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Signal Noise Ratio of Small Intestine Myoelectrical Signal Recorded from External Surface

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Abstract— **Electroenterogram (EEnG), which is the myoelectrical activity of the small bowel, can be non-invasively recorded from abdominal external surface. However, this bioelectrical signal is weak and noisy compared to internal recording from bowel serous layers, because of bioelectric transmission through abdominal layers. Furthermore, it is contaminated with several interferences from other biological activities as cardiac muscle (ECG), skeletal muscles (EMG), or respiration movements. The goal of present work is to study abdominal recording of EEnG and its signal-to-noise ratio by means of the coherence estimation technique. External and internal recordings were obtained simultaneously in 12 sessions, which went on more than two hours in six beagle dogs. Coherence function, based on periodograms, is estimated in periods of 15 minutes. Thus, SNR is calculated from coherence estimation for each recording session. Results show that SNR reaches a maximum value of 8.8 dB for 0.31 Hz, which corresponds to fundamental frequency of the EEnG slow wave. However, SNR is weak at frequencies upper 2 Hz, which corresponds to rapid action potentials (spike bursts) of the EEnG. In conclusion, slow wave can be clearly identified in abdominal recording; however spike bursts are contaminated by noise, attenuation and biological interferences.**

I. INTRODUCTION

Gastroenterologists need to asses the mechanical activity of the small bowel (intestinal motility), since it is directly associated to the process of digestion [1]. However, the complicated access to this portion of the digestive tract has made difficult the development of clinically contrasted techniques for recording such activity. The most direct approach to monitor bowel mechanical activity is to record bowel pressure by means of intraluminal probes. This technique is widely employed since it does not require surgery intervention. However, considerable controversy exists about this approach, due to its inherent physiological and technical problems [2].

Mechanical activity of the intestine muscles is caused by a myogenic control; therefore an alternative option is represented by the recording of myoelectrical activity. Upper trace in Fig. 1 shows 60 seconds of myoelectrical signal recorded with bipolar electrodes implanted on the small bowel serous layer. This biosignal is named electroenterogram (EEnG) and it is widely accepted its relation with intestinal mechanical contractions [1], [3].

The electroenterogram has two components (upper trace in Fig. 1): a slow wave (SW) which is permanently present and regulates contraction rates, and the spike bursts (SB), which are only generated when the smooth muscle cells contract. In Fig. 1, it can be observed that there are 16 SWs in 60 seconds. But they do not imply intestinal contractions. However, last four SW plateaus are accompanied by SBs, which entail bowel contractions. The SB quantification can be used as an intestinal motility index [1], [3]. It is important to know that spectral studies of SW and SB reveal evident differences between them (as their names indicate); since SW energy is concentrated below 2 Hz and SB above 2 Hz [3], [4]. Therefore, if SB quantification is required, spectral studies are more suitable than temporal analysis.

However, recording of the electroenterogram requires surgery - this being an inconvenience for clinical application of the technique. The solution to this problem would be to record the myoelectrical signal from the external abdominal surface (lower trace in Fig. 1). Then, the problem is that external signal is weak and noisy. Furthermore, biological interferences as respiration movements, EMG or ECG restrain the clinical application of this technique [4], [5].

The aim of the present study is to interpret the surface EEnG. For it, signal-to-noise ratio (SNR) is estimated from coherence function.

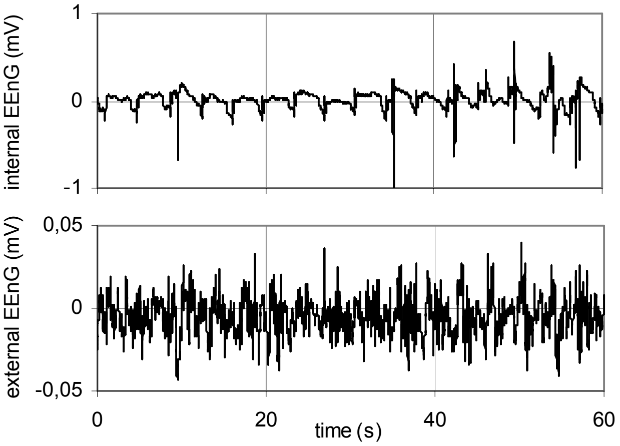

Fig. 1. Electroenterogram (EEnG) simultaneously recorded from internal serous-implanted electrodes (upper trace) and external bipolar electrodes (lower trace). ECG interference was removed from external abdominal recording (lower trace) through adaptive filtering.

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II. MATERIAL AND METHODS

A. Subjects and recordings

Six Beagle dogs were subjected to surgery to implant a bipolar electrode at jejunal level [3] (located at 70 centimeters from the Treitz angle). The intestinal ring at this measurement point was affixed to the internal surface of the abdominal wall, close to the navel, to be used as internal discrete-signal reference (i[n]) for the surface recording. The external discrete-signal (e[n]) was recorded by two Ag-AgCl monopolar electrodes with an inter-electrode distance of 2 cm, and positioned on the abdominal skin in the area over internal reference electrode affixed [4].

Twelve recording sessions were carried out, involving the acquisition of one interdigestive migrating myoelectric complex (IMMC). Each session implied the recording of more than 110 min. of both signals, internal (i[n]) and external (e[n]).

B. Amplifiers and acquisition

The signals were amplified with a bandwidth of [0.05 Hz, 35 Hz]. The sampling frequency was 100 Hz. Following acquisition, external signals were preprocessed.

C. Estimated coherence function

Analysis was limited to phase II of the IMMC, which is characterized by a moderate and irregular intestinal contraction; i.e., the internally recorded electroenterogram consisted of SW and some SB. Fifteen minutes for each session were used in order to calculate the coherence function between both signals as [6]:

$$CF(f) = \frac{\left|G_{ie}(f)\right|^2}{G_{ii}(f) \cdot G_{ee}(f)} \tag{1}$$

where $G_{ie}(f)$ is the estimated one-sided cross-spectral density function, and $G_{ii}(f)$ $G_{ee}(f)$ are the estimated one-sided auto-spectral density functions. Fig. 2 (upper and middle traces) shows the estimated auto-spectral density functions calculated from unmodified periodogram with 59 segments 50% overlapped; i.e. 30 independent windows of 30 seconds.

Normalized error of the coherence function depends on the coherence value for each frequency [6]. Exactly, the maximum value in Fig.2 (lower trace) is CF=0.79 at 0.3 Hz, which coincides with SW frequency, and normalized error value is 0.06, which can be accepted [6]. The frequency resolution is Δf=0.033 Hz, that is 2 cycles per minute.

D. Signal noise ratio (SNR)

The block diagram of the system considered for calculating SNR is shown in Fig. 3. Discrete signals acquired are internal (i[n]) and external (e[n]). But the external signal is contaminated by noise and other biological phenomena, as for example the breathing movements or the electromyogram of the abdominal skeletal muscles. If noise (n[n]) and abdominal signal (s[n]) are un-correlated, signal noise ratio can be calculated as:

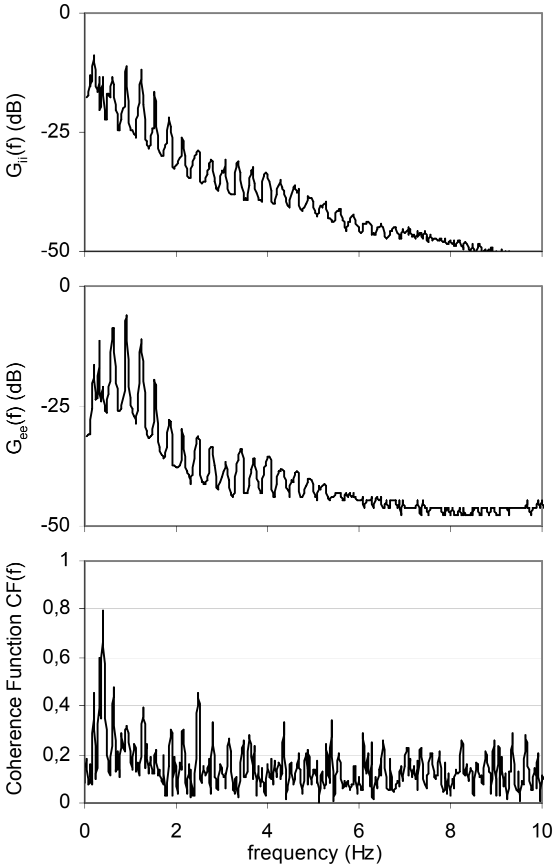

Fig. 2. Estimate of one-sided and normalized auto spectral density from 20 minutes electroenterogram (EEnG) simultaneously recorded from internal serous implanted electrodes (upper trace) and external bipolar electrodes (middle trace). Coherence function (CF) estimated from internal and external recordings (lower trace).

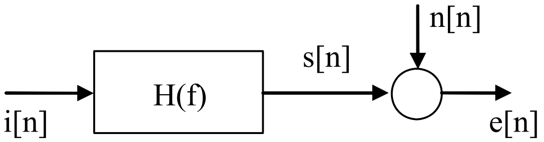

Fig. 3. Block diagram of the system considered in order to calculate signal-to-noise ratio (SNR), where i[n] and e[n] are the acquired signals from internal and external recordings respectively. Noise is n[n] and the objective signal for present study is s[n].

$$SNR(f) = \frac{G_{ss}(f)}{G_{nn}(f)} = \frac{CF(f)^2}{1 - CF(f)^2} \tag{2}$$

where coherence function CF(f) is estimated from (1).

III. RESULTS

Black traces in Fig. 4 are the one-sided auto spectral densities estimated ($G_{ee}(f)$) for external signal (e[n]). Vertical axis is in logarithmic scale, and frequency axis has been divided in two ranges clearly defined: low frequencies (upper traces) which approximately correspond to slow wave frequency band of the EEnG; and higher frequencies (lower traces) which correspond to spike bursts energy of the EEnG.

Grey traces in Fig. 4 are the one-sided auto spectral densities ($G_{ss}(f)$) of the abdominal signal without noise, which has been named (s[n]) in the model proposed (Fig. 3). Results are presented from one recording session, but similar results were obtained from each one of the twelve sessions.

$G_{ss}(f)$ is the power spectra object of the present study because hypothesis assumes that there is not any noise or interference on it. It is possible to observe that maximum peak coincides with SW frequency of the EEnG; i.e., 0.31 Hz (18.6 cycles per minute). But at high frequencies (lower traces) power density is smaller than at SW frequencies. In this case, noise reduction seems to be constant versus irregular noise decrease observed in upper traces.

Coherence functions were estimated from internal and external recording signals, based on periodogram techniques. Similar functions were obtained for each session, although only one session is shown (upper trace of Fig. 5). The peak value at 0.31 Hz corresponds to CF=0.88, which implies that SW recorded from abdominal wall is highly related with internal SW.

Signal-to-noise ratio derived from (2) is shown in Fig. 5 (lower trace). The peak value is 5.8 dB at SW frequency of the EEnG. It means that SW is the strongest part of the EEnG that can be observed in surface external recording. However SNR at SB frequency range are very poor, with values below zero, which implies that the noise and the interferences in these frequency ranges are stronger than the desired signal.

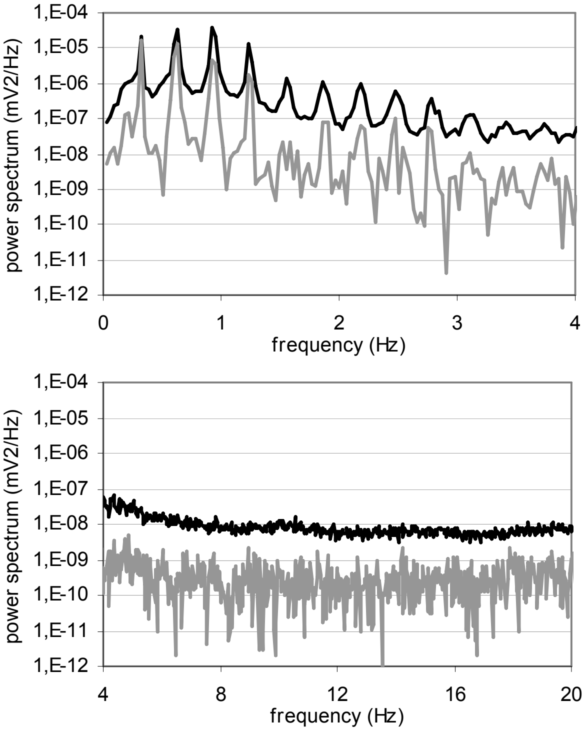

Fig. 4. Estimated power spectra comparison between acquired signal, $G_{ee}(f)$ (black traces), and extracted surface signal $G_{ss}(f)$ (grey traces). Frequency axis is divided in SW band (upper traces) and SB band (lower traces).

Table I is a summary of the parameters obtained from each of the twelve recording sessions. First column persents the peak value obtained from SNR function. There is no difference between sessions and dogs. It is important to point out that these maximum values always correspond to frequencies lower than 1 Hz; precisely most of them are 0.31 Hz (second column in table I). Only in two sessions the maximum value is round 0.6 Hz, which is the first harmonic frequency of the fundamental 0.3 Hz, when noise reduction has been insufficient (see upper traces in Fig. 4). Third column is the average SNR from 1 Hz to 20 Hz, which are the SB frequencies range. These values are almost constant and very low, with a mean of 0.27. It means that noise is about 4 times stronger than abdominal intestinal origin.

IV. DISCUSSION

The myoelectrical signal recorded at small bowel serous layer was used as reference to evaluate the possibility of

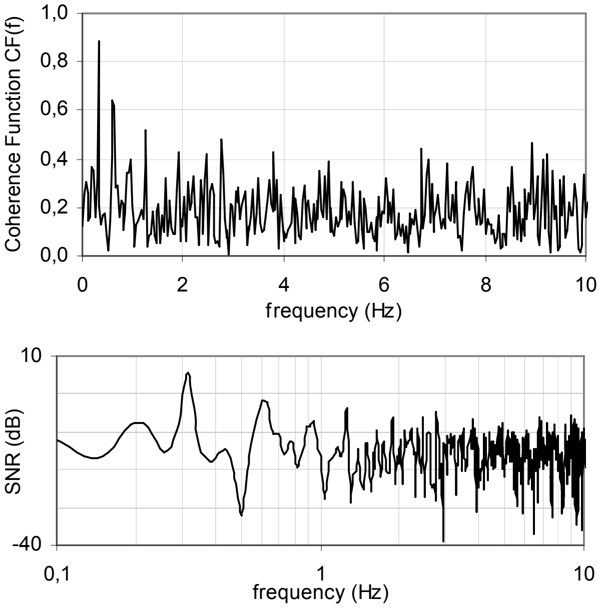

Fig. 5. Coherence function estimated for internal (i[n]) and external (e[n]) signals (upper trace). Signal-to-noise ratio, calculated from the preceding coherence function (lower trace).

TABLE I

PARAMETERS CALCULTED FROM SNR FUNCTIONS (N=12)

Session	SNR Peak (dB)	Frequency (Hz)	SNR 1 to 20 Hz
A1	3.1	0.31	0.30
A2	0.6	0.58	0.29
A3	8.8	0.31	0.25
A4	5.8	0.31	0.28
A5	7.4	0.31	0.23
B1	6.3	0.58	0.22
C1	4.5	0.29	0.30
D1	2.5	0.31	0.27
E1	4.2	0.29	0.29
F1	4.5	0.27	0.25
F2	0.6	0.27	0.34
F3	3.5	0.31	0.23
Mean ± SD	4.3 ± 2.5	0.35 ± 0.11	0.27 ± 0.03

recording the corresponding signal from the external abdominal surface. The mean SNR obtained is 4.3 ± 2.5 dB (Table I), and it indicates the strong presence of the SW, whose frequency in dogs is located in the range of 15 to 20 cycles per minute. This supports the opinion of other authors that small bowel myoelectrical activity can be recorded from the surface of the abdomen [4], [5], [7], [8].

However, SNR at SB frequencies, over 2 Hz, is poorer than SNR at low frequencies, even lower than zero. This result is in disagreement with some works, which obtained SNR by means of spectral techniques [4]. These studies could be more accurate, because they defined the noise and the signal from the external signal power spectra. They assumed that SW energy is constant and therefore, SB signal could be calculated as the difference between periods of maximum contraction and periods of no-contraction. However, present study does not need to make any assumption about signal pattern. Other possible reason for differences is that they do not assume that abdominal layers act as a linear system, what it is a more realistic model [9].

Another important effect to be considered is the non-stationary nature of the signal [10]. Fig. 6 represents the coherence function at low frequencies, calculated from 15 minutes of internal and external signal. It is possible to see the maximum value at 0.4 Hz, but near there is another peak value around 0.3 Hz. The second highest point is known to be the EEnG slow wave, but first peak must be interpreted. It can not be due to the breathing movements, although respiration is more than 20 cycles per minute, because this interference does not appear to internal signal and the proposed model assesses the relation between internal and external signals. It is more reasonable that SW variations have influence on coherence function and thus in SNR function, because of EEnG is a non-stationary signal [10].

Perhaps a higher-order spectral analysis could be more accurate in order to detect the frequency peak in table I. In any case, the energy of the slow wave of the internal recording was concentrated below 2 Hz [4], [5], and at this frequency range the SNR yielded greater values than in frequencies above 2 Hz. This means that the correlation between the internal and external signals is due to the intestinal slow wave. This observation coincides with other studies involving the non-invasive detection of myoelectrical activity, which have focused only on the SW [7], [8].

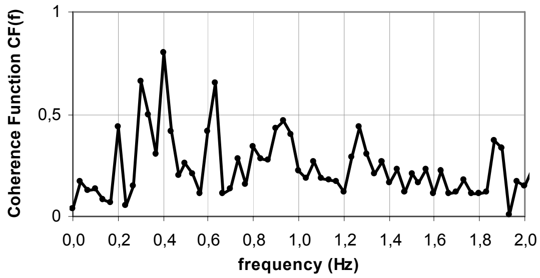

Fig. 6. Coherence function estimated for 15 minutes of internal (i[n]) and external (e[n]) signals.

Present study has been carried out for irregular mechanical activity periods of the small bowel. In this case, omnipresent SWs are accompanied by intermittent superimposed SB activity. But throughout a session recording, small bowel goes from quiescence to maximum activity. We observed differences between both states in signal noise ratio, which are not shown in present work; but these differences reassert the non-stationary nature of the electroenterogram.

V. CONCLUSION

Abdominal recording of the EEnG could be a useful non-invasive tool to assess the small bowel activity. Slow wave energy of the EEnG, which is omnipresent in internal signal, is strongly reflected in abdominal external acquisition. However, the frequency range for spike bursts activity is contaminated with noise and other biological interference; therefore, several filter techniques must be carried out.

Signal-to-noise ratio calculated from the estimated coherence function could be an important tool in order to know better the possible origins of the noise and the contamination of the electroenterogram. It could be even possible to remove this noise if linear model is applicable.

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