Human Body Communication Channel Characterization for Leadless Cardiac Pacemakers

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***Abstract*—Leadless Cardiac Pacemaker (LCP) devices are the cutting edge technology for cardiac rhythm management. An LCP requires to communicate with an external programmer and with different LCP nodes placed in different heart chambers. Human Body Communication (HBC) is an ultra-low power telemetry that exploits body conduction properties to propagate signals. There is a lack of studies in the literature about intra cardiac HBC channel characterization. Channel modeling is fundamental to prototype transceivers able to link different LCP devices. Quasi-Static Simulations based on Finite Element Method (FEM) have been used to characterize all HBC channels involved in LCP telemetry. A very accurate 3D model of a Human Torso has been designed and used to characterize HBC attenuation levels in a frequency range between 40 KHz and 20 MHz. This kind of approach will help to minimize animal trials for a more durable and optimized development.**

I. Introduction

In the last 60 years, electronics downscaling has conducted pacemaker devices to reach very low dimensions. Leadless Cardiac Pacemaker (LCP) is the last evolution in this field. It consists of a small capsule, anchored in one of the heart chambers, that can integrate all the functionalities of standard pacemakers. The technological bottleneck that prevents LCP to completely replace standard pacemakers stands in power budget limits for communication purposes [8]. Human Body Communication (HBC) is an ultra-low power communication that is a good candidate to overcome telemetry power budget issues. HBC is a conductive communication based on Ohmic propagation of currents through body tissues. Indeed an electrode pair is used to build up an electric field that propagates through Human Body reaching a second electrode pair used to receive the signal [14]. Moreover, HBC does not radiate meaning that it does not require an additional antenna, reducing the size of the device, and prevents eavesdropping since direct contact with the body is strictly required. Most of the academic studies about HBC channel modeling are focused on body-surface communications [1], [10], leading IEEE to include HBC as a Physical layer in *IEEE 802.15.6* standard for Wireless Body Area Networks (WBAN). From the dawn of HBC communication, several studies have been performed in order to characterize the human body as a communication channel. HBC channel modeling can be divided in two main categories: electric circuit modeling and computational electromagnetic modeling. Electric circuit models are simplified solutions where human body is represented by a 4-port network made of bio-impedances. Computational Electromagnetic Modeling (CEM) is a computer aided methodology based on analytical or numerical analysis methods. A first approach of HBC channel modeling for implant devices was proposed in [11] where a boundary conditioned problem is analytically solved for HBC communication in a limb. The study shows the importance of the model geometry despite the fact that an approximated body model was used. The work proposed in this paper is based on Finite Element Method (FEM) simulations using a very accurate Torso model to characterize HBC channels involved in LCP applications. In particular, three main channels will be dealt in this paper: intra-cardiac channel between right chambers, Right Ventricle (RV) toward Left Ventricle (LV) and from RV to Body Surface (BS).

II. New Accurate torso Model

A. Quasi-Static Simulations

The Finite Element Method is one of the most reliable numerical methods, it has been used for numerical computation of partial derivative equation systems for almost a century. COMSOL is a Multiphysics software for modeling and simulating complex physics systems. In order to reduce computational cost for low frequency problems COMSOL Multiphysics 5.3 employs a solver called AC/DC module that is based on Electro-Quasi-Static assumptions. Indeed it solves a current continuity equation problem using the FEM given voltage boundary conditions as described in equation system (1). It is worth recalling that quasi-static assumptions are a good approximation if the observation distance is at least ten times lower than the wavelength. LCP communication channels have distances that do not exceed 12 cm. Therefore, it was decided to limit the study at a maximum frequency of 20 MHz since the wavelength in the blood starts to be comparable with channel distances. The low frequency limit must be also considered in order to avoid interferences with electro-physiological signals and it was set at 40 KHz.

$$\begin{cases} \nabla \cdot J &= Q_{j,V} \\ J &= \sigma E + j\omega D + J_e \\ E &= -\nabla V \end{cases} \tag{1}$$

B. Finite Element Model Development

Human Body is a complex anisotropic medium. Therefore, a very accurate model has been used to characterize HBC

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channels. Simulation environment consists of a Torso CAD file based on a validated human model from *IT'IS foundation Zurich*. In particular we choose Duke of the Virtual Population (ViP), that represents a 34 years old man. The Torso CAD file was built by means of Simpleware Software Solution [3], starting from the Computerized Axial Tomography (CAT) image of Duke. Applying this method, it has been created a model made of 5 main structures: organs, bones, cartilage, muscles and connective tissue. This torso CAD file has been imported in COMSOL environment, where heart chambers, whose volumes are reported in table I, have been designed respecting anatomical volumes [7], [12]. In this way, the built model discriminates blood and heart tissue since they have different electrical properties. The model was also enriched of a fat tissue layer that completely surrounds the heart, whose distribution and volume are taken from medical studies [9]. The Torso is surrounded by a sphere of air whose outer surface is set as infinite boundary to avoid that unwanted reflections of the electric field affect simulation results. Dielectric properties of biological tissues are frequency dependent [2], then parametric functions have been used to properly set conductivity and permittivity values for the whole range of interest. The *Institute of Applied Physics* of *CNR* gives free access to a database for dielectric property values of human body tissues [4]. Those values are based on Gabriel's studies [6] where measurements on different biological tissues were performed in order to retrieve dielectrical properties using a 4-term Cole Cole equation[2] covering frequencies from 10 Hz to 100 GHz. The model geometry has been meshed with a custom tetrahedral meshing with minimum element size set to $50\mu m$, while a swept meshing was used for the infinite boundary domains.

TABLE I
HEART CHAMBER VOLUMES OF THE CAD MODEL

Chambers	**RA**	**RV**	**LA**	**LV**
Volume	53ml	96ml	41ml	100ml

Using this complete torso model, comprehensive of heart chambers, an exhaustive study on channel attenuations in a frequency range set between 40 KHz and 20 MHz can be carried out. Next section will point out the results about the main channels involved in the communication of a LCP. In particular, it will deal with three main channels: Intra-cardiac channel between Right Ventricle and Right Atrium, Intra-ventricular channel between Right Ventricle and the epicardium of the Left Ventricle, In-Out channel between Right Ventricle and Body Surface.

III. Simulation Results

A. Intra-Cardiac channel

Two LCP capsules with lengths of 34mm and 28mm were placed respectively in the Right Ventricle (RV) and in the Right Atrium (RA) at a distance circa 9cm. RV capsule has been set as emitter using two voltage boundary conditions on electrode faces placed at the extremities of the capsule. Both boundary

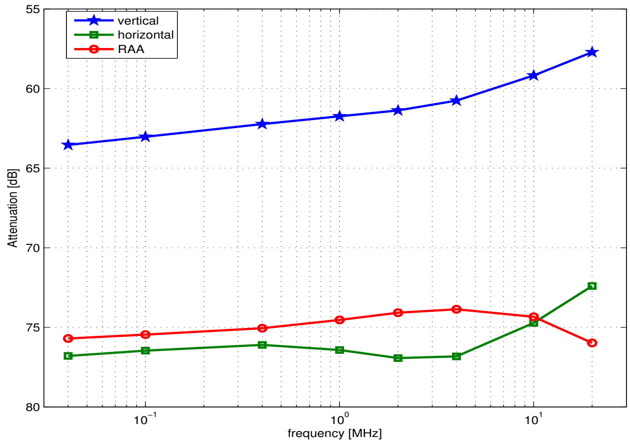

Fig. 1. Attenuation levels of RV-RA HBC channel for three different positioning of the RA capsule

conditions were set with the same potential magnitude with opposite polarity: $V_{TXi} = \pm 1.5$ V. Two voltage boundary probes (V_{RXi}) were set on the electrode faces of the receiver capsule in order to point out attenuation levels as shown in equation 2.

$$A_{dB} = 20 \times \log \frac{|V_{RX1} - V_{RX2}|}{|V_{TX1} - V_{TX2}|} \quad (2)$$

The RV capsule was fixed at the apex, that is located at the bottom of the right ventricular chamber inferior to the flow from the tricuspid valve. The right ventricular apex is the traditional location of standard leads and it has been adopted as a standard location for LCP from electro-physiology standpoints.

1) RA Capsule Position Study: Three different positions were selected for the RA capsule: vertically fixed at the top wall of RA, horizontally fixed at the free wall of RA and in the Right Atrium Appendage (RAA). Those three positioning are the most common placements for atrial leads used by standard pacemakers and they are an exhaustive mapping of right atrium channels [13], [5]. As can be seen in Fig. 1, positioning is very effective. Simulations show that the lowest attenuation is achieved when the RA capsule is vertically fixed at the top wall of the heart, where the attenuation reaches levels that are less than 60dB for frequencies higher than 10 MHz. By the way, it is worth noting the complementary behavior of RAA and Horizontal positions in the frequency region [1-20]MHz. RAA position has a lower attenuation at 4MHz reaching a value of 73.8 dB, while Horizontal position attenuation experiences a slight increase in a frequency range between 1 MHz and 4 MHz reaching 77dB at 2MHz. Positioning effect is due to the distribution of the electric field lines that become normal to the heart surface at high frequencies, improving the communication of capsules fixed at outer walls of the right atrium. Hereafter, all simulations will be performed setting RA capsule in vertical position.

2) Heart Fat Effect: Fat tissue usually covers hearts with a distribution and volume that is different for every patient. This study takes into account a floating heart not uniformly

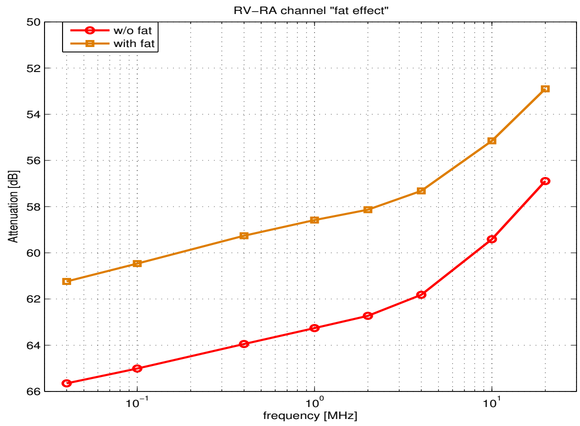

Fig. 2. Fat effect on intra-cardiac HBC channel

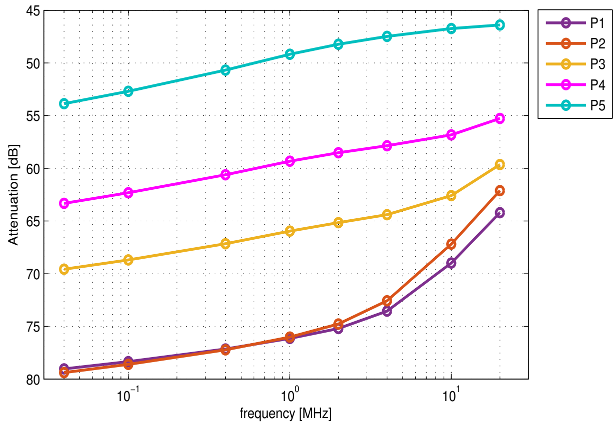

Fig. 4. Attenuation levels of 5 epicardial probes set on the left ventricle

distributed that is described in [9], where most of the fat is placed on the heart surface of right chamber side. Conductivity of fat is almost ten times lower than conductivity of heart tissue and it acts as an isolation layer for HBC communication between right chambers. Simulation results are shown in Fig. 2 where attenuation levels are lowered of almost 4dB for the whole range of study. Then, for this kind of channel it is recommended to not consider the epicardial fat tissue layer since it would represent a worst case scenario that covers the whole patient population.

B. Inter-Ventricular channel

In order to characterize the inter-ventricular channel, 6 voltage probes were set on the most distant surface line of the left ventricle epicardium from Right Ventricle, pointing out the voltage differences of adjacent probes. Adjacent probes are 1.5cm far from each other which is a fair assumption for a hypothetical bipolar epicardial pacemaker capsule. The same RV capsule, placed at the right ventricle apex, of previous studies has been used to set emitter boundary conditions for this kind of analysis. As can be seen in Fig. 4, best results are achieved for probes that are closer to heart apex since the lowest a probe is set the smallest is the distance

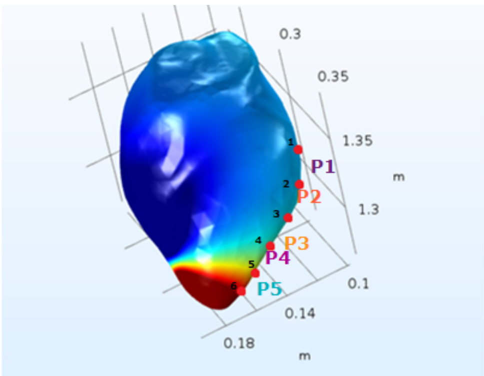

Fig. 3. Heart model showing placement of left ventricle epicardial probes

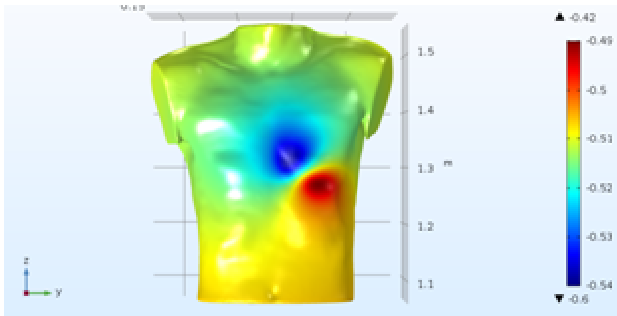

Fig. 5. Blue and red part describes the maximum values for positive and negative polarity pointing out best positioning of patch electrodes for in-out HBC communication with RV capsule

between the emitter capsule and the receiver. Also Inter-Ventricular channels show lower attenuation levels at high frequencies since conductivities of body tissues increase with frequency according to [6] that makes currents better propagate at higher distances. For example the inter-ventricular channel experiences an attenuation level of 62.6 dB at 10MHz with emitter-receiver distance of 6.25 cm (P3). It is worth pointing out that high distance probes have a higher relative benefit of working at high frequencies with respect to short distance ones, where the gap between best case (20MHz) and worst case (40KHz) decreases from 17 dB to only 7.4 dB.

C. In-Out channel

The last channel considered in these preliminary studies is the channel between RV capsule and Body Surface (BS). This channel is extremely important in order to have access to data stored by pacemakers and to reprogram stimulation parameters to adapt therapy to patient response. External programmer would make use of patch electrodes on the skin surface of the body to couple electric field generated by the capsule. Since there are no constraint about patch positioning, this simulation directly points out minimum and maximum potential values achieved on the whole body surface. Figure 5 points out body surface potential polarities suggesting the best positioning of

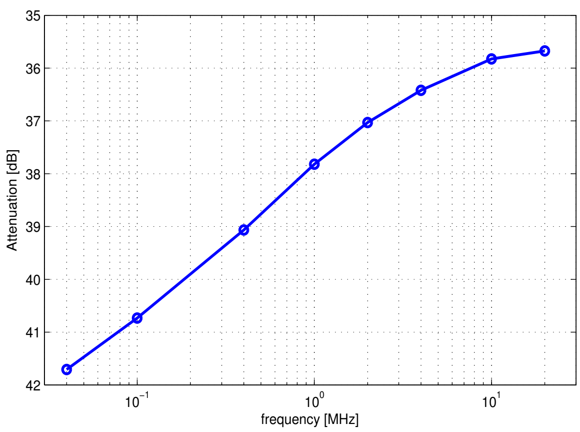

Fig. 6. Pathloss of in-out communication from RV capsule to body surface

patch electrodes. One electrode should be placed on the mid-clavicular line of the fifth intercostal space and the second electrode at the medial end of the fourth intercostal space. Attenuation levels are very promising reaching values in a range between 35.7dB and 41.7dB as can be noted in Fig. 6. These low values of attenuation are obtained thanks to a relatively short distance between RV capsule and body surface that is of almost 4cm and due to a larger inter-electrode distance for patch electrode that is almost 7cm.

Table II resumes the attenuation values of the 3 different HBC channels that involve a Leadless Cardiac Pacemaker at a frequency of 10 MHz.

TABLE II
ATTENUATION LEVELS OF HBC CHANNELS @ 10 MHZ

Channel	$RV \rightarrow RA$	$RV \rightarrow LV$	$RV \rightarrow BS$
Attenuation	59 dB	62.6 dB	35.8 dB

IV. CONCLUSION & FUTURE WORK

The telemetry of a Right Ventricular Leadless Cardiac Pacemaker (LCP) has been completely characterized thanks to this work. All attenuation values of HBC channels involved in a multi-node pacemaker system have been pointed out. It was also shown that the best positioning for an LCP capsule in the right atrium is on the top wall of the chamber. It was shown that epicardial fat tissue improves Intra-cardiac Human Body Communication acting as insulation layer between the heart and the rest of the body. It will be a worst case scenario to not consider fat tissue for intra-cardiac HBC communication and could be a good approach to take into account anatomic variability of patients' hearts. Quasi-Static simulations are an important step for designers to predict trends and voltage levels of the characteristic equations of channel transfer functions and can reduce animal trials for a more durable and cost optimized development. Moreover, this approach is valid for several applications that concern sensors of Body Area Networks not only for intra-cardiac implantable devices. Future works will focus on the verification of HBC channel attenuations by in-vivo measurements. A custom measurement setup has been prototyped and will be used to verify all channels involved in a Leadless Pacemaker system. The measurement setup is the result of the analysis and comparison of two different methodologies and can be used for both in-vitro and in-vivo experiments. Supplementary channels will be also simulated to well characterize the whole communication network for leadless pacemaker devices.

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REFERENCES

[1] M Amparo Callejon, Javier Reina-Tosina, David Naranjo-Hernández, and Laura M Roa. Galvanic coupling transmission in intrabody communication: A finite element approach. *IEEE Transactions on Biomedical Engineering*, 61(3):775–783, 2014.

[2] Kenneth S Cole and Robert H Cole. Dispersion and absorption in dielectrics i. alternating current characteristics. *The Journal of chemical physics*, 9(4):341–351, 1941.

[3] RT Cotton, Christopher W Pearce, Philippe G Young, N Kota, AC Leung, A Bagchi, and SM Qidwai. Development of a geometrically accurate and adaptable finite element head model for impact simulation: the naval research laboratory–simpleware head model. *Computer methods in biomechanics and biomedical engineering*, 19(1):101–113, 2016.

[4] C.Petrucci D.Andreuccetti, R.Fossi. An internet resource for the calculation of the dielectric properties of body tissues in the frequency range 10 hz - 100 ghz. ifac-cnr, florence (italy), 1997. based on data published by c.gabriel et al. in 1996. [online]. available: http://niremf.ifac.cnr.it/tissprop/, 1997.

[5] Asit Das. Electrocardiographic features: Various atrial site pacing. *Indian Heart Journal*, 2017.

[6] Camelia Gabriel, Sami Gabriel, and y E Corthout. The dielectric properties of biological tissues: I. literature survey. *Physics in medicine & biology*, 41(11):2231, 1996.

[7] Alicia M Maceira, Sanjay K Prasad, Mohammed Khan, and Dudley J Pennell. Reference right ventricular systolic and diastolic function normalized to age, gender and body surface area from steady-state free precession cardiovascular magnetic resonance. *European heart journal*, 27(23):2879–2888, 2006.

[8] Matthias Merkel, Philipp Grotherr, Andrea Radzewitz, and Claus Schmitt. Leadless pacing: Current state and future direction. *Cardiology and therapy*, 6(2):175–181, 2017.

[9] SW Rabkin. Epicardial fat: properties, function and relationship to obesity. *Obesity reviews*, 8(3):253–261, 2007.

[10] Yong Song, Qun Hao, Kai Zhang, Ming Wang, Yifang Chu, and Bangzhi Kang. The simulation method of the galvanic coupling intrabody communication with different signal transmission paths. *IEEE Transactions on Instrumentation and Measurement*, 60(4):1257–1266, 2011.

[11] Assefa K Teshome, Behailu Kibret, and Daniel TH Lai. Galvanically coupled intrabody communications for medical implants: A unified analytic model. *IEEE Transactions on Antennas and Propagation*, 64(7):2989–3002, 2016.

[12] Yinshi Wang, Jack M Gutman, David Heilbron, Dennis Wahr, and Nelson B Schiller. Atrial volume in a normal adult population by two-dimensional echocardiography. *Chest*, 86(4):595–601, 1984.

[13] Chance M Witt, Charles J Lenz, Henry H Shih, Elisa Ebrille, Andrew N Rosenbaum, Htin Aung, Martin van Zyl, Kevin K Manocha, Abhishek J Deshmukh, David O Hodge, et al. Right atrial lead fixation type and lead position are associated with significant variation in complications. *Journal of Interventional Cardiac Electrophysiology*, 47(3):313–319, 2016.

[14] Thoams Guthrie Zimmerman. Personal area networks: near-field intrabody communication. *IBM systems Journal*, 35(3.4):609–617, 1996.