Dose Characteristics of Stereotactic Radiosurgery in High Energy Linear Accelerator Photon Beam

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Three-dimensional dose calculations based on CT images are fundamental to stereotactic radiosurgery for small intracranial tumor. In our stereotactic radiosurgery program, irradiations have been performed using the 6 MV photon beam of linear accelerator after stereotactic CT investigations of the target center through the beam's-eye view and the coordinates of BRW frame converted to that of radiosurgery. Also we can describe the tumor diameter and the shape in three dimensional configuration. Non-coplanar irradiation technique was developed that it consists of a combination of a moving field with a gantry angle of 140°, and a horizontal couch angle of 200° around the isocenter.

In this radiosurgery technique, we provide the patient head setup in the base-ring holder and rotate around body axis. The total gantry moving range shows angle of 2520 degrees via two different types of gantry movement in a plane perpendicular to the axis of patient. The 3-D isodose curves overlapped to the tumor contours in screen and analytic dose profiles in calculation area were provided to calculate the thickness of 80% of tumor center dose to 20% of that. Furtheremore we provided the 3-D dose profiles in entire calculation plane.

In this experiments, measured isodose curves in phantom irradiation have shown very similiar to that of computer generations.

Key Words: Stereotactic radiosurgery, Linear accelerator photon beam, Non-orthogonal irradiation, 3-D dose computation

INTRODUCTION

Recent developments of stereotactic radiosurgery based on linear accelerator photon beam have been implemented on treatment of small intracranial lesion and malignant tumor. The interesting of multi-arc in non-coplanar radiosurgery is rapidly growing up in part of neuroscience and radiation therapy[1~5].

The initial radiosurgery experience has been performed with a gamma unit, known as gamma knife, introduced by Leksell in 1968, which was multiple fixed ^{60}Co gamma beams focused to a small target volume with high precision[6].

In contrast to conventional radiotherapy in brain tumor, because the stereotactic radiosurgery technique is to deliver a single high dose, 25-50 Gy, to target volume, the radiosurgery technique requires an accurate localization of target center, surrounding normal tissues of the critical organs and three-dimensional dose descriptions within the entire irradiation area.

Several authors have been showed that the convergent beam of linear accelerator is useful for radiosurgery in small brain tumor and functional diseases[1~6].

Podgorsak[5] and McGinley[7] have been also designed the dynamic rotation of patient for steep gradient of dose distributions in small target volume.

In this experiments, the percent depth dose of small field for 6 MV X ray of linear accelerator was investigated by means of film and ionization detector for dosimetry. The small field was obtained by use of secondary lead collimator for shielding to outside of circular field.

This study also prepared the head-ring holder for fixing the skull phantom, localization ring, target positioner and the software for stereotactic radiosurgery which includes the tumor beam's eye view, 3-dimensional isodose curves and three dimensional dose profile in calculation area.

Especially, this paper has been presented the steep gradient of dose fall-off at outside of the target volume with the double non-coplanar multi-

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arc irradiation technique in 6 MV linear accelerator photon beam.

MATERIALS AND METHODS

1. Preparations

The prepared stereotactic radiosurgery technique is mainly consist of localizing device, and 3-dimensional computation softwares with small radiation field.

The depth doses for 10 and 30 mm in diameter of small field were obtained from dosimetric film (Kodak X-omat V) which was irradiated in 6 MV x ray of linear accelerator.

The main hardware components for this non-coplanar stereotactic radiosurgery are an isocentric linear accelerator (ML-15MDX, MITSUBISHI, JAPAN), a head ring holder, stereotactic localizer ring, target positioner, skull phantom, and circular shaped lead collimator and its holder as shown in Fig. 1.

The skull phantom which was made of Mix-D (Polyethyrene 75% and Paraffin 25%) has been prepared the 100 mm in diameter of hole cavity for mounting the dosimetric film on the axial, sagittal and coronal section.

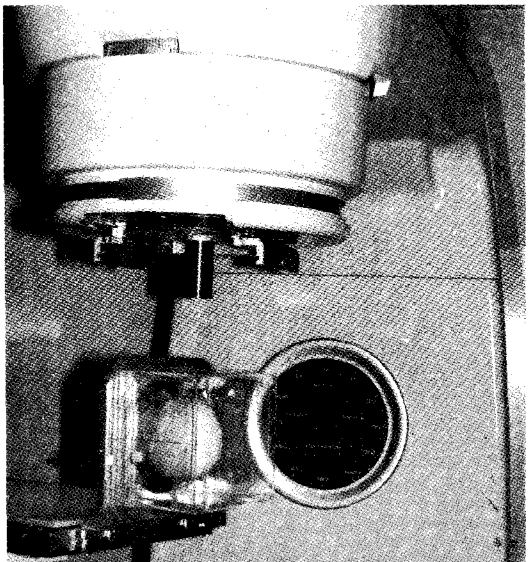

Fig. 1. Device for non-coplanar stereotactic radiosurgery with the linear accelerator.

The skull phantom was mounted on the head ring holder which was attached to patient couch of linear accelerator.

The prepared head ring holder has been opened with 280 mm in diameter of hole for fixing the BRW head ring and it was made of 20 mm thickness and 350×350 mm size of aluminium plate.

This head ring holder was attached to the tip of the patient-couch and screwed it tightly for fixing and for avoiding the intruption of gantry movemements arround the patient head.

The BRW (Brown-Robert-Well) head ring was prepared to immobilize the head of phantom in its holder and it is fundamental tool for fixing head and attaching the localizer ring or target positioner.

The fixation of the BRW head ring[7~9] to the skull phantom was performed with temporary loose velcro straps which are attached to the head ring and placed over the head. The straps are adjusted until the ring is at the proper height and angle. The four fiducial pins are screwed through the phantom scalp for fixing the head. After head ring fixation, the localizer ring is placed on the head ring to set the largest rod (#1) on the right side of the skull phantom in the midtemporal area. This largest rod is identified easily on the localizing scan.

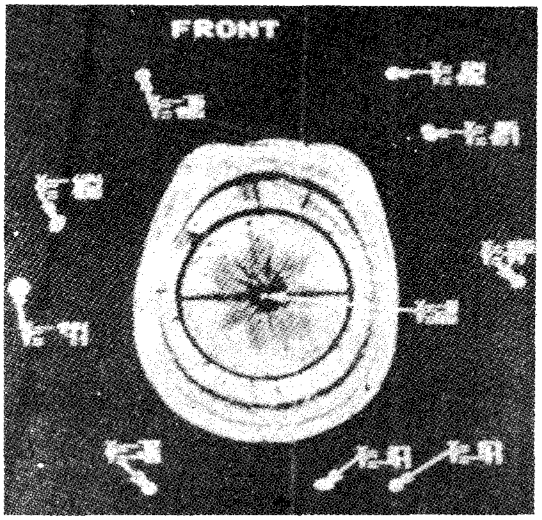

Fig. 2. A typical CT image showing the relative coordinates of intersected rod of localizer corresponding to the numbers on picture with respect to the skull phantom.

The target center is determined by using the stereotactic localizer, BRW localizer ring, based on CT scans as shown in Fig. 2. We can get the orthogonal coordinates through the coordinate transform. Transformation coefficient between the coordinate of BRW and that of CT can be determined from the relative positions of nine pins[8~10]. According to the geometric consideration, the depth from head ring is calculated easily with slanted rods of frame as follows;

$$X_2=D[(g/G)\cos 60-1],$$
$$Y_2=(g/G)H,\ Z_2=(g/G)\ D\sin 60$$
$$X_5=D\{1-[1-(g/G)]\cos 60\},$$
$$Y_5=(g/G)\ H,\ X_5=[1-(g/G)]\ D\sin 60$$
$$X_8=D[1/2-(g/G)],$$
$$Y_8=(g/G)\ H,\ Z_8=-D\cos 30 \quad \cdots\cdots(1)$$

where g, G are the distance from vertical rod to slanted rod in CT image and to other vertical rod, respectively. And D, H are the actual distance of 140 mm from vertical rod to other vertical rod and 189 mm of height of BRW localizer ring, actually this height represents the distance from head ring to the tip of slanted rod.

Since the determination of target center during CT scan is cruded by using the two dimensional screen image, it is required the target center should be reconfirmed with tumor beam's eye view in 3-dimensional display before dose computation and actual irradiations.

The target positioner shaped cubic acryic plate is used to align the center of target with beam of linear accelerator through the coordinate of CT frame. The target positioner is to attached to head ring same as to fix the localizer ring. The schematic procedures for radiosergery using the linear accelerator has been presented as shown in Fig. 3.

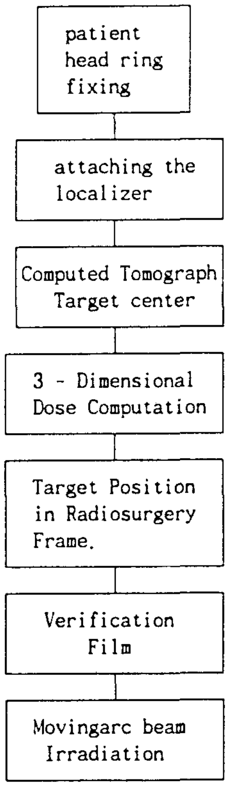

Fig. 3. Schematic diagram of radiosurgery procedures in linear accelerator photon beam.

2. Irradiation

Using the narrow beams of 6 MV high energy photon of a linear accelerator, it was developed the non-coplanar multi-arc irradiation technique that consists of a combination of a moving field irradiation with a total gantry angle of 140 degrees from 20 ° to 160°. A horizontal table rotation is performed with 200 degrees from angle of -10° to 190° of the patient couch around the isocenter[3].

Generally, non-coplanar irradiations technique limits the number of moving arc as depend on target volume.

Designed radiosurgery technique provided the patient head rotation in fixing holder without changing the fiducial pins for more overcoming the limitation of number of moving arc.

In this study, selected dimensions of target size were 10 to 30 mm of diameter in step 5 mm and the dose distributions of that were compared to computer generation and measurement of that with same 8 moving-arc beams.

3. Algorithms

Stereotactic radiosurgery for intracranial target volume requires the detailed information on 3-dimensional dose distribution. An algorithm was derived from the single fixed oriented circular field and a number of surperimposed beam in each point of a 3-dimensional coordinate system.

Authors developed a software for calculation the 3-dimensional dose distribution and transfer the relevant contour with digitizer (K3300). This program was writen by Turbo-C language for calculation and it takes 5 min to several hours of CPU time depending on the number of non-coplanar arc beam and matrix size. The schematic diagram for calculating the 3-dimensional dose distribution has

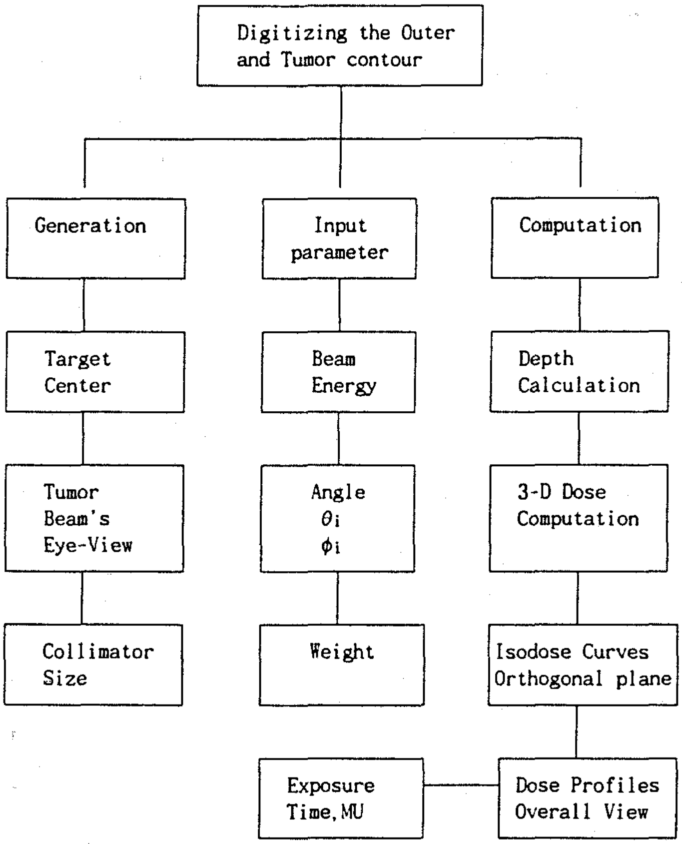

Fig. 4. A block diagram of the three-dimensional dose computation for stereotactic radiosurgedry.

been shown in Fig. 4.

For the entire three dimensional dose distribution, point dose was calculated in grid 3×3×3 mm. The point (x, y, z) dose can be calculated with the percent depth dose (PD) and lateral distance (Kp), as function of beam angle of gantry (ϕ) and patient-table (θ), from central axis of beam in given photon energy as follows;

$$D\ (x,\ y,\ z) = \iint TD\ (1/PD\ (r',\ d_{iso}))\ PD\ (r',\ d')\ K_p\ (r')\ d\theta\ d\phi \quad \cdots\cdots\cdots\cdots (2)$$

where TD is the specification of tumor dose, K_p (r') is the off-axia ratio in given angle of θ, ϕ. respectively. The PD (r', d_{iso}) represents the percent depth dose at isocenter of d_{iso} in given field size r' at surface.

The PD (r', d') is percent depth dose at given depth d' of calculation point.

The percent depth dose at given point PD (r', d_{iso}) is obtained from Tissue-Maximum Ratio as follows[11,12];

$$PD\ (r',\ d_{iso}) = 100 \times TMR\ (r,\ d)\ ((F+dm)/(F+d))^2\ S_p\ (r_d)/S_p\ (r_{dm}) \quad \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

where r' represents the field of surface from field of isocenter and it was obtained from;

$$r' = ((F-(d_{iso}-d))/(F))\ r \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (4)$$

where d and d_{iso} represent the distance from surface to interesting point and that of surface to axis, respectively. And F represents the distance from source to axis. TMR (r, d) is obtained from TMR (0×0), scatter-maximum ratio (SMR) and phantom scatter factor (Sp) as follows;

$$TMR\ (r,\ d) = [SMR\ (r_d,\ d) + TMR(0,\ d)]\ [(S_p\ (0)/S_p\ (r_d)] \quad \cdots\cdots\cdots\cdots\cdots\cdots (5)$$

where TMR (r, d) is a ratio of dose in depth d and field r' to maximum dose of given field r.

The relationship between the absorbed dose in the target point and the monitor nuit, which have to be selected for each non-coplanar arc beam, was obtained from average TMR in moving angle. The monitor unit (MU) for irradiation to target point for given isodose curve is calculated as follows;

$$MU_i = \frac{TD}{SIC \times TMR \times Sc\ (r) \times SP\ (r')} \times Wt_i \quad \cdots(6)$$

where SIC represents the selected isodose curve which include the entire target volume. The Sc (r) is the collimator scatter correction factor at given field size (r) and Sp (r') represents the phantom scatter coorection factor of effective field size (r') at given energy of linear accelerator, respectively.

The Wt_i is a weight of ith beam of the multi-arc irradiations.

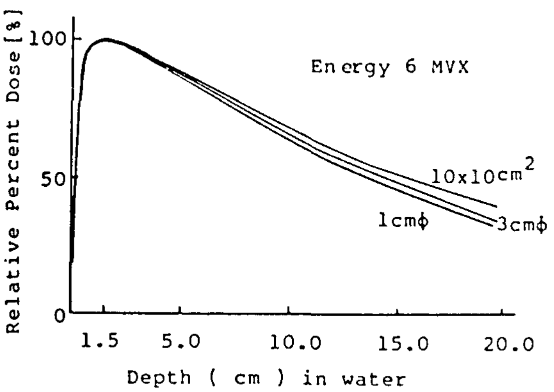

Fig. 5. Depth dose curves of small radiation fields and reference field size 10×10 cm² for 6 MV photon beam in linear accelerator (ML-15 MDX).

RESULTS

The depth dose curve of small fields for 10 mm and 30 mm of diameter in 6 MV photon beam in linear accelerator has been shown in Fig. 5. This depth dose curves were obtained through film dosimeter (WP 102, Wollop, German) with dosimetric film (Kodak X-omat V). The dosages of given depth were normalized to maximum dose at 15 mm of water equivalent depth. The relative percent depth doses of 10 and 30 mm of diameter of field have showed 62.7% and 64.1% at 10 cm of depth, respectively. The reference field size in 10× 10 cm² field has showed 67.5% at 10 cm of depth[16].

Since stereotactic radiosurgery needs to align the beam axis and target center accurately, the gantry isocenter must be described in detail. In this study, the gantry isocenter and couch isocenter showed the 0.3±0.3 mm and 0.4±0.3 mm by narrow beam irradiated on the dosimetric film, respectively as shown in Fig. 6a and 6b. The center of blacked line was investigated with densitometer and the line intersects were calculated by using the simultaneous equation.

In this non-coplanar irradiation technique, irradiation to humanoid skull phantom, immitate the humanoid skull phantom with Mix-D, was performed with two different non-coplanar moving arc which one is supine position and other decubitus. The dummy target which is located on mid portion

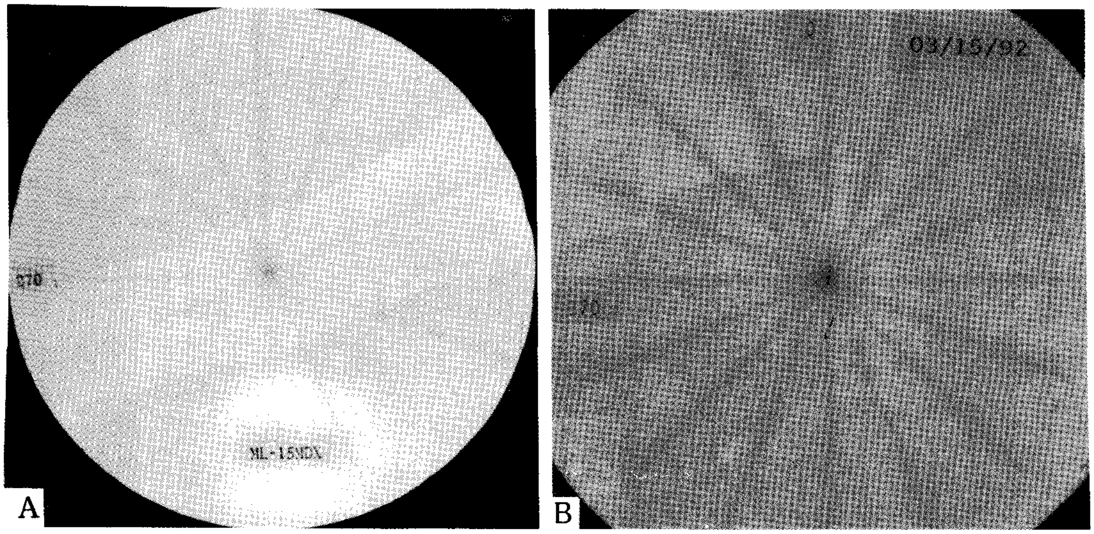

Fig. 6. Gantry isocenter (a) and couch isocenter (b) of ML-15 MDX (Mitsubishi, Japan) were obtained from dosimetric film exposured.

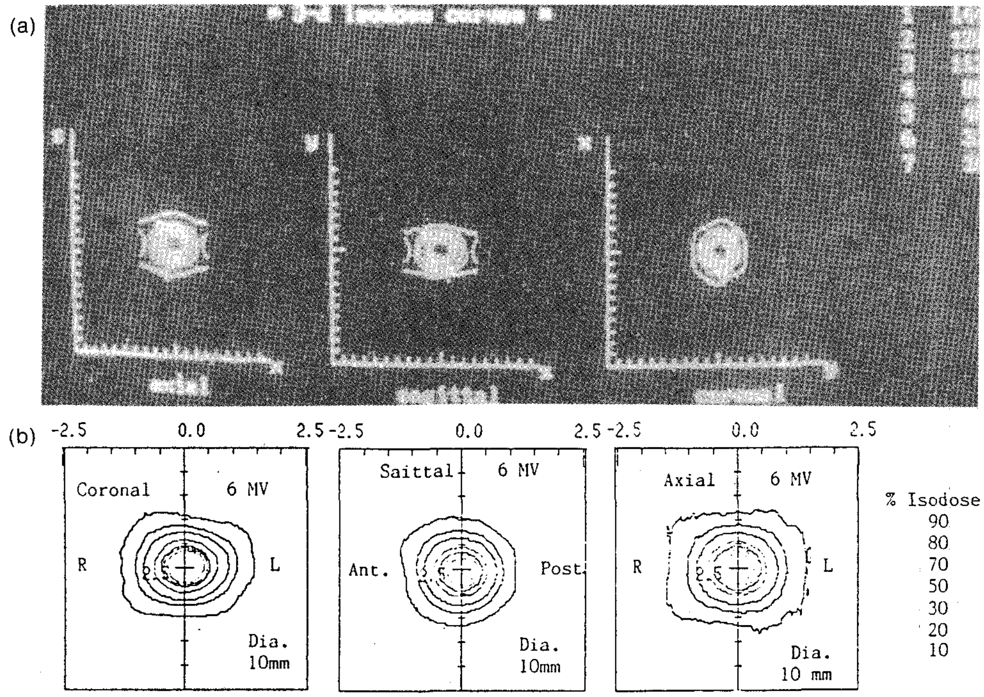

Fig. 7. The dose distribution of 8 non-coplanar arc beam for stereotactic radiosurgery in small intracranial target volume. (a) showed the isodose curve by computation and (b) that of film dosimetry.

of film was selected to stereotactic irradiation.

The small circular field was accomplished with 110 mm of height and 10, 15, 20, 25 and 30 mm of lead in diameter for secondary collimator of linear accelerator.

The computed and experimental dose distributions of axial, sagittal and coronal section of target volume have shown in Fig. 7a. The calculated mode in matrix size is 21×21×21 and selectable grid size is 3 mm. The configurations of isodose curve have showed very similiar to that of experimental measurements as shown in Fig. 7b.

As the accurate spatial location of target and a steep dose falloff outside the target volume are the major important requirements in radiosurgery, in this study, the steepness of dose falloff from the 90% to 20% of maximum dose in target area showed 13.5% per mm in 10 mm of field diameter, however, 7.1% per mm showed in 30 mm of that as shown in Fig. 7a and Fig. 8.

The dose distributions have characterized with relative flatted dose within the 90% isodose curve and symmetric shape within 50% isodose curve in axial, sagittal and coronal plane of target volume.

The three-dimensional dose profile curves have been presented the overall dose shaping in the target volume and surrounding normal tissue as shown in Fig. 9. This profile curves were obtained from irradiation with 20 mm diameter of field size and the eight arc beams through two orthogonal non-coplanar convergence.

The dose profiles of different small field size in non-coplanar stereotactic radiosurgery technique were obtained with computation as shown in Fig. 9.

In this computational dose distributions, the 80% of target center dose coincidented to field margin and the rim thickness from 90 to 20% of that of 10, 15, 20, 25 and 30 mm diameter of field showed 5.6, 7.6, 8.1, 9.3 and 9.8 mm, respectively.

The dose gradients of 80~50% level have changed between 13.0% to 16.7% per mm.

This isodose curves were compared with the calculated and measured dose profiles in two different size of small field through a target volume in provided Mix-D skull phantom for 8 non-coplanar arc beam as shown in Fig. 10.

The profile curves of 10 mm and 25 mm diameter of field were found that the differences of computation to experiment were very small both within 1 mm discripancy as shown in Fig. 10. However the

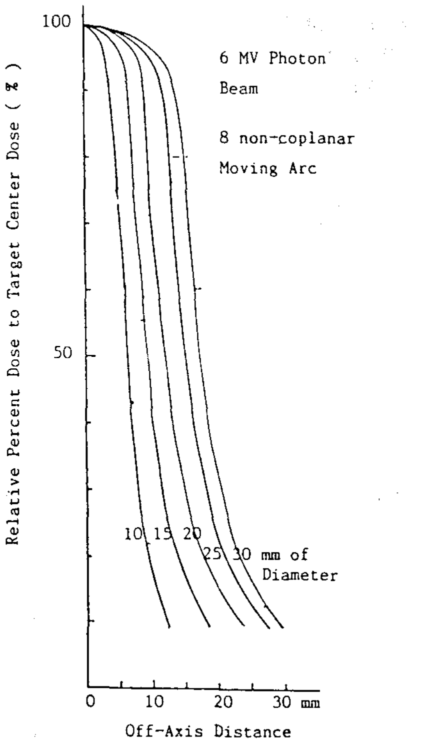

Fig. 8. Dose profile curves of the half of circular fields with different size created by computation in two non-coplanar stereotactic radiosurgery technique.

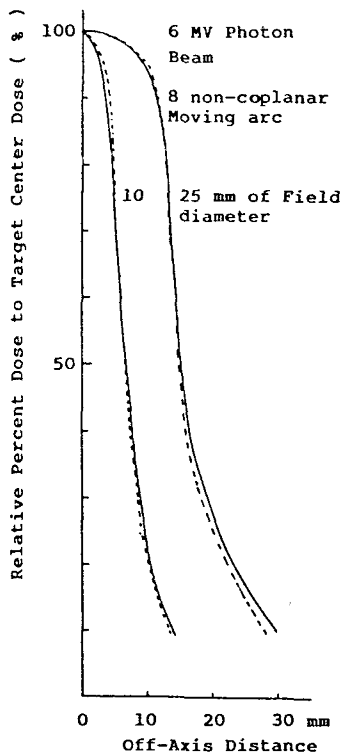

Fig. 10. The comparison of dose profiles with computer generation (------) and experimental film dosimetry (——).

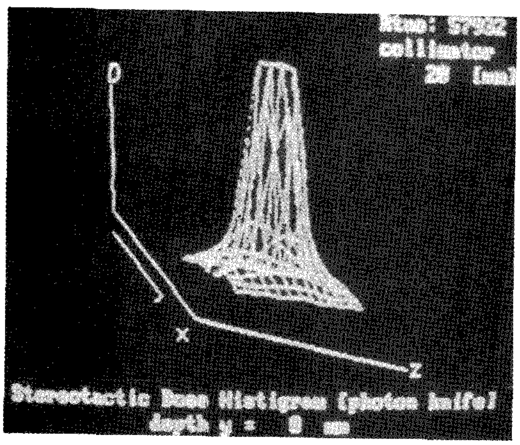

Fig. 9. The computed three-dimensional dose profile curves have been showed the great steepness at outside of target volume with 20 mm diameter of field size and 1120 degrees of moving arc beam in 6 MV photon of linear accelerator. The XZ plane and D represents the axial plane and dose (cGy) in this computation model, respecively.

tail of curve in computed generation showed smaller than that of film dosimetry.

DISCUSSION

Recently the interesting of stereotactic radiosurgery is rapid growing up in neurscience and therapeutic radiation oncology and medical physicists caused by generation of three dimensional target display and dose distribution in high accuracy through the computed tomography[13,14]. Furthermore, this radiosurgery technique using the linear accelerator is sophisticated in spatial dose distribution, for its flexibility in irradiation technique, aid of three-dimensional dose computation and high accuracy for tumor localization.

The head ring holder, target positioner and localizer ring were provided to immobilizer the skull phantom with combined to couch in linear accelerator.

This holder could be used with BRW head ring and stereotactic localizer ring also. The skull phantom was made with Mix-D for measurement the film dosimetry which was mounted on axial, sagittal and coronal plane without change the fixation of head-ring as shown in Fig. 1.

The location of irradiation target was investigated with CT image with similiar to patient head location through the stereotactic localizer ring and equation (1).

In this radiosurgery technique, authors designed the new irradiation method which dose distribution has created a large steepness of gradient outside of target volume within 30 mm of field diameter through two orthogonal non-coplanar moving arc with photon beam of linear accelerator.

Three dimensional dose distributions have been shown less than 5 percent of the target dose in intersected area by this two orthogonal non-coplanar irradiation technique.

The computational dose distribution in 10 to 30 mm diameter of field has round shaped in symmetry within 50% of isodose and it is very similiar to show that of Gary Luxton et al[15]. But the star shaped isodose curve outside of target volume was not created in two orthogonal non-coplanar moving arc in contrast to single non-coplanar irradiations.

Especially, developed device and calculation mode can be altered weight and orientation of beam incidence so as to get adequate dose distributions for small irregular target volume.

In small target volume, the prepared maximum angle of moving beam is 2520 degrees to increase the target dose as seven times higher than sigle rotation technique. However the maximum irradiation angles depend on target size because the large field size will increase the superimposed volume which is created the star-shaped isodose curve on surrounding normal tissues of target volume.

The thickness of 90% to 20% of isodose curve showed 5.6 to 9.8 mm from target margin in 10 to 30 mm of field diameter in provided 1120 degrees of moving arc stereotactic radiosurgery technique. The dose distribution of computer generation has been showed very close to experiment of film dosimetry. The density of film which was irradiated in skull phantom was calibrated to a standard characteristic curve in film dosimetry[16].

Hartmann[3] have been reported the steep gradients which distance of the 80% and 50% of maximum isodose were 7%/mm for diameter of 29 mm and 15%/mm for that of 9 mm field size. The change of relative dose per mm are obtained at the margin of the irradiated volume. They used the 15 MV x ray beam of linear accelerator for non-coplanar irradiation technique.

The steep gradient is very similiar to this experimental data in shallow region but the superimposed area showed more steep than that of other as shown Fig. 8. Especially, in this experiments, the isodose curve showed the round shape in normal weighted beam until to 30% of relative isodose.

CONCLUSION

The BRW head ring is fully available to use in stereotactic radiosurgery using the high energy photon beam of liner accelerator, caused by its enability of accurate localization of CT scan determined targets. However, since the the radiosurgery irradiation is a convergent and single high dose to target, the determination of target volume and its center must be reconfirmed with three dimensional tuor beam's eye view.

The dose distribution of irrdiated target volume were investicated and compared the computer generation and experimental meaurements. The steep gradient have shown 13.0 to 16.7% change of relative dose per mm outside of target volume in both computations and experiments at given 30 mm and 10 mm diameter of field.

The irradiation method of double non-coplanar moving arc has shown the round shaped isodose curve in axial, sagittal and coronal plane within target volume and negligible the star-shaped dose distribution surround the three dimensional target margin.

The experiments using film dosimetry have shown very small discripanycy to computation in dose profile curves of 10 mm and 25 mm diameter of field size.

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= 국문초록 =

고에너지 선형가속기에 의한 입체방사선수술의 선량특성

계명대학교 의과대학 치료방사선학교실

최 태 진 · 김 옥 배

전산화단층촬영에 근거를 둔 3차원선량계산은 소형의 뇌종양에 대한 방사선수술에 있어서 가장 기본이 된다. 본 연구의 방사선수술 프로그램은 전산화단층촬영을 통해 표적 위치, 크기와 모양을 3차원공간에서 결정하고 최적조사면적을 구할 수 있었다.

방사선수술의 선량은 선형가속기의 6메가볼트 고에너지 광자선을 이중 비공면의 회전조사를 가상두부에 실시하여 계산된 3차원적 선량분포와 필름선량계의 실측선량을 비교한 바 거의 일치됨을 확인하였다. 본 연구의 방사선수술에서 80%에서 50%까지 선량곡선의 기울기는 전회전각이 1120도 일때 10 mm 조사면적에서 약 16.7%/mm 였고 30 mm 에서는 13.0%/mm를 보였다. 또한 표적주위의 선량분포는 표적내 최대선량값이 90% 에서 50% 까지 선량분포의 최대폭은 직경 10 mm 조사면에서 2.3 mm를 나타내었으며, 90% 에서 20% 까지의 거리는 5.6 mm를 나타내었으며, 30 mm 직경의 조사면에서는 각각 3.5 mm와 9.8 mm를 보였다. 이러한 선량분포의 급격한 기울기는 방사선수술시 표적주위의 치명부위의 손상을 최소화하기 위한 선량최적화 작업에 지침이 될 것으로 생각되며, 또한 방사선수술방법의 차이에 따라 비교자료가 될 수 있을 것으로 생각된다.