Transmission Mechanisms with Variable Tissue Properties in a Paired Electrode System for Transcutaneous Power

Kara Bocan and Ervin Sejdić
School of Electrical and
Computer Engineering
University of Pittsburgh
Pittsburgh, Pennsylvania 15213
Email: knb12@pitt.edu, esejdic@pitt.edu

Abstract—**Wireless transcutaneous power transfer and communication has the potential to reduce the size of implantable medical devices, thereby reducing patient discomfort and minimizing the tissue area exposed to foreign material. Electromagnetic transmission mechanisms through tissue are determined by tissue structure and associated frequency-dependent tissue properties, which are significant in the design of wireless implantable medical devices. The purpose of this study was to investigate the effects of varying tissue dielectric properties on maximum power transfer to a subcutaneously implanted device in a paired electrode system designed for use in proximity to metallic orthopedic implants. The transcutaneous system including external and implanted electrode pairs was simulated at several radio frequencies (125 kHz, 1 MHz, 13.56 MHz, 403 MHz, and 915 MHz) while varying the dielectric properties of the tissue medium over a range of physiological values. Maximum power transfer was calculated to represent the best-case power gain across the range of tissue properties and frequencies, and greater achievable efficiencies were seen with higher quality factor as a function of the tissue properties. The results suggest that in the paired electrode system, utilization of capacitive coupling allows the system to function in proximity to metallic surfaces such as orthopedic implants. The results also suggest that higher power gains are possible through a choice of implant location based on expected tissue properties.**

I. INTRODUCTION

Much of the challenge of wireless powering stems from the need to deliver power through tissue. Tissue properties affect electromagnetic power transfer such that antenna systems must be specially designed to transmit effectively through tissue [1]–[4]. Biological tissue behaves as a lossy dielectric material, in which transmission occurs through displacement current and conduction current [1], [2], [4], [5]. The contributions of displacement current and conduction current are directly related to tissue dielectric properties of conductivity and permittivity, both of which vary with frequency.

In addition to their frequency-dependence, tissue properties at a single frequency vary among locations on the body, among individuals, and over time, due to differences in cellular structure and water content [2], [3], [6]–[11]. Understanding transmission mechanisms at different frequencies and their relation to tissue dielectric properties is essential to designing efficient power delivery to an implanted device. Additionally, it is important to determine the effects of variations in tissue properties on the function of a system, in order to predict how the system will perform in real applications.

Inductively coupled loops or coils are common in implantable devices. However, the presence of metallic surfaces can interfere with the formation of magnetic fields in the configuration necessary for inductive coupling, also interfering with backscattering communication. A touch probe volume conduction system was developed by Liu et al. and demonstrated to function in proximity to metallic surfaces, for the purpose of identifying orthopedic implants with implanted radio frequency identification (RFID) tags [12], [13]. The touch probe system was designed to utilize pairs of electrodes for power transfer from the skin surface to the implant, and the term "volume conduction" was used with reference to prior work utilizing ionic conductivity of tissue for power transfer. However, since the initial work, the system was observed to function through air, indicating that ionic conduction was not the primary power transfer mechanism. The purpose of this work was to further investigate the power transfer mechanisms in this system, with broader applications to dipole and capacitively coupled transcutaneous systems.

II. METHODS

Simulations were performed to test the effects of tissue dielectric properties on transmission at frequencies covering RF bands from low frequency to ultra-high frequency: 125 kHz, 1 MHz, 13.56 MHz, 403 MHz, and 915 MHz. The simulations were performed in ANSYS HFSS, a three-dimensional electromagnetic solver utilizing the finite element method with adaptive meshing.

A model was constructed in HFSS with two electrode-based antennas separated by 1 cm of tissue. The antenna design is unique in that such an electrode-based design has been successfully implemented at 125 kHz, 13.56 MHz, and 915 MHz [14], [15]. The external antenna contacted the outer surface of the tissue, and the implanted antenna was embedded within the tissue, representing powering and communication between an external transmitter and a passive implanted receiver.

The tissue thickness between the external and implanted antennas was kept constant while other system parameters were varied. The dimensions of the implanted and external

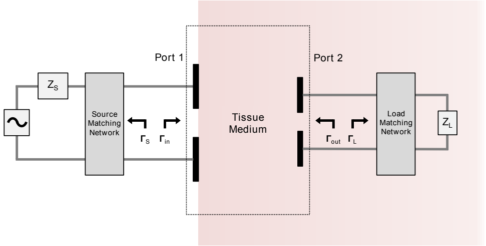

Fig. 1. Block diagram of the transcutaneous system as a two-port network

TABLE I. RANGES OF TISSUE CONDUCTIVITY (σ) AND RELATIVE PERMITTIVITY (ϵ_r) SWEPT IN SIMULATION AT EACH FREQUENCY (f).

f	σ (S/m)	ϵ_r
915 MHz	0.04 - 2.5	5 - 71
403 MHz	0.02 - 25	5 - 75
13.56 MHz	0.01 - 2.0	5 - 400
1 MHz	0.004 - 2.0	20 - 6000
125 kHz	0.02 - 2.0	60 - 14000

antennas were also unchanged when varying tissue conductivity and permittivity.

The tissue medium was defined in terms of conductivity, permittivity, and loss tangent. The values of tissue conductivity and permittivity were varied in simulation according to the range of reported physiological tissue properties, as listed in Table I [4]. Maximum power gain between the external and the implanted antennas was calculated as a metric of comparison among model configurations. The system was analyzed as a two-port network as indicated by the dashed box and port labels in Figure 1, and the network scattering parameters were used to calculate maximum power gain assuming simultaneous conjugate matching.

According to the complex propagation constant, the ratio of conduction current to displacement current is represented by the loss tangent, given in Equation 1 [1], [16]. Based on this ratio, changes in power gain were related to the contributions of conduction current and displacement current at each frequency.

$$\tan\delta = \frac{\sigma}{\omega\epsilon} \tag{1}$$

A transcutaneous system can also be modeled as a linear RLC circuit. The quality factor is then given by Equation 2, representing a ratio of reactive oscillatory power to dissipated power [16].

$$Q = \frac{2\pi f L}{R} = \frac{1}{2\pi f R C} \tag{2}$$

III. RESULTS

The power gain was calculated at each combination of conductivity and permittivity at frequencies of 915 MHz, 403 MHz, 13.56 MHz, 1 MHz, and 125 kHz. At each frequency, as the conductivity approached zero, the power gain approached one, characteristic of a lossless medium.

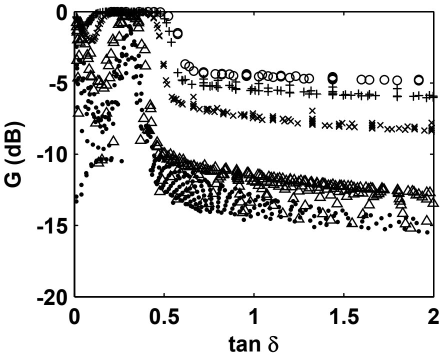

Fig. 2. Power gain as a function of loss tangent at 125 kHz (○), 1 MHz (+), 13.56 MHz (×), 403 MHz (△), and 915 MHz (●).

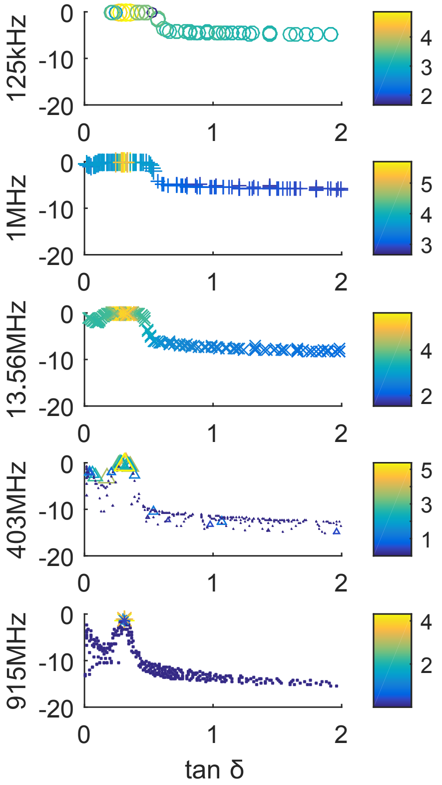

Fig. 3. Gain (dB) versus loss tangent of the tissue medium for each frequency, with color indicating quality factor including matching networks.

At each frequency, there was a peak in maximum power gain at intermediate conductivity, and a plateau at higher conductivities. The peak occurred at a higher conductivity with higher permittivity, and was determined to be related to the loss tangent. The power gain at each frequency versus loss tangent is shown in Figure 2. At all simulated frequencies, there was a

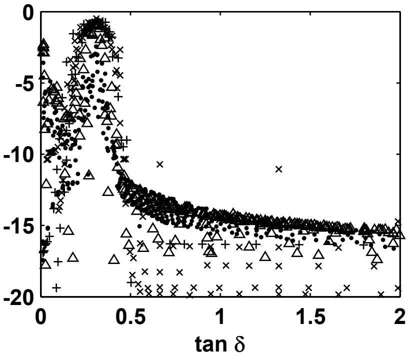

Fig. 4. Power gain as a function of loss tangent at 125 kHz (○), 1 MHz (+), 13.56 MHz (×), 403 MHz (△), and 915 MHz (●) with a 1-cm air gap between the external antenna and the tissue surface.

region of peak maximum power gain around a loss tangent of 0.3. At lower frequencies, the maximum power gain was higher and the power gain remained high over a wider range of the loss tangent. The plateau region at higher conductivities is also represented in the plot of gain versus loss tangent. The power gain of the plateau region was higher for lower frequencies.

To investigate the effect of skin contact on transmission, the power gain was calculated with a 1-cm air gap between the external antenna and the tissue surface, again assuming simultaneous conjugate matching (Figure 4). With the inclusion of an air gap, the power gain at 125 kHz dropped to -100 dB or required inductances greater than hundreds of mH for conjugate matching. The power gain at 1 MHz decreased to a similar gain profile as the higher frequencies, with a sharp peak around a loss tangent of 0.3. The power gain at higher frequencies decreased with the inclusion of an air gap, but the effect was relatively small compared to the effect of an air gap at 125 kHz.

The values for maximum power gain were calculated assuming simultaneous conjugate matching. As shown in Figure 3, the peak gain corresponds to a region of higher *Q*. Note that the loss tangent represented here is the loss tangent of the tissue medium, while the *Q* is that including the source and load matching networks.

IV. DISCUSSION

Biological tissue is classified as a lossy dielectric, with dielectric properties arising from its fluid content and cellular structure. Tissue behavior is frequency dependent, with permittivity shown to decrease and conductivity shown to increase with frequency. In addition, tissue properties vary with tissue structure and water content. Wireless systems transmitting through tissue must be designed based on the operating frequency and expected tissue parameters.

Transmission through lossy dielectrics occurs through conduction current and displacement current. An electric field applied to a dielectric causes polarization, and induces displacement flux and conduction current [16]. The contributions of displacement current and conduction current vary depending on the frequency of the applied field and the properties of the medium. In tissue, conduction current dominates at low frequencies and is highly dependent on ionic conductivity. As frequency increases, the contribution of displacement current becomes more significant [5], [17]. The transmission mechanisms are directly related to tissue dielectric properties of conductivity and permittivity.

The purpose of this work was to investigate transmission mechanisms through tissue in a touch probe system at various frequencies and to study the effects of varying tissue properties on power transmission. The touch probe antenna system was simulated at 125 kHz, 1 MHz, 13.56 MHz, 403 MHz, and 915 MHz, and maximum power gain was calculated across the range of physiological tissue dielectric properties at each frequency. The results of this study indicate the best-case power transfer across a range of physiological tissue properties at each frequency, that is, the maximum power transfer assuming simultaneous conjugate matching for each configuration.

The loss tangent represents a ratio of conductivity to permittivity, equivalently a ratio of conduction current to displacement current. At low conductivity, there were regions of high gain at both frequencies, characteristic of a lossless medium. A peak in power gain was observed around a loss tangent of 0.3 at each frequency. As tissue permittivity increases, the electrical size of the implanted antenna also increases. This effect corresponds to the peak gain occurring at a higher conductivity at higher permittivity, maintaining the peak around a loss tangent of 0.3.

Viewing the system as a series RLC circuit, the peak power gain is related to the quality factor (*Q*) according to the definition in Equation 2 [16]. This is a simplified view of the system as the field interactions are not directly analogous to an RLC circuit, but the model can be used to represent energy distribution in electromagnetic power transfer. High antenna *Q* represents greater energy in the near field. At high *Q*, less input power is needed to achieve the same near field strength [18]. The antennas in this work are operating at a proximity such that near fields are significant in power transfer. This, along with the peak gain at high *Q*, suggests capacitive coupling, and explains the ability of the touch probe system in [13] to function in proximity to metallic implants even without significant ionic conduction.

At loss tangent values greater than 0.3 the power gain plateaued at each frequency, and the power gain of the plateau was greater at lower frequencies. This effect indicates that losses due to conductivity are more significant than the contribution of conduction current at higher frequencies. A relatively small contribution of conduction current at higher frequency indicated that contact between the external antenna and the tissue is not essential to transmission of power. This was confirmed by adding a 1-cm air gap between the external antenna and the tissue surface and recalculating power gain with simultaneous conjugate matching. The power gain at 125 kHz decreased to nearly zero with the inclusion of the air gap, suggesting that conduction current is the primary transmission mechanism and therefore skin contact is necessary for power transfer. At 1 MHz and 13.56 MHz, the power gain with an air gap decreased and the power gain profile across the range of loss tangents became comparable to higher frequencies, indicative of displacement current. At 403 MHz and 915 MHz, the power gain was relatively unaffected by an air gap. The results suggest that contact between the external antenna and the skin may improve maximum power gain at higher frequencies, while transmission at 125 kHz is highly dependent on the interface between the external antenna and the tissue.

Permittivity and conductivity vary for each tissue type due to differences in water content and cellular structure [2]. There is greater variation among the dielectric properties of tissue types at low frequency, and dielectric properties are directly related to the system impedance. As evidenced by the matching impedances calculated in this study, higher operating frequency may therefore provide easier matching network design for power transfer through heterogeneous tissue layers or areas where tissue composition is more variable. The reported properties of skin at 915 MHz fall within the region of high power gain, indicating that 915 MHz is well-suited for powering subcutaneous implants.

Implantation depth is known to affect received power, but it is not a controllable design variable, as it is typically determined by the tissue thickness at the implantation site [15]. Therefore, the tissue thickness was held constant in the current study. The tissue was also assumed homogeneous to simplify analysis of the effects of variations in dielectric properties. Powering and communicating with an implanted device necessitates transmitting through heterogeneous tissue layers (e.g., skin, fat, and muscle) depending on the location on the body. Experiments with multiple tissue layers could further explore the effects of more complex tissue composition on power transmission.

In the current study, the antenna area in contact with the tissue surface was held constant to focus on the effect of tissue properties and mechanisms at different frequencies. The antenna design was based on previous work at low and ultra-high frequency, and reflects the determination of operating frequency based on practical size constraints on the external and implanted antennas. Implantable antennas are size constrained for patient comfort and safety, and the choice of operating frequency is often a function of these constraints. Therefore, maintaining the electrical size of the antennas was neither practical nor relevant to the goals of the current study. The effect of additional antenna geometries and skin contact area within size constraints could be explored in future studies.

V. CONCLUSION

Tissue properties vary with frequency and tissue structure, and the effect of these variations must be considered when designing systems to transmit through tissue. Maximum power gain was determined across a range of tissue properties at frequencies of 125 kHz, 1 MHz, 13.56 MHz, 403 MHz, and 915 MHz. The results indicate: (1) lower frequencies depend more on conduction current and therefore a good interface with the tissue surface, and (2) a higher Q and therefore higher achievable gain is possible for certain configurations of tissue properties and frequency. The results of this study provide insight into the mechanisms of transmission through tissue at various frequencies and tissue environments for dipole and capacitively coupled transcutaneous systems.

REFERENCES

[1] R. Plonsey and D. B. Heppner, “Considerations of quasi-stationarity in electrophysiological systems,” *The Bulletin of Mathematical Biophysics*, vol. 29, no. 4, pp. 657–664, 1967.

[2] J. L. Schepps and K. R. Foster, “The UHF and microwave dielectric properties of normal and tumour tissues: Variation in dielectric properties with tissue water content,” *Physics in Medicine and Biology*, vol. 25, no. 6, pp. 1149–1159, 1980.

[3] H. P. Schwan, “Electrical properties of tissues and cell suspensions: Mechanisms and models,” in *Proceedings of the 16th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 1994, Conference Proceedings, pp. A70–A71.

[4] S. Gabriel, R. W. Lau, and C. Gabriel, “The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues,” *Physics in Medicine and Biology*, vol. 41, no. 11, pp. 2271–2293, 1996.

[5] A. S. Y. Poon, S. O’Driscoll, and T. H. Meng, “Optimal frequency for wireless power transmission into dispersive tissue,” *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 5, pp. 1739–1750, 2010.

[6] C. Gabriel, S. Gabriel, and E. Corthout, “The dielectric properties of biological tissues: I. Literature survey,” *Physics in Medicine and Biology*, vol. 41, no. 11, pp. 2231–2249, 1996.

[7] S. Gabriel, R. W. Lau, and C. Gabriel, “The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz,” *Physics in Medicine and Biology*, vol. 41, no. 11, pp. 2251–2269, 1996.

[8] A. Peyman, A. A. Rezazadeh, and C. Gabriel, “Changes in the dielectric properties of rat tissue as a function of age at microwave frequencies,” *Physics in Medicine and Biology*, vol. 46, no. 6, pp. 1617–1629, 2001.

[9] A. Christ, A. Klingenbock, T. Samaras, C. Goiceanu, and N. Kuster, “The dependence of electromagnetic far-field absorption on body tissue composition in the frequency range from 300 MHz to 6 GHz,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 54, no. 5, pp. 2188–2195, 2006.

[10] H. Kanehisa, M. Miyatani, K. Azuma, S. Kuno, and T. Fukunaga, “Influences of age and sex on abdominal muscle and subcutaneous fat thickness,” *European Journal of Applied Physiology*, vol. 91, no. 5-6, pp. 534–537, 2004.

[11] A. Peyman, C. Gabriel, E. H. Grant, G. Vermeeren, and L. Martens, “Variation of the dielectric properties of tissues with age: The effect on the values of SAR in children when exposed to walkie-talkie devices,” *Physics in Medicine and Biology*, vol. 54, no. 2, pp. 227–241, 2009.

[12] X. Liu, R. Yalamanchili, A. Ogirala, and M. Mickle, “An alternative approach of operating a passive RFID device embedded on metallic implants,” in *IEEE 12th Annual Wireless and Microwave Technology Conference*, 2011, Conference Proceedings, pp. 1–6.

[13] X. Liu, J. L. Berger, A. Ogirala, and M. H. Mickle, “A touch probe method of operating an implantable RFID tag for orthopedic implant identification,” *IEEE Transactions on Biomedical Circuits and Systems*, vol. 7, no. 3, pp. 236–242, 2013.

[14] S. A. Hackworth, Ph.D. thesis, University of Pittsburgh, 2010.

[15] X. Liu, Ph.D. thesis, University of Pittsburgh, 2011.

[16] D. M. Pozar, *Microwave Engineering*, 3rd ed. Hoboken, NJ: John Wiley and Sons, 2005.

[17] A. S. Y. Poon, S. O’Driscoll, and T. H. Meng, “Optimal operating frequency in wireless power transmission for implantable devices,” in *Proceedings of the 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2007, Conference Proceedings, pp. 5673–5678.

[18] M. Gebhart, T. Baier, and M. Facchini, “Automated antenna impedance adjustment for near field communication (NFC),” in *12th International Conference on Telecommunications*, 2013, Conference Proceedings, pp. 235–242.