



## ROLE OF PERMITTIVITY MATCHING IN DESIGNING OF EFFICIENT LIQUID IONIC ANTENNA

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### Abstract

The performance of metal antennas when used in Wireless Body Area Networks (WBAN) particularly when used near to or inside the human body has been a challenge due to high dielectric and conductivity contrast with respect to most parts of the human body. During recent times, researchers have shown that liquid ionic antennas are more suitable for such applications. In this paper, we have elucidated the use of NaCl based ionic solution in biocompatible antenna structures. Limitations of some of the previously used liquid ionic antennas have also been identified especially when they are operated near to or inside the human body. The role of permittivity matching of wearable loop antenna with body tissues has also been discussed and the performance of the liquid ionic solution based loop antenna has been compared with the metallic loop antenna using FEKO.

**Keywords:** WBAN, Liquid Antenna, Dielectric Loaded Antenna (DLA), FEKO, Permittivity Matching

### 1. Introduction

During recent times, there has been a lot of development in the field of biosensors and health-related wearable monitoring devices. This growth has also emphasized the need for the exploration of miniaturized, high-efficiency materials that can be operated over a wide range of frequencies but still can be integrated in wearable and lightweight configurations. Metallic antennas do not operate efficiently when planted extremely close to the human body due to the dielectric discontinuity against human as it causes the disruption of their near field. Generally, such antennas have to be insulated, i.e. surrounded by suitable dielectric, especially when they are operated as body-implanted antennas. The electrical properties of such insulating materials affect the radiation characteristics and input impedance of antennas. The performance can be enhanced by changing the shape, material configuration and other aspects. The effect of changing the materials, their configuration and shape of such dielectric-insulators on radiation characteristics have been studied in [1, 2]. On the other hand, Liquid ionic antennas are typically fabricated by injecting liquid metal or liquid metal alloys into an elastomeric substrate and are therefore flexible and mechanically durable. They have been recently used in a variety of reconfigurable microwave components and antennas [3-6]. Such antennas, will perform dual task of antenna as well as biocompatible coating common in conventional implanted antennas. The bio compatibility is

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achieved as liquid antennas or liquid/dielectric enclosed antennas are resistant to corrosion, deformation etc. and have less toxic effects than metals. In water-based liquid antennas, water is used as the radiating element by using water-based liquids with different conductivity. Water-based liquid antennas can be considered as either dielectric resonator antenna or conducting antennas. They have attractive features such as low-cost, readily accessible and compact size [7-9]. The use of aqueous solution of NaCl as antenna as well as permittivity matching coating of a metal antenna have been suggested in [10-12]. But a few observations made in these papers needs a better interpretation. While identifying the performance of aqueous solution of NaCl as antenna, the authors expected that matching the permittivity of wearable antenna with human body will improve the near field and far field radiation characteristics keeping in view the fact that If NaCl solution is customized for its permittivity by selecting proper concentrations of solute and solvent to have a permittivity around 40, which is near to permittivity of human body (Blood:  $\epsilon_r=58$ , Skin:  $\epsilon_r=37$ ) as compared to metallic antenna ( $\epsilon_r=1$ ), then the near field and far field radiation characteristic of the antenna will be improved. It was also proved in [10,11] that effective range of antenna increases if NaCl solution is used as antenna and that Liquid ionic antenna is more efficient than metallic antenna when operated near human body. There remained a need to provide theoretical as well as experimental basis to explain the EM properties of Liquid-ionic solutions as well as detailed interpretation was required for some of the results which have not been interpreted properly in [10,11].

In the next sections, we will provide theoretical as well as experimental basis to explain the EM properties of Liquid-ionic solutions as well as we will explain some of the results which have not been interpreted properly in [10,11].

## 2. Theoretical Background

### 2.1. Effectiveness of antenna-tissue permittivity matching for the case of wearable antenna

The Electric flux density  $D$  is related to the electric field intensity  $E$  by the relation [13]

$$\bar{D} = \epsilon \bar{E} = \epsilon_0 \epsilon_r \bar{E} \quad (1)$$

The  $\epsilon_r$  is a dimensionless constant that indicates how easily a material can be polarized by imposition of an electric field on an insulating material. If a dielectric material is used as an insulating enclosure for an implanted metallic antenna, then by matching the permittivity of such insulator with the tissue results in a reduced reflection coefficient at insulator-flesh boundary [1]. This results in an improved outward radiations for an implanted antenna. But for the antennas working near but outside the human body, the problem of permittivity matching can be avoided altogether by the use of metal antenna that is not touching the human body directly. In this case, the dielectric loading is not required for matching purpose as in case of implanted antenna and it may radiate like a normal antenna surrounded by air [1].

## 2.2. The efficiency of Liquid ionic Antenna

The salt solution antenna has been simulated as a wearable antenna in [10,11]. When operated outside human body, it should be treated as a Dielectric Loaded Antenna (DLA) with salt solution being the dielectric. This is because of the fact that although the ionic solution is good conductor as compared to other liquids, it is still very poor conductor when compared with other metals. For example for a 2.853 mol/Liter NaCl aqua solution,  $\sigma = 12.4 \text{ S/m}$ , whereas for copper  $\sigma = 5.8 \times 10^7 \text{ S/m}$ .

The presence of dielectric material in the surroundings of small antenna increases the electrical volume of antenna because of the high permittivity values ( $\epsilon_r > 1$ ), thus an improvement in antenna performance can be expected. The effects of physical and electrical size of antenna on resulting radiation parameters have been studied in [14-17]. To analyse such antenna, the Efficiency fractional Bandwidth product (EB) as mentioned by Smith in [11] is used as a measure of performance of DLA. In [19], it has been shown that the EB product of the DLA in case of a small dipole has a peak value when permittivity of the dielectric is varied. Such specific permittivity value, for which the EB is maximum, has been derived experimentally by LDA for the case of a monopole DLA [13]. The EB for capacitive antenna can be expressed as [18]:

$$EB = \frac{R_r}{X} \quad (2)$$

Where  $R_r$  is radiation resistance and  $X$  is absolute input reactance of the antenna. Both of these parameters vary with the permittivity of the loaded dielectric. In case of small monopole DLA, variations of  $R_r$  and  $X$  with respect to permittivity has been derived experimentally in [20] (see Figure 1 & 2).

Figure 3 shows the geometry of monopole antenna as used in [20]. EB is calculated for different values of  $\epsilon_r$  of dielectric material is shown in Figure 4.

From Figure 1, The Radiation resistance as a function of  $\epsilon_r$  is approximated as:

$$R_r(\epsilon_r) = \frac{a}{(\epsilon_r + b)^2} \quad (3)$$

Where “a” and “b” are constants. The relation, between inverse of input reactance  $X$  and  $\epsilon_r$  is approximated from experimental results as shown in Figure 2:

$$f(\epsilon_r) = \frac{1}{X} = c\epsilon_r + d \quad (4)$$

Where  $c$  and  $d$  are real constants. Substituting Equation 2 & 3 into Equation 1 yields a derivable function of EB with  $\epsilon_r$  being variable. Hence, we get a maximum positive value of  $\epsilon_{r(\max)} > 1$  for which the EB product is maximum (Figure 4). Mathematically:

$$\epsilon_{r(\max)} = b - \frac{2d}{c} \quad (5)$$

So, we can conclude that for a small DLA operating outside the human body, the efficiency (in terms of EB) is maximum for a particular permittivity of dielectric set by equation derived in a way similar to derivation of Equation 4. So in order to achieve maximum EB product,  $\epsilon_{r(\max)}$  should be evaluated for wearable liquid antenna instead of matching its  $\epsilon_r$  with tissue. In case of implanted antenna however, the situation is different. Such an antenna is metallic but it is coated with an insulator matched to the

surrounding body material such as muscle, liver etc. The insulator such as glycerine, silica etc. is required for bio-compatibility. By matching the permittivity of insulator with its surroundings tissues, we can reduce reflection coefficient at the dielectric-tissue and thus improve radiation strength.

### 2.3. Permittivity of Ionic Solutions

For a dielectric medium, if  $\alpha_T$  = total polarization,  $\epsilon_r$  = relative permittivity of the medium and  $N$  = like molecules per unit volume, then as has been mentioned in [13]:

$$\frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{N\alpha_T}{3\epsilon_0} \quad (6)$$

This relation is called Clausius-Mossotti relation (or when frequency effects of  $\alpha_T$  are included, the Debye Equation. The term  $\alpha_T$  is further given by:

$$\alpha_T = \alpha_e + \alpha_i + \alpha_d \quad (7)$$

where:

$\alpha_e$  = electronic polarizability arising due to shift of negative electronic cloud w.r.t. to positive nucleus

$\alpha_i$  = ionic polarizability arising due to displacement of negative and positive ions as in ionic liquids

$\alpha_d$  = Effect of permanent dipoles of dielectric medium which depends on temperature.

The factor  $\alpha_i$  is the representation of ionic effect of salt-solution. The relative permittivity ( $\epsilon_r$ ) includes this effect through Equation 6. Hence, the  $\epsilon_r$  also represents the ionic nature of a liquid solution.

### 3. Simulations and Results

Simulations have been performed using FEKO, EM simulation software. Liquid antenna as well as metallic antennas of the same physical dimensions has been simulated. A loop antenna with circumference 37cm and tube diameter of 2.5 mm has been excited at 915 MHz. To model the liquid antenna, two metallic plates joined back to back and with an edge port (a type excitation port in FEKO) in between was used to excite NaCl-solution loop at its outer sides. The excitation is brought about by the Lorentz forces (generated by the plates) acting on the free ions in loop, resulting in oscillation of ions thus generating EM radiations. An approximated homogenous human head phantom (skin  $\epsilon_r=37$ , loss tangent=0.175 @ 915 MHz) was placed underneath the antenna. A summary of Materials used in simulation and simulation configuration are provided in Table.1.

**Table 1: Simulation Properties of materials**

Parameter	PEC /Metal	NaCl aqueous solution	Human Head	Low Loss Dielectric
Dielectric Constant	1	40*	41*	4
Loss Tangent (tan $\sigma$ )	0	0.175*	0.414*	0.005

Parameter	PEC /Metal	NaCl aqueous solution	Human Head	Low Loss Dielectric
Peak Excitation Voltage [V]	1	1	–	1
Total input power [W]	1	1	–	1
Frequency (MHz)	915	915	–	915

The first step is to obtain radiation pattern of loop antenna (metallic + liquid ionic) in the absence of head phantom. Results are shown in Figure 5 & 6. For a loop antenna, the maximum radiation is along the axis of loop when circumference of loop equals operating wavelength, hence in case of metal loop, the maximum radiation is along z-axis as shown in Figure 5. But in case of liquid loop, the maximum radiation is not along z-axis. This indicates that whole antenna is not participating in radiation as it is evident from near field plot shown in Figure 6. In fact, the far field radiation pattern is because of the small dipole formed by excitation plates.

Next, the far field patterns of both antenna types were obtained in the presence of approximated human head phantom. These patterns are shown in Figure 7 & Figure 8 respectively. From Figure 7 we can observe that the lower lobe of maximum field strength of metallic antenna has been significantly reduced by the presence of head phantom. Similarly, in Figure 8, the radiations in lower and rear direction are being blocked by head phantom. It is worth mentioning as has been explained in [10] and shown in Figure 2 and Figure 4, radiation pattern in case of liquid ionic antenna have flattened out particularly in the front side and such pattern have lesser areas of weak signal strength and the lower lobe is more pronounced i.e. signal strength have increased to some extent even in areas blocked by head phantom. But the changes in E-pattern are not due to the permittivity matching of antenna and head phantom as explained in [10] but because of the nature of new radiating shape as shown in Figure 8 i.e. dipole formed by excitation plates. Figure 9 & Figure 10 show the far-field patterns in case of excitation plates only (without any liquid ionic medium). Comparing Figure 9 with Figure 6, it can be concluded that the presence of Liquid-ionic antenna only increases effective electrical size of dipole-antenna formed by plates (exactly the same job as that of a dielectric in Dielectric Loaded Antenna) due to high permittivity of salt solution.

Figure 11(a) shows Far fields of NaCl Solution and metal loop antennas in presence of human head whereas Figure 11(b) shows Configuration of loop antenna and human head. The difference in radiation strengths as shown in Figure 11(a) is owed to loss tangents of dielectric medium. If we compare the radiation pattern of liquid ionic antenna with that of metallic antenna, it's easy to see that in case of metallic antenna, the pattern is more evenly distributed. This is the reason that it was believed previously that range of antenna has been improved for the areas of low radiation in case of metallic antenna but this assumption is not correct. As can be seen in Figure 11(a), the effect of high loss tangent of NaCl solution is significant. Figure 12, illustrates the effects of loss tangent on radiation pattern, a vertical cut of E-fields for liquid-ionic antenna ( $\tan \delta = 0.175$ ), an assumed low-loss dielectric antenna ( $\tan \delta = 0.005$ ) and metal plates only ( $\tan \delta = 0$ ) in the presence of human head phantom are obtained at  $\phi=0$  assuming a matched

source for all three cases showing a significant better performance in case of liquid ionic antenna.

#### 4. Conclusion

The dissipative nature of NaCl based ionic solution renders it to be an inferior choice when compared to metallic antenna. As shown by simulations for this paper, matching the permittivity of wearable loop antenna with body tissues yields no better performance when compared with metallic antenna. However, such ionic solutions can be used as a dielectric loading of metallic implanted antenna for proper matching with the local body tissues, thereby reducing the reflection coefficient from dielectric-body tissue boundary. The advantage of using ionic solution for this purpose lies in its adjustable permittivity which is further based on its salinity.

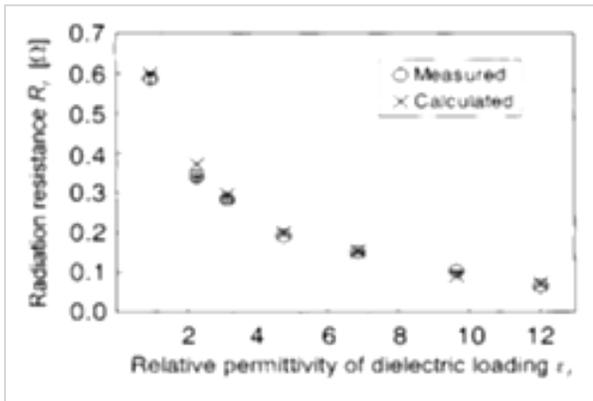


Figure 1 . Permittivity dependence of the radiation resistance  $R_r$  .

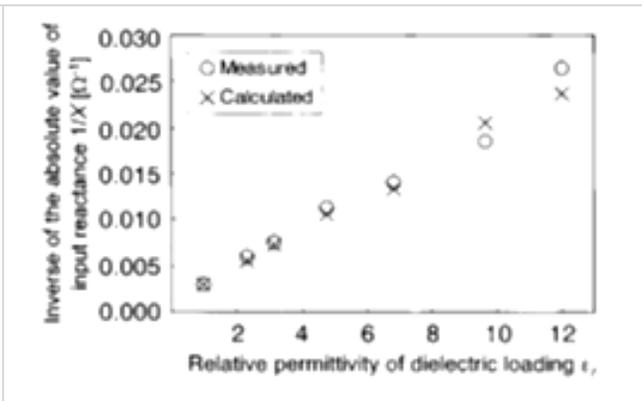


Figure 2. Permittivity dependence of the inverse of the absolute value of the input reactance  $1/X$  .

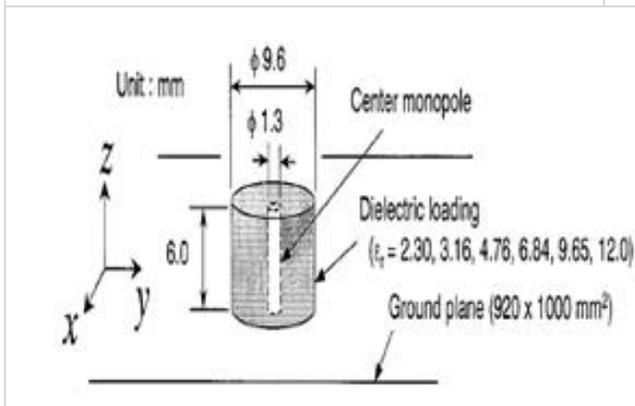


Figure 3. Geometry of the cylindrical DLMA on the ground plane

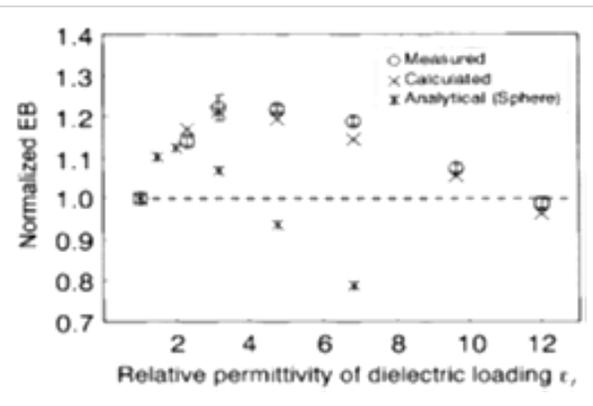


Figure 4. Permittivity dependence of the EB. The broken line is the EB of the bare-monopole antenna. Each EB value is normalized to the EB of the bare-monopole antenna.

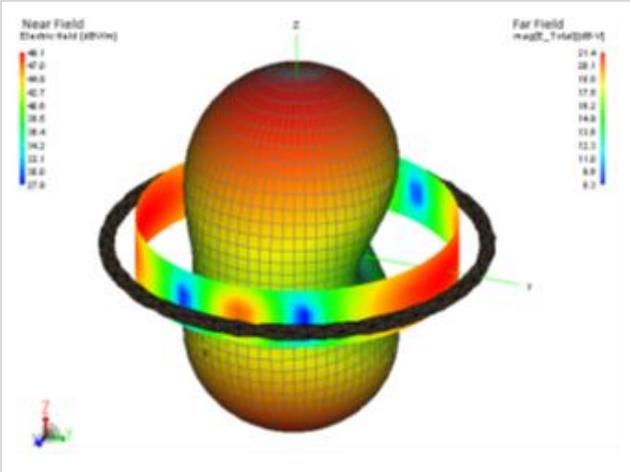


Figure 5. Metallic antenna loop ( 915 Mhz, ). Note the near field plot indicating radiation by whole loop

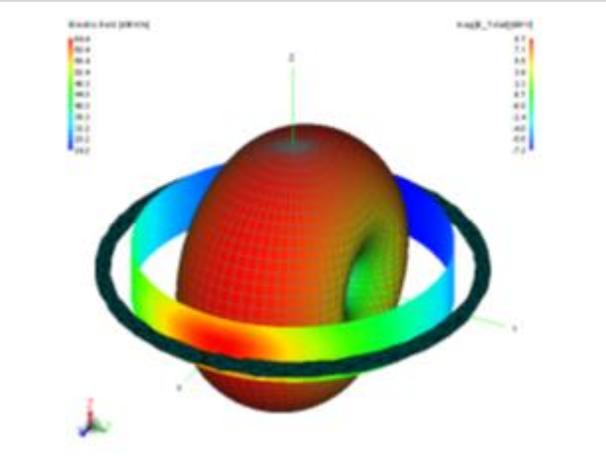


Figure 6. NaCl Solution based antenna ( $\epsilon_r=41$ , loss tangent 0.175) Note the similarity of the antenna pattern to that of dipole. Near field plot clearly shows that only excitation plates are radiating not the whole antenna

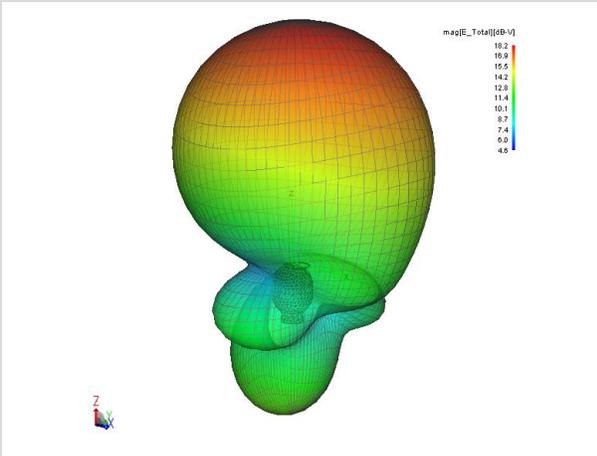


Figure 7. Metallic Antenna in presence of Head Phantom

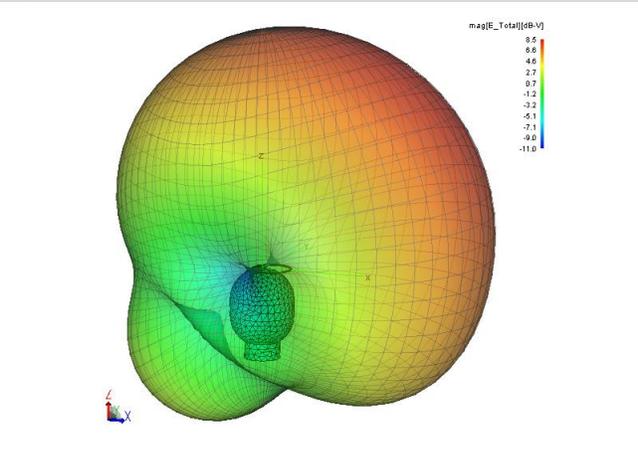


Figure 8. NaCl solution based antenna in the presence of human head

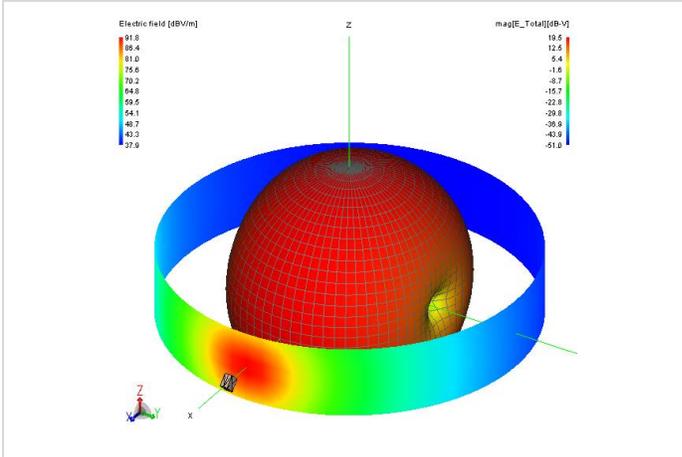


Figure 9. Simulated pattern for excitation plates only, note the similarity to NaCl loops antenna. The radiation in Fig. 6 is primarily due to the dipole formed by excitation plates.

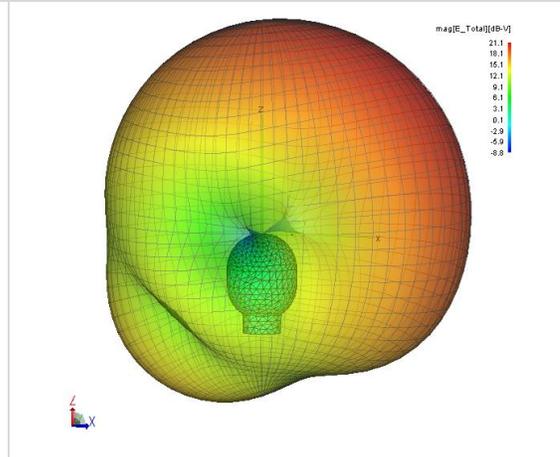


Figure 10 . Excitation plates in presence of human head. Compare with E.pattern of Fig. 8

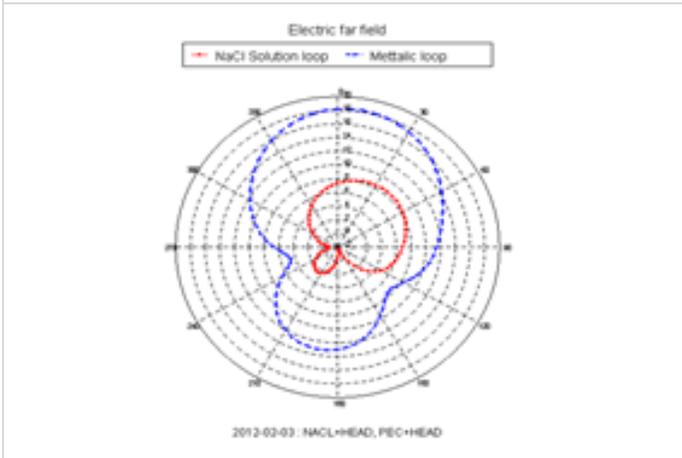


Figure 11(a). Far fields of NaCl Solution and metal loop antennas in presence of human head.( $\phi=0$ ), see adjacent figure for antenna configuration

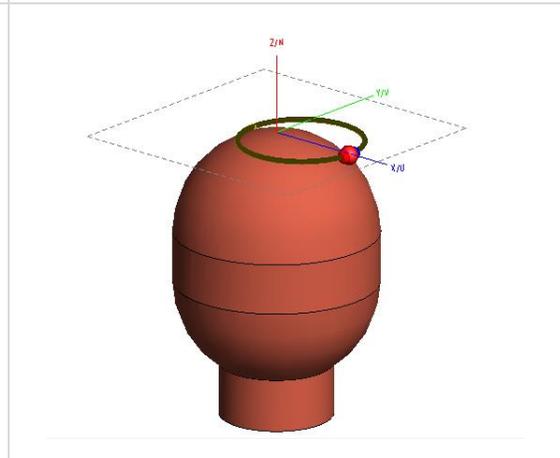


Figure 11(b). Configuration of loop antenna and human head

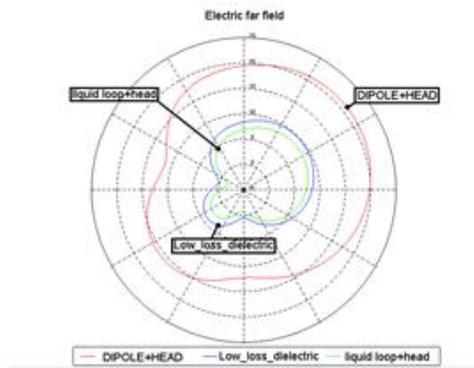


Figure 12. Comparison of E-fields ( $\phi=0$ ) of three different loop materials (pure metal, ionic liquid, low loss dielectric loop)

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