Limits of WPT through the human body using Radio Frequency

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***Abstract*—Recently, the medical community has been developing new technologies to enhance medical treatments and diagnosis means, having in mind the patients' comfort and safety. Implantable medical devices are an example of such solutions. Nonetheless, these devices present some disadvantages, namely need of batteries. Hence, these implants have a limited lifetime, and require periodical surgical interventions to change or to recharge. In order to solve this problem, systems based on Radio Frequency (RF) has been developed to transfer energy inside the organism. However, transmitting power to inside the human body must be performed carefully, since high power levels might be prejudicial to the subject. In this context, the goal of this work is to study the performance of the Wireless Power Transfer (WPT) to inside the human body, while respecting the Specific Absorption Rate (SAR) limits. Therefore, the levels of absorbed power in different body parts were verified by simulation, in order to reach conclusions about the user's safety. More specifically, two biological models that represent the thigh and the arm were considered. The simulation results led us to conclude that it is possible to transmit approximately 140 mW on the limbs location, while respecting the SAR limits. In turn, it is possible to receive a power superior to 93 µW inside the human body. Additionally, real tests were also carried out in three subjects to verify the power attenuation related to each body structure.**

***Index Terms*—On-body Antennas; Propagation inside the human body; SAR; WPT.**

I. Introduction

Nowadays it is common to wireless supply several devices such as: cars, smartphones, earphones, etc. This is based on the Wireless Power Transfer (WPT) method and recently it became a topic of big interest. However, the idea that is behind this method is known for more than a century, since it was started by Nikola Tesla in 1891, when he illuminated two electric lamps wirelessly in his laboratory in New York [1]. Wireless charging is very advantageous to Implantable Medical Devices (IMD), as it can charge batteries without using wires, thereby extending significantly the lifetime of such devices and eliminating the need for possible surgeries, to replace their batteries [5].

The WPT through Radio Frequency (RF) is one of the most used to wireless charging IMD techniques. It consists on using two antennas being located one outside and the other located inside the body. Since this technique imply an electromagnetic (EM) interaction, it is important to take it into account during the system design, specially due to the human body influence on the antennas' efficiency and the EM impact on the human body. Basic restrictions are suggested by the International Commission for Non-Ionizing Radiation Protection (ICNIRP) [2]. These restrictions are really important because EM exposure can cause tissue heating, since EM waves penetrate the body and vibrate the molecules, causing their friction [2]. Furthermore, long term exposure can change the cell membrane permeability, hence causing disturbs in their functions [2]. The power exposure limit values are expressed in terms of Specific Absorption Rate (SAR). The SAR relates the absorbed power on biological tissues per mass unit (W/kg). The limits suggested by ICNIRP for general public exposure are 2 W/kg for the head and trunk, and 4 W/kg for the limbs [2].

In the literature, there are many solutions using WPT to charge IMDs with RF techniques. For example, in [3] the authors present an implantable antenna embedded in the cerebral spinal fluid, coupled with an exterior loop antenna. To ensure safety, rigorous SAR simulations were conducted. In [6] the authors presented a novel RF powered wireless pacemaker using a rectenna and a wearable transmitting antenna array, operating at 0.924 GHz. The system could achieve 10 dBm of output power, and SAR results grant that is safe for the user. In [7] a miniaturized implantable antenna design for triple-band biotelemetry communication is proposed. The system operates at 402 MHz, 433 MHz and 2.45 GHz. The antenna was fabricated and tested using a front leg of pork.

In this paper, it is identified the maximum transmitted power that guarantees the user's safety and estimate the corresponding received inside the human body. In order to achieve this objective, biological models were designed, and from them the respecting the SAR limits were evaluated to obtain the maximum transmitted power. The designed biological models were tested in simulation, and the obtained results were compared with the ones obtained by practical measurements in three subjects with different physiognomies. Knowing that the most common IMDs can consume power in the range of 8 - 560 μW [8]–[12], it is possible to verify if the received power is enough to successfully supply them.

This paper is divided as follows: first, the antenna design and the biological models that were developed are presented in Section II. In this section, the simulation results are also discussed. Then, Section III presents the results corresponding to the practical measurements. Finally, Section IV presents the main conclusions.

II. Antenna and Biological Models

The antenna used in simulations and practical measures was designed in [4] and it consists on a microstrip antenna, with a Rogers RO4360G2 substrate. The physical dimensions of the antenna are $25 \times 25 \times 3.144$ mm and more information related with the antenna design is detailed in [4].The antenna was designed to be placed above the human skin, operating with a frequency of 915 MHz. Fig. 1 shows the biological model considered during the antenna design and optimization process. The used layers thickness are presented in Table I.

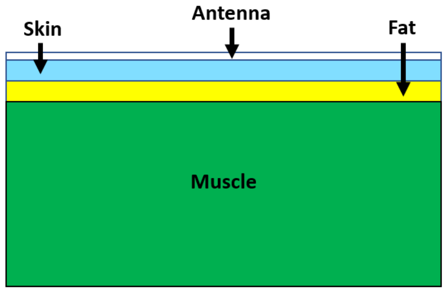

Fig. 1. Biological model used in the antenna design in [4].

TABLE I
Layers thickness of the biological model considered in [4].

Layer	Thickness (mm)
Skin	2
Fat	10
Muscle	28

The goal of this work is to verify if the transmitted power level corresponding to the SAR limits, is enough to supply an IMD, by simulations and practical tests. Therefore, the limbs were the selected body parts for this experiment, having in mind the possibility to later test in different subjects, while respecting their comfort and safety. Thus, skin-to-skin models were designed in the simulation environment, rather than using an implant conventional model, in order to be able to relate the simulation results with the ones obtained during the practical tests.

Two rectangular models with a multi-layer structure were developed to represent the arm and thigh. Subsequently, the transmitting and receiving antennas were on each skin side, as depicted in Fig. 2. The layers thickness are presented in Table II [13] and the biological tissue properties are presented in Table III [13].

The skin-to-skin model was simulated in the CST Studio Suite. Fig. 3 presents the S_{11} parameters considering the model used in the antenna designed and both the skin-to-skin models for the arm and thigh. As one can observe, the transmitting and receiving antennas are not adapted at 915 MHz. Therefore,

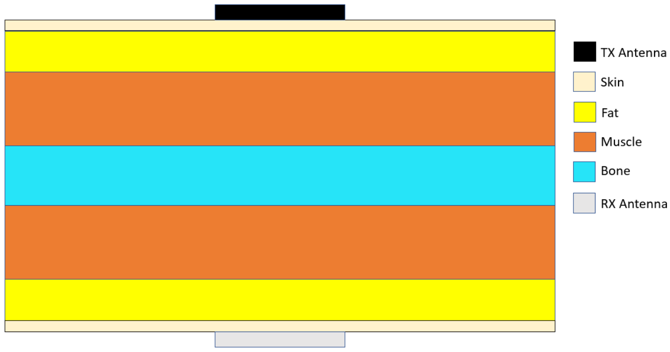

Fig. 2. Skin-to-skin biological model.

TABLE II
Layer thickness for the arm and thigh models in mm [13]

Layer	Arm	Thigh
Skin	2.2	1.9
Fat	10.8	10.4
Muscle	35	45
Bone	24.9	27.2
Total	120.9	141.8

the frequency considered in this analysis was 970 MHz, where the S_{11} parameters present a better value. The frequency used in the analysis was changed, instead of re-optimizing the antenna for this specific model, since in practice it is expected to observe frequency shifts due to the high inter-individual variability, as it is going to be seen in Section III. Different body mass indexes imply different biological models, since each body tissue layer have its specific thickness. On the other hand, although the S_{11} parameters of the skin-to-skin arm and thigh models present a magnitude higher than the one obtained for the original antenna, the results are still considered to be acceptable.

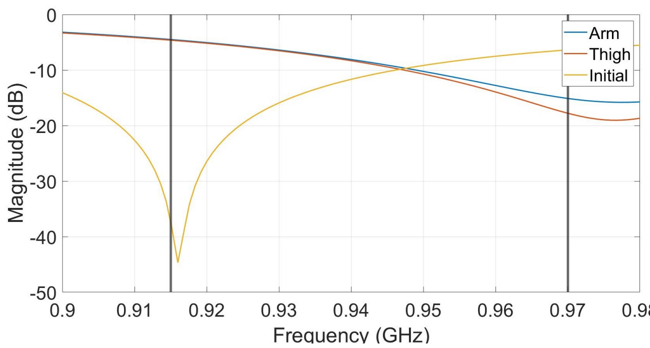

Fig. 3. Simulated S_{11} parameters for initial and skin-to-skin biological models.

SAR (10 g) tests were conducted for the arm and thigh models using CST Studio Suite software, and the results are presented in Fig. 4. As expected, the SAR increases with the transmitted power. The maximum transmitted power

TABLE III
THE DIELECTRIC CONSTANT, ELECTRICAL CONDUCTIVITY AND DENSITY USED IN THE BIOLOGICAL MODEL

Tissue	ϵ_r	σ (S/m)	ρ (kg/m^3)
Skin	41,19	0,88	1100
Fat	11,59	0,092	900
Muscle	55,52	0,902	1080
Bone	12,44	0,145	1000

respecting the suggested limits by ICNIRP are 150 mW and 140 mW for the arm and thigh, respectively. We believe that the 10 mW difference in both models, might be related with the geometry of the analysed body parts and the antennas S_{11} magnitude difference observed in Fig. 3.

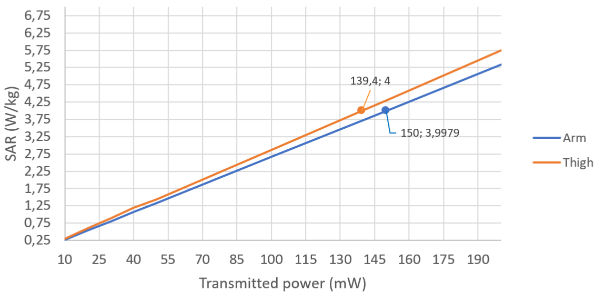

Fig. 4. SAR in terms of the transmitted power at 970 MHz.

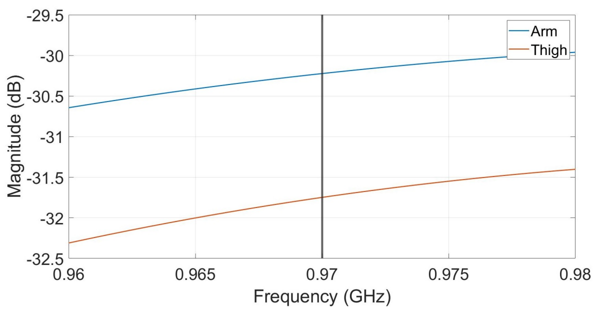

Fig. 5. Simulated S_{21} parameter for the skin-to-skin biological models.

Considering the obtained maximum transmitted power and knowing that the S_{21} parameter (Fig. 5) represents the signal attenuation, it is possible to estimate the received power. So by adding the S_{21} parameter to the maximum transmitted powers, it is obtained 93 μW and 142 μW for the thigh and arm, respectively, neglecting the conversion losses in the RF-DC circuit.

One should note that the power received by an implantable antenna located inside the body, namely close to the fat or the muscle, should be greater than the one obtained by this simulation. This fact is related with the considered skin-to-skin model, since in practice the signal propagates a lower distance and passes through a lower number of tissue layers, when comparing with the one required for the skin-to-skin model. Moreover in [8], [9] the authors support that if the power consumed by the implantable devices is reduced from 10 mW to 8 μW, it could lead to an increase of the device lifetime from 3 days to 10 years. This means that the obtained power for the considered models is sufficient to embrace those consumption. Additionally, this fact indicates that the power range is important not only for the user's safety but also to increase the lifetime of the devices.

III. PRACTICAL MEASUREMENTS

Practical measurements were conducted in three different subjects to support the simulation results with a transmitted power of 10 dBm. For each subject three body zones were analysed: upper arm, lower arm and leg. The transmitting and receiving antennas were located on each side of the considered limb part and the S-parameters were analysed. Fig. 6 presents how the measurement was performed in lower arm for one of the subjects.

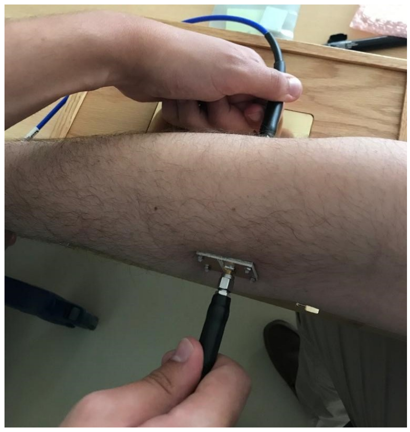

Fig. 6. Measurement setup of the lower arm.

The subjects presented different body mass indexes with the goal of testing the antennas performance when interacting with different physiognomies. The subjects body mass indexes are presented in Table IV. The dimensions of each subject's limbs are presented in Table V.

TABLE IV
THE BODY MASS INDEXES OF THE SUBJECTS

Subject	Body Mass Index (kg/m^2)
A	18.7
B	22.3
C	30

A. S_{11} and S_{22} parameters

Fig. 7, 8 and 9 presents the S_{11} and S_{22} parameters for the lower arm, upper arm and leg respectively. As observed in the previously mentioned figures, all the subjects presented on average acceptable results, in some cases better than the results obtained by simulation. It is also visible that the subject C presents a lower S_{11} and S_{22} magnitude, in almost every body zone when comparing with the other subjects. Furthermore,

TABLE V
BODY ZONES THICKNESS OF THE DIFFERENT SUBJECTS

Subject	Diameter (mm) Lower arm	Upper arm	Leg
A	39.3	58.4	88.7
B	66.4	83.3	117.3
C	82.31	95.04	120.5
Simulated	120,9		141,8

in some cases the S_{22} parameters are different from the S_{11}. Since both transmitting and receiving antennas are the same, this effect might be related with the non symmetric body zones, which have an uneven impact in the antenna performance.

As mentioned in Section II, it is expected that the antenna operating frequency changes when placed in contact with different body parts, and even for different subjects. This effect was indeed observed when analysing the S-parameters, shown in Fig. 7, 8 and 9. Therefore, the chosen frequency for the analysis of the practical results was 930 MHz, since it was the frequency where the best results were observed for all cases.

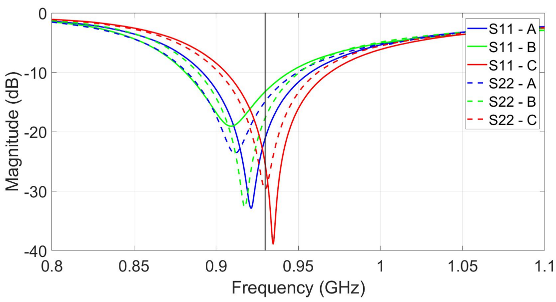

Fig. 7. S_{11} and S_{22} parameters for the lower arm.

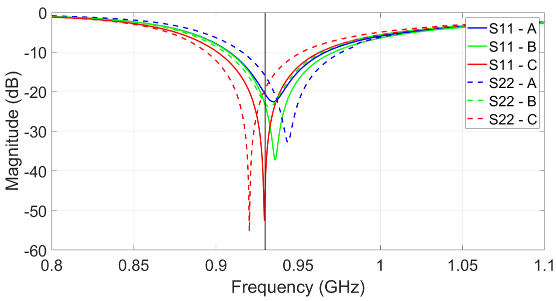

Fig. 8. S_{11} and S_{22} parameters for the upper arm.

B. S_{21} parameter

Fig. 10, 11 and 12 present the S_{21} parameter for the lower arm, upper arm and leg respectively. As it can be observed, the frequency changes to 930 MHz can still be considered valid, since the S_{21} parameter values did not present a significant change within the 930-970 MHz range.

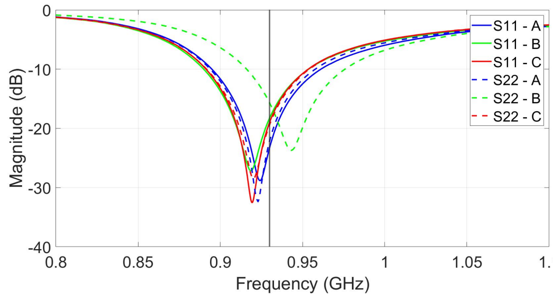

Fig. 9. S_{11} and S_{22} parameters for the leg.

In terms of signal attenuation, subject A is the one presenting the lower values in all the analysed body zones, which was expected since the subject A is in general thinner than the others subjects. Therefore, in these circumstances the signal travels a smaller distance compared with subjects with wider body structures. On the other hand, subject B presented a higher attenuation in the upper arm zone, at the frequency under analysis. By visual inspection, it was observed that subject B presents a developed muscle and less fat when comparing with the other subjects. Table I indicates that the muscle have much more conductivity than the fat layer, inducing higher losses [13], which might explained the obtained S_{21} result. Finally, the high attenuation results observed in subject C, might be related with the thickness of his/her body parts. Table IV indicates that the subject C is the one with larger body parts, which increases the signals travelled path.

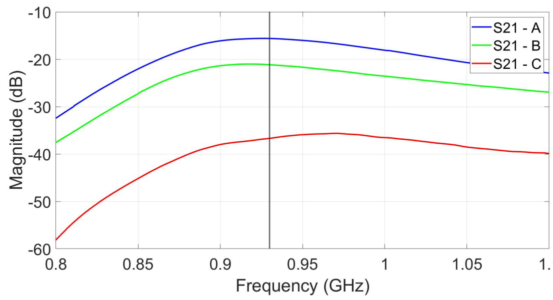

Fig. 10. S_{21} parameter for the lower arm.

IV. CONCLUSION

In this work, biological models were designed and simulated to represent specific body parts, such as the arm and thigh, with the goal to study the performance WPT to inside the human body, while concurrently respecting the SAR limits. The obtained results led us to verify that it was possible to receive a power of 93 μW and 142 μW in the thigh and arm, when transmitting 140 mW and 150 mW, respectively. Nonetheless, one can assume that in practice, the power available at the receiver input is higher than the simulated ones, since the skin-to-skin model represents the worst case

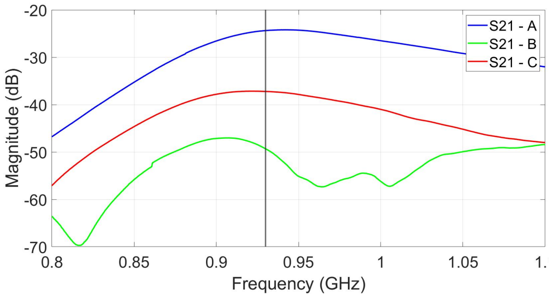

Fig. 11. S_{21} parameter for the upper arm.

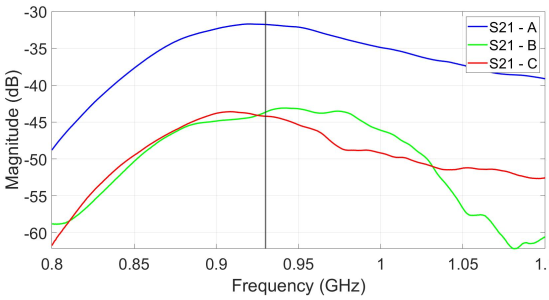

Fig. 12. S_{21} parameter for the leg.

scenario. It should also be mentioned that this model is not totally accurate. Nevertheless, the simulated measurements in this paper may bring some insights.

Afterwards, practical tests were conducted with three different subjects. These subjects presented different body mass indexes, so the tests could cover different body types. The obtained results showed that the S-parameter are highly dependent on the subject's body structure. This means that thinner subjects typically presents lower attenuation (higher S_{21} magnitude). On that account, a strict design of the biological model is crucial for obtaining reliable results.

This is ongoing research and the future work includes the development of an algorithm that could estimate the thickness of the biological tissues based on the subject weight, muscle mass and fat percentage. Additionally, more realistic models should be considered in practice, such as phantoms, in order to measure the SAR values for different input power, and thus validate the simulated results. This phantom, could also be used to validate the received power inside the body.

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