Physiometry 101

## Skin Surface Electrodes 101

If you don't read anything else, read the Safety First section at the end of this article!

Sooner or later, we would guess that your physiometry pursuits will lead you to human subjects. And as we have mentioned elsewhere, an entire book can easily be written about all the details and caveats that surface when you place an electrode on a human subject, in an effort to acquire bioelectric signals, or else to instrument that subject for impedance measurements. We will try to cover some main issues here, but this is by no means an exhaustive treatment! And, by the way, this is written from a technical perspective.

The best connection that supplies the least amount of noise and artifact usually results from needle electrodes carefully inserted into live tissue. But when dealing with human subjects, you will generally NOT be able to use this approach! The best you can do with human subjects is to use skin surface electrodes. These electrodes come in various sizes, but most have a round outer ring of adhesive to hold the electrode to the skin. The actual electrode disk is in the center, and usually covered with some form of conductive gel. On the back side of the electrode is a shiny metal stud electrically connected to the electrode disk. In use, this stud is tightly gripped by a standard snap connector when it is placed down over this stud. The stud/snap attachment both mechanically holds the snap to the electrode and also electrically connects the electrode disk to the lead wire. Most of these electrodes are disposable, i.e. intended for just one application, then thrown away when removed.

We should mention some technical details here. Instrumenting a single channel for bioelectric physiometry usually involves three electrodes. Two of the electrodes are the 'active' electrodes, and the physiometry signal you are after is sensed from these two electrodes. And, for some bioelectric signals, connecting the positive and negative electrode sites correctly to the positive and negative inputs of your amplifier is important! More often than not, a third 'reference' electrode will also be required, which places the rest of the subject's body at the same ground reference as the amplifier. This single reference electrode can often support multiple bioelectric channels however.

It is doubtful skin surface electrodes can ever supply the signal quality of needle electrodes. The best you can do is expend some time and energy necessary to get the skin surface electrode connection as close to the quality of a needle electrode connection as possible. In order to do this, you need to know what it is about both the electrodes and the skin that accounts for sometimes vast differences in connection quality. You also need to understand some crucial steps you can take that can help remedy these differences.

Why does this even matter?

Most bioelectric signals are small, 1 millivolt or (usually) less. And it takes a gain of 1000 or more to enlarge these signals so we can see them, so we can record them. Thats what physiometry is concerned about. And we don't want to run noise into that gain of 1000, or we will get a LOT of noise!

Ok, so this is hypothetical; we really can't poke needles into a person! But if we start with the needle electrode in live tissue, we basically have two electrodes inserted into live tissue in the subject. Some sort of wire will connect those needles to our amplifier. Wire has a very LOW resistance. And a good approximation for the resistance inside the human body is 1,000 ohms. This is not much. With the needles and lead wires, the overall resistance the amplifier sees is very low, and a low noise, clear signal is the result. We should see plenty of the signal we are after! If the lead wires are not shielded, it is possible for some noise to get introduced through the lead wires, especially if they are long. Let's just assume we have shielded the input leads.

Now, let's add a 10,000 ohm resistor between one of the leads and one of the needle electrodes. Just that one resistor will add a bunch of noise. Some of that noise is generated within the resistor. A lot of the noise is picked up by that resistor, as electrical noise constantly blasts through the resistor, and is turned into noise voltage by the resistor. And moving your finger near that resistor may result in even more noise. Either way, the addition of that 10,000 Ohm resistor will probably make it difficult to see the ECG signal (or whatever signal we are trying to acquire). If we happen to have a 5,000 Ohm resistor, and we put it in place of the 10,000 Ohm resistor, that one change can substantially reduce the noise that might be obscuring our target signal.

Well, let's say, after reading the hypothetical example above, you get up and wander around your lab. You find a stray, open pouch that someone has marked 'ecg electrodes' on the side. You pull two electrodes out, remove the adhesive backing, and slap the electrodes onto your subject, one at a time, then connect some standard Snap to safety sheathed leads to the electrodes. Let's also say you just happen to have a UFI Checktrode on the lab bench, and you quickly check the *contact impedance* through those two electrodes that you just put on. Well, you hope for the best, anyway.

What do you think you might find? If the electrodes are good quality Ag-AgCl, wet column electrodes, and the gel column on both electrodes is still plenty moist, you might luck out and see maybe 50,000 ohms. And if your subject showers a lot, and you place the electrodes on skin that is fairly moist and smooth, a hand maybe, you may see a contact impedance down around maybe 20,000 ohms. This is certainly a lot better! And since you are testing through two electrodes, we can guess that is 10,000 Ohms for each electrode. This is not fantastic, but it is not bad either.

But what do you think you will *probably* find? The electrodes are old, and the skin is dry. You could see 100,000 Ohms, but probably more. And with that much resistance in series with an amplifier input, you will see NOISE and more noise. And, on top of that, the optimum electrode site for the physiometry you are after; this site will probably not be over places on your subject that offer favorable contact impedances.

## The Big Picture

It generally takes at least two electrodes to sense a bioelectric (naturally occurring) signal from your subject. With two needle electrodes, the signal is conducted easily into the needles, directly into the leads, and across the lead wires and into your amplifier. For human subjects, in place of the needle electrode in live tissue, we have to use skin surface electrodes, and each skin surface electrode places a *stack* of layers between the bioelectric signal in the live tissue under the skin, and the electrode lead to your amplifier. And sensing your target signal takes two electrodes!

From the live tissue to the input lead, that same bio-electric signal must be conducted through the following layers:

a. Epidermal / Skin layer

The live tissue inside your subject is protected by a layer of dying / dead skin cells. This layer can vary widely in thickness due to many factors. And, as you can guess, the skin layer probably conducts your bioelectric signal far worse than the live tissue underneath. This skin layer can present a substantial resistance through which you will want to be able to sense your target signal. In fact, the actual resistance through the skin, this one quantity can vary WIDELY across most subject pools!

b. Conductive Column

All electrodes include *something*, some sort of conductive material, which needs to stay between the electrode and the subject's skin. This column of (usually) gel must conduct well enough to pass your bioelectric signal from the skin to the electrode with as low a resistance as possible. The gel itself usually conducts well, it is designed to do that. Problems surface in the gel if, for some reason, it does not properly bridge the gap between the skin and the electrode disk. Any breaks in that gap will fill with air. And you need to know that air makes a very lousy conductive column!

c. Electrode Disk

At the top of the stack, some sort of (usually) metal disk or plate (the actual electrode) must collect the faint stream of electrons that constitute the bioelectric signal you are after. The electrode depends on direct contact with the conductive column, in order to be able to collect these electrons. And you can generally assume a very low resistance connection between this disk and the snap, then through the leads and into your amplifier.

Replacing the needle electrodes with this complex stack of layers is just a fact of life when trying to get bioelectric signals from a human subject. The signal you want, that faint signal present in your subject, must flow successfully through all three of these layers! But if you are careful, you can usually optimize that stack nicely, and still get good bioelectric signals.

## The Weakest Link

Let's start with the electrodes. Even if you take no other steps, the quality of the electrodes you use has a profound impact on the contact impedance, and so the quality of your signal. And remember, the cost of the electrodes will usually only be a very small fraction of the hourly expenses for your research!

### a. Ag-AgCl electrodes and Battery Effects

If you place two metals next to each other, separated by some sort of conductive solution, you will make a battery. The voltage generated by that battery will depend more on the free electrons in each of the two metals. This battery voltage can show up as an offset voltage stacked up on top of the signal you are after. This is bad, because such battery voltages are usually much bigger than your target signal. The amplification required for your signal, well that added, large battery voltage can swamp out maybe all signals!

Sparing a lot more chemistry, a two layer electrode made of Silver and Silver Chloride (Ag-AgCl) has been shown to supply the most stable electrode least prone to battery effects. This electrode construction is almost standard across most skin surface electrode types. You should use these electrodes if you can (maybe if you want usable data!). Well, Ag-AgCl electrodes have a minor down side. Light can affect the surface of the electrode, so most come in light blocking pouches. And it is possible for the electrodes to get old, but more about this later.

You might also run into stainless steel electrodes. These electrodes suffer more from offset potentials and drift, so the amplifier needs to be able to handle this. These electrodes are used mainly for specialty applications where stainless steel as a material is preferable for other reasons; durability, continuous use, etc. Most needle electrodes are stainless steel.

### b. Electrode Types (Wet Column vs. Solid Column)

From our vantage point, there appear to be two general approaches to the conductive column in skin surface electrodes.

We mentioned wet column electrodes above. In these electrodes, the conductive column is made up of some form of 'wet' conductive gel. The purpose of the conductive gel is to bridge the gap between the skin and the electrode. ***It is this gel that is supposed to pass your precious target signal from the skin to the electrode!*** A matrix of some type of material is usually added to keep the gel where it belongs.  This matrix can be a loose mesh, very open plastic foam, or something similar.  The conductive gel can only do its job when it is kept between the electrode and the skin.  That is what the mesh or foam is designed to do.

As you probably realize, **this conductive gel column MUST be, must STAY in good, continuous contact with BOTH the Electrode and the subject's skin!**  In other words, if that gel does not make a good connection to **both** the skin **and** the electrode disk, you have just air as the conductive column in that electrode.  You will not see your signal, you will just see noise!

The main issue is that the wet gel will slowly dry out over time.  In extreme cases there might be very little gel left, even if the pouch is still sealed.  If the gel is reduced, the direct conduction path between the skin and the electrodes can be lost.  And note that subject motion can make this even worse, as that contact path comes and goes, seemingly at random!  If the gel column does NOT make good contact with either the electrode or the skin, what kind of signals do you think you will get?   Electrodes usually have a shelf-life or expiration date shown on the package, and this aspect is one of the main reasons.

Beyond conducting your signal, the use of wet gel brings one other important benefit.  The surface of the skin, under magnification, looks a lot like a sponge.  It is not smooth and flat!  It is irregular, porous, rough.  Based on its fluid properties, the gel can quickly flood that skin surface with a conductive path, and so (hopefully) establish a better connection to the underlying, live tissue.  This process is discussed more below.

As a testimony to their effectiveness, wet gel column electrodes have been in use for physiometry for decades.

Another type of electrode is also increasingly more common.  The electrode construction is the same except that the wet gel conductive column and mesh are replaced with a solid block of some sort of bioconductive material that holds its shape.  We refer to these as solid column electrodes.  As you can probably guess, these electrodes are a lot easier to build, and so they cost less.  But the use of a solid block as the conductive column should ring a few bells.  As mentioned above, the surface of the skin is not flat and smooth!  Placing that flat block down over the skin, well, it will take a while to even begin to see reasonable contact impedances with this electrode construction.  The discussion of the normalization process below addresses this more.

Well then, are these solid column electrodes bad? The answer is that depends. It depends on the equipment you are using, among other things. Holter type ECG recording usually takes place over 24 hours or more. The characteristics of wet column electrodes can vary substantially over that period of time, as both evaporation and absorption take their toll on the conductive column. Solid column electrodes are much more stable, and their characteristics drift much less over that same 24 hour period. However, the amplifier used in these recorders must include additional circuitry to deal with the expected higher contact impedances.

So, if you are doing long term recording with equipment designed for them, solid column electrodes are good. If your protocol is shorter, and / or the equipment is not designed for the solid column electrodes, then using them will probably supply poor data. And note that UFI equipment is specifically designed for use with wet column electrodes.

## Normalization and Rehydration

Let's say you actually lucked out, and the two electrodes you threw on your subject in the example above showed approximately 50,000 Ohms ( 50 KOhms) for the contact impedance. Ten minutes later, you check them again, and find maybe 30 KOhms. Then, after ten more minutes, it has dropped to 15 KOhms. What is going on?

How well electric currents can flow from the subject, through that stack that a skin surface electrode presents, and down the lead wire, this process is not fixed and stable, starting from the moment you apply and connect the electrodes. There is a *normalization process* that begins when you apply and connect the electrodes, and it continues as a number of processes 'come fully on line'. If you start recording right away, you may be able to observe the improvement in the quality of your data as normalization takes place.

Two things can happen mechanically as the electrode is placed on the skin. First, the skin surface, with all its pits, grooves and voids, will begin to change shape to conform to the electrode, to the surface presented to it. And this includes conforming to the solid bioconductive material used in solid column electrodes. But this physical conforming process is SLOW, and can take up to an hour or more. (This won't significantly impact a 24 hour holter recording!)

Secondly, the fluid that is the conductive gel, this will begin to permeate, to flow into the nooks and crannies of the skin, and hopefully make its way much closer to the live tissue underneath. This process has a lot of variables, but 5 to 15 minutes might be typical.

The final process involves the availability of charge carriers at the boundaries between, say, the electrode and the gel. This process is complicated, but thankfully this aspect is usually fully on line after maybe 5 minutes.

Well, hopefully you will see that the stack of stuff that results from the use of skin surface electrodes, this stack does not settle down right away! As a result, if your protocol can accommodate some normalization time, this can often help the electrodes perform better. This can mean better signals!

And we are including *rehydration* in this discussion. This term refers to adding a drop or two of clean water to a maybe suspect electrode. Sometimes, doing this can bring an electrode back to life. And, if you get in a bind, maybe this can prove helpful. So, if you pull an electrode out of a pouch, and open it up right before putting it on your subject, and it looks dry; maybe you are seeing open mesh on top or more mesh than gel, or you see voids and open areas in the gel; maybe you should just throw the electrode away, and open up another one (and maybe check the expiration on the pouch!). Like we mentioned above, the cost of the electrodes is a small fraction of the overall costs involved for an hour of research time. But if you have only three electrodes left, and you are facing a deadline, carefully rehydrating the electrodes may bail you out.

But what rehydration can also do is *speed up the normalization process*. If you add one or two drops of water to the conductive gel, right before you place the electrode, the water you just added will flow, soak more quickly into the skin, and the result can be a more rapid normalization time. Adding water to speed the normalization process comes at a cost however. The water will more readily evaporate than the conductive gel, and you *may* see a premature deterioration of the conductive properties later on as a result. And rehydrating does not mean you don't have to take other steps to optimize the quality of the electrode connection.

We have dealt with customers where their actual protocol, their time with their subjects, this had to be over and done in 15 minutes. This is not uncommon. Adding a drop of water, to known good electrodes, can substantially shorten the normalization time in a situation like this.

Optimizing the Skin Surface Electrode stack -- Some Suggestions

You cannot just slap electrodes on your subject and 'just hope' you get good physiometry data. Arriving at a decent connection to your subject takes attention to detail, and a methodical approach to placing the electrodes, EACH electrode. The considerations discussed below may prove helpful!

a. Skin Preparation (Before placing the electrode!)

This step is just important. Skin preparation focuses on two major aspects.

It is important to wipe the electrode sites with Alcohol or something similar because this can help remove skin oils that could hamper secure adhesion of the electrode to the skin. You want the adhesive around the electrode to hold firmly during your recording time, and an electrode falling off in the middle of your protocol is something you would like to avoid. And the activity level of your subject may make this aspect even more important. In some cases, you may even need to augment the electrode adhesive by adding some surgical tape.

Skin prep can also target the removal of some or most of the dead skin layer from the electrode site. This can help reduce the normalization time, and can remove a portion of the resistance that the dead skin can present. An alcohol scrup can help with some of this, but you can also use some sort of non-reactive abrasive pad (such as UFI Biobrade!) or sandpaper to further scrub some dead skin away.

But listen. As helpful as abrading the skin can be in improving your signals, this must be done CAREFULLY!!! And take your time! When the skin STARTS to turn just a little pinkish, this is usually because you are close to live tissue -- STOP!!! It is possible to scrub through into live tissue, which will promptly bleed, and make the site unusable, as well as surface the risk of infection, etc. On the other hand, you will probably encounter some subjects with pretty tough skin. In this case, just look at the abrasive pad to note that you have removed a substantial amount of dead skin, then stop. Experience is often the best teacher when it comes to skin abrasion, and familiarity with this step usually just takes practice. You can start by practicing on yourself.

We discuss our Fetrodes below. We can point out here that the use of Fetrodes can substantially ease skin prep requirements. Abrasion is normally not required where the Fetrodes are used.

b. Keen Powers of Observation

Hopefully from the discussions above, you realize this. If you are using wet column electrodes, and you care about the quality of your data, you absolutely MUST carefully inspect EACH electrode immediately prior to putting that electrode on your subject! Does the gel completely fill the cavity from the metal electrode to the front of the electrode face? Is the mesh or foam completely covered in gel, or are there exposed areas of the mesh or foam? Are there gaps or voids in the gel? Remember that air is a terrible conductor, and an air gap between the electrode and the skin WILL supply terrible data! And if your subject will be moving, this is even more important. And remember again that the cost of an electrode is very small compared to the rest of your research budget! And keep careful track of the expiration dates of your pouches, and keep them tightly closed between uses. This step involves just looking, so its free. But such little things can make a huge difference.

c. Be Careful about putting too much Pressure over the Conductive Column

When you place an electrode on your subject, lightly run your finger around the outer ring over the adhesive, to set the adhesive into the skin. DO NOT press on the snap or the conductive column in the center of the electrode!

However, sometimes it can take a considerable amount of pressing to get the snap to clip onto the stud. The pressure can even force the conductive gel away from the column/electrode in some cases. And the conductive column can be substantially "distressed" by this pressing action. If you have difficulty with this, sometimes you can take your fingers and lightly stretch out the large adhesive diameter of the electrode, to help mechanically stabilize the stud without stressing the conductive column. A lead with a too-tight snap should probably be replaced however.

d. Normalization Time

If your protocol allows it, you should let the electrodes normalize on your subject before starting your research. Just 5 minutes can help, and 15 minutes will help even more. You can apply the electrodes, then have your subject work through some paperwork maybe.

e. Contact Impedance Checking

Even after your best efforts, you really won't know how good a job you have done, unless you have some means to check the contact impedance through the electrodes you have applied. Our Checktrode testers are designed for this exact task! You will invariable test the contact impedance through two electrodes -- from the lead through one electrode and skin into the body, then from the body out through the second electrode and back to the lead. And a fairly good rule of thumb is to target a contact impedance of 5 KOhms or less. We even supply versions of the Checktrode that are designed for use with arrays of electrodes such as EEG caps. If you thought 3 electrodes is a pain, think about the 22 or so electrodes used for EEG studies!

f. Electrode Site Considerations

Sometimes you will do everything right, and still get artifact. You may even re-apply the electrodes and still see the same thing. You need to remember that there can often be multiple bioelectric signals present in the body at the electrode site you are exploring!

For example, maybe you are using a Sternum-V6 setup for looking at the ECG. Your ECG is clean, but you are still seeing funny things. Well, have the subject use their left arm, or push against something with their left arm. It is possible that EMG from the use of that particular muscle is affecting the ECG signal. Not much of the multiple sinusoid signal that is EMG can be seen in the reduced bandwidth for ECG. But you can see a substantial baseline shift just from the use of the arm!

This example just highlights that, for any given site that you are instrumenting for a bioelectric signal, you need to realize that, what you think is noise or artifact, may in fact be another bioelectric signal present at that same site!

g. Keep an Eye Out for Other Problems

A number of other issues can arise that result in poor data. So you have tried your best to optimize the electrode to skin surface stack, and then checked the contact impedance to verify you have done well, but you are still getting noisy or indestinct data... Now what?

Well, realize that there could be a connection problem elsewhere in the overall system. Maybe one of the electrode leads has a loose connection, in the lead, or next to where the lead dives into a connector. Sometimes a visual examination can reveal a cut, or a section of the lead wire that seems to bend too easily. Maybe also one of the connectors is having problems. Does the connector turn, even though it shouldn't? Are all the pins present and straight? Maybe when you plug the electrode leads in, wiggling the connectors can make the signal come and go. You can often hook all the input leads together, which should supply flat-line (no signal) if the leads are fine. If you start wiggling wires, you can often find the culprit. Especially if the equipment you are using has seen a lot of use, remember you could be seeing bad signals, bad data from some other cause besides issues with the electrodes!

Some Other observations

1. Using Solid Column Electrodes for Other Things

We heard of a situation where a hospital mandated the use of solid column electrodes for all researchers. Our equipment does not include the extra circuitry required to handle these special electrodes, and the researcher asked us if there was anything she could do.

The answer is fairly simple. Just apply some sort of bio-potential gel to the exposed surface of the solid column of the electrode immediately prior to application of the electrode to the subject. Just adding that gel will help reduce the normalization time these electrodes can require.

2. How UFI Fetrodes Help

The UFI Fetrodes result in the placement of an extremely high input impedance buffer directly at the electrode site. The use of this buffer can bring the following benefits.

First, the much higher input impedance of the Fetrodes relaxes the sensitivity of the 'skin to electrode interface' to the contact impedance through the electrode into the skin. With Fetrodes, a higher contact impedance does not generate as much noise. Skin abrasion can often be avoided where the Fetrodes are used.

Second, placing the high input impedance buffer directly at the electrode site means that it is much more difficult for cable noise, due to either RF intrusion or cable motion, to impact the sensed signal.

These are reason enough for UFI to include our Fetrodes for all of our equipment that works with bioelectric signals where possible.

3. The One Exception -- Electrodes for Skin Conductance

Skin Surface Electrodes are almost exclusively used to measure Skin Conductance (SCL), which is the actual electrical conductance of the skin measured between the two electrodes. What is being measured is the ability of the skin to pass current, which is largely a result of the activity of sweat glands in the skin, and the amount of sweat and conductive fluid the skin holds. This quantity is measured as conductance, which is the inverse of resistance, so the units are uMho or MicroMho (uSiemens or uS in Europe). As a general rule, human SCL values range between maybe 5 and 20 uMho, and note that 5 uMho corresponds to a skin resistance or impedance of 200,000 Ohms!

Well, the un-optimized resistance through the skin is exactly the quantity we are after if our physiometry pursuit takes us to SCL. We do NOT want to abrade, alcohol wipe, scrub or anything else that would affect the natural resistance or conductance of the skin. So, most everything we mentioned above about steps to take to reduce that contact impedance -- you can forget all that for the skin conductance (SCL) channel! Well, the conductive gel still needs to completely fill the gap between the electrode and the skin. But the rest can quickly ruin the SCL data.

For UFI equipment that supports SCL, we actually supply re-usable Ag-AgCl electrodes. Most SCL studies are performed on the fingers, because this site has been shown to have substantial psychophysiological significance. So, the electrodes we supply have a contoured shape to allow a finger to nestle down over the electrode cavity. And a hook and loop strap is used to hold the electrode to the finger, so no adhesives are involved, and so no alcohol wipe is necessary, and etc. And we provide the conductive gel that goes between the skin and the electrode. And we haven't even talked about recording SCL for Hot Flash research!

But, hopefully you will see, that when you instrument a subject for SCL, you actually need to go out of your way to **avoid** disturbing the natural characteristics of the skin, high contact impedance and all! That is what you are actually trying to measure. SCL electrodes are the one exception to just about everything we said above.

## Safety First!

Did we say enough that you need to be CAREFUL with electrodes? Make sure you put some thought into how your subject feels! Is the skin abrasion hurting? (Then stop!) And what about putting electrodes on the face, near the eyes... And alcohol, near the subject's eyes or nose? Or abrading such sites? And wow, have you ever tried to remove an electrode from right next to the eye? This all becomes even more important for pediatric subjects... Take your time and be careful. Your subjects will appreciate that!

And the lead in your hand, capable of a (hopefully) low impedance connection to your subject -- it is like a LOADED GUN!!! In the past, it was far too easy to plug the subject connected lead into the WRONG locations. A LOT of tragedy and injury followed. The industry has adopted a sheathed female safety connector for electrode leads, and this has really helped. But just remember. That optimized electrode connection you have just added to your subject can also allow you to injure them or worse, if you are tired, 'brain dead' or otherwise just not thinking. That high quality electrical connection places a LOT of responsibility on you, the researcher!

## Conclusion

Instrumenting ECG with Fetrodes is about as 'slap-on simple' as bioelectric physiometry comes. Still, some attention to detail can go a long way in helping you get nice data from your human subjects!