Soft, Comfortable Polymer Dry Electrodes for High Quality ECG and EEG Recording

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28/05/2014
Outline

- Biopotential signals
- Dry electrodes
  - Motivation
  - Types
- Polymer-based dry electrodes
  - Materials and shape
  - Impedance measurements
  - ECG monitoring
  - EEG monitoring
- Conclusions
Main Types of Biopotential Signals

- The frequency and amplitude distribution are different for each biopotential signal.
- in this work: focus on recording of ECG & EEG signals.
### Motivation: why dry electrodes are needed?

<table>
<thead>
<tr>
<th></th>
<th>Conventional Wet-gel electrodes</th>
<th>Dry electrodes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>preparation</strong></td>
<td>• abrasive gel</td>
<td>No need for preparation</td>
</tr>
<tr>
<td></td>
<td>• cleaning by alcohol</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• use conductive gel</td>
<td></td>
</tr>
<tr>
<td><strong>Set-up</strong></td>
<td>• expertise needed</td>
<td>• easier</td>
</tr>
<tr>
<td></td>
<td>• time consuming</td>
<td>• faster</td>
</tr>
<tr>
<td><strong>Long-term usage</strong></td>
<td>signal degradation due to gel drying</td>
<td>no signal degradation</td>
</tr>
<tr>
<td><strong>User comfort</strong></td>
<td>• irritation</td>
<td>depends on design and material</td>
</tr>
<tr>
<td></td>
<td>• discomfort when cleaning gel after use</td>
<td></td>
</tr>
</tbody>
</table>
Types of Electrodes

**Wet Contact**
- 10-40 μm Stratum Corneum (SC) → high impedance
- Gel: Reduce electrode-skin impedance and motion artifact

**Dry Non-contact**
- Capacitive
  - Extremely sensitive to motion artifact
  - signal very small → active electrodes (pre-amplification) and shielding needed
  - safe

**Dry Contact**

**Invasive**
- biomedical safety issue → biocompatible materials needed → more expensive fabrication

**Non-invasive**
- high impedance (electrode-SC layer)
  - prone to motion artifact
  - active electrodes needed for weaker biopotential signals
Types of Electrodes

Wet Contact

- **10-40 μm Stratum Corneum (SC)** → high impedance

Dry Non-contact

Capacitive

- Extremely sensitive to motion artifact
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Dry Contact

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- More expensive fabrication

Non-invasive

- High impedance (electrode-SC layer)
- Prone to motion artifact
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Topic of this paper.

International Electronic Conference on Sensors and Applications 28/05/2014
Soft, Comfortable Polymer Dry Electrodes for High Quality ECG and EEG Recording
Commercially Available Dry Contact Electrodes

- Flat foam electrodes
  Conductive material or with conductive coating layer
  ➔ suitable for hairless position (forehead)

- Metal electrodes
  Hard ➔ uncomfortable

- Metal electrodes + spring
  Complex ➔ expensive

➔ polymer-based electrodes are presented
  ◊ flexible
  ◊ comfortable

Dry Contact

Non-invasive

- high impedance (electrode-SC layer)
- prone to motion artifact
- active electrodes needed for weaker biopotential signals
Soft and Flexible Polymer-Based Dry Electrodes

- Non-conductive polymer electrodes + coating: coating flakes off
- Conductive polymer electrodes: comfortable + stable

Conductive polymer:
EPDM rubber + additives
For conductivity
For other properties
(mechanical, molding, de-molding...)

Various pin configurations are investigated.
Electrodes Characterization

- Impedance
  Lower impedance $\rightarrow$ higher signal quality

- Mechanical properties
  hardness and elastic modulus are defined

- ECG & EEG monitoring
  compare correlation, coherence and signal to noise ratio of signals recorded using wet and polymer dry electrodes
Electrodes Characterization: Impedance

- Impedance sweep though frequency
  
  normalized value at 10 Hz will be shown

Surface normalization since impedance decreases with larger contact area

- measurement equipment: IVIUM

potentiostat with built-in impedance analyzer

- standard wet electrodes as reference (R) and counter (C) electrodes
- impedance of working electrode (W) is calculated by the voltage and current acquired by IVIUM
Impedance Measurements

<table>
<thead>
<tr>
<th>Back to back</th>
<th>Phantom (Pt metal film and electrolyte wet cloth)</th>
<th>human test subjects (on forearm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material impedance</td>
<td>Material / phantom impedance</td>
<td>Material / skin impedance</td>
</tr>
<tr>
<td>characterization</td>
<td>For Reproducibility</td>
<td>Variation between subjects</td>
</tr>
</tbody>
</table>

Z': standard wet gel electrodes

10 cm

Optimization of additive composition: by impedance measurements. Results of various additive compositions will be discussed further.
Impedance Influenced by Conductive Additives (Carbon)

- Impedance decreases with higher carbon content
- Impedance of electrode with ~50% carbon content is 10-fold higher than conventional wet electrode
Mechanical Properties

- Hardness and elastic modulus both increase with increasing carbon content in the polymer electrodes.
- Electrodes with ~ 45% of carbon are sufficiently hard for support when mounting into EEG recording systems and offer still sufficient patient comfort during monitoring.
Electrode Characterization: ECG Monitoring

- Stronger signals

→ passive electrode is OK

![Diagram showing frequency response of different signals (ECG, EOG, EEG, EMG)]
ECG Monitoring on Chest

- No filtering
  - Signals from both electrode types are similar
  - R peaks can be easily detected

- With 50Hz filter
  - Signals from both electrode types are similar
  - R peaks can be easily detected
Electrode Characterization: EEG Monitoring

- Weaker signals
  → active electrodes are needed

![Graph showing frequency vs. amplitude for different signals: ECG, EOG, EEG, and EMG.]

- Electrode
- Active circuit
- Wires (signal, power)
- Recording system

as buffer / pre-amplification
EEG Monitoring with Clinical System

- Intermediate board
- Active electrodes
- Terminal board

Active electrodes used as buffer/pre-amplification

Clinical system used for signals recording

Clinical system (SD LTM by micromed)
Look for typical signal correlation for wet electrodes, check influence of electrode distance on signal correlation

Compare signal correlation between wet and dry electrode with typical correlation for 2 wet electrodes
Signal analysis

- **Filter**
  - Chebyshev type II Bandpass 2-30 Hz filter was applied forward and backwards on the data to eliminate distortion.

- **Pearson’s product moment correlation (correlation)**
  - quantify the similarity between the recordings as they provide information on the time coupling and wave morphology.

- **Coherence (at alpha wave range: 8-13 Hz)**
  - the stability of the similarity by looking at the frequency content.

- **Signal to noise ratio (SNR)**

\[
SNR = \frac{\text{mean} (\text{PSD}_{\text{band of interest}})}{\text{mean} (\text{PSD}_{\text{signal band}} - \text{band of interest})} = \frac{\text{mean} (\text{PSD}_{(8-13\text{Hz})})}{\text{mean} (\text{PSD}_{(2-30\text{Hz})-(8-13\text{Hz})})}
\]

SNR is typically calculated by comparing recordings with open and closed eyes. The ‘frequency band of interest’ corresponds to EEG frequencies of alpha waves present when eyes are closed (between 8 and 13 Hz).
# Reference EEG recording (wet electrodes only)

<table>
<thead>
<tr>
<th>eyes open</th>
<th>eyes closed</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="EEG plots" /></td>
<td><img src="image2.png" alt="EEG plots" /></td>
</tr>
</tbody>
</table>

The alpha waves (~10Hz) are clearly visible.
Correlation of reference recording (wet electr. only)

- Correlation of electrodes placed at shorter distance is higher than that of electrodes placed at longer distance.
- Correlation of electrodes next to each other is around 0.9
- Impossible to have two signals from the same position → correlation of 1 is not expected
EEG monitoring: dry electrode recording

Polymer dry electrode was mounted at the same location as wetL, now called dryL

The alpha waves present when subject’s eyes are closed can be clearly be detected for both wet and dry electrodes.

- Eyes open
  - WetL
  - DryL

- Eyes closed
  - WetL
  - DryL
### EEG monitoring: signal analysis

<table>
<thead>
<tr>
<th>wet electrode recording</th>
<th>dry electrode recording</th>
</tr>
</thead>
<tbody>
<tr>
<td>correlation</td>
<td>coherence (8-13 Hz)</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- **Open eyes:**
  - Wet electrode recording:
    - High correlation and coherence.
  - Dry electrode recording:
    - Moderate correlation and coherence.

- **Closed eyes:**
  - Wet electrode recording:
    - Very high correlation and coherence.
  - Dry electrode recording:
    - Moderate correlation and coherence.

**Observations:**

- The correlation and coherence of wetLL and dryL signals are close to that of wetLL and wetL signals.
- The SNR of polymer dry electrode when eyes closed are slightly lower than wet electrode.
Conclusions (1)

- Soft and flexible conductive polymer-based dry electrodes were fabricated.
- Shapes and composition optimization was done by impedance measurement and nano-indentation test.
  - Impedance of the polymer electrode with ~50% carbon content is 10-fold higher than conventional wet electrode.
  - The hardness and elastic modulus increase with increasing carbon content.
Conclusions (2)

▪ These polymer electrodes have strong potential to be good alternatives of conventional wet electrodes.

◊ All subjects reported that these polymer-based dry electrodes are more comfortable than the conventional wet ones as well as the hard metal dry ones.

◊ ECG and EEG signals acquired from the polymer dry electrodes are very promising.

• Very high quality of ECG signal recording using polymer dry electrodes, R peaks of ECG signal can be easily detected.

• In EEG signals, an active electrode configuration is used.
  o the correlation and coherence of wet-dry electrodes are similar to that of wet-wet electrodes.
  o alpha waves can be easily detected using dry electrodes, proving a high SNR