Monte Carlo simulation of X-ray spectra produced by Linac

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Abstract. This study was conducted to determine the intensity distribution of X-ray energy spectrum of that produced by Linear Accelerator (Linac) with tungsten target (W). The x-ray spectra on the space behind of target is calculated through the simulation method using Monte Carlo N-Particle eXtended version software (MCNPX). Linac is simulated with acceleration voltage 6 MV up to 15 MV using tungsten metal target (W). Based on the simulation of electron source accelerated, X-rays generated mostly (40-75) % are X-rays with energy of 1 MeV to 2 MeV, whereas the intensity of X-rays with energies fit the energies of the shooter's electrons is very small (0.03 -0.340)%. It was indicated that the energy spectra dominated in the 1 MeV to 2 MeV than maximum energy in the x-ray spectrum range along the energy variation of Linac radiotherapy simulation. In addition, also found electrons about 2.24 % to 5.67% compared to the intensity of X-rays, so as to increase the equivalent dose in the patient's tissue later. This information can be used for the manufacture of low energy range filter design that dominate the spectrum and consideration of radiation protection efforts.

1. Introduction
At this time, high energy radiation used has been one of the success factor in cancer radiotherapy methods. The medical Linear Accelerator (Linac) is the one kind of external radiotherapy machines that utilizes the high-frequency electromagnetic waves produced by the clystron to accelerate electron beam, resulting in high-energy ionizing radiation that reaches the MeV order for cancer treatment [6]. The high energy of ionizing radiation causes the commonly used teleterapi cobalt-60 radiotherapy machine to be replaced by Linac, because Co-60 only has 1.33 MeV and 1.17 MeV energy [2]. Furthermore, Linac also has a better level of safety and protection, because the ionizing radiation used for irradiation is produced from an electron accelerator machine, not from radioactive source decay, so that the adverse effects of the use of radiation on Linac can be controlled and minimize. The distribution of high-energy X-ray files that are used must have the right intensity in the cancer cells and surrounding body tissue. X-rays with energy exceeding the threshold energy of the target metal atom can cause producing secondary particles that can add to the equivalent dose of tissue [1]. According to the IAEA 2012, one of the principles of optimization of radiation protection in radiotherapy is the design of the Linac component geometry, especially the anode metal target, because the anode target has an important role in X-ray production in Linac head [3]. The method that can be done to determine the X-ray energy spectrum distribution from the LINAC file is to use the Monte Carlo simulation method [4]. This paper has been done with Monte Carlo simulation method by MCNPX’s software discusses about intensity distribution of x-ray and electrons behind the tungsten target system geometry. The accumulation of x-ray and electron which through the target W might be increased equivalent dose in the body tissue later.
2. Numerical Methods
The method used in this study is a simulation method with Monte Carlo N-Particle eXtended version (MCNPX) software. The geometry model in this simulation refers to the head of the Varian type LINAC by ignoring the collimator and filter systems. Moreover, limiting only the basic geometry that consist to target W and vacuum space, namely target system. The behind side of target W is opposite direction with electron coming and vice versa with in front of target W. The making of the target W geometry is intended for the formation of X-ray radiation, while the vacuum is to avoid the collision of electrons from the source with the particles around. The electrons from source of as they have been accelerated and deflected by a magnet. The position of the electron source coordinates is (-0.5 0 38), which is started after accelerate and deflecting electron from filament source by bending magnet. The electron move towards positive x-axis.

![Figure 1](image.png)

**Figure 1.** The Geometry of (a) 45˚ Target W in vacuum tube (b) Linac head with 0˚ Target W

Figure 1 shows the geometry model in this study, namely the 45˚ target geometry and Linac head geometry. Target 45˚ geometry model with Cu and Al material targets and 40 kV as accelerator voltage for simulation validation programs. Then, the Linac head geometry model with W target and 70 kV as accelerator voltage to determine the radiation and energy energy spectra. The Linac head model is carried out with a 6 MV accelerator voltage of up to 15 MV using the W target, which has a high melting point of 3442˚ C. Beside that, Tungsten (W) was chosen as the target material because the thickness has very low X-ray transmission [5]. The energy spectrum distribution is reviewed in the vacuum space behind the target W to determine the distribution of the transmission X-ray spectra. Tally which chosen for intensity in this simulation is F4 to find out in the geometry volume.

3. Results and Discussion
This paper discussed some result from the study about the X-Ray Spectra from the target inside head Linac, started from verification test for simulation program till the intensity distribution results.
3.1. Verification of the Simulation Program Results.
The success of this simulation program refers to the results of the target metal test obtained from the 45° geometry model simulation results.

| Material | X-Ray Type | $E_{\text{characteristic}}$ (keV) | $\lambda_{\text{simulation}}$ (Å) | $\lambda_{\text{theory}}$ [7] (Å) | Relative Difference (%) |
|----------|------------|---------------------------------|---------------------------------|---------------------------------|-------------------------|
| Cu       | $K_{a,1}$  | 8.01                            | 1.552                           | 1.549                           | 0.249                   |
|          | $K_{a,2}$  | 7.987                           | 1.556                           | 1.577                           | 1.28                    |
| Al       | $K_{a,2}$  | 1.470                           | 8.457                           | 8.638                           | 2.10                    |
|          | $K_{a,3}$  | 1.530                           | 8.134                           | 8.230                           | 1.17                    |
| W        | $K_{a,2}$  | 57.9                            | 0.215                           | 0.214                           | 0.128                   |
|          | $K_{a,3}$  | 60.0                            | 0.207                           | 0.210                           | 1.14                    |

Table 1 shows that the simulation program has met the suitability test with an average relative difference which tends to be 1.01%, so that the simulation program can be discussed further. This model can be modified into the Linac head geometry model form with target 0°.

3.2. The Distribution of X-Ray Spectra behind the Target W Linac
Linac head geometry model simulation produces X-ray spectra from the voltage that needed to result energi 6 MV till 18 MV behind the target W data which is processed into a graphs.

![Figure 2. X-Ray energy Spectra behind Target W](image_url)

Figure 2 shows that the highest amount of X-ray is on the lower energy spectrum range about 0.5 MeV till 1.5 MeV. The X-Ray intensity is getting higher in the increasing voltage that needed to generate energy electron from the source, but the position of the highest amount of x-ray didn’t change. Meanwhile, The X-rays spectra increases uniformly as the electron source energy increases and decreases with the trend that tends to be the same between different accelerator voltages. The decline occurs because the X-ray population in the target space was decrease. Therefore, the biggest amount of x-ray is dominated in lower energy spectra about 0.5 MeV till 1.5 MeV. That distribution details are shown in table 2 below.
Based on table 2, the distribution of X-rays behind the target is heterogeneous enough due to the difference in percentages is much different. Among the energy ranges, X-rays are more abundant in the range of 0.01 MeV to 2 MeV, while X-rays are purely worth the maximum amount of energy. Therefore, in radiotherapy it is necessary to have a flattering filter to filter low-energy X-rays, so that not all X-rays with low energy ranges are involved in interactions with body tissues. The table also explains that if you want to get 6 MeV (high energy) X-rays in radiotherapy you need a higher energy source than the input energy, because the intensity of the maximum X-ray energy is also increasing. 6 MeV energy X-rays will be 0.67% from a 6 MeV energy source, 2.62% from 9 MeV, 3.10% from 12 MeV, 3.18% from 15 MeV.

3.3. The Distribution of X-Ray and Electron around the Target W.
The intensity of X-ray and electrons before and after interactions with the target W can be used to design the contamination particle control, file optimization and time efficiency efforts in the research process in Radiotherapy with electron sources.

Table 2. Energy distribution of the X-ray transmission behind the Target W

| No. | The Energy Distribution of X-Ray (MeV) | Percentage (%) |
|-----|---------------------------------------|----------------|
|     |                                       | 6 MV | 9 MV | 12 MV | 15 MV |
| 1   | 0.01 – 1                              | 50.99| 44.9 | 42.15 | 40.96 |
| 2   | 1.01 – 2                              | 28.23| 27   | 25.24 | 24.06 |
| 3   | 2.01 – 3                              | 12.22| 12   | 12.25 | 11.67 |
| 4   | 3.01 – 4                              | 5.54 | 6.47 | 6.97  | 7.09  |
| 5   | 4.01 – 5                              | 2.35 | 4.27 | 4.53  | 4.59  |
| 6   | 5.01 – 6                              | 0.67 | 2.62 | 3.10  | 3.18  |
| 7   | 6.01 – 7                              | 1.54 | 2.273|       | 2.46  |
| 8   | 7.01 – 8                              | 0.80 | 1.47 | 1.81  |       |
| 9   | 8.01 – 9                              | 0.21 | 0.982|       | 1.29  |
| 10  | 9.01 – 10                             | 0.636|       | 1.05  |       |
| 11  | 10.1 – 11                             | 0.320|       | 0.72  |       |
| 12  | 11.1 – 12                             | 0.090|       | 0.55  |       |
| 13  | 12.1 – 13                             |      |       | 0.35  |       |
| 14  | 13.1 – 14                             |      |       | 0.19  |       |
| 15  | 14.1 – 15                             |      |       | 0.02  |       |

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Table 3 shows the information about electrons and X-rays production on the both sides of the target W which come from the range of electron source energy from 40 keV to 18 MeV. Electrons energy of 40 keV and 100 keV can only produce X-rays in front of the target and have not been able to produce X-rays behind the target, its because electrons are not energetic enough to scatter X-rays by transmission. At 1 MeV, electrons have been able to scatter X-rays to behind the target. That scatter occurs due to production electron behind target which was obtained from couple production that requires minimum energy of 1.02 MeV [6].
### Table 3. The distribution of X-Ray and electron around the Target W

| Electrons Energy (MeV) | X-Ray Intensity $10^3$ photons per electron.cm$^{-2}$ | Electrons Intensity $10^3$ electron.cm$^{-2}$ |
|------------------------|-----------------------------------------------|-----------------------------------------------|
|                        | In front of | Behind | In front of | Behind |
| 0.040                  | 0.195±0.266 | 0      | 57.048±0.011 | 0      |
| 0.10                   | 0.244±0.221 | 0      | 55.510±0.010 | 0      |
| 1                      | 2.949±0.065 | 0.068±0.472 | 52.547±0.010 | 0      |
| 6                      | 14.534±0.007 | 11.910±0.008 | 42.513±0.003 | 0.675±0.046 |
| 9                      | 17.688±0.007 | 25.354±0.005 | 38.945±0.003 | 0.802±0.041 |
| 12                     | 19.501±0.008 | 41.091±0.005 | 36.677±0.003 | 0.923±0.043 |
| 15                     | 20.722±0.007 | 59.051±0.004 | 35.573±0.003 | 1.344±0.033 |
| 18                     | 22.422±0.023 | 77.444±0.011 | 34.245±0.007 | 1.755±0.101 |

Besides that, the accelerate electrons weren’t energetic enough to pound the orbital electrons till released and thrown towards the Target. At energy above 6 MeV to 18 MeV, the amount of X-ray behind target increase with a greater increase portion than in front of the target. The electrons refill in the part that occurs from electrons with target W, either because of the photoelectric effect, Compton, couple production, Knock on even Auger effect. The decrease electron in front of target occurs due to a small portion of the detected electrons are energetic electrons that successfully escape the target volume W, while the greater the source energy, the more energetic electrons will be. In addition, the most electrons are removed as reflected electron from the target W due to pounding of the orbital electrons belonging to the target W and the orbital electrons which are released from the outer shell. Information about the distribution of the energy spectrum of X-ray and electrons in this water can be used to complete the radiation quality specifications needed for consideration of X-ray absorption doses in water [4] and equivalent doses in body tissues of cancer radiotherapy patient.

### 4. Conclusions

Based on the research that has been done, it can be concluded that the MCNPX simulation results from the geometry model of the Linac target system have fulfill the verification simulation program with an average relative difference of $\Delta\lambda_{Ka}$ of 1.01% against the theory reference. At Linac which is operated at 6 MV accelerator voltage up to 18 MV, an X-ray of intensity with an order of $10^2$ photons per electron. cm$^{-2}$, which is increasing behind the W-target. Behind the target, there are many electrons detected from 2.24% up to 5.67%. The X-ray distribution produced by Linac head is dominated by the most intensity in the energy range of 1 MeV to 2 MeV, so the intensity of X-ray energy that has value as much as energy of the electron from source is very small. Beside that, the intensity of electrons is generated due to X-ray interactions in the target space of Linac. Those electrons can increase the equivalent dose to the body tissues of the patient, thus giving a bad effect on the body tissues.
Therefore, the results that have been obtained can be the information for target manufacture based on design, materials or thickness to filter the electrons or x-ray spectra that produced from target.

5. References

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