Wireless Power Transfer to Intra-abdominal Implants Using an Anatomically Adaptive Around-the-Body Loop Antenna

Shahbaz Ahmed#1, Lauri Sydänheimo#2, Leena Ukkonen#3, and Toni Björninen#4
Faculty of Medicine and Health Technology, Tampere University,
Korkeakoulunkatu 10, 33720 Tampere, Finland
{1shahbaz.ahmed, 2lauri.sydanheimo, 3leena.ukkonen, 4toni.bjorninen}@tuni.fi

Abstract

We studied the possibility of wireless powering, the intra-abdominal implants using an anatomically adaptive around-the-body loop antenna. The analysis includes the wireless link characterization and modelling using an anatomical and a simplified homogenous body model. We categorically analyze the power transfer link for four body sizes ranging from 21 to 36 inches of radial dimensions with an implant depth of 48.5 to 101 mm with promising received power level. In this assessment, the transducer power gain of the wireless power transfer link varied from −2.65 to −10.84 dB.

1 Introduction

Wireless power transfer offers a long-term solution for powering the implants. Despite effortless research, robustness of the wireless power transfer link towards lateral or angular misalignments of the coupling antennas and promising power transfer efficiency for deep-seated battery-less implants remains challenging. Nowadays, miniaturized and complex extra-corporal devices enables us to record various body signals. However, for sophisticated measurements of the physiological parameters after the surgical treatment, require more accurate implantable sensors [1]. Therefore, the implantable devices should be free of feed-through-wires approach to enhance portability, compact to comport with application demands, battery-less for long-term monitoring and biocompatible to avoid internal body infections. Most significantly, the inductive coupling link of the system should be robust against receiver-transmitter alignment. Such systems require optimized distance between the skin and the power-transmitting antenna, that usually ranges between 10-20 cm [2,3]. For a small transmitting loop antenna, the misalignment effects on the power transfer efficiency can be huge as the inductive coupling starts diminishing rapidly [4-5] and requires improvements in the wireless power link characterization. This potential has motivated antenna community to investigate wireless powering of the intra-abdominal implants for physiological monitoring.

We studied the possibility of powering deep-seated intra-abdominal implants using an anatomically adaptive loop antenna and the wireless link characterization in detail. Section 2 presents the body models, antennas and the wireless power characterization. We also analyze the implant received power, in case of various body dimensions. We also showed good agreement between the results obtained from both models, justifying simplistic approach for modelling. Section 3 includes the simulated results for the power available at the implant and inductive power transfer efficiency.

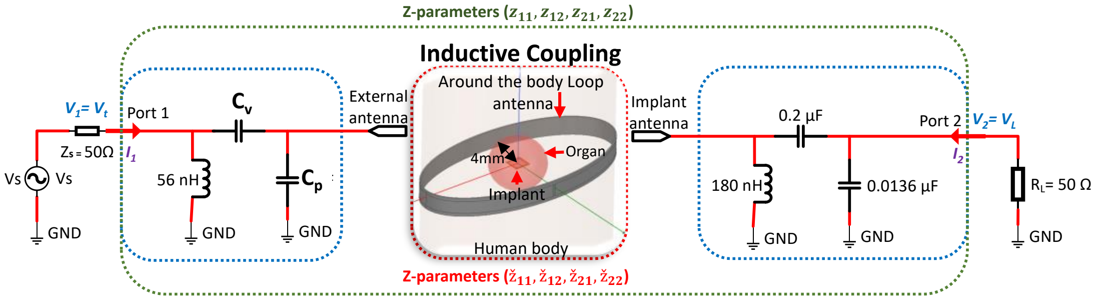

Figure 1. Two port network for the power transfer link with the impedance matching network for 50 Ω source and load impedances.

2 Antennas and the Wireless Link Characterization

We used the anatomical and a homogenous body model to characterize the wireless power transfer link and the effects of the biological tissue in ANSYS HFSS v19.0 and used ADS v2016.01 for the impedance match the power transfer system defined as two-port network.

A. Antenna Structures and Body Models

As the transmitting antenna, we optimized a loop antenna having the trace-width tuned for maximizing the power link efficiency and radial dimension defined by the anatomical model. The around the body loop antenna is wrapped around the abdomen cavity and is isolated from skin using 3 mm thick ethylene-propylene-diene-monomer (EPDM) material that exhibits 1.26 permittivity and 0.007 tangent loss (shown in the Fig. 1). As the application requires the implant antenna with enhanced flexibility, minimal form factor, and simplistic planar structure. In our work, we presented a square loop antenna of dimension 2.3 cm with trace-width of 2.3 mm and fabricated using a 35 μm thick copper tape. Isolation from the body tissues is ensured by coating the antenna with a bio-compatible silicone with a thickness of 0.5 mm. The implant antenna ad the around-the-body are optimized to attain maximum power transfer efficiency defined as maximum available gain at 7.25 MHz. In our study, we have considered the various anatomical models having 21 to 36 inches of waist and the radial dimensions of the around the body loop antenna is defined by the respective body models and the implant depth of 48.5 mm to 101 mm for corresponding models (Table. 2). The anatomical model is used to verify the results obtained from the homogenous body model and rest of the results are obtained using homogenous body model. To model the electromagnetic energy dissipation and the relative permittivity, the electrical properties assigned to the homogenous human body model is skin (dry) [7]. The model accounts for the polarizability and the ohmic loss introduced due to the conduction current in the human tissues. The electrical properties of the tissue listed in [6] and Table 1 summarizes the dielectric properties at the frequency of operation 7.25 MHz [6].

Table 1. Properties of anatomical human body model tissues at 7.25 MHz

Tissues	ε_r	σ(S/m)
Skin	457.02	0.1555
Muscles	220.26	0.60467
Pancreas	210.5	0.70849
Bladder	63.968	0.26165

B. Power Transfer efficiency:

We analyzed the wireless link and the matching circuits as a linear two-port network characterized with Z-parameters (see Fig. 1). The transducer power gain, in terms of Z-parameter (z_{11}, z_{12}, z_{21}, z_{22}) is given by [6]

$$G_t = \frac{4R_S R_L |z_{21}|^2}{|(z_{11}+Z_S)(z_{22}+Z_L) - z_{12}z_{21}|^2}\,, \tag{1}$$

where R_S and R_L are the real parts of the source and load impedance Z_S and Z_L, respectively, and the Z-parameters of the whole system as defined in Fig. 1. computed the maximum attainable power gain ($G_{p,max}$) for the wireless link alone, i.e. excluding the matching circuits (see Fig. 1). The maximum attainable power gain accounts for the inductive coupling between the antennas and the loss in the body tissues, however, does not account for the impedance mismatch loss. Thus, $G_{p,max}$ is the link power efficiency, in terms of the Z-parameters of the link ($\check{z}_{11}$, $\check{z}_{12}$, $\check{z}_{21}$, $\check{z}_{22}$), it can be computed as [5]

$$G_{p,max} = \frac{|\check{z}_{21}|^2}{s+\sqrt{s^2-|\check{z}_{21}\check{z}_{12}|^2}}, \tag{2}$$

where $s=2\mathrm{Re}(\check{z}_{11})\mathrm{Re}(\check{z}_{22}) - \mathrm{Re}(\check{z}_{21}\check{z}_{12})$.

C. SAR Assessment

The transmission power through a wearable or implantable antenna is regulated by US FCC SAR regulation [9], that limits the specific absorption rate to 1.6 W/kg averaged over one gram of tissue. As the SAR_{max} is directly proportional power fed to the transmitting antenna, thus we have

$$P_{t,max} = \frac{1.6\,\frac{W}{kg}\cdot \tau_{in}}{SAR_{max}} P_{test}, \tag{3}$$

where P_{test} is the power available from the numerical test source that we set to 1 W and $\tau_{in} = 1-|s_{11}|^2$ is the power transmission coefficient at Port 1 in Fig. 1. Hence the power available at the implant terminal is given by $P_L = G_t \times P_{t,max}$.

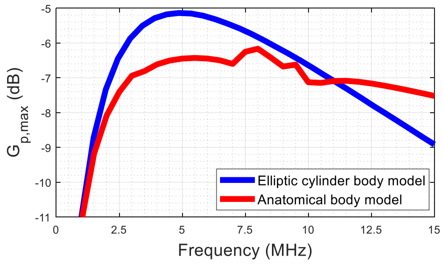

Figure 2. Comparison of the simulation results obtained by homogenous and anatomical human body model for link power efficiency.

3 Simulation results

Two body models are simulated; the anatomical and homogenous body model. As shown in Fig. 2, there is a good agreement between the results from two simulation models with the link power efficiencies $G_{p,max}$ of -6.5 dB and -5.6 dB, from the anatomical and homogenous body models, respectively at the frequency of 7.25 MHz. Therefore, we have used the homogenous body model throughout the rest of the analysis presented in this paper.

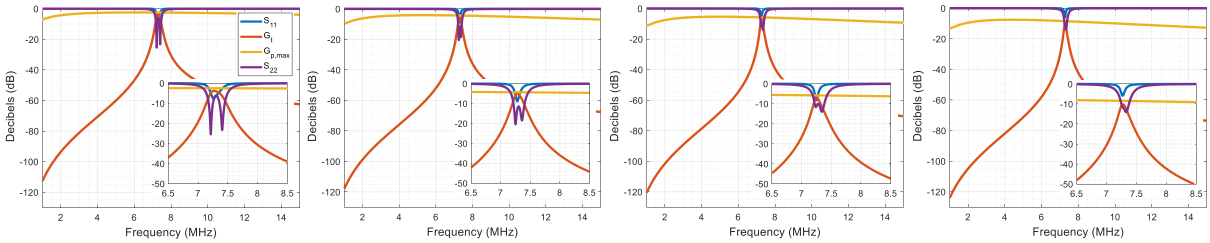

Figure 3. S_{11}, transducer gain G_t, the link power efficiency $G_{p,max}$, and the S_{22} of the two port network for (a)21 inches (b)28 inches (c)32 inches, and (d)36 inches sizes of homogeneous body models (figures with the same legend).

We analyzed the wireless power transfer link for the body sizes listed in the Table. 1. The wireless power transfer link is presented as a two-port network modeled in terms of the $G_{p,max}$, elaborated in equation 2. As shown in Fig. 3(a), (b), (c), and (d), we have been able to do impedance match the respective two-port networks well at 7.25 MHz frequency with the S-parameters attaining promising transducer power gain for each body sizes i.e. small, medium and large (Table. 2). It is evident that, as the body size increases, the around-the-body loop antenna becomes larger and the input impedance of the antenna decreases, and the impedance matching to 50 ohms becomes difficult to achieve. This also increases the mismatch loss factor defined as $\chi = G_t - G_{p,max}$.

Table 2. Homogeneous body models, corresponding maximum operating gain, transducer gain and tuneable capacitors (Cv and Cp) for impedance matching networks.

Size	**Dimensions (Inches)**	**$G_{p,max}$ (dB)**	**G_t (dB)**	**Tuneable Capacitors**	
				C_v (pF)	C_p(pF)
Small	22-28	−2.65 to −3.41	−3.9 to −4.17	1220-1350	12
Medium	28-32	−4.42 to −5.89	-6 to −6.97	820-1000	19
large	32-36	−5.89 to −8.53	−7 to −10.85	680-820	20

As discussed in Section 2, we assessed the power transfer to the intra-abdominal implant for dimensional variations in the homogeneous body models. It can be seen from Fig. 4, the implant in each of the case receives promising power levels ranging from 221.6 to 44.61 mW for 21 inch and 36 inch body sizes, respectively. The received power decreases due to decreased $G_{p,max}$, which is caused by the increasing separation between the antennas. However, the power level received even in the largest body size considered in our study remains sufficient for many low power electronic devices.

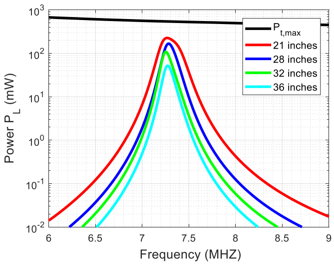

Figure 4. Power received at the terminal of the intra-abdominal implant antenna corresponding to the maximum SAR complaint transmission power

4 Conclusion

We studied the wireless power transfer to intra-abdomen implant and demonstrated the modelling of the power link for various body sizes, with transducer gain varying from −6.57 dB to −10.58 dB, with received power at the implant ranging from 221.6 to 44.61 mW for corresponding SAR compliant transmission power. We also presented a homogenous body model for simplistic simulation approach, which shows good agreement with the anatomical human body model.

References

[1] E. Meng and R. Sheybani, "Insight: implantable medical devices," in Proc. The Royal Society of Chemistry 2014, vol. 14, pages 3233-3240, 12th May 2014, USA.

[2] J. Charthad et al., "An ultrasonically powered implantable device for targeted drug delivery," 2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Orlando, FL, 2016, pp. 541-544.

[3] M. J. Weber, Y. Yoshihara, A. Sawaby, J. Charthad, T. C. Chang and A. Arbabian, "A Miniaturized Single-Transducer Implantable Pressure Sensor With Time-Multiplexed Ultrasonic Data and Power Links," in IEEE Journal of Solid-State Circuits, vol. 53, no. 4, pp. 1089-1101, April 2018.

[4] A. Yakovlev, J. H. Jang and D. Pivonka, "An 11μW sub-pJ/bit reconfigurable transceiver for mm-Sized wireless implants," in Proc. IEEE Transactions on Biomedical Circuits and Systems, vol. 10, no. 1, pp. 175-185, Feb. 2016.

[5] M. Waqas et al., "Loop antenna for deep implant powering in an intracranial pressure monitoring system," 2018 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, Boston, MA, 2018, pp. 207-208.

[6] IT'IS Foundation, Tissue Properties [Online]. Available: https://www.itis.ethz.ch/virtual-population/tissue-properties/downloads

[7] D. L. Means, K. W. Chan, "Evaluating compliance with FCC guidelines for human exposure to radiofrequency electromagnetic fields," Office of Engineering and Technology Federal Communications Commission FCC, Washington D.C, June 2001.