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DERIVATION OF ELECTROMAGNETIC PROPERTIES OF CHILD BIOLOGICAL TISSUES AT RADIO FREQUENCIES

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Abstract—The knowledge of electromagnetic properties of biological tissues is required to assess the radio frequency energy deposition in children exposed to electromagnetic fields. The issue whether children should be considered a dosimetric sensitive group in comparison to adults, to which the confirmation of age-dependence of human tissue electromagnetic properties potentially may contribute remains debatable at scientific forums. This paper derives the formula for calculation of electromagnetic properties (permittivity and conductivity) of children tissues, as a function of height, weight, and age, respectively. By using the proposed formula, we have calculated and presented electromagnetic properties of the muscle, brain (gray matter) and skin for 1-year-old to 10-year-old children for 900 MHz, 1800 MHz and 2.4 GHz, at which frequencies most of radio frequency devices used by children operate. The trend over the age of child electromagnetic properties has been presented, and electromagnetic properties at different frequencies for the same child age have also been compared. For certain tissues, comparison between the children at various age and adult electromagnetic parameters has been given. A database with electromagnetic properties for children, of all ages, tissues and frequencies may be built up with the proposed approach. It will further advance research on the assessment of children exposure to electromagnetic fields. Formula can also be used for the determination of electromagnetic parameters for children with specific height and weight.

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1. INTRODUCTION

Even though the radio frequency devices have become an indispensable part of our today's modern society, continuous exposure to electromagnetic fields raises concerns regarding the potential effects induced to living organisms as a result of exposure.

Assessment of electromagnetic pollution of our daily environment, both indoor and outdoor, is becoming the priority of research institutions, industry and society in general.

Based on research evidence and in order to ensure public safety, relevant authorities have developed the limits and exposure standards and guidelines, and among them, ICNIRP [1] and IEEE [2] are the most cited, which have been lately revised [3]. Following the research trends and in terms of setting precautionary approach, some countries have set even more rigorous country specific limits on exposure to electromagnetic fields compared with the above international mentioned standards.

Some studies, based on exposure parameters, have identified groups sensitive to electromagnetic fields. Yet, the issue whether children absorb more electromagnetic energy in comparisons with adults for the same exposure scenarios remains debatable at scientific forums.

Children have longer lifetime exposure to wireless devices. They follow different physiological and morphological development patterns and are also exposed to some children-specific devices as baby phones and other wireless toys. Moreover, safety guidelines and standards have been developed for adults, and checking their conservativeness for children is an important issue.

Basic restrictions of safety guidelines are given in terms of SAR (Specific Absorption Rate).

SAR depends directly on electromagnetic properties (permittivity and conductivity) of exposed biological tissue. Therefore, the knowledge of the difference between child and adult electromagnetic properties of biological tissues and variation of properties over child age is required to assess electromagnetic energy deposition to children exposed at electromagnetic pollution.

It has to be pointed out that in terms of the impact on safety studies, not only the age-dependence of electromagnetic properties is important but also the relative mass of the exposed tissue. For example, a significant change of electromagnetic parameters of tissue that make up only a small fraction of the body mass is likely to have a limited effect on the safety.

The objective of this study is to contribute to providing electromagnetic properties of child biological tissues necessary for SAR assessment.

To calculate SAR in children some studies [4–6] assigned the adult electromagnetic parameters to children, neglecting age-dependence of electromagnetic properties.

Some studies in animals reported electromagnetic parameters dependence on age for biological tissues [7–10].

A systematic study Peyman et al. [9] confirmed the age-dependence of a rat biological tissues when presenting measurements of electromagnetic properties for 10-day to 70-day old rats for different frequencies and large number of tissues.

Another study [11] demonstrated the electromagnetic properties change for three age groups of pig tissues. Based on discussions that they held with numbers of vets, the studies on pig and human growth curves with markers along curves (e.g., sexual maturity etc.) reported a partial extrapolation of results to humans. The study concluded that it was more straightforward to correlate the end points, i.e., the piglets to be equivalent to very small children and mature pigs equivalent to adults, whereas the ages in between are more difficult to correlate.

Still, there is no scientific-based general correlation formula or extrapolation methodology that would propose the extrapolation of obtained results of animal electromagnetic properties to humans.

Wang et al. [12] derived an empirical formula for the calculation of age dependency of electromagnetic properties as a function of the total body water content (TBW). TBW was taken from Altman and Dittmer [13] measurements of year 1974, according to which the TBW varies to a great extent under 3-year-old, but becomes insignificant to ages over 3-year-old.

As reported in [14], secular trends in the nutritional status of infants and children alter the relation between age or weight and TBW, thus equations proposed in previous decades overestimated TBW in all age groups, including children.

The aim of this study is to derive a formula to calculate electromagnetic properties of children as a function of children's height and weight. This approach can serve to find the electromagnetic properties of tissues in children as a function of their age, provided that their physical development follows to the average growth curve. Alternatively, the height and weight could be used to estimate the corresponding electromagnetic values.

Up to date, based on our knowledge, there is no database with electromagnetic parameters of child biological tissues at different ages.

From this point of view, based on derived formulas, a software application could be developed that would foster SAR assessment at different child body organs exposed to electromagnetic fields.

Experimental measurement in vivo at different child organs is impossible, and extrapolation of animal results to humans might be debatable since animal tissues differ significantly from human tissues, thus empiric formula for estimating electromagnetic properties might be considered as a reasonable solution for the issue that this paper is addressing, even though at this point the opportunity for validation is very limited, and presented theory needs further experimental validation.

2. METHODS: DERIVATION OF FORMULA FOR CALCULATION OF PERMITTIVITY AND CONDUCTIVITY OF CHILD BIOLOGICAL TISSUES

For the material composed of N composition, relative permittivity based on Leichtencker's logarithmic mixture law [15] may be expressed as:

$$\varepsilon = \Pi_{n=1}^{N} \varepsilon_n^{\alpha_n} \tag{1}$$

Even though formula (1) served as a starting point to Wang et al. [12], it has been regarded for a long time as semi-empirical formula without theoretical justification. Recently, a 2010 study [16] has confirmed that formula can be derived by applying Maxwell's equations and the principle of charge conservation to a mixture for which the spatial distribution of shapes and orientations of the components is randomly distributed.

Human biological tissues are composed mainly of water, thus each biological tissue may be considered as composed by two composites, water and organ specific tissue.

Even though concentration of other compounds, organ specific ones, may also vary with age, for simplification purpose we assume that organ specific part is not age dependent, while main part of biological tissue TBW changes as a function of age.

For the materials composed of two mixtures, one with permittivity ε_1 and the other with permittivity ε_2, applying formula (1), the Leichtencker formula takes the following form:

$$\varepsilon = \varepsilon_1^{\alpha_1} * \varepsilon_2^{\alpha_2} \tag{2}$$

where $\alpha_1 = 1 - \alpha$ and $\alpha_2 = \alpha$.

As noted in [16], Leichtencker mixture formula is symmetric with respect to its constitutes thus: $\frac{\varepsilon}{\varepsilon_2} = (\frac{\varepsilon_1}{\varepsilon_2})^{1-\alpha}$ can be written as $\frac{\varepsilon}{\varepsilon_1} = (\frac{\varepsilon_2}{\varepsilon_1})^{\alpha}$.

Based on above relations and the knowledge that biological tissues consist of water (composite 1) and organic material (composite 2), as described on [12], the relative permittivity of child biological tissues may be presented as:

$$\varepsilon_{r_{ch}} = \varepsilon_{r_w}^{\alpha_{ch}} * \varepsilon_{r_o}^{1-\alpha_{ch}} \tag{3}$$

ε_{r_w} is relative permittivity of water that is equal to 74.3 at 37°C as per [17]. ε_{r_o} is organ specific relative permittivity that does not change with age, while α_{ch} is the hydrated rate of child that is related to mass density and TBW_{ch} by $\alpha_{ch} = \rho * \text{TBW}_{ch}$.

Setting the same relation for adults we get:

$$\varepsilon_{r_A} = \varepsilon_{r_w}^{\alpha_A} * \varepsilon_{r_o}^{1-\alpha_A} \tag{4}$$

By eliminating ε_{r_o} and expressing it as function of an adult relative permittivity which is known, as reported on [12], child relative permittivity can be expressed as:

$$\varepsilon_{r_{ch}} = \varepsilon_{r_w}^{\frac{\alpha_{ch}-\alpha_A}{1-\alpha_A}} * \varepsilon_{r_A}^{\frac{1-\alpha_{ch}}{1-\alpha_A}} \tag{5}$$

Lately, the Mellits and Cheeks formula for the determination of child TBW has been reformulated. According to reformulated formula [18], child TBW in liters for age 3-month-old to 13-year-old and for boys can be expressed as

$$\text{TBW}_{ch} = 0.0846\ (\text{Height} * \text{Weight})^{0.65} \tag{6}$$

If we want to express it in liter per kilogram then:

$$\text{TBW}_{ch}(\text{L/kg}) = \frac{\text{TBW}_{ch}}{\text{Weight}} \tag{7}$$

In order to derive formulas (8) and (12), we make some approximations. For tissues, we consider mass density $\rho = 1.071$ g/ml, that might be taken as an average of mass density for most tissues, but not all of them. Some organs, such as lungs, do have mass density that differs significantly, up to 3 times, from the taken average value. For such tissues the proposed formula has to be adopted.

In order to find α_A, we assume adult weight as 75 kg and TBW as 41.9 liters. Based on measurements conducted on [19], 41.9 liters corresponds to a man who is 20–29 years old.

Substituting the above presented data in (5) and after a few approximations, we derive the formula that expresses the relative permittivity of child biological tissue as a function of child height and weight and a function of an adult relative permittivity.

The formula is considered valid if we refer other values of adult TBW and weight that do not reflect significant change of adult hydration rate α_A.

$$\varepsilon_{r_{ch}}(X) = 2.616^{X-6.63} * \varepsilon_{r_A}^{2.4813(1-0.09X)} \tag{8}$$

Variable X, dependent on child weight and height, is expressed as:

$$X = \text{Height}^{0.65} * \text{Weight}^{-0.35} \tag{9}$$

The complex relative permittivity of a child biological tissue may be expressed as:

$$\underline{\varepsilon_{r_{ch}}} \doteq \varepsilon'_{r_{ch}} - j\varepsilon''_{r_{ch}} = \varepsilon_{r_{ch}} - j\frac{\sigma_{ch}}{\omega\varepsilon_o} = \varepsilon_{r_{ch}}\left(1 - j\frac{1}{\omega\tau}\right) \tag{10}$$

on the assumption that τ, which represents dielectric relaxation constant, is not age dependent.

Based on (10), the conductivity of child biological tissues as a function of relative permittivity may be calculated as:

$$\sigma_{ch}(X) = \frac{10^{-9}}{36\pi\tau}\varepsilon_{r_{ch}}(X) \tag{11}$$

Putting (8) on (11), we get:

$$\sigma_{ch}(X) = \frac{10^{-9}}{36\pi\tau}2.616^{X-6.63} * \varepsilon_{r_A}^{2.4813(1-0.09X)} \tag{12}$$

The proposed set of formulas (8) and (12) will be used for the calculation of permittivity and conductivity of child biological tissues.

Child tissue electromagnetic parameters derived using these approaches are the function of child height and weight, and electromagnetic parameters of adult tissues.

Table 1. Permittivity and conductivity of brain for 5 to 10-year-old children.

BRAIN (GRAY MATTER)						
Age (Years)	900 MHz		1800 MHz		2.4 GHz	
	$\varepsilon_{r_{ch}}$	σ_{ch}	$\varepsilon_{r_{ch}}$	σ_{ch}	$\varepsilon_{r_{ch}}$	σ_{ch}
5	57.24	1.02	55.04	1.53	54.13	1.96
6	57.13	1.02	54.91	1.53	54.00	1.95
7	56.88	1.01	54.64	1.52	53.71	1.94
8	56.63	1.01	54.36	1.51	53.43	1.93
9	56.38	1.00	54.08	1.50	53.14	1.92
10	56.01	1.00	53.67	1.49	52.71	1.91

3. RESULTS: VALUES OF RELATIVE PERMITTIVITY AND CONDUCTIVITY OF CHILDREN BIOLOGICAL TISSUES AT 900 MHz, 1800 MHz AND 2.4 GHz

In order to derive electromagnetic parameters values for a certain child age and based on proposed formulas, a correlation between age-height and age-weight has been used, as a standard child growing curves promulgated by World Health Organization. Values of the child height and weight per age are taken as 50th percentile of growing curve that represents an average age value. The method for extracting electromagnetic parameters for different child growth percentiles remains the same.

The adult electromagnetic parameters are taken from most cited source: Gabriel database [20].

Results for 5 to 10-year-old boys, at frequencies used by wireless applications: 900 MHz, 1800 MHz, and 2.4 GHz, for biological tissues, such as brain, muscle and skin, are presented in Table 1, Table 2 and Table 3.

From the presented tables, the trend of age-dependence and frequency-dependence of electromagnetic properties of child tissues is evident. The highest value of permittivity for 5-year-old child appears at 900 MHz frequency.

The difference between skin permittivities of 5- and 10-year-old children for the same frequency is less than 5%, while the difference of skin permittivities of 5-year-old child at 900 MHz in comparison with 1800 MHz and 2.4 GHz is approximately 6%.

For muscle tissue, the difference between permittivities of 5- and 10-year-old children at 900 MHz is less than 2%, while the difference

Table 2. Permittivity and conductivity of muscle for 5 to 10-year-old children.

MUSCLE						
Age (Years)	900 MHz		1800 MHz		2.4 GHz	
	$\varepsilon_{r_{ch}}$	σ_{ch}	$\varepsilon_{r_{ch}}$	σ_{ch}	$\varepsilon_{r_{ch}}$	σ_{ch}
5	59.13	1.01	57.91	1.45	57.29	1.85
6	59.03	1.01	57.81	1.45	57.18	1.85
7	58.80	1.01	57.56	1.44	56.93	1.84
8	58.58	1.00	57.33	1.44	56.68	1.83
9	58.35	1.00	57.08	1.43	56.43	1.82
10	58.01	0.99	56.72	1.42	56.06	1.81

between muscle permittivity of 5-year-old child at 900 MHz and that at 2.4 GHz is approximately 3%.

A similar trend, the 2% difference, is observed between the brain (gray matter) permittivity of 5- and 10-year-old children at 900 MHz, while difference between brain (gray matter)of 5-year-old child at 900 MHz in comparison with 2.4 GHz is approximately 3%.

Table 4 presents variation of relative permittivity of the brain, muscle and skin tissues at 900 MHz frequency for 1-year-old to 10-year-old children.

Table 3. Permittivity and conductivity of skin for 5 to 10-year-old children.

SKIN						
Age (Years)	900 MHz		1800 MHz		2.4 GHz	
	$\varepsilon_{r_{ch}}$	σ_{ch}	$\varepsilon_{r_{ch}}$	σ_{ch}	$\varepsilon_{r_{ch}}$	σ_{ch}
5	47.62	1.00	45.39	1.38	44.67	1.69
6	47.47	0.99	45.22	1.38	44.50	1.68
7	47.11	0.99	44.85	1.37	44.12	1.67
8	46.76	0.98	44.48	1.36	43.75	1.66
9	46.41	0.97	44.11	1.34	43.37	1.64
10	45.89	0.96	43.56	1.33	42.81	1.62

Table 4. Child tissue permittivity.

$\varepsilon_{r_{ch}}$									
Age (Years)	900 MHz			1800 MHz			2400 MHz		
	Brain	Muscle	Skin	Brain	Muscle	Skin	Brain	Muscle	Skin
1	56.70	58.64	46.86	54.44	57.39	44.58	53.50	56.75	43.85
2	57.20	59.09	47.56	54.99	57.87	45.33	54.08	57.25	44.61
3	57.15	59.05	47.49	54.94	57.83	45.25	54.02	57.20	44.53
4	57.20	59.09	47.57	54.99	57.88	45.33	54.08	57.25	44.61
5	57.24	59.13	47.62	55.04	57.91	45.39	54.13	57.29	44.67
6	57.13	59.03	47.47	54.91	57.81	45.22	54.00	57.18	44.50
7	56.88	58.80	47.11	54.64	57.56	44.85	53.71	56.93	44.12
8	56.63	58.58	46.76	54.36	57.33	44.48	53.43	56.68	43.75
9	56.38	58.35	46.41	54.08	57.08	44.11	53.14	56.43	43.37
10	56.01	58.01	45.89	53.67	56.72	43.56	52.71	56.06	42.81

From Table 4, one can easily extrapolate the difference between end ages, 1-year-old and 10-year-old children, but one can also make a comparative analysis between the electromagnetic parameters of specific age range of interest as a difference between skin electromagnetic properties of 5-year-old and 6-year-old children, as an example.

Variation trends of permittivity in children 1- to 10-year-old at frequencies 900 MHz, 1800 MHz and 2.4 GHz for the muscle, brain and skin are also displayed in Table 4.

Even though the values at different frequencies change, the similar variation trend of tissue permittivity as a function of age is observed at three frequencies, 900 MHz, 1800 MHz and 2.4 GHz.

If we compare obtained permittivity values among different tissues, we notice that we obtain the highest values for the muscle and the lowest for the skin.

The difference between muscle and brain permittivities for the same child age is approximately 3%, while the difference between the brain and skin permittivities for the same child age is almost 20%.

The extrapolation of these results for comparative SAR assessment between different child ages, different frequencies and different tissues is important to assess different scenarios of child exposure to electromagnetic fields of radio frequency devices.

The comparison between the permittivity of child muscle at each age, ranging from 1- to 10-year-old and that of adult muscle at 900 MHz

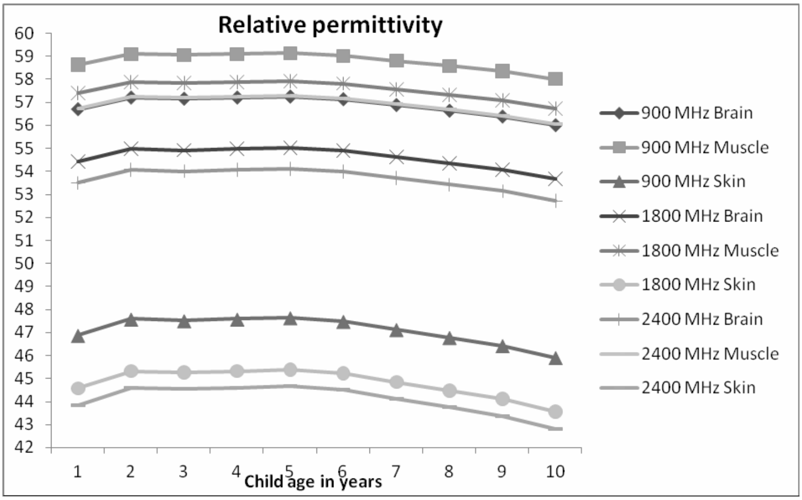

Figure 1. Child tissue permittivity as a function of age.

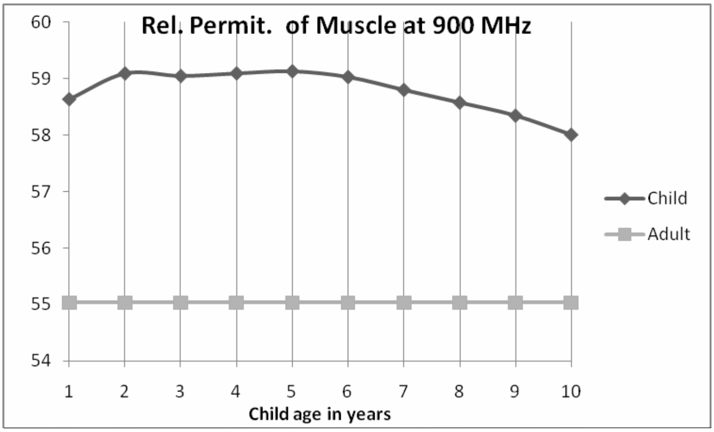

Figure 2. Comparison between child and adult tissue permittivity.

Table 5. Permittivity obtained with different approaches.

Permittivity of 3-year-old child			
	Wang	Our study	Peyman
Skin	43.48	47.49	45.5
Gray Matter	54.25	57.15	51.7

is shown in Figure 2. The difference between the child and adult tissues is 10% in maximum.

Apart from the comparative analysis derived from the data of the present study, the comparison of permittivity calculated using Wang [12] empiric formula and our proposed formula, for the muscle tissue of the 3- and 7-year-old children at 900 MHz is presented.

For 3-year-old children, the derived permittivity using our formula is 59.05 while according to Wang is 57.30. For 7-year-old children, the permittivity derived with our formula is 58.80 while the one derived using Wang is 56.65.

Obtained results derived with our approach, for above presented data, are 3.2% higher than the ones obtained using Wang formula.

In order to make a comparison between methodology of extrapolation of animal tissue electromagnetic properties to human tissues and the calculation of electromagnetic properties with the derived formula, Table 5 presents values of the relative permittivity for 3-year-old children derived from three studies using different approaches.

It should be noted that in study [11] the permittivity is given for ages 1–4 with value 45.5 ± 0.7 for skin. Since the age of 3 is included in this range, for the purpose of comparison we assigned value of permittivity 45.5 for skin. The other range $45.5 + 0.7$ would further converge to result obtained with our approach. The same cannot be concluded for Gray Matter where the difference of obtained results with different approaches is higher.

The comparative analysis of different studies is very limited as there are no systematic studies showing results of electromagnetic properties of children as a variable of tissue and/or age.

On the other hand, the experimental validation remains very limited by the available techniques for measuring the electromagnetic properties of human tissues, even though lately some approaches have been developed for measurement of permittivity of complex tissues that might be used, to some extent, and for biological tissues [21–25].

4. CONCLUSIONS

This paper presents formulas for derivation of electromagnetic properties, permittivity and conductivity of children's biological tissues as a function of children's height and weight.

Electromagnetic properties variation trend as a function of the age, for 50th percentile children, 1-year-old to 10-year-old, has been demonstrated for the brain, muscle and skin at 900 MHz, 1800 MHz and 2.4 GHz.

Even though the values at different frequencies change, a similar variation trend of tissue permittivity as a function of age is observed for the presented radio frequencies.

The highest value of permittivity appears for 5-year-old child at a frequency 900 MHz.

The difference between the permittivities of a 5-year-old and 10-year-old children for the skin is less than 5%, while for the brain and muscle it is approximately 2%.

The difference of the skin permittivities of a 5-year-old child at 900 MHz in comparison with 1800 MHz and 2.4 GHz is approximately 6%, while for the brain and muscle the difference between permittivity of a 5-year-old child at 900 MHz and that at 2.4 GHz is approximately 3%.

The difference between the child and adult muscle tissues is approximately 10%, on average.

The difference between the muscle and brain permittivities for the same child age is approximately 3%, while the difference between the brain and skin permittivities for the same child age is almost 20%.

The advantage of the proposed formula is the possibility of derivation of electromagnetic properties of specific height and weight of children.

The approach can be used to build up an all-inclusive tissue database, with electromagnetic parameters of children at different ages, which do not exist up to date, based on our knowledge.

The results can be used to assess tissue- and age-specific child exposure to electromagnetic fields corresponding to different real-life exposure scenarios.

At the end, a very limited comparative analysis between results obtained with our approach and the other studies has been conducted, which showed a good agreement. Nevertheless, it has to be pointed out that the obtained results of child electromagnetic parameters presented in this paper are predictions of the proposed theoretical model which needs further experimental validation.

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