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Explanatory Notes

With the tissue properties database, IT'IS aims to provide the most complete, reliable, and up-to-date database of values and associated uncertainties for electromagnetic (EM), thermal tissue, flow and acoustic parameters, and for T1/T2 relaxation times. Whenever possible, care is taken to provide material parameters for all tissues included in the 'Virtual Population' models. The calculation of the thermal and dielectric parameters that we provide are based on a critical study of the existing literature. Large variations in reported values can be due to various factors, including the measurement method and conditions, the sample size, the physiological condition of the subjects or tissues studied, inter-subject variation, etc. To achieve sufficient sample size for determining the reported averages and to gain information about parameter variability, the approach adopted to select publication is relatively inclusive. However, studies presenting major flaws are excluded. General considerations used while establishing the database are detailed below.

Thermal parameters

Thermal parameter values are calculated for five key properties: tissue perfusion rate (heat transfer rate, HTR), thermal conductivity (TC), heat capacity (HC), metabolic heat production (heat generation rate, HGR), and density. Literature about these parameters is quite rich, although not for all tissues and all parameters, and educated decisions are made include the best values into the database.

HTR

Determination of the HTR is challenging, primarily because of the natural intra-species variability in physiological condition at the time of measurement. Hence we calculate the mean HTR [ml/min per kg of tissue] by compiling data from human and animal studies. When literature values are reported as percent of cardiac output (% CO), we calculate the mean blood flow rate based on the standard conditions proposed by Williams and Leggett in 1989 [1]. In most cases and whenever possible, only data from young and healthy human subjects are included. When animal data are needed, only animals with physiological properties similar to those of humans are included, assuming that tissue perfusion rates are likely to be comparable. As a matter of fact, the methodologies used in the animal experiments are often more accurate than those used in human experiments and we therefore combine values from human and animal studies in a number of our calculations. In the absence of experimental data for a given tissue, the calculation of the HTR is based on values determined for tissues of similar function and/or with similar cellular composition.

TC and HC

TC and HC, two of the key properties of thermal parameters, are strongly dependent on the composition of the tissue, and on the water content in particular. TC and HC measurements can be found in the literature for only a limited number of tissues. For tissues for which no data is available, we calculate TC

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and HC values based on their water content as proposed in McIntosh and Anderson, 2010 [2]. When water content is not specified, we assume the unknown TC and HC values to be those of a tissue of similar composition and/or function. When a tissue is a mixture of two tissue types with known values for TC and HC, we calculate averages s, e.g., the TC and HC values for thymus are reported as averages of the values for lymph node and fat.
Since we also use review articles as a source of TC and HC values, we may include certain values from a single original study in our calculations multiple times. In such cases, we give those values undue weight. However, these values fall within a narrow range and are unlikely to skew the calculated mean. This is a known limitation that we are addressing.
For fluids, HC and TC are listed for a range of temperatures and in the specific case of air we also propose a fitting function, which is used to generate an additional value at the reference temperature of 37°C.

HGR
HGR is proportional to HTR and is calculated based on Gordon et al., [3]. HTR values used in the equation are drawn from the IT'IS material database and the factors used to convert ml/min/kg to cal/100g/min and subsequently to W/kg are 0.22209 and 0.6973, respectively.

Density
The density values are derived from several publications. When no values are available for a given tissue, we assume that the density is the same as that of a tissue of similar composition and/or function. If no meaningful substitution is possible no value is provided. As for TC and HC values, if a tissue for which no value is available in the literature is a mixture of two tissue types of known density, we report the density as an average.
For fluids, density is listed for a range of temperatures and in the specific case of air we also propose a fitting function, which is used to generate an additional value at the reference temperature of 37°C.

Dielectric parameters
We report dielectric parameter values based on numbers published in the tissue dielectric property database generated by Gabriel et al., 1996 [4], for which dielectric properties were calculated over a frequency spectrum ranging from single Hz to several GHz. This spectral range contains four dispersion regions, and the values can be fit by means of a 4-cole-cole dispersion model. As the Gabriel et al. database covers only a limited number of organs and tissues we use reported dielectric values for an organ of similar function and/or tissue composition in the absence of information. Most other studies reporting measurements of dielectric properties in biological tissues are restricted to a specific frequency range and cannot be described by a 4-cole-cole expression, and are thus not included in the current database. This limitation is being addressed.

Fluid parameters
The dynamic viscosity of different biological fluids is reported at 37°C and whenever possible at various other temperatures. Viscosity data for air and water are available for a large temperature range, which allows the calculation of a temperature-dependent fit. This fit is in turn used to approximate the viscosity of these fluids at 37°C. For certain fluids not all properties are available in the literature. If no meaningful substitution is possible no value is provided.

Acoustic parameters
Data has been collected on the following acoustic properties: speed of sound, attenuation, and non-linearity (B/A). Due to the scarcity of the available information, no distinction is made between attenuation and absorption. For attenuation, a frequency dependence of the form $\alpha=\alpha_0*f^b$ is assumed, where α (Np/m) is the absorption coefficient for a given frequency f, α_0 (Np/m/Hz) is a medium constant, and b is also a numerical constant dependent on the tissue type. In the absence of information (e.g., data points that permit fitting) b is assumed to be 1. For the attenuation relationship, the parameters α and b are obtained by fitting the available data. Whenever a source provides a frequency dependence over a given frequency range, that function is sampled throughout the interval, with a ratio between neighboring frequencies of 1.2 to provide data points for the fit. Cortical bone shows anisotropic attenuation along the longitudinal vs. parallel and radial direction. The reported values are fits along all three directions. For missing data on speed of sound in soft tissues, an arbitrary value of 1500 m/s as this has been done in various studies. To make those cases clearly identifiable n is set to (0). Data on B/A remain sparse and are reported only for a fraction of the tissues in the database.

Longitudinal and transversal relaxation times (T1/T2)
Values are extracted from various publications found in different databases. The longitudinal and transverse relaxation times are reported at 1.5 and 3.0 Tesla. The values in the database originate from *in vivo* studies in healthy adult humans. For blood, both human and bovine studies are included since the blood composition of bovines is comparable to that of humans. Studies with pathological hematocrit and oxygen saturation are excluded. For those tissues for which no values are found, either we assume that the relaxation times are the same as those of tissues of similar composition, or no value is provided.

Low-Frequency Conductivity Values

Health risk assessments of EM fields at low frequency is of great interest to the public, since the utility frequency is 50 to 60 Hz, depending on country, and many electrical appliances operate at low frequencies. It is of utmost importance that the research community has ready access to the most up-to-date, complete, and reliable parameter values required for their research.

The IT'IS dielectric parameter values for frequencies between 10 Hz and 20 GHz are based on the work of Gabriel et al., 1996 [4]. However, these authors state that: "*The predictions of the model can be used with confidence for frequencies above 1 MHz. At lower frequencies, where the literature values are scarce and have larger than average uncertainties, the model should be used with caution in the knowledge that it provides a 'best estimate' based on present knowledge.*" In 2009, Gabriel and colleagues [5] published measurements of the dielectric properties of several pig tissues at frequencies below 1 MHz, and also provided a comprehensive review of the most recent literature on the topic.
The compilation we propose is based on property values for frequencies from 0 – 120 Hz, as reported in the more recent publication of Gabriel et al., 2009 [5]. Whenever possible, we account for tissue anisotropy. To include studies in which tissue anisotropy is not taken into consideration, we calculate the mean of all reported values independent of the direction of measurement. To assure highest accuracy,

we exclude values that are considered as unreliable by Gabriel et al., 2009 [5], and we provide information on the uncertainties in the values we calculate in the form of standard deviations and ranges.

Known Issues

The following list covers some of the problems that arose during the compilation of the material parameter database. Whenever possible, we will address these issues in future updates.

1. There is no data available in the literature for the dielectric properties of urine over the frequency spectrum of single Hz to a few GHz, which is mandatory for fitting to the 4 cole-cole dispersion model. Therefore, for the dielectric parameter values of urine, we have chosen the values for the urinary bladder wall, and for the thermal properties we calculate the mean value of bladder wall and urine.
2. The dielectric properties database generated by Gabriel et al., 1996 [4] contains values for only a few endocrine tissues: thyroid, testes, and ovaries. For all reproductive organs, we use the values reported for testes and, for all other glands, those of thyroid.
3. It is a well-documented phenomenon that the thymus increases in size until puberty and then, with advancing age, undergoes a process known as involution, whereby it gradually becomes reduced in size and the lost volume is replaced by adipose tissue [6]. Since the percentage of thymus tissue replaced varies with age, we express the thymus thermal properties as the mean of the thymus and fat tissue values. However, since in young adults most of the thymus has not yet converted to fat tissue and, in the elderly, the majority of the thymus is already involuted, different thymus:fat ratios should be calculated. For the dielectric properties, we have chosen to fit the 4-cole-cole dispersion model corresponding to the lymph node. However, based on the age of the model in use, fat may be selected for the calculation of the dielectric properties.
4. The content of the stomach and intestine depends on the diet of the subject. For the thermal properties, we calculate an average of water and muscle corresponding to a diet of 50/50 water and meat. For the dielectric properties, we have chosen the values for muscle only.

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