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Design Improvement of an X-ray Tube Applicator to Reduce ORE

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1. Introduction

Many people fear cancer for the preservation of their lives. There are several types of therapy methods for cancer, which include surgery, chemotherapy and radiation therapy and so on. Radiation therapy has many advantages to treat cancer relative to other therapies. It does not induce scar or hair loss, and could can cover larger area than others. However, one the most critical issues about radiation therapy is shielding. Not only unnecessary exposure to patients but also those to doctors or nurses who participate in the treatment have to be lowered as possible. Occupational radiation exposure (ORE) is limited to 50 mSv per year by NCRP's recommendation. [1]

Meanwhile, radiation therapy in Korea has a long history. The first radiation therapy was done in 1986, which was the electron intraoperative radiotherapy for gastric cancer and there was the minimum shielding around the patient's surgical site. Nowadays, as the regulation about occupational radiation exposure has been stricter, more shielding material is added to protect the doctors and nurses. In the process of radiation therapy, many people, including medical physicist as well as doctors or nurses, participate in the surgery. These people hide behind the shielding wall, which can be moved, when the x-ray generator is operating. It is represented in figure 1.

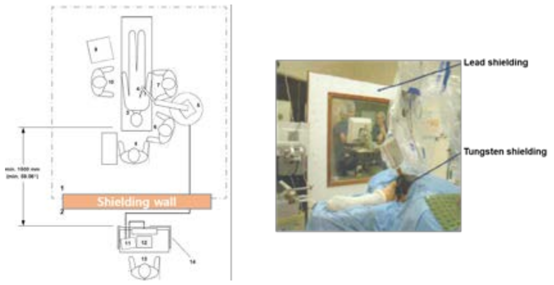

Figure 1. Shielding condition to prevent ORE

The reason why the large shielding material is required is that the existing x-ray generators are hard to shield easily. There are two types of x-ray generator which are radioisotope and x-ray tube. Radioisotope can be easily smaller but it always generates radiation, which means that it is very hard to control. On the other hand, x-ray tube can switch on/off and control the dose easily. However, the size of the x-ray tube is hard to be small because of cooling issue.

Recently, a vacuum-sealed miniature x-ray tube based on a carbon nanotube field-emission electron source has been fabricated by KAIST. [2] Figure 2 is the schematic diagram and represents the actual size of the tube. This x-ray tube uses "cold" electron generated from CNT source unlike the existing x-ray tubes using "hot" electron generated from tungsten filament; therefore, among many advantages over other tubes, the remarkable thing is that it could be very small size because it does not need additional cooling system.

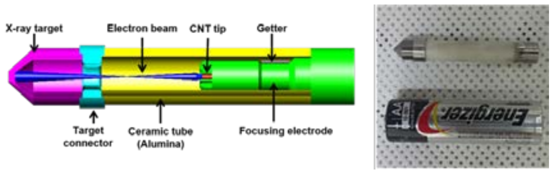

Figure 2. CNT based X-ray tube [2]

If this x-ray tube would be commercialized, the requirement of a shielding material could be eliminated and the process of cancer therapy would be much simpler. This is possible due to the size of the x-ray tube getting dramatically smaller. Thus, if the dose distribution of this tube can be made sufficiently practical, the therapeutic environment can be made more effective by minimizing the shielding.

For analyzing the dose distribution, MCNP6 code was used, which was developed by Los Alamos National Laboratory and the most advanced code using Monte Carlo method. Monte Carlo method is widely used for solving problems involving the random walk process. It is usually employed in the radiation transport. Thus, the dose distribution around the x-ray tube has been evaluated by MCNP6 code.

2. Methods and Results

2.1. Methods

The miniature x-ray tube fabricated with carbon nanotube field has to be connected to receptacle for applying high voltage; therefore, the perfect insulation should be needed by molding Silicon Rubber around the surface. Figure 3 shows the final step of the x-ray tube fabrication, which at this stage, the tube is ready to be applied high voltage.

Figure 3. The miniature x-ray tube insulated by SR

In fact, the miniature x-ray tube can be applicable to various types of cancer treatment procedures depending on the applicators. In this paper, the applicator for skin melanoma cancer is being focused first. The applicator for skin melanoma cancer has flat form and the tube and receptacle are surrounded by metal for shielding which is mainly composed of SUS304. For skin cancer treatment, the percentage dose depth profile along the source to target axis and dose distribution on the patient's skin surface is important; however, to focus on occupational radiation exposure, the radial dose distribution on the same plane as the tube should be known. If the dose distribution can be improved until equivalent dose is low enough to assure safety, then, as figure 4 below shows, the doctor could just grab the tube for treatment without the uncomfortable shielding wall.

Figure 4. The expected therapeutic environment

To simplify calculation, it is first assumed that the x-ray generated from the tube is distributed evenly on any plane which cross the tube. Thus, the dose distribution on only one plane needs to be evaluated. Firstly, the dose rate without applicator was evaluated to compare with that with applicator. The geometry of the first case is represented in figure 5. It is two dimensional image based on the assumption mentioned above. The MCNP6 F4 tallies, which estimate the particle track length per unit, were employed to calculate average flux in the tally cells. Six tallies were set for $0° \leq \Theta \leq 150°$ in 30° increments for along the source to target axis at radial distance of 3 cm from the center of the target. Each tally has 1 cm diameter. The detailed photon physics of the MCNP6 code accounts for incoherent and coherent scattering, photoelectric absorption with fluorescent emission, pair production, and bremsstrahlung radiation. For the simulation, a cutoff energy of 1keV was used for both photons and electrons. The MCPLIB09 photon cross-section library was applied using data from ENDF/B-VI Release 8. For the electrons, El03 interaction data library was used.

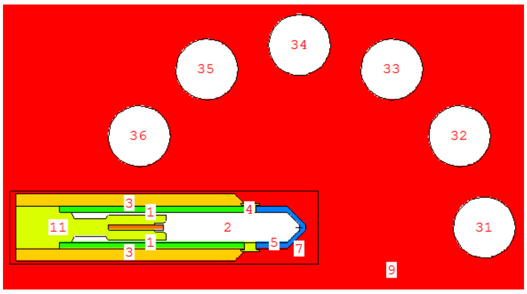

Figure 5. The tube geometry without applicator

In figure 5, #31, #32, and #33 tally are mainly associated with patients; the others, #34, #35, and #36, associated with doctors. The three latter tallies are of our interest in terms of ORE, but all these six tallies are concerned for figuring out tendency of dose rate. Actually, the particle flux not dose rate is deposited to these F4 tallies; therefore, additional flux to dose conversion factor is needed. The factor is introduced in ICRP publication 119 and the values are different with the energy range, so the tally estimator was used in 0.1 keV bins.

In the case with an applicator, the basic assumptions are the same as that of one without an applicator. Figure 8 shows the geometry of the input file. In figure 6, the color orange, designated by #51 is the applicator and the thin vertical layer in the front side, is aluminum filter. The filter is used for eliminating the effect of low energy deposited on patient's skin, which is not concerned in this paper.

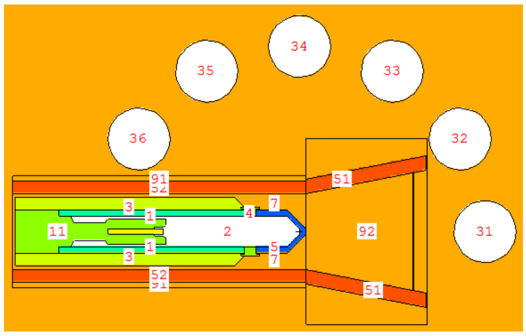

Figure 6. The tube geometry with applicator

Once the energy spectrum at each tallies are obtained, the values of fluence should be converted to effective dose using conversion coefficients provided by ICRP publication 119[3]. Actually, the values are exact fluence because they are sorts of statistical value for one electron; therefore, the number of electron as a function of time should be represented. Since the current of this diode system is intended to 100 mA, the number of electron from cathode to anode per second is like this;

$$100\ \mu A = 0.0001\ A = \frac{0.0001\ C}{1\ sec} \times \frac{1\ electron}{1.60219 \times 10^{-19}} = 6.2415 \times 10^{14}\ {}^{electrons}/_{sec} \quad (1)$$

When the result of simulation and conversion factors are applied to it, the effective dose to doctor per second could be obtained. The conversion factors are from ICRP publication 119 and it shows in figure 7 below. For conservative evaluation, the coefficient based on Antero-posterior geometry (AP) is chosen. This geometry assumes that a mono energetic parallel bam of ionizing radiation is incident on the front of the body in a direction orthogonal to the long axis of the body.

For each run, total fluence of 5×108 electrons was simulated in order to have statistical uncertainty lower than 5% for all points.

ANNEX I. CONVERSION COEFFICIENTS FOR AIR KERMA FREE-IN-AIR AND EFFECTIVE DOSE PER AIR KERMA FREE-IN-AIR

Table I.1. Conversion coefficients for air kerma free-in-air, K_a/Φ, and effective dose per air kerma free-in-air, E/K_a, for mono-energetic photons incident in various geometries on an adult anthropomorphic computational model.

		E/K_a (Sv/Gy)					
Photon energy (MeV)	K_a/Φ (pGy cm^2)	AP	PA	LLAT	RLAT	ROT	ISO
0.01	7.60E+00	6.53E−03	2.48E−03	1.72E−03	1.72E−03	3.26E−03	2.71E−03
0.015	3.21E+00	4.02E−02	5.86E−03	5.49E−03	5.49E−03	1.53E−02	1.23E−02
0.02	1.73E+00	1.22E−01	1.81E−02	1.51E−02	1.55E−02	4.62E−02	3.62E−02
0.03	7.39E−01	4.16E−01	1.28E−01	9.08E+00	9.04E−02	1.91E−01	1.43E−01
0.04	4.38E−01	7.88E−01	3.70E−01	2.05E−01	2.41E−01	4.26E−01	3.26E−01
0.05	3.28E−01	1.11E+00	6.40E−01	3.45E−01	4.05E−01	6.61E−01	5.11E−01

Figure 7. The conversion factors from ICRP publication 119 [3]

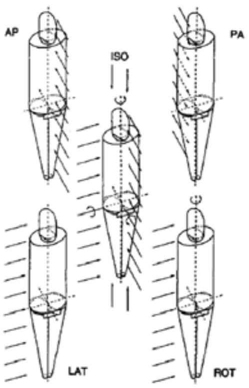

Figure 8. Irradiation geometries of an anthropomorphic phantom. AP, PA, LAT, ROT, and ISO [3]

2.2. Results

To investigate the effective dose at each tally, the energy spectrums were evaluated when there is no applicator first. The energy spectrums are shown in figure 9 shows the complete results for comparison.

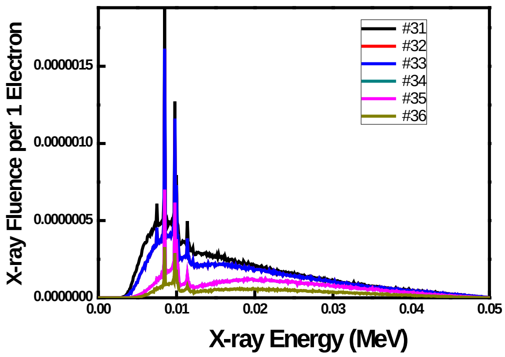

Figure 9. X-ray energy spectrum (without applicator)

The miniature x-ray tube is designed to generate x-ray mostly in the forward direction which is towards the patients; therefore, #31 tally received the highest value of x-ray fluence. Then, the value is reduced towards back side. Applying the conversion factor and the number of electron, the effective dose based on AP geometry is acquired. Figure 10 shows this.

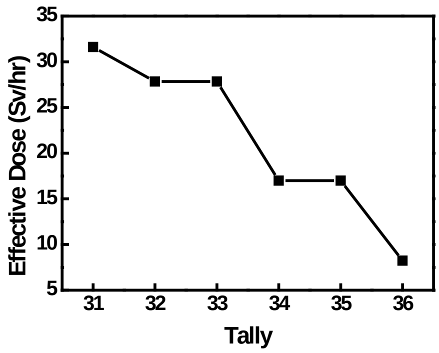

Figure 10. Effective Dose (without applicator)

The unit of effective dose in figure 10 is sievert per hour, which expresses the dose released when the miniature x-ray tube is operated for an hour without any break. One additional assumption of how much time a doctor participates in the radiation treatment is needed. If a doctor would be in charge of the treatment about 30 times a month, which is a very conservative assumption, then the doctor conducts 360 radiation treatments for a year. Since every therapies may not exceeds 10 minutes, a conservative assumption again, the treatment time should be less than 60 hours. Among these tallies above, #34, #35, and #36 tallies are associated more with the doctor as mentioned above. When the tube without applicator is used, the doctor would be irradiated with a maximum dose of 500 Sv over a year. Again, this is ultimately conservative analysis because the position of the tallies are too close to the target as well as the assumption about irradiation time.

Same procedures were repeated in the tube with applicator in figure 11 and 12.

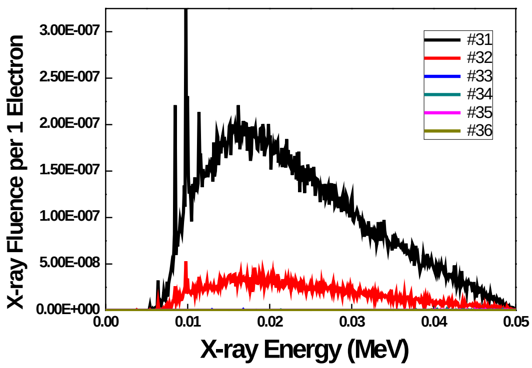

Figure 11. X-ray energy spectrum (with applicator

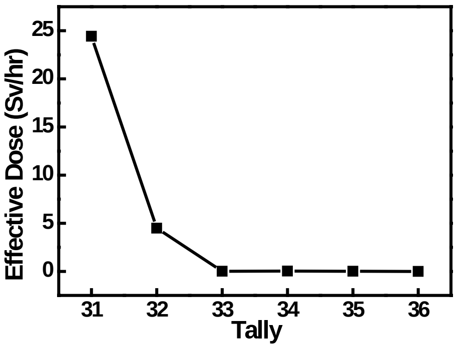

Figure 12. Effective Dose (with applicator)

3. Conclusions

In this study, MC simulations were performed to evaluate the effective dose induced by the miniature x-ray tube. It was confirmed that when the applicator is adopted to the tube, the effective dose to doctor is less than the occupational radiation exposure limit recommended by ICRP. All assumptions used in this calculation were too highly conservative enough to have reliability. However some limitations still exist; for example, the more accurate results could be obtained if most recent version of conversion factors was used or we specified the organs irradiated and weighted the values by the radiation sensitivity.

REFERENCES

[1] Recommendations on the limits for exposure to ionizing radiation. NCRP Report no. 91. Bethesda, Md: National Council on Radiation Protection and Measurements, 1987

[2] Sung Hwan Heo, Hyun Jin Kim, Jun Mok Ha and Sung Oh Cho "A vacuum-sealed miniature X-ray tube based on carbon nanotube field emitters", Nanoscale Research Letters 7 (2012) 258

[3] ECKERMAN, K., et al. ICRP publication 119: compendium of dose coefficients based on ICRP publication 60. Annals of the ICRP, 2013, 42.4: e1-e130.