The estimation of occupational dose in 15 MV varian clinac iX room by Argon-41 as an activation product of photoneutron

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Abstract. Linear accelerator (linac) becomes the most commonly used treatment to damage and kill cancer cell. Photon and electron as the radiation beam are produced by accelerating electrons to very high energy. Neutrons are generated when incident high photon energy interacts with component of linac such as target, flattering filter and collimator via photoneutrons reaction. The neutrons can also produce activation of materials in treatment room to generate radioactive materials. We have estimated the concentration of Argon-41 as activated product from argon-40 in the linac room using foil activation. The results show that the Argon-41 concentration in linac room which is operated 15 MV for 1 treatment (1 minute) is 1440 Bq/m³. Accordingly that concentration, the occupational dose is 6.4 mSv per year.

1. Introduction

In modern radiotherapy, both high energy X-ray and electron beam are often used in the treatment of cancers. These beams mainly are generated by linear accelerator (linac). However, when high-energy accelerators operated roughly at 10 MV or higher, a significant number of neutrons are generated via photoneutron reactions (n, γ). The photoneutron are produced when high energy photon collides with the high atomic number of material in linac system such as the accelerator head, all collimators, the target and flattening filter [1-4]. This reaction consequently brought an undesirable neutron production. Moreover, the neutrons can activate the material in treatment rooms to generate radioactive materials which raise a concern about irradiation safety. Argon is one of the gaseous in the air with stable nuclide in the form of ⁴⁰Ar. Although the argon concentration in air is relatively small, but the chances for activation by neutrons are relatively large because argon has a fairly high cross section value of 162 barn [5]. When the stable Argon ⁴⁰Ar interact with neutron, Argon will be activated as a radioactive in the form ⁴¹Ar. Recently, little attention has been emphasized to gaseous radionuclide ⁴¹Ar which can be generated by thermal neutron activation of stable ⁴⁰Ar in air.

Numerous papers were focused on the study of neutron field and its production in linac, but it mostly concerns to the patients. This study observed that the impact on occupational radiation dose due to activation product contributed by Argon-41 [6]. The neutron activation approach is implemented to estimate the concentration of Argon-41 in linac room. Indium foils are used for neutron activation because it has a high cross section for thermal neutron [7-8].
2. Materials and Methods

2.1. Activation of Indium Foil

The measurements of thermal neutron flux were carried out with the use of induced activity method [7-8]. The indium foils (115In isotope) in the shape of circle with the diameter of 2.3 cm were applied as activation detector. Isotope 115 In has a relatively high cross-section for thermal neutron capture (162 barn). The thermal neutron induces the activity of the foil according to the following reaction:

\[ {^{115}_{49}In} + {^1}_{0}n \rightarrow {^{116}_{49}In}^* \]
\[ {^{116}_{49}In}^* \rightarrow {^\beta}_{-} + {^{116}_{49}Sn}^* \rightarrow {^{116}_{49}Sn} + \text{gammas} \]

The activities of indium foils were determined on the basis of measurement of gamma energy spectrum from deexcitation of 116Sn*. The spectral measurements were performed using HPGe detector connected to a multichannel analyzer. The HPGe detector was calibrated with the filtered source multiradionuclides including 241Am, 133Ba, 137Cs and 60Co. The activities of the foil were determined by counting the gammas of 1293.54 keV. From counting, the activity of indium can be calculated with [9]:

\[ \phi_{th} = \frac{A}{\text{area} \times \text{yield} (E_p)} \]  
\[ \phi_{th} = \frac{\text{area} \times \text{yield} (E_p)}{\text{detector efficiency} \times \text{detection time}} \]  
\[ \text{area} \times \text{yield} (E_p) \]

Other The thermal neutron flux is defined and the induced radioactivities of indium foils, as follows:

\[ \phi_{th} = \frac{A}{\text{area} \times \text{yield} (E_p)} \]

where \( \phi_{th} \) denotes the thermal flux (cm\(^{-2}\) s\(^{-1}\)) which represents an activity of Indium that is counted by gamma spectrometer, \( A \) is the decay constant (2.135X10\(^{-4}\) s\(^{-1}\)), \( \sigma_{th} \) is microscopic cross-section (162 barn), \( N_A \) is Avogadro’s number, \( m \) is the mass of indium foil (g), \( M \) is the atomic weight of indium (114.82), \( a \) is the isotopic abundance of 115In (95.7\%), \( t_i \) is irradiation time and \( t_d \) is the time duration between irradiation and measurement [6].

2.2. Irradiation Treatment

Indium foils (purity 99.993%) with an averaged mass of (1.4884 ± 0.0004 g) placed on and distributed around medical accelerator room (Varian Clinac iX), such as on Figure 1. The accelerator was operated at 15MV for 1 minute and collimator was opened at a field size of 20X20 cm\(^2\).

The irradiated foils were immediately counted using gamma spectrometer with HPGe detector. The measured gamma-ray spectra was collected with a multichannel analyzer and was further analyzed by gamma-spectrum software (Gammavision-32). Foils were placed on the face of detector for counting; the efficiency was determined to be 3.2% at the characteristic gamma-ray energy of 1294 keV which is emitted from activated nuclide \(^{116m}\)In for 5 minutes.

2.3. Estimation of The Argon-41 Concentration and Corresponding Dose

Argon-41 is produced by photonutron reaction between high energy photon and material component in linac. The concentration is difficult to measure directly [8], so activation foil approach is applied. The value of \( \phi_{th} \) from irradiated foil in linac room is used to determine the accumulation of argon-41 concentration (\( C_{Ar} \)) is derived as [6]:

\[ C_{Ar}(Bqm^{-3}) = F \times \phi_{th} \times N_{Ar} \times \lambda_{Ar} \times \left(1 - e^{-\lambda_{Ar}t_i}\right) \]  

where \( F \) correction factor (9.2), \( \phi_{th} \) is the averaged thermal neutron flux in linac room, \( \sigma_{Ar} \) is the neutron capture cross section of argon (0.64 barn) [10], \( N_{Ar} \) is concentration argon-40 in air (3.18X10\(^{22}\)m\(^{-3}\)), \( \lambda_{Ar} \) is the disintegration rate of Argon-41 (1.05X 10\(^{-4}\)s\(^{-1}\)) and \( t_i \) is irradiation time.

The corresponding dose of Argon-41 are calculated from three kind of doses. They are external dose, internal dose and immersion dose. The calculation using dose conversion factor as follows

\[ D^r_{ir} = X^m_i \times F^m_i \]  

where \( D^r_{ir} \) is received dose of organ r from radionuclide i on track m, \( X^m_i \) is the concentration of radionuclide i on track m and \( F^m_i \) conversion factor of radionuclide i for organ r on track m [9].
Figure 1. Distribution of indium foils in linac room.

3. Result and Discussion
3.1. Spatial Distribution of Thermal Neutron in Linac Room.
Table 1 shows the thermal neutron flux $\phi_{th}$ from irradiated foil around in linac room. Based on measurement of 14 indium foils, the average of thermal neutron flux in linac room varied from $1.4 \times 10^2 - 9.7 \times 10^3 \text{ cm}^{-2} \cdot \text{s}^{-1}$. The highest value is founded at the linac isocenter ($9.6 \times 10^3 \text{ cm}^{-2} \cdot \text{s}^{-1}$) and the lowest is at labirin. Figure 1 shows that area of x-negative-axis nearer to concrete than x-positive-axis and the result show that the distribution of $\phi_{th}$ x-negative-axis is higher than x-positive-axis because there are reflected neutron from concrete and contributed from thermalization of fast neutron. Thermal neutron flux has declined gradually with distance from the isocenter and has not detected on the outer door in operator room. It indicates that linac control room has been safely from thermal neutron as activation product of photoneutron reaction.
Table 1. Measurement Result of Thermal Neutron Flux in Linac Room from Indium Foil Placed to around Linac Room.

| Num Foil | Foil coordinate | $\phi_{th}$ ($cm^{-2} \cdot s^{-1}$) |
|----------|-----------------|-------------------------------------|
| 1        | (-3,-6.2)       | 0                                   |
| 2        | (-3,-6)         | 142                                 |
| 3        | (0,-6)          | 304                                 |
| 4        | (3,-4)          | 3429                                |
| 5        | (0,-3)          | 6802                                |
| 6        | (-3,0)          | 8234                                |
| 7        | (3,0)           | 5804                                |
| 8        | (2,0)           | 6753                                |
| 9        | (-2,0)          | 9280                                |
| 10       | (0,-2)          | 7974                                |
| 11       | (-1,0)          | 9619                                |
| 12       | (1,0)           | 8507                                |
| 13       | (0,-1)          | 9619                                |
| 14       | (0,0)           | 9660                                |

Measurement of thermal neutron flux in linac room has been done. It is listed to table II. Medical linear accelerator operating above 10 MV produce photoneutron via interaction high-energy photons with high atomic number (Z) materials. The material of linac will become main factor for releasing secondary neutron to treatment room. Table 2 shows the comparison some of linac type, Varian Clinac iX produce neutron lower than the other type of linac.

Table 2. List of Study Thermal Neutron Flux in Linac Room.

| Reference | Beam | linac   | Area (cm$^2$) | $\phi_{th}$ ($n \cdot cm^{-2} \cdot Gy^{-1}$) |
|-----------|------|---------|---------------|-----------------------------------------------|
| This study| 15 MV| Varian Clinac iX | 20 × 20 | 9.7 \cdot 10^3 |
| Liu, 2011 [2] | 15 MV | Varian Clinac 21EX | 20 × 20 | 2.0 \cdot 10^5 |
| Konefal, 2005 [10] | 15 MV | Primus Siemens | 20 × 20 | 2.9 \cdot 10^5 |
| Gur, 1978 [11] | 18 MV | Philips SL/75-20 | 10 × 10 | 1.4 \cdot 10^6 |
| Pałta, 1984 [12] | 18 MV | Mevatron 77 | 15 × 15 | 2.3 \cdot 10^5 |
| Lin, 2001 [14] | 20 MV | Varian Clinac 2300 | 10 × 10 | 1.5 \cdot 10^6 |
| Uwamino, 1985 [15] | 21 MV | Microtron, MM22 | 10 × 10 | 3.2 \cdot 10^5 |

3.2. The Concentration of Argon
Argon–41 is product by activation Argon–40 in air with neutron as a product of photoneutron reaction. The average thermal neutron flux in linac room can be related to estimate the concentration Argon–41. The activated Argon–41 was assumed to diffuse rapidly and to be uniformly to distribute in the treatment room. As a whole, the average of Argon–41 concentration in linac room calculated by equation (3) is 1440 Bq/m$^3$.

Remembering Argon-41 is a gaseous radionuclide, the Argon-41 concentration in room will be depend on radioactive decay and ventilation. This study has measured the ventilation rate of air on both the intake vent (inlet) and the exhaust vent (outlet). The measurement resulted ventilation rate is 37 m$^3$/h. Refer to the result, we can calculate its ventilation coefficient $T_{1/2}$ is 7.2/min. The half-life of Argon-41 as time function can be expressed as follows [6]:

$$T_{1/2} = \frac{\ln 2}{\lambda}$$
The equation 6 can be used to determine the concentration dynamics of argon-41 in the linac room during treatment activities. Figure 2 shows the concentration dynamics of argon-41 during weekdays or treatment activities (8 hours) by taking the assumption that every 20 minutes there is irradiation using high energy 15 MV.

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Figure 2. Argon-41 Concentration with time during a treatment.

Figure 2 shows that in the 20 minutes, concentrations of Argon-41 is about 184 Bq/m$^3$, it decreases 87% from the initial concentration when treatment irradiation with the energy of 15 MV was done. The concentration of argon-41 in the linac room can be used as information for determining a safe time to entry in linac room for nurses or medical personnel. The safe time of entry is time in which the concentration of argon-41 in the room has been fully exhausted. By knowing the safe time of entry, it can be used to radiation protection efforts on the medical staff.

### 3.3. Radiation Dose of Argon-41

The corresponding dose of Argon-41 in linac room can be contributed from three ways. They are external dose (contributed from gamma irradiation when people are in irradiation field), internal dose (contributed from inhalation of Argon-41) and beta immersion dose (contributed from absorbed Argon-41 to whole body surface). They are express in mathematically as follows:

\[
D_{eks} = t \cdot \sum X_{Ar-41} \cdot F_{Ar-41}^{eks}
\]

\[
D_{immers} = t \cdot \sum X_{Ar-41} \cdot F_{Ar-41}^{immers}
\]

\[
D_{inhalasi} = t \cdot \sum X_{Ar-41} \cdot F_{Ar-41}^{int}
\]

where $D$ is dose (mSv), $t$ is time exposure (s), $X$ is concentration (Bq/m$^3$), $F$ is conversion factor (mSv/Bq m$^3$.jam).
Determination of the dose of the contribution of the activated argon-41 using dose conversion factors. Thus, it is necessary to determine the value of the dose conversion factors. Dose conversion factors referenced in the 1977 USNRC for external dose, internal and immersion in a row at $4.5 \times 10^{-7}$, $1.4 \times 10^{-7}$ and $4.5 \times 10^{-7}$ with unit (mSv/min)/(Bq/m$^3$) [15]. There are additional correction for immersion dose. This correction factor is caused each person’s body is different. Mattar estimated the surface area of the skin in the function of mass and height [16], then refined by Wa’id which incorporates gender as in the following equation (10):

$$S = 0.0072B^{0.425} \times T^{0.725} \times f(m^2)$$

where $S$ is the surface area of the skin (m$^2$), $B$ is body mass (kg), $T$ is the body height (cm) and $f$ is the shape correction factor for gender or gender function $f$, as in the following equation (11):

$$F_k = 4.5 \times 10^{-7} \times \frac{1.78}{\text{surface body}}$$  \hspace{1cm} \text{(male)}

$$F_k = 4.5 \times 10^{-7} \times \frac{1.73}{\text{surface body}}$$  \hspace{1cm} \text{(female)}

By using immersion dose conversion factor in equation (11) and (12), we need the data of mass and height workers who are around in such as linac operator, medical physicists and nurses. This study has made generalization for using standard data of mass and height based on IAEA, mass and height standards for the Asian men and women respectively are 60 kg; 170 cm and 51 kg; 160cm [19]. Thus, the conversion factor for immersion dose are $4.97 \times 10^{-7}$ for male and $4.90 \times 10^{-7}$ for female.

As a whole, the conversion factor for three doses can be tabulated in Table 3 as follow:

| Type of dose | Conversion factor (mSv/ menit) |
|--------------|-------------------------------|
| External     | $4.5 \times 10^{-7}$          |
| Internal     | $1.4 \times 10^{-7}$          |
| Immersion    | $4.9 \times 10^{-7}$          |

By knowing these dose conversion factors, it can be predicted how many additional doses contributed by Argon-41 obtained if people are in the linac room during $t$ time. If a worker is assumed in the linac room operated at energy 15MV for 5 min after irradiation and the daily working period of worker is seven hours and five days in a week, thus calculation dose can be listed at Table 4. It is still relatively small when related to the annual dose for occupational exposure.

| Type of dose | Calculation |
|--------------|-------------|
| external     | 2.4 mSv    |
| Internal     | 0.7 mSv    |
| Immersion    | 2.6 mSv    |
| Total        | 5.7 mSv    |

4. Conclusion
Argon-41 is an activation product due to secondary neutron which is created via photoneutron reaction with material of linac. This study aims to estimate the concentration of Argon-41 using neutron activation approach and predict the radiations dose received by worker. The result show that the annual
occupational dose from Argon-41 is estimated equal to 6.4 mSv. This exposure can be significantly reduced with maintenance or ventilation and a delay of few minutes between the end of the irradiation and the entering inside the treatment room. Other paragraphs are indented

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