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Distortion of the Dose Profile in a Three-dimensional Moving Phantom to Simulate Tumor Motion during Image-guided Radiosurgery

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Purpose: Respiratory motion is a considerable inhibiting factor for precise treatment with stereotactic radiosurgery using the CyberKnife (CK). In this study, we developed a moving phantom to simulate three-dimensional breathing movement and investigated the distortion of dose profiles between the use of a moving phantom and a static phantom.

Materials and Methods: The phantom consisted of four pieces of polyethylene; two sheets of Gafchromic film were inserted for dosimetry. Treatment was planned to deliver 30 Gy to virtual tumors of 20, 30, 40, and 50 mm diameters using 104 beams and a single center mode. A specially designed robot produced three-dimensional motion in the right-left, anterior-posterior, and craniocaudal directions of 5, 10 and 20 mm, respectively. Using the optical density of the films as a function of dose, the dose profiles of both static and moving phantoms were measured.

Results: The prescribed isodose to cover the virtual tumors on the static phantom were 80% for 20 mm, 84% for 30 mm, 83% for 40 mm and 80% for 50 mm tumors. However, to compensate for the respiratory motion, the minimum isodose levels to cover the moving target were 70% for the 30~50 mm diameter tumors and 60% for a 20 mm tumor. For the 20 mm tumor, the gaps between the isodose curves for the static and moving phantoms were 3.2, 3.3, 3.5 and 1.1 mm for the cranial, caudal, right, and left direction, respectively. In the case of the 30 mm tumor, the gaps were 3.9, 4.2, 2.8, 0 mm, respectively. In the case of the 40 mm tumor, the gaps were 4.0, 4.8, 1.1, and 0 mm, respectively. In the case of the 50 mm diameter tumor, the gaps were 3.9, 3.9, 0 and 0 mm, respectively.

Conclusion: For a tumor of a 20 mm diameter, the 80% isodose curve can be planned to cover the tumor; a 60% isodose curve will have to be chosen due to the tumor motion. The gap between these 80% and 60% curves is 5 mm. In tumors with diameters of 30, 40 and 50 mm, the whole tumor will be covered if an isodose curve of about 70% is selected, equivalent of placing a respiratory margin of below 5 mm. It was confirmed that during CK treatment for a moving tumor, the range of distortion produced by motion was less than the range of motion itself.

Key Words: Moving phantom, Isodose, Radiosurgery, CyberKnife

Introduction

Since installation of the CK on 2002, we have treated above 1,000 extracranial body tumor, including lung and liver tumor with stereotactic radiosurgery. Because tumor motion induced by respiration or adjacent organ motion would give limitation in precise treatment, especially in the point that the CK has a unique algorithm to fill the tumor volume with multiple beams of circular cone, the abdominal compression method was implicated to reduce the tumor motion for liver and lung tumor in our institute. However, tumor motion error was still remained significantly during treatment.

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In general, intra-fractional organ motion effects related to dose distribution caused by patient breathing during treatment can be divided into two types.[1] One type is the dose blurring effect which is reproduced at the tumor margin during conventional radiation treatment.[2,3] This effect can be disregarded if enough margin is given according to the amount of respiratory movement, as the dose distribution affected by the motion within the field is minimal. The second effect is the "interplay effect".[4,5] This effect occurs only in the dynamic delivery technique where the collimator also moves dynamically during the movement of tumor, as with CK radiosurgery, IMRT (Intensity Modulated Radiation Therapy) and tomotherapy. Because this effect causes the distortion of dose profile in a different way from the blurring effect and can not be measured simply by the fluoroscopy, the amount of margin necessary to cover respiratory motion in clinical practice is not known well. If the distortion of dose distribution induced by patient breathing can be experimentally observed, it can be used to overcome uncertainties in the dynamical delivery technique. We were especially concerned with two clinical issues. One issue is how much of the tumor area is not covered due to tumor motion, which it will be a cause of marginal failure. The second issue is that if a meaningful under-dose area happens to be inside of a tumor, and not peripheral to the tumor, then it will cause inside failure.

This study was performed to observe the distortion of dose profile using a moving phantom experimentally. Ultimately, the understanding of the distortion of dose distribution could provide useful information in the actual treatment of patients.

Materials and Methods

1. Phantom material and irradiation method

In order to simulate three-dimensional respiratory motion, we assembled a 2-axes Cartesian robot (Cartesian Robot-2Axis, FARA RCM4H, Samsung Mechatronics, Korea) (Fig. 1). It was sep up to make phantom move elliptically 5 mm, 10 mm and 20 mm to right-left, anterior-posterior and craniocaudal direction, respectively, in cycle of 4.4 seconds based on the average values obtained from a tumor motion study for 12 patients in our institute (unpublished data).

The phantom was composed four separate 2.5×2.5×5 inch size rectangular polyethylene and was fastened with bolts and nuts of polyethylene material. Two 5 inch Gafchromic films (MD-55 ISP technologies Inc. USA) were placed crosswise inside (Fig. 2). In the upper part of the phantom, four gold markers (0.8 diameter×4.5 mm length) were inserted for target tracking.

To analysis the relation between tumor size and movement, we proposed virtual tumors were sphere forms with diameters of 20, 30, 40 and 50 mm respectively. For treatment planning, phantom imaging for was obtained by 2 mm slices using CT (Somatom Emotion, Siemens). The treatment planning (CK TPS Ver. 3.4.1) was performed by drawing virtual tumors of each size in the center of film images acquired by CT. Prescribed dose was 30 Gy to virtual tumors and 108 beams were used through single center mode. The size of collimator for treatment was same as the diameter of tumor. At first, irradiation was done for a static phantom and then all process was repeated as same mode to the moving phantom controlled by 2-aixs Cartesian arm.

2. The measurement of 2 dimensional dose distribution profiles and under dose area

Two-dimensional isodose curves were acquired on Gafchromic films by optical density analysis. Because two films were crossed at rectangular angle, one film showed dose information in the craniocaudal and anterior-posterior (CC/AP) direction and another film showed dose information in the right-left and anterior-posterior (RL/AP) direction. The top and

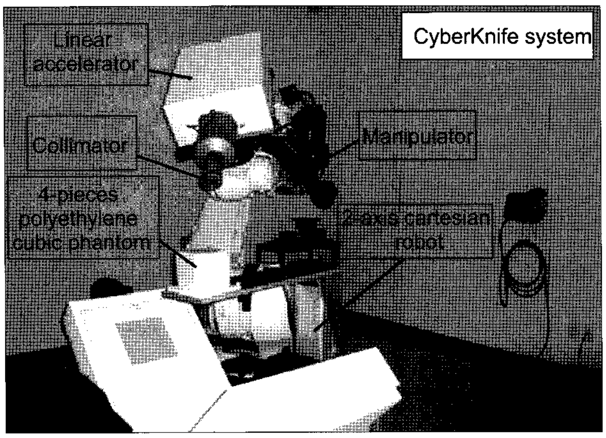

Fig. 1. Overall view of the CyberKnife and the 2-axis cartesian robot.

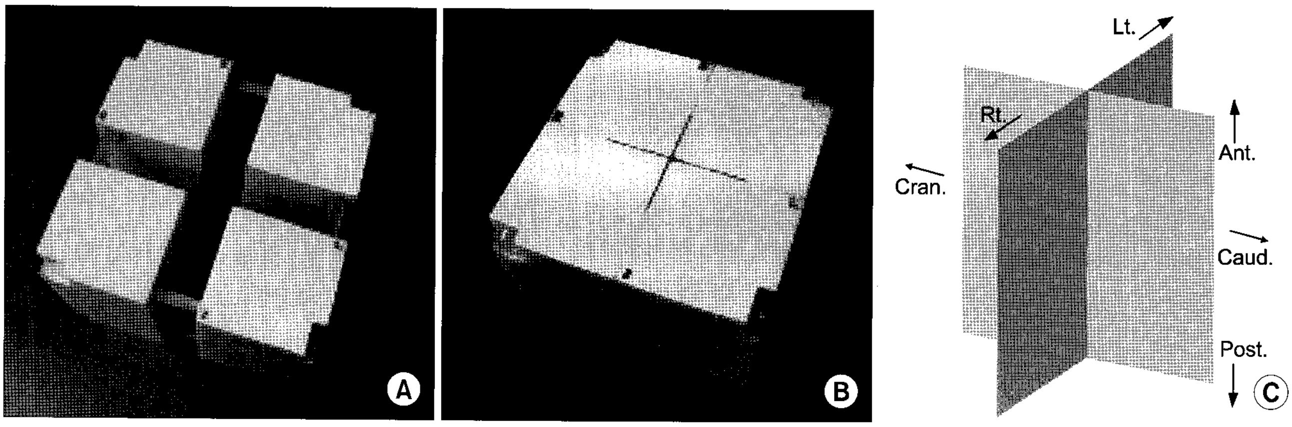

Fig. 2. Polyethylene cubic phantom (A, B) and a schematic drawing showing directions of the two films crossed in the cubic phantom (C).

bottom sides of all films indicates the anterior-posterior directions, respectively.

In the films shown in Fig. 3～6, three lines were drawn. The dotted red color line shows the virtual tumor, the blue line is the minimum isodose curve to cover the virtual tumor for prescribed dose in the static phantom, and the black line shows the distorted minimal isodose curve obtained while the phantom was irradiated under movement.

The under dose area was measured using Image analysis software Image J Ver. 1.34s, which can calculate the area of red color not to be covered by the black line in each craniocaudal and right-left direction film. As under dose in the anterior-posterior direction was not observed in all of the tumors, this direction was excluded in this analysis.

Beam profiles were measured to observe the dose distribution of many sections and to identify the dose distribution inside and peripheral of the tumor. Three beam profiles were obtained along ±45 degree sections including the RL direction or CC direction, respectively for each film (Fig. 3～6).

Results

1. 2-dimensional dose distribution profiles according to tumor size and motion

From an analysis of two films placed within the phantom at the RL/AP direction and CC/AP direction, Fig. 3～6 show two-dimensional dose profiles according to the tumor size and direction of the film. The red line of the film represents a virtual tumor, while the blue and black colors indicate the isodose curves after irradiation of a static phantom and a dynamic state where the phantom was moving, respectively. In the planning, the prescribed isodose to cover the virtual tumors on the static phantom were 80% for 20 mm, 84% for 30 mm, 83 % for 40 mm and 80 % for 50 mm tumors. Beam profiles shown below the films were also measured in order to show the dose distribution of inside and around the tumor. Beam profiles on the left are those at the RL/AP direction, while beam profiles on the right are those of the CC/AP direction. The blue color shows beam profiles when the phantom was at a static condition, while the red line displays those while the phantom was moving. The black-colored straight line is a minimum isodose to cover tumors in computer planning, and the green-colored line shows how much the isodose rate should be reduced for covering the whole tumor when the phantom was moving.

Two-dimensional profiles were observed at the direction where the under dose area is the largest. As the area showing 100% within a tumor was very small, we could not find areas indicating 100% in the two-dimensional dose profiles. Most area was distributed almost in the range of 90～96% under the conditions in which the tumor does not move. In a moving phantom, about 90% isodose covered almost the central area of tumors (Fig. 3～6).

In the films shown in Fig. 3, distortion between moving and static phantom was the severest at the right and CC directions, followed by the AP direction, but there was no difference at the left direction. The distortion of two-dimensional dose distribution profiles also was the most

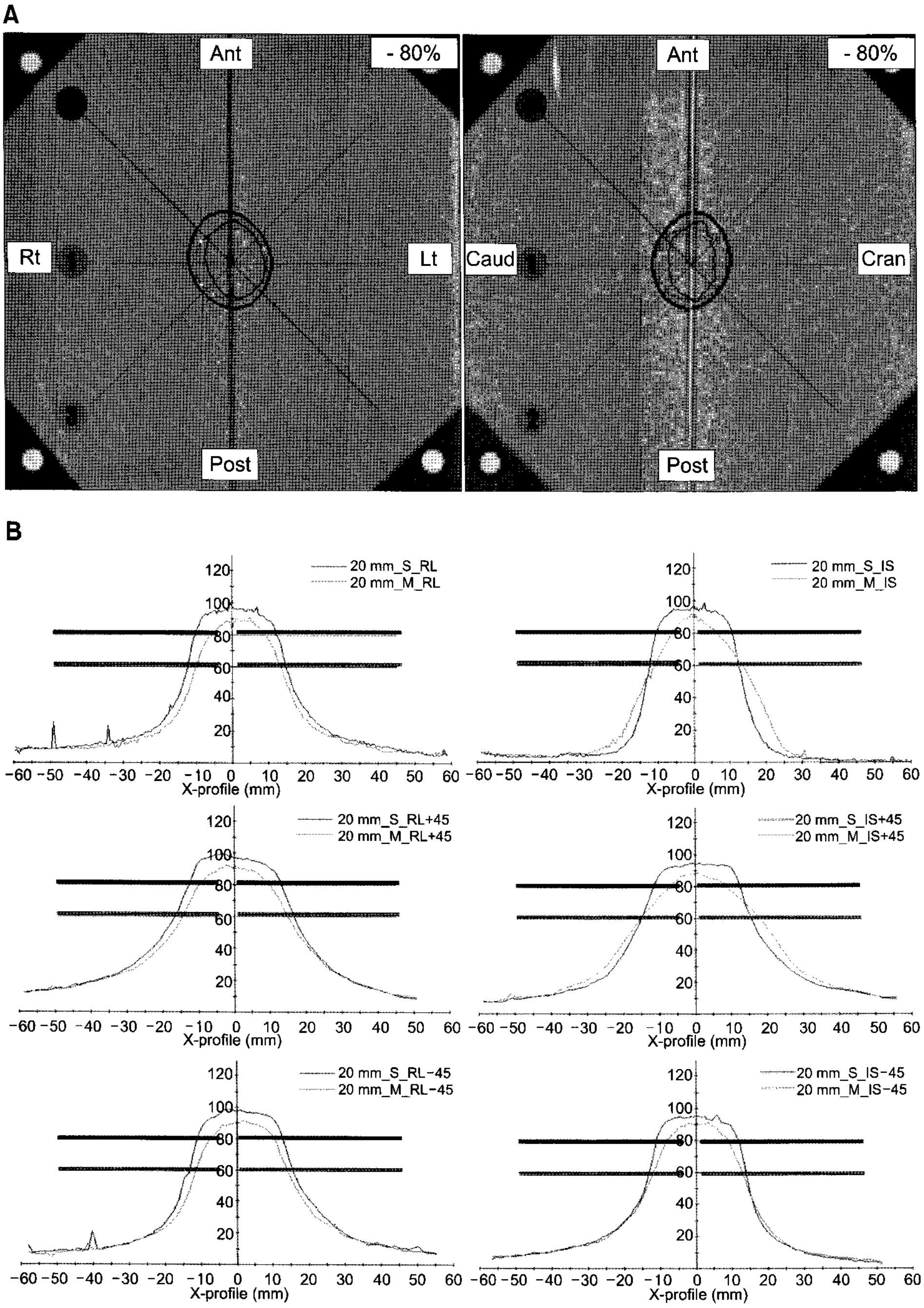

Fig. 3. The films (A) and two-dimensional dose profiles (B) when a 20 mm tumor was moving by 5, 10, 20 mm at the right-left, anterior-posterior and cranio-caudal directions, respectively.

severe than for the other tumor sizes. To compensate for tumor motion, the isodose had to be reduced from 80% to 60% to cover the whole tumor. However, there was no point less than 80% minimum isodose inside the tumor, and in the area beyond the tumor, there was not much difference in dose distribution owing to the motion (Fig. 2). For a 30 mm diameter tumor, the difference in distortion was more severe for the anterior and CC directions (Fig. 4). In comparison with the 20 mm diameter tumor, however, the difference in the dose profiles affected by the motion was reduced and whole tumor could be covered when lowering the isodose rate from 84% to 70% (Table 1). As shown in Fig. 5 and 6, the minimum isodose was lowered from 83% to 70% and from 80% to 70% for the 40 and 50 mm diameter tumors, respectively. Moreover, as the size of the tumor increases, the distortion of dose distribution profiles was reduced, in

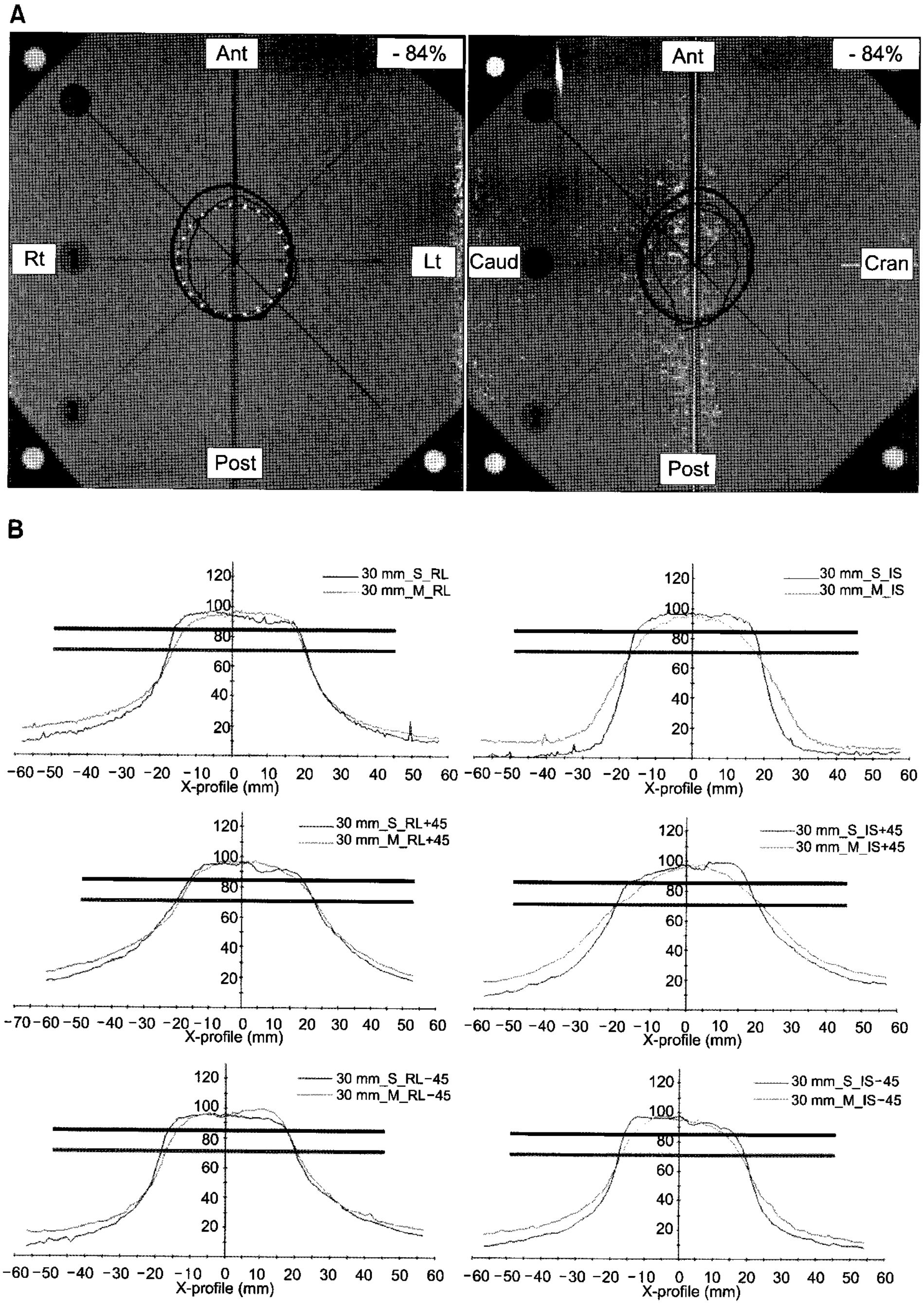

Fig. 4. The films (A) and two-dimensional dose profiles (B) when a 30 mm tumor was moving by 5, 10, 20 mm at the right-left, anterior-posterior, and cranio-caudal directions, respectively.

comparison for the 20 mm diameter tumor even with the same motion.

2. Under dose area due to tumor motion

The underdose areas, which was the area that received less than the prescribed dose due to tumor movement, and the ratio according to the tumor sizes in each CC and RL direction were listed on Table 2. In case of the 20 mm tumor, the ratio of under dose area were 15%, 19%, 16% and 1.8%, in CC and RL direction, respectively. Furthermore, the gap between isodose curves by the motion was 3.2, 3.3, 3.5 and 1.1 mm, in the CC and RL direction, respectively. For the 30 mm tumor, ratios of the under dose area were 10%, 13%, 7.9% and 0%, in the CC and RL direction, respectively. Gaps between isodose curves were 3.9, 4.2, 2.8 and 0 mm in the CC and the RL direction, respectively. In case of the 40 mm tumor, ratios were 7.9%, 10%, 0.2% and 0% and gaps between isodose curves by the motion were 4.0, 4.8, 1.1 and 0 mm, in the CC and the RL direction, respectively. In case of the 50 mm diameter tumor, ratios were 6.1%, 6.1%, 0% and 0% and gaps were 3.9, 3.9, 0 and 0 mm in the CC and the RL direction, respectively.

Discussion and Conclusion

To mimic tumor respiration, we selected 5 mm, 10 mm, and 20 mm moving in the RL, AP and CC directions, respectively, as the range of motion to simulate tumor motion on basis of evaluation of 12 lung cancer patients in our hospital. Furthermore, the moving cycle of the phantom was

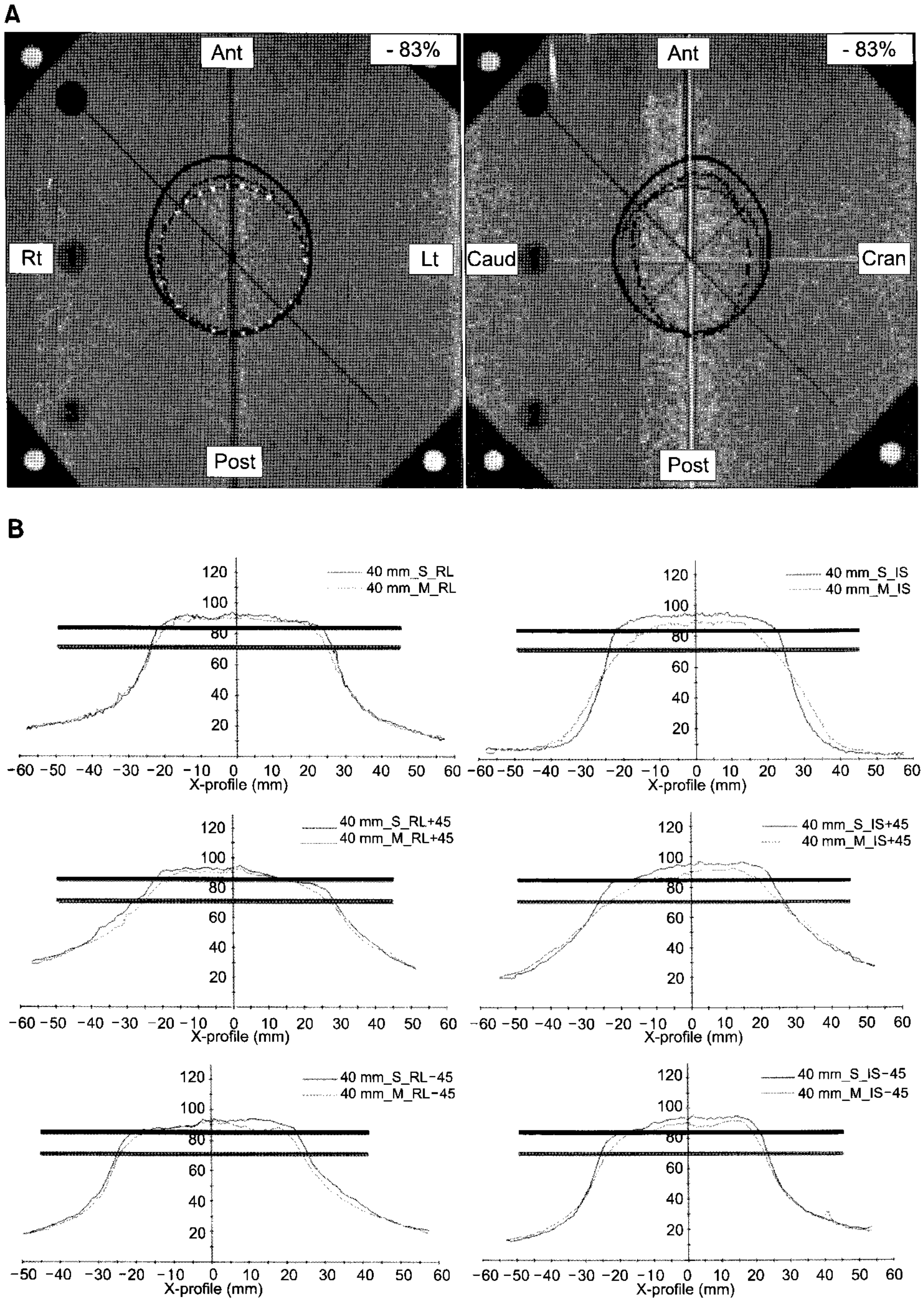

Fig. 5. The films (A) and two-dimensional dose profiles (B) when a 40 mm tumor was moving by 5, 10, 20 mm at the right-left, anterior-posterior, and craniocaudal directions, respectively.

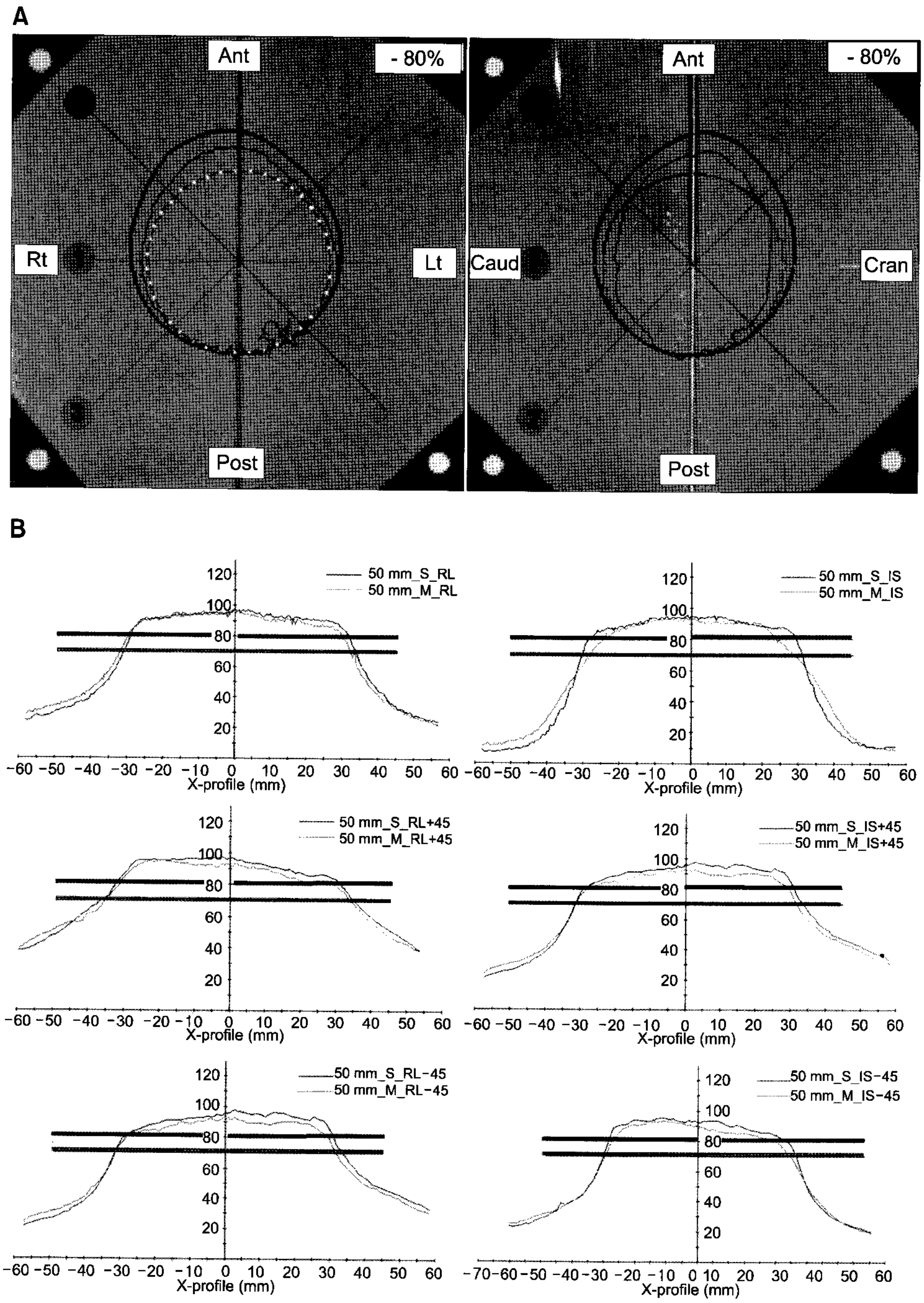

Fig. 6. The films (A) and two-dimensional dose profiles (B) when a 50 mm tumor was moving by 5, 10, 20 mm at the right-left, anterior-posterior, and cranio-caudal directions, respectively.

Table 1. Minimum Isodose Rates Required to Cover the Distortion of Dose Profiles Induced by Movement of the Phantom

Diameter of tumor (mm)	Minimum Isodose rate (%) to cover the tumor	
	Static phantom	Moving phantom
20	80	60
30	84	70
40	83	70
50	80	70

set as 4.4 seconds, an average obtained through a fluoroscopy study of patients. In a study by Jiang and colleagues[6] simulating tumor motion, the moving cycle of the phantom was maintained in the range of 3.5~4 seconds, which was based on a previous study by Ozhasoglu et al.[7]

In the case of IMRT, the interplay effect has been well studied but few studies have been performed for tomotherapy and there have been no studies using a CK. As a result

Table 2. Under Dose Area and Ratio according to the Tumor Diameter Under a Moving Range of 5, 10, and 20 mm

Diameter of tumor (area)	Film orientation	Underdose area (mm^2)	Underdose area ratio (%)	Gap* (mm)
20 mm (314.2 mm^2)	Cranial	46.7	14.9	3.2
	Caudal	59.4	18.9	3.3
	Right	51.5	16.4	3.5
	Left	5.5	1.8	1.1
30 (706.9 mm^2)	Cranial	71.2	10.1	3.9
	Caudal	91.9	13.0	4.2
	Right	55.7	7.9	2.8
	Left	0	0	0
40 (1,256.6 mm^2)	Cranial	99.5	7.9	4.0
	Caudal	128.7	10.2	4.8
	Right	10.2	0.2	1.1
	Left	0	0	0
50 (1,963.5 mm^2)	Cranial	120.6	6.1	3.9
	Caudal	118.9	6.1	3.9
	Right	0	0	0
	Left	0	0	0

*Gap between planned and distorted isodose curve due to movement

obtained by mathematically simulating the interplay effect using an analysis model in IMRT using a multi-collimator, Yu and colleagues8) reported that this effect is detemined by the relative speed of the tumor and multi-collimator and the relative width of the multi-leaf gap and tumor motion. In addition, Pemler and colleagues9) showed that the change of dose distribution was caused by a variety of factors, including wedge angle, the amount of tumor motion, respiratory speed, asymmetry of the respiratory cycle, energy and dose rate, in IMRT using dynamic wedges. However, this study was criticized because a single beam was used and a multi-collimator and the tumor motion occurred in the same direction. For that reason, Jiang and colleagues6) assumed that the mutual motion of the tumor and collimator cannot be in the same direction in a clinical situation and thus the interplay effect can be completely different depending on an angle between the tumor and the moving collimator. For example, a tumor moves in the CC direction while the collimator moves in the RL direction in treating lung cancer and thus the study was done that the tumor was moving perpendicularly to the collimator.

In studies performed by Yu and colleagues8) and Pelmer and colleagues,9) a conclusion was reached that the difference of dose distribution can be reduced by expanding the width of the leaf of the multileaf collimator. However, the study by Jiang and colleagues6) in which the collimator moved perpendicular to that of the phantom, it was concluded that the leaf was not important to determine difference of dose distribution. Unlike the situation with a single fraction, if 30 fractions were implemented, the changes in dose distortion became minimal, which was induced by the convolution effect.2,6,10,11) The time of beam exposure and the respiratory cycle of a patient are different every time for each fraction or for many radiation fields, which could compensate for the tumor motion. That is, for one field and single fraction study conducted for two patients, the maximum dose difference due to motion was 12% and 30%, respectively, while in the case performed with five radiation fields and 30 fractions, the difference was 1.5% and 5%, respectively. As a radiation dose rate (%) gets lower, namely as the treatment time gets longer, the interplay effect decreases. This suggests that the interplay effect in RT with many radiation fields or many fractions in clinical applications may not be significantly meaningful. However, when the fraction size decreases or the number of radiation fields are reduced, the interplay effect would not be negligible.

The interplay effect and convolution effect that occur both CK treatment as well as IMRT. In conventional radiation therapy, if a tumor is assumed to move 20 mm, 30 mm and 40 mm in the AP, RL, and CC direction as in our study, we must put the margin in the same range to cover the blurring effect. However, this study shows that the margin can be placed at a maximum of 5 mm below half of the moving range. Because CK treatment takes 28 minutes and uses 104 beams to irradiate with a dose of 30 Gy, this study also shows that more radiation fields and an increase of treatment time can decrease the interplay effect through the convolution effect, as seen in the study of Jiang and colleagues.

In our study, two parameters were considered that affected the interplay effect. In clinical practice, because tumor motion in patients arises in three-dimensions, the interplay effect becomes more complicated than in single dimenstion. In this study, we adopted the maximum amount of possible motion that can occur in actual patients and so motion range of every tumor could be assumed to be included in this range. Another parameter is the size of the tumor. In this study, tumors were considered as spheres with diameters of 20 mm, 30 mm, 40 mm and 50 mm. It was shown that the ratio of under dose area to the tumor area increases with the decreasing size of the tumor. In a tumor with a 20 mm diameter, the area where a tumor was covered with less than the prescribed dose was as much as 33% of the tumor area in a plane. For a 50 mm diameter tumor, up to about 12% was covered with less than the prescribed dose. These results indicate that much care should be taken as a tumor becomes smaller as the relative ratio of under dose area becomes higher. In addition, the under dose distribution in a tumor takes place along the CC direction where the tumor motion is the largest, and this has a tendency to be higher in the caudal direction.

In a tumor of 20 mm diameter, treating the tumor with an 80% isodose curve can be planned, but in actual treatment, a 60% isodose curve will should be chosen owing to tumor motion. In tumors with a diameter of 30 mm, 40 mm and 50 mm, the entire tumor was covered if an isodose curve of ~70% was selected. It is almost equivalent to put a respiratory margin of about 5 mm in every direction even when the tumor was under the three-dimensional respiration range of 5 mm, 10 mm, and 20 mm in the RL, AP and CC direction. We confirmed that during CK treatment for a moving tumor, the range of distortion produced by the motion was much less than the range of motion itself. However, as the size of a tumor got smaller, the ratio of the under dose area became larger. Thus, when a smaller size tumor under movement is treated by radiosurgery, more attention is necessary.

In addition, the under dose area was wider for the caudal direction than for the cranial direction and for the right direction than for the left direction regardless of the size of a tumor. Further studies should be necessary to evaluate the reasons.

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국문초록

방사선수술에서 종양 움직임을 재현시킨 움직이는 팬텀을 이용하여 선량 분포의 왜곡에 대한 연구

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목 적: 호흡에 의한 종양의 움직임은 사이버나이프를 이용한 정위적 방사선수술과 같은 정확한 치료에 있어 고려할 만한 방해 요인이다. 이 연구에서는 사이버나이프를 이용한 방사선 수술의 interplay 현상을 보고자 팬텀을 움직이게 하고 또한 움직이지 않게 하여 선량 분포의 왜곡을 조사하였다.

대상 및 방법: 팬텀은 2.5×2.5×5.0인치의 4개의 직육면체로 구성된 폴리에틸렌과 2장의 Gafchromic 필름으로 구성되었다. 치료 계획은 20, 30, 40, 50 mm 지름을 가진 구를 가상하여 사이버나이프 치료기를 이용하여 104개의 빔 방향과 single center mode의 치료 계획 하에 총 30 Gy를 조사하였다. 특별히 제작된 로봇은 팬텀을 좌우, 전후, 두미쪽으로 각각 5, 10, 20 mm 움직이도록 고안되었다. 필름의 optical density을 이용하여 정적인 상태의 팬텀과 로봇에 의해 움직일 때의 팬텀의 선량 분포를 구하였다.

결 과: 정적인 상태에서 종양을 모두 포함할 수 있는 최소의 등선량은 20 mm 종양의 경우 80%, 30 mm에 84%, 40 mm에 83%이며 50 mm 종양에 80%였다. 정적인 상태와 움직일 때의 팬텀 사이에서 발생한 선량 분포의 차이(gap)는 20 mm 종양에서 두미방향으로 각각 3.2, 3.3 cm이며 오른쪽 3.5 mm, 왼쪽 1.1 mm였다. 30 mm 종양의 경우는 각각 3.9, 4.2, 2.8과 0 mm였고 40 mm 종양은 각각 4.0, 4.8, 1.1, 0 mm였다. 50 mm 종양의 경우 각각 3.9, 3.9, 0.0 mm였다.

결 론: 20 mm의 적은 종양을 치료할 때 80%의 등선량이 계획되더라도 움직이는 실제 치료에 있어 종양 움직임을 보완하기 위하여 60% 등선량으로 처방할 필요가 있다. 이때 두 등선량 곡선의 차이는 5 mm 정도이다. 또한 30, 40 과 50 mm의 종양에서는 움직임을 보완하기 위하여 등선량 곡선을 70% 정도로 처방할 필요가 있다. 이때의 차이도 약 5 mm 미만이다. 이는 사이버나이프를 이용한 방사선수술 시 움직임 그 차체 보다 여유폭을 적게 줄 수 있다는 의미이며 이는 일반 방사선치료와 다른 점이라 할 수 있다.

핵심용어: 팬텀, 종양 움직임, 등선량 곡선, 방사선수술