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Evaluation of radiation exposure in Ir-192 brachytherapy for treatment of keloids

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Abstract

Nippon Medical School Hospital recently developed a high dose rate superficial brachytherapy (HDR-SBT) for keloids, which has been carried out since 2008. In this treatment, Ir-192 sources are placed on the affected area through flexible tubes, which has the advantage of providing high dose concentration to complicated shapes. Obviously, unnecessary radiation exposure to high-energy gamma rays must be reduced for vital organs around the affected area. We have developed a system which can evaluate the radiation exposure of tissues and organs in a MIRD-5 phantom using the PHITS Monte Carlo code when the prescribed dose was delivered uniformly to a flat surface based on the actual geometry in HDR-SBT. In the PHITS simulation, an affected area was assumed on the chest of the MIRD-5 phantom, then the dwell time at each dwell position was optimized to deliver 6 Gy uniformly over the affected area in the actual geometry with the lead shields and the bolus. In addition, the radiation exposures of each tissue and organ in the MIRD-5 phantom during the irradiation were calculated. The biologically equivalent dose of the thymus was the highest at 1145.60 mGy followed by the heart at 236.14 mGy and the breasts at 95.32 mGy.

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Keywords: Brachytherapy; Keloid; Radiation exposure; Monte Carlo simulation

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1. Introduction

Keloids are overgrowths of scar tissue because fibroblasts produce excessive collagen fiber due to continuous inflammation in the process in which injured skin is healed. Although keloids are benign tumors of the dermis, they extend beyond the borders of the original wound with pain, pruritus and cosmetic disfigurement as they grow, and therefore surgical excision (keloidectomy) with postoperative radiotherapy to prevent recurrence is selected as an efficient treatment for keloids [1]. Electron beam radiotherapy (EBT) has been widely performed as a postoperative radiotherapy after keloidectomy. However, it is difficult to deliver a uniform dose to affected areas with complicated shapes or curved surfaces because the beam shaping and collimation cones are fixed in EBT.

EBT is used in the Nippon Medical School Hospital as a postoperative radiotherapy and a high dose rate superficial brachytherapy (HDR-SBT) has been employed since 2008 using a remote afterloading device with an iridium-192 (Ir-192) source in order to solve the difficulty mentioned above. Because the encapsulated Ir-192 radioisotope is fixed close to the affected area through catheters and an applicator in HDR-SBT, HDR-SBT excels in dose concentration and has the advantage that it can deliver the prescribed dose more uniformly during the irradiation while keeping a constant distance from skin surface by using the flexible applicator and catheters.

Although HDR-SBT after keloidectomy has delivered satisfactory clinical results, extra radiation exposure for at risk organs near the affected area is a concern because high energy gamma ray reaches deeper compared with an electron beam of 4-6 MeV as used in ERT [2]. In this study, an evaluation system for irradiation plan was established to deliver the prescribed dose uniformly over the flat affected area, and radiation exposures to tissue, organs and whole body were estimated using the PHITS Monte Carlo code.

2. Brachytherapy

2.1. Ir-192 radiation source

The mHDR-v2r Ir-192 brachytherapy source (Mallinckrodt Medical B.V.) stored inside the microSelectron HDR-v3 remote afterloading device (Nucletron Technologies GmbH) has been used at the Nippon Medical School Hospital. The Ir-192 source has a source strength directional dependence because its active core consists of a pure iridium metal cylinder and it is encapsulated with stainless steel.

2.2. Applicator for superficial irradiation

Various applicators for superficial irradiation are widely used in HDR-SBT. For skin, the Freiburg Flap Applicator (Nucletron Technologies GmbH) has been used as the specialized applicator for HDR-SBT in Nippon Medical School hospital. Fig. 1 shows a photograph of the Freiburg Flap Applicator. The Freiburg Flap Applicator is a flexible mesh style applicator composed of many silicon rubber beads (diameter 1 cm, density 1.12 g/cm³) arrayed in a plane, and the center of each bead has a hole which enables catheter insertion to transfer the Ir-192 source. The Ir-192 source travels through each catheter, and it stops in 1 cm steps at the centre of beads called “dwell positions” for respective optimized time. This applicator size is 24 cm × 24 cm, and it can be cut to any size depending on the desired irradiation area.

Fig. 1 (a) The design of Freiburg Flap Applicator; (b) The patient's actual treatment in HDR-SBT.
2.3. Irradiation method in HDR-SBT

Keloids occur most frequently on areas where skin tension is the highest (i.e., shoulders, chest, neck, upper arms, earlobes and cheeks, etc.) [3]. An example irradiation setup for a chest keloid is shown in Fig. 2. HDR-SBT has various irradiation geometries depending on the shape and size of the affected areas. The applicator is fixed directly on the affected area, and a 0.5 cm bolus (CIVCO Medical Solutions) made of tissue equivalent material (density 1.03 g/cm³) is placed on the applicator to adhere tightly. Lead shields of 0.5 cm-thickness and 5.5 cm-height are placed 1 cm away from the end of the applicator on three sides of the applicator, except for the direction of the connection part between catheters and transfer tubes.

3. Calculation method

3.1. Monte Carlo simulation

Monte Carlo codes for particle transport simulation (i.e., MCNP, GEANT4, EGS5 and PHITS, etc.) have been widely used to evaluate absorbed dose distributions of Ir-192 sources [4,5,6]. The Particle and Heavy Ion Transport code System (PHITS) version 2.85, which was used in this study, is a general-purpose Monte Carlo code developed mainly in Japan through a collaboration between JAEA, RIST and KEK. PHITS has been used in the fields of accelerator technology, radiotherapy, space radiation, and in many other fields, because it can analyze dosimetric behavior of various particles (i.e., electron, photon, neutron and proton, etc.) over a wide energy range in three dimensional modeling systems [7]. From ver.2.76, the electron and photon transport algorithm based on EGS5 (Electron Gamma Shower Version 5), so-called EGS5 mode, was incorporated into the PHITS code. In this work, the absorbed dose was calculated using the EGS5 mode in the PHITS simulation [8].

For the Ir-192 source geometry, the design of the mHDR-v2r source as described by Granero et al. [9] was used in the PHITS simulation. In addition, for beta rays and gamma rays released from the Ir-192 source, various energies and their emission probabilities [10] were taken into account in the simulation. We considered the Ir-192 source activity as 370 GBq which is the standard radioactivity in this study.

Computational human phantoms, which can be compiled by the Monte Carlo code, have been used to evaluate the absorbed dose to tissue and organs of the body in the internal radiation dosimetry. There are two types of computational phantoms, which are a stylized phantom and a voxel phantom. For a stylized phantom, the size and form of a body and organs are described by combinations of expressions representing simple mathematical equations of analytical geometry such as spheres, circular cylinders, ellipsoid etc. On the other hand, a voxel phantom consists of digital images based on scanning of real persons by computed tomography or magnetic resonance imaging.

Because simulation using a voxel phantom requires huge voxel data, computer memory and calculation time [11], a numerical phantom proposed by the Commission on Medical Internal Radiation Dose (MIRD), the MIRD-5 phantom, was used in this study. The MIRD-5 phantom was developed as a partially hermaphroditic adult stylized numerical phantom by Snyder at the Oak Ridge National Laboratory in 1969 [12]. It is composed of skeleton, a pair of lungs, and soft tissue, and the body intended to represent a healthy-average adult male, which is 73 kg in weight and 174 cm in height, defined by the International Commission on Radiological Protection (ICRP). However, oral mucosa and salivary glands are not defined in MIRD-5 phantom, then we defined them based on anatomical structures. Figs. 3 and 4 show the cross sectional views of the MIRD-5 phantom.
In this study, an affected area of 4 cm x 4 cm was assumed on the chest of MIRD-5 phantom after keloidectomy. Therefore, the radiation source area was defined as 5 cm x 5 cm, as shown in Fig. 2, because we used the Freiburg Flap Applicator (5 cm x 24 cm) which enables the Ir-192 source to be placed directly on the edges of the affected area for sufficient irradiation. The centre of the (x, z) coordinate in the radiation field was (0, 55). The total prescribed dose in HDR-SBT for keloids is 18 Gy (6 Gy per fraction) at the reference depth of 2.0 mm under patient’s skin in Nippon Medical School hospital. Therefore, the absorbed dose distribution at a depth between 2.0-2.1 mm under the patient’s skin was simulated using the PHITS for the Ir-192 point source located at the centre of the coordinate without lead shields. The size of the dose estimation tallies is a 1-cm grid of the (x, z) coordinate and the 81 tally grids are located over an area of 9 cm x 9 cm to estimate the dose also in the farther area. This simulation result was used for an estimation of the appropriate dwell time at each dwell position as described in Section 3.2. On the other hand, to evaluate the absorbed dose rate of each organ and tissue in Section 3.3, PHITS simulations with lead shields were performed for 25 different dwell positions of the Ir-192 source. To get good statistics in a realistic time, we set the number of histories to $10^7$ source gamma-rays in the simulation, and the statistical errors of calculated absorbed dose were approximately 1-2 % near the source and 3-4% in tallies at the edge.

![Fig. 3 Anatomical coronal view of MIRD-5 phantom (y = 1cm).](image)

![Fig. 4 Anatomical axial view of MIRD-5 phantom (z = 53cm). The body is facing in the negative y-axis direction in this case.](image)

### 3.2. Optimization of dwell time

The radioactive Ir-192 source, which has a half-life is 73.83 days, is renewed every 4 months to keep the irradiation time within the limits required by clinical practice at Nippon Medical School hospital. For a 4 month old Ir-192 source, the actual treatment irradiation time is under 15 minutes to deliver 6 Gy uniformly to the affected area. If the total time of the irradiation is 15 minutes, decrease of radioactivity of the Ir-192 source is 0.01 %. Therefore, radioactivity decrease due to the decay during irradiation was neglected in this study.

As mentioned in Section 3.1, the 81 tally grids over an area of 9 cm x 9 cm were defined to evaluate the absorbed dose in an area larger than the actual source area of 5 cm x 5 cm. Since the two-dimensional spatial distributions of absorbed dose due to different source positions are considered to be relatively similar, the simulation result performed with the point source at the centre can be copied to the other source positions with different contribution factors which are proportional to the dwell time in this case. Using this assumption, an algorithm was developed to optimize the dwell time at each dwell position to deliver a uniform dose (6 Gy) to the affected area.
which was included in the 25 tally grids (5 cm x 5 cm area) in the central square inside the area of 9 cm x 9 cm. First of all, the absorbed doses at each of the 25 tally grids were sequentially summed up for the all 25 dwell positions with 1 sec as an initial dwell time. The algorithm then finds the tally grid with the lowest absorbed dose in the summed data and the distribution for a 0.1 sec contribution of the corresponding source position is added to the summed distribution. 0.1 sec is the minimum acceptable unit in the remote afterloading device. This process repeats until the difference in absorbed dose between the highest and the lowest positions is less than 0.01% of the lowest value where the optimized dwell times at each position converge to the same values. Finally, the lowest absorbed dose over the 25 tally grids is normalized to 6 Gy and a set of optimized dwell times for the 25 source position was obtained.

3.3. Evaluation of the radiation exposure to tissue and organs

Based on the optimized dwell times described above, the radiation exposures of each tissue and organ in the MIRD-5 phantom during the irradiation were then calculated. Each absorbed dose distribution simulated for the 25 dwell positions described in Section 3.1 is multiplied by the respective dwell time calculated in Section 3.2, and all of them are summed up. The relative biological effectiveness (RBE) was used to consider the biological effects of different types of radiation, which is defined as 1.0 for beta rays and gamma rays. Finally, the biologically equivalent dose (Gy) is given by the physical dose (Gy) multiplied by the RBE factor.

Furthermore, we adopted the estimation method of effective dose in ICRP Publication 103 [13] to evaluate the radiation exposure of the whole body. Since the concept of effective dose is a radiological protection quantity defined for uniform irradiation, it is not appropriate to use effective dose to evaluate the radiation exposure for a locally irradiated medical situation. However, since there is no other quantity which can evaluate the radiation exposure of whole body whilst taking the relative risk of each tissue and organ into account, it was evaluated in the same way as the effective dose in this study. The radiation weighting factor (wR) is a multiplicative factor used for a radiological protection to account for the biological effects between different types of radiation, which is defined as 1.0 for beta rays and gamma rays in ICRP Publication 103. Therefore, the equivalent dose (Sv) is given by the physical dose (Gy) multiplied by the wR factor, then the radiation exposure of the whole body is calculated by summing individual organ equivalent doses multiplying the tissue weighting factor (wT) specific for each organ.

Table 1 shows the tissue weighting factors (wT) in ICRP Publication 103. The Extra thoracic (ET) region and lymphatic nodes were excluded in this study because it was impossible to define them in the MIRD-5 phantom. The colon consists of the ascending colon, transverse colon, descending colon and sigmoid colon, and the absorbed dose of the colon (D_{colon}) was calculated using Equation 1 in ICRP Publication 67 [14]. The average absorbed dose of the ascending colon and transverse colon was defined as the dose in the upper part of the colon (D_{ULI}), and that of descending colon and sigmoid colon was also defined as the dose in the lower part of the colon (D_{LLI}). In addition, the absorbed dose of bone surface and red marrow were calculated by multiplying the absorbed dose of individual bone with the respective mass ratio of bone surface and red marrow cited from ICRP Publication 110 [15].

\[ D = 0.57 \times D_{ULI} + 0.43 \times D_{LLI} \]  

(1)

<table>
<thead>
<tr>
<th>Organ</th>
<th>Tissue weighting factor wT</th>
<th>( \sum w_T )</th>
</tr>
</thead>
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<tr>
<td>Red bone marrow, Colon, Lung, Stomach, Breasts, Remainder tissues*</td>
<td>0.12</td>
<td>0.72</td>
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<tr>
<td>Gonads</td>
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<td>0.08</td>
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<tr>
<td>Bladder, Esophagus, Liver, Thyroid</td>
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<td>0.16</td>
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<tr>
<td>Bone surface, Brain, Salivary glands, Skin</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1.00</td>
</tr>
</tbody>
</table>

* Remainder tissues: Adrenals, Extra thoracic region, Gall bladder, Heart, Kidneys, Lymphatic nodes, Muscle, Oral mucosa, Pancreas, Prostate, Small intestine, Spleen, Thymus, Uterus cervix.

4. Results and Discussion

Fig. 5 shows the absorbed dose distribution at the reference depth of 2.0 mm for the Ir-192 point source simulated by the PHITS. The dose distribution has a three-dimensional spatial distribution which attenuates with the
distance from the source. Table 2 shows the dwell times in each dwell position to deliver 6 Gy uniformly to the affected area. The dwell times became longer at greater distance from the center because the total contribution from each source position was smaller. Fig. 6 shows the absorbed dose distribution with a 1-cm grid calculated by considering the optimized dwell times shown in Table 2. The absorbed dose distribution in the 5cm x 5cm region which includes the affected area ranged from 99.1% to 100.3% of 6 Gy, which indicated that the optimization process in this study has successfully met the treatment requirement. Since the actual irradiation to the affected area is performed at each dwell position by 1 cm steps in SBT using the Freiburg Flap Applicator, we evaluated the absorbed dose distribution with a 1-cm grid in the optimization of dwell time. However, since the smaller grid size can generally yield a more accurate dose distribution, figs. 7 and 8 show more detailed two-dimensional absorbed dose distributions with a 0.25-cm grid considering the dwell times in the horizontal and vertical planes, respectively, in the MIRD-5 phantom simulated by the PHITS Monte Carlo code.

Fig. 5 Absorbed dose distribution for the point source at the centre. Fig. 6 Absorbed dose distribution summed up with all dwell sources.

Table 2. Dwell time in each source dwell positions (sec).

<table>
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<tr>
<th>z-axis position</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
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<td>6.7</td>
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<tr>
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<td>8.6</td>
<td>1.6</td>
<td>3.8</td>
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<td>8.6</td>
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<tr>
<td>53</td>
<td>19.2</td>
<td>8.5</td>
<td>11.7</td>
<td>8.7</td>
<td>19.1</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
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<td>221.7</td>
</tr>
</tbody>
</table>

Fig. 7 Horizontal plane view of absorbed dose distribution in MIRD-5 phantom simulated by PHITS. Fig. 8 Vertical plane view of absorbed dose distribution in MIRD-5 phantom simulated by PHITS.

Table 3 shows the radiation exposure of tissue and organs in the MIRD-5 phantom in the irradiation calculated as the biologically equivalent dose. The radiation exposures of the whole body were 41.39 (mSv) and 51.29 (mSv)
for the male and female phantoms, respectively. The biologically equivalent dose of the thymus was the highest at 1145.60 (mGy) followed by the heart at 236.14 (mGy) and the breasts at 95.32 (mGy) because they are located close to the radiation source.

Lead shielding is usually used to reduce direct radiation to the healthy tissue and the organs around the affected area in HDR-SBT. However, for the organs located directly under the radiation source such as thymus and heart, it is difficult to reduce the radiation exposure because the radiation is emitted into the patient’s body directly without shielding. Therefore, it is important to evaluate the radiation exposure of these at risk organs under the radiation source, and an oncologist has to judge whether HDR-SBT is suitable for a patient.

Table 3 shows the radiation exposure of tissue and organs in the irradiation calculated as the biologically equivalent dose. The radiation exposures of the whole body were 41.39 (mSv) and 51.29 (mSv) for the male and female phantoms, respectively. The biologically equivalent dose of the thymus was the highest at 1145.60 (mGy) followed by the heart at 236.14 (mGy) and the breasts at 95.32 (mGy) because they are located close to the radiation source.

We developed a system which can evaluate the radiation exposure of tissues and organs in a MIRD-5 phantom when the prescribed dose was delivered uniformly to a flat surface based on the actual geometry in HDR-SBT by using the PHITS Monte Carlo code. This system is useful for the evaluation of radiation exposure in HDR-SBT with flat body parts such as the chest and back, and is also useful for analysis of the optimal shielding geometry to reduce the radiation exposure.

Although keloids can be occurred anywhere in the human body and this evaluation system is limited to the flat surfaces, we plan to extend the system to the evaluation of curved surfaces in the future.

Acknowledgements

We would like to thank Mr. Saito for useful discussions and technical advices in programming.

5. Conclusion

Although keloids can be occurred anywhere in the human body and this evaluation system is limited to the flat surfaces, we plan to extend the system to the evaluation of curved surfaces in the future.
References


Here introduce the paper, and put a nomenclature if necessary, in a box with the same font size as the rest of the paper. The paragraphs continue from here and are only separated by headings, subheadings, images and formulae. The section headings are arranged by numbers, bold and 10 pt. Here follows further instructions for authors.