Radiation Performance of Antennas Implanted in Small Animals for Neuroengineering

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Abstract—**Wireless data communication could improve the performance and reliability of biomedical implants used in fundamental neuroscience research by removing infection-prone transcutaneous cabling. The small size of common research animals like mice and rodents, however, presents an additional challenge in the design of implantable antennas due to the resonance effects of the host body. In this work, we demonstrate how the far-field radiation performance of an antenna implanted in a rat cadaver is impacted by the electrically small size of the rat's body. We further discuss design strategies for developing implantable antennas in small animals to obtain robust wireless link budgets for the considered size- and energy-constrained wireless implantable systems.**

Index Terms—**Implanted antennas, radiation performance, small animals, neural implants.**

I. INTRODUCTION

With recent progress in materials and fabrication, new capabilities of wireless, battery-free, and fully implanted bioelectronics new capabilities continue to be investigated for applications in biomedical research and clinical medicine [1]–[7]. One application is neuroengineering, in which implantable neural interfaces with diverse operational modes can achieve closed-loop stimulation and recording in freely behaving animals, particularly rodents [8], [9]. Due to the size constraints of working with rodent models, many neuroengineering platforms rely on implanted electrodes with transcutaneous connectors to interface with an external system, such as a headstage [7]. Transcutaneous cabling can reduce mobility and increase the risk of infection, however, leading many researchers to investigate fully implantable alternatives [9], [10].

A critical challenge in designing implantable wireless systems is developing miniaturized antennas with high efficiency. Due to the high permittivity and losses of biological tissues, the characteristics of implanted antennas are strongly dependent on the implantation site and the geometry and dimensions of the host body [11]. For implants in humans or larger animals, some canonical body models, such as an elementary electromagnetic (EM) source implanted in a spherical or planar body phantom, are used for the characterization of implanted antennas [12]–[18]. However, as the size of the host body approaches the EM wavelength, the radiation performance and characteristics of

implanted antennas become harder to predict.

In this paper, we present the far-field radiation performance of an antenna subcutaneously implanted in a rat cadaver. Section II presents the selected experimental method and results. Section III provides a discussion of the radiation characteristics observed based on the prior knowledge of the loss mechanisms of implanted antennas [15]–[18] and design strategies for antennas implanted in small animals. Section IV concludes with a summary of the findings and future work.

II. MEASUREMENTS AND RESULTS

For this work, we investigated the far-field performance of an implanted antenna using a planar dipole antenna designed for the unlicensed 2.4 GHz industrial, scientific, and medical (ISM) band. The specific operating frequency was chosen based on the small operating wavelength relative to rodent models (e.g., rats), the wide bandwidth of the frequency band, and the prevalence of low-cost, off-the-shelf electronics available for the selected frequency. The antenna was fabricated on a polyimide substrate (thickness 0.1 mm) and encapsulated with biocompatible films made of Ecoflex silicone rubber (total thickness 1 mm), as shown in Fig. 1.

The antenna was measured after being subcutaneously implanted in a rat cadaver (2 hours post-euthanasia). The rat was obtained in accordance with EPFL's Animal Research and Ethics committee under license VD3290.1. Specifically, the planar dipole antenna was implanted subcutaneously in the coronal plane above the rat vertebrae, where the orientation of the dipole is perpendicular to the spine. The measured reflection coefficient, shown in Fig. 1, was found to be below −15 dB over the entire 2.4 GHz ISM band (2.4 to 2.5 GHz), demonstrating adequate impedance matching.
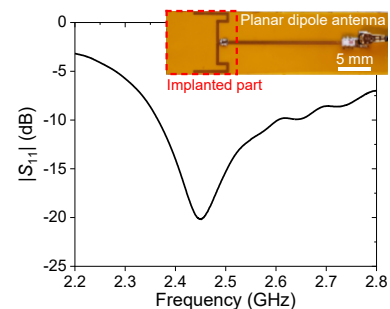

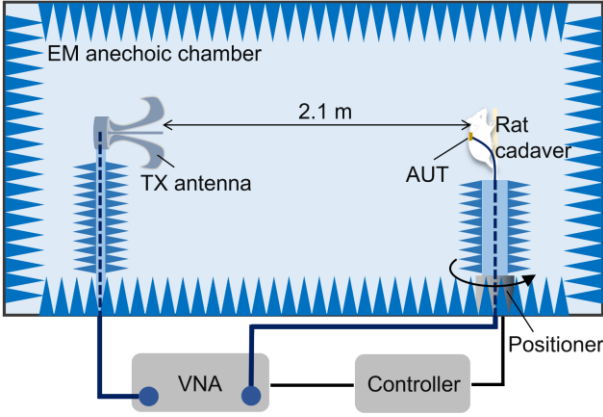Fig. 1. Measured reflection coefficients $|S_{11}|$ of the implanted antenna.

Fig. 2. Schematic diagram of the far-field measurement setup.

The far-field radiation patterns of the antenna were measured in an EM anechoic chamber using the setup shown in Fig. 2. By using the 2.4 GHz ISM band and a small rodent model, it was possible to achieve accurate measurements of the radiation performance at a distance of 2.1 metres. For these measurements, a 50 MHz–20 GHz Network Analyzer (8720C, Agilent HP) and a wideband quad-ridge horn antenna (QH400, MVG Industries) were used.
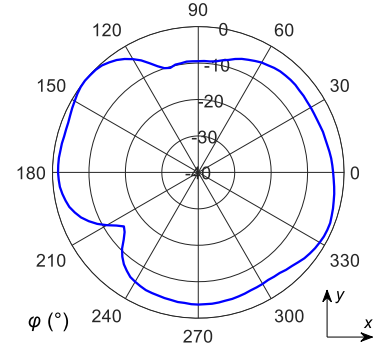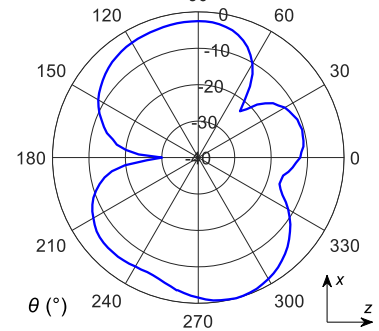

(a)
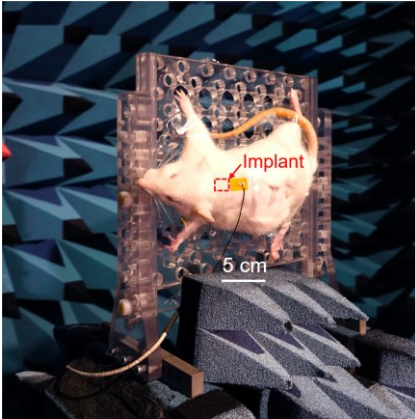
(b)

Fig. 3. Measurement setup for the antenna subcutaneously implanted in a rat cadaver. The rat body is placed (a) vertically and (b) horizontally for different pattern measurements.

(a)

(b)

Fig. 4. Measured far-field radiation patterns in (a) x-y plane and (b) x-z plane at 2.45 GHz.

By changing the orientation of the rat body, as shown in Fig. 3, the far-field radiation patterns on the x-y plane (horizontal polarization) and x-z plane (vertical polarization) were measured and normalized by the maximum directivity, as shown in Fig. 4(a) and (b), respectively. On the x-y plane, the radiation pattern exhibits two wide beams (i.e., maximum values in $\varphi = 138°$ with a beamwidth of 72° and $\varphi = 336°$ with a beamwidth of 99°) and the difference in maximum directivity is 1.2 dB. On the x-z plane, the main lobe has a beamwidth of 45° in the direction of $\theta = 285°$. As for the radiation gain of the antenna under test, the measured maximum gain in Fig. 4(a) is –19.38 dBi.

III. DISCUSSION OF RESULTS

Unlike antennas implanted in large body models, the maximum directivity of the radiation pattern in this case was in the direction towards the ventral side of the rat body rather than from the implant to the nearest body–air interface (Fig. 4(b)). These results demonstrate that, for small host bodies, limited dielectric loss (i.e., losses due to lossy biological tissues) and irregular body geometry lead to instability and unpredictability in the obtained far-field radiation patterns. With the knowledge of the loss mechanisms of implanted antennas [15]–[18], additional insight can be obtained:

1) Since the EM waves reaching the body interface of small animals are not severely dissipated and attenuated, sometimes retaining most of the near-field components, the entire small animal body needs to be regarded as a radiating

structure [17]. Within the small animal bodies with irregular geometries and diverse tissue compositions, EM waves excited by the implanted antenna undergo complex internal reflections and resonances. A possible simplified approach is to analyze the surface currents on the body using the Love's equivalence principle.

2) For antennas implanted in small animals, body phantoms with simplified geometry are no longer suitable for the analysis of their specific radiation performance, neither applying the same implantation depth in planar phantoms or similar dimensions in spherical phantoms [18]. This is due to the assumption of near-field losses that must be met in order to apply a simple body model, which differs significantly from what occurs in small animals owing to their irregular geometry and small size relative to the operating wavelength.

3) An effective approach for analyzing antennas implanted in small animals would be to carry out numerical simulations with high-resolution anatomical models of the animal. Given the differences between models and real animals, measurements of implanted antennas in small animals are believed to be the most reliable validation. Note however that even small changes in implantation site and antenna orientation could change the final radiation pattern and total radiation efficiency.

IV. CONCLUSIONS AND FUTURE WORK

In this work, we conducted preliminary studies on the radiation performance of antennas implanted in small animals, illustrating the complexities and possible approaches for analysis and design. We highlight how properties of these small animals, namely limited dielectric loss and irregular body geometries, render traditional body phantom models using canonical geometries inaccurate. By measuring the far-field patterns of an antenna subcutaneously implanted above the spinal column of a rat cadaver, we demonstrate how an antenna's gain pattern is altered inside a small animal model. These results indicate that refined numerical simulations and/or measurements are crucial to grasp the unpredictable radiation characteristics, which will determine the optimal placement of external base stations.

Future work will exploit these findings to design *in vivo* electrophysiology wireless systems. Precise knowledge of the antenna radiation characteristics can improve the link budget for miniaturized wireless implant systems where modest changes in antenna gain can significantly alter performance, e.g. two-way link budgets in backscatter communication [19], [20]. Further analysis of the specific absorption rate (SAR) of antennas in small animal models should also be performed to ensure their safe and ethical use.

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