Effective Atomic Numbers and Electron Densities of Some Human Tissues, Tissue Substitute Substances and Water for Proton, C and O Heavy Charged Particles Interaction in the Energy Range 10 keV – 1GeV

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Abstract. Various parameters of dosimetric interest such as effective atomic numbers and electron densities have been used to evaluate the water and tissue equivalence of some human tissues. Such as adipose tissue (ICRU-103), Lung Tissue, ICRP and muscle, skeletal (ICRP-ICRU 201), muscle, striated (ICRP-ICRU-202), Bone compact (ICRU-119), Bone, Cortical (ICRU-120), and six substitute substances, A-150 ICRU-099, LN10-75 LUNG, MS20 (ICRU-200), Muscle Equiv. Liq. with Sucrose (ICRU-203), Muscle Equiv. Liq. without Sucrose (ICRU-204), and B100 (ICRU-111). These parameters were computed for the total interactions with Proton, C ion and O ion in the wide energy range of 10KeV - 1GeV. The water and tissue equivalent properties have been investigated with respect to Z_{eff} and N_e values to evaluate their ability to be used with heavy charged particles applications. Some conclusions were drawn depending on variation of Z_{eff} throughout the energy range and tissue and water equivalency. Data reported here should be useful in determining best water and the best tissue equivalent substances for proton, C and O ion interaction within the energy range specified.

Key words: effective atomic number, electron density, heavy charged ions, water equivalence- human tissues, tissue substitutes, and SRIM code.

Introduction

With the increasing use of charged particles in various fields such as industry, medicine and agriculture, the study of their interaction with different composite materials has become an important issue for radiation physicists. For practical applications in medicine, therapy and diagnosis it is important to study charged particle interaction with dosimeters, human tissues, and substitutes which are used to simulate the human tissues and organs in diagnostic and therapeutic radiology. Charged particle therapy (CPT) is currently based on the use of protons or carbon ions for the treatment of deep-seated and/or radio-resistant tumors, which offer significant advantages in comparison to conventional megavolt photon therapy, because of the radiobiological advantages (depth to dose distribution, reduction of radiation dose in patients' body, smaller sensitivity for oxygen-depleted tissues). Charged particles now in use in CPT are ^{1}H, ^{4}He, ^{12}C, and ^{16}O, which are considered the most relevant candidates for advancing particle therapy, and is presently available in the most advanced particle therapy clinical centers (Tommasino et al., 2015: 429-438). There are various parameters used to characterize the materials in terms of radiation response such as mass stopping power for electrons, protons and heavy ions, from which other parameters of dosimetric interest like effective atomic number and electron density could be derived; these help in the basic understanding of radiation interactions with multi-element materials. It was pointed out by Hine (1952: 725) that the effective atomic number cannot be expressed by a single number due to the different partial interaction processes at different energy regions and the various atomic numbers present in the compound have to be weighted differently. Effective atomic number *(Z_{eff})*, for multi-element materials, is calculated from the atomic numbers of the constituent elements, weighted according to the different partial interaction process by which the ion interacts, so it is an energy-dependent parameter (Murty, 1965: 398-399). Closely related to effective atomic number, is the electron density, N_e, which refers to the number of electrons per unit mass of a multi-element material, and it represent the probability of finding an electron at a particular point in space.

It becomes a common practice to study the radiological properties of materials such as dosimeters, human tissues and phantom material, with respect to their effective atomic number and electron density, and use them as a tool for evaluation of radiation equivalence of two materials, that is water equivalence and tissue equivalence of tissue and tissue substitute (Parthasaradhi et al., 1989: 653-654).

In literature several studies of Z_{eff} and electron density N_e of human tissues, and substitutes are been carried out for electron, proton and He ion in a wide range of energies (Kurudirek, 2016: 508-520; Kurudirek, 2014: 1-7), for other ions these studies was done within limited energy range. There is a need of studying these parameters for the interaction of heavy charged particles such as Proton, He, C and O ion and other ions that has important rule in radiotherapy. This is the motivation behind this work.

In this paper, radiological properties of some human tissues were investigated with respect to their effective atomic number and electron density for Proton, C, O ion total interaction, in the energy range 10KeV – 1GeV. Variations of atomic number and electron density with energy have been investigated. In addition, water and tissue equivalence of the material have been investigated.

Material and Methods

The elemental composition of Adipose Tissue (ICRP ICRU-103), Muscle, Skeletal (ICRP ICRU-201), Muscle, Striated (ICRP ICRU-202), Bone, Compact (ICRU-119), Bone, Cortical (ICRP ICRU-120), A-150 Tissue-Eqiv. Plastic (ICRU-099), MS_20 Tissue Substitute (ICRU-200), Muscle Equivalent Liquid with Sucrose (ICRU - 203), Muscle Equivalent Liquid Without Sucrose (ICRU - 204), B-100, Bone-Equivalent Plastic (ICRU-111) and Water was obtained from compound dictionary available within SRIM program (Ziegler, 2020), Lung Tissue, ICRP (White, 1989) and LN10-75 LUNG was obtained from (Singh and Gagandeep, 2002: 442-449).

In order to calculate Z_{eff} using interpolation method, SRIM code (Ziegler, 2020) has been used to obtain the elemental mass stopping powers within ion energy range 0.01-1GeV, spanning the minimum and the maximum elements present in the considered materials. The mass stopping power for each material was then calculated using Bragg's additive rule, and the Stopping cross sections (σ_{tissue}) were then obtained by dividing mass stopping power of the tissue by the total number of atoms present in one gram of the material. Finally, Z_{eff} values were calculated by the linear logarithmic interpolation of Z values between the adjacent elemental stopping cross section data. This calculation done following procedure adopted by Kurudirek (Kurudirek, 2014a: 1-7; Kurudirek, 2014b: 130-134; Kurudirek, 2014c: 139-146; Kurudirek and Onaran 2015: 125-138). The electron density N_e of the tissues has been calculated using the formula:

$$N_e = Z_{eff}\ N_A/\langle A\rangle\ (electron/g)$$

Where N_A is the Avogadro's number and $\langle A\rangle$ is the relative atomic mass of the tissue. The uncertainties in the present work base on the uncertainties arise in derivation of stopping powers derived from SRIM software.

Tissue and water equivalence of substances under study is expressed as relative difference percent, as follows:

$$RD\% = \frac{Z_{eff}(Material) - Z_{eff}(Water)}{Z_{eff}(Material)}$$

Results and Discussion

The variation of effective atomic number (Z_{eff}) and electron density (N_e) with energy for proton, C and O ion total interaction in the energy range 0.01KeV – 100MeV, are shown graphically in Fig. 1 and Fig. 2, respectively.

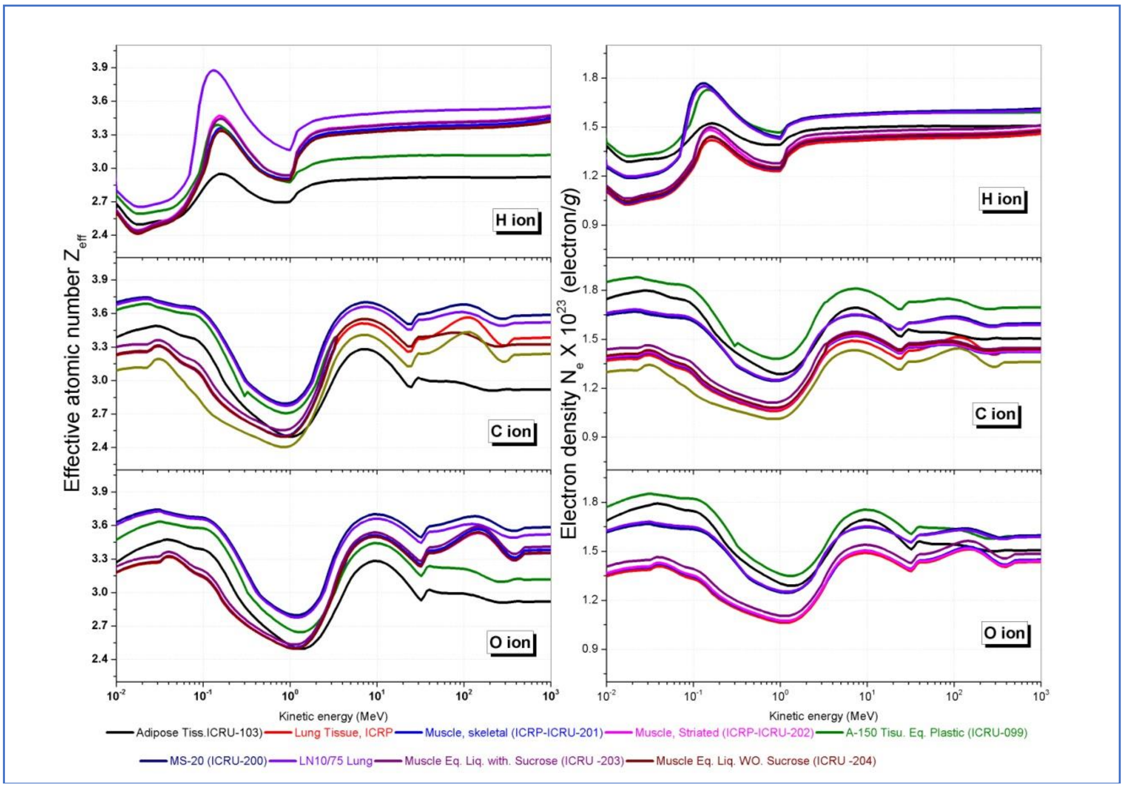

Fig. 1.Variation of Z_{eff} and N_e soft tissues and muscles with H, C and O ion energy

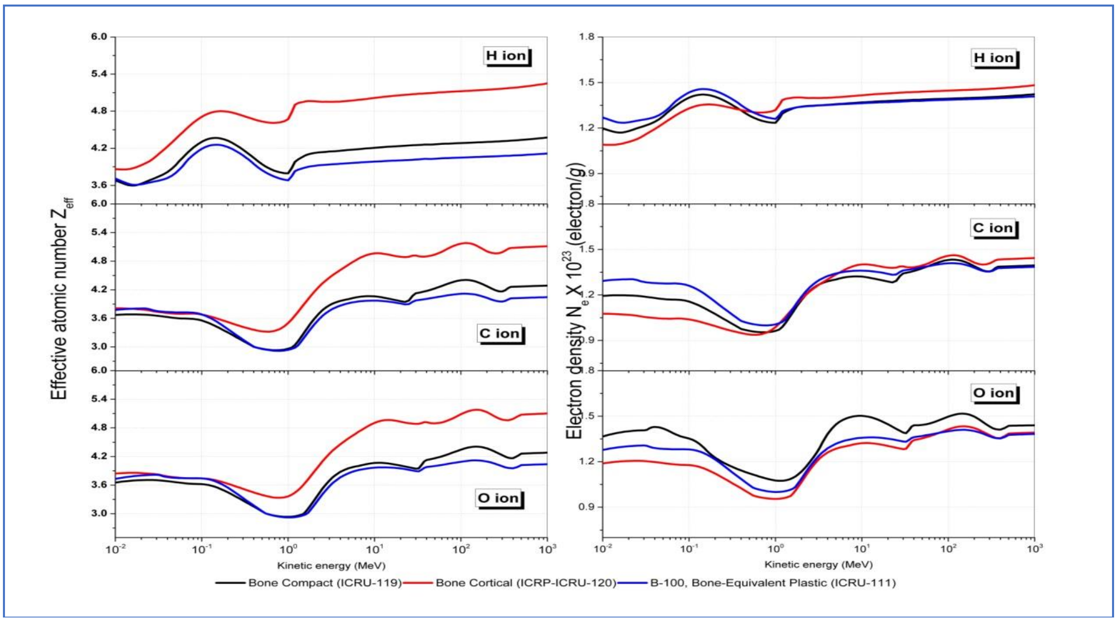

Fig. 2.Variation of Z_{eff} and N_e Bones compact, bone cortical and B-100, Bone-Equivalent Plastic (ICRU-111), with H, C and O ion energy

For Proton interaction, Z_{eff} has minimum values at lower energies and makes peak between 0.13 and 0.17 MeV, it start to increase again after 1 MeV and then keep constant. For C and O ion interaction, high values where observed at low ion energies, and in relatively high energies at (7.0 - 8.0 MeV) for C ion and 10 MeV for O ion. The minimum values are observed at intermediate energies of (0.8-1.0 MeV) and (1.1-1.4MeV) for C and O ion respectively.

For materials under study, highest value of Z_{eff} were observed for LN10/75 LUNG for all ions and MS-20 (ICRU 200) for proton interaction only. Meanwhile lowest Z_{eff} values were observed for Adipose Tissue (ICRP ICRU-103) for proton interaction and at energies greater than 1.0 MeV of C and O ion interaction. Lung Tissue ICTP, Muscle, Equiv. Liq. Without Sucrose (ICRU-204) and Muscle, Skeletal (ICRP ICRU-201) possesses lowest values for C and O ion below 1.0 MeV. In general, peaks were shifted towards higher energies with increasing atomic number of ion. As shown in Fig. 1. and Fig. 2, it is clear that variation of electron density N_e have same trends as variation of Z_{eff}, as expected.

Table1. Below shows basic statistical information on Z_{eff} and N_e dependence on incident ion energy. The highest variation in Z_{eff} for ion interaction is 35% (Tissue Substitute MS-ICRU-200), 33% (Lung ICRP) and 33% (Lung ICRP and Skeletal (ICRP ICRU-201)) for Proton, C and O ion respectively

Table 1. Statistical information on Z_{eff} and Ne of human tissues and substitutes for Proton, C and O ion interaction, (1) Adipose Tissue (ICRP ICRU-103), (2) Lung Tissue, ICRP (3) Muscle, Skeletal (ICRP ICRU-201) (4) Muscle, Striated (ICRP ICRU-202), (5) Bone, Compact (ICRU-119), (6) Bone, Cortical (ICRP ICRU-120) (7) A-150 Tissue-Equivalent Plastic (ICRU-099), (8) MS_20 Tissue Substitute (ICRU-200), (9) LN10-75 Lung, (10) Muscle Equivalent Liquid with Sucrose (ICRU - 203), (11) Muscle Equivalent Liquid Without Sucrose (ICRU - 204), (12) B-100, Bone-Equivalent Plastic (ICRU-111), (13) Water

S.N	Proton					C ion					O ion			
Z_{eff}	Mean	STD	Min	Max		Mean	STD	Min	Max		Mean	STD	Min	Max
1	2.82	0.14	2.50	2.95		3.03	0.28	2.50	3.28		3.04	0.28	2.50	3.28
2	3.13	0.33	2.41	3.44		3.17	0.33	2.50	3.57		3.17	0.33	2.50	3.57
3	3.14	0.33	2.42	3.45		3.16	0.32	2.50	3.55		3.17	0.33	2.51	3.57
4	3.18	0.34	2.45	3.48		3.16	0.32	2.50	3.55		3.16	0.32	2.50	3.53
5	4.13	0.23	3.60	4.38		3.79	0.44	2.93	4.41		3.78	0.43	2.94	4.41
6	4.81	0.39	3.86	5.25		4.32	0.67	3.32	5.18		4.31	0.66	3.33	5.18
7	3.02	0.20	2.59	3.39		3.21	0.29	2.64	3.44		3.22	0.29	2.64	3.44
8	3.42	0.35	2.66	3.97		3.48	0.29	2.79	3.70		3.48	0.29	2.80	3.70
9	3.36	0.33	2.65	3.88		3.44	0.29	2.77	3.66		3.44	0.29	2.78	3.66
10	3.18	0.34	2.44	3.47		3.19	0.30	2.55	3.55		3.20	0.32	2.53	3.59
11	3.12	0.32	2.42	3.42		3.16	0.32	2.49	3.55		3.16	0.32	2.50	3.54
12	3.96	0.17	3.61	4.26		3.72	0.36	2.92	4.12		3.72	0.36	2.92	4.12
13	2.99	0.31	2.34	3.31		3.13	0.46	2.40	5.17		3.04	0.32	2.41	3.43
S.N	Proton (H ion)					C ion					O ion			
N_e	Mean	STD	Min	Max		Mean	ST	Min	Max		Mean	STD	Min	Max
1	1.45	0.07	1.29	1.52		1.56	0.15	1.29	1.80		1.57	0.15	1.29	1.79
2	1.33	0.14	1.02	1.46		1.34	0.14	1.06	1.51		1.34	0.14	1.06	1.51
3	1.34	0.14	1.03	1.47		1.35	0.14	1.07	1.52		1.36	0.14	1.07	1.53
4	1.36	0.14	1.04	1.49		1.36	0.14	1.07	1.52		1.36	0.14	1.07	1.52
5	1.34	0.07	1.17	1.42		1.23	0.14	0.95	1.43		1.23	0.14	0.95	1.43
6	1.36	0.11	1.09	1.48		1.22	0.19	0.94	1.46		1.22	0.18	0.94	1.46
7	1.54	0.10	1.32	1.73		1.64	0.15	1.35	1.86		1.64	0.15	1.35	1.85
8	1.52	0.16	1.19	1.77		1.55	0.14	1.24	1.67		1.55	0.13	1.25	1.67
9	1.52	0.15	1.20	1.75		1.55	0.14	1.25	1.68		1.55	0.13	1.25	1.68
10	1.38	0.15	1.06	1.51		1.39	0.14	1.11	1.55		1.39	0.14	1.10	1.56
11	1.35	0.14	1.05	1.48		1.36	0.14	1.08	1.54		0.37	0.14	1.08	1.53
12	1.36	0.06	1.23	1.46		1.28	0.12	1.00	1.41		1.2	0.12	1.00	1.41
13	1.26	0.13	0.99	1.39		1.32	0.20	1.01	2.17		1.28	0.14	1.01	1.44

The Z_{eff} difference percent relative to water (DR%) has been also calculated to evaluate degree of water equivalence of the given substances for different ions interaction, and represented graphically in Fig. 3. It has been observed that A-150 Tissue-Eqiv. Plastic (ICRU-099), Muscle Equivalent Liquid Without Sucrose (ICRU - 204), Skeletal (ICRP ICRU-201), Muscle, Muscle Equivalent Liquid with Sucrose (ICRU-203) and Muscle, Striated (ICRP ICRU-202), have the best water equivalence in the entire energy range with relative difference of ≤-3%, ≤4%, ≤5%, ≤5%, ≤6% for H ion. Also, Lung Tissue, ICRP, Muscle, Striated (ICRP ICRU-202), Muscle Equivalent Liquid with Sucrose (ICRU - 203), Muscle Equivalent Liquid without Sucrose (ICRU–204) show diff. of ≤5% through entire energy range for C, and O ion.

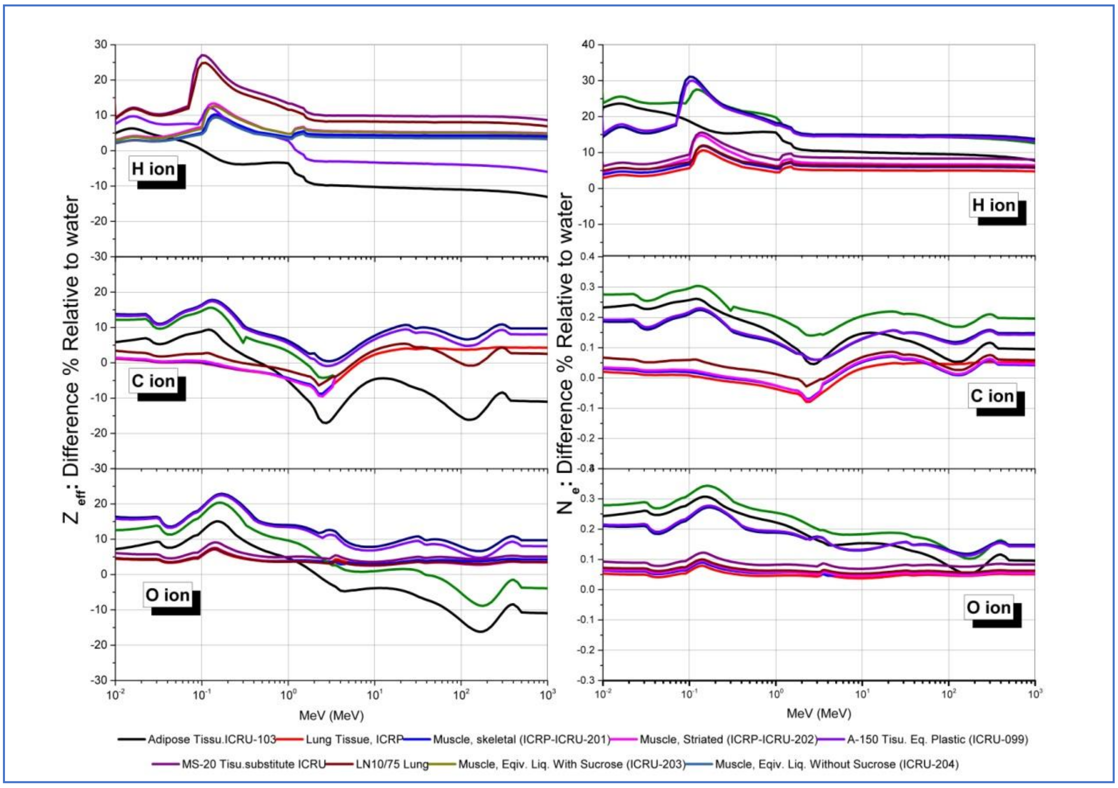

Fig. 3. Differences in Z_{eff} of tissues and muscles relative to water

The Z_{eff} difference percent relative to tissue (DR %) has been also calculated for some tissue of human organs relative to tissue substitute and shown graphically in Fig. 5. It is found that A-150 Tissue-Eqiv. Plastic (ICRU-099), simulates Adipose through the entire energy range for all ions studied, with differences less than 6% while shows high differences (up to 15%), for H ion in the energy range of (0.01-1.0 MeV). Also, LN10/75 Lung shows good tissue equivalence with Lung Tissue ICTP with differences less than 5% at energies of (2-1000MeV), (3-1000MeV), (5-1000MeV) for H, C and O ion interaction, high difference up to (26% at 0.1 MeV), (22% at 0.14MeV) and (21% at 0.18MeV) is observed for proton, C and O ion respectively, mean while full matching is observed around 100 MeV for C and O ion. Muscle without matching well with muscle skeletal and muscle striated with relative differences of <1.0% and <3% for H ion, < 0.6% and 0.1% for C ion, and 0.1% for O ion ,with slightly high differences at 0.1-10MeVfor both C and O ion. With respect to with sucrose, differences of 2% - -4% were observed at energy of (0.1-3.0MeV) for H and C ion, and difference is almost Zero for the rest of the energy regions. B100 shows well matching with compact 119, with low differences of

<5% for H ion, and between -4% at low energies below 1.0 M eV and 6% for the rest of range for C and O ion.

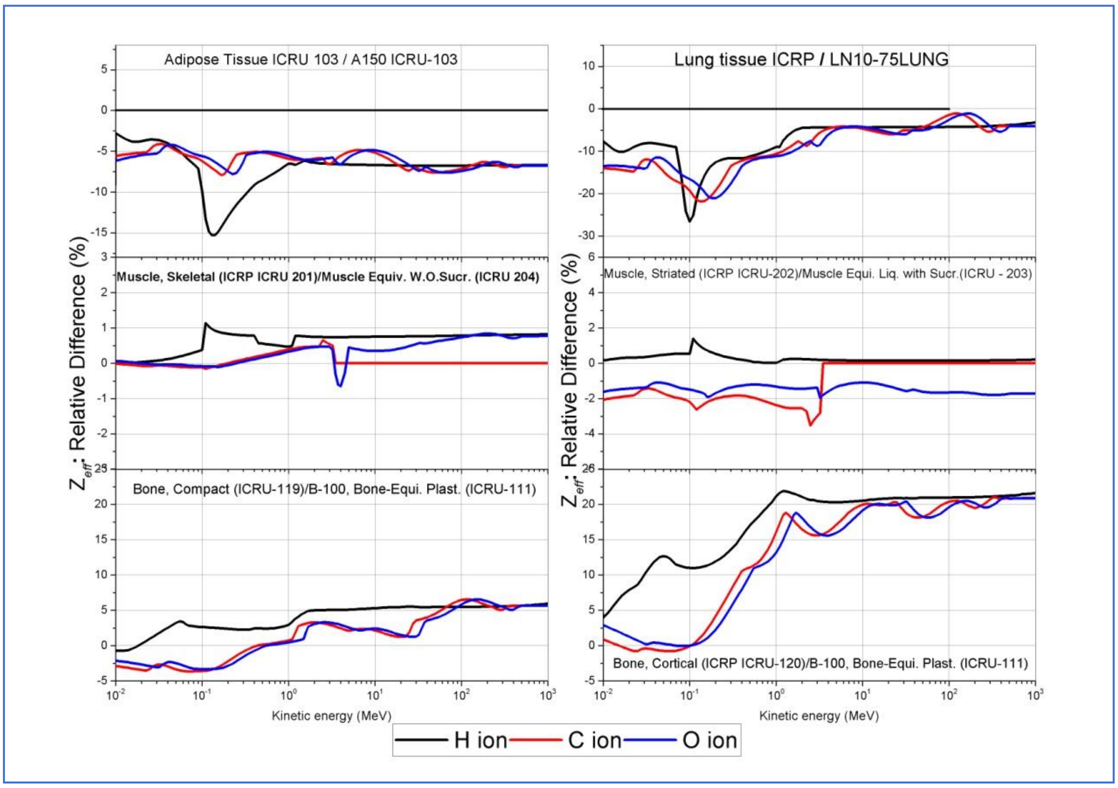

Fig. 4. Difference percent in Z_{eff}, all substances relative tissues

Conclusion

The effective atomic number and electron density of tissue and tissue substitute substances have been calculated in the energy range10KeV-1GeV for H, C and O ion total interaction.

We have shown that variation in Z_{eff} values is observed in the entire energy region from 10 keV to 1GeV.

The lowest values of Z_{eff} were obtained in LN /75 LUNG for all ions, whereas the highest values were obtained in Bone cortical and bone compact These high values are due to the presence of high Z element (Ca, Z =20) with relatively high weight fraction within its constituents.

The maximum values of Z_{eff} depends on ion type and shift towards higher energies with increasing of the atomic number of the incident ion.

Electron density is closely related to the effective atomic number and has the same quantitative energy dependence as Z_{eff}

The water and tissue equivalence properties of the given substances have been compared for different types of ions (H, C, and O ion).

A-150 Tissue-Eqiv. Plastic (ICRU-099), Muscle Equivalent Liquid Without Sucrose (ICRU - 204), Skeletal (ICRP ICRU-201), Muscle, Muscle Equivalent Liquid with Sucrose (ICRU-203) and Muscle, Striated (ICRP ICRU-202), have the best water equivalence in the entire energy range with relative difference of ≤-3%, ≤4%, ≤5%, ≤5%, ≤6% for H ion. Also, Lung Tissue, ICRP, Muscle, Striated (ICRP ICRU-202), Muscle Equivalent Liquid with Sucrose (ICRU - 203), Muscle Equivalent Liquid without Sucrose (ICRU–204) show diff. of ≤5% through entire energy range for C, and O ion.

It is found that A-150 Tissue-Eqiv. Plastic (ICRU-099), simulates Adipose Tissue ICRU 103 very well in the entire energy region for H, C and O ion interaction, except in the range of 10KeV-1.0 MeV for H ion interaction.

LN10/75 Lung shows good tissue equivalence with Lung Tissue ICRP with differences less than -5% for all ions, in the energy range 3MeV-1 GeV.

Muscle without was found to be equivalence to muscle skeletal and muscle striated with relative differences +/-1.0%

With respect to with sucrose, differences of 1% - -1% were observed at energy of (0.1-3.0MeV) for H and C ion, and difference is almost Zero for the rest of the energy regions.

Data reported here gives essential information about interaction of different types of charged particles with different materials and could be useful in the energy range specified.

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