Beam Shaping by Independent Jaw Closure in Stereotactic Radiotherapy

Yong Chan Ahn, M.D.*, Byung Chul Cho, Ph.D.†, David R. Choi, Ph.D‡,
Dae Yong Kim, M.D.*, Seung Jae Huh, M.D.*, Do Hoon Oh, M.D.†, Hoonsik Bae, M.D.†,
In Hwan Yeo, Ph.D.*, and Young Eun Ko, M.S.†

*Department of Radiation Oncology, Samsung Medical Center, Sungkyunkwan University, School of Medicine,
†Department of Radiation Oncology, Kangdong Sacred Heart Hospital, Hallym University, School of Medicine,
‡Department of Radiation Physics, Tom Baker Cancer Centre, Department of Oncology, University of Calgary

Introduction: Stereotactic radiation therapy (SRT) can deliver highly focused radiation to a small and spherical target lesion with very high degree of mechanical accuracy. For non-spherical and large lesions, however, inclusion of the neighboring normal structures within the high dose radiation volume is inevitable in SRT. This is to report the beam shaping using the partial closure of the independent jaw in SRT and the verification of dose calculation and the dose display using a home-made soft ware.

Materials & Methods: Authors adopted the idea to partially close one or more independent collimator jaw(s) in addition to the circular collimator cones to shield the neighboring normal structures while keeping the target lesion within the radiation beam field at all angles along the arc trajectory. The output factors (OF's) and the tissue-maximum ratios (TMR's) were measured using the micro ion chamber in the water phantom dosimetry system, and were compared with the theoretical calculations. A film dosimetry procedure was performed to obtain the depth dose profiles at 5 cm, and they were also compared with the theoretical calculations, where the radiation dose would depend on the actual area of irradiation. Authors incorporated this algorithm into the home-made SRT software for the isodose calculation and display, and was tried on an example case with single brain metastasis. The dose-volume histograms (DVH's) of the planning target volume (PTV) and the normal brain derived by the control plan were reciprocally compared with those derived by the plan using the same arc arrangement plus the independent collimator jaw closure.

Results: When using 5.0 cm diameter collimator, the measurements of the OF's and the TMR's with one independent jaw set at 30 mm (unblocked), 15.5 mm, 8.6 mm, and 0 mm from the central beam axis showed good correlation to the theoretical calculation within 0.5% and 0.3% error range. The dose profiles at 5 cm depth obtained by the film dosimetry also showed very good correlation to the theoretical calculations. The isodose profiles obtained on the home-made software demonstrated a slightly more conformal dose distribution around the target lesion by using the independent jaw closure, where the DVH's of the PTV were almost equivalent on the two plans, while the DVH's for the normal brain showed that less volume of the normal brain receiving high radiation dose by using this modification than the control plan employing the circular collimator cone only.

Conclusion : With the beam shaping modification using the independent jaw closure, authors have realized wider clinical application of SRT with more conformal dose planning. Authors believe that SRT, with beam shaping ideas and efforts, should no longer be limited to the small spherical lesions, but be more widely applied to rather irregularly shaped tumors in the intracranial and the head and neck regions.

INTRODUCTION

For many years, linear accelerator based stereotactic radiation therapy (SRT) has become an established radiotherapy modality that can deliver highly focused radiation to the small and spherical target lesion. The basic concept of SRT technique can be summarized as multiple non-coplanar arc therapy converging to an isocenter using the circular collimator cones with the aid of stereotactic immobilization and localization system. The recommendation to achieve a spherical isodose surface in SRT by XKnife-3 system (Radionics Inc., Burlington, MA, USA) is to use the so-called "standard arcs", which adopts the total arc degree of 300° or greater with 30° to 45° couch separations.(1) This recommendation is usually most effective for relatively small and spherical lesions. The "standard arcs", however, may often lead to significant radiation exposure of the surrounding critical normal structures and their irreversible damages, especially if the target lesions are neither in the spherical shape nor of small size. Occasions are encountered not infrequently, when it is very difficult to exclude the radiation-sensitive critical normal structures from within the circular collimator cones, as they are parallel and quite close to the target lesion. Several modifications for better dose distribution around the target lesion may be considered depending on the size and the shape of the lesion, and the geographic relationship to the surrounding normal structures that should not be given high dose radiation to avoid complication risk. Examples of such modifications include individualized positioning of the arcs, adjustment of the arc magnitude, use of multiple isocenters, use of collimator cones of different sizes on the same isocenter, and the differential weighting of each arc. Authors reported a few of these modifications for beam shaping in SRT for irregular shaped and relatively large lesions, which are very frequently encountered in routine clinical practice.(2) XKnife system was commissioned and has been in clinical use since Feb. 1995 in the authors' institute. More than 300 cases were treated with either single fraction stereotactic radiosurgery or fractionated stereotactic radiotherapy until the end of 1999 at the authors' institute. Authors adopted the idea of partial closing of one or more independent collimator jaw(s) to shield the normal structures from the circular field without losing the advantage of mechanical accuracy. This study is to report the beam shaping by the independent jaw closure and the verification of dose distribution by home-made soft ware.

MATERIALS AND METHODS

The idea of closing the independent collimator jaw(s) is schematically demonstrated in the Fig. 1. When the target lesion needing high dose irradiation is so located that it is very close and parallel to the normal structure (the spinal cord in this illustration), it is inevitable to include some portion of the neighboring normal structure within in the circular beam of SRT. In this situation, one can rotate the collimator assembly so that it is parallel to the interface between the target and the normal structure and close one independent collimator jaw to shield and exclude the normal structure out from the circle. One should arrange the collimator assembly rotation angle and the independent jaw setting to make sure that the target lesion is within the area of irradiation while maintaining the maximal shielding of the normal structure at all arc angles along the arc trajectory. In other words, the magnitudes of the jaw closure and the collimator rotation are individually determined on the beam's eye view (BEV) projections.

The XKnife-3 system was capable of dose calculation and display for the circular collimator settings only and not for the shaped beams by independent jaw closure. The changes of the output factor (OF) by the collimator jaw closure and the subsequent shrinkage of the radiation field were calculated by the equivalent field formalism based on the fact that they should depend on the actual area of the radiation exposure. The conventional tissue-maximum ratio (TMR) dose calculation algorithm of the circular collimator was expanded to the dose calculation of the shaped beams using the independent jaw closure (Equation).

Equation : $D\ (d,r,fs_{Eq})=OF\ (fs_{jaw};\ fs_{Eq})\times TMR\ (d,fs_{Eq})\times OAR_{cone}(r)\times OAR_{jaw}(x)\times OAR_{jaw}(y)\times F^2$

The OF depended on both the equivalent jaw opening (fs_{jaw}) and the equivalent field size (fs_{Eq}) which was determined by the area of the unblocked field. The TMR was determined by equivalent field formalism. The penumbra was modeled by fitting the penumbra function, and the whole penumbra was the production of each off-axis ratio (OAR) of the cone size (r), x and y jaw openings, respectively. F^2 meant the inverse square correction.

In order to see whether the calculations were valid or not, actual measurements of the OF's, and the TMR's were undertaken using the Exradin A-14 micro ion chamber (0.009 cc, Exradin Inc, Lisle, IL, USA) in the water phantom dosimetry system using 6 MV X-rays. One of the independent jaws was set at 30 mm, 15.5 mm, 8.6 mm, and 0 mm from the central beam axis, respectively, with the 5.0 cm diameter circular collimator cone. These measurement data were then compared with the theoretical calculation data. Once authors became confident of the validity of the calculation, a film dosimetry procedure was performed using Kodak XV-2 film and VIDAR VXR-12 scanner (Vidar Systems Corp. Herndon, VA, USA) to obtain the dose profiles. The collimator size and the independent jaw settings were the same as the OF and TMR measurements. The dose profiles at 5 cm depth were obtained and they were also compared with the theoretical calculations.

Authors incorporated this algorithm into the home-made SRT software for the isodose calculation and display, and was tried on an example case with single brain metastasis. After establishing the optimal arc arrangements, while using the circular collimator cone only, the dose-volume histograms (DVH's) of the planning target volume and the normal brain were obtained. A rival plan was established, which employed the same arc arrangement plus the independent jaw closure for normal brain shielding, and the subsequent DVH's of the same anatomical regions were reciprocally compared.

RESULTS

The micro-ion chamber measurements of the OF's with one independent jaw set at 30 mm (unblocked), 15.5 mm, 8.6 mm, and 0 mm from the central beam axis, respectively, showed good correlation to the theoretical calculation within 0.5% error range (Fig. 2). The actual measurements of the TMR's with the same independent jaw settings also showed very good correlation to the theoretical calculation within 0.3% error range, and two examples (independent jaw set at 15.5 mm and 0 mm) were demonstrated on the Fig. 3. The dose profiles at 5 cm depth obtained by the film dosimetry and those by calculations based on the authors' equation were demonstrated on the Fig. 4, with the independent jaw setting at 30 mm (unblocked), 15.5 mm, and 0 mm, which also showed very good correlation to each other.

The Fig. 5 displayed the SRT plan by 6 MV X-rays of an example case with solitary brain metastasis, in which the maximum and minimum lengths of the tumor were 50 mm and 33 mm, respectively. The total arc degree of 540° (with the 40 (couch separations by five arcs of 50 mm diameter circular collimator

Fig.4. 참조

cone was used to adequately cover the tumor and was established as the control plan, and the planning target volume (PTV) was 28 ml. After establishing the control plan, a rival plan was derived by changing the independent jaw settings with the same arc arrangements. During this modification, the positions of the independent jaw and the collimator angles were adjusted to conform to the target shape on the BEV projections (Fig. 5). The resulting isodose profiles demonstrated that, by using the independent jaw cl osure, a slightly more conformal dose distribution around the target lesion was achievable (Fig. 6). The DVH's of the PTV was almost equivalent on the two plans, while the DVH's for the normal brain showed that less volume of the normal brain receiving high radiation dose by using this modification than the control plan employing the circular collimator cone only (Fig. 7). The volume of normal brain exposed to higher radiation than the minimum dose of the PTV (80% of isocenter dose) was reduced to 66% after applying the beam shaping by the independent jaw closure.

DISCUSSION AND CONCLUSION

The mechanical devices for the accuracy in the target localization with the guaranteed level and the computerized treatment planning software are the essential requirements for successful SRT.1, 3 7) It has been generally accepted that SRT should be ideally limited to the relatively small and spherical intra-cranial lesions. On many practical and frequent occasions, however, the shapes of the target lesions are not always spherical, but rather irregular and larger. Authors designed and made new collimator cones with relatively larger aperture sizes for fractionated stereotactic radiation therapy.8) Recent incorporation of the concept of ‘ conventional fractionation' into the stereotactic method has contributed to the decrement of radiation complication risk.5, 6, 9) Multiple fractional treatments using stereotactic method have become possible with the development of the non-invasive and relocatable stereotactic frames.3, 5, 6, 9) With the widening clinical indications of SRT, the need for more conformal radiation dose to and around the target lesions has increased. Alternative solutions to overcome the risk of complication when treating tumors of irregular shape and of large size may include the use of dynamic micro-multi-leaf collimator inx SRT or 3-dimensional conformal radiotherapy (3-D CRT). But the dynamic beam shaping by the micro-multi-leaf collimator system still remains to be improved for practical application, and 3-D CRT using either multiple static beams or rotating arcs may lack the mechanical accuracy in patient immobilization of the same level as in SRT. The main aim of this report was to lower the risk of complication by excluding the radiation sensitive normal structures from the circular target using the independent collimator jaw closure, while making the maximum use of SRT system that has the advantage of accurate immobilization and localization.

Authors have already used a few other modification methods in SRT dose planning. Individualized determination of the number of targets, the sizes of the collimator cones, and the positions and magnitudes of the arcs so that each convergent arc hits as little amount of the critical normal structures as possible on the beam's-eye-view projections are the examples.2) Using micro-ion chamber and film dosimetry measurements of several parameters for dose calculation with partially closed independent collimator jaw, authors could verify that the theoretical calculations were quite close to the actual measurements. Our goals are to achieve as homogenous dose in the target as possible while minimizing the radiation exposure of the surrounding normal structures, which can be accomplished after the comparison of the DVH's derived by a few rival plans.4, 10) Deriving a few rival plans and their comparison with respect to dose distribution and DVH profiles became possible by the software developed by the authors. With these modifications, authors usually have been able to achieve more favorable dose distributions in and around the target lesions by a few modifications than the usual standard arc plans. We were able to incorporate the idea of independent jaw closure technique into the home-developed stereotactic planning software after through dosimetric verification procedures described above. With the beam shaping modification using the independent jaw closure, authors have realized wider clinical application of SRT with more conformal dose planning. Authors believe that SRT, with beam shaping ideas and efforts, should no longer be limited to the small spherical lesions, but be more widely applied to rather irregularly shaped tumors in the intracranial and the head and neck regions.

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국문 초록

정위방사선치료 시 독립턱 부분폐쇄를 이용하는 선량분포개선 방법

성균관대학교 의과대학 삼성서울병원 치료방사선과학교실[*], 한림의대 강동성심병원 치료방사선과학교실[†]
캘거리대학 Tom Baker 암센터 방사선물리학과[‡]

안용찬* · 조병철[†] · 최동락[‡] · 김대용* · 허승재* · 오도훈[†] · 배훈식[†] · 여인환* · 고영은[†]

서 론 : 정위방사선치료는 높은 정밀도로 크기가 작고 구형인 병변에 국한하여 방사선을 조사할 수 있는 기술이지만 병변의 모양이 구형이 아닌 경우에는 병변 주변의 정상조직에 고선량의 방사선이 조사될 수 있다. 본 연구는 독립턱을 부분적으로 폐쇄하여 방사선량 분포를 개선하는 방법, 선량계산과 선량분포의 도시방법을 보고하고자 한다.

방 법 : 정위방사선치료 시의 호의 궤적상 병변은 방사선조사영역 내에 포함하면서 주변 정상조직을 최대한 차폐하도록 원형 콜리메이터와 독립턱 부분폐쇄를 적절히 조합하였다. 물 펜톰과 마이크로 전리함을 이용하여 출력인자와 조직최대선량비를 측정하여 이론적 계산치와 비교하였다. 필름선량측정계를 이용하여 5 cm 깊이에서의 심부선량분포를 측정하여 계산치와 비교하였다. 이와 같은 측정자료를 자가 개발한 치료계획 프로그램에 반영하여 뇌전이 환자의 정위 방사선치료 선량계산과 도시에 적용하여 원형 콜리메이터만을 이용하였을 경우와 독립턱 부분폐쇄를 추가하였을 경우의 병변과 정상 뇌의 선량체적표를 각각 비교하였다.

결 과 : 5.0 cm 직경의 원형 콜리메이터를 사용하고 한 쪽 독립턱을 중심축으로부터 30 mm, 15.5 mm, 8.6 mm, 0 mm 까지 열었을 때 측정한 출력인자와 조직최대선량비는 계산치와 각각 0.5%와 0.3%의 오차범위로 잘 부합하였다. 필름선량계로 얻은 5 cm 깊이의 심부선량분포도 역시 계산치와 잘 부합하였다. 자가 개발한 치료계획 프로그램으로 병변과 정상 뇌의 선량체적표를의 상호 비교를 통하여 독립턱 부분폐쇄를 적용한 경우에 있어서 보다 개선된 선량분포를 얻을 수 있음을 확인하였다.

결 론 : 정위방사선치료에 있어서 독립턱의 부분폐쇄를 적용함으로써 보다 개선된 선량분포계획을 얻을 수 있으며 이를 적용하여 비교적 크기가 크고 모양이 불규칙한 병변에 대하여도 정위방사선치료를 확대 적용할 수 있겠다.

핵심용어 : 정위방사선치료, 선량분포계획

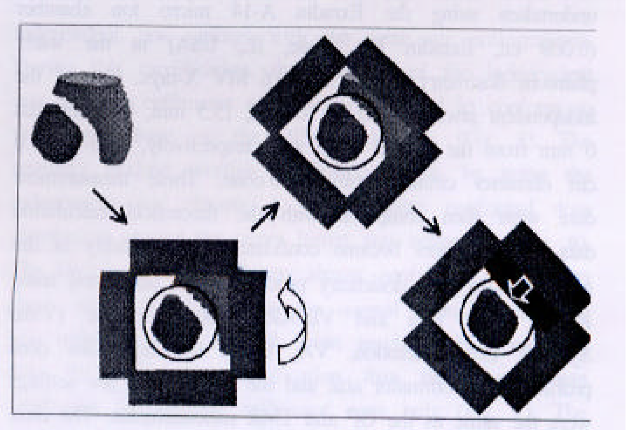

Fig. 1. Schematic illustration of beam shaping idea by independent collimator jaw closure. Suppose that the tumor is in more or less elongated shape and close and parallel to the brainstem, inclusion of some portion of the brainstem within the circular collimator field is inevitable. After rotating the collimator jaw assembly so that it parallels the tumor-brainstem interface, one independent collimator jaw is partially closed to exclude the brainstem from the radiation field. The determination of the collimator rotation and the independent jaw closure is made on the beam's eye view projection along the entire arc trajectory considering the tumor shape and its relationship to the surrounding normal tissue.

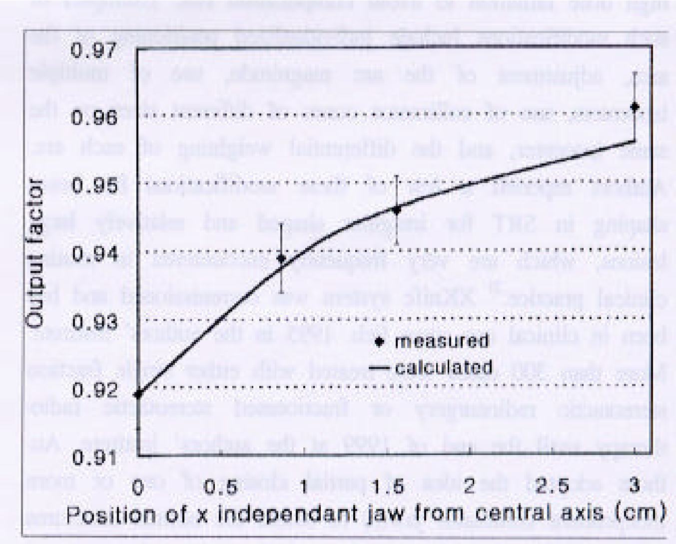

Fig. 2. The measured (symbol) and calculated (line) output factors as a function of the independent jaw position from the central axis for 50 mm diameter collimator cone. The measurements were done with one independent ja positions at 30 mm (unblocked), 15.5 mm, 8.6 mm, and 0 mm from the central axis, respectively, using 0.009 c micro ion chamber (Extradin A-14). All the measured data were within 0.5% error range of the calculated values (err bar).

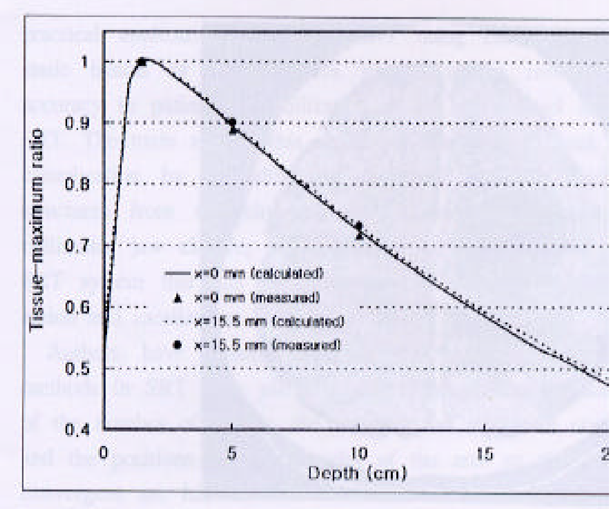

Fig. 3. The measured (symbols) and calculated (lines) tissue maximum ratios as a function of the independent jaw positions from the central axis for 50 mm diameter collimator cone. The measurements were done with one independent jaw positions at 15.5 mm and 0 mm from the central axis, respectively, using 0.009 cc micro ion chamber (Extradin A-14). All the measured data were within 0.3% error range of the calculated values.

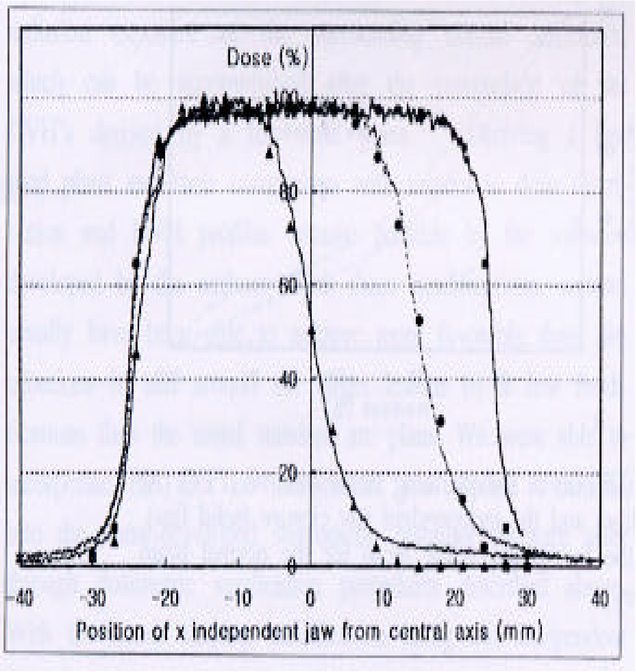

Fig. 4. The measured (lines) and calculated (symbols) dose profiles at 5 cm depth for 50 mm diameter collimator cone. The measurements were performed with one independent jaw positions at 30 mm (unblocked), 15.5 mm, and 0 mm from the central axis, respectively, using film dosimetry procedure (Kodak XV-2 film and VIDAR VXR-12 scanner).

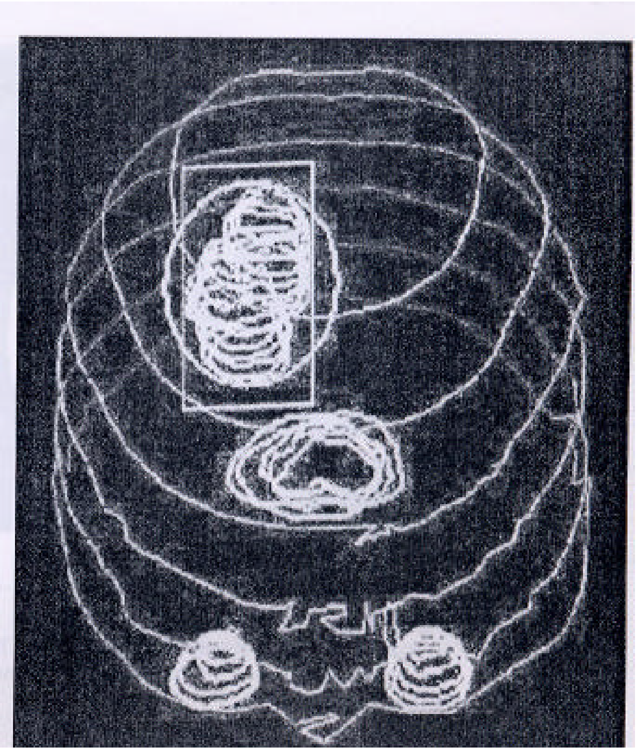

Fig. 5. Partial closure of independent collimator jaws on the beam's eye view projection in an example case with solitary brain metastasis is demonstrated.

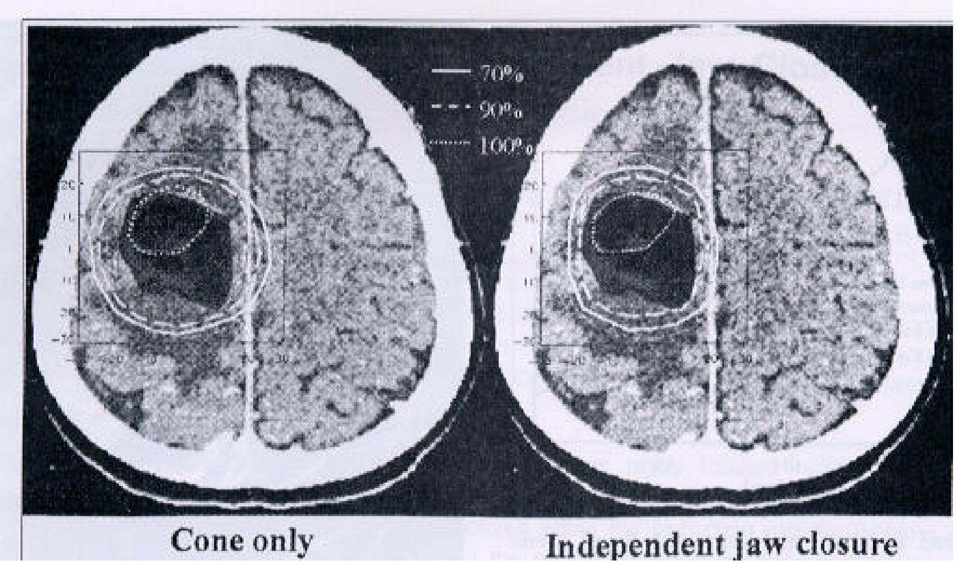

Fig. 6. Isodose profiles by circular cone only (left) and by independent jaw closure (right) on an example case of single brain metastasis. The isodose profiles demonstrated that, by using the independent jaw closure, a slightly more conformal dose distribution around the target lesion was achievable.

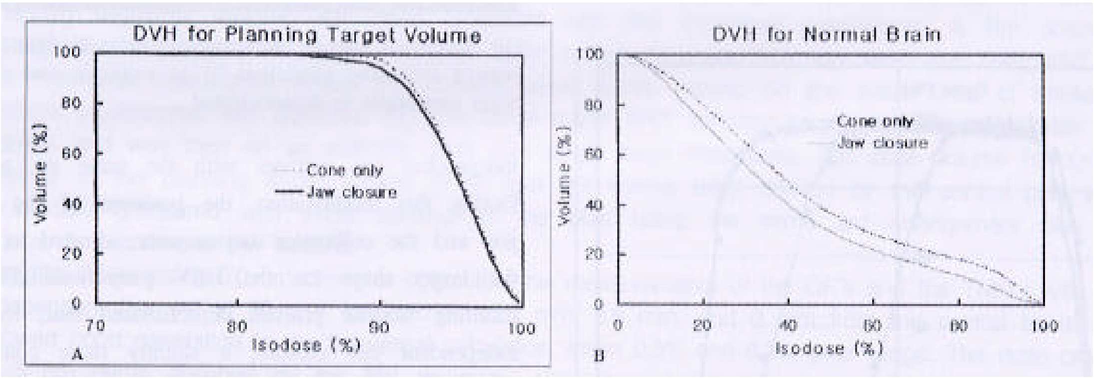

Fig. 7. Comparisons of the dose-volume histograms (DVH's) of the planning target volume (PTV) (A) and the normal brain (B) by the cone only (dotted line) and the independent jaw closure (solid line). The DVH's of the PTV was almost equivalent on the two plans, while those for the normal brain showed that the advantage by using this modification.