Instrumentation Basics
from the Amplifier to the Skin

Methods to:
- Minimize Artifact
- Lower risk for Electrosurgical Unit Burns
- Lower risk for MRI Burns

Brett Netherton, MS FASNMCNIM
Rocworks, LLC & Signal Gear, LLC
brettn@rocworks.org
Presentation Goals

Look at our recording pathway from beginning to end

Hone in on and hopefully find some meaningful ways to optimize:

- Recording Electrodes
- Ground Electrode
- Ancillary OR Equipment
- Power Cords

Avoid Electrode Lesions (electrode burns)

- Electrothermal Burns from the Electrosurgical Unit (ESU)
- Electrothermal Burns from the MRI
- Electrochemical lesions from batteries
Presentation Goals

It helps to start with some very basic principles

Ohm’s Law

Understanding Capacitance
Ohm’s Law

- Air
- Wet Concrete
- Jello
Air

Wet Concrete

Jello

Current flow of quarters

Current flow of electrons

Z = small

Z = medium

Z = high
Least effort? = Air
Medium effort? = Jello
Most effort? = Wet Concrete

Least Voltage buildup? = Small impedance
Medium Voltage buildup? = Medium impedance
Most Voltage buildup? = Large impedance
Understanding Capacitance

Skin is much like a battery

Skin has high capacitance and can hold a charge
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What are we trying to Record?

Assuming that 1 microvolt = 1 inch

$E_{P_{sens}} \approx 10 \mu V$
What are we trying to Record?

Assuming that 1 microvolt = 1 inch

\[ \approx 338 \text{ V} \]
What are we trying to Record?
Assuming that 1 microvolt = 1 inch

Bipolar mode
~ 1000 V
What are we trying to Record?
Assuming that 1 microvolt = 1 inch

ESU mode
≈ 10000 V
What are we trying to Record?
Our most basic recording circuit from the source to the skin

Our amps, cables and IOM machine

Our most basic recording circuit from the skin to the amps

Simply the electrodes
I propose that by far, the largest layout improvement opportunity exists between the skin and the amplifiers.
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Our skin to amps circuit
Our skin to amps circuit
Our skin to amps circuit

Ideal world
Our skin to amps circuit

Real world

Solutions:
1. Low, balanced electrode impedances
2. High amplifier input impedance
How do we “pick up” radiated electromagnetic waves?

Simple Dipole Antenna

Not Unlike this
What happens when our leadwires are subjected to RF energy?
When you pass a magnetic field (or magnetic flux) by a stationary wire, a current is generated in the wire.
Not only is our most basic circuit the route for the physiologic signal, it also is an antenna, picking up unwanted electrical noise.
In Summary

1. Our recording circuit has numerous resistances and capacitances spread throughout that need to be balanced and low.

2. Our recording circuit is very susceptible to picking up unwanted non-physiologic ambient electrical noise.
How can we optimize our recording leadwires?

- Bring recording wires together
- Use shortest leadwires possible
- Avoid extensions
Bring recording wires together

loose pair leadwire

ribbon pair leadwire

twisted pair leadwire
loose pair leadwire

What signal will be amplified at the amplifier?

The difference!
The difference:

ribbon pair leadwire
twisted pair leadwire

The difference:
loose pair leadwire

ribbon pair leadwire

twisted pair leadwire
What tools do we have in our toolbox?

Bring recording wires together
How can we optimize our recording leadwires?

- Bring recording wires together
- Use shortest leadwires possible
- Avoid extensions
Use shortest leadwires possible
How can we optimize our recording leadwires?

- Bring recording wires together
- Use shortest leadwires possible
- Avoid extensions
Avoid extensions
Avoid extensions

Let’s add extenders and adapters

Do you want to add the extra antenna as well as all of the extra resistors and capacitors?
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What does the ground electrode do?
They now see the waves (noise) the same
Without our ground electrode applied
With our ground electrode applied

Grounding ties the amp and the spot of ground patient connection together so they see the exact same noise.

Is the ground electrode isolated on modern equipment?

YES
When our equipment stopped using earth ground in favor of isolated ground, we lost a powerful tool in the battle against stimulus artifact and ambient noise artifact.
Without the earth ground electrode applied, the massive SA charge generated at the capacitance of the stimulating electrodes travels up the limb on the skin surface to the recording electrodes, where it adulterates the EP recording.
With the ground electrode applied, this massive SA charge travels up the limb on the skin surface to the earth ground electrode, where it flows to the chassis of the amplifier, which is better equipped to deal with it than are the recording electrodes.

Note the surface area of the earth ground electrode. It has a huge capacitance. In this case the capacitance is desirable so that it eagerly draws the SA charge up.
baseline

w subdermal iso ground
StimCh1

baseline
w subdermal iso ground
w hydrogel iso ground
StimCh1

baseline

w hand on top of iso ground
If the earth ground is ideal for removing stimulus artifact and other access charge, why do we use isolated ground now in our equipment?

Patient safety – to avoid ground loops
In Summary

The isolated ground position on our IOM equipment has limited ability to reduce ambient noise artifact or stimulus artifact in our recordings.

But it is much safer for our patients than using earth ground!
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Ancillary OR Equipment

If it has one of these...

Then it’s a potential source of noise
Ancillary OR Equipment

Fluid warmer example

Don’t be afraid to manipulate potential noise sources as long as you are coordinating it with the rest of the OR team. Most fields are directional.
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In Summary

Avoid power cord extensions as they add leakage current and parasitic add on 60 cycle artifact

Don’t be afraid to manipulate power cords as they, like equipment give off directional fields

And remember... Every extra bit of distance away from the power cords you can get buys you quieter recordings.
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Very important note: None of the burns to be shown will be due to faulty ESU!
Let’s have a look at a capacitively coupled burn
Let’s have a look at a capacitively coupled burn
Subdermal Burn from the ESU active cable

Example Active ESU capacitively coupled SDN burn
Subdermal Burn from the ESU return cable (compromised)

ESU RETURN CABLE: Danger if return pad compromised!

SDN leadwire near ESU return cable
Is surface area important?

Subdermal needle electrode

Surface hydrogel electrode

Clearly electrode surface area is important
Does pairing needles make a difference?

Paired needles near ESU
active cable
Does having leadwires on skin make a difference?
So far, we have relied on our eyes to see electrical arcing to know if we are burning tissue. A better way is to measure delivered, dangerous current.

- 10 Ω resistor
- Oscilloscope measuring voltage
- Fully embedded needle
ESU at 190 Watt Cutting Mode (highest setting available)

36” length 19” distance from ESU active cable w/o pigskin

36” length 19” distance from ESU active cable with pigskin
ESU Related Electrothermal Burn Summary

- ESU Pencil Cable is dangerous

- Jeopardized ESU Return Pad is dangerous

- Pairing our leadwires does not minimize this danger

- Keeping our leadwires off of skin does decrease danger

- Distance from dangerous cabling does decrease danger
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What are the dangers of leaving electrodes on the patient during MRI?

<table>
<thead>
<tr>
<th>Displacement force</th>
<th>Very minimal danger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement torque</td>
<td>Very minimal danger</td>
</tr>
<tr>
<td>RF heating</td>
<td>MAXIMAL DANGER</td>
</tr>
<tr>
<td>Image artifacts</td>
<td>Very minimal danger</td>
</tr>
</tbody>
</table>
Several magnets and one source of RF energy are used to accomplish this imaging.
Main Magnet: Creates very strong, static magnetic field. This field aligns the slightly polarized protons of the billions of hydrogen atoms in the body into alignment with the main magnet field.

Main Magnet = very strong (as much as 3 teslas) but it is static and does not change

if 1 millitesla is 1 inch, 3 Teslas is the height of a giant redwood tree

MAGNETIC STRENGTH = HUGE
ELECTRODE LEADWIRE CURRENT = SMALL
GENERATOR POTENTIAL = SMALL
Gradient Magnets: Create very small fluctuations to the main magnetic field in the axial, frontal and sagittal planes at a rate of around 1 Kilohertz (KHz). Fluctuation necessary for a 3 dimensional view.

Gradient Magnets = weak (around 24 milliteslas)
if 1 milliteesa is 1 inch, 24 milliTeslas is the height of a car tire.
The gradient magnets are very small compared to the strength of the main magnet!

MAGNETIC STRENGTH = SMALL
ELECTRODE LEADWIRE CURRENT = SMALL
GENERATOR POTENTIAL = SMALL
RF Pulse Coil: Bathes the bore of the MRI with a pulse of RF energy at the very high frequency of 63 Megahertz.

Remember: Impedance due to capacitive coupling decreases dramatically with increasing frequency.

63,000,000 Hertz is a very high frequency!

MAGNETIC STRENGTH = TINY

ELECTRODE LEADWIRE CURRENT
GENERATOR POTENTIAL = HUGE
Displacement force

Displacement torque

RF heating

Image artifacts

Radio Frequency Source
Displacement force

Displacement torque

RF heating

Image artifacts

Even if the leadwires are disconnected from the headbox, are there potential current pathways?
Displacement force

Displacement torque

RF heating

Image artifacts

3yo girl: MRI in a 1T scanner with 3 ECG leads attached for cardiopulmonary monitoring, resulting in full thickness burns.

Karoo at al, Full-thickness burns following magnetic resonance imaging: A safety discussion of the dangers and safety suggestions, Plastic and reconstructive surgery, Oct, 114(5):1344-5, 2004

Fig. 1. Three full-thickness circular burns were noted at the points where the electrocardiograph electrodes were attached to the chest of a 3-year-old girl.
Patient under general anesthesia received burns under ECG electrodes during MRI examination.

Jones et al, Burns associated with electrocardiographic monitoring during magnetic resonance imaging, 22:#5, 420-421, 1996, Reprinted with permission from Elsevier.

Figure 1. Case 1. Areas of full-thickness burns to the patient’s chest wall.
Common methods to limit electrode RF heating

- Impedance in leadwires
- Short leadwires
Impedance in leadwires
Impedance in leadwires
Impedance in leadwires
RF heating

Impedance in leadwires
Impedance in leadwires
Impedance in leadwires
Impedance in leadwires
Impedance in leadwires

Which set of electrodes limits dangerous current from RF energy the most?

-or-

RF heating
“Abstract. The acquisition of electroencephalograms (EEG) during functional magnetic resonance imaging (fMRI) experiments raises important practical issues of patient safety. The presence of electrical wires connected to the patient in rapidly changing magnetic fields results in currents flowing through the patient due to induced electromotive forces (EMF), by three possible mechanisms: fixed loop in rapidly changing gradient fields; fixed loop in a radio-frequency electromagnetic field; moving loop in the static magnetic field. RF-induced EMFs were identified as the most important potential hazard. We calculated the minimum value of current-limiting resistance to be fitted in each EEG electrode lead for a representative worst case loop, and measured RF magnetic field intensity and heating in a specific type of current-limiting resistors. The results show that electrode resistance should be >13 kΩ for our setup. The methodology presented is general and can be useful for other centres.”

“Finally, it is sensible to place the resistor as close as possible to the electrode to minimise the risk of a loop forming which allows current to flow through the patient without passing through the protective resistor.”

Short leadwires

RF heating
RF heating

Short leadwires

Simple Dipole Antenna

Not Unlike this
MRI compatible EEG electrode system for routine use in the epilepsy monitoring unit and intensive care unit

Seyed M. Mirsattari, Donald H. Lee, Daniel Jones, Frank Bihari, John R. Ives

Clinical Neurophysiology 115: 2175-2180, 2004

Fig. 1. MRI compatible EEG electrode set-up for the international 10–20 system. a, electrode cup; b, plastic heat-shrink tubing; c, electrode wire; d, crimp terminal; e, connector housing of an electrode bundle.

Fig. 2. EEG electrodes covered by a bandage with and MRI compatible sponge used to keep the connectors away from skull to avoid susceptibility artifact. The sponge is removed after the scanning.
Short leadwires

MRI compatible EEG electrode system for routine use in the epilepsy monitoring unit and intensive care unit
Seyed M. Mirsattari, Donald H. Lee, Daniel Jones, Frank Bihari, John R. Ives

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Abstract
Objective: We report on the development of an electroencephalographic (EEG) recording system that is Magnetic Resonance Imaging (MRI) compatible and can safely be left on the scalp during anatomical imaging or used to obtain simultaneous EEG and metabolic or hemodynamic data using functional imaging techniques such as functional MRI or MR spectroscopy.

Methods: We assembled a versatile EEG recording set-up with medically acceptable materials that contained no ferromagnetic components. It was tested for absence of excess heating and distortion of the image quality in a spherical phantom similar in size to average adult human head in a clinical 1.5 T GE scanner. After testing its safety in four volunteers, 100 consecutive patients from our epilepsy long term monitoring unit were studied.

Results: There was no change in the temperature of the EEG electrode discs during the various anatomical MRI sequences used in our routine clinical studies (maximum temperature change was -0.45 °C with average head SAR ≤ 1.6 W/Kg in the selected subjects) nor were there any reported complications in the others. The brain images were not distorted by the susceptibility artifact of the EEG electrodes.

Conclusions: Our MRI compatible EEG set-up allows safe and artifact free brain imaging in 1.5 T MR scanner with average SAR ≤ 1.6 W/Kg. This EEG system can be used for EEG recording during anatomical MRI studies as well as functional imaging studies in patients requiring continuous EEG recordings.
What’s New regarding SHORT LEADWIRES?

It’s important to understand some antenna theory

First by understanding how antenna length impacts “tuned” wavelength

Seeing physical harmonics in action helps understand

Why is this important?

<table>
<thead>
<tr>
<th></th>
<th>Freq</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5T MRI RF coil</td>
<td>63.8MHz</td>
<td>15.4 feet</td>
</tr>
<tr>
<td>3.0T MRI RF Coil</td>
<td>127.6MHz</td>
<td>7.7 feet</td>
</tr>
</tbody>
</table>
What’s New regarding SHORT LEADWIRES?

Why might the wavelength matter?

Current intensity at scalp = 0
What’s New regarding SHORT LEADWIRES?

Why might the wavelength matter?

Leadwire

Current intensity at scalp = maximal

DANGER!!!

Findings presented at ACNS tends to support this theory. Balasubramanian et. Al. For inquiries, email john@iveseegsolutions.com

More research needed, but current products limit heating
RF heating

Heat is created from power dissipation

Let’s simulate with different impedances driving a constant current (96ma) to see what happens.

267 Ohm
325 Ohm
381 Ohm

1 Ohm
RF heating

Heat is created from power dissipation

267 Ohm 325 Ohm 381 Ohm
1 Ohm 1 Ohm 1 Ohm

2.5 Watts Power 3.0 Watts Power 3.5 Watts Power
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When DC current is applied to skin two things occur:

- Acidic buildup under the anode
- Basic (alkaline) buildup under the cathode

Each is capable of creating an electrochemical burn in a short time.
In electrodes, electrons are the charged particle that moves to make current flow.

In tissue, ions (electrolytes) are the charged particle that moves to make current flow.
NaCl and H₂O
NaCl and H₂O
2H₂O $\rightarrow$ O₂ + 4H⁺ + 4e⁻

H⁺ + Cl⁻ $\rightarrow$ HCl

Longer duration = more acid & alkali buildup!

More current = more acid & alkali buildup!

Na⁺ + OH⁻ $\rightarrow$ NaOH

4e⁻ + 2H₂O $\rightarrow$ 2H₂ + 2OH⁻