MEASUREMENT OF ABSORBED DOSE RATE IN WATER PHANTOM MAINTAINED AT BODY TEMPERATURE BY ^{60}Co IRRADIATOR – COMPARISON OF EXPERIMENTAL RESULTS AND MONTE CARLO SIMULATION

by

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To analyze the biological effects of radiation, it is important that the conditions of in vitro experiments match closely with those of in vivo experiments. In this study, we constructed an irradiation system to conduct irradiation experiments under conditions similar to those of in vivo experiments. The Dongnam Institute of Radiological and Medial Sciences has a gamma irradiator including ^{60}Co radioisotope for research purposes and accreditation for standard calibration of the ion chamber. The temperature of the water phantom was maintained the same as that of the normal human body, and the physical dosimetry was carried out accurately using the ion chamber with traceability. We report the measurement of lateral profiles, depth profiles, and absorbed dose rate in water, D_w, at the irradiation location of the blood samples using a farmer-type ion chamber. We simulated the source, collimator, irradiator, phantom, and extra structure of the gamma irradiation system using the Monte Carlo code and compared the simulated and the experimental results. The experimentally and theoretically evaluated dose rates were 0.2975   0.0055 Gymin^{-1} (at coverage factor k = 2) and 0.2978   0.0052 Gymin^{-1} (at coverage factor k = 2) at source-to-surface distance of 100 cm and 5 gcm^{-2} depth in the water phantom, respectively. Blood irradiation will be conducted in vitro, under conditions similar to in vivo conditions, to provide the dose-response curve based on dosimetry with traceability.

Key words: absorbed dose, water phantom, blood irradiation, standard calibration, MCNPX code

INTRODUCTION

The ^{60}Co radioactive isotope-based irradiator is widely used in medical science, radiation measurement, radionuclide analysis, industry applications, biological experiments, and standard irradiation [1-7]. Dongnam Institute of Radiological and Medical Sciences (DIRAMS) has a ^{60}Co irradiator (Gammabeam X-200, BEST Theratronics) for research purposes.

Korea Research Institute of Standards and Science (KRISS), as the primary standard dosimetry laboratory [8] in Korea, has primary standards for determining the air kerma and absorbed dose to water at ^{60}Co beam quality. The DIRAMS, an internationally accredited calibration, and testing laboratory belong to the Korea Laboratory Accreditation Scheme (KOLAS).

Ion chambers, calibrated with ^{60}Co gamma-rays, are used at DIRAMS for absolute dosimetry of high energy electron (6, 10 MV) and photon (6, 10 MeV) beams using appropriate beam quality corrections following the International Atomic Energy Agency (IAEA) Technical Report Series (TRS) 398 [9, 10]. The DIRAMS has provided standard calibration of ion chamber for air kerma and absorbed dose to water, with traceability using ^{60}Co beam quality, which was used in various research fields with high reliability using calibrated ion chambers following the IAEA TRS-398 and Korean standard [11].

Chromosome aberrations in lymphocytes are used to assess absorbed dose to overexposed persons. The number of abnormalities in the lymphocytes are demonstrated in terms of absorbed dose by reference to a dose-response calibration curve. The curve should be offered by exposure of blood *in vitro* to doses of the proper radiation quality. The doses given to the sam-

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ples should be evaluated through physical equipment such as an ionization chamber, to a primary or secondary standard with traceability [12-14]. We will provide dose-response calibration curve of biological effect assessment based on physical irradiation system that has standard dose rate using ^{60}Co beam quality with traceability.

MATERIALS AND METHODS

Gamma-ray irradiation conditions

A Gammabeam X-200 irradiator was loaded with 6197.3 Ci (approximately 6200 Ci) of ^{60}Co radionuclide which had a reference date of June 1st, 2012. The source assembly consists of a set of sleeves, plugs, cases, *etc*. in the drawer and it is located at the center of the irradiator during the irradiation by the pneumatic system. The square-shaped beam can be adjusted in the beam field using a tungsten collimator and it is surrounded by a lead shield on the outside, around the source.

The water phantom had the dimensions of 30 cm (length), 50 cm (width), and 25 cm (height). It was covered with tissue-equivalent Poly Methyl Methacrylate (PMMA) materials. To prevent the blood coagulation, and platelets, and to reproduce the in vivo conditions, heaters were installed inside the phantom to maintain the temperature at 37. Lymphocytes should be irradiated *in vitro* approximately as closely as possible to the *in vivo* situation, due to protect chromosome aberrations unrelated to irradiation. When this is done, the equivalent dose-response curve will be obtained [13, 14].

The beam field size was set to 10 cm (vertical) × 25 cm (lateral) for irradiating the sample and the measurements were conducted at a source-to-surface distance (SSD) of 100 cm with a 5 gcm^{-2} depth in water phantom, considering the total irradiation time per sample to be less than 15 minutes [13]. The lateral beam profiles and depth profiles were also measured. The lateral beam profiles were measured at intervals of 1.5 cm, and the depth profiles were measured at 1 gcm^{-2} intervals, from 2 gcm^{-2} to 15 gcm^{-2} in the beam direction, with the ion chamber fixed at a source-to-chamber distance (SCD) of 105 cm, as shown fig. 1. Figure 1 presents experimental set-up for the lateral beam profiles and geometric structure of the irradiation system [15]. Measurements at one position were conducted 10 times per minute. The irradiation dose rate is evaluated by averaging those 10 measurements for each position and a total of 10 background measurements. The position of absorbed dose to water, in simulation, was located at source-to-sample distance of 105 cm, same as with the ion chamber measurement.

The ion chamber, which was calibrated by the standard method for calibration factor in water, $N_{D,w}$, to maintain traceability, was used as a farmer-type ion chamber (TM300013, PTW) with a waterproof coating and no build-up cap. The ion chamber, which was used in the experiment, was calibrated using the farmer-type ion chamber (TM30011-1, PTW) that was calibrated at SCD 105 cm with calibration coefficient of 0.05286 GynC^{-1}. An electrometer (6517B, KEITHLEY), thermometer (LABCAL PRO, LABFACILITY), barometer (CPG2500, MENSOR), and humidity meter (RN300, DEKIST) with traceability, were used for standard calibration of the ion chamber [9-11].

The calibration factor of farmer type TM300013 in water, $N_{D,w}$, by standard calibration was 0.05400 GynC^{-1} at SCD 105 cm. The uncertainty contained systematic uncertainties such as beam homogeneity, positional reproducibility, electrometer, temperature, pressure, and humidity, as well as statistical uncertainty [9-11].

Biological effects of radiation

The dose-response curves are essential for biological dose assessment, as the number of chromosome aberrations is correlated with the irradiation

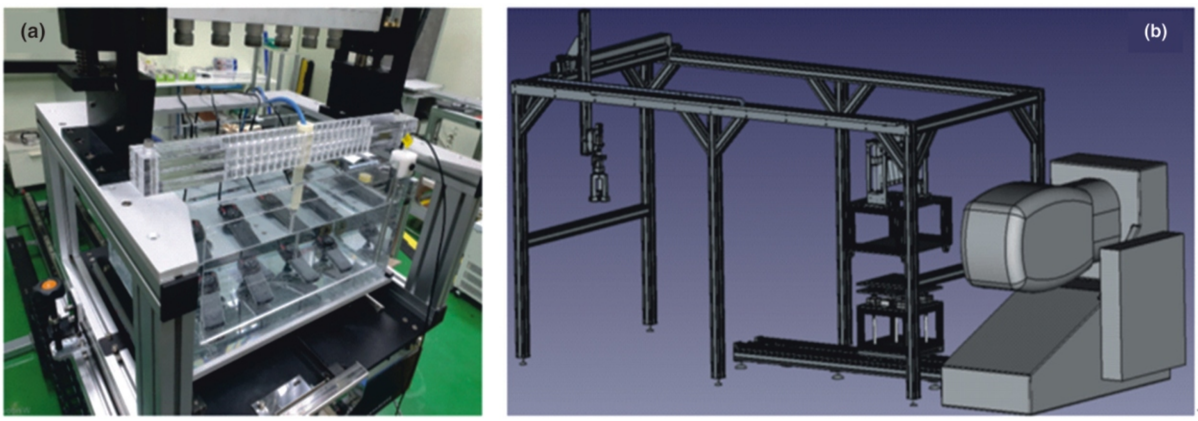

Figure 1. Irradiation system of ^{60}Co isotope for (a) experimental set-up for absorbed dose in water and (b) geometric structure of water phantom

dose [12]. Accurate dose delivery should be accompanied to obtain an accurate dose-response curve and the lymphocytes should be irradiated in vitro to replicate the *in vivo* experimental conditions. Furthermore, the blood should be exposed at least 1 m away from the source, to reduce the difference in uniformity of irradiation to less than 2 % [13]. Sinking and coagulation of blood were also considered. The blood samples were rotated during the irradiation to prevent sinking, and a water phantom, maintained at the normal human body temperature, was produced and used for the assessment of absorbed dose in this experiment. In addition, the sample mount was rotated at a constant speed for uniform irradiation. The measured absorbed dose rate to water was compared with simulated dose rate to water by using Monte Carlo simulation. Blood is made up of more than 96 % water and 4 % of other low atomic substance, so the absorbed dose of blood can be estimated measuring the absorbed dose to water.

Monte Carlo calculation

The MCNPX 2.7.0 code was used to evaluate the dose rate for Monte Carlo calculations [16]. The geometric structure of the irradiator consists of source drawer, irradiator body, head, collimator of Gammabeam X-200, and the calibration room. The effective size of the source, which contains stack of ^{60}Co pellets of 1 mm diameter, is 2 cm in height and 2 cm in diameter, with a 1.1 mm stainless steel cover in the source drawer. There is a square-shaped tungsten collimator in the beam direction from the center of the source, surrounded by a lead shield, as shown in fig. 2. We used an energy deposition tally in the MCNPX code with a directly obtained relative error from the code of less than 1 % [16]. The material information of tungsten, PMMA, water, stainless steel, *etc.* was used by compendium of material composition for the MCNPX code [17].

Figure 2 shows the vertical and lateral geometric structure of Gammabeam X-200 for Monte Carlo simulation. The values of the simulated absorbed dose rate to water, $D_{\mathrm{w,s}}$, are denoted by

$$D_{\mathrm{w,s}} \quad E_{\mathrm{d}} c_{\mathrm{f}} \varepsilon_{\gamma} \tag{1}$$

where E_{d} is the energy deposition value in Monte Carlo simulation with the unit of MeVg^{-1} per photon in the MCNPX code [16], c_{f} is the correction factor of 8.1034 10^{13} for absorbed energy to dose rate, ε_{γ} are photon emission rates of 0.9985 and 0.9999, correlated with the ^{60}Co source based on the response of 1.173 MeV and 1.333 MeV, respectively, on the date of the measurement [18].

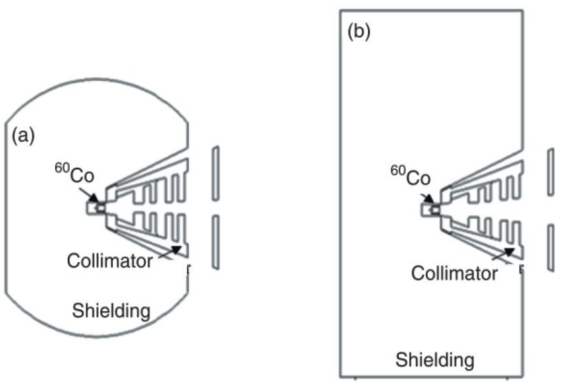

Figure 2. Geometric structure of **^{60}Co irradiator for Monte Carlo simulation for (a) vertical axis and (b) lateral axis**

RESULTS

The measured dose rate of the ion chamber was 0.2975   0.0055 Gymin^{-1} (at coverage factor $k = 2$) with the gamma field (10 cm × 25 cm at SSD of 100 cm) at a depth of 5 gcm^{-2} in the water phantom. Under similar conditions as that of the experimental set-up, the calculated dose rate from the Monte Carlo simulation was 0.2978 0.0052 Gymin^{-1} (at coverage factor $k = 2$). Results from the measurements agreed well with the simulated results. Figure 3 shows differential photon fluence at sample irradiation location by MCNPX simulation. The high photon fluence was generated by moderating the gamma rays of 1.173 MeV and 1.333 MeV from ^{60}Co to low energy region, at a depth of 5 gcm^{-2} in water phantom.

Figure 4 shows that, overall, there is a good agreement between different measurements and Monte Carlo simulations, for profiles of the lateral axis. However, there is a discrepancy in the dose rate values at the edge of the beam field due to inability to accurately retrace the position. But the discrepancy is negligible for irradiation because it is conducted at the center of the beam field.

The relative bias, B_{D}, for evaluating of the disparities between calculated and measured results was expressed as

$$B_{\mathrm{D}} \quad \frac{D_{\mathrm{w,m}} \quad D_{\mathrm{w,s}}}{D_{\mathrm{w,m}}} \tag{2}$$

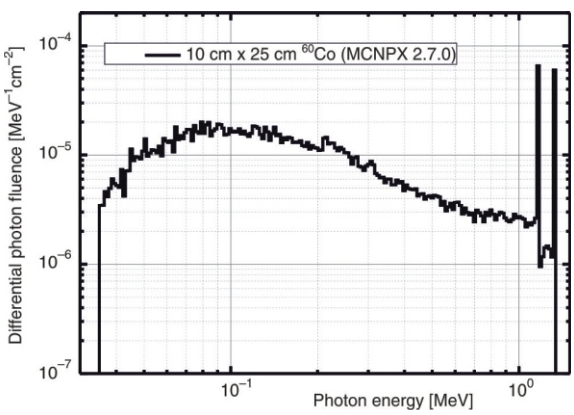

Figure 3. Differential photon fluence of ^{60}Co irradiator by Monte Carlo simulation with gamma field (10 cm × 25 cm at SSD of 100 cm) at 5 gcm^{-2} depth in the water phantom

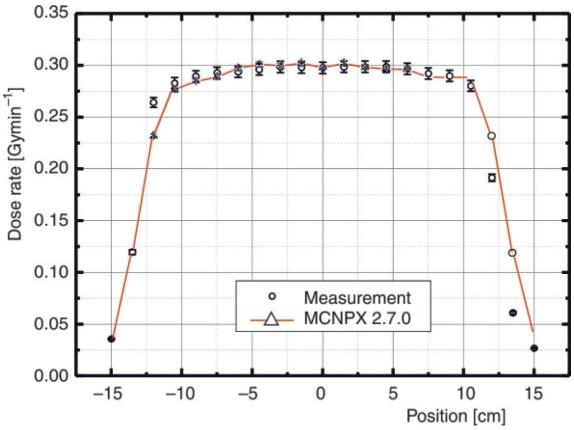

Figure 4. Comparison of lateral beam profiles for absorbed dose between measurements and Monte Carlo simulations with gamma field (10 cm × 25 cm field at SSD of 100 cm) at 5 gcm^{-2} depth in the water phantom

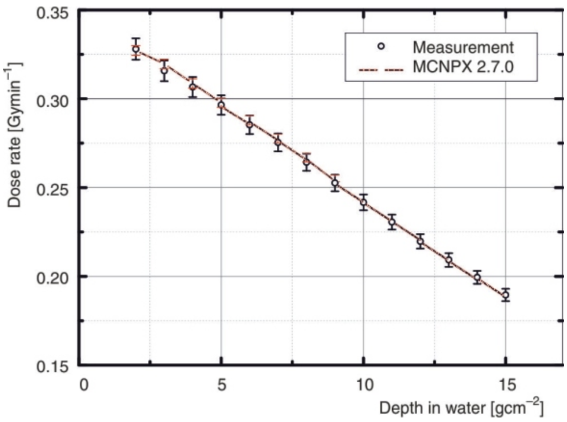

Figure 5. Comparison of depth profiles for absorbed dose between the measurements and Monte Carlo simulations with gamma field (10 cm × 25 cm field at SCD of 105 cm) in the water phantom

where $D_{w,m}$ is the measured absorbed dose rate in water and $D_{w,s}$ – the simulated absorbed dose rate in water [18, 19]. The measured and simulated depth profiles for the absorbed dose rate in water, D_w, are in good agreement, as shown in fig. 5, showing a relative bias B_D of less than –0.012. According to fig. 5, there is an approximately 3.5 % difference between the front surface (depth at 4.25 gcm^{-2}) and the back surface (depth at 5.75 gcm^{-2}) of the blood tube during the irradiation because the diameter of tube is 1.5 cm. Thus, the disparity of the total amount of dose rate was reduced by rotating the sample mount.

DISCUSSION

It is essential to accurately evaluate the amount of radiation dose delivered to the sample for assessing the biological effects of radiation. Here, we measured the dose rate of the lateral profile and the depth profile of the beam field in a water phantom. We compared the measured values with the Monte Carlo simulation, using a standard calibrated ion chamber with traceability following the IAEA TRS-398. The phantom used in this experiment was designed to maintain the temperature to 37 °C, due in order to protect chromosome aberrations in lymphocytes by thermal fluctuation, and it was rotated for reproducing the *in vivo* condition, uniform irradiation, and preventing blood coagulation and sinking during irradiation. The geometric structure of ^{60}Co source, collimator, lead shield, calibration room, and calibration rail involved with scattering on of photons, in the Monte Carlo code, was designed to closely match the real measurement set-up. Theoretical and experimental results agreed well with each other.

CONCLUSION

The objective of this study was to provide a standard method of irradiation to construct a dose-response curve of biological effect by irradiation, through precise measurement of absorbed dose to water in comparison with Monte Carlo simulation. Dose response curves, produced by precise irradiated dose, can improve the accuracy of retrospective dosimetry of radiation workers, or the public, in radiation emergencies. Based on our measured dose rate results and irradiation system, the blood samples will be irradiated with a precise dose with physical traceability. Finally, the dose-response calibration curve will be provided through further studies that additionally analyzes chromosome aberrations in lymphocytes by standard irradiation.

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AUTHORS' CONTRIBUTIONS

The idea for this study was initiated by Y-R. Kang, W-S. Jo, J-K. Kim, and Y-U. Kye. Data collection and statistical analysis were carried out by Y-J. Seo, Y-U. Kye, H-J. Kim, and J-E. Lee. Y-R. Kang supervised presented research and helped with its development that resulted in this paper. All the authors participated in the discussion of the presented results.

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МЕРЕЊЕ ЈАЧИНЕ АПСОРБОВАНЕ ДОЗЕ У ВОДЕНОМ ФАНТОМУ ОДРЖАНОМ НА ТЕЛЕСНОЈ ТЕМПЕРАТУРИ ПОМОЋУ ^{60}Co ОЗРАЧИВАЧА – ПОРЕЂЕЊЕ ЕКСПЕРИМЕНТАЛНИХ РЕЗУЛТАТА И МОНТЕ КАРЛО СИМУЛАЦИЈЕ

За анализу биолошких ефеката зрачења, важно је да се услови *in vitro* експеримената блиско поклапају са условима *in vivo* експеримената. У овом раду конструисали смо систем озрачивања за спровођење експеримената зрачењем под условима сличним онима у експериментима *in vivo*. Донгнам институт радиолошких и медицинских наука има гама озрачивач који укључује ^{60}Co радиоизотоп за истраживачке сврхе и акредитацију стандардне калибрације јонске коморе. Температура воденог фантома одржавана је на температури нормалног људског тела, а физичка дозиметрија спроведена је прецизно коришћењем јонске коморе са праћењем процеса. Овде извештавамо о мерењу бочних профила, профила по дубини и јачини апсорбоване дозе у води, а на локацији зрачења, узорака крви помоћу јонске коморе фармер-типа. Симулирали смо извор, колиматор, озрачивач, фантом и посебну структуру система гама зрачења користећи Монте Карло код и упоредили симулиране и експерименталне резултате. Експериментално и теоријски процењене јачине дозе биле су 0,2975 0,0055 Gy min^{-1} (при фактору покривености к = 2) и 0,2978 0,0052 Gy min^{-1} (при фактору покривености к = 2), на удаљености од извора до површине од 100 cm и 5 gcm^{-2} дубине у воденом фантому, респективно. Зрачење крви биће спроведено *in vitro*, под условима сличним условима *in vivo*, да би се обезбедила крива доза-одзив заснована на дозиметрији са праћењем процеса.

Кључне речи: айсорбована доза, водени фантом, зрачење крви, сшандардна калибрација, MCNPX код