The human body in the presence of electromagnetic spectrum

To study the interaction between human vodies and EM spectrum, we need a description of the ϵ and σ as a function of frequency for the different parts of the human body, especially the skin and the fat/muscle that immediately follows the skin. We can safely assume that $\mu = \mu_0$ as for most substances in nature.

As explained earlier, we can fit a Debye model for the complex permittivity of the different parts of the human body. Similarly, as a first approximation, we can assume that the human body is made up predominantly of salt water and put in the appropriate conductivity. A second order Debye model fitted to various human parts is shown in Table 1 [OG 95].

Tissue	ϵ_∞	ϵ_{s1}	ϵ_{s2}
Muscle	40.0	3948	59.09
Bone/cartilage	3.4	312.8	7.11
Blood	35.0	3563	66.43
Intestine	39.0	4724	66.09
Liver	36.3	2864	57.12
Kidney	35.0	3332	67.12
Pancreas/spleen	10.0	3793	73.91
Lung	10.0	1224	13.06
Heart	38.5	4309	54.58
Brain/nerve	32.5	2064	56.86
Skin	23.0	3399	55.59
Eye	40.0	2191	56.99

Here, $\tau_1 = 4.62 \times 10^{-8} s$ and $\tau_2 = 9.1 \times 10^{-11} s$
chosen as the average of the optimum values for fat and muscle

Table 1: A Table of estimated Debye constants for various constituents of the human body

We note two things here: ϵ_{s1} is much larger than (2 orders) ϵ_2 and τ_1 is three orders longer than τ_2. This implies that at lower frequencies, we can ignore the contribution because of ϵ_{s2} without any significant loss in accuracy of the results. Also, since the values of all the parameters are in the same order for all parts of the human body, we will further simplify by using just one average model.

For conductivity, it is in general very difficult to experimentally fit to the model in (24) for various parts of the human body and as far as I am aware, has not been attempted. Therefore, we will assume a simplification. Experimentally measured conductivity of muscle at different frequencies will be used to estimate the **g** parameter in the complex conductivity equation (24) and thus we can extrapolate the results into higher frequency ranges. An experimental fit gives us $g = 7.2445 \times 10^9$ and $N = 1.337 \times 10^{17}$ which matches with the observed conductivity of muscle between 50Hz and 835MHz. From observing plasma, we note that the imaginary part of the complex conductivity results in interesting behavior. It propagates the EM waves without attenuation. Moreover, the refractive index can be purely imaginary, resulting in total reflection and scattering of EM waves. We can therefore conclude that the imaginary part of the complex conductance exhibits itself as scattering and reflections of EM waves.

In order to study the interaction between the human body and EM spectrum, we need to first chalk out the different frequency regimes a low power line frequenices (50Hz) to near optical frequencies. Table 2 lists some frequency regions that we analyze in this project.

Frequency	Wavelength in air	Order of Relative size
< 3MHz	> 100m	2
3MHz - 30MHz	100m - 10m	1
30MHz - 300MHz	10m - 1m	0
300MHz - 3GHz	1m - 0.1m	$\frac{1}{10}$
3GHz - 30GHz	0.1m - 0.01m	$\frac{1}{100}$
30GHz - 3THz	$10^{-2} - 10^{-4}$m	10^{-4}
> 3THz	$< 10^{-4}$m	very small wrto humans

Table 2: Frequency ranges and the relative sizes of the wavelengths wrto humans

We have listed 7 different frequency ranges where we expect different behavior of the interaction between humans and EM waves. The first range is two orders larger than humans and is where most of radio communications take place. These wavelengths, being much larger than humans, travel unhindered by the human presence. There is a very small damping because of the finite, real conductivity of the humans. The permittivity is essentially real at these frequencies. Figures 2 and 3 illustrate the frequency dependence of conductance and permittivity, from low frequencies to near optical frequencies.

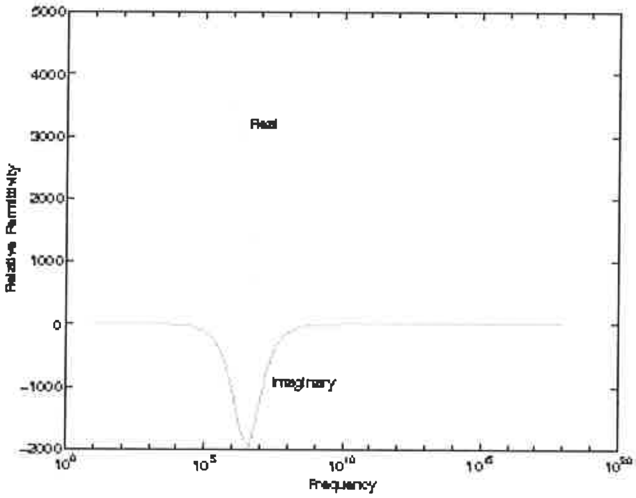

Figure 2: Plot of relative permittivity of human muscle as a function of frequency

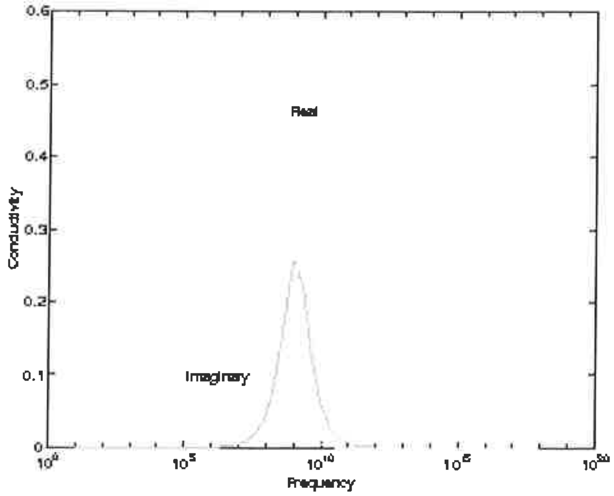

Figure 3: Plot of conductivity of human muscle as a function of frequency

The two figures illustrate very interesting frequency regimes. In Fig. 2, we see that for low frequencies, it is essentially real. Significant complex values begin to occur for frequencies greater than 100KHz. There is a very interesting regime between 100KHz and 100MHz where the permittivity is significantly complex. At about 4MHz, the imaginary part peaks in its value. In this range, the conductivity is esseentially real. From our earlier discussion, we understand that this implies that in this range of frequencies, there is significant dispersion and attenuation (both from the conductivity and from the imaginary part of the permittivity) of frequencies. At 4MHz, the absorption is the highest and the human body essentially acts opaque in this neighbourhood. Beyond 100MHz, the permittivity is essentially real valued. Observing the conductivity plot (Fig. 3), we find that beyond a THz, the human body acts as a dielectric material with **0** conductivity. Between a GHz and a THz, the conductivity is complex and the permittivity is real. Between 10MHz and 1GHz both the quantities are complex. In the GHz-THz band, a complex conductivity implies both significant attenuation (from the real part of the conductance) and scattering of EM waves with a gradual transition from attenuation to scattering as frequencies increase. In the band between 10MHz and 1GHz, with both the quantities being complex, it is difficult to solve the Maxwell's equations to determine behavior because of the multiple cross terms. A numerical simulation is probably an easier alternative. However, we can safely conclude that propagation, attenuation, dispersion and scattering will all be present in varying proportions in this band. We plot the attenuation versus reflection of EM energy from the human body across the frequency range from 1Hz to 10THz in figures 4 and 5.

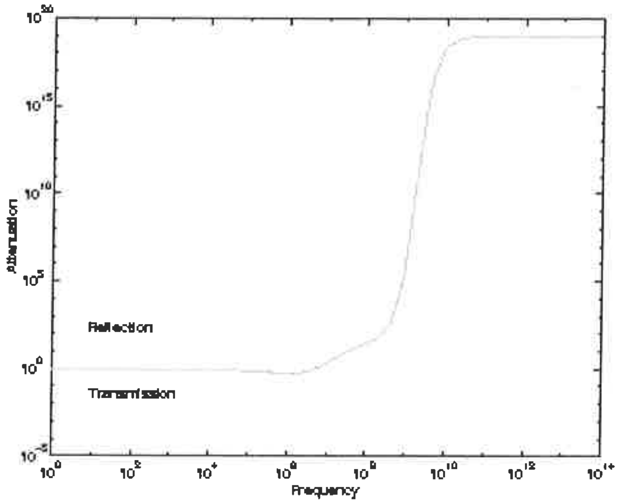

Figure 4: Attenuation and Reflection of a parallely polarized plane EM wave at different frequencies

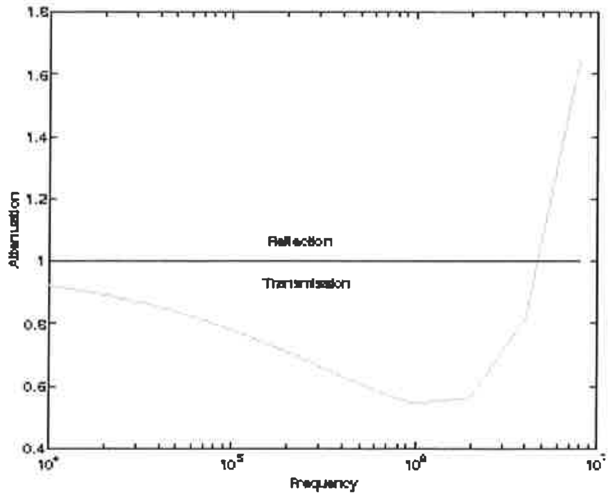

Figure 5: Same figure as above, zoomed into the knee region

Literature review in this frequency band indicates that while people have not studied the exact nature of the interaction, there is significant absorption of EM energy by the human body [OG 95,GC 95]. We have ignored the other constituents of the human body such as fat, bones and skin and have based our reasoning upon muscle. This is because the muscle values represent about the average properties of the human body. There might be minor errors in the exact frequencies but the nature of the plots remains unchanged.

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