Middle-East Journal of Scientific Research 5 (4): 268-279, 2010
ISSN 1990-9233

Tissue Injury Monitoring During X-Ray Irradiation Using Bioimpedance Spectroscopy

[1]Ahmed M. El Khatib, [1]Nabil Kassam Madi, [2]Moustafa M. Mohamed, [3]Samia A.M. Rezk and [1]Ahmed M. Elhaj

[1]Department of Physics, Faculty of Science, Alexandria University, Egypt
[2]Department of Medical Biophysics, Medical Research Institute (MRI), Alexandria University, Egypt
[3]Department of Radiology, Faculty of Medicine, Alexandria University, Egypt

Abstract: The effects of X-irradiation on electrical properties of rat liver, kidney and muscle tissues are studied. Multiple frequency bioelectrical impedance analysis (MFBIA) method is used to describe change in electrical properties of the irradiated tissues as a function of frequency and time, frequency dependence of conductivity and relative permittivity are measured. The rats were, whole body, exposed to (400 rads) X-rays from a clinical therapeutic 6 MV linear accelerator. At time intervals, the excised samples were obtained by sacrificing rats according to experimental (1, 2, 4, 9, 16, 23, 30 day post-irradiated). Electrical impedance of each excised sample is measured between 100 Hz to 5 MHz for (93) frequency points. Changes in electrical properties and readings at low, intermediate and high frequency as function of time for all samples reveal that there exist significant differences between both conductivity and permittivity of non-irradiated and irradiated muscle tissues ($p < 0.05$). At high frequency (1 MHz), the conductivity values (0.67 4 to 0.767 S/m) of longitudinal muscle and (0.582 to 0.731 S/m) of transverse muscle of irradiated tissues for all times, are higher than non-irradiated values (0.573 and 0.546 S/m) respectively. The differences in conductivity values between non-irradiated and 30 days post-irradiated, for longitudinal and transverse muscles are (34.103% and 33.922 %) respectively. The normalized values of relative permittivity at both low (5KHz) and high (1 MHz) frequencies are (26.38% and 36.641%) and (44.901% and 18.202%) for longitudinal and transverse muscles respectively. No significant differences in the conductivity and permittivity for liver and kidney were observed. Statistically significant differences observed only in muscle tissues therefore the effect due to whole body exposure are appeared more rapidly at 30 days in the muscle tissue than other organs (liver and kidney).

Key words: Electrical impedance · Conductivity · Permittivity · Longitudinal and transverse muscles

INTRODUCTION

The radiation as a non discriminating agent affects every component of the exposed tissue. It is equally likely to damage both the parenchymal and vascular tissues. The severity of radiation damage is dependent on dose with a latent period that varies with the type of tissue involved. Some studies explore the potential of electrical impedance spectroscopy (EIS) to deduce and monitor the progression of radiation-induced tissue injury in the treatment field through frequency-dependent changes in electrical properties [1]. These properties appear to be sensitive to the continued progression of normal tissue injury and could become important factors in the evaluation of the primary treatment site for retreatment in cases of tumor recurrence. More recent studies give much knowledge on the electrical properties of many normal tissues over a wide range of frequencies [2-5]. Alterations in the impedance spectra are known to occur with physiological change. The biological tissues have complex electrical impedance, which are dependent on frequency and specific tissue type. The electrical impedance of tissue is a function of its structure and it can be used to differentiate normal and cancerous tissues in a variety of organs. On the other hand, different types of tissues are known to have different electrical impedance properties [3-7]. The electrical properties of tissue are dependent upon the structural organization of

Corresponding Author: Ahmed Mahamed Aly El Khatib, Department of Physics, Faculty of Science, Alexandria University, Egypt, Tel: +20120419758

cells within the tissue [8]. Electric charge accumulates at the lipid membranes, restricting current to flow through the extracellular space at low frequencies. As increasing frequency (1-100MHz) the cell membranes are becoming largely shorted out, allowing current to flow through intracellular space at higher frequencies [4,8,9]. Beta dispersions were found in the electrical property spectrum. Consequently, the β-dispersion frequency range contains information about both the extra-and intracellular environments, making it well suited for sensing tissue injury responses such as edema and inflammation (extracellular) or necrosis and apoptosis (intracellular) [10]. In radiotherapy it may be used electrical impedance spectroscopy (EIS) to measure radiation damage and radiation recovery. The changes in dielectric dispersions suggesting that the measurement of the electrical properties of the irradiated tissue might be used in the follow-up to the radiation-induced effects [11]. Investigation in patients exposed to radiation indicate that the irradiated skin revealed a reduction of both the conductivity and the dielectric constant, especially in the low frequency. Also impedance spectra represent a significant shift of the beta-dispersion, with the irradiated tissue if compared with normal tissue displaying its dispersion at higher frequencies [11]. The electrical properties of tissue have been studied for many years [9]. These properties are conveniently described by using, the complex permittivity which comprises the permittivity ε_r and conductivity (σ). Conventionally, the complex permittivity (ε^*) is expressed [2] as:

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{1}$$

$$= \varepsilon_r - j\frac{\sigma}{\omega\varepsilon 0}$$

$$\varepsilon' = \varepsilon_r$$

$$\varepsilon'' = \frac{\sigma}{\omega\varepsilon 0}$$

Where ε_r denotes relative permittivity and σ denotes absolute conductivity (in units of S /m) and ω is the angular frequency of the field (radians per second) and ε_0 is the permittivity of free space (8.85 x $10^{-}12$ F / m).

The series equivalent complex impedance (Z^*) given [2] as:

$$Z^* = \frac{\sigma - j\omega\varepsilon 0\varepsilon_r}{\sigma^2 + (\omega\varepsilon 0\varepsilon_r)} \tag{2}$$

The frequency dependence of the complex permittivity of biological tissue in the so-called β-dispersion is attributed to capacitive charging of cellular membranes and dipolar relaxation of proteins, it has a typical centre frequency of 3 MHz [2].

MARIAL AND METHODS

The experiments were carried out with a total of 49 adult albino rats weighing 130 g on average. The rats were, whole body, exposed to (400 rads) X rays from a clinical therapeutic 6 MV linear accelerator facility of medicine Alexandria university. The rats were divided into seven subgroups each of 6 male rats and 6 rats for non-irradiated group. The experiments were performed with freshly excised tissues from rats. Fresh liver , kidney and muscle tissues were excised within minutes after the animals were sacrificed. At intervals, starting from the first day after irradiation. An excised samples were obtained by sacrificing the rats on different days according to the experimental (1, 2, 4, 9, 16, 23, 30 days) post-irradiated. After excision, the electrical impedance of each excised sample is measured between 100 Hz and 5 MHz for 93 frequency points. Computer-controlled automatic scanning and data recording were performed with an impedance LCR meter (HIOKI 3532-50 LCR meter 42 Hz to 5 MHz HiTester, Japan).

The measured complex impedance of the sample can be written as

$$Z^*_m = R_m + jX_m \tag{3}$$

where R_m and X_m are measured resistance and reactance of impedance data which were converted to their volume independent tissue property equivalents by exploiting (the two-parallel plane electrodes). as,

$$z^* = (R_m + jX_m) * A/d \tag{4}$$

In terms of Z-components the conductance (G) and capacitance (C) can be given [12] as:

$$G = \frac{R_m}{R_m^2 + X_m^2} \tag{5}$$

$$C = \frac{R_m}{?\,(R_m^2 + X_m^2)} \tag{6}$$

Where $\omega = 2\pi f$.

The conductivity (σ) and relative permittivity (ε^*) can be calculated according to the following formulas.The complex relative permittivity, ε^* expressed as:

$$\varepsilon^* = \varepsilon' - j\varepsilon''$$

where ε is the relative permittivity of the material and ε'' the out-of-phase loss factor.

The conductivity (σ) and relative permittivity (ε') which, depending on the nature of the sample are related to cell constant factor, $\frac{d}{A}$ by the equation [12]:

$$\sigma = \frac{d}{A}, G \tag{7}$$

and relative permittivity, ε_r is related as:

$$\varepsilon' = \varepsilon_r = \frac{d}{A}, \frac{C}{\varepsilon 0} \tag{8}$$

$$\varepsilon'' = \frac{\sigma}{\varepsilon 0 \omega} \tag{9}$$

where d and A are the average separation between the electrodes and the surface area of electrode unit, approximately the thickness length and cross-sectional area of the sample.

The wideband electrical impedance data measurement at each excised sample (liver, kidney, muscle) are fitted to extrapolate the parameters from data spectra according to Cole-Cole expression [13]:

$$z^* = R_\infty + \frac{(R_0 - R_\infty)}{1 + (j\omega\tau)^{1-\alpha}} \tag{10}$$

where ω is the angular frequency, R_x is the high frequency resistance, τ is the low frequency resistance, α is the relaxation time constant, α is the parameter that allows for the broadening of the dispersion.

RESULTS AND DISCUTION

Cole-Cole Parameters: Electrical impedance measurements were plotted for sample tissues of irradiated rats at the various times. (1, 2, 4, 9, 16, 23 and 30days). The electrical parameters over frequency range from100 Hz to 5 MHz were plotted for each sample of liver, kidney and both the longitudinal and transverse muscles. The fitting parameters of the Cole-Cole equation of impedance spectra for liver and kidney are presented both in Table 1 and for longitudinal and transverse muscles are presented in Table 2. In each table the first column represents several different days according to the experimental studied and zero reading indicates non-irradiated measurements. Each reading in these tables are the mean of determinations carried out on all samples of the non-irradiated and experimental irradiated groups. The second column in tables give differences resistivity ($\Delta R = R_0 - R_8$) at low and high frequency corresponding to each specific time post-irradiation. The third and fourth columns are relaxation time and distribution parameter corresponding to broad range of relaxation times. In both tables from the third column it can be noticed that the relaxation times of all irradiated animals are varied. Reaching the peaks at 16, 4, and 9, days post-irradiation for liver, kidney, longitudinal and transverse muscles respectively. In the fourth column it can be noticed that the values of distribution parameter (**??**) of all irradiated

Table 1: Cole-Cole parameters for non-irradiated and various post-irradiation tissues for liver and kidney

	Liver			Kidney		
Time (days)	Δ R (Ω-m)	τ (μs)	α	Δ R (Ω-m)	τ (μs)	α
0	18.25	68.1	0.37	28.85	116.0	0.49
1	17.71	61.8	0.33	18.59	94.0	0.49
2	19.78	75.6	0.33	23.89	125.0	0.49
4	22.43	123.9	0.33	24.27	136.8	0.49
9	30.58	129.4	0.32	25.68	117.3	0.50
16	32.69	172.2	0.33	30.40	132.4	0.50
23	25.31	107.1	0.33	20.95	105.2	0.49
30	26.77	115.5	0.34	25.93	102.7	0.48

Table 2: Cole-Cole parameters for non-irradiated and various post-irradiation tissues for longitudinal and transverse muscles

	longitudinal muscle			transverse muscle		
Time (days)	Δ R (Ω-m)	τ (μs)	α	Δ R (Ω-m)	τ (μs)	α
0	4.45	42.3	0.35	8.23	48.9	0.36
1	4.09	45.0	0.36	6.09	52.8	0.37
2	5.36	46.3	0.35	8.02	62.4	0.36
4	4.48	46.4	0.34	8.10	64.8	0.34
9	3.61	38.0	0.36	9.97	65.5	0.33
16	3.36	38.2	0.35	7.97	52.2	0.35
23	3.40	39.0	0.35	7.42	52.0	0.35
30	3.81	41.7	0.32	6.30	48.0	0.35

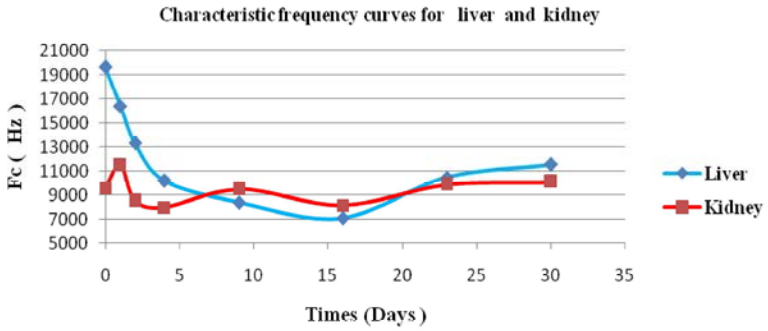

Fig. 1: (a) The characteristic frequency versus time for liver and kidney of non-irradiated and irradiated animals

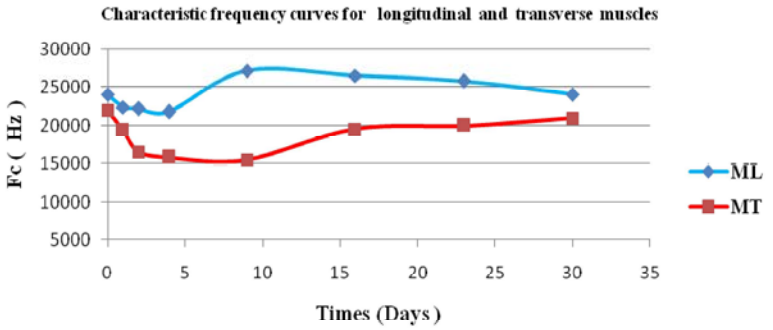

Fig. 1: (b) Characteristic frequency versus time for longitudinal (ML)and transverse muscles (MT) of non-irradiated and irradiated animals

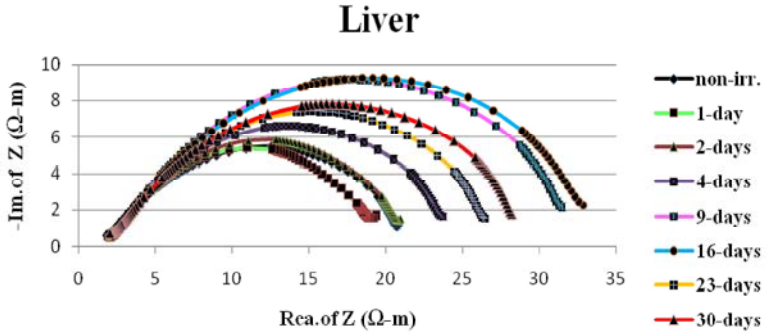

Fig. 2: Plot of spectral data in the complex impedance plane of the liver grouped separately by time post-irradiation

animals are lower than the non-irradiated tissues for liver but approximately on change for other organs (kidney and both muscles) as compared with non-irradiated tissues. By adding the figures available in Tables. (1, 2) for liver, kidney and both the longitudinal and transverse muscles. Figure 1. (a) shows characteristic frequency (f_c) of the samples of liver and kidney as function of time for both non-irradiated (marked at zero days) and irradiated animals. It can be noticed that the characteristic frequency slightly decrease as time increased reaching its lower values at 16 days for liver then progressively increasing upwards. This also occurs for kidney where the characteristic frequency slightly decrease (from 1 day) as time increased reaching its lower values at 4 days then increasing upwards. In figure 1. (b), the plot indicates that the curves of the characteristic frequency decrease as time increased reaching their lower values at (4 and 9 days) for longitudinal and transverse muscles respectively then progressively approaching non-irradiated level at the end (30 days). These results indicate dramatic change in characteristic frequency for all samples until 4 days after irradiation. It also clearly shows that the liver, kidney and both the longitudinal and transverse muscles exhibit changes in characteristic frequency as indicator of changing in electrical properties due to post-irradiation time.

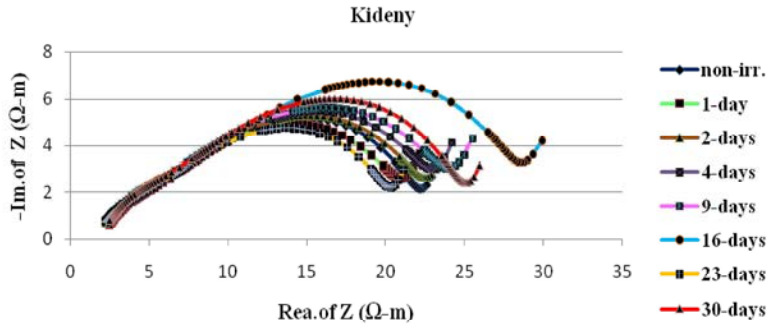

Fig. 3: Plot of spectral data in the complex impedance plane of the kidney grouped separately by time post-irradiation

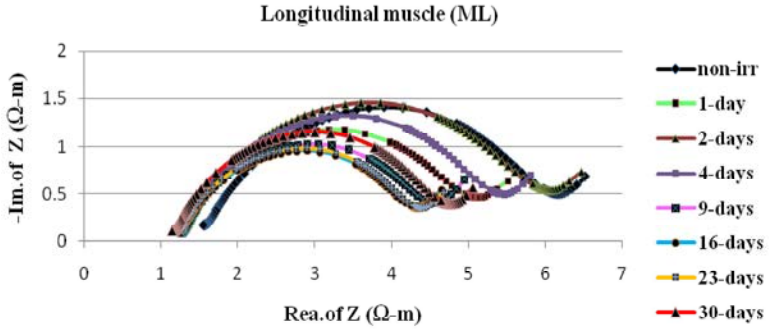

Fig. 4: (a) Plot of spectral data in the complex impedance plane of the longitudinal muscle grouped separately by time post-irradiation

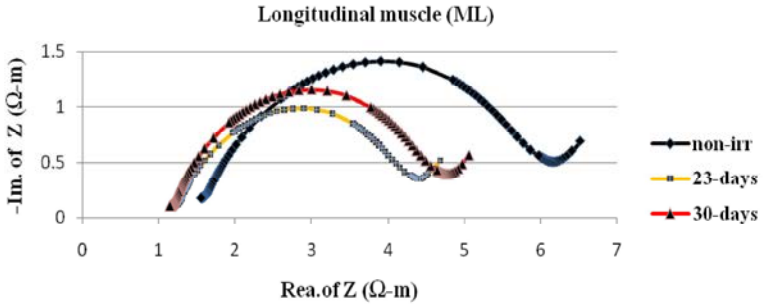

Fig. 4: (b) Plot of spectral data in the complex impedance plane of the longitudinal muscle for 23 and 30 days post-irradiation tissues

Impedance Curves: The impedance spectral curve in figure 2 for liver shows a clear separation between the non-irradiated and, irradiated animals. The plot shows further spectral separation accompanied by a marked increase in impedance occurs at curves of 9 and 16 days post-irradiation. For all curves a systematic increase can be noticed but there appears to be a reduction of the low-frequency impedance occurs at the curves marked by 23 and 30 days. According to the obtained experimental data one can suggest that the transient effect of 400 rads of X-irradiation has affected liver cells at this dose, but they recover rapidly after several days. Similar interpretation can be made about impedance spectral curves for kidney (Figure 3) with some differences. There are little systematic (consistent) separations between the curves for non-and irradiated samples at low frequencies as in Figure 3. The exceptions are more dramatic separation occurs at the curve (16 days). An additional reduction of the low-frequency impedance occurs at the curves marked by 23 days. In both samples liver and kidney. A clear wide separation occurs at low-frequency impedance but on significant separation can be noticed at high-frequency impedance. the stability of high frequency impedance readings suggests no dramatic change in the ionic properties of the intra and extracellular material or alterations in sub-cellular structures [8]. The muscle is highly anisotropic. all measurements were made longitudinal and transverse to the muscle fiber's

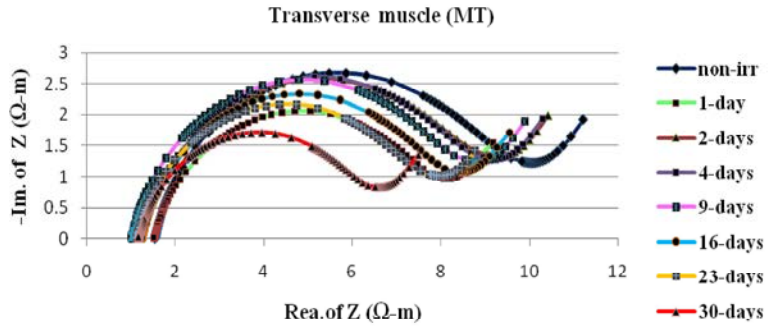

Fig. 5: (a) Plot of spectral data in the complex impedance plane of the transversal muscle grouped separately by time post-irradiation for single doses 400 rads

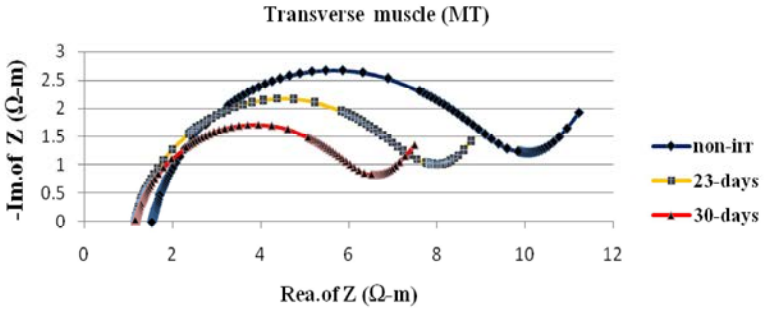

Fig. 5: (b) Plot of spectral data in the complex impedance plane of the transverse muscle for 23 and 30 days post-irradiation tissues

primary axis [5,9,14,15]. To get more insight, plots of impedance data for both longitudinal and transversal muscles are separately each with two graphs representing by times (1, 2, 4, 9, 16 days) and (23, 30 days). Two plots of each sample are shown in Figures 4 (a, b) and Figures 5 (a, b). The representation of impedance spectrum for longitudinal muscle at low frequency shows systematic separation between the curves (2, 4, 9 and16 days) for irradiated and non-irradiated. The exceptional curves at (1 and 23 days) are appeared in reduction below curves (4 and 30 days) respectively. There is no separation is evident between the curves for irradiated themselves. But a slight shift in the real component of electrical impedance can be noticed at high frequency (left portion of plot) between the non-and irradiated samples. This shift attributed to a radiation-induced change indicating that the destruction of the structure of muscle tissue may be partially changed or destroyed by membrane-bound organelles such as the mitochondria [16]. Similar as longitudinal muscle. In Figures 5 (a, b) there are systematic separations in the impedance spectrum of transverse muscle at low-frequency for non-and irradiated samples. The exceptionally is a curve (1day) which indicates the reduction below the curve (16days). There exist a slight shift in the high-frequency portion of the spectrum (left side of the plot) between the curves for irradiated themselves and non-irradiated samples (Figure 5 (a)). This shift of high frequency impedance suggests that there is a change in the ionic properties of the intra and extracellular material or alterations in sub-cellular structures. In previous studies, using external beam irradiation techniques, they have observed greater levels of inflammation and recorded larger shifts in high frequency impedance [10]. In this study a more dramatic shift in high frequency impedance of both muscle samples appeared between the curves of non-irradiated and 30 days post-irradiation. These deference are ($\Delta R_\alpha = R_\infty$ 0.333 Ω-m) for longitudinal muscle and for transverse muscle (ΔR_α = 0.266 Ω-m). These significant separation in real component of impedance at high frequency would be expected with large-scale necrosis or inflammation.

Conductivity: Additional insight and understanding is gained by examining the data in terms of its electrical property (*Conductivity and permittivity*) in order to clarify the relationship between radiation-induced change

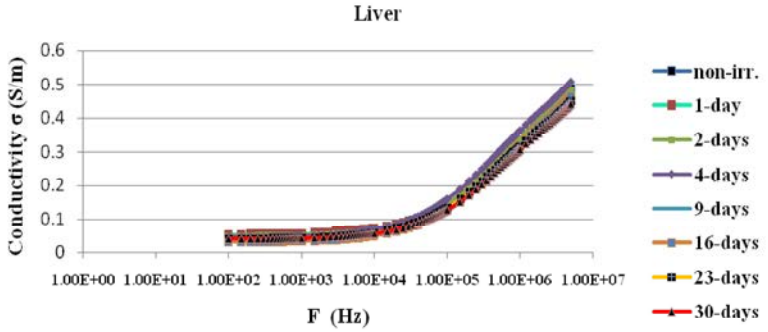

Fig. 6: (a) Conductivity (S/ m) of liver as a function of frequency (Hz) for non-irradiated and irradiated animals

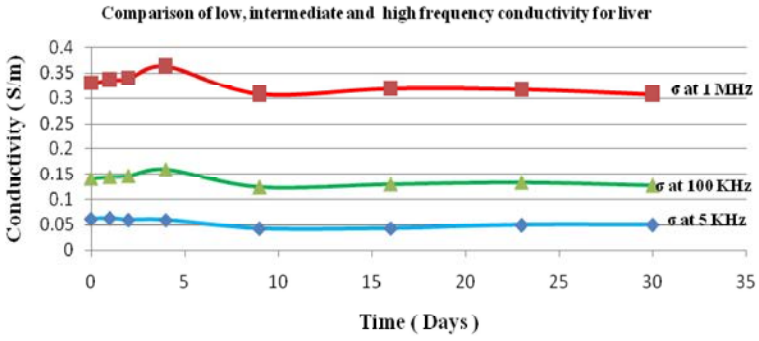

Fig. 6: (b) Conductivity (S m-1) of liver as a function of time post-irradiation (days). The curves at low (5 KHz), intermediate (100 KHz) and high frequency (1 MHz)

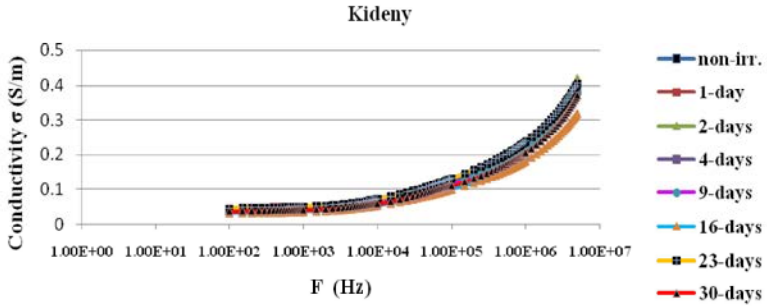

Fig. 7: (a) Conductivity (S/ m) of kidney as a function of frequency (Hz) for for non-irradiated and irradiated animals

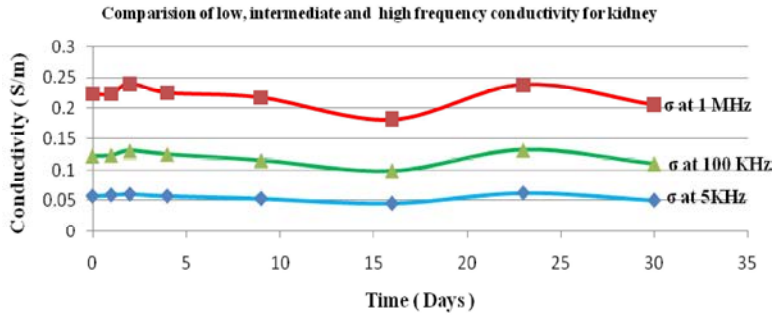

Fig. 7: (b) Conductivity (S m-1) of Kidney as a function of time post-irradiation (days). The curves at low (5 KHz), intermediate (100 KHz) and high frequency (1 MHz)

and electrical property. The four samples, liver, kidney and both anisotropic muscle tissues are studied. The spectral Conductivity for liver as in Figure 6 (a) showed no significant shift with non-and irradiated rats for all curves. A more careful analysis of measurement variability in both non-and irradiated tissues reveals some changes in the conductivity. We study low, intermediate and high-frequency conductivity values at (5 KHz, 100 KHz and 1MHz) to demonstrate changes in conductivity for all samples (liver, kidney and both muscles). Figure 6 (b) show the comparison of low, intermediate and high frequency conductivity versus time post-irradiation for liver. It can be noticed that a little change in the conductivity at low frequencies is observed all the time. But clear changes relative to the non-irradiated are appeared at intermediate and high frequency. It is clearly appeared at high frequency (1 MHz) that the conductivity (Figure 6 (b)) reaches a maximum value (0.364 S/m) at 4 days then decrease following days after but remaining lower than non-irradiated level. The conductivity spectra for kidney, showed no significant change with non-irradiated as appeared in Figure 7 (a). However, no separation at low frequencies (> 10 kHz) but a change (reduction) appeared at high frequency conductivity for the curve marked by (16, days). A more analysis is shown in Figure 7 (b) which represent the comparison of low, intermediate and high frequency conductivity versus time post-irradiation. It can be noticed that the conductivity is observed to decrease with time after irradiation reaching minimum value (0.181 S/m) at 16 days then increase following days (23 days) after. This is clearly appeared at high frequency (1 MHz) conductivity. Also the conductivity value at 30 days is lower than non-irradiated sample. The changes in conductivity of kidney mentioned above interpreted that the high frequency conductivity increases from 16 days to stable after 30 days post irradiation (the end of our procedure) with just a little varying beneath the non-irradiated level. Those changes suggesting a return towards pre-irradiation biochemistry *or* sub-cellular structure but sustained post-irradiation morphology injured at the cellular level. In both liver and kidney a systemic decrease in conductivity (or increase in the size of the impedance curve) as a function of time post-irradiation was observed. This may be due to decrease in water content such that in the previous studies [17-19], suggesting that the direct effects of ionizing radiation on the kidney cannot be accurately determined if the whole body is exposed to low doses of γ-or X-irradiation. Thus, For significant cellular damage (for example kidney tissue) to be noted it is necessary to use doses of 1500 rads or more [18,20]. In Figure 8 (a) the conductivity spectrum of longitudinal muscle tissue showed significant change with non-irradiated samples. Both at low and high frequency the conductivities were elevated. At the low frequency (> 10 KHz) conductivity appears to increase by similar amount, suggesting that low frequency conductivity would not be affected by a change in cell structure. At the high frequency (< 10 KHz) conductivity appears to increase gradually resulting a wide shift at the end. This significant shift can be clearly appeared at the curves (23, 30 day) post-irradiation, suggesting that the high frequency increase can be explained by a change in the conductivity of the inter and/or intracellular fluid. Alternatively, a decrease of small membrane-bound structures [15]. In this case, additional insight can be gained from figure 8 (b) which shows the comparison of low, intermediate and high frequency conductivity versus time post-irradiation. It can be noticed that the conductivity is observed to increase with increasing time after irradiation. It is clearly appeared that the conductivity values at high frequency (1 MHz) of irradiated tissues for all times, ranging (0.67 4 to 0.767 s/m) are higher than non-irradiated value (0.573 s/m). There exist statistical significant differences between conductivity of non-irradiated and irradiated muscle tissues ($p < 0.05$). From table 4 the difference in conductivity values between non-irradiated and 30 days post-irradiated, normalized to non-irradiated value are 27.616%, 29.801% and 34.103% at low, intermediate and high frequency respectively Some readings at low, intermediate and high frequency as function of time for all samples reveal that there exist significant differences between both conductivity and permittivity of non-irradiated and irradiated muscle tissues ($p < 0.05$). At high frequency (1 MHz), the conductivity values (0.67 4 to 0.767 S/m) of longitudinal muscle and (0.582 to 0.731 S/m) of transverse muscle of irradiated tissues for all times, are higher than non-irradiated values (0.573 and 0.546 S/m) respectively. The difference in conductivity values between non-irradiated and 30 days post-irradiated, normalized to non-irradiated value are (34.103%, 33.922 %) for longitudinal and transverse muscles respectively. The normalized values of relative permittivity at both low (5KHz) and high (1 MHz) frequencies are (26.38% and 36.641%) and (44.901% and 18.202%) for longitudinal and transverse muscles respectively. No significant differences in the conductivity and permittivity for liver and kidney ($p > 0.05$) were observed.

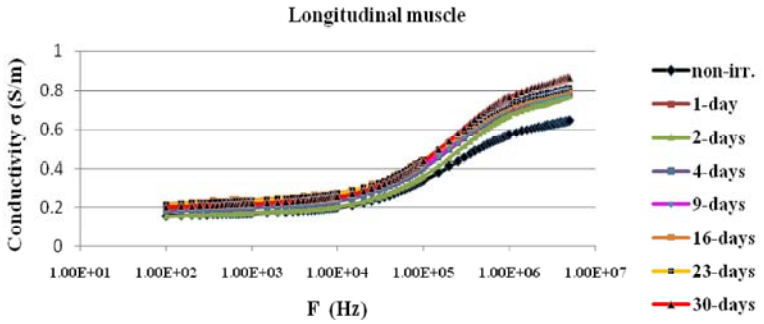

Fig. 8: (a) Conductivity (S m-1) of longitudinal muscle as a function of frequency (Hz) for non-irradiated and irradiated animals

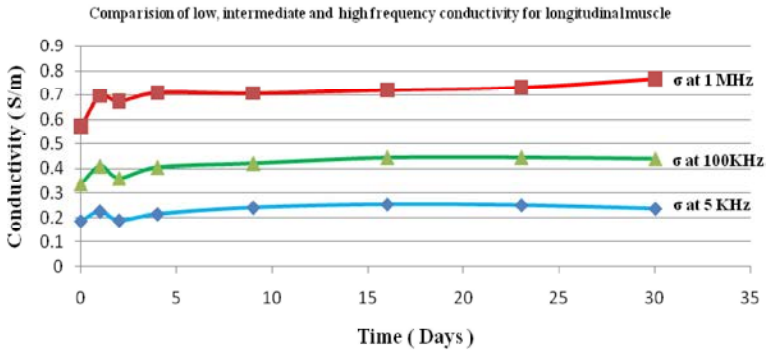

Fig. 8: (b) Conductivity (S m-1) of longitudinal muscle as a function of time post-irradiation (days). The curves at low (5 KHz), intermediate (100 KHz) and high frequency (1 MHz)

Table 3: Comparison of conductivity between non and 30 days post-irradiated tissues for two samples Liver and Kidney at low, intermediate and high Frequency, the differences normalized to non-irradiated value in per cent, based on statistical analysis. (probability associated with student's t-test)

	σ (S/m) for	liver		σ (S/m) for	kidney	
Frequency	NON-Irradiation.	30 days post-irra.	Difference in per cent %	NON-Irradiation.	30 days post-irra.	Difference in percent %
5 KHz	0.062	0.050	-18.786	0.057	0.051	-11.496
100 KHz	0.141	0.127	-10.081	0.123	0.111	-10.061
1 MHz	0.330	0.307	-6.912	0.223	0.206	-7.939

Table 4: Comparison of conductivity between non-irradiated and 30 days post-irradiated tissues for two samples Longitudinal and transverse muscles at low, intermediate and high Frequency, the differences normalized to non-irradiated value in per cent, based on statistical analysis

	σ (S/m) for	longitudinal muscle		σ (S/m) for	transverse muscle	
Frequency	NON-Irradiation.	30 days post-irra.	Difference in percent %	NON-Irradiations	30 days post-irra.	Difference in percent %
5 KHz	0.186	0.237	27.616 (p= 0.032)	0.114	0.169	48.884 (p=0.001)
100 KHz	0.337	0.438	29.801 (p= 0.019)	0.225	0.328	45.681 (p=0.002)
1 MHz	0.573	0.769	34.103 (p= 0.001)	0.546	0.731	33.922 (p=0.000)

The permittivity differences (-4.577% and-11.373%) and (-9.334% and-7.16%) for liver and kidney respectively both at low and high frequency. Similar as in the case of longitudinal muscle. The conductivity spectrum of transverse muscle tissue showed significant change with the non-irradiated as in Figure 9 (a). The conductivities at both low and high frequency were elevated above non-irradiated, indicating that the low frequency conductivity (> 10 kHz) appears to be increase by similar amount reaching some frequency. But at the high frequency (< 10 kHz) the conductivity appears to increase gradually resulting a wide shift which is remarkably noticed at 9 days post-irradiation. As this time increases the value of high frequency conductivity drops from 9 to 30 (day levels) at the end, suggesting a return towards pre-irradiation biochemistry/sub-cellular structure [15].

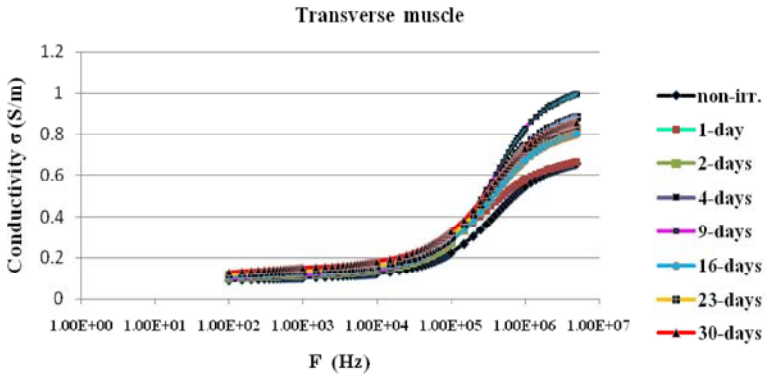

Fig. 9: (a) Conductivity (S m-1) of transverse muscle as a function of frequency (Hz) for non-irradiated and irradiated animals

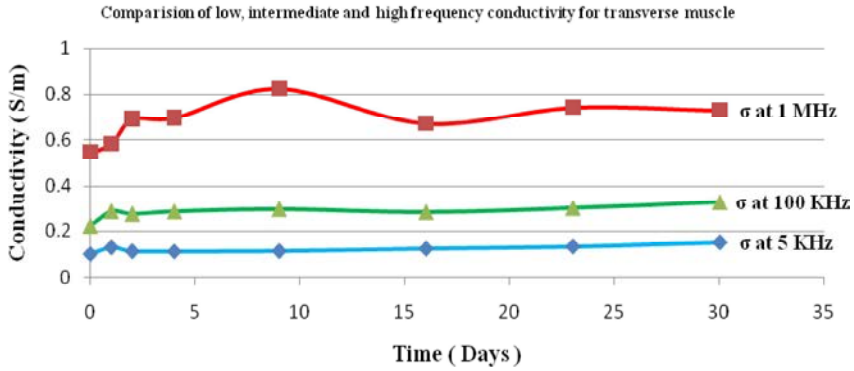

Fig. 9: (b) Conductivity (S m-1) of transverse muscle as a function of time post-irradiation (days). The curves at low (5 KHz), intermediate (100 KHz) and high frequency (1 MHz)

An additional insight can be gained from comparison of low, intermediate and high frequency conductivity. Figure 9 (b) is depicted to show the comparison of low, intermediate and high frequency conductivity versus time post-irradiation for transverse muscle (MT). It can be noticed that the conductivity at higher frequency (1 MHz) is observed to increase with time after irradiation, reaching a maximum value (0.827 S/m) at 9 days then decrease following days after. The conductivity values (0.582 to 0.731 S/m) of transverse muscle of irradiated tissues for all times, are higher than non-irradiated value (0.546 S/m). The difference in conductivity values between non-irradiated and 30 days post-irradiated, normalized to non-irradiated value are 48.884%, 45.681% and 33.922 % (statistically significant $p < 0.05$) for low, intermediate and high frequency respectively. in statistical analysis, the probability associated with student's t-test demonstrates that the change in conductivity values between 30 days post-irradiated and non-irradiated tissues do not significant for liver and kidney, but statistical significant for longitudinal and transverse muscle tissues as represent in Table 3 and Table 4. This comparison indicates that the conductivity is frequency dependence and sustained lower than the non-irradiated (with little change) for liver and kidney, whereas for longitudinal and transverse muscles (significant change) are frequency dependence and sustained higher than the non-irradiated.

Permittivity: In the case of permittivity versus frequency and time. for liver tissues. there is no variance between the curves for non-irradiated and irradiated samples. This also occurs for both muscles. But permittivity readings at low and high frequency at 30 days post-irradiation reveal some change non-irradiated and 30 days irradiation samples. In Figures 10 (a, b), the diagrams of relative permittivity for four sample tissues at low and high frequency (5KHz, 1 MHz) respectively show some change (do not significant) for liver and kidney but statistically significant for muscle tissues. Differences at low frequency are-4.577% and-11.373% and at high frequency are-9.334% and-7.16% for liver and kidney respectively . For both longitudinal (ML) and transverse (MT) muscles. The change of permittivity appeared at both low and high frequency are (26.38% ($p = 0.038462$) and 36.641%

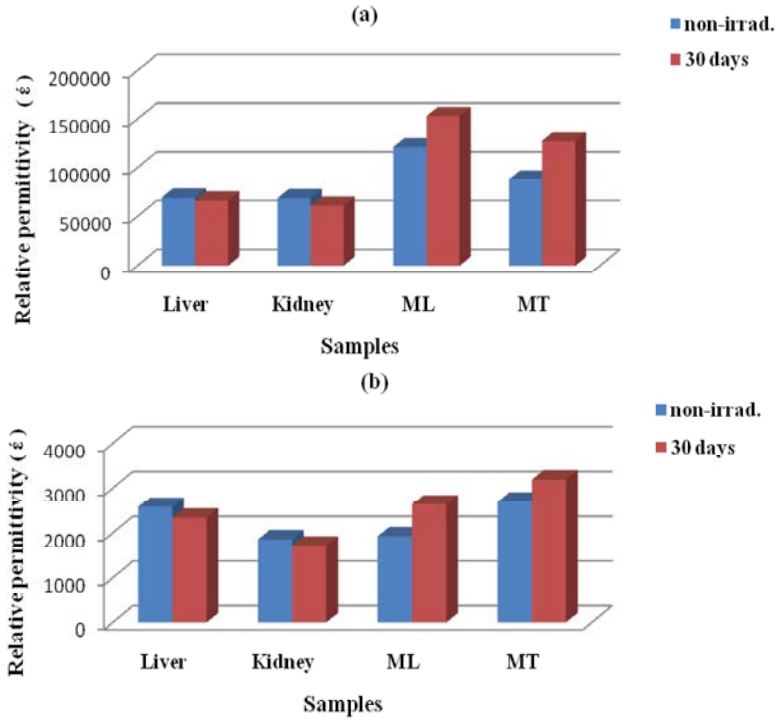

Fig. 10: Comparison of relative permittivity all samples between non-irradiated and 30 day post-irradiated tissues (a) at low frequency (5 KHz) and (b) at high frequency (1 MHz)

(p = 0.042389)) for ML and (44.901% (p = 0.005505) and 18.202% (p = 0.064297)) for MT The change in the dielectric constant of tissue at high frequency in beta-dispersion are mainly associated with electrical double layers occurring at membrane surfaces and the relative permittivity reflects the extent to which 'localized' charge distributions can be distorted or polarized under the influence of the field [21]. The noticeable changing of permittivity at low and high frequency appear for both muscles (but less for liver and kidney) indicate that the severity of radiation damage is dependent on dose with a latent period that varies with the type of tissue involved [20]. The affect due to whole body exposure more rapidly appear in the muscle tissue (at 30 days) than other organs (liver and kidney). In recent studies, the direct effects of ionizing radiation on the liver, kidney, muscle, bone, lung and connective tissues which are often classified as radioresistant, cannot be accurately determined if the whole body is exposed to low doses of X-irradiation [19,22,23].

Thus, For significant cellular damage (for example kidney tissue) to be noted it is necessary to use doses of 1500 rads or more [18,20]. In this study it can be considered that the changes in the impedance, conductivity and permittivity in muscle tissues must be attributed to changes in the electric properties of the organ due to their effects of the progression of radiation-induced tissue injury.

CONCLUSION

It is well established that 400 Rads of whole-body irradiation will not necessarily reflect the immediate effect of radiation. Therefore, the responses of some organ tissues will be observed several days after. Several plots are shown in Figures (1-5) and Tables (1, 2) including the complex impedance spectrum demonstrate some changes. The Figures (6-10) and Tables (3, 4) including the conductivity and relative permittivity as a function of frequency and some readings at low, intermediate and high frequency as function of time for all samples reveal that the differences between the irradiated and non-irradiated spectra are changed relative to variations in all conductivity spectra of organs (liver, kidney and muscle). And no significant change relative to variations in dielectric properties of liver and kidney but a significant change appeared in conductivity and permittivity spectra of muscle tissue measurements. Therefore the change in

electrical properties due to whole body exposure are appeared more rapidly at 30 days in the muscle tissue than other organs (liver and kidney).

REFERENCES

1. Rezyani, M., J.W. Hopewell and M.E. Robbins, 1995. Initiation of non-neoplastic late effects: The role of endothelium and connective tissue. Stem Cells, 13(1): 248-256.
2. Foster, K.R. and H.P. Schwan, 1996. Dielectric properties of tissues, in: Polk C, Postow E (Eds.), Handbook of Biological Effects of Electromagnetic Fields, 2nd edn., CRC Press, Boca Raton, pp: 25-102.
3. Gabriel, C., S. Gabriel and E. Corthout, 1996. The dielectric properties of biological tissues: I. Literature survey Phys. Med. Biol., 41: 2231-2249.
4. Gabriel, S., R.W. Lau and C. Gabriel, 1996. The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues Phys. Med. Biol., 41: 2271-2293.
5. Gabriel, S., R.W. Lau and C. Gabriel, 1996. The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz Phys. Med. Biol., 41: 2251-2269.
6. Kozlowskatt, J., B. Rigaudt and J.P. Moruccit, 1992. Determination of impedance of tissue in the frequency range 10^{-6}-20 MHz: preliminary results Clin. Phya. Physiol. Meas., 13(Suppl. A,): 3-75.
7. Smith, S.R. and K.R. Foster, 1985. Dielectric properties of low-water-content tissues Phys. Med. Biol., 30: 965-973.
8. Osterman, K.S., P.J. Hoopes and K.D. Paulsen, 2004. Non-invasive assessment of radiation injury with electrical impedance spectroscopy Phys. Med. Biol., 49: 665-683.
9. Foster, K.R. and H.P. Schwan, 1989. Dielectric properties of tissues and biological materials: a critical review Crit. Rev. Biomed Eng., 17: 25-104.
10. Paulsen, K.D., K.S. Osterman and P.J. Hoopes, 1999. *In vivo* electrical impedance spectroscopic monitoring of the progression of radiation-induced tissue injury Radiation. Res., 152: 41-50.
11. Tamurat, T., T. Lahtinent, T. Repol and H.P. Schwan, 1994. Modelling of the dielectric properties of normal and irradiated skin Phys. Med. Biol., 39: 927-936.
12. Mohammad, A., P.M. Fogerson and S.B. Rutkove, 2009. Electrical characteristics of rat skeletal muscle in immaturity, adulthood and after sciatic nerve injury and their relation to muscle fiber size Physiol. Meas., 30: 1415-1427.
13. Cole, K.S. and R.H. Cole, 1941. Dispersion and absorption in dielectrics. I. alternating current field. J. Chemical Physics, 1: 341-351.
14. Aaron, R., M. Huang and C.A. Shiffman, 1997. Anisotropy of human muscle via non-invasive impedance measurements Phys. Med. Biol., 42: 1245-62.
15. Epstein, B.R. and K.R. Foster, 1983. Anisotropy in the dielectric properties of skeletal muscle Med. Bio. Eng. Comput., 21: 51-5.
16. Hsu, H.Y., C.Y. Chai and M.S. Lee, 1998. Radiation-induced muscle damage in rats after fractionated high-dose irradiation. Radiation Res., 149: 482-486.
17. Threlfall, G., A.B. Cairnie, D.M. Taylor and A.T. Buck, 1966. Effect of whole body X-irradiation on renal compensatory hypertrophy. Radiation Res., 27: 559-565.
18. Wachtel, L.W. and L.J. Cole, 1965. Abscopal effects of whole-body X-irradiation on compensatory hypertrophy of the rat kidney. Radiation Res., 25: 78-91.
19. Wachtel, L.W., Cole, L.J. and V.J. Rosen, 1966. Abscopal and direct effects of whole-body X-irradiation: Rat kidney mitotic activity and DNA content after uninephrectomy. Intern. J. Radiation Biol. Rad. Res., 10: 75-82.
20. Ariyama, K., N. Fausto and J.L. Van Lancker, 1970. Effects o f X-Radiation on Amino Acid Incorporation into Regenerating Liver Proteins Radiation Research, 42: 528-538.
21. Pethig, R. and D.B. Kell, 1987. The passive electrical properties of biological systems: their significance in physiology, biophysics and biotechnology Review article Phys. Med. Biol., 32: 933-970.
22. Maisin, J., A. Dunjic and J.R. Maisin, 1971. Lymphatic system and thymus. In: Pathology of Irradiation (C.C. Berdjis, Ed.), Williams and Wilkins Co., Baltimore, pp: 496-541.
23. Mandl, A.M., 1963. The radiosensitivity of Oocytes at different stages of maturation. Proc. Roy. Soc. (London) B., 158: 119-141.