Mode Conversion

The ac and ECG signals are both measured through the electrodes into the ECG preamplifier subsystem, making it very important to ensure that the common-mode signal is not converted to “differential mode.” The combination of mismatches in impedance of the ECG electrodes, cable capacitance, and the protection circuitry associated with

defibrillator protection, which typically takes the form of resistors and SCR/argon voltage limiters, makes common-mode-to-differential conversion more likely.

#### Tissue/Electrode Issues

The “stratum corneum,” the outermost layer of skin, has the highest impedance component of skin composition to the electrode itself and is highly variable at low frequencies and changes as a function of frequency. The impedance is a function of electrode material, size, adhesive, electrolyte used, and the outer layer/condition of the skin itself. In order to ensure the lowest impedance and more stability in the electrode interface, some skin preparation techniques use “sandpaper” as a “skin prep” prior to the placement of the electrode. Various compositions of Ag/AgCl electrodes provide some of the lowest impedances and offsets of other commonly used materials. The difference in impedance between electrodes can be as high as 50,000  $\Omega$  over a range of frequencies. Reducing this mismatch helps to reduce common-mode-to-differential conversion. (See reference 2.)

### ECG Cable

Some ECG cables embed protection resistors, for defibrillator protection of the circuitry, which can range from 2.5 k $\Omega$  to as high as 49.9 k $\Omega$  electrode. If the resistance is not in the cable, then it is typically on the PCB layout. Matching of these resistors is important as it interfaces with the RFI filter. One technique used to minimize the impact of mismatch in cable impedance is an active drive of the cable shield.

### RFI Filter

The typical X2Y RFI filter used to prevent RFI from entering the input stage of the in-amp must be matched in differential and common-mode impedance. Integrated 2XY RFI filters have superior specifications to standard surface mount-capacitors, and the construction lends itself to superior performance. (See reference 6.)

## TECHNIQUES USED TO LOWER THE INCOMING COMMON-MODE SIGNAL

### RLD

Right leg drive, as describe by Winter, Wilson, Spinelli, et.al., (see references 4 and 5) is a technique to reduce the incoming level of the common-mode signal appearing at the differential inputs of the in-amp. The improvement in common-mode reduction is limited by the amount of RLD current that can be provided to the patient. Usage of a transimpedance amplifier as described by Spinelli for the RLD should be considered.

### Faraday Shield

A Faraday shield is often used to cover the ECG front end and protect it from environmental RFI and ac mains coupling as shown in Figure 2. The Faraday shield helps in reducing the ac mains coupling into other various entry points along the signal chain, prior to in-amp inputs, such as Ce1 and Ce2.

### In-Amp

The in-amp must be run with supply voltages that are high enough to accommodate the differential and common-mode input voltage ranges, typically  $\pm 1.0$  V. In some applications, higher differential input levels are needed:  $\pm 2.0$  V. The in-amp must have a bias current of 1 nA or less (preferably 100 pA), very low noise current, very low noise voltage, and high common mode rejection through the fifth harmonic of the highest ac mains frequencies. Typical frequencies of concern: 16.666 Hz, 50 Hz, 60 Hz, 100 Hz, 120 Hz, 150 Hz, and 180 Hz.

The first stage in-amp is typically set for a differential dc gain of between 5 and 10. In cases where the input in-amp is capable of providing gain to the ac portion of the signal and

not the dc portion, higher gains are practical. The trade-offs are noise performance, dynamic input range, and power supply voltage.

### DSP Reduces the Common-Mode Signal

After “hardware” mitigation is implemented, residual common-mode signals can be handled in the digital domain. Some techniques utilized include FIR notch filters, adaptive filters, and “digital subtraction” of the common-mode signal itself. A designer must be careful to ensure that “diagnostic integrity” of the ECG signal is not compromised through use of these various techniques to ensure that the clinicians “differential diagnostics” are not adversely affected by some of the potential techniques. Usage of a notch filter is sometimes contraindicated due to its impact on the phase/amplitude distortion of the signal of interest. Compliance with standards for “diagnostic bandwidth” ECG systems must be maintained.

## SUMMARY

The design of ECG subsystems for high common-mode rejection requires the designer to keep the patient and operator safety requirements in the forefront. Some techniques for enhanced common-mode rejection may actually increase leakage currents and, therefore, must be avoided. The techniques mentioned here have been proven over time to result in excellent diagnostic performance.

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**RESOURCES**

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