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On the Use Factor Analysis and Adequacy Evaluation of CyberKnife Shielding Design Using Clinical Data

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Although the current internationally recommended standard for the use factor (U) applied to CyberKnife is 0.05 (5%), the CyberKnife shielding standard is applied more stringently. This study, based on clinical data, was aimed at examining the appropriateness of existing shielding guidelines. Sixty patients treated with G4 CyberKnife were selected. The patients were divided into two groups, according to whether they underwent skull or spine tracking. Based on the results, the use factors for each wall ranged from 0.028 (2.8%) to 0.031 (3.1%) for the intracranial treatment and 0.020 (2.0%) to 0.022 (2.2%) for the body treatment. Excessive barrier thickness resulted in inefficient use of space and higher cost to the institutions. Furthermore, because the use factor is influenced by the position of the robot, the use factor determined based on the clinical data of this study would facilitate more reasonable treatment room design.

Keywords: Radiation protection, Radiation shielding design, G4 CyberKnife, Use factor

Introduction

Recent developments in treatment technology have enabled high energy radiation therapy using higher than 15 MV to become a common tumor treatment method along with surgery and chemotherapy. Intensity Modulated Radiation Therapy (IMRT), Image-Guided Radiation Therapy (IGRT), CyberKnife (Accuray Inc., Sunnyvale, CA, USA), Novalis (Varian Medical System Inc., Palo Alto, CA, USA), and Tomotherapy (Accuray Inc., Sunnyvale, CA, USA), have been developed, where the exit window of the radiation is extended to the entire space in the treatment room. Furthermore, the overdose is 5 to 10 times higher than that of conventional methods. While high energy radiation therapy is highly effective for tumor treatment, it poses considerable risks to workers, patient caregivers, and the

general public owing to radiation scattering and leakage. Thus, adequate shielding design of treatment facilities using high-energy radiation is required to mitigate such risks, which are strictly regulated by law in every country.^{1,2,4)}

CyberKnife is a machine for hypo-fractionated stereotactic radiotherapy; it irradiates a high dose in one to five treatment fractions and requires high accuracy in patient set-up and radiation delivery. The robot based G4 CyberKnife system is distinguished from conventional radiotherapy equipment by the design of the treatment room. Unlike the gantry based linear accelerator, which transmits cross-sectional radiation through the isocenter, CyberKnife delivers a 6 MV non-coplanar pencil beam around the target over a wide solid angle.³⁾ As a result, CyberKnife requires more barrier than conventional radiotherapy, when using equivalent energy. The NCRP 151 report recom-

mends that because devices capable of rotation, such as CyberKnife, deliver the beam at various angles, the primary beam should be shielded against all the shielding walls surrounding the treatment room.⁴⁾

Use factor (U) is the fraction of a primary beam workload that is directed toward a given primary barrier. The value for use factor will depend on the type of radiation installation. With SRS and SBRT, high individual absorbed doses are delivered to patients and therefore both the primary and secondary barrier workloads can be greater than in the standard case. Likewise, multiple, oblique angles are used and this can skew assumptions about the use factors for the barriers if they were not explicitly considered in the design. Although the maximum shielding of use factor (U)=1 (100%) is unnecessary, it would be safe to apply the maximum shielding in case the device could be used for fixed irradiation.^{1,2)} The use factor for a rotating irradiation equipment can be determined by considering the ratio of the time used for the rotating irradiation of the equipment and the direction of the beam. Because a narrow beam is delivered into various directions in CyberKnife, it is common to apply a low use factor in calculating the annual dose rate of the primary shielding wall.⁸⁻¹⁰⁾ Recently, Henzen D⁵⁾ published results related to the radiation protection of the M6 CyberKnife and the effect of CyberKnife shielding with MLC (Multi Leaf Collimator).

In the recommended standards, the use factor is 0.05 (5%), which is useful in the shielding design for rotating

therapy equipment and more stringent than that for the conventional radiotherapy equipment.⁴⁾ Thus, the radiation shielding facilities of high energy therapy equipment such as CyberKnife should be precisely and strictly regulated and supervised. However, the highest level of shielding is an important factor determining the material type and thickness of the shielding wall, and particularly, the increase in the thickness of the shielding wall in the radiation shielding system significantly influences the increase in the cost of the institution. Accordingly, the design of the radiation treatment room should be adapted to each treatment equipment and installation site. Therefore, this study was aimed at analyzing the use factor of each direction in the treatment room based on the clinical data of patients who were treated with G4 CyberKnife in this hospital and further investigating the appropriateness of the current CyberKnife shielding guidelines.

Materials and Methods

1. Shielding guidelines

Fig. 1 presents an inside view of the bunker where the G4 CyberKnife robot is installed on the right side of the couch. The bunker size of our institution is $6.1 \times 7.4 \text{ m}^2$, and the height from the ceiling to the floor is 3.7 m. A few of the features to be considered when designing a CyberKnife shielding system are covered in the CyberKnife shielding

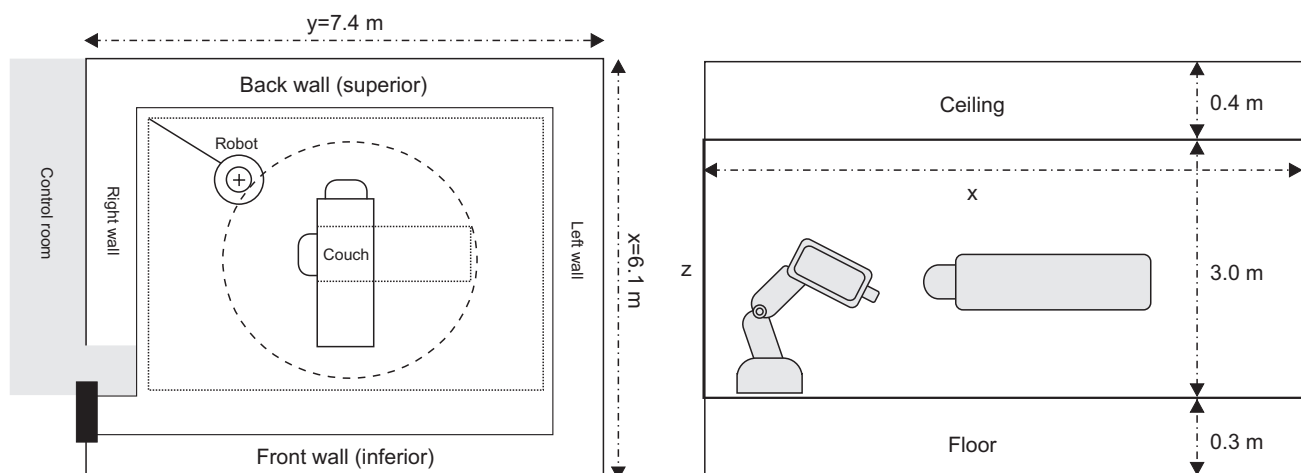


Fig. 1. G4 CyberKnife treatment room coordinate system. Draw of the CyberKnife treatment room with indicated dimensions and coordinate system.

guidelines.^{4,6,7)} The design guidelines for the CyberKnife shielding facility that are described in the report on radiation protection and shielding provided by the National Council on Radiation Protection and Measurements (NCRP Report 151), reports provided by the CyberKnife manufacturer, and books related to CyberKnife shielding design. NCRP 151 report is one of the standard guidelines for shielding design.⁴⁾ A “CyberKnife Treatment Room Design & Radiation Protection” published in 2005, is the first book on CyberKnife shielding and has been used as a guide for defining the shielding concept to date.⁷⁾ These two guidelines have been used to measure primary workload and use factor based on CyberKnife clinical data from Georgetown University.⁸⁾ The shielding white paper provided by Accuray®, the CyberKnife manufacturer, collected clinical data from several institutions to report leakage doses and secondary shielding requirements.⁶⁾ The above guidelines recommend that equal use factor values should be applied to all the walls in a treatment room. The internationally recommended criteria for CyberKnife use factor value are currently limited to 0.05 (5%) because the largest number of beam MUs originating from one node is approximately 0.05 (5%) of the total number of MU.¹⁰⁾

2. Patient selection

Sixty patients who underwent intracranial and body treatment were selected from among 280 patients treated with CyberKnife in this hospital from February 2016 to March 2017. According to the tracking type, the selected patients were divided into two groups of 30 individuals each: skull tracking and spine tracking. The CyberKnife model was G4 with the version 9.5, and the software was of version 4.5. Up to four fixed collimators and iris collimators, forming beams with diameters from 7.5 mm to 35 mm were selectively used for patient treatment. The treatment plan was designed using a one path head mode with approximately 120 nodes and a one path body mode with approximately 90 nodes. But in this study, prostate cases that do not use one path bodies during the body treatment were excluded.

3. Robot coordinate acquisition and data analysis

This study extracts the path data from the beam data of actual treatment patients to obtain the robot log file. The coordinates of the points symmetric to the coordinates of the beam irradiated in the three dimensional space and each wall of the treatment room (front wall, back wall, left wall, right wall, ceiling, and floor), were obtained using the coordinate transformation equations. A composite function method was used to perform rotational transformation about two axes in three dimensional space. The rotation of the robot is represented by a quaternion. A quaternion is a method of describing rotation using rotation vectors and angles. A robot rotation is a rotation about a single coordinate axis.¹²⁻¹⁴⁾ Enumerating the x -, y -, and z -axis with 1,2,3, the coordinate rotations, for $i \in \{1,2,3\}$, are

$$R_1(\alpha) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & \sin(\alpha) \\ 0 & -\sin(\alpha) & \cos(\alpha) \end{bmatrix} \quad (1)$$

$$R_2(\alpha) = \begin{bmatrix} \cos(\alpha) & 0 & -\sin(\alpha) \\ 0 & 1 & 0 \\ \sin(\alpha) & 0 & \cos(\alpha) \end{bmatrix} \quad (2)$$

$$R_3(\alpha) = \begin{bmatrix} \cos(\alpha) & \sin(\alpha) & 0 \\ -\sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3)$$

The calculated data were reproduced in the treatment room by using the analytical software (OriginLab, ver. 9.1, MA, USA). To obtain the coordinate values represented by three numerical values (x, y, z) for any vector in the treatment room, a reference coordinate system must be defined; a reference coordinate system consists of three orthogonal unit vectors consistent with the origin.

A robot coordinate rotation of this form is illustrated in Fig. 2, which shows a rotation about the z -axis by an angle α . Fig. 2 shows the variation between the two coordinate systems when the two base vectors of the m coordinate system are rotated by θ with respect to the x -axis of the i and m coordinate systems that were initially matched with different reference axes of rotation. R denotes an arbitrary

vector, and this coordinate value is represented by R^i and R^m for the i and m coordinate systems, respectively. The coordinate values R^i and R^m , which are the coordinate values for the vector R in the two coordinate systems, satisfy the following equations. As the number of three-dimensional vectors that can be reproduced in three-dimensional space is very broad, the beam intensity formed on the walls of the treatment room were analyzed by designating the beams irradiated onto each wall of the treatment room as hot zone.^{14,15)}

Results

1. Patient characteristics and data analysis

Fig. 3 presents the results of the analysis of beam data for 60 patients with 30 patients for each tracking mode. In this study, the prescribed iso-dose lines of intracranial and

body treatments are mostly concentrated in the 75%~80%, and the treatment plans were established after selecting from 70%~85% depending on the tumor's location, size and prescription dose. The average prescribed dose for intracranial patients was 2,301 cGy with an average maximum dose of 2,876 cGy, treatment sessions divided into an average of 1.9 times, and an average total MU of 18,163. The average number of beams used in the intracranial treatments was approximately 147, and the fixed and iris collimators were used with collimator size of 7.5 mm to 20 mm. The mean prescription dose and the maximum dose for the patients under body treatment were 3,460 cGy and 4,438 cGy, respectively, and their treatment sessions were divided into 3.63 times on average, where the dose delivered was 1,221 cGy per session. The average number of beams was 166.6, and the average total MU was 47,942 (Table 1).

Table 1. Characteristics of CyberKnife clinical workload data.

Treatment site	Intracranial	Body
# of case	30	30
Tracking type	Skull tracking	Spine tracking
Avg. prescribed treatment dose (cGy)	2,301.33	3,460.00
Avg. maximum dose (cGy)	2,876.72	4,438.33
Prescribed iso-dose line (%)	80.23	77.60
Avg. # of fractions per treatment	1.90	3.63
Avg. total treatment MU	18,163.5	47,942.46
Avg. Gy per fractions	12.11	9.53
Avg. MU/fractions	9,559.74	13,207.29
Avg. MU/cGy	7.89	13.86
Avg. # of beams	147.20	166.63
Collimator size (mm)	7.5~20	7.5~35

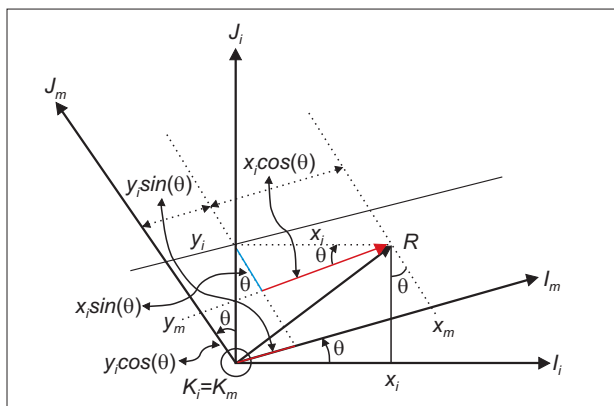


Fig. 2. Unit coordinate transformation through rotation by θ about z axis.

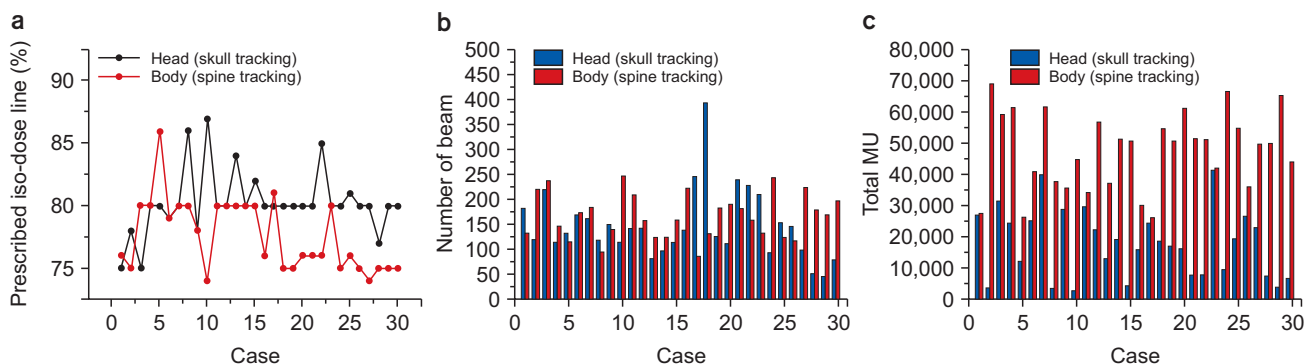


Fig. 3. The history of prescribed iso-dose line (a), the number of beam (b) and total MU of patients (c).

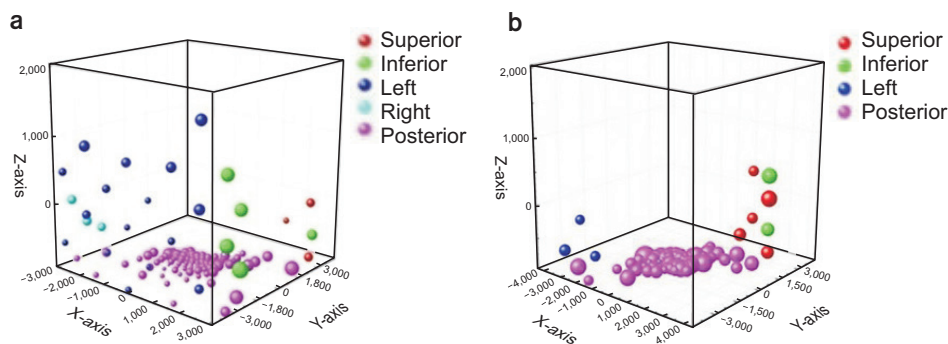


Fig. 4. The projection of radiation beams for each tracking mode in CyberKnife, (a) skull tracking-beam intensity, (b) spine tracking-beam intensity (Superior: Front wall, Inferior: Back wall, Anterior: Ceiling, Posterior: Floor).

Table 2. The analysis of MU and use factor (U) for each projection in CyberKnife treatment room.

Direction	Intracranial (skull tracking)		Body (spine tracking)	
	MU of hot zone	Use factor	MU of hot zone	Use factor
Superior (Back wall)	0.5%	0.031 (3.1%)	0.3%	0.020 (2.0%)
Inferior (Front wall)	0.6%	0.030 (3.0%)	0.5%	0.020 (2.0%)
Left	3.3%	0.031 (3.1%)	0.6%	0.022 (2.2%)
Right	0.2%	0.028 (2.8%)	0.1%	-
Anterior (Ceiling)	-	-	-	-
Posterior (Floor)	75.3%	0.031 (3.1%)	89.0%	0.022 (2.2%)

2. Use factor analysis using clinical data

This study analyzed the beam data for patients who were actually treated according to the tracking methods of CyberKnife, to investigate the use factor of beams irradiated in each direction in the treatment room. In both the intracranial and body treatments, the fraction of the beam distributed at the bottom of the treatment room was the highest, that is 75% and 89% (average 82%) of the total beam for intracranial and body treatment. The fraction of the beam directed to the ceiling was negligible. The average fraction of the beams directed to the front and back walls of the periphery were 3% and 4%, respectively. In the skull tracking mode, the average fraction of the beam distribution on the left and right (with respect to the couch) walls were 8.5% and 4%, respectively (Fig. 4).

Table 2 presents the results of the analysis of the MU of each projection and use factors according to each direction of the beams distributed in the treatment room. MU analysis results for the effective beam in intracranial and

body treatments using the skull tracking are summarized in Table 2. MU for the treatment room's front and back walls received 0.3% to 0.6% of the total MU, and the right wall, where the robot is located, displayed lower MU values than the left wall. For head treatment, the use factors in the directions of the front wall, back wall, left wall, right wall, and floor are 0.031 (3.1%), 0.030 (3.0%), 0.031 (3.1%), 0.028 (2.8%), and 0.031 (3.1%), respectively. The use factor in the direction of the ceiling was not verified because of the absence of effective beam. For body treatment, the use factor values in the directions of the front wall, back wall, left wall, and floor were 0.020 (2.0%), 0.020 (2.0%), 0.022 (2.2%), and 0.022 (2.2%), respectively. As in the head treatment, there was no effective beam in the direction of the ceiling; moreover, an effective beam toward the right wall direction with respect to the couch could not be identified. According to the result of this study, the CyberKnife use factor average value was approximately 0.025 (2.5%), which is marginally lower than the recommended standard of 0.05 (5%).

Discussion

This study analyzed the use factor by using the clinical data of actual G4 CyberKnife treated patients to verify the appropriateness of the shielding guidelines currently applied to CyberKnife. The radiation to be considered when designing the shielding system includes the primary beam, leakage beam, and scattered beam. The primary beam is the radiation emitted from the exit window of the linear accelerator, and the direction of the used beam includes all the internal area that ranges from the collimator to the source when the collimator is completely opened. The leakage beam is the radiation transmitted through the con-

ventional radiotherapy head ; all radiation therapy equipment is designed and manufactured following guidelines in order to maintain a dose rate less than or equal to 10^5 of the dose rate for the primary beam. The scattered beam is the radiation that is scattered when the primary radiation or the leakage radiation collides with the patient, couch, as well as the ceiling, floor, and walls of the treatment room. The scattering rate changes depending on the collision area, energy, and scattering angle of the radiation.²⁾

Yang J¹⁰⁾ analyzed the accumulated clinical data using G4 CyberKnife, an identical model to this study. They assumed the source position, targeting position, the direction of beam, etc., and compared it to the international shielding guideline using the analyzed data program. However, Yang J did not explain specifically about how to extract robot coordinate through the beam data. Accordingly, this paper, not using the program but using coordinates equation alone through the beam data extracted from log file of the clinical data, attempted to study whether the direction of G4 CyberKnife robot beam and an analysis of MU/cGy are possible. As a result, it could be identified that the use of the beam data extracted from the clinical data facilitates the analysis of the beam direction and MU/cGy according to each direction. When this study was compared to the results of Yang J, it was identified that when a treatment planning was established, there were differences in MU/cGy value according to dose, fraction and MU/cGy, but beam direction according to treatment area showed similar result. Also, it can be identified that comparing this study to the article such as Yang J showed that the installation robot was an additional factor to determine the direction of effective beam. And it is thought that if the data of diverse institutions are accumulated, they could be the data to use for the design of CyberKnife shielding rooms later, because the shielding room size, shielding type, CyberKnife robot version, etc. of each institution are not identical.

In this study, according to the tracking types, the use factors were 0.025 (2.5%) and 0.014 (1.4%) for the intracranial and body, respectively, which are lower than the internationally recommended standard of 0.05 (5%). The IMRT factor was approximately 12, which is also lower than the internationally recommended standard. The use factors of conventional radiotherapy equipment currently recom-

mended by NCRP reports a range of approximately 0.04 (4%) to 0.40 (40%), which is larger compared to that of CyberKnife.^{1,2)}

Most of the CyberKnife beams point directly toward the floor, except in the case where the treatment room is particularly large or the iso-center is high above the floor. In this study, the effective beams in the treatment room were not present in the roof direction and right directions of couch, which mean that the effective beams toward the left and right directions were determined based on the position of the robot in the treatment room. In this work, the use factors of the floor were 0.03 (3.0%) and 0.021 (2.1%) for the head and body treatments, respectively, and the beam intensity was further concentrated on the floor. However, in the case of an anterior wall and body treatment, the effective beam could not be identified on the right wall.

In this study, the prescribed iso-dose lines of intracranial and body treatments are mostly concentrated in the 75%~80%. When the MU of the hot zone in each direction of the treatment room was analyzed in this study, no major differences were detected for the head and body treatment in the superior (back wall) and inferior (front wall) directions. Yang J also reported no major differences in those two directions.¹⁰⁾ However, this study revealed higher MU values in the hot zone compared to Yang J and the cause is believed to be the total MU which is 3 times higher. Also, this research showed higher MU distribution on the left side wall from the couch, and Yang J showed higher MU distribution on the right side of the wall. It is believed that the directions of effective beams are determined by the location of the CyberKnife robot's installation. Recent M6 CyberKnife are designed to be installed at the center, on top of the couch. Therefore, the robot's left and right side beam distributions show the tendency of uniform distribution.^{5,17)} However, G4 CyberKnife are installed the right or left side of the couch, the effective beam determined by the position of the robot in the treatment room. Most beams from the CyberKnife robot are directed toward the floor owing to the mechanical characteristics of the robot, and the CyberKnife is mostly set with the head first supine (HFS) position wherein the patient's feet are located at the end of the couch, these limit the reach of the robotic arm, and most beams from CyberKnife tend to be concentrated in

the direction of the patient's head.^{4,5,12)} Thus, the direction of the effective beams is determined according to the position of the robot in the treatment room.

The latest paper released by Henzen D⁵⁾ announced that because the robot and couch of M6 CyberKnife have structural features that keep themselves placed symmetrically, the left and right walls in a treatment room showed a symmetrical MU distribution regardless of the collimator type and treatment site. But as a result of this study, the left wall showed a higher MU distribution. It is thought that because a G4 CyberKnife was installed on the right or left of a couch. In other words because the position of the robot determines the direction of the effective beam, it is necessary to consider the robot position in designing the CyberKnife shielding.^{16,17)} Likewise, after studying the effects on each treatment site in various collimator systems, they announced that MU difference was not large. However, when the fixed collimator was used, MF value was higher than when using MLC collimator. Accordingly, they announced that the select of collimators influenced MF according to each treatment site. And in this paper, they analyzed MF as a variables effecting shielding. The MF is a shielding variable applied to the CyberKnife, similar to the IMRT MF used for shielding calculations. This is the average MU required per cGy delivered over all SADs and tumor depths.⁶⁾ And it was identified that because a larger shielded area, while the size of bunker increases, naturally leads to a smaller number of MU/pixel, the size of bunker is also a parameter to be considered when the area is shielded. In this study, 5% of MU/fraction was delivered to the wall in the treatment of intracranial, but beams directly delivered in the treatment of extra-cranial were not identified. The floor and the wall behind the patient's head showed an extreme MU/cGy distribution of 0% to 79%, but on the ceiling, effective beams were not identified similar to our study's results.

In this work, we analyzed the MU/cGy of each treatment area using the log file extracted from the database, and analyzed the beam direction and use factor by applying the matrix transformation to the rotation of the robot. But this study did not consider scattering ray and reflected trajectory beam, which will be investigated in the follow-up studies focusing on these beam along particular directions

of the treatment room based on further clinical data.

Conclusion

The International Commission on Radiological Protection (ICRP) and the CyberKnife manufacturer typically apply more stringent shielding standards than conventional radiotherapy equipment because CyberKnife is a non-isocenter treatment equipment with a high IMRT factor. This application causes in more barriers, resulting in inefficiency of space usage and higher costs of shielding in treatment facilities. However, the actual irradiation area of CyberKnife is a maximum of 60 mm, and the irradiation area of the number of primary beam is small. Furthermore, the workload, which is concentrated on the shielding wall in one direction of the actual treatment room, is relatively marginal. Therefore, the use factor and workload verified in the present study, which are lower than the internationally recommended standard, would enable the design of treatment room that are economical and reasonable for each treatment site by reducing the number of shielding components required in the actual CyberKnife shielding facility.

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Conflicts of Interest

The authors have nothing to disclose.

Availability of Data and Materials

All relevant data are within the paper and its Supporting Information files.

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