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Characterization of the Sensitivity of a TCB Laplacian sensor for surface EEnG recordings

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Abstract— **The improvement of the quality of electroenterogram (EEnG) recordings on abdominal surface could lead to a non-invasive technique to diagnose intestinal motility dysfunctions. In this context, the use of coaxial active electrodes, which permit to record the laplacian potential, can help to achieve such signal enhancement. In this paper, we present a methodology to obtain the maps of sensitivity of this kind of electrodes to pick up the activity of electric dipoles of different orientations. The proposed methodology employs mathematical models, as well as experimental studies (phantoms) to check the theoretical results. The mathematical model of the electrode, and of the human abdomen is developed by means of ANSYS ®. A simplified physical model is formed by real ring electrodes, a methacrylate tank of size 50 × 50 × 50 cm filled with a saltwater mixture of 2.5 g/l concentration, and moving electric dipoles made by wires of 0.3 mm in diameter. Sensitivity of the sensor is obtained for different depths and different axial distances of vertical and horizontal dipoles. Preliminary results of tripolar ring electrodes in bipolar configuration (TCB) are shown. The obtained results prove the agreement between mathematical and experimental results. The validated model will allow us to study the behavior of laplacian ring electrodes of different dimensions and materials to record the EEnG activity and to analyze the influence of the abdominal layers.**

I. Introduction

PATHOLOGIES of the gastrointestinal tract such as irritable bowel syndrome, paralytic ileum or intestinal obstruction involve intestinal motility dysfunctions. These pathologies are difficult to diagnose with currently available techniques. On the other hand, the intestinal motility is directly related to the myoelectrical activity of the small bowel, which is called electroenterogram (EEnG). Therefore, the recording of EEnG on the abdominal surface could become a technique that would permit to diagnose intestinal pathologies non-invasively.

The EEnG is composed of a basic electric rhythm, also called slow wave (SW), and spike bursts (SB). The SW is a pacemaker activity that is always present. Its frequency is 8-12 cpm in humans. Meanwhile, SBs are fast action potentials, which only appear in the slow-wave plateau when the small intestine contracts, indicating the presence and intensity of intestinal contraction. The main difficulties of surface EEnG recordings are: the very low amplitude of the signal, about tens of μV; and the fact that the power spectrum of its components (SW and SB) are close, even overlapped, to the spectrum of its main interferences such as respiration (12 -24 cpm) and ECG (0.5-100 Hz) [1].

With the aim of improving the quality of conventional bipolar surface recordings of the EEnG, our research group is working on the use of techniques that permit to estimate the laplacian potential on abdominal surface. Since the laplacian of the surface potential is negatively proportional to the two dimensional divergence of the tangential components of the current density at the body surface, and it is proportional to the normal derivative of the normal component [2], theoretically, the laplacian of the external EEnG recording should pick up the intestinal activity under the abdomen, rejecting bioelectrical interferences which propagate tangentially. Preliminary results of the estimation of the laplacian of EEnG by means of the 5 points method [3] and by TCB concentric ring electrodes [4] have proved to diminish the effect of breathing and to highly attenuate the ECG interference. Nevertheless, on one hand the 5 points method requires large recording areas, which imply a loss in spatial resolution. On the other hand, by means of ring electrodes better spatial resolution can be achieved by reducing the diameter of the rings. However, the smaller the dimensions of the electrode, the lower the amplitude of the recorded signal. Therefore, there is a trade-off between spatial resolution and signal amplitude.

The aim of this work is to develop a tool which permits to asses the sensitivity of TCB coaxial ring electrodes to pick up the activity of an electric dipole with different orientations and positions, in order to know the influence of the parameters of the electrodes so as to optimize them for the recording of the EEnG on the abdominal surface.

The best way to study the influence of the different parameters involved in the design of coaxial ring electrodes such as its dimensions would be to have the analytic equations that rule its behavior. However, the fact of dealing with mixed boundary conditions extremely complicates this solution. Therefore, we have decided to use numerical models that, by means of finite elements methods, allow to easily obtaining the sensitivity of the electrode with different geometrical parameters of the electrode itself, and the

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characteristics of the abdominal layers and of the dipoles. Nevertheless, this mathematical model needs to be validated by an experimental model in order to have reliable results and conclusions.

II. Material and Methods

A. Mathematical Model

In this work, the human abdomen is considered to be formed of, from outer to inner, the following layers: 1) skin, 2) fat, 3) muscle, 4) omentum and 5) abdominal cavity. Each of these layers is considered to be an homogeneous and isotropic medium of a conductivity σ_i (i=1..5) and a thickness e_i (i=1..5), see figure 1. The conductivity of each layer can be easily changed before solving the model, so the effect of this parameter on the map of sensitivities could be studied. As a first step, preliminary results are obtained for $\sigma_1=\sigma_2=\sigma_3=\sigma_4=\sigma_5=0.45$ S/m. In order to exploit the axial symmetry in the solution of the model, the abdominal space is modeled to be a cylinder, coaxial to the laplacian TCB electrode, of 30 cm in radius and 30 cm in length. The electrode is modeled by 3 concentric cylinders of the dimensions to be tested, and of a conductivity $\sigma_e=10^5$ S/m. The inner disc and the outer ring are shortcut (TCB configuration) by means of a disc of conductivity σ_e and 2 mm of height, being the radius dependent on the ring dimensions. See figure 1.

To calculate the sensitivity map of the laplacian electrode to record the activity generated by an electric dipole, the lead field is assessed as the current density in the abdominal space generated by the injection of a unitary current between the poles of the laplacian electrode [5]. The calculus of the current density is restricted to a region of interest (ROI) far enough from the bounds of the model, so as to be able to consider the model semi-infinite. The ROI is set to be a cylinder of 10 cm in radius and 10 cm in length, coaxial with the rest of the model, being its nearest plane at 3.5 cm from the electrode. See figure 1.

The calculus of the lead field in the ROI is obtained as a result of solving the model by means of finite elements (Ansys ®). In order to do so, it is taken advantage from the axial symmetry of the model, which reduces it to a bidimensional problem. Square elements of 0.5 mm are used to create a uniform meshing in the ROI. Then, triangular elements are used for the rest of the model, up to a total of 107747 elements. Once the model is solved for the injection of a unitary current through the poles of the laplacian electrode, the vectorial components of the current density at each node of the ROI are extracted. Finally, as a consequence of the reciprocal principle, the projection of the current density vector at each node of the ROI on the direction of the electric dipole to be studied, provides the distribution of the laplacian electrode sensitivity to pick up the activity of the dipole orientated in that direction.

To check the influence of the finite size of the model on the sensitivity at the ROI, the external radius of the cylinder and the thickness of the abdominal layer were doubled and the model was re-messed and solved again.

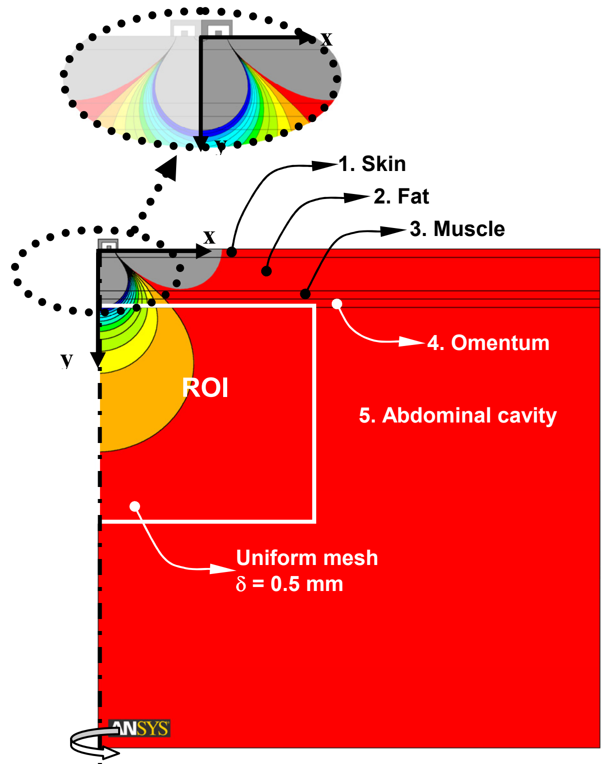

Fig. 1. Mathematical model. Isopotential curves considering e_1=0.5 cm, e_2=2 cm, e_3=0.5 cm, e_4=0.5 cm, e_5=26.5 cm, $\sigma_1=\sigma_2=\sigma_3=\sigma_4=\sigma_5=0.45$ S/m.

B. Experimental Model

The experimental validation of the mathematical model is performed by a *phantom*, see figure 2. The experimental model of the abdominal space consists on a tank of similar dimensions to the mathematical model. Precisely, a methacrylate tank of size 50×50×50 cm is used. This tank should be filled by layers of material of the same conductivity and thickness as the ones mathematically modeled. In a first approximation, so as to simplify the model, the same conductivity is considered for all the layers: $\sigma_1=\sigma_2=\sigma_3=\sigma_4=\sigma_5=0.45$ S/m. This is achieved by filling the tank with unionized water at 25ºC with a 2.5 g/l concentration of NaCl. In future work, layers 1 to 4 are planned to be made of hydrogels based in Agar [6], whose conductivity can be determined by the proper concentration of salts and acids such as H_2SO_4.

The electrode to be tested is placed in the centre of the tank's base (plane x-z), see figure 2. In order to calculate the sensitivity of the electrode to electric dipoles of different orientation, it will be obtained the response to 2 dipoles: one with x-axis orientation (horizontal) and the other one with y-axis orientation (vertical). There is no need of using a dipole with z-axis orientation since for the points in the radial axis of cylinder the axial symmetry of the model can be considered. Enamelled wires of 0.3 mm in diameter are used to generate the dipoles. The ends of the wires are orientated in the above mentioned directions, see figure 3. The wires of this diameter are rigid enough to maintain their orientation, whereas their section is small enough to neglect their influence on the model. The wires are guided through a glass tube of 75 mm in length, 4 mm and 2 mm in outer and inner diameter respectively. With the aim of obtaining a map of sensitivities, the dipoles were moved along the y axis varying the depth of the glass tube and along the x axis by displacing a platform that lies on the top of the tank and holds the tube.

For each position of the dipoles, an excitation current is injected through the horizontal dipole and subsequently through the vertical dipole. In order to control this current, a transconductance amplifier is used. A sinusoidal current of 1 mA_{pp} and 100 Hz proved to show a linear behaviour of the dipole, avoiding the influence of the electrode-electrolyte interface and generating a sinusoidal electric field in the medium. For every position and orientation of the dipoles, voltage in the electrodes is amplified and the amplitude and phase is measured. Synchronized averaging is performed to reduce background noise. Finally the sensitivity is obtained as the ratio between the electrode's voltage and the injected current through the dipoles.

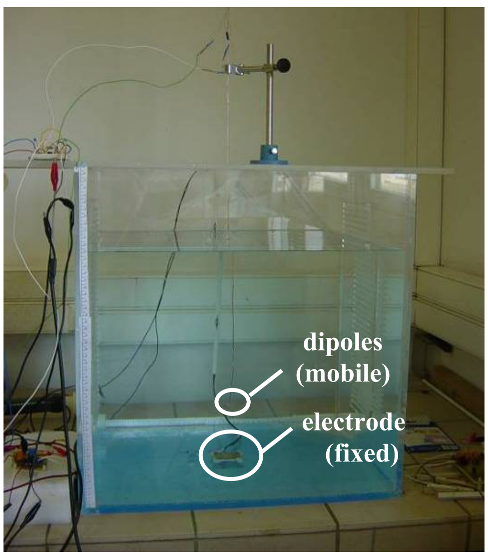

Fig. 2 .Photograph of the *phantom* of the mathematical model considering the same conductivity for all abdominal layers.

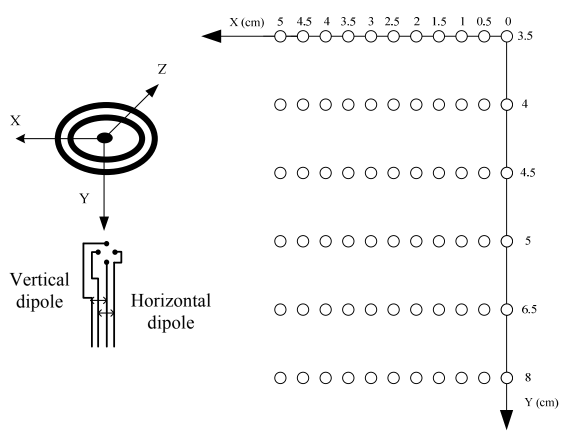

Fig. 3 Configuration of the electric dipoles (left), and dipoles' positions tested in the study (right)

III. Results

The node to node comparison between the sensitivity value at ROIs of the model and of the double-sized model revealed a maximum and mean difference of 1.5% and 0.3% respectively, which suggests no influence on our results of the model boundaries.

Figure 4 shows the sensitivity of a TCB concentric ring electrode of 24 mm in outer diameter to pick up the activity generated by horizontal and vertical dipoles in different X positions with a constant depth of 35 mm. Considering the thickness of the modeled abdominal layers, this position is the closest an electric dipole of intestinal origin can be from the external abdominal surface. As expected, the results show that the laplacian electrode rejects the activity from tangential sources (horizontal dipole), and presents higher sensitivities to normal sources (vertical dipole). This fact confirms the potential capability of laplacian electrodes to reduce ECG interference, which mainly propagates tangentially to the body surface, and to pick up intestinal activity on abdominal surface recordings. This figure also reveals the very close agreement between the results obtained from the mathematical and from the experimental model. Therefore, it can be stated that, under these conditions, the mathematical model is correct.

Still, it should be mentioned that differences between mathematical and experimental results exist, and they are greater for the horizontal dipole. Specifically, it can be seen that the experimental sensitivity at X=0 mm is not zero for the experimental model, although theoretically and according to the mathematical model it should. This could be due to: possible misalignments of the axis of the horizontal dipole and the electrode plane, errors in the settlement of the origin of the X axis, and in a greater extent due to the presence of a remaining common-mode voltage that could not be cancelled completely by the signal instrumentation. The effect of these possible errors is more evident when the sensitivity of the electrode is low and hence the voltage in the electrode is of very low amplitude.

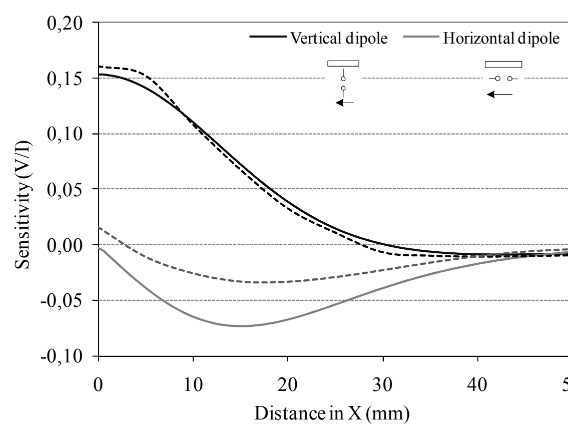

Fig. 4 Sensitivity of the TCB electrode to vertical dipoles (black) and horizontal dipoles (grey) derived from the mathematical model (solid lines) and from the experimental model (dashed lines) versus X displacements. Depth Y=35 mm

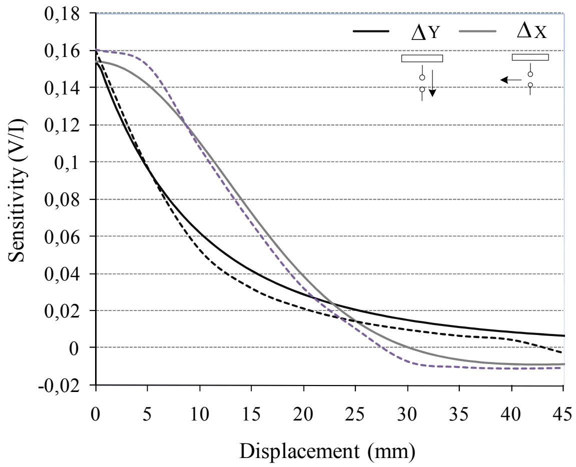

Fig. 5 Sensitivity of the TCB electrode to vertical dipoles derived from the mathematical model (solid lines) and from the experimental model (dashed lines) versus X (black) and Y (grey) displacements. Initial position X=0 mm, Y=35 mm

Figure 5 shows the influence of vertical and horizontal displacements on the sensitivity to pick up the activity of a vertical dipole. It can be observed that for short displacements from the initial position, the sensitivity to horizontal displacements decays smoothly, whereas the gradient of the sensitivity is much higher for vertical displacements. This means that, in order to pick up the activity of the exciting dipole, it is more important the depth of the dipole than a possible misalignment respect to the axis of the ring electrode. Therefore, the laplacian electrode would record the activity of smooth muscle cells from intestinal segments that are close to internal abdominal wall, but the activity of those located deeper would be severely attenuated. Future work will focus on the effect of the rings' diameters and separation on these curves in order to optimize the design of the laplacian electrode for the EEnG recordings on the abdominal surface.

IV. Discussion

The scientific community has widely studied the picking up of bioelectric potentials by means of electrodes from the analytic point of view. Equations that rule the behavior of different kind of electrodes such as punctual electrodes or disc electrodes of finite dimensions have been defined. There have even been obtained approximations to the analytic solution of coaxial ring electrodes [7]. However, the fact of dealing with mixed boundary conditions extremely complicates the solution of Laplace's equation. On the other hand, when intending to know the behavior of such electrodes in the external recording of EEnG, it should also be analytically characterized the influence of the abdominal layers that the intestinal myolectrical signal has to cross to get to the abdominal surface.

Other authors have looked for alternatives to the analytical solution in order to characterize the sensitivity of coaxial ring electrodes [8]. These alternatives, and this work, are based on mathematical models and tank experiments. However, the mathematical model presented by other authors is formed only by one layer, and nor the width of the ring, neither the influence of the electrode on the measured field are considered. Moreover, those works are focused on vertical dipoles and the sensitivity to horizontal dipoles is not studied [8]. Additionally, in the present work not only the effect of horizontal displacements is studied, but also the sensitivity for different dipole's depth. On the other hand, the electric dipole used in previous works was made of 2 copper discs on both sides of a printed circuit board. Hence, the material, the thickness and the dimensions of the board could distort the current flow and the electric field. Finally, in other studies a square voltage was used for the signal injection through the dipole [8]. This complicates to control the parameter that generates the electric filed which leads to the voltage in the electrode, and to confirm the linear behavior of the dipole due to the electrode-electrolyte interface.

V. Conclusion

This work presents a mathematical and an experimental model of TCB ring electrodes and of human abdomen that permits to obtain the sensitivity of laplacian electrodes to pick up the activity of electric dipoles of different orientations and positions inside the abdominal cavity. The performed tank experiments overcome some limitations of previous works, and they have permitted to validate the results derived from the mathematical model. This model will allow us to study the behavior of laplacian ring electrodes of different geometrical parameters to record the EEnG activity and to analyze the influence of the abdominal layers.

References

[1] J. Garcia-Casado, J.L. Martinez-de-Juan and J.L. Ponce, "Noninvasive measurement and analysis of intestinal myoelectrical activity using surface electrodes." *IEEE Trans. on Biomed. Eng.*, vol 52, sup 6, pp 983-91, 2005.

[2] G. Li, Y. Wang, W. Jiang, L.L. Wang, C.-Y. Lu, and W. G. Besio, "Active Laplacian Electrode for the Data-acquisition System of EHG," J*ournal of Physics: Conference Series*, vol. 13 pp. 330-335, 2005.W.-

[3] G. Prats-Boluda, J. Garcia-Casado,J. L. Martinez-de-Juan, and J. L. Ponce, "Identification of the slow wave component of the electroenterogram from Laplacian abdominal surface recordings in humans". Physiol Meas., vol. 28, no. 9, 2007, pp. 1115-1133

[4] G. Prats-Boluda, J. Garcia-Casado,J. L. Martinez-de-Juan, and Y. Ye, "Design and Development of an active Laplacian Sensor for non-invasive recordings of the intestinal bioelectrical signal," in *Proc. of Biomedical Circuits and Systems Conference*, USA, 2008, pp. 77-80

[5] Malmivuo J., "Biomagnetism" *The Biomedical Engineering Handbook.* Ed. Bronzino JD., Vol 1. CRC Press, 1995

[6] Y. Machi; H. Aoki; AND K. Koshiji,. "Fat Thickness Estimation Method Using Bio Electrical Property Examination by Gel Phantom Model Test", *International Symposium on Micro-NanoMechatronics and Human Science*, Japan, 2006, pp. 1-6,

[7] Farina D. and Cescon C. "Concentric-Ring Electrode Systems for Noninvasive Detection of Single Motor Unit Activity", *IEEE Trans. on Biomed. Eng*. vol 48, n. 11, 2001, pp 1326-1334.

[8] W. Besio W, R. Aakula, K. Koka, and W. Dai, "Development of a tri-polar concentric ring electrode for acquiring accurate Laplacian body surface potentials". *Ann.Biomed.Eng*, vol 34, no 3, 2006, pp. 426-435.