Energy Dependent Effective Atomic Number Calculation for Newly Developed 2-Acrylamido-2-methyl propane Sulfonic Acid Polymer Gel Dosimeter

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The aim of the study is to evaluate the water equivalency of the newly developed polymer gel dosimeter [2-acrylamido-2-methyl propane sulfonic acid (AMPS)] in terms of its effective atomic number (Z_{eff}) and effective electron density (N_{eff}). Auto-Z_{eff} computer program was used to calculate the Z_{eff} for photon energies ranging from 0.01 to 1000 MeV. 2-Acrylamido-2-methyl propane sulfonic acid polymer gel shows the good water equivalency with less than 1.56 % deviation from water over the energy range of 0.01 to 1000 MeV. Since 2-acrylamido-2-methyl propane sulfonic acid is less toxic and a very good water equivalent medium for photon energies from 0.01 to 1000 MeV it can be employed in clinically. The study also reveals that it is a good alternative gel for poly acrylamide gelatin *tetrakis* hydroxyl phosphonium chloride (PAGAT) in terms of its less toxicity and water equivalency.

Keywords: 2-Acrylamido-2-methylpropane sulfonic acid, Effective atomic number, Electron density, Polymer gel.

INTRODUCTION

Most of the polymer gel dosimeters are fabricated by radiosensitive monomers in gelatin matrix under normal atmospheric conditions [1-5]. Upon irradiation, free radicals are generated in the gel medium making the monomers active. Activated monomers form the polymer network. Absorbed dose of the radiation is correlated with the amount of polymerization by different readout modalities such as magnetic resonance imaging (MRI), optical computed tomography (OCT), X-ray computed tomography (X-ray CT), UV-visible spectrophotometer and ultra sound computed tomography (UCT) [6-10]. Since, water equivalency property is a major concern in radiation dosimeter, it is necessary to evaluate water equivalency for any medium which has to be used as an alternative for water. Effective atomic number (Z_{eff}) is the agreeable parameter to evaluate the water equivalency for a given medium [11]. The number that is introduced to describe the multi element material in terms of equivalent element is called the effective atomic number [12]. Most of the polymer gels are reported for good water equivalency [13,14]. Although, gel dosimeter has many advantages, its toxicity is making it inferior to other commercial dosimeters. Abtahi [15] introduced novel polymer gel with less toxic monomer by taking the well-known PAGAT formalism. In this formula acrylamide was replaced by 2-acrylamido-2-methyl propane sulfonic acid (AMPS) and it is less toxic in comparison to acrylamide. With the introduction of new

dosimeters (AMPS), different parameters were reported such as effective atomic number, toxicity and temporal stability. In the present study, the AMPS based polymer gel dosimeter's water equivalency based on its Z_{eff} was evaluated. Due to different photon interaction cross sections, different weights with respect to atomic composition, is given in the compound medium. Therefore a single number is not an appropriate way to express the Z_{eff} of the compound medium [16]. 2-Acrylamido-2-methylpropane sulfonic acid gel dosimeter is an appreciable good gel dosimeter because of its low toxicity. To better establish its usability in clinical setting, the evaluation of Z_{eff} with different photon energies shows its water equivalency. Eventually, it would encourage the researchers to improve its applicability clinically. The Z_{eff} calculation was performed for PMMA, soft tissue, poly acrylamide gelatin *tetrakis* hydroxyl phosphonium chloride (PAGAT) and water as well for comparative study with AMPS gel dosimeter.

THEORETICAL ANALYSIS

Effective atomic number (Z_{eff}): Taylor *et al.* [17] developed the Auto-Z_{eff} computer program to compute the Z_{eff} for photon energies from 10 keV to 1 GeV. In this computer program, photon interaction cross section matrices are constructed for the energy range of 10 KeV to 1 GeV and for the elements ranging between Z = 1 to 100. More details about the program are reported in the elsewhere [17]. Elemental compositions were obtained from XCOM database. Z_{eff} was

calculated also for some radioactive sources such as Co^{60}, Ir^{192}, Pd^{103} and Ra^{226}. The mean photon energies of radiation sources have been calculated using the following relation by taking the ratios of photons per disintegration from the radiation source [12].

$$E_m = \frac{\Sigma_i W_i E_i}{\Sigma_i W_i} \qquad (1)$$

where W_i is a branching ratio of each emitted photon of different energy, E_i is the energy of the ith photon having the W_i branching ratio.

Effective electron density (N_{eff}): For an element electron density (N_{eff}) is given by the following equation:

$$N_e = \frac{N_A Z}{A} \qquad (2)$$

But this expression cannot be used for multi elemental composition and it is altered by following relation.

$$N_{eff} = N_A \frac{n Z_{eff}}{(A)} \qquad (3)$$

where A is the average atomic mass of the material, n is the total number of atoms in the molecule and N_A is the Avogadro number.

RESULTS AND DISCUSSION

The following Table-1 shows the mean photon energies for various γ-emitting sources.

TABLE-1
MEAN PHOTON ENERGIES FOR γ-EMITTING SOURCES

Radiation source	E_{eff} (MeV)
Pd^{103}	0.020
Ra^{226}	0.150
Ir^{192}	0.400
Co^{60}	1.253

Effective atomic number and effective electro density:
Fig. 1 shows the energy dependent effective atomic number of different water equivalent material. Initially (0.01 MeV) all the compounds started with maximum value of Z_{eff}. The energy range below 0.01 MeV photoelectric absorption is the dominant process. Since, it is directly proportional to Z^{4-5} AMPS, PAGAT and soft tissue has slightly higher Z_{eff} at this energy due to presence of high Z elements such as P, Cl, S, Na and K. Although water does not have any high Z component, it still has higher Z_{eff} than PMMA at low energy region because of the presence of large proportion of oxygen in water. The reason for the rapid fall of Z_{eff} in intermediate energy (0.01 to 0.1 MeV), is that the photoelectric absorption does not dominate photon interaction after a few hundred keV. Compton cross section is directly proportional to Z and it makes Z_{eff} of all the compounds low and maintains constant value from 0.15 to 3 MeV. From 3 to 150 MeV the gradual increase was found since the process of pair production replaces the Compton process. Since, pair production is proportional to Z^2, the Z_{eff} was less than in photo electric absorption region. Beyond the 150 MeV, Z_{eff} was maintained at a constant pattern. Since at very high energy range, pair production is the dominant process
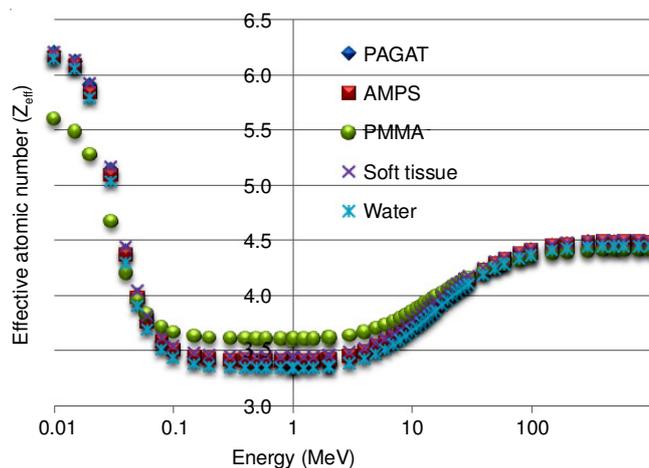

Fig. 1. Energy dependent effective atomic number for PAGAT, AMPS, PMMA, soft tissue and water

and it is proportional to Z of the material (beyond 150 MeV). Fig. 2 shows the Z_{eff} of all the compounds for some γ-emitting radiation sources.
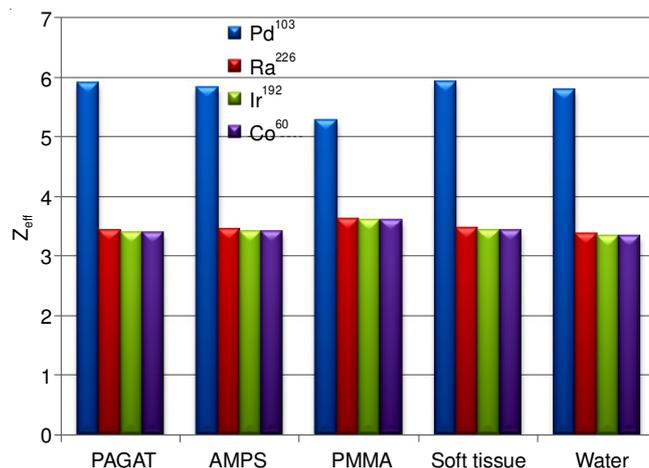

Fig. 2. Energy dependent effective atomic number of PAGAT, AMPS, PMMA, soft tissue and water for Pd^{103}, Ra^{226}, Ir^{192} and Co^{60}

The effective energy of the Pd^{103} is less and the maximum interaction process could be attributed to the photoelectric absorption. This interaction process makes higher Z_{eff} for all the compounds at the energy of Pd-103 source comparable with other radiation sources. Similar behaviour is observed for the values of N_{eff} for all the analyzed compounds Fig. 3. Water and soft tissue has higher N_{eff} than the other compounds since the average atomic number of both the compounds are less than the others.

Since N_{eff} is derived from the value of Z_{eff}, it has a pattern similar to Z_{eff} as seen in Fig. 1. The variation in N_{eff} is slightly affected by the average atomic number of the compound. Fig. 4 shows the N_{eff} of all the compounds for different gamma emitting sources. Fig. 5 shows the strong co-relation between N_{eff} and Z_{eff}.

At low energies, the difference % of AMPS and PAGAT increases up to 2.5 % (Fig. 6 Maximum percentage difference (2.5 %) was observed at 0.04 MeV for PAGAT gel). From 0.05 to 2 MeV the difference % of AMPS was less than 2.1 %.
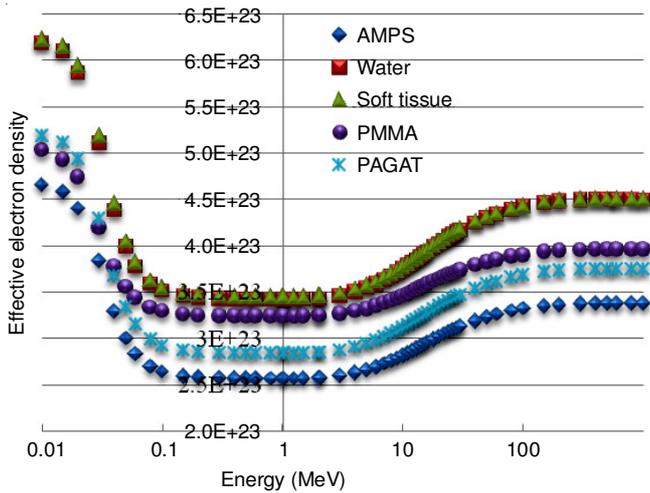
Fig. 3.   Energy dependent effective electron density for PAGAT, AMPS, PMMA, soft tissue and water
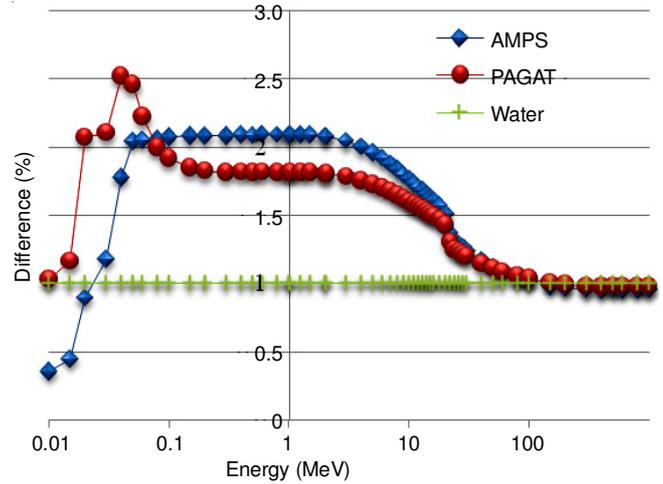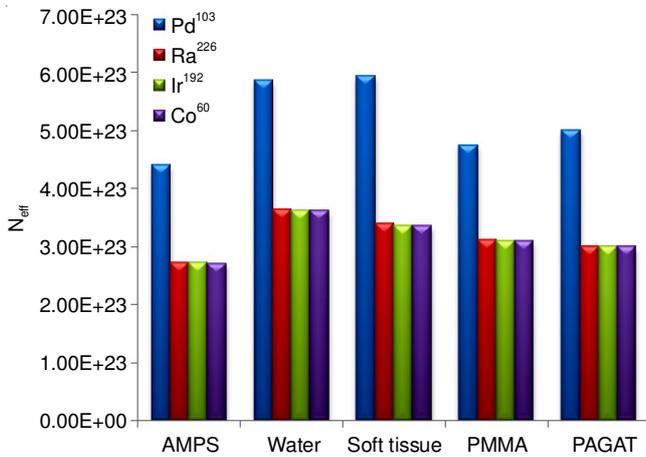

Fig. 4.   Energy dependent effective electron density of PAGAT, AMPS, PMMA, soft tissue and water for Pd^{103}, Ra^{226}, Ir^{192} and Co^{60}
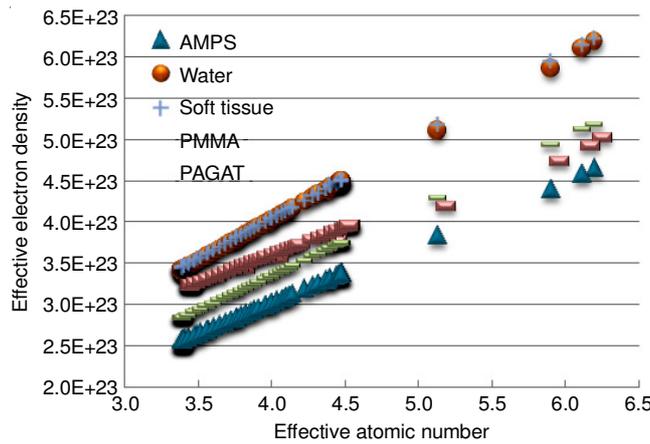

Fig. 5. Relation between Effective atomic number and electron density

The average percentage differences throughout the energy (0.01 to 1000 MeV) for AMPS and PAGAT are in between 1.56 and 1.54 %. The Z_{eff} of AMPS was found to be little higher from the PAGAT. The higher concentration of gelatin, less concentration of water and the presence of sulfur may be the reasons for this variation.

Fig. 6.   Variation in the effective atomic number of AMPS and PAGAT with respect to water

Tetrakis(hydroxy methyl)phosphonium chloride (THPC) contains phosphorus and chlorine and AMPS contain sulfur. These elements have higher Z than hydrogen, carbon and nitrogen. Hence, the presence of THPC and AMPS increases the total mass attenuation co-efficient in the low energy region (0.01 to 0.08 MeV). Beyond that the impact of THPC and AMPS was found to be insignificant as seen in Fig. 7.
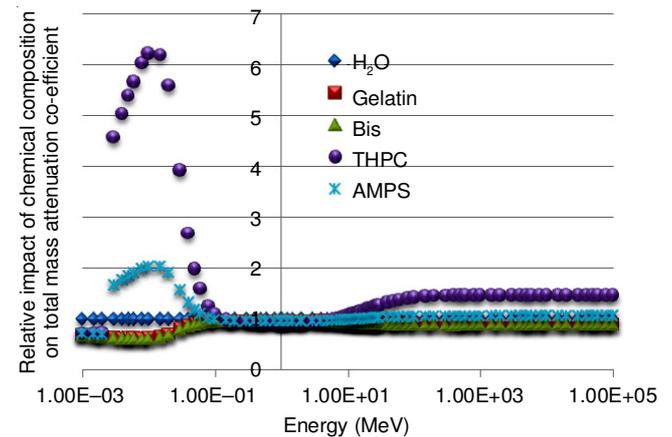

Fig. 7. Impact of chemical composition in energy absorption coefficient

Conclusion

Effective atomic number and effective electron density was successfully calculated for AMPS gel and the results were compared with existing phantom materials such as water, PMMA, soft tissue and PAGAT gel. Promising results were obtained for AMPS gel. The modification and introduction of new monomer in the well-known PAGAT formation has not affected the water equivalency of AMPS polymer gel significantly. Since AMPS is less toxic as well as a very good water equivalent medium from 0.01 to 1000 MeV, it can be employed in clinical applications. It is a good alternative gel for PAGAT in terms of its less toxicity and water equivalence property.

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