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Ye Lin, Y.; Martínez-De-Juan, JL.; Jareño-Silvestre, A.; Prats-Boluda, G. (2022). Concentric ring electrodes for non-invasive recording of gastric myoelectric activity. Measurement. 188:1-9. https://doi.org/10.1016/j.measurement.2021.110607

The final publication is available at

https://doi.org/10.1016/j.measurement.2021.110607

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Additional Information

1. TITLE PAGE

Journal:

Measurement

Title of paper

Concentric ring electrodes for non-invasive recording of gastric myoelectric activity

Abbreviated title

Gastric activity recording with CRE

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2. Abstract

Electrogastrography has emerged as a non-invasive technique for diagnosing an extensive variety of gastrointestinal disorders. The non-invasive electrogastrogram (EGG) remains a challenge due to the poor spatial resolution of conventional disk electrodes. In this work we attempted to determine the possibility of detecting gastric myoelectric activity using concentric ring electrodes (CRE) proposed to improve the spatial resolution of bioelectrical recordings. We simultaneously recorded 8 bipolar and bipolar concentric (BC) EGGs acquired by disk electrodes and CREs, respectively. The BC EGG showed lower signal amplitude than the bipolar recordings but were less influenced by cardiac interference and had a slow wave (SW) detectability above 80% when positioned over the stomach. We found a similar gastric SW frequency in both bipolar and BC EGG records in both fasting and postprandial states and a similar postprandial/fasting power ratio, suggesting the feasibility of using CRE to identify gastric myoelectric activity.

Keywords: Gastric myolectric activity, Gastric slow wave, electrogastrography, electrogastrogram, concentric ring electrode.

Highlight (3-5 points, maximum 85 characters, including spaces, per bullet point)

1.- Concentric ring electrodes can be used to record gastric myoelectric activity

2.- Bipolar Concentric recordings are less influenced by cardiac interference

3.- Bipolar Concentric EGG signal is 2-3 times lower than bipolar, but with better SNR

4.- Multichannel cross spectrum can identify gastric slow wave frequency

5.- Slow wave from Bipolar Concentric signals has high temporal and spatial stability

TEXT

1. Introduction

Gastrointestinal (GI) diseases are now widespread. Subacute and chronic symptoms are common in primary care, and their prevalence is also high in epidemiological studies [1]. Functional gastrointestinal disorders, which include functional dyspepsia, functional vomiting, functional constipation, diarrhoea and irritable bowel syndrome together with GI motility disorders, are the most common GI disorders in the general population. While estimates vary, about 1 in 4 people or more in the United States may suffer from any of these disorders [1]. Worldwide, the prevalence rates of functional dyspepsia and irritable bowel syndrome in the general population according to the Rome III diagnostic criteria are 5.3–20.4% and 1.1–29.2%, respectively [2]. These disorders not only have a significant impact on the patients' everyday activities and quality of life, their chronic symptoms cause emotional distress and may also result in heavy economic burdens through direct medical expenses and loss of productivity [3].

Many routine medical tests such as endoscopic exams, CT scans, blood tests and radiological imaging fail to diagnose these functional GI disorders and GI motility disorders since there is no inflammatory, infectious, or structural abnormality [4]. Electrogastrography has emerged as an alternative technique for diagnosing functional gastric abnormalities. The electrogastrogram (EGG) is a recording of gastric myoelectric activity obtained by positioning cutaneous electrodes on the upper abdominal surface [5]. Traditionally, a bipolar configuration that consisted of obtaining a differential potential was acquired using two conventional disk electrodes. The EGG is made up of two components: omnipresent slow waves (SW), which are generated and propagated through the network of interstitial cells of Cajal's, and spike bursts, which are rapid action potentials directly related to the presence and intensity of gastric contractions [5]. In a healthy human stomach, gastric slow waves originate from a pacemaker region in the upper corpus region of the greater curvature in the proximal stomach at a frequency of 3 cycles per minute (cpm) and propagate towards the antrum [6] at a normal frequency range of between 2-4 cpm (normogastria). If the EGG's dominant frequency is ranged between 0.5-2 cpm and 4-9 cpm, it is considered as bradygastria and tachygastria, respectively [7]. Gastric arrhythmia in which there is no dominant peak power in the spectrum has also been reported [7].

However, surface EGG recordings not only contain gastric myoelectric activity but are usually contaminated by cardiac interference, ultra-low frequency components [8] and respiration between 12 to 25 cpm [7] and may also occasionally record the small bowel slow wave (9-12 cpm) [7]. Since both cardiac, respiration and small bowel slow wave activity do not generally overlap in frequency with that of gastric SW, EGG signal analyses are usually performed in the spectral domain, since this latter information was found to be more reliable than temporal characteristics. Previous studies showed that the association of gastric contractions with the SW frequency was 80-85%, while its association with amplitude was 30-40% [9]. In contrast, the presence of ultra-low frequency components, which are more likely to be associated with spontaneous variations of skin-electrode contact potential and motion artifacts [8], could make gastric SW identification difficult, giving rise to misinterpretation of frequency components in the bradygastria range. As the power contribution of their harmonics in the range of 2-4 cpm can be even higher than that of the ongoing gastric

SW activity, the diagnosis of bradygastria, normogastria, or tachygastria cannot be made simply on the basis of the power distribution in the EGG spectrum [8]. In the literature, normal EGG recordings have traditionally been defined as presenting a dominant frequency in the 2-4 cpm range for at least 70% of the recording time [10][11]. Although the SW does not represent gastric motility, it does control the propagation and occurrence frequency of the gastric contractions [5]. It is well known that gastric SW dysrhythmias have been implicated in several GI motility disorders, including chronic unexplained nausea and vomiting, gastroparesis, functional dyspepsia, reflux with regurgitation, gastroparesis, and motion sickness [12][13][14].

Despite this, EGG's clinical application is still limited, since there is some controversy about the relationship between the EGG temporal and spectral parameters and gastric pathologies [15][16][17]. In this respect, the latest research focuses on estimating the propagation speed of gastric SW activity by high-resolution gastrointestinal electrical mapping. With a spatially dense electrode array directly on the invasive serosa multichannel recordings, Berry et al found that resection of the gastric pacemaker during laparoscopic sleeve gastrectomy resulted in an aberrant distal unifocal ectopic pacemaker with retrograde propagation, which can persist in the long term, inducing chronic dysmotility or bioelectrical quiescence [18]. An abnormally rapid propagation velocity was also found, whereas frequency and amplitude were unchanged [18]. Other authors have found aberrant initiation and conduction of the SW in subjects with gastroparesis [13] and chronic unexplained nausea and vomiting [12] using serosa high-resolution gastrointestinal electrical mapping, which occasionally led to premature termination and colliding wavefronts. Half of the subjects exhibited spatial abnormalities that occurred at the normal 3 cpm [12][13]. This suggests that single channel EGG recordings are unable to detect such abnormalities [9] [19] and slow wave propagation speeds act as reliable signatures of the occurrence of dysrhythmic events [20][21].

Despite the diagnosis value of high-resolution gastrointestinal electrical mapping, its clinical application is restricted due to its invasiveness, while non-invasive high-resolution surface EGG mapping has emerged as an alternative for obtaining gastric propagation properties. Gharibans found that spatial patterns from high-resolution non-invasive EGG correlate with the severity of symptoms in patients with functional dyspepsia and gastroparesis [17]. However, the accurate estimation of the propagation speed of non-invasive EGG recording could be impaired by the poor spatial resolution of conventional disk electrodes due to the blurring effect of the volume conductor [9] [22], which could not be resolved by simply increasing the number of surface recording electrodes [23]. In other words, two nearby cutaneous electrodes record similar signals since they record the average activity in overlapping volumes of tissue. In fact, it has been found that dysrhythmic SW activity contributes to functional GI motility disorders, although the specific mechanisms and classification of dysrhythmias could not be elucidated due to low-resolution approaches using cutaneous EGG obtained from conventional disk electrodes [6].

The surface Laplacian potential has been proposed to improve spatial resolution of non-invasive bioelectrical recordings such as the electrocardiogram [22][24], electromyogram [25], electroencephalogram [26], electroenterogram [27] and electrohysterogram [28]. Theoretically, surface Laplacian potential is proportional to the derivative of the current density orthogonal component to the body surface and can be interpreted as a filter that allocates more weight to the bioelectrical dipoles adjacent to the recording points. The surface Laplacian emphasizes superficial localized sources while suppressing widespread and coherent deep and shallow sources. This property allows us to detect accurate gastric slow wave propagation from the abdominal surface [9]. The surface Laplacian signal can be estimated using discrete methods from an array of spatially distributed disk electrodes, as conducted by Gharibans who showed the possibility of estimating slow wave propagation speed using a 5x5 disk electrode array[10]. The surface Laplacian potential can also be directly acquired by concentric ring electrodes (CRE) [22][28] and has been shown to better estimate the surface Laplacian potential than discrete methods. As to date there have been no reports on the use of CRE to obtain gastric myoelectric activity, the aim of this work was to determine the feasibility of picking it up by means of CREs and to compare their characteristics with those acquired from conventional disk electrodes.

2. Materials and methods

2.1. Signal acquisition

A total of 8 recording sessions were conducted on 8 healthy subjects (4 men and 4 women with an average age of 24.4±7.9 years and body mass index of 20.7±2.9 Kg/m^2). The subjects were previously informed of the study's nature and provided written informed consent forms. The University Ethics Committee approved the study protocol, which adhered to the Declaration of Helsinki.

Each session included 30-minutes of recording in a fasting state and 30-minutes after ingesting a solid meal (400 kcal with a fat content of 20%). The subjects were allowed to have some water if needed. For each recording session, the abdominal skin was carefully prepared using an abrasive paste (Nuprep, Weaver) to reduce skin–electrode contact impedance. One conventional disposable disk electrode and three CREs (CODE5000S0, SPESMEDICA) were positioned on the upper abdominal surface as shown in Figure 1 to simultaneously obtain three bipolar EGG recordings (BIP) and three bipolar concentric (BC) EGG recordings. The conventional disposable disk electrode consisted of a central Ag/AgCl conductor disk attached by adhesive, i.e. they had a monopolar configuration. Due to the bipolar configuration's ability to reject common mode interferences, this latter configuration was usually used for acquiring bioelectrical signals by obtaining the differential potential picked up by two conventional disposable disk electrodes. In this work, the three bipolar recordings were obtained by acquiring the differential potential between the CREs' central disk and the conventional disk electrode E4. We also used CRE in a bipolar configuration, which consisted of obtaining the differential potential acquired from external ring and central disk electrodes and then annotated them as bipolar concentric (BC) recordings. CRE in bipolar configuration can be interpreted as a generalised discrete method in which the recording electrodes surrounding the central disk tend to be infinite. The CRE's central disk diameter was 16 mm and the internal and external diameter of the outer ring were 28 mm and 42 mm, respectively. Another disposable Ag/AgCl electrode was placed on the subjects' right hip as the ground electrode. For the respiration signal, a thermocouple sensor was positioned in the nasal passage to detect the temperature variation between the exhaled and inspired air flows (1401G from Grass Technologies). All bioelectrical signals were amplified and band-pass filtered at [0.01, 30] Hz using commercial biopotential amplifiers (P511, Grass Technologies) and sampled at 100 Hz using NI USB-6229 BNC. The cut-off frequency of the analogue high-pass filter was set to as close as possible to 0.5 cpm, since the basic fundamental frequencies of the EGG signal range between 0.5-9 cpm [7]. In the same way we established the cut-off frequency of the analogue low-pass filter at 30 Hz to be able to quantify the electrocardiogram (ECG) interference embedded in the EGG recording.

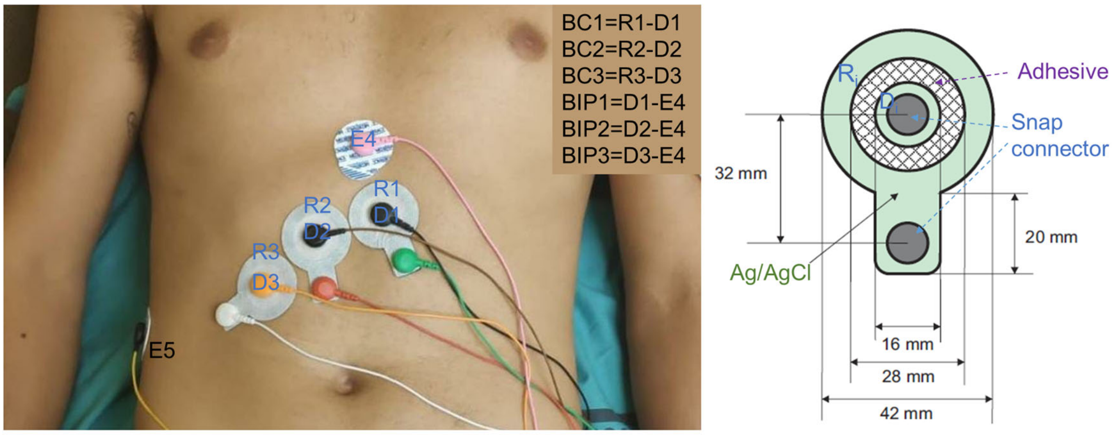

Figure 1. Left image shows the electrode positions on the abdomen for EGG signal recording (CRE1-3) Concentric ring electrodes for acquiring three BC EGG recordings, where Ri and Di are the biopotentials picked up by the external ring and internal CRE disk respectively. (E4) Biopotential acquired by the active disposable Ag/AgCl electrode 4 common to three bipolar recordings. (E5) Ground electrode. CRE dimensions are given on the right.

2.2. Data analysis

2.2.1 Signal quality assessment

Since the gastric slow wave mainly distributes its energy below 30 cpm [29], raw EGG signals were bandpass filtered in the 0.6-30 cpm frequency range with a zero-phase 5-th order Butterworth filter and resampled at 4 Hz. This latter is referred to hereinafter as the *preprocessed EGG signal*. The digital low pass filter's cut-off frequency was set taking the respiration rate into account (12-25 cpm) [7] to be able to quantify the respiration interference embedded in the EGG recording. Since relatively slow gastric dynamic and dysrhythmic events may occur within 1–2 min [11], we performed the data analysis in 5-minute moving windows with an 80% overlap.

Taking into account the basic fundamental frequencies of EGG signals [7], we computed the gastric slow wave amplitude (GSWA) as the root mean square value of the EGG signal in the 0.6-9 cpm frequency range.

To determine signal quality, we quantified both the cardiac and respiration interference embedded in the EGG recording. Since ECG interference mainly distributes its energy above 1 Hz, the S/I_{ECG} was defined as the ratio between GSWA and the estimated ECG interference calculated as the root mean square value of the resulting signal after applying a high-pass filter with cut-off frequency at this frequency to record the raw EGG (see Eq. 1).

$$S/I_{ECG}\ (\mathrm{dB}) = 20 \cdot log_{10} \frac{GSWA}{ECG} \quad (1)$$

As the human respiration frequency can vary throughout the recording session, we quantified the respiration interference in the spectral domain. Firstly, a periodogram with a hamming window was used to obtain the dominant frequency of the simultaneously recorded respiration signal (DF_{resp}). The S/I_{resp} parameter was then defined as the ratio between the EGG signal power in the 0.6-9 cpm bandwidth and respiration interference embedded in the EGG recording, which was computed as the EGG signal power in the DF_{resp}±1 cpm frequency range (see Eq. 2).

$$S/I_{resp}\,(\mathrm{dB}) = 10 \cdot log_{10} \frac{\sum_{0.6cpm}^{9cpm} PSD_{EGG}}{\sum_{DF_{resp}-1cpm}^{DF_{resp}+1cpm} PSD_{EGG}} \quad (2)$$

Where PSD_{EGG} is the power spectral density of the preprocessed EGG signal using the periodogram method with a Hamming window.

2.2.2 Identifying gastric myoelectric activity

We further attempted to characterize the gastric SW frequency since this latter is one of the most relevant characteristics of the EGG signal and ultra-low frequency components can mask this activity, giving rise to erroneous results. We therefore aimed to estimate the gastric SW frequency from multichannel EGG recordings based on prior information. Firstly this activity detected in multichannel EGG recording should be highly coupled [30], i.e. the SW should present similar frequencies at different points. As it should also remain over time [5], we determined the gastric SW frequency using the cross spectrum. For each 30-minute recording session (both fasting and postprandial states), we performed the cross spectrum using the Welch's method (10-min hamming window with overlapping of 50%) between the three bipolar (BIP1-2, 2-3 and 1-3) and three BC recordings (BC1-2, 2-3 and 1-3), obtaining a total of six cross spectra. We then determined the dominant frequency in each cross spectrum in the typical SW frequency range (from 2 cpm to 4 cpm). Theoretically the six cross spectra should have the same dominant frequency. In practice, they do not always match due to interference, after which we defined the global gastric slow wave frequency (GGSWF) as the mode value of the different cross spectra's dominant frequency at 2-4 cpm.

Since gastric SW frequency can vary slightly around GGSWF, we attempted to determine the dominant frequency in the GGSWF±0.3 cpm range in the power spectrum obtained using a covariance method-based autoregressive (AR) model in 5-minute moving windows with an 80% overlap (hereinafter DFCS). We preferred these parametric spectral estimators to determine gastric SW frequency since the latter provide better frequency resolution than non-parametric techniques for a given window length [31]. A grid search was made of model order between 60 and 150 with a step size of 30, order 120 being a trade-off between dominant frequency detectability and its variability between consecutive windows.

We also computed the DFAR parameter, which is commonly used in the literature for EGG SW identification [7][11][15]. DFAR is the dominant frequency in the typical SW frequency range (2-4 cpm) of the preprocessed EGG signal, using an autoregressive model of the same order to compare it with the DFCS in detecting gastric SW frequency.

For each channel (fasting and postprandial), we computed the mean and standard deviation of both DFAR and DFCS for all the analysed windows. For both DFAR and DFCS, we assessed gastric SW detectability by computing the ratio between the number of windows with a dominant frequency in the typical SW frequency range (2–4 cpm) and in the GGSWF±0.3 cpm range and the total number of windows analysed (hereinafter %DFAR and %DFCS, respectively). To analyse gastric SW frequency variability throughout the recording, we also computed the frequency instability coefficient (FIC), which is the ratio between the standard deviation and the average value [32]. Lower values indicate higher stability of frequency components over time. To evaluate gastric SW spatial variability we also computed the percentage of slow wave coupling (%SWC) between each pair of bipolar and BC EGG recordings. For this purpose, we first determined for each analysis window if the SWs in two channels was coupled with the difference between their frequencies less than 0.2 cpm [33]. The %SWC was then calculated as the ratio between the total number of windows in which the SW were coupled and the total number of windows analysed.

Bland and Altman plots [34] were used to determine the degree of agreement between bipolar and BC EGG recordings in detecting gastric SW frequency for both DFAR and DFCS in both fasting and postprandial states.

Finally we computed postprandial/fasting power ratio (PR) since the literature reports the postprandial/fasting response in the typical SW range (2-4 cpm) [35], but also in the high frequency range around 50-80 cpm in EGG recordings [36][37]. PR can therefore help to assess the uptake of gastric activity on the surface. We calculated three postprandial/fasting power ratios in 2-4 cpm (PR_{LF}), 30-60 cpm (PR_{HF1}) and 30-90 cpm (PR_{HF2}). Due to their being less complicated, PR energy ratios were computed rather than the power associated with the dominant frequency peak [38].

So as to assess the statistical significant difference between the different parameters from conventional bipolar and BC recordings, and between fasting and postprandial state, in this work we used paired Wilcoxon signed-rank test (α=0.05). In addition, due to the limited sample size, we also worked out the statistical power of the probability of rejecting a null hypothesis that is actually false. In this respect we only considered the statistically significant differences if their statistical power was over 70%.

3. Results

Figure 2 shows five minutes of simultaneous recordings from the three bipolar, BC EGG and respiration signals. Gastric SW activity can be seen at 3 cpm, except for bipolar 3, in which no gastric myoelectric activity was found. Bipolar recordings had higher amplitude (peak-to-peak amplitude: ~400 μV for BIP1 and BIP2 vs. 100-150 μV for BCs) and stronger cardiac interference than those from BC EGG. In this case, there was no respiration interference embedded in the EGG recordings.

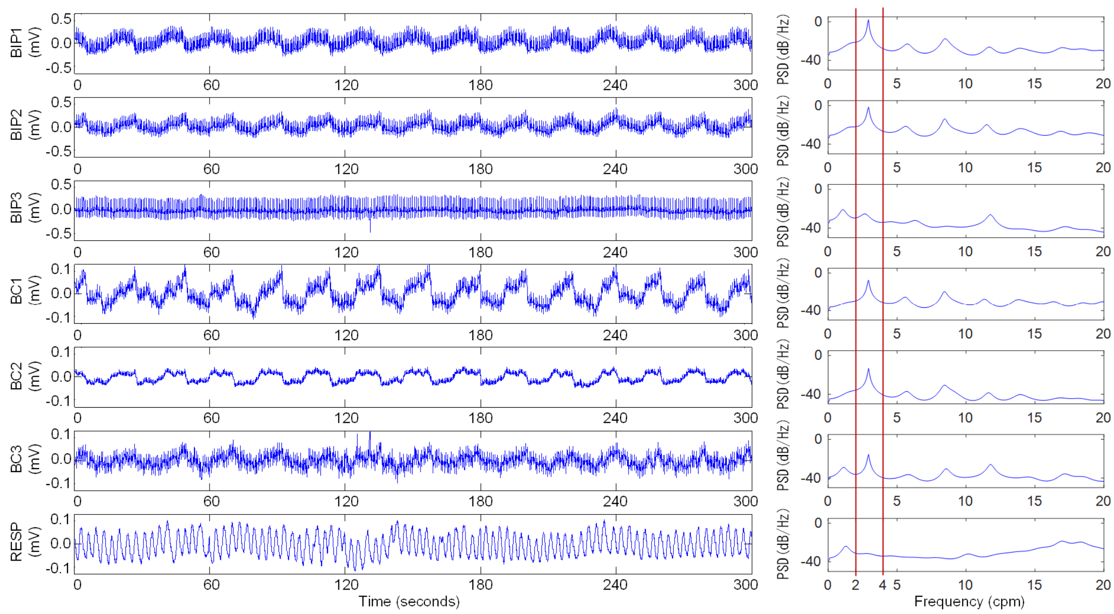

Figure 2. Five minutes of simultaneous recordings of three bipolar and BC EGG signals acquired from subject 3 during postprandial state (left) and their power spectra density (right) estimated by AR model of order 120. From top to bottom: EGG from bipolar channel 1 (BIP1), 2 (BIP2), and 3 (BIP3), bipolar concentric channel 1 (BC1), 2 (BC2), and 3 (BC3), and respiration. Vertical black lines show the normogastric slow wave bandwidth boundaries (2-4 cpm).

Table 1 shows the mean and standard deviation of GSWA, S/I_{ECG} and S/I_{resp} of both conventional bipolar (BIP) and BC EGG recordings in fasting and postprandial states. The three postprandial to fasting power ratios are also shown in this table. Regardless of recording channel, bipolar recording amplitude was 2-3 times higher than that of BC EGG recordings, which was found to be statistically significant. There was generally wide variability in GSWA between subjects. The GSWA amplitude slightly increased with inter-electrode distance (BIP1<BIP2<BIP3), while no considerable difference was found between the three BC channels as the inter-electrode distances remained constant. In general, food ingestion increased GSWA, except for BC3 in which even slightly lower postprandial GSWA was obtained. Similar postprandial/fasting power ratio in 2-4 cpm was found for bipolar and BC EGG records, ranging from 1.1±0.9 to 1.9±0.6 for BC3 and BC2, respectively. With the exception of BC3, food ingestion also increased high frequency components between 30-60 cpm to a similar power ratio as that of 2-4 cpm, which was consistently found in both bipolar and BC recordings. These results cast doubt on the detectability of gastric activity in the BC3 recording. In the 30-90 cpm frequency band, this increasing trend after food was also found in BC1 and BC2 recordings, while no appreciable change occurred in the postprandial/fasting power ratio computed in 30-90 cpm in bipolar recordings. By contrast, BC3's postprandial power in this frequency band was even less than in the fasting state ($PR_{HF2}<1$ for BC3). In general, no significant difference between conventional bipolar and BC recording was found for the different postprandial/fasting power ratios, except for BC3 for which PR_{HF1} was significantly lower than that of those from BIP3. In bipolar recordings there was strong cardiac interference, giving rise to a relatively low S/I_{ECG} ratio (below 0 dB). This means that the ECG interference amplitude was even higher than GSWA, while BC EGG presented a significantly higher S/I_{ECG} ratio than that of bipolar EGG. Regardless of recording channel and electrode type, there was no noteworthy respiration interference in EGG recordings, obtaining S/I_{resp} ratios higher than 15 dB. No significant difference was found for this latter between conventional bipolar and BC recordings. Neither GSWA, S/I_{ECG} nor S/I_{resp} obtained significant difference between fasting and postprandial state.

Table 1. Mean and standard deviation of the GSWA, S/I_{ECG} and S/Iresp that quantify signal quality from bipolar recordings (BIP) and bipolar concentric recordings (BC) in fasting and postprandial states; and postprandial/fasting power ratios in the 2-4cpm frequency bands (PR_{LF}), 30-60cpm (PR_{HF1}), and 30-90cpm (PR_{HF2}). * showed a significant difference between conventional bipolar and BC recording (BIP1 vs. BC1, BIP2 vs. BC2, BIP3 vs. BC3), and o indicated the significant difference between fasting and postprandial state (only for GSWA, S/I_{ECG} and S/Iresp).

Channel	State	GSWA (μV)	S/I_{ECG} (dB)	S/I_{resp} (dB)	PR_{LF}	PR_{HF1}	PR_{HF2}
BIP1	Fasting	35.4±19.6 *	-5.5±5.5 *	17.4±7.8	1.5±1.0	1.5±0.5	1.0±0.2
	Postprandial	40.5±20.3 *	-4.0±4.4 *	16.7±6.0			
BIP2	Fasting	36.1±13.9 *	-4.4±4.7 *	17.4±8.1	1.7±0.9	1.5±0.6	1.0±0.3
	Postprandial	46.2±18.1 *	-2.2±3.8 *	16.6±5.8			
BIP3	Fasting	45.0±18.7 *	-5.7±4.9 *	17.8±7.0	1.3±0.3	1.5±0.6 *	1.1±0.3
	Postprandial	59.8±12.3 *	-2.4±3.9 *	16.5±6.3			
BC1	Fasting	15.4±8.8 *	1.8±5.5 *	17.1±8.2	1.7±1.0	1.9±1.3	1.5±1.3
	Postprandial	19.4±12.5 *	3.9±4.0 *	17.1±6.2			
BC2	Fasting	14.4±7.0 *	5.5±6.2 *	17.0±9.8	1.9±0.6	2.0±1.3	1.4±0.5

	Postprandial	19.8±9.9 *	7.7±4.3 *	15.1±9.5			
BC3	Fasting	15.8±10.7 *	10.0±6.7 *	16.3±5.3	1.1±0.9	0.8±0.4 *	0.7±0.4
	Postprandial	14.6±10.8 *	11.6±4.8 *	18.0±4.9			

Table 2 gives the parameters related to the identification of the gastric SW frequency and Figure 3 shows the SW frequency FIC and %SWC, which assesses its stability over time and spatial variability in fasting and postprandial states, respectively. In general, average DFAR values were around 2.70-2.80 cpm. DFAR did not show a clear trend in gastric SW frequency after food ingestion, i.e. BIP1 and BIP2 obtained somewhat lower values while other channels showed slightly higher postprandial values. Regardless of recording channel and electrode type, the %DFAR was higher than 96% and also had low variability, while DFAR showed a relatively high instability over time, with FIC ranging from 4.1 ± 1.5% to 13.33 ± 4.06% for BIP1 and BC3 respectively. In general, no significant differences were found for these gastric SW frequency parameters (DFAR, %DFAR, FIC_{DFAR}) between conventional bipolar and BC recordings, and between fasting and postprandial state, except that the DFAR of BC3 showed significant higher instability over time than those from BIP3 after food ingestion (see figure 3 : FIC_{BC3_DFAR}>FIC_{BIP3_DFAR}).
As for spatial stability, bipolar recordings obtained high SW frequency coupling between channels in both fasting and postprandial states and was the highest coupling obtained for BIP1 and BIP2. The SW frequency coupling estimated from DFAR between BC recordings dropped considerably, with a %SWC below 50% for both fasting and postprandial BC1-BC3 and BC2-BC3, being statistically significant between BIP and BC recordings in postprandial state (see figure 3).

Table 2. DFAR and DFCS for gastric SW frequency detection and the corresponding percentage time in which gastric SW frequency was detected. Decreased and increased gastric SW frequency after food ingestion is shaded in grey and green, respectively. * showed significant difference between conventional bipolar and BC recording (BIP1 vs. BC1, BIP2 vs. BC2, BIP3 vs. BC3), and o indicated the significant difference between fasting and postprandial state.

Channel	State	DFAR (cpm)	DFCS (cpm)	%DFAR	%DFCS
BIP1	Fasting	2.80±0.13	2.81±0.13	100.0 ± 0.0	94.9 ± 7.5
	Postprandial	2.78±0.19	2.83±0.17	99.4 ± 1.6	87.8 ± 19.7
BIP2	Fasting	2.82±0.12	2.82±0.15	100.0 ± 0.0	95.8 ± 3.9
	Postprandial	2.80±0.17	2.83±0.17	96.6 ± 6.7	89.7 ± 15.2
BIP3	Fasting	2.81±0.10	2.81±0.12	99.0 ± 1.8	91.2 ±10.4 *
	Postprandial	2.82±0.12	2.85±0.16	99.1 ± 1.6	87.8 ±14.5 *
BC1	Fasting	2.77±0.16	2.78±0.15	100.0 ± 0.0	96.5 ± 5.7
	Postprandial	2.78±0.16	2.82±0.18	99.1 ± 2.5	87.6 ± 19.0
BC2	Fasting	2.75±0.15	2.78±0.12	100.0 ± 0.0	82.8 ± 23.1
	Postprandial	2.82±0.19	2.80±0.23	97.9 ± 4.0	84.5 ± 20.2
BC3	Fasting	2.74±0.12	2.75±0.10	96.9 ± 4.8	61.1 ± 29.0 *
	Postprandial	2.77±0.16	2.82±0.23	96.4 ± 4.5	48.9 ± 23.7 *

DFCS showed similar values to those of DFAR, the average value being slightly higher. After food, a consistently increasing trend was found for gastric SW frequency regardless of recording channel and electrode type. In general, %DFCS was higher than 82% except for BC3, and was considerably lower than %DFAR. Whatever the recording channel, electrode type or recording condition (fasting or postprandial), DFCS showed less FIC (<4.5%) and higher %SWC (>76%) than that of DFAR (blue vs. green bar), suggesting that the gastric SW frequency identified by DFCS presented high temporal and spatial stability. Again, we did not find any significant differences for these parameters (DFCS, %DFCS, FIC_{DFCS}, $\%SWC_{DFCS}$) between conventional bipolar and BC recordings, and fasting and postprandial state, except that %DFCS of BIP3 was significantly higher than that of BC3.

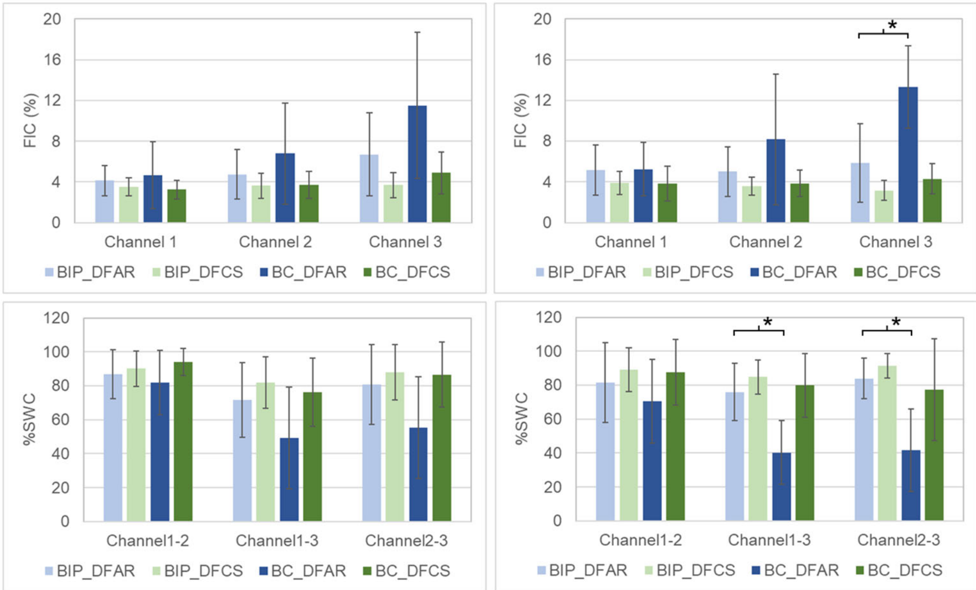

Figure 3. FIC (upper trace) and %SWC (lower trace) of gastric SW frequency that assess its stability over time and spatial variability in both fasting (left) and postprandial (right) states, respectively. * showed significant differences between conventional bipolar and BC recording (BIP1 vs. BC1, BIP2 vs. BC2, BIP3 vs. BC3), and ο indicated the significant difference between fasting and postprandial state.

Figure 4 shows the Bland and Altman plot of DFAR and DFCS between bipolar and BC EGG recordings. For both fasting and postprandial state the mean frequency difference between bipolar and BC recordings was less than 0.06 cpm. DFAR frequency difference seemed to be higher those of DFCS (left: difference of ±0.3 cpm for DFAR vs. right: ±0.2 com for DFCS). This result means that both types of recordings are equally valid for picking up gastric SW frequency components and DFCS even outperforms in detecting gastric SW frequency.

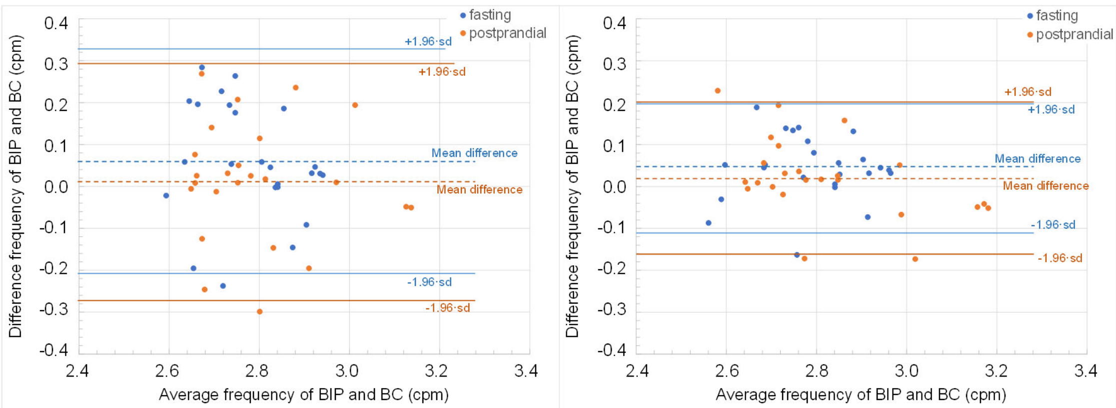

Figure 4. Bland and Altman plot of DFAR (left) and DFCS (right) between bipolar and BC EGG recordings in both fasting (blue dot) and postprandial (orange dot) states.

4. Discussion

Multichannel EGG recordings were used to map the abdominal surface and identify gastric disorders providing spatio-temporal patterns of gastric electrical activity [39]. Gharibans et al attempted to estimate the body surface Laplacian potential from multichannel recordings acquired from a high density electrode array using discrete methods to identify abnormal spatial gastric patterns related to gastric pathologies such as functional dyspepsia and gastroparesis [17]. CRE allows the direct estimation of the Laplacian potential on the abdominal surface instead of using monopolar electrodes and discretization techniques. There is no evidence for the feasibility of using CRE to pick up gastric activity in abdominal surface recordings. As far as we are aware, this is the first work to attempt this issue and also to determine their capacity to attenuate physiological interference such as ECG.

We found that the amplitude of the bipolar EGG was of an order of magnitude of tens or hundreds of microvolts, which is within the range of values reported in the literature [7][40]. In contrast, BC EGG amplitude was two or three times less than in bipolar recordings, which agrees with other authors who used CRE to record other bioelectric signals [41][42]. This could be mainly due to the relatively short distance between its recording electrodes. The postprandial/fasting power ratio in 2-4 cpm obtained for BCs was similar to that obtained in bipolar recordings [8] [35]. It has been hypothesized that this amplitude increase could be related to the stomach being closer to the surface [9] and/or due to increased gastric contractilty after ingesting food.

A regularly increasing trend was found for postprandial/fasting power ratio in 30-60 cpm for both bipolar and BC EGG except for BC3, whose value was similar to the PR_{LF}. However, when the signal power in 30-90 cpm was analysed, a similar trend and value was obtained for BC but not for bipolar recordings. This could have been due to the strong cardiac interference (around 60-70 cpm) embedded in bipolar recordings, which can mask the power increase after ingesting food. This confirms that most of the energy above 60 cpm in surface EGG recordings is associated with cardiac interference, which was hypothesized when defining the S/I_{ECG} parameter in the present work. As expected, the closer the recording channels (channels 1 and 2) to the heart, the lower the S/I_{ECG} ratio obtained. This problem was partially mitigated by BC EGG, which provided a relatively higher S/I_{ECG} ratio because of its ability to reject distant bioelectric dipole sources. These high frequency components with a postprandial increase could be related to gastric contractile activity, which has been shown to range from 50 to 80 cpm [37][43]. However, they could also be attributed to gastric SW activity harmonics in high frequency components since the postprandial/ fasting power ratio in both low and high frequency ranges was similar. Futher studies are still needed to determine the origin of these components and the feasibility of detecting gastric spike bursts in suface EGG recordings. In this regard, the analysis of the interdigestive migrating motor complex pattern in fasting combined with the CRE's ability to reject distance dipoles such as cardiac interference could be helpful in clarifying this issue. As regards respiratory interference, both bipolar and BC recordings yielded similar S/I_{resp} ratios in fasting and fed stages. This finding agrees with previous studies on intestinal myoelectric signals recorded by CRE and may be due to the fact that respiration interference is of mechanical and non-bioelectrical origin [27][44].

Gastric SW frequency is undoubtedly one of the most relevant characteristics of EGG recordings. Due to physiological interference from different origins, its identification in surface EGG recordings remains a challenge and is one of the main obstacles in transferring the EGG technique to clinical practice. Gastric SW frequency has traditionally been identified as the dominant frequency of the filtered EGG signal in the target bandwidth (similar to the DFAR parameter). Other authors have proposed using empirical mode decomposition to detect the instantaneous frequency of the intrinsic mode functions [15][45][40]. In this study, we proposed to use the dominant frequency in the multichannel EGG recordings' cross-spectrum (DFCS) for robust assessment of high spatial stability components, which has previously been used to detect SW uncoupling in multichannel EGG in dogs (surface and serosal) and humans (surface) [46]. Firstly, both DFAR and DFCS were around 2.70-2.80 cpm, which were within the range of normal values for this component [47][48]. In bipolar recordings, both %DFAR (>96%), their corresponding FIC (<15%) and %SWC (>80%) were within the range of values reported by other authors [30] [49] [50] (%DFAR ~95%, FIC 17-38% and %SWC~80%). The slight difference could be attributed to the subject's position during recording. According to Jonderko et al, the gastric SW frequency's FIC values obtained in a reclining position were lower than when the subject was sitting during the recordings [49]. In comparison to DFAR, slightly higher values were obtained for DFCS (see Table 2). This result may suggest the presence of some frequency peaks around 2 cpm with a higher amplitude than the gastric SW, which could be from the very low frequency components' harmonics from fluctuating skin-electrode contact potential. The %DFCS was thus slightly lower than that of %DFAR. Even so, except for BC3, both %DFAR and %DFCS were higher than 70%, which was set as the normal percentage of gastric SW in abdominal surface recordings based on empirical studies in healthy subjects [11], suggesting the detectability of the gastric SW frequency for both bipolar and BC recordings. In addition, the gastric SW frequency identified by the cross spectrum method provided high temporal and spatial stability, giving rise to relatively lower FIC (DFCS<6% vs. DFAR<15%) and higher %SWC. We also found that gastric SW frequency slightly increased after food ingestion, which was consistent with a previous study that found that SW frequency slightly increased after ingesting solid food [51]. Solid food with up to 400 kcal and less than 50% fat increases both the amplitude and frequency of gastric slow waves in healthy subjects [33].

To sum up, our results suggest the feasibility of picking up gastric myoelectric activity from CRE. In comparison to conventional bipolar recordings, the gastric SW frequency identified in BC recordings was similar, while BC EGG was less influenced by cardiac interference. However, CRE's ability to pick up gastric myoelectric activity was highly influenced by the electrode position. Firstly, no postprandial response was obtained for BC3 (see Table 1: GSWA and postprandial/ fasting ratio). Although the dominant frequency DFCS for both fasting and postprandial states was similar in the three BC recordings, the %DFCS of the BC3 was considerably lower than those of BC1 and BC2. As can be seen in Figure 1, CRE1 and CRE2 were both placed over the stomach, while CRE3 was further away. Our electrode positions were partly influenced by the lack of standard electrode positions on the abdomen for EGG recording. Most studies have been conducted with the electrodes aligned horizontally below the left costal margin and between the xyphoid process and the navel, with a reference electrode in the right upper abdomen quadrant [7][11]. The placement of the electrodes was slightly different in this work since the EGG recordings were carried out with the subject lying in the supine position, while in many other studies they were picked up with the volunteers seated. The position of the stomach is lower when sitting than lying down, which was why an arrangement was proposed following the anatomical situation of the stomach in that position. Our findings agree with theoretical studies of the two-dimensional spatial transfer function, which showed that CRE are more sensitive to

vertical dipole sources just below the electrode, the sensitivity of these electrodes being much lower than bipolar recordings for distant dipoles [52][53]. To precisely estimate gastric slow wave propagation from body surface Laplacian potentials it is necessary to properly position the CRE array just above the stomach. Depending on the position of the body and the amount of food it contains, the stomach is capable of altering its size and shape, an empty stomach being about 30 cm long and 15 cm across at its widest point. We should reconsider the CRE dimension for estimating body surface Laplacian potentials to achieve a trade-off between the number of CRE that can be positioned above the stomach and gastric myoelectrical activity detectability. Previous studies have pointed out that the external diameter of the electrode must be similar to the distance between the surface recording point and the signal source [54]. Other works have claimed that the diameter of the outer ring should be, at the most, half the size of the organ being studied [55]. Furthermore, the CRE chosen in the present work (7 mm between inner disk and external ring) met Garibans' requirements regarding a maximum edge-to-edge distance of 12.5 mm [10] to study the gastric SW propagation.
The present work is not without certain limitations, such as the small number of patients in its database and the possible bias associated with age and the body mass index, which is intended to be remedied in future work. In addition, in this work we did not carry out the gastric slow wave propagation speed from signals picked up by concentric ring electrodes. Further studies are needed to determine the gastric SW propagation speed from body surface Laplacian mapping using a high density CRE array in both healthy subjects and patients with gastric disorders such as mechanical and idiopathic gastroparesis [56]; tachygastria and delayed gastric emptying or studying the origin of nausea and vomiting, especially in pregnant women [57].

5. Conclusions

The experimental results revealed that DFCS from multichannel recordings can robustly estimate the gastric SW frequency of EGG recordings with high temporal and spatial stability, obtaining thereby a steadily rising trend in gastric SW frequency after ingesting food. In addition, we checked the feasibility of using CRE to detect gastric SW activity, obtaining a similar gastric SW frequency in simultaneous bipolar and BC EGG recording in both fasting and postprandial states and also a similar postprandial/fasting power ratio. In comparison to bipolar recordings, the gastric SW activity acquired by CRE was of significantly lower amplitude and less influenced by cardiac interference, obtaining a significantly higher S/I_{ECG} ratio. These results could be very helpful for the non-invasive detection of gastric spike burst. Unlike conventional disk electrodes, CRE's gastric activity detectability is highly influenced by the relative positions of the electrode and the stomach due to its enhanced spatial resolution. This property also minimizes the blurring effect of the volume conductor and could be used for more precisely estimating the gastric slow wave propagation speed from surface Laplacian potential mapping.

Acknowledgments

Research supported by a grant from the Spanish Ministry of Economy and Competitiveness, the European Regional Development Fund (MCIU/AEI/FEDER, UE RTI2018-094449-A-I00-AR)

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