Effects of Configuration and Dimension of Concentric Ring Electrodes in EEnG Recording Applications

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Abstract: Implementing Laplacian techniques through ring electrodes in bioelectrical records can improve the signal quality and spatial resolution in comparison to that obtained with conventional disk electrodes. Different dimensions of the rings and recording settings in one electrode can facilitate bioelectric mapping, and provide flexibility to studies in the field of bioelectrical signal recording. A concentric multi-ring electrode (multi-CRE), flexible, with gel, auto-adhesive, that can be configured for monopolar and bipolar records is presented in this paper. Simultaneous recording of intestinal myoelectric activity (electroenterogram, EEnG) by means of multi-CRE and conventional disk electrodes, respiration and electrocardiogram signals were performed in healthy subjects. The results revealed that the ability to detect intestinal slow waves was greatly influenced by the ability to reject its main interferences. Regarding the recording configuration, it can be concluded that the use of flexible concentric electrodes in bipolar configuration improves the quality of EEnG signals. Regarding to the effect of the electrode size, the middle ring (30 mm) reached a balance between better performance against respiratory interference of small rings and better response to low frequency interference of large rings.

1 INTRODUCTION

The following section introduces Laplacian bioelectrical recordings and concentric electrodes as method to obtain such recordings in contrast to conventional recordings with disc electrodes. Also, a brief introduction to the intestinal myoelectrical signal, the current state of the art of its recording and the importance of intestinal slow waves.

1.1 Biolectrical Laplacian Recordings

Bioelectric signals records are usually performed with conventional disc electrodes, either monopolar or bipolar configurations. One disadvantage of these electrodes is their poor spatial resolution, mainly caused by the blurring effect due to the different conductivities of the volume conductor (Bradshaw et al., 2001; Besio et al., 2004, Boudria *et al*, 2014). In this context, the Laplacian potential has been shown to reduce the smoothing effect caused by the volume conductor and performs a better spatial resolution.

Different configurations of the concentric electrodes have been used to estimate the Laplacian bioelectric potential in the body surface (Lu y Tarjan, 1999; Besio *et al.*, 2006, Boudria *et al*, 2014). However, the electrodes proposed in those works were implemented on rigid substrates, which can cause discomfort to the patient since they cannot properly adapt to the body curvature and also require external adhesive for fixing to the skin. In this regard, one of the objectives of this paper is to analyze the performance of an electrode that not only permits to directly estimate the Laplacian of the potential, but also it is comfortable for the patient and easy to use. Moreover, at it will be detailed later, the presented electrode admits multiple configuration of monopolar and bipolar configuration for different ring sizes.

1.2 Intestinal Myoelectrical Activity

The electroenterogram (EEnG) is the record of the myoelectric activity of the small intestine, which has two components: the Slow Wave (SW) and the Spikes Burst (SB) at low and high frequencies, respectively. The SW are slow and periodic

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oscillations that act as pacemakers and determine the maximum frequency of the SB and hence of intestinal contractions. Intestinal SW frequency varies along the small intestine, and can range from about 12 cpm in the duodenum, and 8 cpm approximately at ileum. Although SW is always present, the force of contraction of the small intestine is directly related to the intensity of SB (Fleckenstein & Oigaard, 1978; Quigley, 1996; Vantrappen, 1997).

Few studies of EEnG surface recordings in humans have been reported (Chen et al., 1993; Chang et al., 2007; Prats-Boluda et al., 2011). One reason may be because the EEnG is a very weak signal and it is greatly affected by physiological interference such as respiration, affecting mainly the SW activity, and ECG which overlaps with the bandwidth of the SB.

Another objective of this paper is to analyze and study the potential benefits of estimating Laplacian EEnG signal by using concentric ring electrodes in different configurations and sizes. The study in this paper is focused in the SW, which is the component that has greater amplitude in EEnG surface records, and due to the fact that abnormal SW patterns are related with diabetes (Ouyang, 2015) and several intestinal pathologies, such as mechanical intestinal obstruction, irritable bowel syndrome, paralytic ileus, and intestinal ischemia (Quigley, 1996; Somarajan *et al.*, 2015).

This paper is organized as follows. Section 2 includes the material and methods that describes the manufactured concentric multi-pole sensor, the protocol for signal recordings and the signal analysis that was carried out. Section 3 shows the results obtained: recorded signals and characteristic parameters. In section 4 such results are discussed and compared to previous works. The conclusions of this work are summarized in section 5.

2 MATERIAL AND METHODS

This section firstly describes the penta-polar concentric electrode (inner disc and 4 out rings) which was manufactured and evaluated in this work. Secondly, the recording protocol which was carried out to obtain EEnG signals from healthy humans with the proposed mulitring electrode and with conventional disc electrodes. Finally, the methods and parameters used for characterizing the different EEnG signals and comparison of recording configuration are presented.

2.1 Multi-ring Concentric Electrode

In this work a concentric multi-ring electrode (multi-CRE) formed by four concentric hook-shaped and an inner circular electrode was implemented. The external diameters of the sensing rings were set to 20, 30, 40 and 50 with a constant thickness of 2 mm. The diameter of the inner disc diameter was set to 10 mm.

The flexible electrodes were screen-printed with a biocompatible Ag/Ag-Cl paste (Gwent C2130429D3) printed onto a flexible polyester film (Dupont Melinex ST506) using a high precision screen stencil printer (AUREL 900). The ink curing period was 130º C for 10 min.

A double sided layer of biocompatible adhesive 104 µm thick (MacTac TM8710), adapted to dimension of the rings, was used in order to improve the electrode-skin adhesion. Therefore, the adhesive remains between the skin and the polyester film leaving a small gap in the rings so as to deposit a conductive gel layer to reduce contact impedance.

The bipolar and monopolar signals derived from multi rings electrodes are given by:

$$BC_n = MC_{n+1} - MC_1 \tag{1}$$

Where, MC_{n+1}, n=1…4 are the monopolar concentric biopotentials picked up by each ring; MC1 is the biopotential picked by the inner disc; n+1 is the number of ring ranging from 2 to 5.

2.2 Signal Recordings

Ten recording sessions of 60 min were carried out in healthy human volunteers in fast state (>6h). Subjects were lying in a supine position inside a Faraday cage. Firstly, the abdominal body surface was exfoliated to remove dead skin cells to reduce contact impedance. The abdominal surface was also shaved in male subjects.

The conductive gel was placed on the multi-CRE without removing the adhesive backing, spreading the gel carefully on all rings. Thereafter, the adhesive backing was removed and the electrode placed 2.5 cm below the umbilicus, as shown in figure 1. Similarly, two monopolar Ag/Ag-Cl disk electrodes of 8 mm of diameter were placed 2.5 cm above the umbilicus and separated the same distance. One bipolar conventional recording of EEnG was obtained from these electrodes.

The main sources of physiological interference usually presented in surface EEnG recordings were also recorded. Such as, ECG which was monitored by Lead I using disposable electrodes; respiration

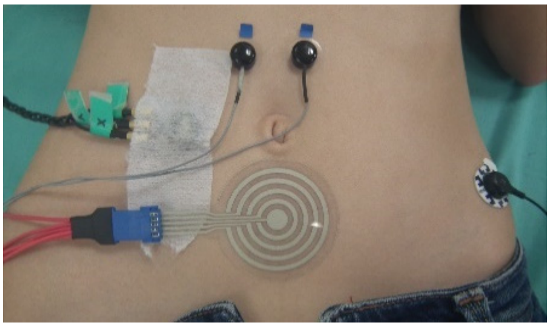

Figure 1: Multi-ring concentric electrode, conventional disc electrodes and accelerometer sensor positions.

which was measured with an airflow transducer (1401G Grass Technologies, Warwick, USA) and movements which were sensed by a triaxial accelerometer (ADXL 335, Analog Devices).

A disposable electrode was placed in the left ankle and used as bioelectric reference, another electrode was placed on the left hip to be used in the monopolar measurements.

All signals, except from acceleration, were amplified and band-pass filtered (0.1 – 100 Hz) by means of conventional bioamplifiers (P511, Grass Technologies, Warwick, USA). Signals were simultaneously recorded at a sampling rate of 1 kHz.

2.3 Signal Analysis

In order to study the effect of the configuration and of the dimensions of the electrode rings in the detection of SW of the EEnG, ten signals were analysed in each session: five monopolar concentric (MC), four bipolar concentric (BC) and one conventional bipolar (BIP). The EEnG signals and respiration signal were low-pass filtered (f_c =0.5 Hz) and resampled at 4 Hz.

The power spectral density (PSD) of these signals was estimated by means of autoregressive parametric techniques (AR, order 120). The PSD was estimated in moving windows of 120s every 15s of the recorded signals. The dominant frequency (DF) was calculated in each moving window, being defined as the frequency of the maximum energy peak above 6 cpm. On the other hand, signals' quality, in terms of respiration interference and low frequency components was also evaluated. For this purpose, it was calculated the Welch periodogram for each moving window so as to compute subband energies. To sum up, the following parameters were calculated (Garcia-Casado *et al.*, 2014):

- $\%DF_{TFSW}$: defined as the ratio of analysed windows whose DF is inside the typical frequency range of intestinal SW (8-12 cpm).
- $PR_{SW/RESP}$: defined as the ratio between the power within the SW frequency range and the power in the respiratory bandwidth, calculated as follows:

$$PR_{SW/RESP}\ (dB)=10\cdot \log\left(\frac{\text{Power(EEnG)}|_{8\text{ cpm}}^{12\text{ cpm}}}{\text{Power(EEnG)}|_{DF_{RESP}-1\text{ cpm}}^{DF_{RESP}+1\text{ cpm}}}\right) \quad (2)$$

- $PR_{SW/LF}$: defined as the ratio between the power within the SW frequency range and the power in the low frequency bandwidth, calculated as follows:

$$PR_{SW/LF}\ (dB)=10\cdot \log\left(\frac{\text{Power(EEnG)}|_{8\text{ cpm}}^{12\text{ cpm}}}{\text{Power(EEnG)}|_{6\text{ cpm}}^{8\text{ cpm}}}\right) \quad (3)$$

- $\%DF_{SW}$: defined as the ratio of analysed windows whose DF, after discarding peaks on the low frequency and respiration bandwidth, is in the range of SW.

3 RESULTS

Figure 2a shows an example of recorded signals. The amplitudes of the monopolar concentric signals appear similar. However, the amplitude of bipolar concentric signals increases as it does the size of the ring. On the other hand, the ECG interference was more present in monopolar concentric and conventional bipolar signals, while the bipolar concentric was less affected. However, in the BC3 it was observed a slight increase in this interference. This work is focussed only on the study of the SW and the energy of ECG signal is mainly outside the slow wave frequency range, thus no further study of this interference was done.

The identification of SW in the time domain was difficult mainly due to cardiac interference in MC and BIP records, and to low amplitude in BC records. The figure 2b shows the PSD of the filtered records of the signals shown in figure 2a, extending the analysis window to 120s. It can be observed more energy in the range of 8-12 cpm (SW frequency range) in BC records than in MC and BIP. In table 1 mean and standard deviation values of the calculated parameters are shown. It can be seen that mean of $\%DF_{TFSW}$ was 57.5% (MC1), 61.4% (BC2) and 50% (BIP). Also, the power ratio of signal/interference of respiration ($PR_{SW/RESP}$) was higher for bipolar concentric signals acquired from smaller rings (6.15 dB in BC1, 5.96 dB in BC2) than monopolar concentric and conventional bipolar (4.52 dB and 3.51 dB for MC4 and BIP respectively). This could also be appreciated in the PSD (Figure 2b) where the MC and BIP records are

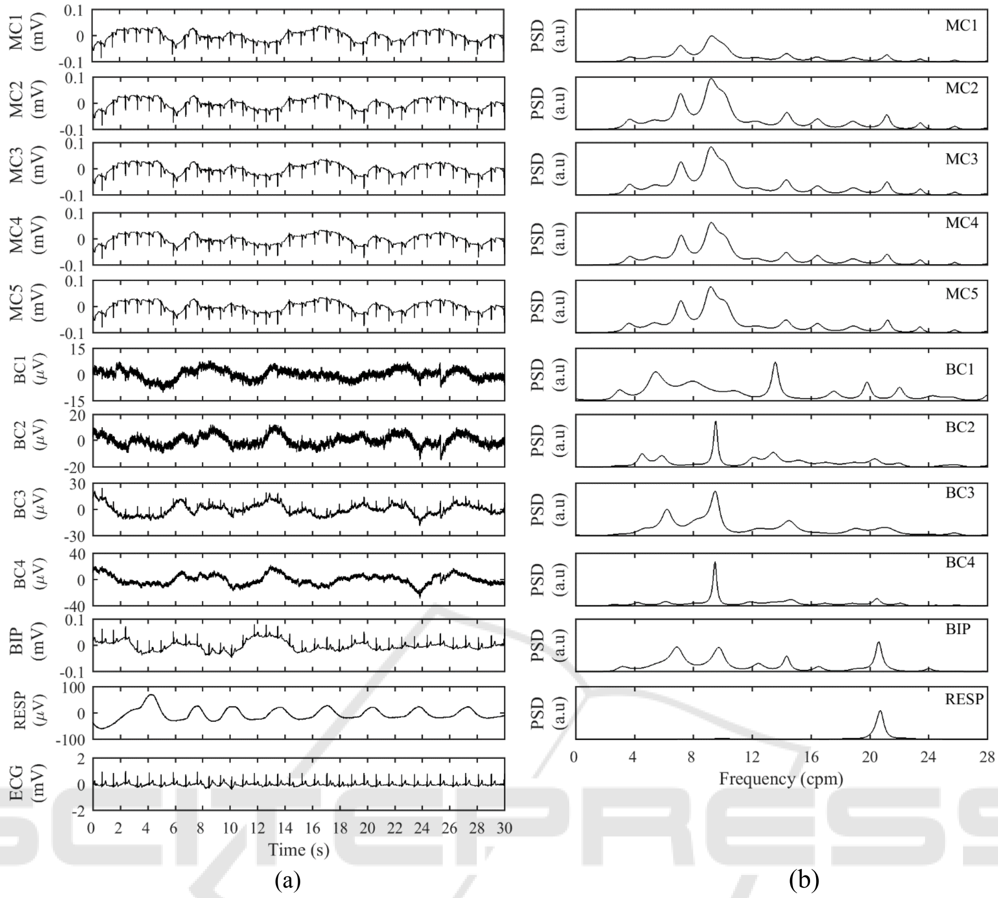

Figure 2: (a) Simultaneous recordings: MC1-5 monopolar concentric EEnG; BC1-4 bipolar concentric EEnG; BIP conventional bipolar EEnG; RESP respiration; ECG electrocardiogram (b) Power spectral density of corresponding windows of 120s of signal in (a).

more affected by respiratory interference. In addition, the PSDs and Table 1 reflect that the larger the ring size, the higher the respiratory interference.

On the other hand, conventional bipolar recordings were less affected by low frequency interference; with $PR_{SW/LF}$ ratio of 4.63 dB. The monopolar concentric records showed similar values for all dimensions of rings (around 3.9 dB); while bipolar concentric shows that larger diameters result on smaller low frequency interference (opposite behavior to that of respiratory interference), with values from 2.9 to 4.0 dB.

The ability to pick up the SW, once discarded the PSDs' peaks associated with main interferences (respiration and low frequency) was better for bipolar concentric, with mean values reaching 94.9% (BC2) compared to monopolar concentric and conventional bipolar (around 89% in all these cases).

4 DISCUSSION

In this work, it was developed a flexible multi-CRE for surface EEnG recording so as to analyse the influence of ring dimension and recording configuration on the sensed signal. The multi-CRE allows flexibility in order to select the best ring to pick up the SW component of the EEnG and it can be easily adapted to determine the optimum dimension of CRE for surface recording of other weak bioelectrical signals, such as electrohysterogram, electromyogram, electrogastrogram and/or electroencephalogram. Also, its flexibility permits that this electrode design can estimate directly the Laplacian of the signal when performing bipolar recordings with the inner disc and one of the outer rings. Laplacian bioelectrical recordings have proven to enhance spatial resolution (Boudria *et al*, 2014) which can be

Table 1: Results of parameters (mean ± standard deviation) of EEnG signals.

Signal	$\%DF_{TFSW}$	$PR_{SW/RESP}$ (dB)	$PR_{SW/LF}$ (dB)	$\%DF_{SW}$
MC1	57.5±10.1	5.04±3.68	3.75±3.25	89.4±5.1
MC2	57.1±10.4	4.93±3.71	3.90±3.22	89.4±5.4
MC3	56.3±10.2	4.66±3.74	3.82±3.12	88.5±6.1
MC4	55.3±9.6	4.52±4.07	3.85±3.06	89.1±5.8
MC5	54.1±8.5	4.56±3.46	3.97±3.22	87.3±5.5
BC1	60.1±6.5	6.15±3.25	2.90±2.88	92.4±4.3
BC2	61.4±10.1	5.96±4.31	3.54±2.87	94.9±3.7
BC3	52.9±13.1	4.47±4.86	3.77±2.98	92.2±3.8
BC4	54.7±18.1	4.17±6.26	4.00±3.10	92.9±3.3
BIP	50.1±10.2	3.51±3.73	4.63±3.44	88.5±8.8

a key factor for the estimation of propagation velocity of slow waves that are of critical importance for analysing motor patterns of the small intestine (Huizinga *et al.,* 2015). Moreover, this multi-CRE was developed on a flexible substrate which allows a better adaptation to the curvature of the body compared to rigid electrodes (Besio *et al.*, 2006; Prats-Boluda *et al.*, 2011, Boudria *et al*, 2014). Additionally, in contrast to other ring electrodes implemented of flexible substrates (Garcia-Casado *et al.*, 2014) no other materials for fixing it to the skin were required due to self-adhesive characteristics. This may be useful in long term recording (> 60 min). Similarly, the electrolytic gel also improves electrode-skin contact impedance, and reduces the needs regarding intensity of skin abrasion in comparison to previous works (Prats-Boluda *et al.*, 2011; Garcia-Casado *et al.*, 2014).

The bipolar concentric recordings were more immune to respiratory and ECG interference, improving the quality of EEnG records, compared to those of monopolar concentric and conventional bipolar records. This is in agreement with other studies carried out using CRE implemented on rigid and flexible substrate (Prats-Boluda *et al.*, 2011; Garcia-Casado *et al.*, 2014). This feature facilitates the detection of the SW component of the EEnG. Although this work was focused on the analysis of the low frequency component (SW range), the fact that bipolar concentric signals are more immune to the ECG interference, can facilitate the detection of spike burst at high frequency in future EEnG studies. As for the MC configuration, similar values of SW detectability were observed for the five ring sizes. However, in BC configuration, the slow wave could be best picked up by the medium rings (BC2, 30 mm), reaching a trade-off between better performance against respiratory interference of small rings and the best response of large rings to attenuate low frequency interferences. Similar size and configuration of tripolar electrodes was used to record intestinal SW in previous works, but unlike them in this work the multi-CRE did not require any active preamplification circuits (Garcia-Casado *et al.*, 2014).

5 CONCLUSIONS

A multipole concentric ring electrode, flexible, with gel, and auto-adhesive, which permits many different settings of simultaneous recording of bioelectrical signals has been successfully developed.

The feasibility to capture intestinal slow waves is greatly influenced by the ability to reject the main interferences that affect its recording. It can be concluded that the use of flexible concentric electrodes in bipolar concentric configuration (Laplacian estimation) improves the signal quality of EEnG compared to monopolar configuration and to traditional bipolar records with disc electrodes.

Regarding to the effect of the electrode size, the middle ring (30 mm) reached a balance between better performance against respiratory interference of small rings and better response to low frequency interference of large rings. The use of such kind of electrodes could bring this technique closer to clinical applications.

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