Water and tissue equivalence properties of biological materials for photons, electrons, protons and alpha particles in the energy region 10 keV–1 GeV: a comparative study

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ABSTRACT
Purpose: To compare some biological materials in respect to the water and tissue equivalence properties for photon, electron, proton and alpha particle interactions as means of the effective atomic number ($Z_{	ext{eff}}$) and electron density ($N_e$).

Methods: A Z-wise interpolation procedure has been adopted for calculation of $Z_{	ext{eff}}$ using the mass attenuation coefficients for photons and the mass stopping powers for charged particles.

Results: At relatively low energies (100 keV–3 MeV), $Z_{	ext{eff}}$ and $N_e$ for photons and electrons were found to be constant while they vary much more for protons and alpha particles. In contrast, $Z_{	ext{eff}}$ and $N_e$ for protons and alpha particles were found to be constant after 3 MeV whereas for photons and electrons they were found to increase with the increasing energy. Also, muscle eq. liquid (with sucrose) have $Z_{	ext{eff}}$ and $N_e$ values close to the Muscle Skeletal (ICRP) and Muscle Striated (ICRU) with difference below 10%. Muscle eq. liquid (without sucrose) have $Z_{	ext{eff}}$ and $N_e$ values close to the Muscle Skeletal (ICRP) and Muscle Striated (ICRU) with difference below 10%.

Conclusions: The reported data should be useful in determining best water as well as tissue equivalent materials for photon, electron, proton and alpha particle interactions.

Introduction
Studies on the interactions of different type of radiations such as photons, electrons, protons and heavy ions with the materials are of importance in nuclear physics and medical physics-related applications, e.g. imaging as well as cancer therapy. $Z_{	ext{eff}}$ and $N_e$ are energy and chemical composition-dependent parameters and are used in characterization of radiological properties of the biological materials and tissue phantoms. $Z_{	ext{eff}}$ is used to describe the radiation interaction properties in terms of equivalent elements and it applies to the irradiated material not the charged particle. Regarding definition of $Z_{	ext{eff}}$, it is assumed that the actual atoms of a given molecule can be replaced by an equal number of identical (average) atoms, each of which having $Z_{	ext{eff}}$ electrons and $Z_{	ext{eff}}$ is closely related to the electron density, which is expressed in number of electrons per unit mass (Manohara et al. 2009). Since $Z_{	ext{eff}}$ describes the multi-element materials in terms of equivalent elements, then this parameter may be used to differentiate different materials. Also, $N_e$ would give conclusive information about how radiation would be scattered through the medium. Effective atomic number and electron density are exclusive parameters used to characterize different types of materials and they can be used to distinguish materials with respect to their $Z_{	ext{eff}}$ and $N_e$ in the continuous energy region. Only when the tissues and/or other biological materials are better distinguished from each other, precise diagnostics of certain diseases would be obtained with the help of the clear images of the medium. For example, Grinyov et al. (2007) developed dual-energy radiography for separate detection of materials differing in their effective atomic number and local density and they concluded that deviations of the physical parameters such as effective atomic number by 15–20% from their normal values can be used to estimate early detection of tumors, atherosclerosis and osteoporosis (Grinyov et al. 2007). Torikoshi et al. (2007) developed a dual-energy X-ray CT method using synchrotron radiation to obtain high-resolution $Z_{	ext{eff}}$ images for medical diagnosis (Torikoshi et al. 2007). More recently, Qi et al. (2010) have developed a novel computed tomography (CT) imaging technique and they used this technique to obtain effective atomic number and electron density (Qi et al. 2010). Also, with the help of prior estimations on how the radiation response of the medium is, more precise dose estimations would be performed to kill the tumors and also damage to healthy tissues would be minimized as well. From this point of view, the tissue equivalence studies should be very crucial. Ideal dosimeters should be radiologically water or tissue equivalent so that they have the similar physical properties of governing absorbed dose in real tissue. The radiological properties of a dosimeter include the radiation interactions that may occur in the target material. Thus, the water and tissue equivalence of a radiation dosimeter can be calculated by comparing the radiological properties of the materials with water and tissue.
dosimeter with those of water and tissue for the energy range of interest for charged or uncharged radiation. It is a common practice to use the $Z_{eq}$ and $N_e$ as a means of characterizing the radiological properties of dosimeters, human tissues and water. This practice will verify the validity of calculation algorithms by comparing the generated doses with the measured doses in tissue equivalentphantom substances (Shivaramu et al. 2001). The growing interest in use of MV cone beam computed tomography in radiotherapy treatment planning requires accurate values of electron density of the tissues to compute dose distributions accurately (Hughes et al. 2012). The dosimetric and tissue equivalent properties of materials make them very useful in clinical applications such as radiological examinations and treatment planning. Since high doses are sometimes used in radiation therapy, experiments are done with water and tissue equivalents in order to get prior estimation about how radiation interacts with the real target. More detailed explanation on where these constants are used is given elsewhere (Kurudirek 2014a).

It was pointed out by Hine 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 material have to be weighted differently (Hine 1952). The atomic number, $Z$, is a ubiquitous parameter in atomic and nuclear physics representing interaction of radiation with atoms of a single element. For a complex medium, on the other hand, the effective atomic number, $Z_{eq}$, is representing interaction with a material, which is composed of several different elements. For each of the different processes, by which radiation can interact with matter, the various atomic numbers in the material have to be weighted differently. As an example for photons, it should be mentioned that the photon energy range in which photons interact with matter can be divided into three main regions where photoelectric effect, Compton scattering and pair production are the principal photon interaction modes. The photoelectric effect ($\tau$), Compton Scattering ($\sigma$), and pair production ($\kappa$) cross sections are related to photon energy and the atomic number ($Z$) of an interacting medium according to three equations:

$$\tau = \frac{Z^5}{E^3}$$  \hspace{1cm} (1)

$$\sigma = \frac{Z}{E}$$ \hspace{1cm} (2)

$$\kappa = \frac{rZ^2(E - 1.022)}{E}$$ \hspace{1cm} (3)

where $\rho$, $q$, and $r$ are constants. For a composite material, $Z_{eff}$ can be used as a good approximation for $Z$ in above equations. Thus, $Z_{eff}$ and photon energy are responsible for interaction probability where any of these three interaction processes dominate. Accordingly, $Z_{eff}$ has not a unique value that can be used in the entire energy region of a certain ionizing radiation, due to the fact that multi-element materials have many constituents with different atomic numbers, which results in different radiation interaction probabilities in different energy regions. Therefore, $Z_{eff}$ is considered as an energy dependent parameter which depends on energy and chemical composition of the corresponding material. Thus, $Z_{eff}$ and $N_e$ are not true constants for a given material but vary with energy, depending on the interaction processes by which charged or uncharged radiation are interacting. They also depend on the type of the radiation as well, because, different types of radiations, i.e. charged or uncharged radiation, may have different types of interaction mechanisms in the continuous energy region, which could yield different values of $Z_{eff}$ and $N_e$.

Literature is rich in studies dealing with calculation of $Z_{eff}$ and $N_e$ for photons in biological and other compounds (Manjunathaguru and Umesh 2006; Manohara et al. 2009; Polat and Icelli 2010), in semiconductors (Cevik et al. 2008), in solutions (Kurudirek 2011), in tissues from human organs (Manjunatha and Rudraswamy 2013), in alloys (Han et al. 2012), in dosimetric materials (Mann et al. 2012; Un 2013) and in some polymers (Kucuk et al. 2013). However, studies on $Z_{eff}$ for different type of radiations are rarely available. The $Z_{eff}$ of fat, muscle and bone for photons and electrons has been calculated with a restriction to the $Z$ exponents and their variation with energy (White 1971). A study has been performed based on $Z_{eff}$ for electron interactions with TLD-100 and TLD-100H thermoluminescent dosimeters and investigated the influence of dopant concentrations and impurities on $Z_{eff}$ (Taylor 2011). $Z_{eff}$ of composite materials have been derived for total as well as partial interaction processes of photons (1–50 MeV), electrons (1–50 MeV) and protons (1–200 MeV) (Guru Prasad et al. 1997). The $Z_{eff}$ of biological materials have been studied in the energy region 1–50 MeV for photons, electrons and He ions and it has been found that the $Z_{eff}$ for photons and electrons increases with energy, and remains, about the same, for He ions (Parthasaradhi et al. 1989). However, those studies restricted to a limited energy range and a limited number of materials were considered. Also, $Z_{eff}$ of a large number of biological and dosimetric materials for total electron interaction has been investigated in the wide energy region 10 keV–1 GeV (Kurudirek 2014b). Moreover, the water and tissue equivalent properties of different materials including tissues, tissue equivalents, biological compounds and water have been studied in the energy range of 1 keV–10 GeV for total proton interaction (Kurudirek 2014c). In the light of the available studies for different types of radiation, it has to be mentioned that there is almost no study dealing with direct comparison of $Z_{eff}$ and $N_e$ for photons, electrons, protons and alpha particles in the wide energy region 10 keV–1 GeV. In this regard, the present study aimed at comparison of $Z_{eff}$ and $N_e$ for different types of radiation such as photons, electrons, protons and alpha particles (heavy ions) in the energy region 10 keV–1 GeV.

**Methods**

The chemical composition data for the used materials is listed in Table 1. The calculation method adopted is similar to the ones described elsewhere (Parthasaradhi et al. 1989; Guru Prasad et al. 1997; Taylor 2011; Kurudirek 2014b, 2014c). For photons, the Auto-$Z_{eff}$ program has been used to calculate
| Chemical composition (Fraction by weight) | Chemical composition (Fraction by weight) |
|----------------------------------------|----------------------------------------|
| Water                                  | A-150 Tis. Eq. (ICRP)                   |
| Adipose Tissue (ICRP)                  | Air, Dry (Sea level)                    |
| Aluminum Oxide                        | B100 Bone Eq. Plastic (ICRU)           |
| Bone Compact                           | C-552 Air Eq. Plastic (Ca Fluoride)     |
| H                                      | 0.112                                 |
| C                                      | 0.101327                              |
| N                                      | 0.035057                              |
| O                                      | 0.052316                              |
| F                                      | 0.017422                              |
| Na                                     | 0.0005                                |
| Mg                                     | 0.000002                              |
| Si                                     | 0.00016                               |
| P                                      | 0.00016                               |
| S                                      | 0.00073                               |
| Cl                                     | 0.00119                               |
| Ar                                     | 0.012827                              |
| K                                      | 0.00032                               |
| Ca                                     | 0.018378                              |
| Fe                                     | 0.000002                              |
| Zn                                     | 0.000002                              |
| Ceric Sulf. Dos. Sol.                  | Ferrous Sulf. Dos. Sol.                |
| MS20 Tissue Subs. (ICRP)               | Muscle, Ske. (ICRP)                    |
| Muscle, Str. (ICRU)                   | Muscle Eq. Liq., w Suc.               |
| Muscle Eq. Liq., wo Suc.              | Muscle Eq. Polyethy., Terep. (Mylar)   |
| Ts. Eq. Gas (Met. based)               | Ts. Eq. Gas (Pro. based)               |
| H                                      | 0.107596                              |
| C                                      | 0.108259                              |
| N                                      | 0.00027                               |
| O                                      | 0.00027                               |
| F                                      | 0.00027                               |
| Na                                     | 0.000022                              |
| Mg                                     | 0.130287                              |
| Al                                     | 0.010637                              |
| Si                                     | 0.010783                              |
| P                                      | 0.017798                              |
| S                                      | 0.012968                              |
| Cl                                     | 0.01997                               |
| Ar                                     | 0.009234                              |
| K                                      | 0.101969                              |
| Ca                                     | 0.003451                              |
| Fe                                     | 0.005076                              |
| Zn                                     | 0.005076                              |
| Ce                                     | 0.005076                              |

Table 1. Chemical composition data for the selected materials.
$Z_{\text{eff}}$ for the given materials (Taylor et al. 2012). In Auto-$Z_{\text{eff}}$, photon interaction cross section matrices are constructed spanning the energy range of 10 keV–10 GeV and the elements ranging between $Z = 1$ and $Z = 100$. Calculation of the coefficients for the materials is made using linear additivity of the fractional constituents and contrasted against the pre-calculated matrices at individual energies. Thereafter, the effective atomic numbers are obtained via interpolation of adjacent cross section data (Taylor et al. 2012). For electrons and protons the $Z_{\text{eff}}$ values taken from the previous studies (Kurudirek 2014b, 2014c) were calculated using the following procedure described for alpha particles. When it comes to the $Z_{\text{eff}}$ values for alpha particles, they have been calculated in the present work by an interpolation procedure. Briefly, a Z-wise interpolation procedure has been adopted to obtain $Z_{\text{eff}}$ for electrons, protons and alpha particles. First, the mass stopping powers for alpha particles of the given materials were obtained using the NIST database (Berger et al. 2005). Then, a pool of elemental stopping power data has been constructed using NIST database spanning the minimum and the maximum elements present in the considered materials between 10 keV and 1 GeV. Using the stopping cross sections for elements as well as the materials, $Z_{\text{eff}}$ then can be obtained by interpolation of Z values between the adjacent stopping cross section data. Detailed information about the interpolation procedure can be found elsewhere (Kurudirek and Onaran 2015).

When it comes to the definition of electron density, consider first for an element. Electron density, $n_e$, which is expressed in number of electrons per unit mass is given through:

$$n_e = \frac{N_A Z}{A} \quad (4)$$

where $N_A$ is Avogadro's number, $Z$ is atomic number and $A$ is atomic weight of the element.

This expression can be generalized to a multi-element material, thus the effective electron density is expressed by the following relation:

$$N_e = N_A \frac{\sum n_i A_i}{\sum n_i A_i} = N_A Z_{\text{eff}} \left( \frac{\text{electrons}}{g} \right) \quad (5)$$

**Figure 1** (a–d) Variation of $Z_{\text{eff}}$ with energy for photons and with total kinetic energy for electrons, protons and alpha particles (a) Ceric sulfate dosimetric solution, (b) Water, (c) Adipose tissue, and (d) Aluminum oxide.
where is the average atomic mass of the material. Therefore, it is assumed that the actual atoms of a given molecule can be replaced by an equal number of identical (average) atoms, each of which having $Z_{\text{eff}}$ electrons. The total number, $n$, of atoms in the molecule and the molar fraction $f_i$ are:

$$n = \sum_i n_i f_i = \frac{n_i}{\sum_j n_j} = \frac{n_i}{n} \tag{6}$$

where $n_i$ is the number of atoms of the $i$th constituent element.

It follows from above that while the electron density of an element does not change with energy since the elements have a single atomic number independent of the energy, the electron density of a multi-element material varies with energy since multi-element materials cannot be represented by a single atomic number over the entire energy range but have different effective atomic numbers dependent on energy.

### Results and Discussion

The uncertainties in calculation of $Z_{\text{eff}}$ are mainly based on the uncertainties estimated for mass attenuation coefficient and mass stopping power data. It has been reported that the uncertainties of the calculated collision stopping powers for electrons are estimated to be 1–2% above 100 keV, 2–3% (in low-Z materials) and 5–10% (in high-Z materials) between 100 keV and 10 keV (International Commission on Radiation Units and Measurements [ICRU] 1984). The uncertainties of the radiative stopping powers are estimated to be 2% above 50 MeV, 2–5% between 50 MeV and 2 MeV, and 5% below 2 MeV (ICRU 1984). The uncertainties in the present work base on the uncertainties arise in derivation of stopping powers. The uncertainties of the collision stopping powers in the high-energy region are stated to be 1–2% for elements, and 1–4% for compounds whereas they are estimated to be 2–5% at 1000 keV, 5–10% at 100 keV, 10–15% at 10 keV, and at least 20–30% at 1 keV (ICRU 1993). Uncertainties in those data are reported and discussed in detail elsewhere (ICRU 1984, 1993; Hubbell 1999; Berger et al. 2005).

### Table 2. Basic statistics for $Z_{\text{eff}}$ and $N_i$ through the entire energy region (10 keV–1 GeV).

| Material | Photon | Electron | Proton | Alpha particle |
|----------|--------|----------|--------|---------------|
|          | Mean   | Min     | Max    | Mean   | Min     | Max    | Mean   | Min     | Max    | Mean   | Min     | Max    |
| Water    | 3.99   | 3.33    | 6.14   | 3.50   | 2.97    | 4.41   | 3.13   | 2.31    | 3.43   | 3.14   | 2.72    | 3.50   |
| A-150 Tissue (ICRP) | 3.70   | 3.19    | 5.72   | 3.27   | 2.93    | 3.96   | 3.29   | 3.02    | 3.87   | 3.34   | 3.16    | 3.71   |
| Adipose Tissue (ICRP) | 3.46   | 2.99    | 5.21   | 3.09   | 2.79    | 3.80   | 3.11   | 2.95    | 3.64   | 3.11   | 2.95    | 3.37   |
| Air, Dry (Sea level) | 7.31   | 7.26    | 7.51   | 7.28   | 7.27    | 7.31   | 7.22   | 6.89    | 7.87   | 7.28   | 6.97    | 7.41   |
| Aluminum Oxide | 10.24  | 10.00   | 10.88  | 9.59   | 8.92    | 10.20  | 8.94   | 5.91    | 10.10  | 8.77   | 5.47    | 10.00  |
| B100 Bone Eq. Plastic | 5.35   | 4.18    | 9.07   | 4.48   | 3.91    | 5.53   | 3.96   | 3.34    | 4.51   | 3.93   | 3.62    | 4.43   |
| Bone Compact (ICRU) | 5.62   | 4.41    | 9.21   | 4.73   | 4.13    | 5.85   | 4.15   | 3.48    | 4.70   | 4.06   | 3.61    | 4.64   |
| C-552 Air Eq. Plastic | 5.90   | 5.48    | 7.06   | 5.66   | 5.38    | 6.09   | 5.21   | 3.74    | 5.56   | 4.97   | 3.95    | 5.50   |
| Ca Fluoride | 13.59  | 12.68   | 15.50  | 12.91  | 12.52   | 13.94  | 12.29  | 8.60    | 13.94  | 12.82  | 12.08   | 14.66  |
| Ceric Sulfate Dos. Sol. | 4.15   | 3.41    | 4.63   | 3.60   | 3.03    | 4.54   | 3.22   | 2.44    | 3.50   | 3.22   | 2.80    | 3.65   |
| Ferrous Sulfate Dos. Sol. | 4.09   | 3.40    | 6.31   | 3.58   | 3.02    | 4.51   | 3.20   | 2.42    | 3.49   | 3.21   | 2.79    | 3.62   |
| MS20 Tiss. Subs. | 4.26   | 3.66    | 6.31   | 3.84   | 3.39    | 4.59   | 3.68   | 3.43    | 4.40   | 3.64   | 3.51    | 4.04   |
| Muscle, Skeletal (ICRP) | 4.12   | 3.47    | 6.22   | 3.65   | 3.14    | 4.52   | 3.34   | 2.65    | 3.58   | 3.32   | 2.92    | 3.80   |
| Muscle, Striated (ICRU) | 4.08   | 3.44    | 6.20   | 3.62   | 3.10    | 4.48   | 3.31   | 2.62    | 3.53   | 3.29   | 2.90    | 3.76   |
| Muscle Eq. Liq. with Sucrose | 4.09   | 3.49    | 6.07   | 3.63   | 3.17    | 4.49   | 3.41   | 2.84    | 3.84   | 3.37   | 3.02    | 3.89   |
| Muscle Eq. Liq., without Sucrose | 4.05   | 3.44    | 6.08   | 3.60   | 3.10    | 4.46   | 3.34   | 2.72    | 3.64   | 3.31   | 2.94    | 3.79   |
| Polyethylene, Terephthalate (Mylar) | 4.93   | 4.55    | 6.07   | 4.73   | 4.62    | 5.18   | 4.49   | 3.76    | 5.06   | 4.42   | 3.99    | 4.96   |
| Tis. Eq. Gas (Methane based) | 3.81   | 3.29    | 5.57   | 3.65   | 3.07    | 4.22   | 3.48   | 3.17    | 4.27   | 3.44   | 3.17    | 4.18   |
| Tis. Eq. Gas (Propane based) | 3.71   | 3.24    | 5.38   | 3.56   | 3.01    | 4.10   | 3.41   | 3.02    | 4.15   | 3.38   | 3.22    | 3.81   |

$Z_{\text{eff}}$ where the uncertainties estimated for mass attenuation coefficient and mass stopping power data. It has been reported that the uncertainties of the calculated collision stopping powers for electrons are estimated to be 1–2% above 100 keV, 2–3% (in low-Z materials) and 5–10% (in high-Z materials) between 100 keV and 10 keV (International Commission on Radiation Units and Measurements [ICRU] 1984). The uncertainties of the radiative stopping powers are estimated to be 2% above 50 MeV, 2–5% between 50 MeV and 2 MeV, and 5% below 2 MeV (ICRU 1984). The uncertainties in the present work base on the uncertainties arise in derivation of stopping powers. The uncertainties of the collision stopping powers in the high-energy region are stated to be 1–2% for elements, and 1–4% for compounds whereas they are estimated to be 2–5% at 1000 keV, 5–10% at 100 keV, 10–15% at 10 keV, and at least 20–30% at 1 keV (ICRU 1993). Uncertainties in those data are reported and discussed in detail elsewhere (ICRU 1984, 1993; Hubbell 1999; Berger et al. 2005).
as water, adipose tissue, aluminum oxide and ceric sulfate dosimetric solution in Figure 1. Also, the calculated values of $Z_{\text{eff}}$ and $N_e$ have been provided within the supplementary documents. The basic statistical data for $Z_{\text{eff}}$ and $N_e$ of the given materials are presented in Table 2 for photons, electrons, protons and alpha particles.

According to Figure 1, it should be noted that variation of $Z_{\text{eff}}$ with the energy varies depending on the type of radiation considered. There are different energy regions where $Z_{\text{eff}}$ varies less for different types of radiation. For example, at low energies ($< 100$ keV) in general the $Z_{\text{eff}}$ seems to be varying much more and the variation seems to be non-uniform for all types of radiation. It has to be noted that the variation of $N_e$ with the energy is quite similar to that of $Z_{\text{eff}}$ since the $N_e$ is qualitatively dependent on $Z_{\text{eff}}$ through Equation (1).

Among the different types of radiations, it has to be noted that the highest values of $Z_{\text{eff}}$ has been observed in the low energy region for photons. This might be due to the fact that the photoelectric absorption is the dominant interaction process at lower energies and its cross section is directly proportional to the $Z^2$ and inversely proportional to the $E$. This highest $Z$ dependence clearly explains the highest values of $Z_{\text{eff}}$ observed for photons in the lowest energy range. Figure 2 shows variation of the photoelectric absorption as well as radiative stopping with atomic number of elements. Since the derivation of $Z_{\text{eff}}$ is based on interpolation using adjacent cross section values of elements, the higher values of cross sections at low photon energies due to higher $Z$ elements in the material will correspond to the high $Z_{\text{eff}}$ values, whose value will be close to the higher $Z$ in the material. This is the case for radiative stopping for electron interaction as well (Figure 2). The partial electron interaction processes dominating different $Z_{\text{eff}}$ and $N_e$ are the collisional and radiative processes. The radiative interaction process is dominant at higher energies and its $Z$ dependence is greater than the collisional interaction. This state clearly explains why $Z_{\text{eff}}$ and $N_e$ have the highest values at higher energy regions for total electron interaction.

The coulomb interactions with the electrons of the target atom are the primary processes that protons and heavy ions such as alpha particles lose their energy. The electronic stopping power, which refers to the collision stopping power in protons and alpha particles, thus gives heavier weight to the total proton and alpha particle interactions than nuclear stopping power (Figure 3). In the intermediate energy region (100 keV–3 MeV), the variation of $Z_{\text{eff}}$ seems to be less for photons and electrons while it varies much more for protons and alpha particles. The highest values of $Z_{\text{eff}}$ for protons (around 100 keV) and alpha particles (around 1 MeV) lie in this energy region. When it comes to the high-energy region (over 3 MeV), it is seen that the values of $Z_{\text{eff}}$ remain more or less the same for protons and alpha particles whereas it increases as the energy increases for photons and electrons.

**Comparison of the water equivalence based on $Z_{\text{eff}}$**

In order to investigate the radiation effects on human tissues, some dosimetric materials are commonly used as tissue substitutes if they have similar properties to those of the tissues with respect to the radiation absorption and scattering under the same conditions. These materials are very useful for dosimetry in clinical applications such as radiological examinations, therapeutic treatments and also in radiological protection. Therefore, tissue equivalence studies in the wide energy region for different types of incoming radiation are of great importance in order to find best matching material for the tissue and the water. The given materials have been compared in terms of water equivalent properties with respect to the different type of radiation. It has been observed that the A-150 Tissue equivalent plastic show better water equivalence properties for photons and electrons in the low energy region ($< 1$ MeV) than the protons and alpha particles. Over 1 MeV, the water equivalent property of A-150 is quite satisfactory.
for all types of radiations. For adipose tissue, the water equivalence is good for protons and alpha particles after 200 keV whereas it is good for electrons below 200 keV.

\[ RD\% = \frac{Z_{\text{eff}}(\text{Material}) - Z_{\text{eff}}(\text{water})}{Z_{\text{eff}}(\text{Material})} \times 100 \]

(7)

Difference (%) in \(Z_{\text{eff}}\) relative to water for adipose tissue (given above) is above 10% for photons in the entire energy region. The ceric sulfate dosimetric solution has found to be one of the best water equivalent materials for all types of radiation except for around 50 keV where there is difference greater than 10% for photons. The relative difference is even lower for \(N_e\). The higher difference could be attributed to the K-edge absorption effects for photons as such the ceric sulfate dosimetric solution has a high Z element, Cerium (Z = 58, K-edge \(\approx 40 \text{ keV}\)) as a constituent. Over 2 MeV, difference is less than 3% and in the entire energy region the difference is below 9% except for around 50 keV (Figure 4(a,b)). The ferrous sulfate dosimetric solution on the other hand is the other material that shows excellent water equivalence properties (Figure 5(a,b)).

The difference is always less than 7% in the entire energy region for all types of radiations while it is below 4% over 200 keV. The difference in \(Z_{\text{eff}}\) relative to water has been found to be below 10% for MS20 tissue substitute for all type of radiations after 3 MeV. It should be noted that the MS20
tissue substitute seems to be good water equivalent for photons in the entire energy region (difference below 10%). When it comes to muscle skeletal and muscle striated, it is seen that they show good water equivalence for all types of radiation over 300 keV. They show good water equivalence property for all type of radiations except for protons in the entire energy region (Figures 6 and 7). It has been found that the difference between muscle equivalent liquid (with sucrose) and water is below 6% for photons and electrons in the energy region 10 keV–1 GeV (Figure 8). Over 1 MeV, difference is below 10% for all types of radiation. The differences (%) of muscle equivalent liquid (without sucrose) were found to be below 5%, 5% and 10% for photons, electrons and alpha particles, respectively (Figure 9). Over 300 keV, difference (%) is always below 10% for all radiation types.

**Comparison of the tissue equivalence based on Z_{eff}**

The comparison of some tissues with tissue equivalents have been made for all type of radiations based on the values of Z_{eff} and N_e (Figures 10–15). It has been found that the A-150 tissue equivalent plastic is a good adipose tissue equivalent for all types of radiation in the energy range of 1.5 MeV–1 GeV (Dif. <10%). In the low energy region 10–300 keV, differences are below 10% except for the photons. It is also worth mentioning that it shows good tissue equivalence for electrons in the entire energy region (Figure 10). From Figure 11, it is seen that B100 bone equivalent material is an excellent bone equivalent (Bone compact, ICRU) for all types of radiations in the whole energy range of 10 keV–1 GeV (difference below 6%). Muscle equivalent liquids
with and without sucrose show good muscle skeletal (ICRP) equivalence in the entire energy regions for all radiations with differences below 7% and ≤4%, respectively (Figures 12 and 13). Muscle equivalent liquids with and without sucrose show good muscle striated (ICRU) equivalence in the entire energy regions for all radiations with differences below 9% and 4%, respectively (Figures 14 and 15).

Conclusion

For the first time, water and tissue equivalence properties of some common dosimetric materials have been compared in respect to the different types of radiation fields such as photons, electrons, protons and alpha particles in the wide energy region 10 keV–1 GeV. Comparison has been made as means of $Z_{\text{eff}}$ and $N_e$. Significant variations in these parameters have been observed in the entire energy region depending on the type of the radiation. Ceric sulfate and ferrous sulfate dosimetric solutions have shown best water equivalency in the entire energy region for all type of radiations considered. B100 Bone Eq. Plastic and Bone Compact (ICRU) tissue match with each other with a relative difference below 3, 1, 2 and 6% for $N_e$ and 6% for $Z_{\text{eff}}$ in the entire energy region for photons, electrons, protons and alpha particles, respectively. Also, muscle eq. liquid (with sucrose) have $Z_{\text{eff}}$ and $N_e$ values close to the Muscle Skeletal (ICRP) within relative differences below 7% and 9% and close to the Muscle Striated (ICRU) within relative differences between 7% and 9%, respectively. Muscle eq. liquid (without sucrose) have $Z_{\text{eff}}$ and $N_e$ values close to the Muscle Skeletal (ICRP) and Muscle Striated (ICRU) within relative difference below 10% and 9%, respectively. The reported data should be useful in

| Energy (MeV) | Photon | Electron | Proton | Alpha particle |
|-------------|--------|----------|--------|----------------|
| 0           | 10     | 14       | 12     | 14             |
| 1           | 12     | 16       | 14     | 16             |
| 2           | 14     | 18       | 16     | 18             |
| 3           | 16     | 20       | 18     | 20             |
| 4           | 18     | 24       | 20     | 24             |
| 5           | 20     | 28       | 22     | 28             |
| 6           | 22     | 30       | 24     | 30             |
| 7           | 24     | 32       | 26     | 32             |
| 8           | 26     | 34       | 28     | 34             |
| 9           | 28     | 36       | 30     | 36             |
| 10          | 30     | 38       | 32     | 38             |
| 11          | 32     | 40       | 34     | 40             |
| 12          | 34     | 42       | 36     | 42             |
| 13          | 36     | 44       | 38     | 44             |
| 14          | 38     | 46       | 40     | 46             |
| 15          | 40     | 48       | 42     | 48             |

**Figure 7.** Differences in $Z_{\text{eff}}$ and $N_e$ of muscle striated relative to water for photons, electrons, protons and alpha particles (Energy refers to total kinetic energy for charged particles).

**Figure 8.** Differences in $Z_{\text{eff}}$ and $N_e$ of muscle eq. liquid with sucrose relative to water for photons, electrons, protons and alpha particles (Energy refers to total kinetic energy for charged particles).
Figure 9. Differences in $Z_{\text{eff}}$ and $N_e$ of muscle eq. liquid without sucrose relative to water for photons, electrons, protons and alpha particles (Energy refers to total kinetic energy for charged particles).

Figure 10. Differences in $Z_{\text{eff}}$ and $N_e$ between Adipose tissue and A-150 tis. eq. plastic for photons, electrons, protons and alpha particles (Energy refers to total kinetic energy for charged particles).

Figure 11. Differences in $Z_{\text{eff}}$ and $N_e$ between bone compact and B100 bone eq. plastic for photons, electrons, protons and alpha particles (Energy refers to total kinetic energy for charged particles).
Dif. (%) in Z_{eff} and Ne between muscle skel. (ICRP) and muscle eq. liq. with sucrose for photons, electrons, protons and alpha particles (Energy refers to total kinetic energy for charged particles).

**Figure 12.**

Dif. (%) in Z_{eff} and Ne between muscle skel. (ICRP) and muscle eq. liq. without sucrose for photons, electrons, protons and alpha particles (Energy refers to total kinetic energy for charged particles).

**Figure 13.**

Dif. (%) in Z_{eff} and Ne between muscle striat. (ICRU) and muscle eq. liq. with sucrose for photons, electrons, protons and alpha particles (Energy refers to total kinetic energy for charged particles).

**Figure 14.**
determining best water as well as tissue equivalent materials for different types of radiation, i.e. photon, electron, proton and alpha particle in specific energy regions of interest.

Disclosure statement

The author reports no conflict of interest. The author alone is responsible for the content and writing of the paper.

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Figure 15. Differences in $Z_{\text{eff}}$ and $N_e$ between muscle striat. (ICRU) and muscle eq. liq. without sucrose for photons, electrons, protons and alpha particles (Energy refers to total kinetic energy for charged particles).
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