Biophysical limitations on the measurement of the biological permittivity using TDR method

Adnen RAJHI

Abstract— In order to measure accurately the broadband frequency dependent of the complex biological permittivity, the dielectric measuring method by the time domain reflectometry method (TDR) using two types of sample holders is presented; the biological medium exhibit different physical behaviours when excited by an EM field; these could be source of errors in the measuring phase and can lead to some limitations. Indeed we can classify the permittivity measurement errors in two types:

- External errors due to the TDR equipment itself.
- Internal errors due to the dielectric sample nature.

In this paper, we attempt to improve the broadband dielectric measurement by taking into account the effect of the biological different physical behaviours in the TDR calibration system, which can be considered as internal calibration factors. We associated the measuring value of the permittivity with three factors and their limits have been investigated with different errors due to the biological sample (S factor), due to the coaxial transmission line holder (T factor) and due to the Laplace transform (L factor); these three factors (T, L and S) and their correlation between them are investigated for the different physical concepts due to the EM interactions with the biological sample. We find the necessity to introduce an internal calibration due to the EM properties of the biological sample leading to correcting coefficients.

Index Terms— complex permittivity, time domain refllectometry, Laplace transform, lumped capacitance, coaxial matched line, DC conductivity, multi-dispersion.

1 INTRODUCTION

HISTORICALLY and for many decades, there is a great interest given by industrials and scientists in an accurate knowledge of the biological bulk dielectric properties (loss factor and dielectric constant) and it has been related to minimise the biological effect due to the hazardous EM radiation of the radio frequency spectrum or to optimize the focalisation of the EM energy beam in a medical diagnostics and therapeutic treatments and for a development of biological sensors for the automation and control of different medical treatments. At first the safety problem were limited to higher frequencies but recently safety problem at lower frequencies is becoming an important subject to be investigated; although the safety limits (from ELF- GHz region) differ from one nation to another, and one of the reasons of this dissimilarity is deemed to the insufficient available basic data for determining the safety limit, specially in the low frequency range. In order to solve some EMC problems and to understand well the EM interactions with biological media, there is an emergency for an accurate measurement of the strongly frequency dependent dielectric properties of the complex relative permittivity of the biological media ($\varepsilon_r^* = \varepsilon_r^{'} - j\varepsilon_r^{"}$).

- *The author is currently teaching in the electrical engineering department in the Higher School of Technology and Computer Sciences at Carthage University, Tunisia. He obtained the Master degree in 1990 and PHD degree in 1994 from the faculty of engineering of Tohoku University in Japan. His research fields are electromagnetic compatibility of electrical communication systems, bioelectromagnetics.*
E-mail: adnen.rajhi@esti.rnu.tn

The dielectric properties measurement techniques and an extensive overview of the different methods are given by many contributors [1]-[8] explaining that each method has its proper features for a particular application and showing also the necessity of the knowledge of the different material dielectric properties which are finding many applications as food processes, environmental problems, medical treatments, biological sensors, agricultural products, etc.

The frequency domain methods, to measure the dielectric properties of materials, are investigated by different contributors [9]-[13] such as the lumped circuit and the balanced bridge methods at low frequencies and the resonant cavity or waveguides at high frequencies and the time domain methods, [14]-[38], (the lumped capacitance method the transmission/reflection method, the open ended coaxial probe) are also given and treated in detail. For biological applications, Stuchly et al [39] have measured the different dielectric properties of different tissues. It has also been reported that the complex permittivity of the biological tissue is related to many concepts, such as the water content percentage in the tissue and its chemical composition and also physical concepts such as the biological thermoregulatory system and the multi-dispersion phenomena. Andrzej [40] has detected the water concentration and its correlation with the dielectric properties. For the physical multi-dispersion concept, K. R. Foster et al [41] have measured the dielectric constant and the loss factor of muscle fibres according to different dispersions (i.e. the dipolar relaxation due to the water content and the dielectric relaxation due to the proteins) and giving a correlation between the temperature and the relaxation time and consequently the dielectric properties dependency with temperature. Also R.Shirakashi et al[42] have developed a coplanar

waveguide circuit line probe of 280 μm to 1mm in order to measure accurately the relaxation properties of soft materials using the differential time domain reflectometry allowing the measurement of the dielectric spectra of a thin layer material.

In [43], it has been shown that the coaxial structure for the sample holder is best suited for low dielectric materials with an error around ±1% and ±5% for higher dielectric materials and can give a broadband measurement dielectric values (from few MHz to 20 GHz). The measurement of the relative complex dielectric permittivity of the biological body using the TDR method have been investigated and the accuracy of this method for biological medium is still not achieved due to the complex nature of this medium which have different physical concepts such as the multi relaxation phenomena of the tissue, the thermoregulatory system, no homogeneous and anisotropic medium; Fig 1 presents the effect of the sample water concentration on the measured and calculated results [44] and [45] of the conductivity and dielectric characteristics for different biological tissues such as the high water content tissues (muscle, blood) and low water content tissues (bone, fat); showing a relatively an important differences between the different values of the conductivities (σ) and the relative permittivity ($\varepsilon_r^{'}$).

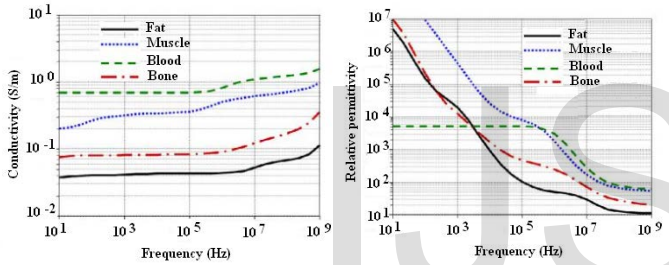


Fig 1. The conductivity and relative permittivity for some biological tissues.

These results can not be used in order to predict the biological effect for hazardous radiation or for an accurate non invasive therapeutic application unless if we take into account the measurement errors due to the nature of the living tissue.

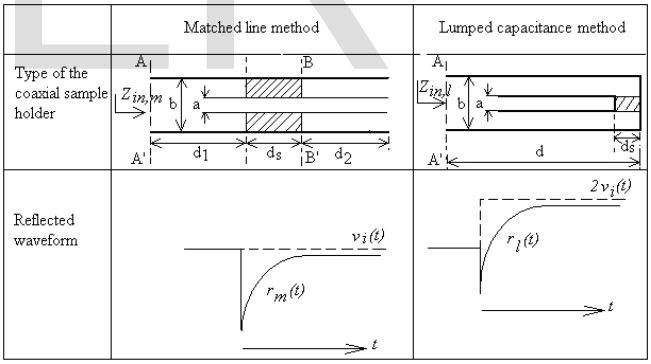
In this paper, we try to include, in the measurement system, the different characteristics of the biological medium which will be source of errors if they are ignored. According to these uncertainties of the measured values of the conductivity and the permittivity by the TDR method, the paper is organized as follow; in section II The basic principle of the measuring TDR method using the matched line and lumped capacitance line from its theoretical point of view and from its experimental point of view is presented. In section III, theoretical considerations of the TDR method are exposed showing that the measured value of the complex permittivity depends on three factors (T, L, S factors). In section IV, the effects of the different characteristics of the living tissue in the measured results are presented and analyzed with respect to T, L and S factors and what correction should be made in the experimental results.

The ambiguities in the measurement due to the specimen size, to the multi-dispersion behaviour of the tissue, to the DC conductivity and to the high frequency permittivity are investigated and exhibiting different sources of errors for both sample holders and discussing the efficient sample holder for different frequency ranges to reduce their effects. These factors due to the nature of the biological sample show that both methods can be complementary to reach more accuracy. In section V, concluding remarks are given and further research points are exposed in order to improve the accuracy of the broadband TDR measurement technique.

2 Basic Principles of the TDR method using two coaxial sample holders

According to the data measured by many contributors, it is shown that the dispersive part $\varepsilon_r^{'}$ and the dissipative part $\varepsilon_r^{"}$ of biological tissue vary from extremely low frequency (at 10Hz, $\varepsilon_r^{'} \approx 0.65 \cdot 10^7$ and $\varepsilon_r^{"} \approx 1.22 \cdot 10^8$) to MW frequencies (at10GHz, $\varepsilon_r^{'} \approx 039$ and $\varepsilon_r^{"} \approx 118.524$). Stuckly et, al.[46] have shown that this wide range variation of $\varepsilon_r^{'}$ and $\varepsilon_r^{"}$ affects the accuracy when only the lumped capacitance cell is used as a sample holder. Low frequency values can not be estimated using this method because of the multi-dispersion behaviour of the tissue [5]; therefore we find the necessity to use also the matched line cell in order to cover the low frequency range. For the broadband time domain measurement method, we used two types of coaxial sample holders (the matched line method and the lumped capacitance method) as shown in the Table I; it can be seen that $r_l(t)$ is larger than $r_m(t)$ for a given sample length; this difference give more information (more accuracy) on the dielectric response and can be used in the global TDR analysis instead of a simple analysis.

TABLE I. THE TWO COAXIAL SAMPLE HOLDERS.



2.1 TDR principle

In the TDR method, an incident short rise time pulse ($V_i = 200mV$ with a finite rise time $T_r < 40ps$) is generated from the TDR equipment and is applied to two different coaxial sample holders (the coaxial matched line cell and the lumped capacitance cell); if the coaxial sample holder has a matched impedance terminal (perfect case) equal to the characteristic impedance Z_0 of the coaxial line, the propagating incident pulse will be completely absorbed at the terminal end of the line without reflection pulse toward the TDR source. But if an impedance discontinuity (due to sample) is present, it will cause the appearance of a reflected wave toward the TDR source. In term of impedances, if the impedance sample is lower than Z_0 , this will lead to a reflected pulse which op-

poses the incident pulse; if the impedance sample is higher than Z_0 , this will lead to a reflected pulse which reinforces the incident pulse. The calibration of this measuring system is made by two types of terminals (short circuit and open circuit). The TDR system, which is sensitive to any impedance variations, displays the reflected pulse in the time domain depending on the coaxial line length and the analysis of the complex reflection coefficient which varies from -1 to 1 for an appropriate line length will give the possibility to measure the dielectric properties of the materials. Fig. 2 shows the measured reflected waves for two different high water content tissues (beef muscle and mouse muscle). The TDR waveform is digitized at 1024 equal time intervals and stored for the analysis using Laplace transforms, and during the analysis period, some systematic errors appears like the time to frequency conversion errors, slow decay of the incident pulse from the limiting constant value (V_i), Wall loss effects of the sample holder cells. These types of errors are minimized by using a sample reference and by increasing the intrinsic signal to noise ratio (SNR) of the TDR equipment by adjusting the degree of averaging of each waveform.

The broad band frequency dependency of the biological complex dielectric permittivity from DC to few GHz, let us make use of two kind of sample holders in the TDR measuring system.

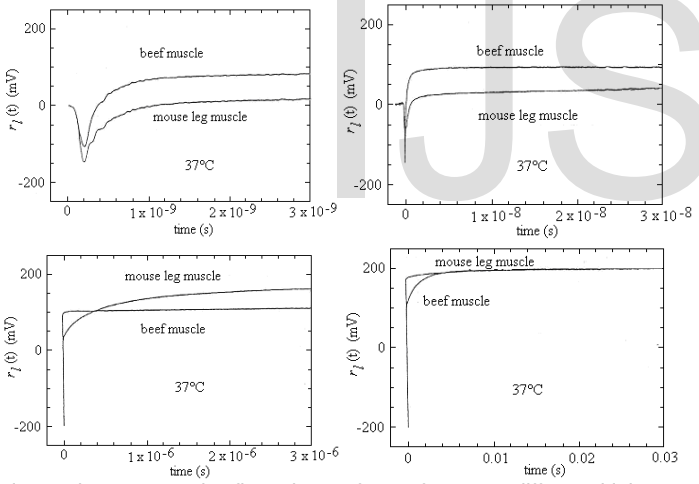


Fig 2. The measured reflected waveforms from two different high water content tissues beef muscle and mouse leg muscle) with different time windows using TDR method.

2.2 The lumped capacitance method

The dielectric response waveform $r_l(t)$ is determined from the difference between the waveform when the sample is inserted and the waveform of the empty cell.

From the theory of a coaxial transmission line, the equivalent circuit of the lumped capacitance sample holder is shown in Fig.3.

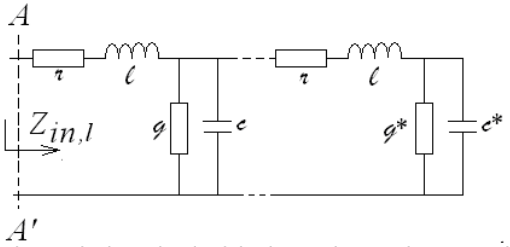


Fig 3. The equivalent circuit of the lumped capacitance method.

From the transmission line theory, at the measuring plane A-A′, the input impedance $Z_{in,l}$ can be written as :

$$Z_{in,l} = Z_0\left(\frac{Z_L + Z_0\tanh(\gamma d)}{Z_0 + Z_L\tanh(\gamma d)}\right) \quad (1)$$

with d is the transmission line length and γ is the propagation coefficient of the transmission line filled with the sample. This method perform the higher frequency limit but a serious problem appear at very high frequencies when the values of the stray capacitance C_s is comparable to the empty cell capacitance C_0, and to avoid this effect on the complex permittivity values, the experiment was repeated with a pure sample.

2.3 The matched line method

The coaxial sample holder is terminated with a load of the same characteristic as the empty line (50 Ω) and the dielectric response behaviour is analysed by calculating the reflected waveforms $r_m(t)$ which is the differences between the waveform when the sample is inserted and the waveform of the empty cell. The equivalent circuit of the matched line sample holder is shown in the Fig. 4. At the plane B-B′, the input impedances can be approximated by :

$$Z_{in}^{B} = Z_0\left(\frac{Z_L + Z_0\tanh(\gamma d_2)}{Z_0 + Z_L\tanh(\gamma d_2)}\right) \quad (2)$$

and at the measuring plane A-A′, the input impedance is expressed by:

$$Z_{in,m} = Z_0\left(\frac{Z_{in}^{B*} + Z_0\tanh(\gamma(d_1 + d_s))}{Z_0 + Z_L\tanh(\gamma(d_1 + d_s)}\right) \quad (3)$$

with $$Z_{in}^{B*} = Z_{in}^{B}\,//(\frac{1}{g*})//(\frac{1}{jc*\omega})$$

For lossless coaxial transmission line ($r = 0,\ g \to \infty$) and for nonmagnetic samples:

$\gamma d_2 = j\frac{\omega}{c} d_2 \sqrt{\varepsilon_r} = j\beta$, $Z_{in}^{B*} = Z_{in}^{B} // (\frac{1}{jc^*\omega})$,

and for an open end transmission line ($Z_L \to \infty$), the input impedance Z_{in}^{B} is expressed by $Z_{in}^{B} = -jZ_0 \coth(\beta)$ and

$$Z_{in}^{B*} = \frac{-jZ_0 \coth\beta}{1+\varepsilon^* c\omega Z_0 \coth(\beta)} \quad (4)$$

we note that when the quantity $\left|\varepsilon^* c\omega Z_0 \coth(\beta)\right| << 1$

$\Rightarrow \omega \coth\beta << 1/cZ_0$,

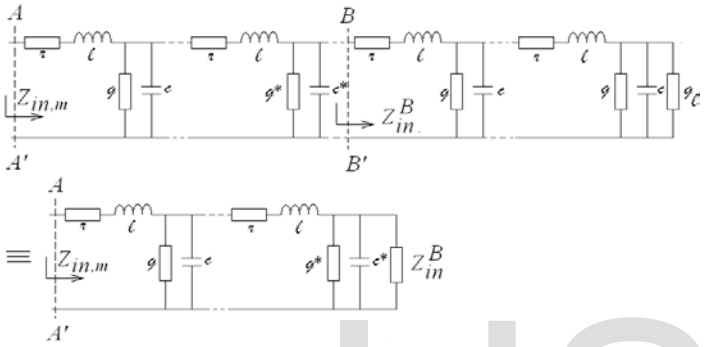


Fig 4. The equivalent circuit of the matched line method.

we find that $Z_{in}^{B*} = Z_{in}^{B}$ and the measured signal does not give any information on the dielectric permittivity; therefore the matched line method can be used for the dielectric measurement in the case when $\left|\varepsilon^* c\omega Z_0 \coth(\beta)\right| > 1$.

The DC properties (when $\omega \to 0$) of the material is determined from the sample response amplitude and is correlated with the value of the quantity $\left|\varepsilon^* c\omega Z_0 \coth(\beta)\right|$; for that and for extremely low frequency measurements, the length d_s of the sample should be variable.

3 Theoretical Description

At the measuring plane A-A' for both sample holders, the incident and reflected pulses are measured and stored after making the appropriate calibration test for each sample holder and by determining the capacity C_0 of the empty cell sample (filled with air) or the impedance Z_{0a} and secondly for more accurate measurements, we make an adjustment in the efficient length which is expressed by $\frac{Z_s}{Z_{0a}} d$ (with Z_s sample impedance and d is the line length) and this adjustment can be realised by the use of the matched coaxial sample; for the low frequency domain, the value of the sample length d_s should be relatively important; however for higher frequencies, it should be very small.

For lossless lines and for nonmagnetic samples $\gamma d = j\frac{\omega}{c} d\sqrt{\varepsilon_r} = j\beta$, and for an open end transmission line ($Z_L \to \infty$), we obtain the expression of the $Z_{in} = Z_0 \coth(j\beta)$; if the line is filled with air ($\varepsilon_r = 1$), the characteristic impedance of the sample area filled with air is expressed by $Z_{0a} = Z_0\sqrt{\varepsilon_r}$ and using the following relation $\coth(j\beta) = -j\coth(\beta)$, an approximate relation of the input impedance [20] of the line filled with the sample:

$$Z_{in} = \frac{Z_{0a}}{\sqrt{\varepsilon_r}} \coth(j\beta) = -j\frac{Z_{0a}}{\sqrt{\varepsilon_r}} \coth(\beta)$$
$$= -\frac{Z_{0a}\beta}{\beta\sqrt{\varepsilon_r}} \coth(\beta) = -j\frac{cZ_{0a}}{\omega d\varepsilon_r} \beta\coth(\beta) \quad (5)$$

And which can be calculated also experimentally after Laplace transformation of the incident and reflected waves by:

$$Z_{in} = Z_0\left(\frac{V_i(s)+V_r(s)}{V_i(s)-V_r(s)}\right) \quad (6)$$

Assuming that $A^-(s) = V_i(s) - V_r(s)$ is the Laplace transform of the signal difference between the incident and the reflected signal ($v_i(t) - v_r(t)$) and $A^+(s) = j\omega(V_i(s)+V_r(s))$ is the Laplace transform of the derivative signal of the sum ($\frac{d}{dt}(v_i(t)+v_r(t))$) and by considering $z = \frac{Z_{0a}}{Z_0}$ as normalized characteristic impedance between the line and the sample, we obtain finally the expression of the complex permittivity by:

$$\varepsilon_r^* = c(\frac{z}{d})\left(\frac{A^-(s)}{A^+(s)}\right)\beta\coth(\beta) \quad (7)$$
$$\underbrace{\quad}_{T} \quad \underbrace{\quad}_{L} \quad \underbrace{\quad}_{S}$$

We can deduce that the measured value of the dielectric permittivity depends on three factors:

* T factor which is related to the transmission line holder
* L factor which is related to the used Laplace transformation of $v_i(t) - v_r(t)$ and $\frac{d}{dt}(v_i(t)+v_r(t))$.
* S factor which is related to the nature of the sample.

Using the equation (7) in order to measure the dielectric permittivity leaves us to many questions such as:

- Can we use this equation for any type of materials (low constant dielectric, high loss, multi-dispersive,…)?
- Since $A^-(s)$ and $A^+(s)$ are Laplace transforms of the $v_i(t)-v_r(t)$ and $\frac{d}{dt}(v_i(t)+v_r(t))$ respectively, therefore for broadband results can we use any transformation windows?
- Since z/d is a transmission line parameter, is there any correlation with the choice of the transformation window and the transmission line parameter?
- Is there any optimization of the sample size for DC conductivity measurement?

Indeed for an accurate measurement of the complex expression of the dielectric permittivity, we need to optimize the above equation according to the three terms T, L, S factors and according also to their correlations.

4 Results and Discussion

It is known that the TDR method is used in order to measure the broad band frequency dependent of the dielectric properties for different materials in liquid or solid states; but for soft materials such as biological (muscle tissue, fat tissue,..), the internal errors due to the physical concepts of the biological medium can not be neglected and they are due to the strong frequency dependency of the biological tissue, and specially due to the sample size due to the EM attenuation in the sample, due to the multi-dispersion phenomena occurring at different frequencies (from low to high frequencies) and due to the DC conductivity giving rise to some practical limitations.

4.1 Optimisation of the transmission line factor (T factor)

In [16], it has been mentioned that the sample should be matched within the coaxial transmission line, which is efficient at frequencies where the sample length is not a multiple of the half wavelength in the material to avoid large spikes which appear in the measured real part of the complex permittivity at these resonant frequencies. Also an overview of the different methods to measure the dielectric properties of biological substances, using the coaxial TEM lines, has been investigated by [46], showing their accuracy in a specific band of frequency; and according to Stuchly et al., [47]-[48], they showed the existence of an inherent ambiguity due to the introduction of a sample in a transmission line known by the capacitance of the empty sample which should be adjusted to an optimum capacitance C_0 with respect to the substance constitution (high water or low water content tissues) and they have shown that if the values of $\varepsilon_r^{'}$ and $\varepsilon_r^{''}$ have to be determined at frequency f_0 then the inherent error is minimized at this condition. The empty cell capacitance is approximated by the inner diameter a and the gap distance d_s as shown in Table I; and Table II presents the estimated optimum geometrical dimension of the empty cell (expressed by the ratio d_s/a^2 for high water content tissue and for low water content tissue), and we can see the strong dependency of this ratio with the frequency and with the nature of the tissue.

In our experimental cell, $d_s = 4.5mm$ and $a = 8mm$ and its optimum frequency will be at 400 MHz for HW content tissue and at 6.5 GHz for LW content tissue and no ambiguity exists at these frequency and the optimum capacitance has been derived as:

$$C_0 = \frac{1}{2\pi f_0 Z_0 \sqrt{\varepsilon'(f_0)^2 + \varepsilon''(f_0)^2}} \quad (8)$$

with (Z_0 is the characteristic impedance of the coaxial line, f_0 is the frequency at which the optimum capacitance is chosen giving accuracy in the results; but the ambiguity appears at the frequencies different from f_0, therefore to determine the error E due to this ambiguity we can assume that the real and imaginary part of dielectric constant at an arbitrary frequency can be expressed by:

$$\varepsilon'(f) = \varepsilon'(f_0) + (\frac{\partial \varepsilon'}{\partial f})\Delta f \quad (9)$$

$$\varepsilon''(f) = \varepsilon''(f_0) + (\frac{\partial \varepsilon''}{\partial f})\Delta f \quad (10)$$

Then the inherent error which accompanies the results in the sample impedance can be expressed by the following equation:

$$\frac{1}{f^2C^2} = \frac{1}{f_0^2C_0^2} + 4\pi^2 Z_0^2[((\frac{\partial \varepsilon'}{\partial f})^2 + (\frac{\partial \varepsilon''}{\partial f})^2)\Delta f^2 + 2(\varepsilon'(\frac{\partial \varepsilon'}{\partial f}) + \varepsilon''(\frac{\partial \varepsilon''}{\partial f}))\Delta f] \quad (11)$$

with C is the arbitrary optimum capacitance at the arbitrary frequency f; the first term of equation (11) is determined from the geometrical dimension of the cell at frequency as shown in Table II and the second term shows the inherent error which accompanies the results due to the strong frequency dependency of the complex permittivity.

Fig. 5 shows the variation of the inherent error for different specimen sizes which is higher for more conductive dielectric tissues; we can see that at frequencies lower than f_0 this ambiguity is changing sharply but at frequencies higher than f_0 it is almost constant to a specific level, and also for low water content tissue we can conclude that this ambiguity is negligible comparative to error due to the high water content tissue.

TABLE II.

FREQUENCY DEPENDENCY OF THE OPTIMUM SPECIMEN SIZE WITH RESPECT TO THE GEOMETRICAL CONFIGURATION OF THE EXPERI-

MENTAL LUMPED CELL.

Frequency (GHz)	Optimum specimen size (d_s) with respect to the inner diameter (a) of the sample holder expressed by (d_s / a^2)	
	High water content tissue (HW)	Low water content tissue (LW)
0.001	16.308	0.400
0.01	24.812	0.95
0.1	38.596	2.130
0.433	75.514	6.153
0.915	119.780	11.835
2.45	267.202	30.075
5	507.098	60.940

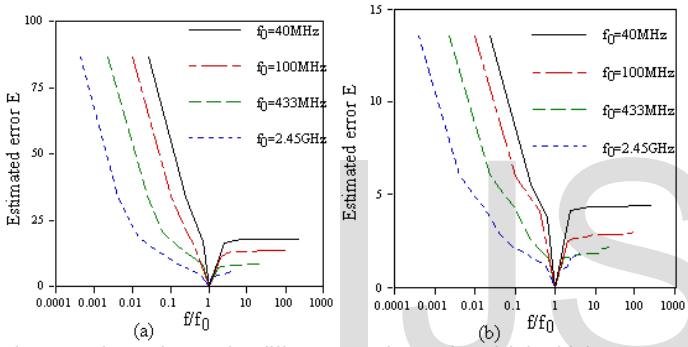


Fig 5. Estimated error for different specimen size; (a) for high water content tissue; (b) for low water content tissue.

4.2 Considerations due to the biological sample factor (S factor)

4.2.1 Considerations due to the sample attenuation

This phenomenon specially occurs when the thickness d_s of the sample is of the order of the wavelength in the dielectric, first and multiple reflections can occur in the lumped capacitance method in the MW range as well as in the matched line method at lower frequencies. Since the complex dielectric permittivity ε^* as well as the attenuation α are both frequency dependent and two important cases appears with respect to d_s when $\alpha d_s > 1$ and $\alpha d_s < 1$; Fig.6 shows the calculated transmitted power ratio due to the attenuation effect for the H.W water content tissue showing different variations when $\alpha d_s < 1$; It is clear then to have accurate measurement in a specific range of frequencies, the specimen size should be adjusted to the case $\alpha d_s > 1$. Fig.6 shows also the necessity of repetitive measurement for different sample thickness when the matched line method is used.

4.2.2 Considerations due to the multi-dispersion

For a specified dispersion process which can be characterized by a particular relaxation pulsation ω_r, the complex relative permittivity is expressed by the following equation according to the Debye model introducing the static relative permittivity $\varepsilon_{rs}^{'}$, the relative permittivity $\varepsilon_{r\infty}^{'}$ when the angular pulsation $\omega \to \infty$:

$$\varepsilon_r^{'}(\omega) = \varepsilon_{r\infty}^{'} + \frac{(\varepsilon_{rs}^{'} - \varepsilon_{r\infty}^{'})}{1+(\frac{\omega}{\omega_r})^2} - j\frac{\frac{\omega}{\omega_r}(\varepsilon_{rs}^{'} - \varepsilon_{r\infty}^{'})}{1+(\frac{\omega}{\omega_r})^2} \quad (12)$$

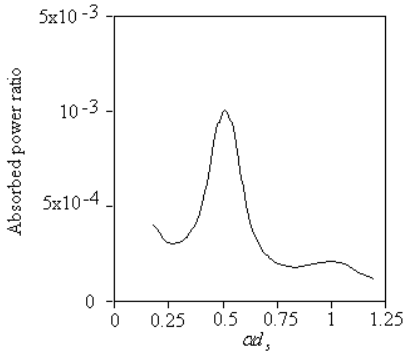


Fig 6. Absorbed power ratio due to the attenuation in the high water content tissue at 2.5 GHz for a specimen size varying from 0.3 cm to 2 cm.

The time dependence of the reflected wave is closely related to the different dispersions of the biological substance; and in practice a serious problem appear in the choice of the optimum capacitance based on the conducting behaviour , or on the single Debye dispersion or on the multi-dispersion behaviour. The specific function $\varepsilon^*(\omega)$ representing a particular dispersion (single Debye dispersion, two Debye dispersion, ...) is determined from equation (7) and the uncertainties in the analysis are extended to the different dispersions and on the determination of their different relaxation times from the complex plot of the permittivity. The accuracy of the various relations from the fitted data to the single Debye dispersion and double Debye dispersion are compared and the results are shown in Fig. 7; where it can be concluded that the fitted data from the single Debye dispersion gives good results at high frequencies and at lower frequencies, the data fitted the double Debye dispersion and the experimental data will depend on the time window and on the method itself.

The experimental fitted data determined from different time windows as in Fig.8 (a) shows the behaviour of almost two dispersions one occurring in the MW range and the other in the RF range and when the matched line method is used, a third dispersion appears occurring at lower frequencies as shown in Fig.8 (b) in which the results are in good approximation with the data given from [49].

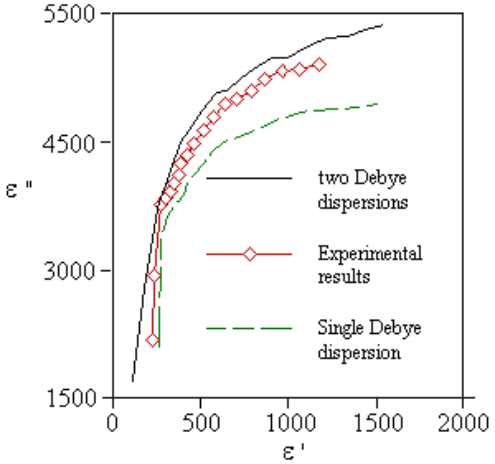


Fig 7. The fitted experimental data to different dispersions.

Fig. 8 shows also that the lumped capacitance method with a larger time window leads to an important error especially in a range less than $0.1 f_0$ (f_0 frequency in which the optimum capacitance is chosen); both methods have the ability to determine the dielectric properties according to different time windows.

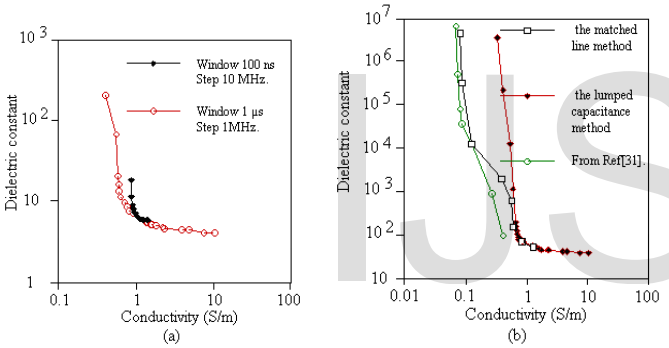


Figure 8. Fitted experimental data for the complex permittivity of beef muscle, (a) from lumped capacitance method, (b) broad band results from both methods.

4.3. Considerations due to the correlation between Laplace transform (L factor) and biological sample (S factor)

In this section we investigate the specimen size with respect to the D.C conductivity.

A conducting dielectric inserted in the coaxial sample holder will introduce an optimum capacitance. The reflection signals in the limit $t \to \infty$ gives a finite value for an arbitrary sample length which is related to the static conductance σ_s.

The matched line method is requested for the measurement of the low conductivity in which the incident pulse reaches a limiting value Vi or $2V_i$ as $t \to \infty$, the limiting value of the reflected signal is given by :

$$u = \lim_{t\to\infty} \frac{r_m(t)}{v_i(t) - v_{sc}(t)} \qquad (13)$$

with $v_i(t)$: signal from empty cell, $v_{sc}(t)$: signal from short circuit and the asymptotic approximation of the static conductivity can be expressed by:

$$\sigma_s = -\frac{u}{1+u}\frac{2c\varepsilon_0}{d_s} \qquad (14)$$

The response of the finite limiting value $r_m(\infty)$ is plotted in Fig 9; as a function of the optimum capacitance for a conducting dielectric as the D.C conductivity is varying for different substances. The offset level $r_m(\infty)$,which is determined by the intrinsic properties of the sample as $\Delta r_m(t) = r_m(t) - r_m(\infty)$, shows that an important error occurs if the value of the DC conductivity is relatively smaller than 0.1 mS/cm, and their direct dependency on the capacitance value for a large value of $r_m(\infty)$ ($\Delta r_m(t)$ too small); but for relatively higher values of $\Delta r_m(t)$, limitations due to the capacitance and conductivity are less seen.

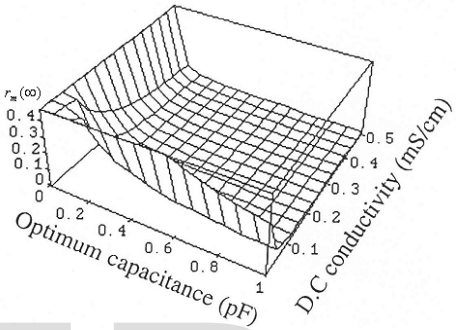


Figure 9. The effect of the static conductivity on the dielectric response as $t \to \infty$ with respect to the optimum capacitance.

4.4 Considerations due to the correlation between transmission line (T factor) and biological sample (S factor)

In this section we try to investigate the correlation between the specimen size with the high frequency permittivity.

The multiple internal reflections in the dielectric sample at short times leads to a complex relations between the reflected wave and dielectric response function therefore the lumped capacitance method is preferred to calculate the high frequency permittivity and the results are shown in the Fig. 10 with respect to the optimum capacitance and for different high frequency permittivity values.

It can be seen that up to certain frequency that a weak dielectric response $\Delta r_l(t)$ will depend only on the optimum capacitance independently on the high frequency value of the dielectric constant, and above a certain frequency (higher capacitance like in the matched line method) the dielectric response will increase as the frequency increases. It can be concluded with the results shown in Fig. 10, that the optimum capacitance up to a certain frequency will depend on the low conductivity and is limited by an other higher frequency in which the optimum capacitance depend only on the high frequency permittivity and for medium frequencies it will depend on both the high frequency permittivity and the low conductivity of the substance.

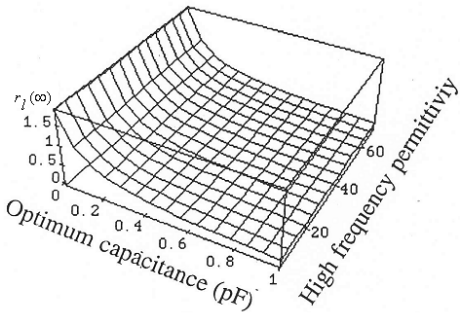


Figure 10. The effect of the high frequency permittivity to the dielectric response with respect to the optimum capacitance.

5. Conclusion

In this paper, we described the TDR method as a promoting broadband biological dielectric measurement by using two types of sample holders; at high frequency the lumped capacitance cell is suitable and the results can be fitted to a single Debye dispersion and at frequency below 100 MHz, where different dispersions occur the matched line method with a controllable sample length is suitable to determine the dielectric constant and the DC conductivity. The TDR analysis is followed by a detailed analysis of the T, L and S factors and their correlations according to the physical concepts of the living biological tissue leading to different internal source of errors due to the nature of the living samples and how to adjust these errors. Indeed the TDR method can not be used similarly for different materials (such as high dielectric constant with low loss factor, low dielectric constant with low loss factor, lossy dielectrics), but some considerations due to the nature of the sample should be taken into account in the dielectric measurement values.

The matched line method and the lumped capacitance method has a number of important advantages with different limitations over the conventional frequency domain; One of the most important advantages of the matched line method is that it can be used to perform measurements at low frequencies; and for measurement accuracy, it is advised to design a controllable sample length coaxial holder in the matched line method allowing repetitive measurements with a good accuracy for different time windows; but this method is limited by the ambiguity of the occurrence of the multi-dispersion complexity in the proper operating frequency range; but for the lumped capacitance method, valuable results are achieved at frequencies above 100 MHz and the most advantage is its suitability for high frequency ranges in which the data can be fitted to a single Debye dispersion with the free water relaxation frequency (25 GHz at 37°C), but the results are limited by the value of the optimum capacitance C_0 and by the rise time T_r of the generated pulse from the measuring system.

We showed that in addition to the well known external calibration of the TDR system (such as open circuit, short circuit, adapted circuit), further study should be investigated on the changes of the relaxation times with respect to the different dispersions occurring in the biological substance and on the possibility of electrode polarisation errors in the measurements due to the existence DC conductivity which is observed at the end of the spectrum for the biological substance. Also the analysis according to the Bounce diagram should be investigated in order to optimise the effect of L factor and the concept of Maxwell-Wagner should be taken in consideration in order to optimise the S factor.

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References

[1] [1] Venkatesh, M.S. and Raghavan, G.S.V." An overview of dielectric properties measuring techniques", Canadian Biosystems Engineering/Le génie des biosystèmes au Canada 47: 715 - 730, 2005.

[2] National Physics Library, A Guide to the Characterization of Dielectric Materials at RF and Microwave frequencies, London : The institute of Measurement and Control, 2003.

[3] C Gabriel, S Gabriely and E Corthout," The dielectric properties of biological tissues: I. Literature survey", Phys. Med. Biol., vol- 41, pp. 2231–2249, 1996

[4] Schepps, J.R., and Foster, K.R.," The UHF and microwave dielectric properties of normal and tumor tissues: variation in dielectric properties with tissue water content.", Phys. Med. Biol., vol. 25, pp 1149-1159, 1980.

[5] Foster, K.R., Schepps, J.L., Stoy, R.D., and Schwan, H.P., " Dielectric properties of brain tissue between 0.01 and 10 GHz.", Phys. Med. Biol. vol. 24, pp 1177-1187, 1979.

[6] M.C. Steel and R.J. Sheppard," Dielectric properties of lens Tissue at Microwave Frequencies", Bioelectro-magnetics 7, pp 73-81, 1986.

[7] Kraszewski, A., Stuchly, M.A., Stuchly, S.S., and Smith, A.M.," In vivo and in vitro dielectric properties of animal tissues at radio frequencies.", Bioelectromagnetics, vol. 3, pp 421-433, 1982.

[8] Schwan, H.P., and L.K.," Capacity and conductivity of body tissues at ultra high frequencies.", Proc. IRE, vol. 41, pp 1735-1740, 1953.

[9] Tanabe, E., and Joines, W.T.," A nondestructive method for measuring permittivity of dielectric materials at microwave frequencies using an open transmission line resonator", IEEE Trans. Instrum. Measure., vol. IM-25, pp 222-226, 1976.

[10] Munikoti S. Ramachandraiah, Marc C. Decreton," A resonant cavity approach for the nondestructive determination of complex permittivity at Microwave frequencies," IEEE Trans. Instr. & Meas., vol. IM-24, N°. 4, pp. 287-291, Dec. 1975.

[11] Shihe Li, Cevdet Akyel, Renato G. Bosisio,"Precise calculations and measurements on the complex dielectric constant of lossy materials using TM010 cavity perturbation techniques," IEEE Trans. Micro. Theo. & Tech., vol. MTT-29, N°. 10, pp. 1041-1048, Oct. 1981.

[12] Stuchly, S.S., Stuchly, M.A.,and Crraro, B.," Permittivity measurements in a resonator terminated by an infinite sample.", IEEE Trans. Instrum. Measure., vol. IM-27, pp436-439, 1978.

[13] H.E. Bussey," Measurement of RF properties of materials. A survey," Prc. IEEE, vol. 55, pp. 1046- 1053, 1967.

[14] Clifton Carthelle Courtney,"Time domain measurement of the electromagnetic properties of materials", IEEE Trans. Microwave Theory & Techniques, vol. MTT-46, N°5, pp. 517-522, 1998.

[15] R. Nozaki, T.K. Bose, "Broadband complex permittivity measurements by time domain spectroscopy", IEEE

Trans.Instr.& Measr., vol. IM-39, N°6, pp. 945-951, 1990.

[16] K Kupfer, E Trinks, N Wagner and Ch Hübner," TDR measurements and simulations in high lossy bentonite materials", Meas. Sci. Technol. 18, 1118, 2007.

[17] Nicolson, A.M., and Ross, G.F.," Measurement of the intrinsic properties of materials by time domain techniques.", IEEE Trans. Instrum. Measure., vol. IM- 19, pp 377-382, 1970.

[18] Iskander, M.F., and Stuchly, S.S.," A time domain technique for measurement of the dielectric properties of biological substances.", IEEE Trans. Instrum. Measure., vol. IM-21, pp 425-429, 1972.

[19] Nightingale, N.R.V., Dawkins, A.W.J., Sheppard, R.J.,et al.," The use of time domain spectroscopy to measure the dielectric properties of mouse brain at radiowave and microwave frequencies.", Phys. Med.. Biol. vol. 25, pp 1161-1165, 1980.

[20] K. Baba, T. Fujimura," Time domain analyses for various Types of dielectric relaxations by a lumped capacitor method," Jap. Jou. of Appl. Phys., vol. 24, N°. 4, pp. 487-490, April 1985.

[21] Ian Woodhead, Graeme Buchan, Ian Platt and John Christie" Improved electric field modelling for TDR", Meas. Sci. Technol. 18 1110, February 2007.

[22] N. R. V. Nightingale, A.W. J. Dawkins, et al.," The use of time domain spectroscopy to measure the dielectric properties of mouse brain at radiowave and microwave frequencies," Phys. Med. Biol., vol. 25, N°. 6, pp. 1161-1165, 1980.

[23] Tapan K. Bose et al,"Development of a dipole probe for the study of dielectric properties of biological substances in radiofrequency and Microwave region with time domain reflectometry", IEEE Trans. Instrum. & meas., vol. IM-35, N°.1,pp. 56-60, March 1986.

[24] Bone S, Ginzburg B Z, Morgan H, Wilson G and Zaba B, "Time domain spectroscopy applied to cell suspensions", Phys. Med. Biol. 38, pp. 511-520, 1993.

[25] C Huebner and K Kupfer, " Modelling of electromagnetic wave propagation along transmission lines in inhomogeneous media, Meas. Sci. Technol. 18 1147, February 2007.

[26] Van Gemert, M.J.C., and Sugget, A.," Multiple reflection time domain spectroscopy.II A lumped element approach leading to an analytical solution for the complex permittivity.", J. Chem. Phys., vol. 62, pp 2720-2726, 1975.

[27] A.W.J Dawkins, E H Grant and R J Sheppard," An on-line computer-based system for performing time domain spectroscopy III. Presentation of results for total reflection TDS," Phys.E: Sci. Instrum., vol. 14, pp. 1429-1434, 1981.

[28] R. Lisin, H. Z. Ginzburg, M. Schlesinger, and Y. Feldman, "Time domain dielectric spectroscopy study of human cells. I. Erythrocytes and ghosts", Biochim. Biophys. Acta 1280, pp. 34-40, 1996.

[29] Iskander M F and Stuchly S S,"A time domain technique for measurement of the dielectric properties of biological substances", IEEE Trans. Instrm. Meas., IM-21, pp.425-429, 1972.

[30] Merabet M and Bose T K, " Dielectric measurements of water in the radio and microwave frequencies by time domain reflectometry", J.Phys. Chem., 92, pp. 6144- 6145, 1988.

[31] Gabriel C, Grant E H and Young I R, "Use of time domain spectroscopy for measuring dielectric properties with a coaxial probe", J. Phys. E: Sci. Instrum., 19, pp. 843-846, 1986.

[32] Bose T K, Bottreau A M and Chahine R, "Development of a dipole probe for the study of dielectric properties of biological substances in radiofrequency and microwave region with time domain reflectometry (TDR)", IEEE Trans. Instrum. Meas., IM-35(1), pp. 56-60, 1986.

[33] Cole R H , "Time domain reflectometry", Ann. Rev. Phys. Chem, 28, 283-300, 1977.

[34] Cole R H, Mashimo S and Winsor P, "Evaluation of dielectric behaviour by time domain spectroscopy, Precision difference methods", J. phys. Chem., 84, 786-793, 1980.

[35] Nakamura H, Mashimo S and Wada A, "Application of time domain reflectometry covering a wide frequency range to the dielectric study of polymer solutions", Japan J. Appl. Phys., 21, 467-474, 1982.

[36] R. H.Cole, J.G.Berberian, S.Mashimo, G.Chryssikos, and A. Burns, "Time domain reflection methods for dielectric measurements to 10 GHz, J.Appl. Phys., 66, 793-802, 1989.

[37] Cole R H ," Time domain reflectometry", Ann. Rev. Phys. Chem., 28, pp. 283-300, 1977.

[38] Cole R H , "Evaluation of dielectric behaviour by time domain spectroscopy. II.Complex permittivity", J . Phys. Chem., 79, pp. 1369-1374, 1975.

[39] M.A.Stuchly, T.W.Athey, G.M Samaras and G.E. Taylor."Measurement of Radio Frequency Permittivity of Biological Tissues with an Open-Ended Coaxial Line: Part II- Experimental results,"MTT-30, Vol.1, Jan.1982.

[40] Andrzej Kraszewski,ed., Microwave Aquametry: Electromagnetic wave interaction with water-containing materials, New York: IEEE Press, 1996.

[41] K.R. Foster, J.L. Schepps and H.P.Schawan,"Microwave dielectric relaxation in muscle, a second look", Biophysical Journal, Vol.29, Feb. 1980, pp. 271-282.

[42] R Shirakashi1,3, T Ogawa2 and J Yamada2,"Dielectric spectroscopy of a thin surface layer by differential time-domain reflectometry using a coplanar waveguide circuit line probe ", Measurement Science & Technology, Vol 24, N° 2, February 2013.

[43] National Physics Library, A Guide to the Characterization of Dielectric Materials at RF and Microwave frequencies, London : The institute of Measurement and Control, 2003.

[44] A. W. Guy, "Analyses of electromagnetic fields induced in biological tissues by thermographic studies on equivalent phantom models," IEEE Trans. Microw. Theory Tech., vol. MTT-19, N°. 2, pp. 205–214, Feb.1971.

[45] H.-R. Chuang, "Numerical computation of fat layer effects on microwave near -field radiation to the abdomen of a full-scale human body model," IEEE Trans. Microw. Theory Tech., vol. 45, N°. 1, pp.118–125, Jan. 1997.

[46] Stuchly, M.A., and Stuchly, S.S.," Coaxial line reflection methods for measuring dielectric properties of biological substances at radio and microwave frequencies- a review.", IEEE Trns. Instrum. Measure., vol. IM-29, pp 176-183, 1980.

[47] Stuchly, S.S., Rzepecka, M.A., and Iskander, M.F.," Permittivity measurements at microwave frequencies using lumped elements.", IEEE Trans. Instrum. Measure., vol. IM-23, pp 56- 62, 1974.

[48] Rzepecka, M.A., and Stuchly, S.S.," A lumped capacitance method for the measurement of the permittivity and conductivity in the frequency and time domain- a further analysis.", IEEE Trans. Instrum. Measure., vol. IM-24, pp 27-32,1975.

[49] James C. Lin, Arthur W. Guy, Curtis C. Johnson," Power deposition in a spherical model of man exposed to 1-20MHz electromagnetic fields," IEEE Trans. Microwave Theory Tech., vol. MTT-21, pp. 791- 797, Dec. 1973.