Radiation Limitations for Small Implanted Antennas

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***Abstract*—Medical implants with communication capability are becoming increasingly popular with today's trends to continuously monitor patient's condition. This is a major challenge for antenna designers since the implants are inherently small and placed in a communication-wise very lossy environment. Our goal is to determine the fundamental limitations of such antennas when placed inside human bodies and to develop guidelines for most efficient design. We base our findings on in-house analysis tools based on spherical and cylindrical wave expansion applied to simplified spherical and cylindrical body models respectively. These give us insight into wave propagation and show the maximum power density levels that can be reached just outside the body. Based on the obtained limits we can propose a useful upper bound for more complex scenarios.**

***Index Terms*—implanted antennas, spherical wave propagation, fundamental limits.**

I. Introduction

We are witnessing a large growth of interconnected sensors and devices aimed at providing better medical care to in-hospital and out-hospital patients. Many of these devices are medical implants which are quite a challenge for engineers due to size limitations. In addition, from the perspective of antenna engineers, the small size and large losses imposed by the body tissue are a very complicated design situation.

Limits on the performances of electrically small antennas have been studied in the pioneering work started by Chu [1], Wheeler [2], Harrington [3], and continued by Collin et al. [4], Fante [5] and Fano [6]. More recently further advances on this topic have been achieved in [7-10]. However, these principles are valid for antennas radiating in free space, while the implanted scenario places the antenna into a very lossy medium. In such an environment, most of the common ideas and practices are not valid. In [11] it is clearly shown that fundamental antenna characteristics like the far field, the antenna radiation pattern or the bandwidth do not apply when the antenna radiates into an infinite lossy medium. Therefore, large part of the theoretical developments and results which are still used by antenna engineers to assess the potential of an antenna should be modified for antennas radiating into a lossy medium. Recent advances in characterization and in-body link modelling can be found in [12-13].

For this reason, our focus in this paper is to investigate some fundamental physical limits on the total power and maximal power density that can reach free space for a specific implanted antenna scenario. We will use a spherical model as a replacement for the lossy human wearer and place encapsulated elementary antenna sources inside. This first look at the spherical model is only a coarse approximation, but it provides useful insights and can be very efficient as it uses an algorithm based on spherical modes expansion [14, 15].

II. Analysis Fundamentals

The basis of our analysis in this paper is a spherical model of a human body. It is a rough estimate, however it gives useful results and valuable insight [16]. The analyzed structure in Fig. 1 is composed of a sphere (with radius r_{body}) and of an implanted antenna. The sphere modeling the body can be either homogeneous or formed by concentric layers in order to mimic a part of the human body (skin, fat, muscle, bone, for instance) by using dielectric properties that are similar to those of real human tissues. The implanted antenna is modeled as a small sphere with radius r_{impl} (filled with air) and a current source (either an electric or a magnetic dipole) and its location and geometry is depicted in Fig. 1.

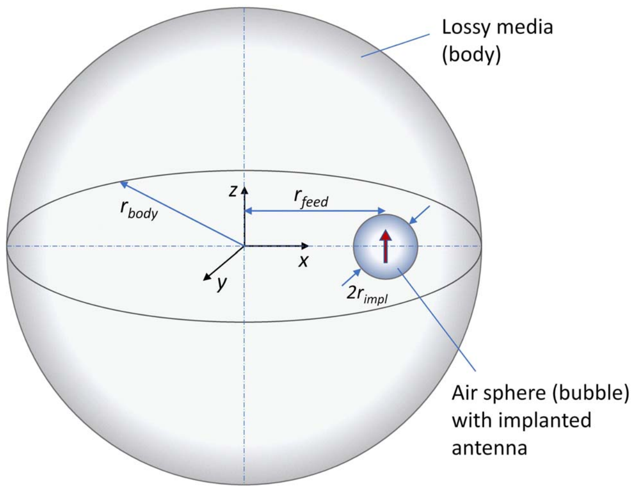

Fig 1. View of the analyzed structure with the excitation moved away from the center.

The solution procedure makes use of the spherical-wave modal expansion. The electromagnetic field in a spherical structure (with zero free-charge density) can be represented using vector spherical harmonics [17,18] as:

$$\mathbf{E} = -\sum_n \sum_m a_{mn} \mathbf{M}_{mn} + b_{mn} \mathbf{N}_{mn} \,, \tag{1a}$$

$$\mathbf{H} = -\frac{j}{\eta} \sum_n \sum_m b_{mn} \mathbf{M}_{mn} + a_{mn} \mathbf{N}_{mn} . \tag{1b}$$

where

$$\mathbf{M}_{mn} = \nabla \times \mathbf{r} \psi_{mn} \,, \qquad \mathbf{N}_{mn} = \frac{1}{\beta} \nabla \times \mathbf{M}_{mn} \tag{2}$$

$$\psi_{mn}(\beta, r, \theta, \phi) = \frac{1}{\beta r} \hat{Z}_n(\beta r) P_n^m(\cos\theta) e^{jm\phi} \tag{3}$$

Here ψ_{mn} is the elementary solution of the Helmholtz differential equation, i.e. $\hat{Z}_n$ denotes Schelkunoff type of spherical Bessel or Hankel functions [18], and β denotes the wavenumber of the considered media. Further details and the complete analysis procedure are given in [14, 15].

III. Maximum Power Density

We begin our study of the radiation properties by verifying the usefulness of our spherical model approach. The quantity assessed is the fundamental limit for the maximum power density levels that can be reached just outside the body. To this aim, we simulated using CST Microwave Studio an air sphere antenna implanted inside a *cube body phantom* with the cube side length equal to the diameter of the considered sphere. We compared the results to the ones obtained using a *spherical body phantom* and our spherical waves expansion. The working frequency is 403.5 MHz, the body sphere has r_{body} = 9 cm radius and permittivity is $\varepsilon_{body} = 43.50 - j34.75$ [19, IEEE Head model]. The implanted antenna in this case is a short electrical dipole located in a 2mm diameter air sphere (implanted antenna) placed in the center of the body phantom. The comparison for power density results (in the cube phantom case, the power density is observed on the line passing through the center of the cube side and perpendicular to the excitation electric dipole) is given in Fig. 2 and it shows that the actual shape of the body is not crucial. Moreover, this result validates the applicability of the spherical model in our investigation. Note that the power density is normalized with the factor $W_0/(8\pi/3)\cdot r^2 = W_0/(8\pi/3)\cdot(r_{obs} - r_{feed})^2$, were W_0 is the maximum value of the real part of the power density component normal to the surface of implanted antenna, i.e., just inside the lossy medium.

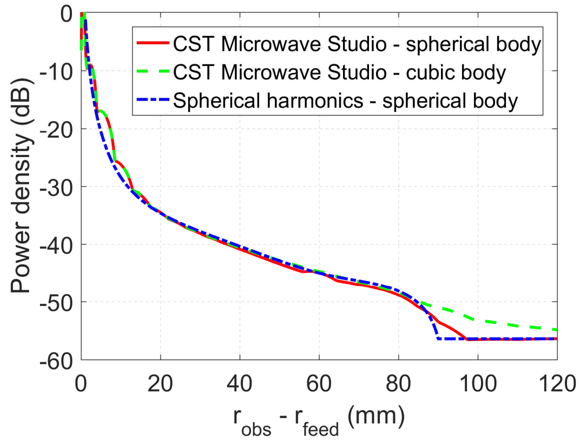

Fig. 2. Radial component of the normalized real part of power density at different distances from the implanted antenna placed in spherical and cubic body. The source is placed at the center of the body.

To study the effect that size of the body and position of the implant have on the power density we will fix the distance of the antenna to the body interface and assume that the orientation of the dipole is transverse to the direction of observation. Fig. 3 shows the power density distribution for two canonical antenna cases – short electric and magnetic dipole inside a spherical air-filled capsule, and for three different spherical body sizes. It is evident that regardless of the size of the body if the implant is at the same distance to the boundary, the maximum obtainable power density is practically the same.

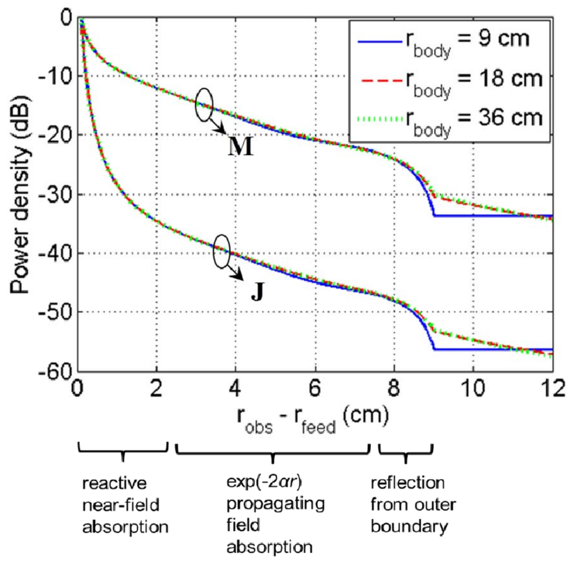

Fig. 3. Radial component of the normalized real part of power density at different distances from the implanted antenna. The source is kept fixed at 9 cm distance from the body boundary. Results for the electric and magnetic dipole are shown.

In both excitation cases however, three segments are visible: reactive near-field part, propagating field part and reflection part. The last two loss contributions are unavoidable for the signal to reach free space, however, the antenna designer should work on the first to minimize the loss. Therefore, the good implanted antenna design will “keep” the reactive near-field inside the capsule. This is also the main difference between the capsules with electric and magnetic dipoles – the magnetic dipole has dominant magnetic reactive near field which does not interact with the host body, while the electric dipole excites dominant reactive electric field which “feels” the lossy surrounding medium.

The position of the implant in the body has a small effect on the power density just outside the body, however the position does give rise to the focusing effect since the body acts similar to a spherical lens. This is illustrated in Fig. 4 in which the angular dependency of the normalized power density is shown as a function of the dielectric sphere radius. The source is kept fixed at a 9 cm distance from the body boundary and the power density is calculated at 0.1 cm distance from the outside boundary of the dielectric sphere. It can be seen that the value of the power density strongly depends on the distance from the source, i.e. on the amount of propagating field absorption losses. In other words, we see once more that for the maximum value of the power density outside the body the shape and dimension of the host medium has very little importance.

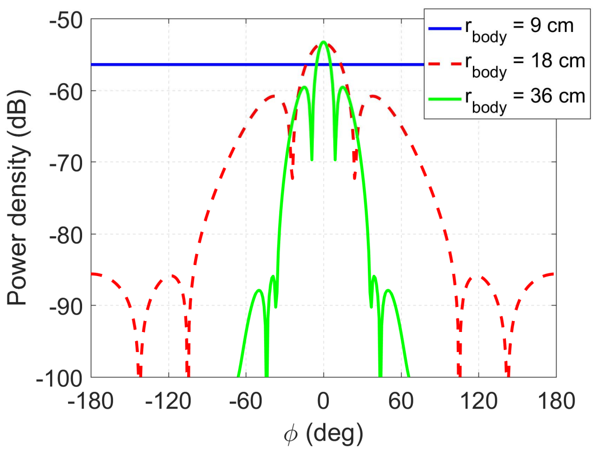

Fig. 4. Angular dependency of the normalized power density as a function of dielectric sphere radius. The *z*-oriented electric dipole is located at the *x*-axis 9 cm away from the boundary in all cases (Fig. 1) and the angular dependency is taken in *xy* plane 0.1 cm away from the outside boundary of the dielectric sphere.

Starting from the spherical mode expansion it is possible to derive the expression for the maximum power density that is obtainable from the implantable antenna located in a body of arbitrary shape and dimensions (see [20] for details):

(a) for the magnetic type of antenna of radius r_{impl} placed at distance Δ inside the body

$$W_{\max} = W_0 \frac{r_{impl}^2}{\Delta^2} \frac{|\bar{\beta}|^2}{2\alpha / r_{impl}} \exp(-2\alpha(\Delta - r_{impl})) \tag{4}$$

(b) for the electric type of antenna of radius r_{impl} placed at distance Δ inside the body

$$W_{\max} = W_0 \frac{r_{impl}^2}{\Delta^2} \frac{|\bar{\beta}|^2 \operatorname{Re}\{\bar{\eta}\}}{\operatorname{Im}\left\{\bar{\eta} / \left(\bar{\beta} r_{impl}^3\right)\right\}} \exp(-2\alpha(\Delta - r_{impl})) \cdot \tag{5}$$

Here $\bar{\beta}$ and $\bar{\eta}$ are complex propagation constant and wave number: $\bar{\beta} = (2\pi/\lambda_0)\sqrt{\varepsilon_{body}} = \beta - j\alpha;\ \bar{\eta} = \eta_0 / \sqrt{\varepsilon_{body}}$ Note that in our spherical model $\Delta = r_{body} - r_{feed}$. Furthermore, the maximum bound does not take into account losses due to reflections since these losses depend on the body boundary properties. A good approximation can be obtained with the large-radius approximation of the spherical body:

$$e_{\substack{\text{losses}\\ \text{due to}\\ \text{reflections}}} \approx \left| \frac{2\sqrt{\varepsilon_{body}}}{1 + \sqrt{\varepsilon_{body}}} \right|^2 \Big/ \operatorname{Re}\left\{\sqrt{\varepsilon_{body}}\right\}. \tag{6}$$

IV. Conclusion

Key performance indicators for small implanted antennas are largley still undefined. Using a spherical body model as reference and encapsulted electric and magnetic current sources we investigated the total radiated power and power density just outside the body as a function of implant size, body sphere size, body shape and position of the implant relative to the body boundary. As shown, the critical dimension for maximum obtainable power density is the depth of the implant, not the shape or the size of the phantom. These results are good indication for realistic cases and can be used to predict obtainable power levels in actual application scenarios.

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