

An Analysis on the Role of Water Content and State on Effective Permittivity Using Mixing Formulas

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Abstract

Two and three-phase Maxwell Garnett mixing formulas are used in conjunction with uncertainty analysis to investigate the extent to which water content and state (free or bound) influence the effective permittivity of biological materials. The results show that a given percent variation in water content can potentially translate into an even larger variation in effective permittivity. Coupled with bound water effects, the variations can account for an appreciable amount of permittivity ranges found in literature. Realizing the considerable effects of water, researchers can benefit by tightly controlling or noting the water content and state when measuring or modeling biological tissue.

1. Introduction

Controversies on the biological effects of electromagnetic fields have existed for many years and, to date, investigators still have not identified the mechanisms by which such fields interact with the body. In order to advance our understanding of these processes, the utmost care must be taken by researchers when acquiring experimental data and performing theoretical studies - the lack, of which, can lead to erroneous results and inaccurate conclusions. Investigations on how the fields penetrate and propagate in the body is a function of the biological tissue's material properties such as permittivity and conductivity. Much work has been done to elucidate these electrical properties in biomaterials over a wide frequency range. However, a review of the literature (Schwan and Foster 1980, Stuchly and Stuchly 1980, Stuchly 1981, Kraszewski et al 1982, Foster and Schwan 1989, Gabriel et al 1996a, b) quickly reveals discrepancies in the measured values of the properties. For example, permittivity ranges for various biological materials at two different frequencies are shown in Table 1. The permittivity provided in the table and throughout the paper is the real part of the complex permittivity and is given relative to the permittivity of free-space, $\epsilon_0 = 8.854 \times 10^{-12}$ F/m. For simplicity and clarity, the focus of this paper will be only on the real permittivity term; however, the methods to be described can be applied to investigate the conductivity term as well. Since the specific absorption rate (SAR) is partly dependent on permittivity (Hurt et al 2000, Gajsek 2001, Keshvari 2006), uncertainties in its value make it difficult to accurately determine electromagnetic field behavior in biological material and to assess potential health risks.

Table 1: Literature ranges of measured water content for man (Altman and Dittmer 1972) and relative permittivity for tissues from man and various animal (Gabriel et al 1996a, b).

Tissue	Water Content Range (%)	Permittivity Range	
		1 MHz	100 MHz
Muscle	73-78	411-3,500	39-90
Bone	44-55	30-209	17-23
Skin	60-76	432-1,000	49-59
Brain	68-73	400-789	53-68

The permittivity of a material is a function of numerous factors including its constituent materials. It is therefore logical to try to elucidate the role that these materials play in accounting for the variability found in literature. Investigators have developed methods in the form of mixing formulas to quantify permittivity due to the levels of the constituent materials. Thus, knowing the permittivity and relative proportions of the materials, one can predict a combined effective permittivity that would result from the mixing of the materials.

For biological materials, water is one of the major constituents. It is important to realize when making biological measurements that the relative percentage of water in the body varies with such things as gender, age, physiologic state, and tissue type (Spector 1956, Altman and Dittmer 1961, Altman and Dittmer 1972). For example, the total body water is generally greater in men than women and the amount of extracellular water tends to decline with age. Water levels for various human tissues are shown in Table 1. In addition to the amount of water, the state of the water can also vary according to how electrochemically bound it is to surrounding biomaterial such as cells and proteins (Cooke and Wien 1971, Berenyi et al 1996, Moser et al 1996, Sulyok 2006). Table 2 shows the relative distribution of water states in the body for various tissues.

Table 2: Distribution of water state for various tissues. Values are percentages of the total tissue water.

	Free	Loosely Bound	Tightly Bound
Skin	26-45	48-64	6-14
Muscle	23-32	54-65	10-16
Liver	20-25	45-63	14-33

Various studies have been performed that have recognized the amount and type of water present when measuring the dielectric properties of tissue (Foster et al 1979, Schepps and Foster 1980, Foster and Schepps 1981, Smith and Foster 1985, Campbell and Land 1992). The studies show that the water variables can account for substantial differences in the dielectric properties of tissues. The objective of this paper is to use mixing theory and uncertainty analysis to investigate the effect of water level and water state on tissue permittivity. The theoretical analysis is being performed to provide deeper insight on the extent to which water variations can account for the wide range of permittivity values found in literature.

2. Theory and Methods

2.1. Mixing Formulas

There are several mixing formulas that can be used to theoretically determine the effective permittivity of a host - inclusion dielectric mixture. One commonly used formula is the Maxwell Garnett mixing rule shown in (1) (Maxwell Garnett 1904). Here, ϵ_{eff} is the effective permittivity, ϵ_w is the permittivity of water (the host material), ϵ_{inc} is the permittivity of the inclusion, and vf is the volume fraction of the inclusion in the host.

$$\epsilon_{eff} = \epsilon_w + 3 \cdot vf \cdot \epsilon_w \frac{\epsilon_{inc} - \epsilon_w}{\epsilon_{inc} + 2\epsilon_w - vf(\epsilon_{inc} - \epsilon_w)} \quad (1)$$

Equation (1) is a two-phase model involving only two constituent materials, spherical inclusions and the surrounding host material. In this work, it is assumed that the host is water and the inclusions are other biomaterials. In addition to the 2-phase model, there exist three-phase versions of the Maxwell Garnett mixing formula (Sihvola 1999, Robinson and Friedman 2002). In one version, there exist two separate inclusions in the host material. In the other version, (2), the

two inclusions exist as concentric spheres, a spherical core surrounded by a spherical shell or layer where vf_a and vf_b are the volume fractions of the bound water shell and inclusion core with permittivity values ϵ_{ia} and ϵ_{ib} , respectively. The concentric spheres model was used for cases in which bound water was considered.

$$\frac{\epsilon_{eff} - \epsilon_w}{\epsilon_{eff} + 2\epsilon_w} = (vf_a + vf_b) \frac{(\epsilon_{ia} - \epsilon_w)(\epsilon_{ib} + 2\epsilon_{ia}) + \frac{vf_b}{vf_a + vf_b}(\epsilon_{ib} - \epsilon_{ia})(\epsilon_w + 2\epsilon_{ia})}{(\epsilon_{ia} + 2\epsilon_w)(\epsilon_{ib} + 2\epsilon_{ia}) + 2\frac{vf_b}{vf_a + vf_b}(\epsilon_{ib} - \epsilon_{ia})(\epsilon_{ia} - \epsilon_w)} \quad (2)$$

Since the effective permittivity becomes a highly nonlinear function of the volume fraction for large permittivity contrasts $\epsilon_{inc}/\epsilon_w$ (Sihvola 1999), a maximum permittivity contrast limit of 20 was allowed between the core and host inclusions in all cases for which (1) and (2) were used.

2.2. Uncertainty Analysis

One of the objectives of this investigation was to use mixing formula theory to explore tissue permittivity variations with changes in water concentration. Two approaches can be taken to perform the investigation. The first method involves the use of (1) where the inclusion volume fraction, vf , is directly adjusted to reflect the desired change in the water volume fraction. The second method is a more formal procedure involving uncertainty analysis. In order to minimize the complexity, and since free and bound water volume fractions are not independent, both methods will use the simpler two-phase mixture equation.

In the first method, the direct application of (1), a value for the inclusion permittivity must be assumed or calculated from a biomaterial. When calculating from a biomaterial, the material's permittivity cannot simply be substituted for the inclusion permittivity and mixed with the newly desired amount of water. Doing so would result in an amount of total water greater than expected. For example, if a tissue contains 50% water and a new level of 75% is desired, simply mixing 75% water with 25% tissue would result in a total water level of 87.5% since half of the original tissue consists of water. Therefore, the process that was used was to first solve the two-phase Maxwell Garnett equation for the inclusion permittivity. The theoretical inclusion permittivity was then calculated by substituting the tissue's permittivity and water volume fraction from literature in for the effective permittivity and volume fraction, respectively. When using literature values, the midpoint of the literature range was used. The calculated inclusion permittivity was then mixed with the desired amount of water to obtain the effective permittivity at the new water level. This process is referred to as an inverse homogenization problem (Cherkaev 2001, Weiglhofer 2001) and it was used to determine the range of ϵ_{eff} for a biological tissue over the desired range of water volume fractions.

The second method used to investigate the effect of water level changes was the uncertainty analysis technique (Northrop 1997, Doebelin 2004). The method is often used to determine the overall level of uncertainty of a measurement when system components or measurement devices have a level of error or uncertainty associated with them. Likewise, the method can be used to investigate the expected level of variability in permittivity if there is uncertainty in the level of water volume fraction. The general formula to determine the total absolute error of ϵ_{eff} due to uncertainties, Δx_i , in the N independent variables x_i , is shown in (3) (Northrop 1997). The approximation in (3) is due to the equation being derived from a Taylor series expansion in which higher order terms are disregarded.

$$Error_{abs} \approx \sum_{i=1}^N \left| \frac{\partial \epsilon_{eff}}{\partial x_i} \Delta x_i \right| \quad (3)$$

Applying the partial derivative to (1), where only the volume fraction of the water is assumed to have error (i.e. the water and inclusion permittivities are assumed to have no error), results in (4). Although vf is the inclusion volume fraction, it can be adjusted to take on the variations of the water volume fraction since the two constituent materials must add up to one in the two-phase model.

$$Error_{abs} \approx \left| \frac{\partial \epsilon_{eff}}{\partial vf} \Delta vf \right| = \left| \frac{3\epsilon_w (\epsilon_{inc} - \epsilon_w) (\epsilon_{inc} + 2\epsilon_w)}{[\epsilon_{inc} + 2\epsilon_w - vf \cdot \epsilon_{inc} + vf \cdot \epsilon_w]^2} \cdot \Delta vf \right| \quad (4)$$

Allowing Δvf and ϵ_{inc} to change, a family of curves can be plotted to investigate the error in ϵ_{eff} as a result of the uncertainty in water volume fraction.

2.3. Bound Water Correction

As described previously and shown in Table 2, water is present in the body in various states – free, loosely bound and tightly bound. The variations of water state can affect the relaxation time of water and its ability to polarize in an electric field. Thus, numerous water properties are affected by its state (Schwan 1965, Pennock and Schwan 1969, Cooke and Kuntz 1974) including the relative permittivity which is about 74 at 37°C for free water over a large frequency range. Investigators have shown that the relative permittivity for tightly bound water between 1 MHz and 1 GHz can be as low as 4 at the material surface and rise to that of free water as the distance from the interface increases (Takashima et al 1986, Teschke et al 2001). Others have determined the permittivity of bound water at microwave frequencies to be 32 or larger (Takashima et al 1986, Sihvola 1999). Ignoring the presence of bound water and its unique permittivity when using mixing theory can lead to the misinterpretation of results and inaccuracies in permittivity calculations.

In order to compensate for the bound water, (2) was symbolically solved for the inclusion permittivity and the water level was adjusted as previously described. Next, a bound water amount assumed to be equal to 5% of the inclusion volume fraction was included, where the bound water permittivity, $\epsilon_{bw} = 4$. The assumption is based on the idea that the bound water is a spherical shell around the inclusion and should therefore be proportional to the amount of inclusion. The bound water volume fraction was, however, subtracted from the volume fraction of free water. The amount of bound water was selected to be at the low end of the tightly bound water range (see Table 2) since the permittivity increases rapidly towards that of free water with distance from the inclusion.

2.4. Effective Permittivity vs. Frequency

To gain insight on the effect of water content and state over a portion of the frequency spectrum, the previously described methods were applied to biological tissue at different frequencies. Though the mixing formulas of (1) and (2) do not have a frequency term in them, they are applicable at various frequencies simply by using permittivity values corresponding to the frequencies of interest (Sihvola 1999). Thus, tissue permittivity values and water volume fraction values at various frequencies were used to first determine ϵ_{inc} . Cases were excluded whenever the calculated ϵ_{inc} to ϵ_{eff} contrast ratio exceeded the limit of 20. The water volume fraction was then adjusted by plus or minus 10% to determine a permittivity range then bound water was incorporated at the 5% level. The process was performed for two biomaterials having different water volume fractions. Additionally, the biomaterials have numerous experimentally measured values available from literature, albeit from different animal species and at different temperatures.

3. Results

Using the Maxwell Garnett mixing formula directly, insight can be gained on the extent to which the volume fraction of water alters the effective permittivity. Figure 1 shows the theoretical ranges of effective permittivity for various inclusion permittivity values when the water volume fraction, or alternately the inclusion volume fraction, is varied from 0% to 100%. It is easy to recognize the two extreme cases of 0% and 100% inclusion where the bars are at the permittivity of water (74) and the value of the inclusion permittivity, respectively. The asterisk line is indicative of the effective permittivity for 70% water and the white portion of the bars shows the range when the water volume fraction range is adjusted $\pm 10\%$. The figure shows that a change of water content from 63% to 77% can theoretically cause an effective permittivity range of 45 to 55 or a $\pm 10\%$ change when $\epsilon_{inc} = 10$.

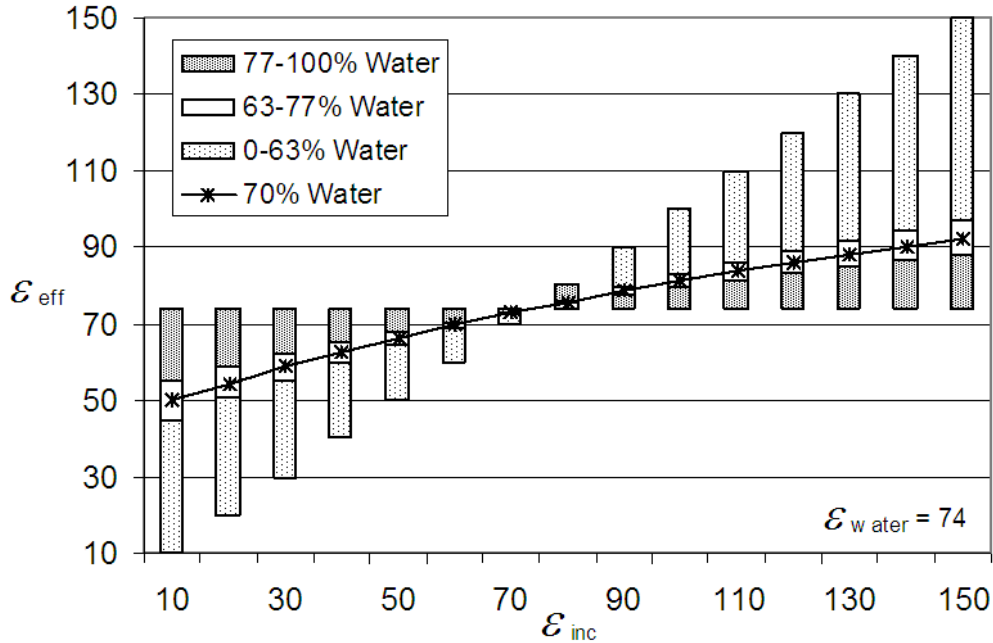


Figure 1: Effective permittivity at various water volume fractions for different values of inclusion permittivity.

Using uncertainty analysis, a more generalized snapshot of the effect of water uncertainty on effective permittivity can be seen as shown in Figure 2. The cases shown are for a water volume fraction equal to 0.75 with no bound water and a water uncertainty range of 0-15%. The inclusion permittivity was allowed to approach the permittivity contrast limit and ranged from 5 to 1400. The plot shows that greater permittivity contrasts between water and the inclusion result in greater percentage errors in the effective permittivity.

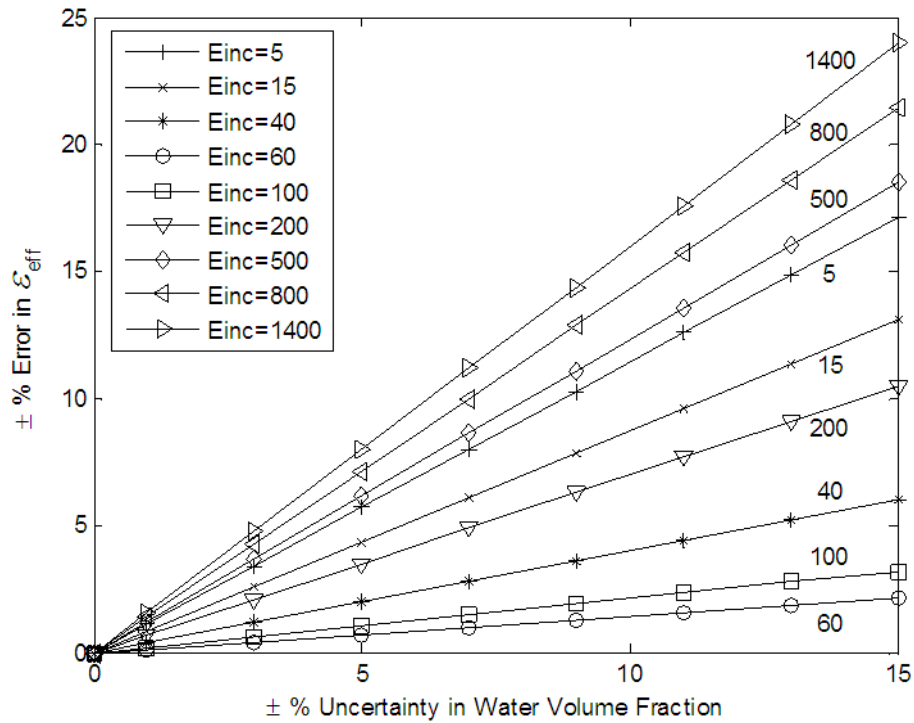


Figure 2: Theoretical error in effective permittivity for various uncertainties in water volume fraction.

In order to determine the effects of water volume fraction uncertainties on biological tissues, ϵ_i must first be calculated. Figure 3 can be used to gain a sense of the inclusion permittivity required to obtain various effective permittivity values. Expectedly, the figure shows that ϵ_i must be greater than the water permittivity to achieve ϵ_{eff} values greater than 74 and vice versa and that the inclusion permittivity for small inclusion volume fractions must deviate more from the host permittivity to achieve the same ϵ_{eff} as for large inclusion volume fractions. The curves also indicate that there is a limit to the ϵ_{eff} that can be achieved for each case. For example, the 10% inclusion curve has a total ϵ_{eff} range of approximately 64 to 98 but, using only positive inclusion permittivity values, it can not reach 100.

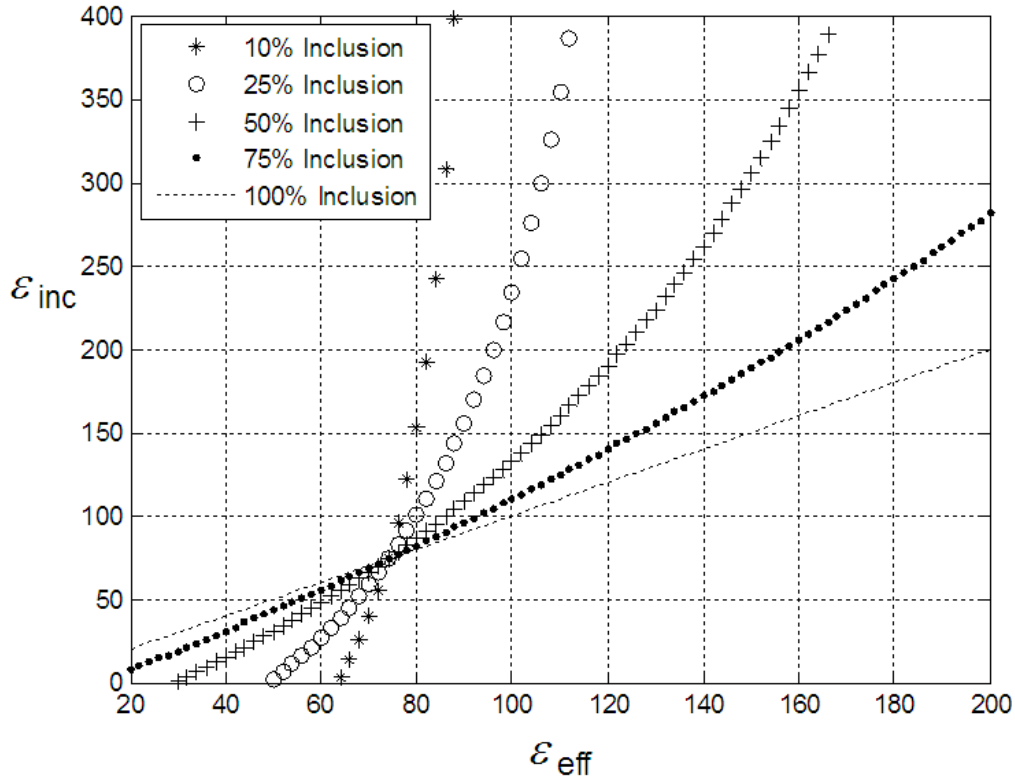


Figure 3: Inclusion permittivity values necessary to achieve effective permittivity values for different volume fractions. $\epsilon_w = 74$

After calculating ϵ_{inc} for the biological tissue cases, the effective permittivity was calculated with water content adjusted to the $\pm 10\%$ level and bound water included at the 5% level. Table 3 shows the calculated inclusion permittivity value that was used and the effective permittivity values with their percent change from the initial condition. Additionally, the amount of the literature permittivity range that is covered by the total range of the four water-adjusted cases is also shown in the “Covered Range” column. For example, for bone at 0.1 MHz, the literature permittivity range has a span of 180 whereas the calculated cases have a span of 97 (111 to 208) or 54% of the literature range. Calculations were done at various frequencies for each material. The data presented are for those cases where the permittivity contrast constraint was met.

Table 3: Effective permittivity for variations in water level and type for bone and muscle at different frequencies. vfw is water volume fraction, bw is bound water

	Freq.	$\epsilon_{material}$ midpoint (range)	ϵ_{inc}	$\epsilon_{eff,+10\%}$	$\epsilon_{eff,-10\%}$	$\epsilon_{eff,+10\%}$ 5%bw	$\epsilon_{eff,-10\%}$ 5%bw	Covered Range
Bone vfw=0.5	0.1 MHz	190 (100-280)	545	174 (-9%)	208 (10%)	111 (-42%)	120 (-37%)	54%
	1 MHz	119.3 (30-208.6)	186	114 (-4%)	125 (5%)	88 (-26%)	91 (-24%)	21%
Muscle vfw=0.76	100 MHz	64.5 (39-90)	40	67 (4%)	62 (-4%)	66 (2%)	59 (-9%)	16%
	1 GHz	53.5 (43-64)	9	59 (11%)	48 (-10%)	59 (10%)	47 (-13%)	57%

4. Discussion

For the tissues shown, the effective permittivity calculated with the $\pm 10\%$ water variation and 5% bound water adjustment covered between 16% to 57% of the permittivity range found in literature. Depending on the initial permittivity, adding 10% to the water volume fraction caused a 4% to 11% change in the permittivity magnitude. Applying the 5% bound water correction shifted the calculated permittivity values downward. As expected, the addition of the low permittivity bound water had a greater effect on the effective permittivity for materials with a larger initial permittivity.

For the analysis shown here, it was assumed that 5% of the water was bound and that $\epsilon_{bw} = 4$. Depending on the actual amount of bound water and the permittivity used, the effective permittivity can be shifted minimally or appreciably towards smaller values. Substantially lower permittivity values would be measured if significantly more bound water is present. Alternatively, ignoring bound water when applying mixing formulas can result in an overestimation of permittivity.

Application of the methods to the bone and muscle tissues which contained different water volume fractions was not particularly revealing. However, comparing the general plot of Figure 2 at a water volume fraction of 0.76 to cases with lower volume fractions (not shown) indicates that the effective permittivity is less sensitive to water content uncertainties for tissues with a lower water volume fraction. Applying the methods at different frequencies only changed the initial tissue permittivity. Although the permittivity values can limit the range for which the methods are applicable, frequency-related information is otherwise inconsequential.

The uncertainty analysis technique was used to show the extent to which variations in water content can affect the overall permittivity of a mixture. The analysis revealed that, depending on the inclusion permittivity, the resultant percent change can be greater than the constituent's percent change. For example, a 5% change in the water volume fraction can cause a 0% to 8% change in the effective permittivity. The analysis can also take into consideration uncertainties in the constituent's permittivity values since they are independent variables. However, it can not be applied to both the water and inclusion volume fractions simultaneously since they are dependent variables.

Since the calculated inclusion permittivity and water level adjusted permittivity values in Table 3 are just isolated cases of the curves shown in Figures 2 and 3, the values can be estimated directly from the figures. Thus, given a material's permittivity and the uncertainty in water content, the inclusion permittivity and the percent permittivity error can be estimated from the figures if the water volume fraction is 0.76.

4.1. Limitations

There are limitations when applying the Maxwell Garnett equation. First, as can be seen in Figure 3, there are cases when a relatively small range of effective permittivities is achieved for a large range of inclusion permittivities. The problem is accentuated for cases possessing small inclusion volume fractions. Second, setting a contrast limit between the host and inclusion permittivities also limits the range of effective permittivities that can be achieved. Together, these limitations also limit the frequency range for which the methods can be applied. In a related topic, the inclusion permittivity necessary to achieve a desired effective permittivity might be very large. For example, the calculated inclusion permittivity for one of the cases in Table 3 is 545. It is assumed in this work that it is practical to use inclusion permittivities of this magnitude.

For the purposes of simplicity and clarity, the analysis methods were applied only to the real part of the complex permittivity, thus ignoring the imaginary conductivity term. However, since the mathematical manipulations centered around the volume fraction term, the real permittivity term can be replaced by a complex permittivity term throughout the work and the same results should be reached. To test this idea and to corroborate the results of the theoretical analysis using the

widely applicable, albeit simple, mixture models presented here an experimental follow up investigation would be appropriate.

5. Summary

Water content and state play important roles in determining tissue permittivity and field distributions in the body. In this work, mixing theory and uncertainty analysis have been used to quantify the extent to which water content and state affect biological tissue permittivity. The results show that a given water percentage variation can potentially translate into an even larger effective permittivity variation. Coupled with bound water effects, the variations can account for an appreciable amount of the permittivity range found in literature. However, numerous other factors such as temperature, orientation, measuring techniques, instrumentation, and tissue dissimilarities can also affect the measured permittivity of biological tissues. Nevertheless, realizing the considerable effects of water, researchers can benefit by either tightly controlling or taking close note of water level and type when measuring or modeling biological tissue. Doing so might help to reduce further discrepancies and erroneous conclusions and allow investigators to more quickly determine the mechanisms, detriments, and benefits of electromagnetic fields on the body.

References

1. Altman P L and Dittmer D S 1961 *Blood and other body fluids* (Washington, D.C.: Federation of American Societies for Experimental Biology)
2. Altman P L and Dittmer D S 1972 *Biology data book* 2nd Edn. vol 1 (Bethesda, MD: Federation of American Societies for Experimental Biology)
3. Berenyi E, Szendro Z S, Rozsahegyi P, Bogner P and Sulyok E 1996 Postnatal changes in water content and proton magnetic resonance relaxation times in newborn rabbit tissues *Pediatr. Res.* 39 1091-1098
4. Campbell A M and Land D V 1992 Dielectric properties of female human breast tissue measured in vitro at 3.2 GHz *Phys. Med. Biol.* 37 193-210
5. Cherkhev E 2001 Inverse homogenization for evaluation of effective properties of a mixture *Inverse Prob.* 17 1203-1218
6. Cooke R and Kuntz I D 1974 The properties of water in biological systems. *Annu. Rev. Biophys. Bioeng.* 3 95-126
7. Cooke R and Wien R 1971 The state of water in muscle tissue as determined by proton nuclear magnetic resonance *Biophys. J.* 11 1002-1017
8. Doebelin E O 2004 *Measurement Systems: Application and Design* 5th Edn (New York: McGraw Hill)
9. Foster K R and Schepps J L 1981 Dielectric properties of tumor and normal tissues at radio through microwave frequencies *J. Microw. Power* 16 107-119
10. Foster K R, Schepps J L, Stoy R D, and Schwan H P 1979 Dielectric properties of brain tissue between 0.01 and 10 GHz *Phys. Med. Biol.* 24 1177-1187
11. Foster K R and Schwan H P 1989 Dielectric properties of tissues and biological materials: A critical review. *Crit. Rev. Biomed. Eng.* 17 25–104

12. Gabriel C, Gabriel S and Corhout E 1996 The dielectric properties of biological tissues: I. Literature survey *Phys. Med. Biol.* 41 2231–49
13. Gabriel S, Lau R W and Gabriel C 1996 The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz *Phys. Med. Biol.* 41 2251–69
14. Gajsek P, Hurt W D, Ziriak J M, and Mason P A 2001 Parametric dependence of SAR on permittivity values in a man model *IEEE Trans. Biomed. Eng.* 48 1169-1177
15. Hurt W D, Ziriak J M and Mason P A 2000 Variability in EMF permittivity values: Implications for SAR calculations *IEEE Trans. Biomed. Eng.* 47 396-401
16. Keshvari J, Keshvari R and Lang S 2006 The effect of increase in dielectric values on specific absorption rate (SAR) in eye and head tissues following 900, 1800 and 2450 MHz radio frequency (RF) exposure *Phys. Med. Biol.* 51 1463-1477
17. Kraszewski A, Stuchly S S, Stuchly M A and Smith A M 1982 In vivo and in vitro dielectric properties on animal tissues at radio frequencies *Bioelectromagnetics* 3 421–32
18. Maxwell Garnett J C 1904 Colours in metal glasses and in metallic films *Philos. Trans. R. Soc. London, Ser. A*, 203 385-420
19. Moser E, Holzmueller P and Krssak M 1996 Improved estimation of tissue hydration and bound water fraction in rat liver tissue *MAGMA* 4 55-59
20. Northrop R B 1997 *Introduction to Instrumentation and Measurements* (Boca Raton, FL: CRC Press)
21. Pennock B E and Schwan H P 1969 Further observations on the electrical properties of hemoglobin-bound water *J. Phys. Chem.* 73 2600-2610
22. Robinson D A and Friedman S P 2002 The effective permittivity of dense packings of glass beads, quartz sand and their mixtures immersed in different dielectric backgrounds. *J. Non-Cryst. Solids* 305 261-267
23. Schepps J L and Foster K R 1980 The UHF and microwave dielectric properties of normal and tumour tissues: Variation in dielectric properties with tissue water content *Phys. Med. Biol.* 25 1149–59
24. Schwan H P and Foster K R 1980 RF-Field interactions with biological systems: Electrical properties and biophysical mechanisms. *Proc. IEEE Inst. Electr. Electron Eng.* 68 104-113
25. Schwan H P 1965 Electrical Properties of Bound Water. *Ann. N. Y. Acad. Sci.* 125 344-354
26. Sihvola A 1999 *Electromagnetic mixing formulas and applications* (London: IEE)
27. Smith S R and Foster K R 1985 Dielectric properties of low-water-content tissues *Phys. Med. Biol.* 30 965-973
28. Spector W S 1956 *Handbook of biological data* (Philadelphia: Saunders)
29. Stuchly M A and Stuchly S S 1980 Dielectric properties of biological substances - tabulated *J. Microw. Power* 15 19–26
30. Stuchly M A 1981 Dielectric properties of animal tissues in vivo at frequencies 10 MHz–1 GHz *Bioelectromagnetics* 1 93–103

31. Sulyok E 2006 Physical water compartments: A revised concept of perinatal body water physiology *Physiol. Res.* 55 133-138
32. Takashima S, Casaleggio A, Giuliano F, Morando M, Arrigo P and Ridella S 1986 Study of bound water of poly-adenine using high frequency dielectric measurements *Biophys. J.* 49 1003–1008
33. Teschke O, Ceotto G and de Souza E F 2001 Interfacial water dielectric-permittivity-profile measurements using atomic force microscopy *Phys. Rev. E* 64 1-10
34. Weiglhofer W S 2001 On the inverse homogenization problem of linear composite materials *Microw. Opt. Techn. Lett.* 28 421 – 423