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Dry-Contact and Noncontact Biopotential Electrodes: Methodological Review

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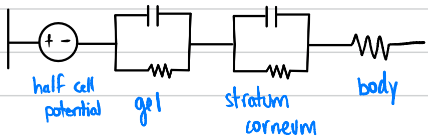
I. Introduction	Gold standard for biopotential measurements is Ag/AgCl electrodes w/ some conductive gel Usefulness/performance categories for gel-less (dry) electrodes: 1.) signal quality (noise, motion sensitivity) 2.) comfort Dry/noncontact electrodes are pretty bad when it comes to adhesion in exchange for comfort This paper compares various electrodes with a focus on quantifying noise and motion sensitivity as a function of physical/electrical parameters
II. Skin-Electrode interface	electrode- redox rxn between metal and an electrolyte Generally speaking, electrode skin coupling can be described as a series combination of parallel RC circuits. See Fig 1 for different configurations

This paper compares wet contact, dry contact, and noncontact electrodes. There is a general tradeoff between signal quality and comfort. An electrode is a redox rxn between metal and an electrolyte. The electrode-skin interface can be modeled as a circuit.

Electrode model

Wet Ag/AgCl structure:



Typically, one of the RC elements dominates and the electrical can be represented with a single conductance g_c in parallel with capacitance C_c:

Simplified admittance eq: $Y_c(j\omega) = g_c + j\omega C_c$

The conventional notion that lower impedance (higher conductance) is essential for electrode performance is misleading base on simple circuit theory

Based on modeling of a general, actively shielded amplifier topology, the following formula is derived:

$$V_{s,RMS} \approx \frac{4kTg_c}{|Y_c(j\omega)|^2} = \frac{4kT}{g_c + \frac{\omega^2 C_c^2}{g_c}}$$

Noise reduction

So noise reduction can be optimized based on either ∞ coupling conductance or ∞ coupling impedance (contact vs noncontact)

Ag/AgCl electrodes dominate clinical settings due to them being cheap and having good signal quality. While it's conventionally thought that the way to get good signals is from having lower impedance, it can actually be achieved in two ways: ∞ coupling conductance (low R contact) and ∞ coupling impedance (noncontact).

	Only tested electrode w/ consistently higher observed was wet contact Ag/AgCl electrodes at lower frequencies cotton layer of noncontacts noise performance and electrode coupling is resistance-dominated rather than capacitance-dominated (more common for noncontacts)
Motion artifacts	motion artifacts are main reason why dry contact and and noncontact electrodes aren't as widely accepted in mobile clinical settings Two sources of motion artifacts: 1.) transversal motion 2.) lateral motion and friction Ways to mitigate transversal: - variable voltage gain or trimmed capacitance active shield - unity gain active shielding ≈ 1 with minimizing input capacitance

Motion artifacts are the main reason dry contact and noncontact electrodes aren't as common in clinical settings. There are some ways to mitigate this thru circuit optimization, but the effects are still there and significant.

Practical Design Considerations	Two approaches to resolve skin-electrode contact impedance for low noise + low artifacts: 1.) Skin abrasion (piercing stratum corneum?) 2.) very high input impedance via amplifier such that skin-electrode impedance is negligible ↳ only viable option for dry contact and noncontact Nonconductive noncontact sensing difficult in practice bc skin-electrode coupling is very complex due to many layers and interplay between electrode conductance and capacitance
III. Electrode Technologies Dry electrodes	Dry electrodes use skin moisture (sweat) as electrolyte Successful dry designs use: 1.) active electrode circuit to buffer circuit 2.) penetrate the skin Adding an adhesive to a dry electrode to mitigate motion artifacts removes any comfort advantages over wet electrodes Dry is ideal for short, infrequent use - heart rate monitors on exercise machines or watches

There are two techniques to reduce contact impedance: skin abrasion and using a high impedance amplifier to mitigate the effects so the skin-electrode impedance is negligible. Dry contact electrodes use sweat as the electrolyte and are ideal for short, infrequent use in nonclinical settings.

↳ although consumer products have significantly increased since 2010.

	stratum corneum penetration w/ microneedles achieves good contact, but authors observed irritation and slight pain ↳ how? SC is not innervated
	Technique for EEG recordings thru thick hair: - thin fingers that can go thru hair, but much larger
Insulate electrodes	large anodized metal attached to FET buffer amplifier with redundant sensing sites + algorithm for picking which channel - has possibility for clinical grade signals - in practice is usually similar to dry electrodes
Noncontact, Capacitive Electrodes	noncontacts allow sensor to operate w/o dielectric layer and thru insulation like hair, clothing, or air
	typical problems: - amplifier design - high enough input impedance - stable bias network - susceptible to stray interference and motion artifacts
	conventional systems use driven-right-leg active ground to minimize common-mode noise

The stratum corneum acts as a high resistive element, so puncturing it could lead to better conductance. Noncontact electrodes have many problems but also have the most room for improvement.

	noncontacts typically have high settling times due to high-pass characteristic at the electrode
IV. Systems	
ECG	in general, wet contact electrodes are king
	some chest strap/harness dry contacts have been demonstrated - could be viable for long term monitoring
	Small bandage-like patches are even more convenient than chest strap - useful for arrhythmia detection
EEG	no clinical dry/noncontact device on market ↳ as of 2010; in 2025, there are a fair amount ↳ YM Chi works at Cognionics? dry contact used a lot in research ↳ OpenBCI headsets come to mind
V. Conclusion	Circuit design issues are largely well understood and described in literature There is plenty of room for innovation at system level

Wet contact electrodes will continue to dominate clinical settings until innovations are made at the systems/application level for dry contact and noncontact alternatives.

Notably, dry contact and noncontact have significantly improved since 2010. They are used in research and commercial settings a lot. However, Ag/AgCl wet contact electrodes remain as the gold standard in clinical settings.