RESEARCH

Electrocardiogram Interference: A Thing of the Past?

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Abstract

This paper focuses on the problem of high and/or imbalanced electrode-skin impedances changing electrocardiogram (ECG) morphology. After reproducing ECG interference in a controlled laboratory setting—similar to what was observed during cardiopulmonary bypass surgery— and then understanding the cause, this knowledge was applied to clinical settings. Most interference was reduced by using electrode impedance meters and consistent skin prep.

Introduction

In spite of many improvements in patient monitors, electromagnetic interference (EMI) of the electrocardiogram (ECG) has been a problem for over four decades[1-2] and continues to be an issue today.[3-4] Consistently resolving ECG electromagnetic interference requires the use of a separate and dedicated device—an electrode impedance monitor, which is not built into today's patient monitors.

Interference-free waveforms enable accurate diagnosis and increase alarm reliability. False positive dysrhythmia alarms are a factor in alarm fatigue, complicating care by desensitizing clinicians.[5] This desensitization has been recognized as one of the root causes in an adverse event resulting in a patient's death.[6]

Interference occurs when two or more waves combine to form a new, distinctly different waveform. The primary waveform is the patient's intrinsic cardiac electrophysiological activity, which comprises the usual characteristic waveform morphology of the ECG. A secondary and interfering wave can originate from multiple devices, such as intravenous infusion pumps, rapid fluid infusers, and dialysis machines.

ECG interference is common throughout hospitals, particularly during cardiac surgery.[7-16] The authors have observed baseline wander and electrostatic discharge when healthcare providers move hands and torsos in proximity to the patient, tap their feet on the floor, or touch the patient's bed. Such interference can trigger false positive dysrhythmia alarms, signaling ventricular tachycardia and premature ventricular contractions.

When ECG interference is first encountered, in most instances, there is not an immediate need for intervention. The waveforms displayed are usually "good enough." Because interference is so ubiquitous, many clinicians have learned to visually filter it out and ignore any ensuing false positive alarms.

Most clinicians do not have an understanding of how to resolve the problem and accept ECG interference as inevitable. Life-threatening arrhythmias may therefore go undetected, users can be confused or misled to believe spurious information is accurate[17] or unnecessary interventions[18] may result.

> **Interference-free waveforms enable accurate diagnosis and increase alarm reliability.**

ECG interference has four major presentations: synchronous, irregularly shaped pulses (e.g., matching heart-lung machine roller-head pump speeds), a wandering baseline, notches or spikes caused by static electricity discharge, and repeated high frequency spikes that blur and/or thicken baseline waveforms.

Contributing factors include sensitive measurements (such as low voltage signals), complex electronics, shielding, filtering, material properties (polyvinylchloride or PVC, and silicone), fundamental physics (tribo- and piezo-electric phenomenon), patient variability, and cable wear. Environmental factors that may influence EMI include nearby equipment, electrical power distribution, heating and ventilation, and seasonal changes in relative humidity.

The complex problem of EMI has persisted for more than 40 years. ECG monitors were designed on the assumption that all electrodes are attached to the patient's skin with relatively low and equal impedance.[19-20] Electrical impedance is the property to attenuate and/or oppose alternating current (AC).

Most biomedical measurements are not direct current (DC) and are opposed by impedance rather than by resistance. Impedance and resistance are similar: Both are expressed in Ohms (Ω). In DC circuits the terms are synonymous. When all ECG electrodes are not at a low and equal impedance, any extrinsic cause will likely introduce interference on the ECG waveform.

Our study focused on the problem of skin impedance changing ECG morphology. After reproducing ECG interference in a controlled laboratory setting—similar to what was observed during cardiopulmonary bypass surgery—and then understanding the cause, this knowledge was applied to clinical settings.

Materials and Methods

Laboratory

Solar 8000i (General Electric Medical Systems, Waukesha, WI) and MP70 (Philips, Andover, MA) monitors were used in this study. One end of a shielded lead wire set and ECG cable, supplied by the same manufacturer as the monitor, was connected to the monitor. The other side of the lead wire was attached to the appropriate connection of an ECG patient simulator (Bio-Tek Instruments model MPS-1, Winooski, VT).

To create a controlled electrode impedance mismatch (simulating four electrodes placed on a patient with correct skin preparation and one without) the left leg lead wire was connected to one side (red) of an adjustable resistor called a decade box (Tenma Products model 72-7270, Centerville, OH). The other side of the decade box (black) was connected using an alligator clip wire to the left leg connection of the patient simulator.

Each monitor was placed within three meters of a heart-lung machine pump head or rotary peristaltic pump (Figure 1). The simulator-decade box assembly was placed 1 meter from a peristaltic pump. The ECG cable and pump tubing were placed within 30 cm of each other, but not in direct contact.

The baseline ECG simulator waveform was observed for evidence of interference, with the peristaltic pump off, and then on—both times with zero additional impedance from the decade box. Impedance was sequentially added at 50kΩ, 100kΩ, 200kΩ, and 300kΩ with the peristaltic pump running and moving liquid through the tubing.

Liquid was required in the tubing to successfully induce ECG interference from a peristaltic pump since preliminary studies showed that inducing interference with the peristaltic pump running and the tubing completely dry (no liquid whatsoever) did not occur. We hypothesized that when wet, the tribo- or piezoelectric properties of PVC tubing change.

Interference was also introduced by tapping a foot on the floor while standing in proximity of the test equipment (within one meter), and waving hands within 10 cm of the ECG cable/peristaltic tubing. Due to variability discussed below, no attempt was made to quantify interference amplitude.

Clinical

We investigated the practices used to measure ECGs in the cardiac stress test (CST) and electroencephalography (EEG) laboratories, which require optimum contact of electrodes to assure decreased aberrant activities. This is especially critical in the CST laboratory since patients are ambulatory on treadmills, and ECG skin-electrode impedances are often measured

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with applied impedance monitors. To reduce EMI, EEG recording systems frequently have impedance monitors built into them and a user interface to easily identify problem connections.

A literature search for accepted skin preparation techniques revealed few published articles on the topic. The literature indicates that procedures and recommendations vary, and are inconsistent when studied.[21,22]

When ECG interference was reported intraoperatively by the anesthesiologist, impedance of the ECG electrodes was measured with a meter (Model EIM-105 or EIM-107 Multi-Lead Prep Check Plus, General Devices, Ridgefield, NJ USA). Using these meters, if impedance was found to be out of acceptable range, the skin was prepped intraoperatively using various techniques (such as abrading skin with gauze or abrasives, rubbing alcohol, or degreasers) and impedance re-measured.

After months of successfully eliminating interference retrospectively, demonstrating cause and effect in clinical conditions, determining a reliable skin prep technique (an electrolyte gel with pumice, e.g., NuPrep Gel, Weaver and Co. Aurora, CO, used according to the manufacturer's labeling worked most

Figure 1. Laboratory Apparatus for Controlled Imbalance of Patient Electrode Impedances on ECG Monitor

consistently for us), and having confidence that our laboratory findings indicated real-world conditions, the next challenge was introducing new and additional workflow to our clinicians' practice and patient care.

Results
Laboratory
Both monitors undergoing laboratory testing behaved consistently (see Figures 2 and 3), and exhibited interference 100% of the time when impedance was set above 50kΩ. Indeterminate variability made precise interference reproducibility, even from controlled sources (e.g., peristaltic pumps), difficult.

This interference was constant for individual tests, but varied from one day to the next. The interference amplitude changed with the distance between pump tubing and patient cables (closer created greater amplitude, and further decreased the amplitude), but was constant when tested at a distance of 30 cm.

All waveforms shown in Figure 2a and 3a, free of interference, were generated from monitors connected (as above) with the variable impedance decade box set to zero and the peristaltic pump running.

Waveforms in Figures 2b and 3b were generated under identical conditions, but with the left leg electrode at a higher impedance, and the decade box set to 100kΩ. The left and right arms had no additional impedance, so lead I in Figures 2b and 3b is free of interference. The left leg had an additional 100kΩ impedance; this electrode is used in all other ECG leads (except for the MCL displayed by the Philips monitor), all of which display interference.

Monitor ECG filters have user selectable settings that can change the characteristics of waveforms as well as amount and/or type of interference displayed. The strips generated from the monitor in Figure 2a and b have a frequency range of 0.05-100 Hz, while the monitor in Figure 3 a and b uses 0.05-150 Hz.

Clinical
Patients in our Cardiac Stress Test (CST) lab had their skin prepped, and a confirmed electrode impedance of under 5kΩ. Patients ambulating during a stress test with electrodes below 5kΩ displayed interference-free ECG waveforms.

Skin-electrode impedance was measured from 60kΩ to over 200kΩ (the maximum these
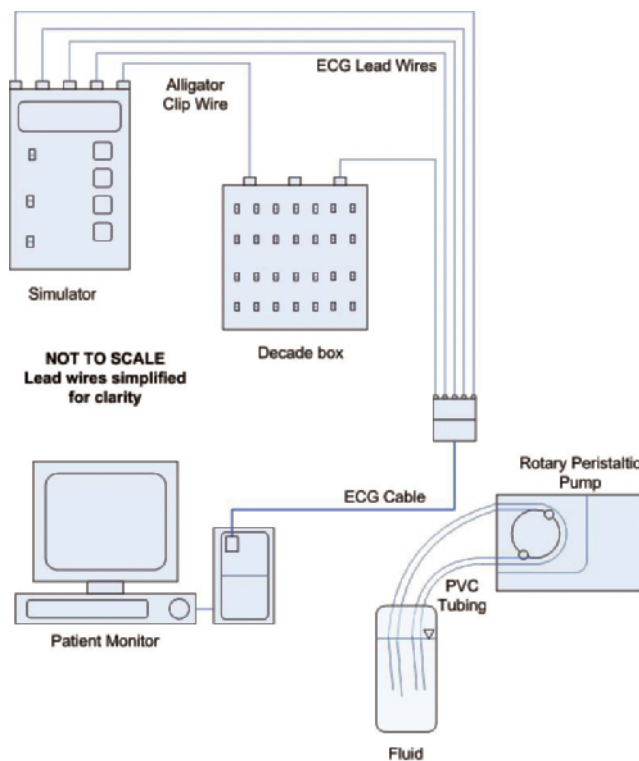
meters display) without skin prep on healthy volunteers and patients intraoperatively. Similar readings were observed on patients troubleshooting interference problems in other hospital areas. Due to the lack of a formal study, all measurements obtained were not captured, but values over 100kΩ were common.

Figure 4 demonstrates clinical cause and effect in a case where something went awry with the left leg electrode intraoperatively (coincidental with our laboratory apparatus). The top waveforms were observed intraoperatively, after prospective skin prep and impedance measurements, but with the heart-lung machine pumps turned off. The middle waveforms were recorded under the same conditions, but with the heart-lung machine pumps turned on. The bottom waveforms were recorded after remedial skin prep, electrode placement within the acceptable range, and the heart-lung machine pumps turned on.

When electrodes were applied to patients with an impedance of under 5kΩ, interference was completely eliminated and all ECG waveforms displayed accurately and free of interference. We observed interference even in instances where impedance measurements were relatively low, but above the acceptable range (<5kΩ). The sample set of ECG interference in three patients is shown in Table 1.

On rare occasions, interference persisted regardless of our efforts. We have not identified possible causes because these instances occur so rarely, and require so much time that they offer diminishing returns. Although our goal was to eliminate interference 100% of the time, we reduced most of the interference by using electrode impedance meters and consistent skin prep.

Discussion

With our laboratory apparatus, we were able to introduce ECG interference in a controlled environment that emulated patient care conditions encountered in any hospital. The experimental control of electrode impedance, on a patient simulator in our apparatus, clearly demonstrated cause and effect: Increasing one electrode's impedance caused interference on any lead using that electrode to measure and display an ECG waveform. In clinical practice, applying ECG electrodes on patients at low
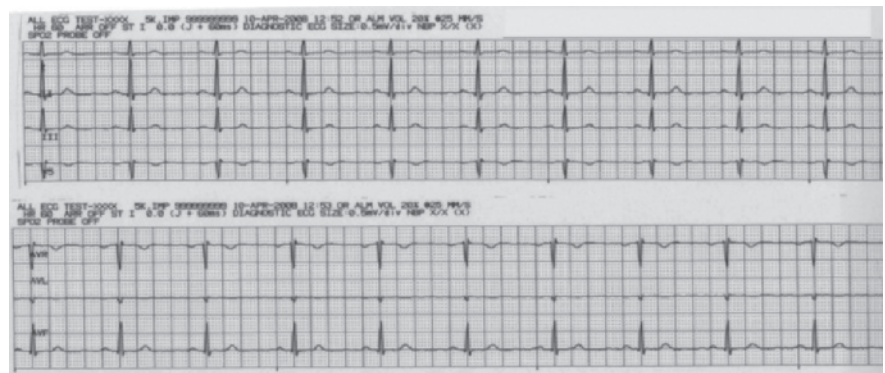
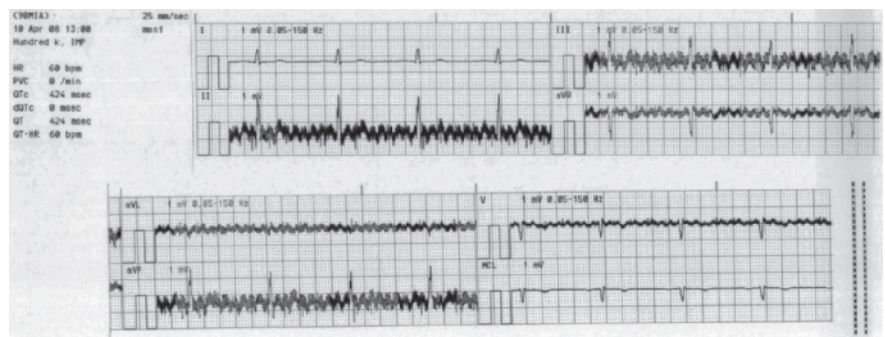
A

B

Figure 2. A) GE Solar 8000i monitor with <5kΩ on all electrodes and peristaltic pump running. B) GE 8000i monitor with 100kΩ on left leg, all other electrodes <5kΩ, and peristaltic pump running.
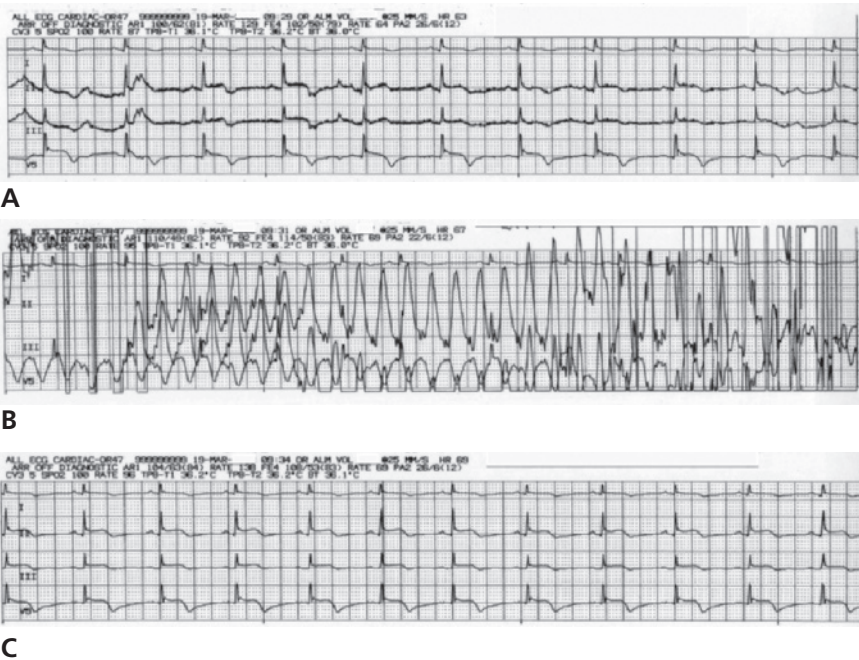

A

B

Figure 3. A) Philips MP70 monitor with <5kΩ on all electrodes and peristaltic pump running. B) Philips MP70 monitor with 100kΩ on left leg, all other electrodes <5kΩ, and peristaltic pump running.

Figure 4. A) 9:29 a.m., intraoperative call before remedial skin prep and pump turned off. B) 9:31 a.m., same electrode conditions with pump running, C) 9:34 a.m., after remedial skin prep and verifying impedance on left leg electrode with pump running.

Electrode location	Impedance (kΩ)
Patient 1	
Left arm	25
Right arm	10
Left leg	47
Right leg	51
V	10
Patient 2	
Left arm	14.8
Right arm	13.3
Left leg	6.3
Right leg	26.3
V	6.3
Patient 3	
Left arm	25.3
Right arm	2
Left leg	48.7
Right leg	1.6
V	1.7

Table 1. ECG Interference in Three Patients. (Impedance measurements are always between at least two points. In all these measurements, the RL and V electrodes were used as the reference and therefore one of the two must always equal the lowest value. More advanced impedance monitors such as EIM-107 do not have this constraint.)

impedance— attainable only by prepping skin, using good (not desiccated or otherwise damaged) electrodes, and the regular use of dedicated meter—virtually eliminated interference.

The sole indicator for our clinical results, other than impedance measurements, was the lack or presence of ECG interference. We were able to trigger various false positive dysrhythmia alarms (e.g., PVC and ventricular tachycardia) with the laboratory apparatus, but that was not the focus of the experiment. No effort was made to establish a universal skin prep technique, or study patient conditions, age, and/or skin to correlate with impedance measurements.

After months of troubleshooting ECG interference problems, we found that normal skin variability and prep technique inconsistencies required the regular use of an impedance meter. Product literature[23] and monitoring theory[24] indicated ECG skin-electrode impedance needs to be at or below 5kΩ, not the 60-200kΩ or higher observed in practice. Higher values (5-15kΩ) are marginal, and anything above that is considered poor.

To filter interference correctly, today's monitors are designed, built, and tested on the presumption that patient electrodes are attached within the narrow impedance range of 0.5-5kΩ.

This range is unrealistic in clinical settings without skin prep and consistent use of an impedance meter. An electrode impedance of 5kΩ was more than an order of magnitude smaller than values measured without skin prep.

We established a baseline with all electrodes at the same low impedance and saw no visible interference (Figure 2a and 3a) with a pump running. With the left and right arm electrodes, and the right leg electrodes all at the same impedance, the interference detected at the right leg was the same as that detected in lead I (left arm to right arm). The monitor's differential amplifier common-mode rejection worked well for lead I, and the result was an interference-free lead I waveform (Figure 2b and 3b).

With the left leg electrode 100kΩ higher than the right leg electrode in our laboratory apparatus, the interference detected at the right leg was different from that detected in either leads II or III (right arm to left leg, and left arm to left leg respectively). This impedance imbalance (100kΩ) created a voltage difference between the interference detected at the right leg versus the left leg.

The voltage difference results with visible interference (noise) in leads II and III. The interference on leads II and III is not found on lead I (Figure 2b and 3b). With an impedance imbalance between the left and right leg electrodes, the monitor's differential amplifier common-mode rejection does not work well for leads II and III, and the result is a noisy waveform.

The right leg electrode is a reference electrode and not used in specific lead measurements in the same way as other electrodes are. It is used to measure background electrical noise, primarily due to electrical power lines, detected by all leads. A right leg drive system averages this background noise (orders of magnitude greater than the ECG signal), detected at the right leg electrode, inverts and adds it to any and all lead waveforms displayed.

This negative feedback loop[25] helps the monitor's circuits create a stable baseline and accurate waveform representation of the myocardium's electrophysiological activity. A similar negative feedback loop, used in consumer electronics readers may be familiar with, is used by noise canceling headphones to eliminate undesirable background sounds.

Often, electrical signals that interfere with acquiring a patient's ECG are present to an almost equal degree at nearly all locations on the patient's body. The electric fields generated by power wiring in the patient's vicinity and by the "static" electricity that a peristaltic pump can produce are two common sources of this type of interference. Because these signals are "common" to each electrode, they are customarily referred to as common mode interference. Good common mode rejection is necessary to minimize their disruptive impact on acquisition of the desired ECG.

The right leg electrode and the monitor circuits to which it is connected do an excellent job of rejecting the impact of the average common mode component of signals from the other electrodes. However, there are usually subtle differences amongst the interference signals sensed from the other electrodes. It is these differences that show up as interference in the ECG traces. The interaction of the contact quality of a particular electrode's connection with the ECG device's circuits has a profound impact on these differences, and thus impacts the extent to which artifacts appear in the ECG obtained using that electrode.

For example, a poor connection at the left leg electrode (while all other electrodes are well-connected) will yield maximum artifact in leads II and III, no artifact in lead I, and intermediate levels of artifact in all other ECG leads. When all electrodes have equal and good (low impedance) contact quality, there will in general be minimal artifact in all ECG leads.

Practically speaking, however, when electrode contact quality is poor on all electrodes, there will usually be much artifact no matter how well matched the electrode connections are. Careful design of the ECG device's circuits helps reduce—but may not be able to completely eliminate—the impact of poor electrode contact quality.

The impedance difference between the left and right leg electrodes (100kΩ), depicted in figures 2b and 3b, produces a proportional voltage difference between the two electrodes. This difference negates the monitor's differential amplifier's ability to eliminate common mode interference on leads II and III. Since the monitor's filter design presumes all electrodes are at roughly the same impedance, Ohm's Law prevails and any lead that uses the left leg

electrode will include interference. The monitor's filters cannot discern whether this differential signal is real physiological signal or interference, and displays erroneous artifact.

After months of testing various options and identifying a reliable means to prep skin and multi-lead impedance meters, we began broadly changing practice. Introducing clinical workflow changes in a large organization is rarely a simple task, particularly when it requires added work. Some individuals were not convinced that something as simple as attaining low skin-electrode impedance was going to resolve this chronic problem, or did not believe that ECG interference was a concern in the first place. At times, compliance required intervention. Today, with a few years of consistent skin prep and regular use of impedance meters, we have virtually eliminated ECG interference in cardiac surgery (and in other care areas that follow the necessary procedures).

We occasionally observed individual workflow preference that clinicians followed, and some patient variability. Some clinicians found it was necessary to stabilize the lead wires by taping them down to the patient with a little slack (creating a strain relief), and/or to seal the electrodes from liquids (such as surgical prep solutions) as appropriate to the care setting.

We also found that proper preparation of skin to attain the low impedance values required can redden the area where electrodes are applied. This reddening can introduce other complications (some people described the reddened areas as lesions) in the patient's care if not recognized by the care team prospectively.

As described, we did not study all possible facets and multitudes of contributing factors. Our findings indicate ECG monitors are not currently built to meet real-life patient care conditions and consistently display interference free waveforms. We found that patient skin impedance properties vary significantly, and that ECG monitor design presumes that they do not.

Conclusion

The major contributing factor to ECG EMI is a 40- to 50-year old design assumption that all electrodes are attached to the patient at roughly

Today, with a few years of consistent skin prep and regular use of impedance meters, we have virtually eliminated ECG interference in cardiac surgery (and in other care areas that follow the necessary procedures).

Relatively simple changes, short-term and long-term, could be made to potentially dramatically improve the performance of our ECG monitors and corresponding alarms.

Short-term Solutions

Steps that that clinical staff and healthcare technology management personnel can take to improve ECG performance include:

1. **Identify care areas that would benefit** from employing the preventive measures outlined below, prospectively, such as cardiac surgery (or other care areas) where providers keenly monitor ECG waveforms in the presence of interference generating equipment, or emergency departments (patients complaining of chest pain, where interference can mask critical ST segment or T wave changes that potentially indicate ischemia or alternatively mask a reassuring ECG tracing).

    a. If ECG interference preventive measures are not employed prospectively, the same steps can be followed remedially after the problem is reported.

      i. The primary advantage to waiting until the problem is reported is that it reduces the amount of work clinicians perform when applying electrodes on the vast majority of patients.

      ii. The primary disadvantage is that the monitor will likely display interference and may trigger greater false positive alarms.

2. **Purchase impedance meters** and use them to determine whether electrodes on patients are in the acceptable range. Depending on how you choose to connect the impedance meters (to the electrodes themselves, lead wires, and/or trunk cable) and your facility's monitors, adapters or custom cables may have to be terminated on site. Additional product development on cable connections is required.

3. **Help determine or establish the best skin prep technique(s)** for your site. Our experience was that the traditional skin prep techniques (alcohol, sand paper) were not as effective as products that use a combination of gel and pumice. To reduce interference, prep skin and use an impedance meter every time an electrode is applied to the patient.

4. **Actively manage your electrode inventory.** Avoid having open bins (or bags) of ECG electrodes for extended periods, as this will cause electrodes to dry out. In areas where it makes sense, consider using sealed packs of five electrodes.

5. **Train clinical and technical staff** on what causes the problem (high electrode impedance and/or imbalance). Make the necessary tools available (such as informational posters, skin prep materials, fresh electrodes, impedance meters, and new cables when needed), and teach staff how to resolve the issue when it appears.

the same, low impedance. This condition cannot be attained reliably without the use of a dedicated impedance meter, which is not readily available to most clinicians today. Relatively simple changes, short-term and long-term, could be made to potentially dramatically improve the performance of our ECG monitors and corresponding alarms.

Longer-term work by researchers and the industry could focus on understanding skin impedance properties, better quantifying impedance and its relation with interference, and how monitors and/or electrodes could be used to best (and accurately) inform end users that there may be latent problems to resolve.

It would be advantageous to investigate what changes are required in ECG monitors to enable greater variability in electrode impedance, or to incorporate impedance meters used to inform users of potential electrode imbalance problems. Future work could also help determine what impact minimizing ECG interference might have on alarm specificity and related alarm fatigue. ∎

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