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Proceeding Paper

The Influence of Distance between the Electrode and Noise Reduction Buffer Amplifiers in ECG Monitoring Using Knitted Electrodes †

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Abstract: Knitted electrodes provide numerous advantages over the gel electrodes typically used in clinical practice when designing wearable Electrocardiogram (ECG) systems. They typically have enhanced durability, better textile integration and do not dry out. However, the higher skin/electrode impedance makes them susceptible to noise from electrical interference. Adding a buffer amplifier circuit close to the electrode, creating an 'active' electrode, is one way to mitigate this. However, the choice of where to integrate these amplifiers in the garment remains. Therefore, this work measured the signal-to-noise ratio (SNR) of an ECG output when comparing the distance between the electrode and the operational amplifier (op-amp) buffer and found that when the buffer was placed directly under a knitted electrode, the noise was lower than that seen with gel electrodes. This also provided information on the impact of distance on the SNR.

Keywords: ECG; electrography; health monitoring; knitted electrode; active electrodes

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1. Introduction

Continuous, user-friendly ECG monitoring is desirable as ECG signals can be used as indicators for several medical conditions (e.g., arterial fibrillation) and as a fitness metric for athletes. This has led to a desire to create ECG-monitoring e-textiles [1].

The clinical standard for ECG monitoring uses electrodes made of a moist, conducting gel. These lightly adhere to the skin, producing a reliable, low impedance electrical connection. However, they integrate poorly into textiles and dry out after extended use. Electrodes knitted from conductive yarn are an alternative that feature the durability and flexibility necessary for e-textile integration. However, knitted electrodes, because they are not adhesive, have a much higher skin/electrode impedance than gel electrodes and thus more susceptible to electromagnetic noise, which obscures the signal [2]. This is primarily induced by 50 (or 60 Hz) electrical mains interference (EMI) and occurs because, from a high impedance source, a small induced current will produce a large voltage offset. In the case of ECG, it is challenging to remove the noise by filtering, as might be possible in other applications, because it exists in the same frequency range as the ECG signal itself (approximately 1–100 Hz).

Other factors that influence the noise amplitude are the transmission distance and the signal amplitude; a shorter connection means that there is less space for noise to be received, and a higher signal amplitude will improve the signal-to-noise amplitude, even if the noise amplitude stays the same. Adding active signal buffering close to the electrode can lead to improvements in both these regards [3]; an active buffer will typically have a very low output impedance, meaning that its signal can travel a longer distance without accumulating noise.

This work sought to quantify this effect and assess whether suitably buffered knitted electrodes can provide signals of a quality that matches the gel-based clinical standard.

2. Method

Electrodes were tested using the AD8232 dedicated ECG front-end IC in the circuit shown in Figures 1 and 2. This circuit includes an instrumentation amplifier which generates the difference between the two input electrodes, a feedback circuit to generate the driven right leg (DRL) reference electrode voltage and a filtering circuit to remove high-frequency noise.

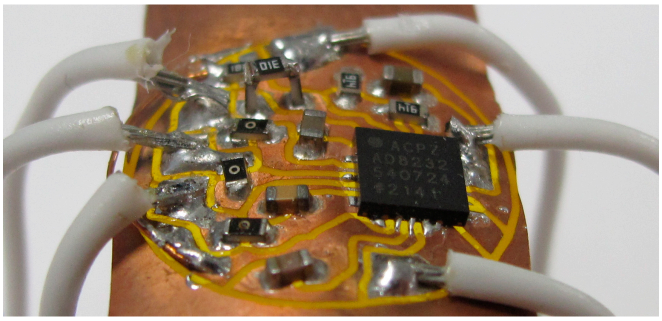

Figure 1. AD8232 circuit used for differential amplification and reference generation.

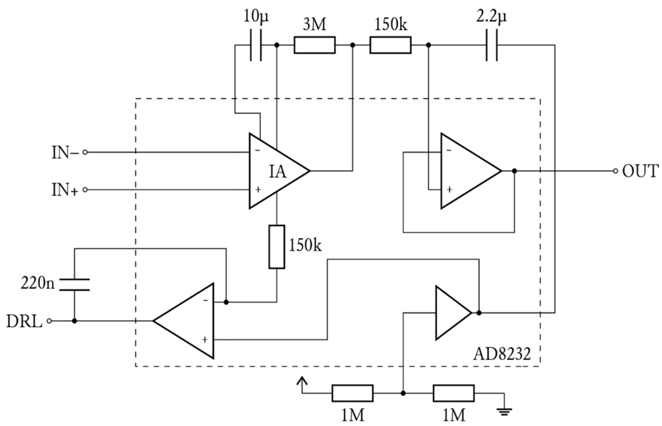

Figure 2. Schematic of the circuit shown in Figure 1.

A pair of 2.5 cm × 2.5 cm electrodes knitted from a conductive yarn were compared against a pair of gel electrodes (Everyway Medical Instruments Co., Ltd., New Taipei City, Taiwan, SA10-5x5 cm). During testing, the electrodes were positioned at the top- and bottom-left of the rib cage, with the DRL reference electrode at the bottom left (lead III of the standard five-lead ECG arrangement). When testing the knitted electrodes, a TLV9061 op-amp, configured as a unity gain buffer, was connected first directly under the electrode (Figure 3), then at distances from 2 cm to 20 cm away. The output of the op-amp as well as its ground and 3.3 V supply were connected to the AD8232 circuit by a 65 cm ribbon cable. The output of the AD8232 circuit was recorded using a Tektronix MSO3014 oscilloscope at 5 kHz.

Figure 3. A knitted electrode with the op-amp circuit mounted beneath.

The signal and noise were then separated digitally using boxcar smoothing with a kernel width of 1000 samples (200 ms). This allowed the signal-to-noise ratio (SNR) to be calculated, and this was used as a measure of signal quality.

3. Results

As can be seen in Figure 4, there is a clear correlation between the distance to the op-amp the amplitude of the noise, with the lowest distances appearing to have less noise than the standard gel electrodes.

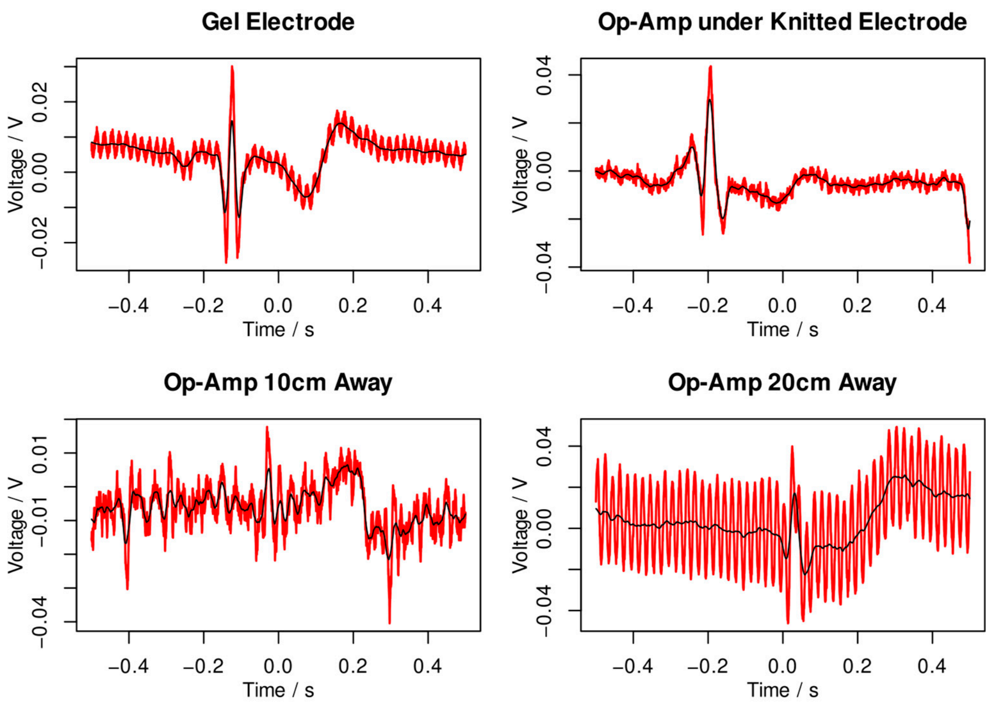

Figure 4. ECG output waveforms from the system (red) and with the noise removed via digital boxcar filtering (black).

When applying the digital smoothing filter, to create the black lines in Figure 4, it was noted that the amplitude of the QRS complex (the large down–up–down spikes) was significantly reduced in amplitude. This artificially reduces the calculated signal-to-noise ratio, so the area around the complex was excluded from SNR calculations, the results of which are shown in Table 1.

Table 1. SNR of the output for different electrode configurations, excluding the area around the QRS complex, which was handled poorly by the smoothing.

SNR/dB	
4.507	Gel Electrode
4.917	Knitted with buffer 0 cm away
3.396	Knitted with buffer 2 cm away
4.67	Knitted with buffer 5 cm away
3.157	Knitted with buffer 10 cm away
−3.733	Knitted with buffer 20 cm away

These values confirm that, with the op-amp buffer directly under the knitted electrode, the signal quality was superior to the clinical standard.

4. Conclusions

Adding the op-amp buffer amplifier circuits directly below knitted electrodes leads to a signal-to-noise ratio of 4.92 dB during ECG measurement, an 8.65 dB improvement compared to the SNR when the buffer was 20 cm away and even surpassing the signal quality of the gel electrodes, which are the clinical standard.

This allows the creation of ECG-monitoring e-textiles using electrodes that integrate much better into the fabric and have improved durability and washability compared to gel electrodes without compromising the signal integrity.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The raw and smoothed ECG data recorded during this work, and the scrips that are used to process it are available at https://doi.org/10.5258/SOTON/D2927.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Fobelets, K.; Hammour, G.; Thielemans, K. Knitted ECG Electrodes in Relaxed Fitting Garments. *IEEE Sens. J.* **2023**, *23*, 5263–5269. [CrossRef]
2. Terada, T.; Toyoura, M.; Sato, T.; Mao, X. Noise-Reducing Fabric Electrode for ECG Measurement. *Sensors* **2021**, *21*, 4305. [CrossRef] [PubMed]
3. Paul, G.; Torah, R.; Beeby, S.; Tudor, J. Novel active electrodes form ECG monitoring on woven textiles fabricated by screen and stencil printing. *Sens. Actuators A Phys.* **2015**, *221*, 60–66. [CrossRef]