# Evaluation of Bannisters Subsurface-to-Air Model for Implanted Antennas

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***Abstract*—The applicability of P. R. Bannister's subsurface-to-air propagation model for the estimation of the path loss of electromagnetic waves propagating along approximately plane body surfaces and emanating from sources within the body, e.g. wireless implants, is evaluated. Compared to common numerical simulations in the case of antennas within a human body the proposed and exemplarily conducted method allows a de-embedding of the antenna structure and propagation channel.**

## I. INTRODUCTION

In everyday clinical practice a wide range of radio applications are in use. In-Body applications are those which are implanted, injected or administered orally. Often these devices have several purposes at once, like supporting, monitoring and communicating vital functions. A huge challenge in the development of such applications, is the design of the antenna which allows the communication. Various electrically lossy materials and interactions of electromagnetic waves with the interface of the body have an effect on wave propagation and impede a systematic characterization of antennas. The attenuation of electromagnetic waves though is the most dominant effect in human tissue. Additionally, the propagation of electromagnetic waves in inhomogeneous human tissue can be approximated by the propagation of electromagnetic waves in an homogeneous material, which acts as an effective material [1].

Considering a simple and basic antenna structure (i.e. an elementary dipole) immersed in an homogeneous and isotropic electrically lossy material, the physical mechanisms of electromagnetic wave propagation are well-understood and mathematically formulated [2]. However, in the case of an implanted antenna also the interface of the human body and the surrounding medium of the body have to be taken into account.

## II. P. R. BANNISTER'S FORMULAS

Emanating from K. A. Norton's model of an antenna in medium air, close to the surface of a homogeneous electrically conductive material [3] and theories of propagation of electromagnetic waves originating from antennas of Underwater Vehicles, P. R. Bannister found formulas i.a. for the electric and magnetic field components of elementary dipoles, immersed in an electrically conductive medium close to the interface to air [4]. He named his model *subsurface-to-air propagation*. In his formulations he regarded the two interface forming materials as each filling one infinite half space. Bannister's formulas are restricted to materials with an absolute index of refraction equal to or higher than ten. Furthermore, he stated the validity of his formulas also for the *quasi static range*, which is a region relatively close to the respectively regarded antenna structure [4].

Fig. 1 shows a schematic outline of the Bannister model in the case of subsurface-to-air propagation. In his formulas, Bannister considered elementary dipoles normally oriented to the interface, like shown on the left side of Fig. 1, and also dipoles oriented parallel to the interface, like shown on the right side. The center of the antennas is considered in negative z-direction, right under the origin of the coordinate system.

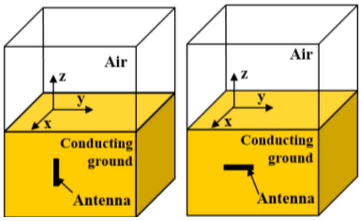


Fig. 1. Schematic outline of the Bannister model

## III. APPLICATION OF BANNISTER'S FORMULAS

We investigated the applicability of Bannister's formulas in the case of small dipole antennas (as an approximation to elementary dipoles) within the human body, close to the interface to air, by comparing results generated by electromagnetic simulation software (EMPIRE XPU) with results gained from analytical calculations with the Bannister formulas. Since it is in good agreement with the demanded material properties for the validity of the Bannister formulas, we chose muscle tissue as an effective body material with material parameters according to [5]. Furthermore, we chose an excitation frequency of $f$ = 2.45 GHz which lies within the industrial, scientific and medical (ISM) radio band.

Fig. 2 shows the considered scenario: A full body model was used for numerical simulations with the Finite Difference Time Domain method (FDTD). The small dipole with a length of $l = 1$ mm was inserted in the tissue material with an immersion depth of $d = 10$ mm within the left breast. The same dipole was considered in two different orientations. First, the dipole was oriented normally to the body surface and afterwards the dipole was oriented parallel to the surface, with the longitudinal axis of the antenna pointing to the legs. In a constant height $h = 10$ mm from the body's surface the absolute electric field values were recorded along the body and are shown in Fig. 3 and Fig. 4. The field values along the three dashed paths shown in Fig. 3 (a) and Fig. 4 (a) are plotted as a function of the distance from the antenna in Fig. 3 (b) and Fig. 4 (b).

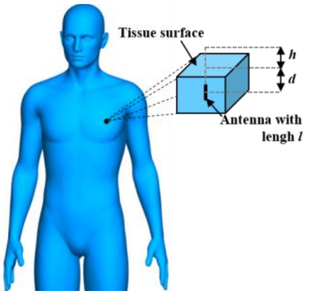
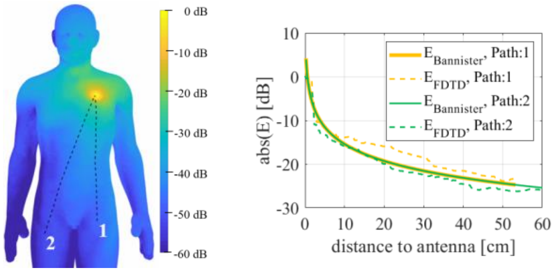


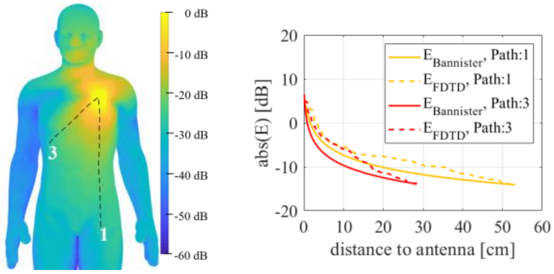
Fig. 2. Schematic outline of the considered scenario



(a) FDTD solution for the absolute electric field

(b) FDTD and Bannister solutions for the respective path

Fig. 3. Analytical and numerical results for a normally oriented dipole



(a) FDTD solution for the absolute electric field

(b) FDTD and Bannister solutions for the respective path

Fig. 4. Analytical and numerical results for a parallel oriented dipole

In order to enable the comparison of the numerical results with results gained analytically from the Bannister formulas, the same dipole antenna as in the numerical simulations had to be considered for the analytical calculations. Hence the dipole moment of the used antenna had to be inserted in the Bannister formulas. The current flowing on the antenna structure and thus the electric dipole moment can be gained from a numerical simulation of the antenna in its immediate environment, like represented by the box in Fig. 2. After characterizing the antenna structure inserted in the medium, desired propagation paths of the electromagnetic waves can be calculated analytically with the Bannister model. However, the current on the antenna structure was determined and the corresponding dipole moment was calculated by multiplying the current with the antenna length. For the calculation of the Bannister solution all paths were considered as in the body model with an height h. The antenna in the two orientations was considered to be immersed as well with an distance d from the interface in muscle tissue. The corresponding solutions from the Bannister formulas can be seen with the solid curves in Fig. 3 (b) and Fig. 4 (b). In the case of a perfectly level and flat interface the radiation of the normally oriented dipole is isotropic in the plane parallel to the surface. Thus the solid green and yellow lines have the same curve progression.

From Fig. 3 (b) and Fig. 4 (b) it can be seen that the results gained by applying the Banister formulas correlate with the results gained from the numerical simulations. Those results indicate that the application of the Bannister formulas allows an estimation of the path loss of the electromagnetic waves along approximately plane body paths, like those shown in Fig. 3 (a) and Fig. 4 (a).

## IV. CONCLUSION

The applicability of the Bannister formulas for the estimation of the path loss of electromagnetic waves, propagating along body surfaces and emanating from small dipole antennas, was exemplarily shown for dipoles inserted in muscle tissue. The bannister model allowed a de-embedding of the antenna structure and the propagation channel. This results in the major advantage of the possibility to characterize one antenna for different application purposes, since the evaluation of different propagation paths is possible by utilizing the Bannister model. A similar approach can be seen for on-body antennas in [6]. Every Antenna structure can be considered as the superposition of elementary dipoles, thus the presented results indicate, that the electromagnetic fields of each antenna structure, along an approximately plane body area, can be estimated by using the Bannister model.

## REFERENCES

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