Shielding Studies for Radioactive Isotopes used in Nuclear Medicine.

I.J. Mora-Zeledón[1], J.L. Contreras-González[2]

[1]Servicio de Medicina Nuclear, Hospital San Juan de Dios, Caja Costarricense del Seguro Social, San José, Costa Rica, Centroamérica.
[2]Departamento de Física Atómica, Molecular y Nuclear, Universidad Complutense de Madrid, España

Abstract: This paper presents the results of the study made about the dose distributions existing near the interfaces between different materials put together, which are reached by a photon radiation field of different energies. As a result, the surface dose rates on the hands of personnel who operate some radioactive sources used in nuclear medicine are shown. An effective and low cost method to reduce these doses, as an enhancement to the common existing shielding has been proposed.

Keywords: dose depth profiles (DDP), Monte Carlo (MC), radiochromic film, dose gradient.

1. Introduction

This study is based on the fact that the distribution of doses in a material due to an incident photon radiation field, depends among other factors, in the mass density and in the atomic number of the material [1], because of this, if there are inhomogeneities in the material or this is composed of various materials, such dose distribution will be drastically affected, and besides, the greater the difference in density and in the atomic number between the materials, the greater the change in the distribution. A typical case in which this situation appears is in Nuclear Medicine when a shield containing an radioactive source is in contact with the hands of the staff. The dose depth profiles obtained using Monte Carlo (MC) techniques shown an complex behavior of doses rates near the interface between the materials.

It is well known the dose distribution behavior in a single material, first there is the build up region in which the absorbed dose increase with depth from zero to a maximum value when it reaches the equilibrium thickness, after that, the doses decreases exponentially with depth. Another material put next to it will show a different dose depth profile, now the build up region will be replaced by an negative absorbed dose gradient starting at an positive dose value and is due to the track length of the electrons ejected from the first material and enter in the second one, they continue part of their path delivering energy quickly and extending distances similar to their range in the material [2], typically hundreds of microns in materials of low Z.

This study presents the doses depth profiles (DDP) of three different simple geometries as syringes and boxes containing an radioactive source.

Monte Carlo simulations and experimental measurements using radiochromic films show an significant increase of the doses in the build up region of the absorber, after that, the doses decrease exponentially with depth. This high superficial absorbed dose in the hands of the staff are well above the minimum distance of 70 μm established by the Nuclear European Society [3] from which the superficial dose should be asses and can be reduced putting between the two materials a thin layer made of a material with low Z. We have used 1 mm thickness layer of PVC reducing the superficial doses in a factor of 55%.

2. Materials and Methods

To study the DDP produced in the most common geometries used in Nuclear Medicine we have performed three different assemblies similar to syringes, and cylindrical and rectangular syringes shields. For the three geometries, from left to right, we will have first the primary photon beam, second the shield and finally the absorber. In this order the three geometries would be: 380 keV > Lead > Tissue like-material; 511 keV > Tungsten > Water; 662 keV > Lead > Tissue like-material. The average energies above correspond to radioactive sources of ^{192}Ir, ^{18}F and ^{137}Cs respectively.

For the ^{192}Ir and the ^{137}Cs sources mentioned above experimental measurements using lead layers and radiochromic films as well as detailed MC simulations of the assemblies performed have been made. For the ^{18}F source we present MC simulations of syringes containing this isotope inside and all contained in a typical tungsten cylindrical shield.

2.1. Monte Carlo Simulations.

To describe the MC calculation methodology we have followed some of the recommendations established by the AAPM TG-43 [4] used to describe low energy brachitherapy sources (< 50 keV), in spite of this low energy, some considerations apply very well for more energetic sources [5].

All the simulations have been implemented using GAMOS/GEANT4 [6] Monte Carlo code version 2.1.0 running in Linux-Fedora platform.

To simulate the three different radioactive sources we have obtained the spectra from LUND/LBNL [7].

Iridium-192. For ^{192}Ir we have used the most sixteen probable emissions and they are shown en **Figure 1**. The average energy of the emissions is 380 keV and being the emission in 316.5 keV the stronger one.

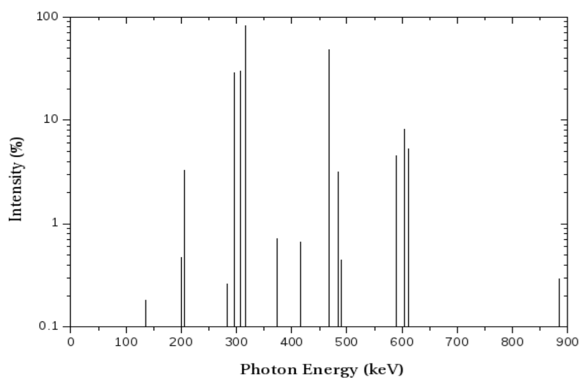

Figure 1. Photon spectrum used to simulate the ^{192}Ir source. The semi-logarithmic plot shows the percentage intensity versus photon energy.

The radioactive source used was the microSelectron Digital V2 (No. 105.002) and it was simulated following the guidelines provided by Daskalov [9] and are the same followed by the AAPPM-TG43 [4]. The source is basically a cylindrical capsule of iridium with the isotope homogeneously distributed on it, the capsule is contained in a cylinder made of steal bounded to a steal wire that is connected to the hydraulic system. The capsule is 4 mm long and 1 mm diameter.

Cesium-137. In the case of ^{137}Cs source the spectrum is simpler and is simulated with a strong peak of 662 keV with an probability of emission of 85 %, besides we have included the less probable emissions of photons (~1%) with energies of 31.8, 32.2 and 36.4 keV. We have used the ^{137}Cs LDR source pellet type from Amersham that is composed by seven radioactive seeds, the geometry used appears in the ESTRO catalog [10]. Seeds are distributed in a line less than 5 mm long and inside of an cylinder made of steal simulated the true steal spring that holds the pellets.

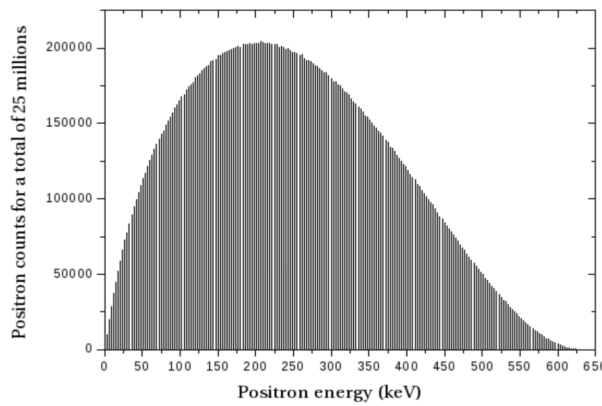

Figure 2. Positron spectrum used to simulate the ^{18}F source. The plot shows the counts of positron versus positron energy.

Flourine-18. Finally for simulate the beta emitter ^{18}F, GAMOS used the positron emission spectrum present in LUND/LBNL and is shown in Figure 2. The small path length of positrons in water quickly produce a photon spectrum with a high probability peak of 511 keV and sometimes this spectrum is simulated as a monoenergetic one. The source was simulated as an cylinder of water in which the ^{18}F is distributed homogenously and it is contained in a plastic cylinder 63 mm high and 4.3 mm diameter similar to an common syringe.

Using the sources described above the geometry simulated for ^{137}Cs and ^{192}Ir tries to reproduced the geometry described in the next section. In both the lead layer dimensions are 10 cm × 15 cm × 2 mm. The radiochromic films under the lead layer have been simulated as one block made of 42% of C, 40% of H, 16% of O and 4% of N, Li and Cl, with density equal to 1.334 g/cm^3 according with Devic *et all* [11]. The dimensions of the block are 2” × 4” and it has a thickness of 2.134 mm for iridium source and 1.872 mm for cesium. The block has been voxelised as little boxes with an traversal area of 1 mm^2 and thickness of 0.117 mm, so the block can be seen as several thin bidimensional matrices simulating the radiochromic films forming all together an 3D array. The mesh has the half of the thickness of the films, so to obtain the absorbed doses we most obtain the average between every two bidimensional matrices. The DDP can be obtained fixing the values in X and Y and moving through the Z axes, on the other hand dose map distribution are obtained fixing Z and computing the values in X and Y.

The flourine geometries have cylindrical symmetry due to syringe shape of the source. We have simulated the source contained in a PVC surrounded by a 3 mm coaxial cylinder made of tungsten as a shield and finally a coaxial cylinder of 5 mm made of water. The mesh in this case from which the dose has been obtained is composed by thin coaxial cylinders of 0.05 mm obtaining from them the DDP in the radial direction.

2.2. Experimental Measurements.

The measurements have been made in the Doce de Octubre Hospital in Madrid using two different brachitherapy sources. The first one was the high dose rate ^{192}Ir source microSelectron V2 and the second one was one of the low dose rate ^{137}Cs from Amersahm. Both are described in detail in section 2.1.

Shielded syringe carries are basically a rectangular box made of several high Z layers put together, DDP in each of the layer are very similar and present the geometry mentioned in the *Introduction*, in this case, ^{192}Ir >> lead >> radiochromic film; and ^{137}Cs >> lead >> radiochromic film.

The assembly has been performed over a little wood table, the first material over it is a block made of several radiochromic films Gafchromic EBT [8] of 10 cm × 20 cm each one with a thickness of 0.234 mm, we used 10 layers for ^{137}Cs and 8 layer for ^{192}Ir source; over the radiochromic block there is the lead layer and over it another radiochromic layer has been put to obtain an autoradiograhy of the source, finally over this layer an automatic hydraulic system drives the brachitherapy source to the center of the layer and keeps it there during a time. The ^{192}Ir source had an activity A = 6.3 Ci and it irradiated the layers for 30 seconds. The ^{137}Cs had an A = 30 mCi and it irradiated the layers for 4 hours. These times of irradiation were used trying to obtain absorbed doses in the layers in the order of 1 Gy due to the energy range of the radiochromic films used, the *Garfchromic® EBT* film with a range of 1cGy – 800 cGy.

The way to obtain the absorbed dose in the radiochromic films imply irradiate the films, and using an scanner, obtain the 2D digital value (DV) distribution in the films, we have used the scanner *Umax Power Look 3000;* after that it is desirable to get an calibration curve of absorbed dose versus DV. To do that and because the response of the films are independent of the photon energy from the keV range into the MeV range [8], we have irradiated 8 films of 2”×2” with doses of 0, 0.5, 1, 2, 5, 10, 20 and 30 Gy using the linear accelerator *SIEMENS Artiste* from “*Hospital de Fuenlabrada”* in Madrid, once the films have been scanned we obtained an bi-exponential calibration curve with the DV versus the well known dose values. The calibration curve allow to obtain the deposited dose value for any DV achieved in the radiochromic films i.e. the 2D dose distribution. The DDP could be obtained manipulating doses matrices and plotting the dose values in the point (x_i, y_i) in each film whit its corresponding depth in the radioactive film block. We present the DDP for the three geometries studied.

3. Results and Discussion.

As a first result the **Figure 3** shows the experimental autoradiography in the radiochromic film as well as the obtained with the simulation. We had been able to obtain the simulated radiography manipulating the 2D dose distribution values using MATLAB.

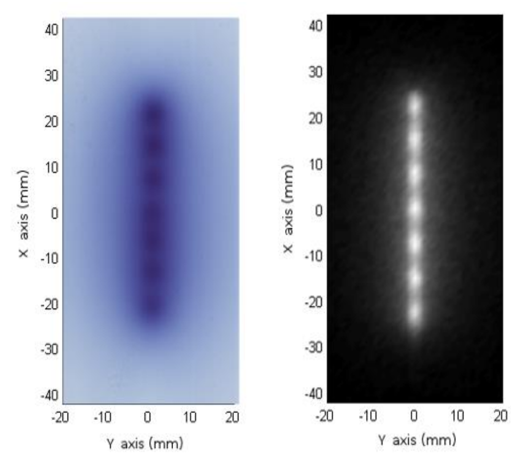

Figura 3. Autoradiographys of the ^{137}Cs source obtained from a) the radiochromic film and b) from the MC simulation using MATLAB.

The difference in the images is the opposite contrast and besides Matlab only uses an gray scale of

256 so the contrast is higher and lot of details in the blur region are lost, in spite of this, the digital values keep all the information, this loss of detail is only an visual effect due to the limited gray scale. We have obtained for both sources the dose maps for every radiochromic film and for every bidimensional dose distribution of the MC simulations under the lead layer. DDP were obtained choosing the ROIs with the higher doses i.e. the values just under the source. All the analysis was done using ImageJ [12].

The DDP for ^{137}Cs source is shown in **Figure 4**. The Y axis shows the absorbed dose in Gy after a irradiation time of 4 hours. There is a good agreement between the experimental values and he simulated ones. At 3 mm from the sources where is situated the first film the simulation brings higher values than the auto-radiography this most be due to the saturation of the film , after a maximum value allowed of 8 Gy the system probably star losing sensibility varying the dose absorbed.

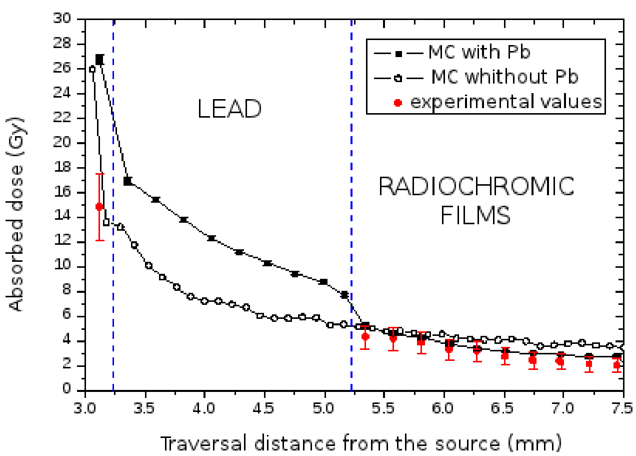

Figure 4. Dose depth profile for ^{137}Cs source.

The aim of a shield is to reduce the absorbed dose in the other side of the source so one can expect the depth dose after the shield most decay parallel under the depth dose profile in the other material when the shield is absent. Due to the secondary radiation leaving the lead layer and specially the electrons, the absorbed dose in radiochromic films do not decay parallel to the dose without the shield. There is an increment or an excess in the absorbed dose in radiochromic films near the interfaces. The plot shows after 6.5 mm depth both experimental and MC values decay constantly under the other curve but between 5.25 and 6.5 mm the dose is higher and do not follow these behavior. The electron fluency could be affecting the DDP as we is explained forward.

The **Figure 5** shows the DDP for ^{192}Ir source. In this case as represent the red points we have used eight radiochromic films instead of ten as we did with cesium. The lower average energy or iridium make us think that the effect of perturbation near the interface is smaller due to the lower energy of the electron escaping from the lead layer, electrons with energy of ~300 keV have a range in water about 600 μm and this is the distance we expect the perturbation takes place.

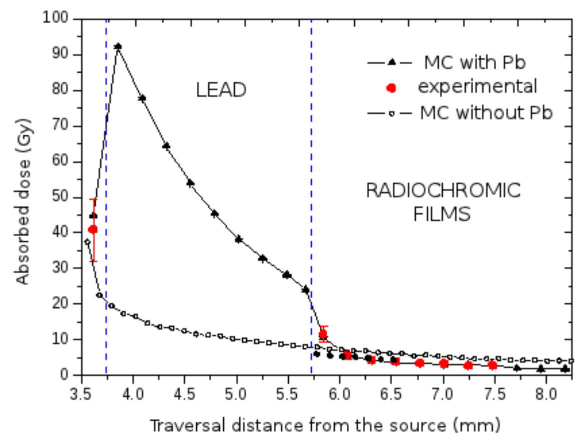

Figure 5. Dose depth profile for ^{192}Ir source.

The higher number of events simulated for this source allow us to obtain more defined profiles. As the plot shows there is a really good agreement between the measurements and the MC values. We could say both the profiles with an without the lead layer decay parallel from 6.5 mm depth and the dose perturbation extends a distance from 5.75 mm to 6 mm, it means a distance in the order of 0.25 mm that is in agreement with the electron path length in water. It is really interesting the behavior close to the interface, in the first film after the lead layer surprisingly the deposited dose is higher with the shield than without it, after a distance the doses are the same and then continuous decaying under the dose curve with out the shield. The dose region after the interface could be understood as an negative dose gradient with a range similar to the path length of the electrons in this medium. In the plot appears under the dose gradient some filled black circles, they represent how the dose would be if the secondary electrons wouldn't exit.

For the ^{18}F as we explained before we present the results of the MC simulations. The DDP for ^{18}F source is shown in **Figure 6**. The radioisotope ^{18}F is homogeneously distributed in water inside one syringe then there is an tungsten cylindrical shield and finally another water cylinder surrounding the shield.

The four profiles presented are different situations, as is shown in the plot legend, there are two profiles with two syringes of different materials, other without the syringe with the space left filled with water and finally the geometry without the tungsten and the space left filled with water. The profiles for both the PVC and the polypropylene (PP) syringes are very similar. When there is not the syringe the dose rate fall dawn to 3,7 mGy/s due to the bigger volume in which the same number of events occur. Finally the profile without the shield shows a rapid and continuous fall of the dose rate.

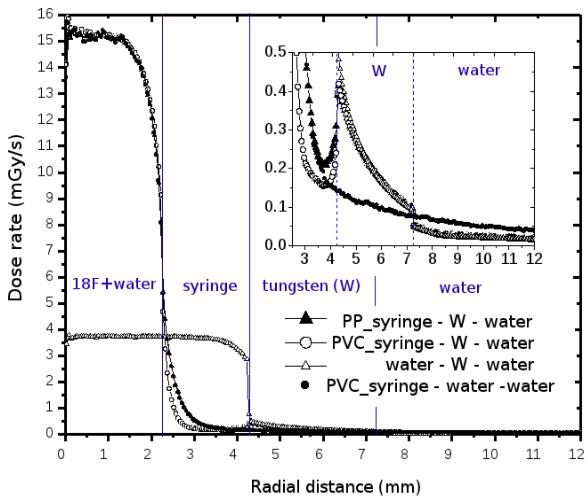

Figure 6. Dose depth profile for ^{18}F source.

The graph in the box magnifies the interface region between the tungsten and water showing an dose rate after the shield always lower than the dose rate without the shield, in spite of this, the dose rate of the three geometries are not parallel to the profile without the shield in the first millimeter after the shield and it is the same dose gradient behavior that occur with the sources of ^{137}Cs and ^{192}Ir. This distance is in agreement with the range of the electrons in water, for energies of ~400 keV is ~1 mm.

The next figure is the distribution of electrons and photons reaching the water after the tungsten. The are electrons of high energies in ~440 keV and 500 keV and a continuous distribution whit lower energies. Photoelectric absorption in the K (70 keV) and L (12 keV) edges of tungsten produce this two peaks of electrons and incoherent scattering produces the lower energy distribution. The photon histogram shows a dominant peak of 511 keV due to the photons than escape from tungsten without any interaction and scattered photons with continuous distribution of lower energies.

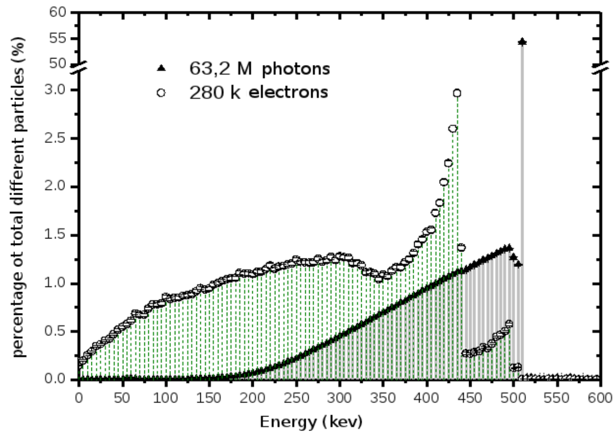

Figure 7. Histograms of the number of photons, electrons and positrons entering in the water cylinder after the tungsten**.**

We have found with three sources and with different geometries that after the shield containing the source there is an negative gradient of the absorbed dose in a distance similar to the range of the electrons in the medium.

The dose gradients are due to electrons escaping from the shield delivering all their energy quickly as a superficial dose. We thought that an important part of electrons can be stopped adding a thin film of a low Z material after the shield. We have simulated a cylindrical PVC film of 1 mm thickness after the tungsten. The histograms of the electrons and the photons in water after the tungsten are shown in **Figure 8.**

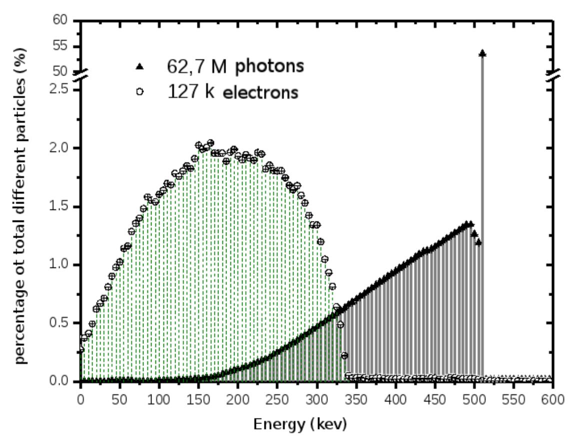

Figure 8. Histograms of the number of photons and electrons and entering in the water cylinder when a 1 mm PVC layer is surrounded the tungsten.

The number of electrons have been reduced 55 % from 280000 to 127000 and the electrons stopped had been the most energetic then is logical to think that the absorbed dose will also be reduced in the same factor. The photons present practically the same histogram as we can expect.

We can expect that doing the same with the cesium and iridium sources there will be an appreciable reduction in the number of electrons, actually in figures 4 y 5 the fifth experimental value is very similar at the value that one would obtain adding 1 mm PVC film due to the radiochromic films have a thickness of 0.234 mm and they have similar physical properties than PVC. We obtain an reduction factor of 35 % for cesium-137 and 68 % for iridium-192 souce.

4. Conclusions.

The results of the experimental measurements and the MC simulations show the existence of a dose gradient in the surface of a shield containing a photon emitter source with energies of 320, 511 and 662 keV. The dose gradient is due to electrons escaping from the shield and enter in the next material, they deposit their energy quickly in a distance similar to the range of the electrons in the medium. We have show that adding a PVC layer 1mm thick the superficial dose rate can be reduced in a factor of 55% for 10 mCi of fluor-18 containing in a shield made of tungsten 3 mm thick. The superficial doses due to the contact with sources shielded occur in distances that are well above the minimum distance of 70 μm established by the Nuclear European Society [3] from which the dose should be asses. This doses can be significantly reduced adding a thin PVC layer outside the shield.

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