Commissioning of modulator-based IMRT with XiO treatment planning system.

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ABSTRACT

This paper describes the procedures for the correction of the modulator thickness and commissioning of XiO treatment planning system (TPS) for the modulator based intensity modulated radiation therapy (M-IMRT). Our modulator manufacturing system adopted methods in which the modulator is milled using a floor-type computer-aided numerical control milling machine (CNC-mill) using modulator data calculated by XiO TPS.

XiO TPS uses only effective attenuation coefficients (EAC) for modulator thickness calculation. This paper describes a modified method for modulator thickness. A two-dimensional linear attenuation array was used to correct the modulator thickness calculated by XiO. A narrow-beam geometry was used for measuring the linear attenuation coefficient (LAC) at off-axis positions (OAP) for varying brass thickness. An equation for two dimensional LAC ratio (2D-LACR) can be used to calculate the corrected modulator thickness. We assumed that the broad beam EAC of a small field varies with the brass thickness and the OAP distance in the same way as that of LACR. Therefore, the two-dimensional EAC (2D-EAC) is equal with the EAC corrected by using the LACR.

We evaluated the dose distribution for 3 geometric patterns and one clinical case for low energy x-ray (4 MV) with the large field size (20 x 20 cm^2). At each pattern, the optimized brass modulator had a good agreement with the dose and the dose distribution calculated by TPS. Our method for the correction of the brass modulator thickness using the 2D-LACR is effective in accuracy improvement of M-IMRT in XiO TPS.

The important problem for the brass modulator is the milling condition such as the drill diameter and the cutting pitch size. It is necessary for the accuracy improvement of M-IMRT that the “softening“ effect and the “hardening” effect of the beam are considered for dose calculation in the patient and modulator profile design.

1. INTRODUCTION

Intensity modulated radiotherapy (IMRT) is a major development in the delivery of three-dimensional conformal radiation therapy. A major advantage that IMRT offers is a more conformal radiation dose to the planning target volume (PTV) and minimize the dose to surrounding normal tissues. IMRT is based on the use of optimized non-uniform radiation beam intensities incident on the patient. Either computerized dynamic multileaf collimator (D-MLC) IMRT[1, 2)] or segmental MLC (S-MLC) IMRT[3,4)] have been most commonly used. Another method such as physical modulator (compensating filter) IMRT (M-IMRT)[5-7)], intensity-modulated arc therapy (IMAT)[8,9)], helical tomotherapy IMRT[10)], and Robotic linear accelerator IMRT[11)] are available in modern radiation therapy. The University of North Carolina began to develop the compensator-IMRT technique in 1993 before any accelerator MLC systems were commercially available[12)].

We focused in M-IMRT in these methods because it has many advantages over S-MLC IMRT and D-MLC IMRT. The advantages of M-IMRT in comparison to the traditional IMRT with the MLC are fine spatial resolution, a variation of consecutive intensity gradation, lower monitor units and short treatment time, the possibility of larger field sizes (no need for split fields), a good daily reproducibility, and less complicated quality assurance (QA) procedure[13)]. The most important advantage is the application for a moving target IMRT and large field IMRT. Ehler et al[14)] reported that M-IMRT consistently provided the most temporally uniform dose to the moving target while DMLC provided the least. Many commercial three-dimensional treatment planning systems (3D-TPS) including XiO treatment planning system (TPS) (CMS. Inc., St. Louis, Missouri, USA) are available to calculate the MLC field shape and the leaf sequence pattern and also to design the modulator for IMRT. We performed commissioning for M-IMRT with XiO TPS.

Our modulator manufacturing system adopted a method, in which the modulator is milled using a floor type computer-aided numerical control milling machine (CNC-mill) with the modulator data calculated by XiO TPS using .decimal(Sanford, FL, USA) application. The data file is sent to a filter delivery service, and a modulator is machined in the factory. But our hospital does not use such a delivery service. Therefore, we decided to machine a modulator in our institution. The problem is that a user cannot specify cutting materials, because this application of XiO TPS is specialized for a filter delivery service by .decimal. Modulator materials used in XiO are fixed to a specific brass called “decimalbrass”, and it is not possible to use different modulator materials prepared by user. We cannot use “decimalbrass”, therefore we developed a method to correct a difference of effective attenuation coefficient (EAC) of “decimalbrass” and our brass.

Dose calculations involving modulators requires consideration of the hardening of the primary photon spectrum, beam contamination from the modulator scattered photons, and electron[15-19]. Jiang et al[5] called these effect “beam perturbations” and they described the scatter kernels and energy spectral changes. The change in percentage depth dose (PDD) caused by beam hardening is not significant as that by the mean beam energy. The dose distribution can be calculated from the optimized fluence profile of primary photons without the necessity of considering the scattered photons. The scattered photons influenced in the surface dose are independent of the modulator pattern, and secondary electrons do not have large influence for the deep depth dose. The “beam perturbations” through the modulator are not considered in XiO dose computations[20]. In XiO, the beam modeling process under the modulator is complex and difficult and takes much time and does not include in the commissioning procedure for the .decimal compensator[21]. Therefore in this study, we did not perform the beam modeling corresponding to modulator and used a simple beam model (open field and without treatment aids).

The calculation of the modulator thickness from an intensity map (IM) using the EAC. In XiO, the modulator thickness is calculated by only one EAC that measured in CAX and under an average modulator thickness (3 cm) slab[21, 22]. However, Weber et al[16] reported that dose calculations involving beam modulators that consider only the EAC and the local thickness of the modulator can yield large errors. Jiang et al[5] reported that the calculation of the transmission data for polyenergetic beams is using either analytical method or Monte Carlo simulation. And the point source model can be used in the process of modulator design and modulator thickness calculation is necessary for considering the only primary photons. Dimitriadis et al[23] reported that the broad beam attenuation coefficient varies in a similar manner for large field sizes with filter thickness. We use the narrow beam geometry because of the reduced amount of scatter involved. The linear attenuation coefficient (LAC) of the modulator due to materials, thickness and off-axis position (OAP) in the field are evaluate and consider to correcting the EAC by a LAC array to improve more accurate dose distributions for M-IMRT.

Our correcting procedure for the brass modulator thickness consists of two phases. The first phase is the process to correct the difference of the modulator thickness by the physical density of the brass material. This process uses the EAC acquired in a specific condition and the correction for the changes of the EAC depends on the modulator material. The second phase is the process to correct a modulator thickness array. We measured the two-dimensional LAC

(2D-LAC) for various sets of modulator thickness and OAP. We revised the EAC by the 2D-LAC and made the function for modifying the modulator thickness.

This paper describes the procedures of the correction of the modulator thickness using modified EAC and the commissioning of the dose distributions for the M-IMRT using .decimal application in XiO TPS.

2. MATERIALS AND METHODS

In this study, we used 4 MV x-ray beams from Varian 2100 (Varian Medical Systems, Palo alto, CA, USA). We used XiO three-dimensional treatment planning system version 4.33. A superposition method [24](calculating matrix pitch: 0.2 cm) was selected for dose calculation. An intensity map (IM) matrix size is 0.5 cm and the IM consists of about 45 levels. The modulator thickness (t) calculated by XiO is obtained in two-dimensional matrix (x, y) and each matrix distance is 0.2 cm. The coordinate system (x, y) is defined at the bottom plane of the modulator (x is cross-line direction and y is in-line direction).

The modulator material is the third-level brass (Japan Industrial Standards: JIS C2801, physical density: 8.47 g/cm^3) and the maximum thickness is 6 cm and the minimum thickness is 0.6 cm (base plate thickness). The brass registered in XiO is "decimalbrass" and its maximum thickness is 5.08 cm. The maximum field size in our system is 22 cm x 22 cm at isocenter.

The brass modulator was milled by CNC-mill (Robodrill α-T14iDs, FANUC LTD. Oshino, Yamanashi, JAPAN) (Fig. 1a). The CNC-mill has three drills, whose radii are 1 cm, 0.5 cm, and 0.3 cm. The machine mills the brass by a raster scan method. By this method, the machine cuts the brass in a cross-line (transverse) direction and moves to a step-over in-line (radial) direction and cuts it again in the cross-line direction. In the cross-line direction along the path of the cutter, we interpolate linearly the thickness data. However the resolution in the in-line direction depends on the step-over distance such as 0.2 cm. Figure 1b shows the brass modulator that is attached to a wedge filter slot of a linear accelerator collimator head, and the source to wedge slot distance was 57.6 cm.

The measurement devices are as follows.

・0.6-cm^3 thimble type ion chamber (A12: Standard imaging. Inc., WI, USA) for the measurement of the EAC and the LAC value.

・0.13-cm^3 thimble type ion chamber (CC13: Scanditronix-Wellhoefer. Inc., Schwarzenbruck, Germany) used with the three dimensional water phantom (OmniPro-Accept, version 6.3: Scanditronix-Wellhoefer. Inc., Schwarzenbruck, Germany) for the measurement of the dose profile in water.

・Radiographic film (EDR-2, Eastman Kodak Company, Rochester, NY, USA) for measurement of the two dimensional dose distribution. DD-System version 2.1 (R-Tech. Inc., Tokyo, JAPAN) was used to analyze the EDR-2 film.

・Solid water phantom (Gammex RMI, WI, USA) was used to measure the EAC and for EDR-2 film.

・Mini phantom (Toyo medic. Inc., Tokyo, JAPAN: diameter is 4 cm) made by PMMA material was used to measure the LAC and the measurement depth was 10 cm.

2A. Measurements of EAC

Transmissions of brass material were measured in the solid water phantom with a 0.6-cm^3 ion chamber. A 1 cm thick slab of the brass was placed in the beam at level of wedge filter tray (57.6 cm from the source). Measurements of EAC for the brass was made at the depth of 10 cm in the solid water phantom for the field size of 5 x 5 cm^2, 10 x 10 cm^2, 15 x 15 cm^2, 20 x 20 cm^2, and 25 x 25 cm^2 at 90 cm source-to-surface distance (SSD).

2B. Corrections of EAC for modulator material

We corrected the difference of the modulator thickness by the difference of EAC of the brass and “decimalbrass” registered in XiO using the EAC from calculating dose distribution of XiO (μ_{eff}^{calcu}) and measured EAC ($\mu_{eff}^{measure}$). XiO designed the IM for a two tone pattern geometry shown in Figure 2a. We obtained doses at two symmetric points (OAP ±5cm) on the dose distribution calculated with XiO. We assumed the thickness of brass t for the XiO calculation.

We made the modulator calculated by the plan mentioned above and measured a beam profile by Blue Phantom. We measured dose at two symmetric points (OAP ±5cm). We assume real thickness of brass t'; the measured EAC ($\mu_{eff}^{measure}$) is obtained from the measured dose distribution.

We assumed that the thickness t' cm of the brass of $\mu_{eff}^{measure}$ was necessary to obtain the same transmission as the thickness t cm.

Therefore,

(1)

Thus the modulator thickness matrix after the density correction is given by:

(2)

where is the modulator thickness matrix before the density correction (original brass thickness matrix data by XiO).

2C. Measurements of LAC for various brass thickness and off-axis positions (OAP).

We used Mini-phantom in the air and measured the change in attenuation characteristics with the distance from the beam axis. A change of attenuation coefficient in the field is a function of distance of a radial direction from central axis (CAX). In other words distribution of in field is function of radial distance .

The experimental setup for the transmission measurements is shown in Figure 3. Attenuation coefficient measurements with a narrow-beam were carried out at an extended SSD and for a small field size. The ion chamber was set up coaxially with beam and field size were 3 x 3 cm^2 at isocenter which is sufficient to enclose the mini phantom. Asymmetric jaws were used to define the size of square fields at OAP. Measurements were performed for each OAP using gantry angle (θ) of 1.2°, 2.3°, 3.4°, 4.6°, and 5.7°, corresponding to the distance of 2.0, 4.0, 6.0, 8.0, and 10.0 cm from the central axis (CAX), respectively. The brass attenuator thicknesses were 0.5, 1.0, 2.5, 4.0, and 6.0 cm. The 2D-LAC was obtained by

(3)

where is the LAC when the modulator thickness is *t* cm and the OAP is *r* cm. is the incident dose when the OAP is *r* cm and is the transmission dose when the modulator thickness is *t* cm and the OAP is *r* cm.

A linear attenuation coefficient ratio (LACR) is defined by the ratio of the LAC ( ) and the reference LAC ( ). The LACR ( ) is thus:

(4)

We expressed the specific change of the LACR depending on the brass thickness and the OAP by a cubic polynomial approximation as follows:

(5)

where , , , and are also cubic polynomials of brass thickness cm. We call the LACR array the two dimensional linear attenuation coefficient ratio (2D-LACR).

2D. Modulator thickness correction method using 2D -LACR

The 2D-LACR is a function to express the relative change of the LAC as a function of the OAP and the modulator thickness, and it is normalized by the reference position and thickness. We corrected the thickness of the brass modulator by the difference of the physical density with equation (1), and its reference was the LAC of 5 cm of the OAP and 5.08 cm of the brass thickness. We decide the same point for the LACR reference point.

We assumed that the change of the EAC due to the OAP and the brass thickness was proportional to the 2D-LACR. We considered that the EAC changed by the OAP and the brass thickness was corrected approximately by using the 2D-LACR, therefore the brass thickness could be corrected. This correction includes the scatter component of the EAC and evaluates a primal energy fluence change of the OAP. We call the EAC array the two-dimensional effective attenuation coefficient ratio (2D-EAC) :

(6)

As for the relation of the final collected modulator thickness matrix and the physical density corrected modulator thickness matrix by equation (2), both transmissions are equal in a basic condition of the density correction.

(7)

From equation (6) and (7),

(8)

2D-LACR ( ) is 1.0 in a basic condition, and the corrected modulator thickness is equal to the thickness after the density correction. We can calculate the corrected modulator thickness by dividing the density correction of the modulator thickness matrix by the 2D-LACR.

2E. Dose verification of geometric patterns using an ion chamber.

We prepared three simple patterns (A, B, C). Pattern A had the oblique intensity distribution in the cross-field direction. Pattern B was a pyramidal pattern. Pattern C was a reversed pyramidal pattern. We calculated the dose distribution for three geometric patterns by XiO and designed two types (with or without correct thickness) of the modulator for each pattern. We measured dose profiles along the main axis direction (in-line (90), cross-line (0)) and two diagonal directions (diagonal (45,135)), by CC13 ion chamber using Blue Phantom. Measurement was for 8cm (average depth in the head and neck region) depth and SSD was 92cm. We inspected the dose distribution accuracy of the modulator by comparing the measured dose and the calculated dose.

2F. Dose verification of geometric patterns using EDR-2 film.

We measured the two-dimensional dose distributions for three patterns (A, B, C) of modulator using EDR-2 film. The EDR-2 film was placed at 8 cm depth in the solid water phantom and the source-to-film distance was 100 cm. We used γ – method[25)] for the comparison of the dose distributions of the calculations and the measurement results. The levels of the evaluation criteria were 3mm 3%, 4mm 4%, and 5mm 5% using the DD-system.

2G. Dose verification of complex pattern (Pharynx model) using EDR-2 film.

We generated a seven-field IMRT plan with XiO (Fig. 9a) for a PMMA prism phantom. This phantom includes a pharyngeal target, neck lymph nodes, parotid glands and spinal cord. We measured two-dimensional dose distributions using EDR-2 films. The EDR-2 film was placed at isocenter plane for each section (transverse, coronal, sagittal). The method for measurements and evaluation are the same as ⅡF. The levels of the evaluation criteria were 4mm 4% using the DD-system.

3. RESULTS

3A. Measurements of EAC

The EAC of 1 cm brass slab for 4 MV, 10 x 10 cm^2 x-ray beam was 0.4058cm^{-1}. The EAC depended on the field size and it decreased slowly when the field size becomes large. The EAC were 0.4082 cm^{-1}, 0.4058 cm^{-1}, 0.4046 cm^{-1}, 0.3977 cm^{-1}, and 0.3879 cm^{-1} for the field size of 5 x 5 cm^2, 10 x 10 cm^2, 15 x 15 cm^2, 20 x 20 cm^2, and 25 x 25 cm^2, respectively. The range of variation of EAC was about 5.0 %.

3B. Corrections for EAC of modulator materials

We show the transmission dose distributions calculated by XiO and the measured dose of the brass modulator (Fig. 2b.) of IM (Fig. 2a). In this case, the maximum thickness of the modulator was 5.08 cm and the minimum thickness was 0.6 cm. The calculated EAC was 0.3754 cm^{-1} and the measured EAC was 0.3271 cm^{-1}.

Therefore, the modulator thickness corrected by the physical density is as follow from equation (2),

The dose transmission of 5.08 cm thickness of "decimalbrass" and the brass for 4 MV x-ray are 18.62 % and 23.10 %, respectively. The brass thickness of equal dose transmission factor to "decimalbrass" is 5.83 cm.

3C. Measurements of LAC by combination of various brass thicknesses and OAP.

The measurements of the LAC were carried out for the various modulator thickness (t) and OAP (r) and the results are shown in Table 1. The LAC decreases with the increase of the brass thickness and the LAC increases with the decrease of the OAP (cm). The LAC decreases when the brass thickness becomes thick and the OAP is near the field edge. The maximum variation of the LAC was 0.0572 cm^{-1} (14.3 %) and it was larger than 0.0203 cm^{-1} (5.0 %) of the maximum variation of the field size.

The LAC was normalized at the reference value, which was 0.3819 cm^{-1} (the brass thickness was 5.08 cm and the OAP was 5 cm). This is the LACR in Fig. 4. The constants ($a_1 \sim d_4$) in the equation (5) are listed in Table 2. The average of the difference from the absolute value to calculated value was ±0.11 %. Its standard deviation is 0.083 %. The error of this formula is less than 0.38%.

3D Modulator thickness optimization method using 2D-LACR

Table 3 shows the corrected brass thickness after the thickness correction calculation using the 2D-LACR. In this case, the function of 2D-LACR was approximated using an actual value up to 10 cm of the OAP, but it was extrapolated up to 13cm. It was constant for more than 13 cm OAP.

The optimized correction brass thickness decreases generally because the reference LAC for the normalization is 5 cm OAP and 5.08 cm brass thickness. On the other hand, when the brass thickness is thicker than the reference modulator thickness, the corrected quantity becomes positive value.

3E. Dose verification of geometric patterns using ion chamber.

A pattern A was normalized at CAX (Fig. 5). The corrected beam profiles (closed circle) agreed better with the calculation value of XiO (solid line) than the uncorrected beam profile (open circle). The amount of maximum dose range in the diagonal profile (45°) was 133 %, 112 %, and 136 % for calculation by XiO, before corrected, and corrected, respectively. The corrected measurement values agree with the calculation value within ±3 % for inside of 6 cm OAP in main axis, but an error tends to increase at the field edge. In the beam profile at the diagonal profile (45°), the maximum error was about ±5 % near the field edge but the good agreement within ±3 % is shown in another diagonal direction.

A pattern B was normalized at maximum dose point at 8.5 cm OAP in the cross-line dose profile (Fig. 6). The dose of non-corrected profile exceeded at all positions and the maximum error was +5.2 % at CAX. Furthermore the dose range was narrow. On the other hand, the corrected profile agreed well with the calculated profile within ±3 % for inside of 7 cm OAP in main axis, and within ±3 % for inside of 12 cm OAP in the diagonal axis. The under estimation of the dose was found around the field edge of main axis. Particularly, the dose decreased about 5 % in the in-line profile.

A pattern C was normalized at CAX (Fig. 7). Before corrected dose profiles show better agreement with the calculated profiles than the optimized profiles. However, the dose range of before corrected profile is narrow. Generally, near the field edge, the modulator becomes thicker, and then the error is increased.

3F. Dose verification of geometric patterns using EDR-2 film.

Figure 8 shows gamma distributions. In the area inside of 10 cm OAP, the evaluation criteria of 3mm 3% was satisfied for all patterns. In a little area of the field border where the dose was maximum or minimum, the error was large as more than the level of the criteria of 5mm 5%. In the large dose gradient area, the error was large in a direction along a cross-line axis.

3G. Dose verification of complex pattern (Pharynx model) using EDR-2 film.

Figure 9(b-c) shows gamma distributions. In some little area where the dose is maximum or minimum, the error is large as more than the level of the criteria of 4mm 4%. Bottom area in transverse and coronal plane has large error. Large error occurs in the field border.

4. DISCUSSION

We used the narrow-beam geometry for our measurements of the LAC. The fact that the measured LAC increases with increasing OAP means the "beam softening" effect[17, 18]. And the measured LAC decreases with increasing thickness of brass attenuator. This means the "beam hardening" effect[18, 19]. Commonly used attenuation functions are considered to some problems associated with the beam hardening, the beam softening, and the field size dependence. Chang et al[12] used the function that assumed the narrow bean EAC in the CAX, beam hardening through the compensator material, beam energy variation at off axis distance and field size dependence. Plessis[26] showed the EAC of a measured value to a function depending on depth and field size and corrected OAP. Plessis[15] calculated EAC using EGS based DOSXYZ Monte Carlo simulations. We expressed the 2D-LACR depending on the brass thickness and the OAP by a cubic polynomial approximation. We assumed that the broad beam EAC varies in a similar manner for change of the 2D-LACR with the brass thickness and the OAP distance. Therefore, the 2D-EAC is equal with the EAC value corrected using the 2D-LACR as Eq. (6).

We prepared the dose distribution for 3 geometric IM patterns and evaluated the transmission dose and dose distributions of brass modulators. The dose profile is smooth at each direction (main axis and diagonal axis). This is the advantage of the M-IMRT delivery method. For all patterns, the corrected brass modulator shows a good agreement with the dose and the dose distribution calculated by XiO within ±3 % error or less than 4mm 4% of γ-method criteria. This result showed that dosimetric characteristics of the brass modulator using the 2D-LAC array agreed well with the planning dose distribution calculated by XiO. But at the field border and in the high or low dose area, the error was larger than the criteria of 5mm 5%. And in large dose gradient regions, the error was also large in the direction along a cross-line axis.

Figure 5 shows typically pattern with calculation dose error. That indicates the tendency that calculated dose increases under thinner modulator thickness area and calculated dose decreases under thicker modulator thickness area than without corrected the brass modulator. The modulator placed in the beam, not only attenuates the primary fluence but also produces scattered photons and leads beam hardening effect that will reach the patient. Such results show that the beam hardening correction through the modulator is not considered by the dose calculation algorithms in XiO. In the outside of field, calculated dose is less than the measured dose. Such results show that XiO dose calculation algorithm does not consider the amount of the scattering photons from the modulator. XiO uses the superposition algorithm, which computes the dose by convolving the total energy released in the patient with Monte Carlo-generated energy deposition kernels[7]. The XiO system displays the mean energy of the spectrum to aid in the beam modeling process and spectrum evaluation. Animesh[20] described that the off-axis spectra have been created on the basis of the default spectra using published changes in average energy as a function of off-axis distance. But XiO does not consider the effect of off-axis softening in pencil beam kernel, a primary photon beam hardening effect and generation of scattered photon and electrons by the modulator.

This study, we used a simple beam model (open field and without treatment aids) based on a Jiang et al[5]. They used a 6 MV photon beam but we used a 4 MV photon beams. Therefore, beam modeling with a modulator will require 4 MV photon beam so that a beam hardening effect is estimated than 6 MV photon beam greatly. It is thought that this is the result that beam modeling of XiO is insufficient for the modulated beams. Furthermore, it will be necessary to incorporate a dose calculation including influence of a beam perturbations effect by modulator in TPS. As the photon spectrum shifts in the modulator and the flattening filter, the energy spectrum shift correction algorithm[13, 27-29] must be applied to the dose calculation method. The scatter dose generated from the modulator[30-34] must be also applied to the dose calculation algorithm. Chang et al[35, 36] uses an in-house treatment planning system (PLanUNC, Univ. of North Carolina), Plessis et al[37] uses a fast Monte-Carlo dose calculation to solve this problem. The accuracy of modulator design and calculated dose depends on the calculation algorithm in the TPS.

In this study, we assumed the IMRT treatment for head and neck region. We chose the low energy x-ray (4 MX), the large field size (20 cm x 20 cm) and the isocenter depth of 8 cm. In these conditions, the evaluation of the modulator design and the dose calculation are very difficult because the change of the energy spectrum and the scatter from the modulator are very large. Under such a condition, in the most regions in the field, the dose verification satisfies 3mm 3% criteria, and in all regions, it satisfies 4mm 4% criteria of the γ-method. Salz et al[38] reported that the dose deviations of the tin granules compensator amount to ± 3 % in the high-dose region, exclude for dose gradients, and the deviations are found to be lager (up to 6%) for small areas (＜ 2 cm x 2 cm) with much higher or lower fluence. Their report gave the same accuracy of the M-IMRT with our result. The bottom area in transverse and coronal plane has large error in Figure 9. We think that their causes are the effect of treatment couch.

We think that there are some reasons for the observed disagreements between planning dose profile and measured one. The important problem in the M-IMRT is the milling error of CNC-mill. CNC-mill cuts the brass by the raster technique. It cuts with data pitch (step-over distance) of 0.2 cm along the in-line direction while it cuts along the cross-line direction using data interpolated linearly. Therefore, the resolution in the in-line direction depends on the data pitch distance (step-over distance), the size of the cutting tool diameter and the angle of the tool tracing the profile. In our result, the difference of the modulator thickness is 0.7 cm and the inclination is 74 degree between two data (0.2 cm pitch) in the large dose gradient area. Along the in-line direction, data are not interpolated, so the cutting surface becomes the stepped shape. Hence the error occurs in the in-line direction. The cutting limits of the ball end-mill was discussed by Meyer et al[39], the maximum angle of the modulator inclination with the dose error of ±2.5 % is 61 degree. Therefore, further investigation for the cutting condition or the interpolation of data along the in-line direction in the large dose gradient area is required. This problem depends on the modulator calculate matrix pitch vs. a drills radii.

5. CONCLUSION

We performed a modulator based IMRT commissioning using XiO treatment planning system. A new method was proposed for the implementation of intensity-modulated beams. This method uses the 2D-LACR for the correction of the brass modulator thickness for IMRT and it is showed that overall dosimetric characteristics of the brass modulator using the 2D-LAC array agreed well with the planning dose distribution calculated by XiO. Our method using the 2D-LACR for the correction of the brass modulator thickness for IMRT is effective in the accuracy improvement of M-IMRT in XiO TPS.

The important problem for the brass modulator is the milling condition such as the drill diameter and the cutting pitch size. The “softening“ effect and the “hardening” effect of the beam must be considered for dose calculation in the patient and modulator profile design those are necessary in the accuracy improvement of M-IMRT.

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REFERENCE

[1] D. J. Convery, and M. E. Rosenbloom, "The generation of intensity-modulated fields for conformal radiotherapy by dynamic collimation," Phys. Med. Biol. 37, 1359-1374 (1992).

[2] C. C. Ling, C. Burman, C. S. Chui, G. J. Kutcher, S. A. Leibel, T. LoSasso, R. Mohan, Y. Bortfeld, L. Reinstein, S. Spirou, X. H. Wang, Q. Wu, M. zelefsky and Z. Fuks, "Conformal radiation treatment of prostate cancer using inversely-planned intensity modulated photon beams produced with dynamic multileaf collimation," Int. J. Radiat. Oncol. Biol. Phys. 35, 721-730 (1996).

[3] T. Bortfeld, A.L. Boyer, W. Schlegel, D. L. Kahler and T. J. Waldron "Realization and verification of the three dimensional conformal radiotherapy with modulated fields," Int. J. Radiat. Oncol. Biol. Phys. 30, 899-908 (1994).

[4] W. De Neve, C. De Wagter, K. De Jaeger, M. Thienpont, C. Colle, S. Derycke and J. Scheifhout, "Planning and delivering high doses to target surrounding the spinal cord at the lower neck and upper mediastinal levels: Static beam-segmentation technique executed with a multileaf collimator," Radiother. Oncol 40, 271-279 (1996).

[5] S. B. Jiang, and K. M. Ayyangar, "On compensator design for photon beam intensity-modulated conformal therapy," Med. Phys. 25, 666-675 (1998).

[6] P. S. Basran, W. Ansbacher, C. G. Field, and B. R. Murray, "Evaluation of optimized compensators on a 3D planning system," Med. Phys. 25, 1837-1944 (1998).

[7] S. X. Chang, T. J. Cullip, and K. M. Deschesne, "Intensity modulation delivery techniques: "Step & shoot" MLC auto-sequence verses the use of a modulator," Med. Phys. 27(5), 948-959 (2000).

[8] C. Yu, M. J. Symons, M. N. Du, A. A. Martinez, and J. W. Wong, "A method for implementing dynamic photon beam intensity modulation using independent jaws and a multileaf collimator," Phys. Med. Biol. 40, 769-787 (1995).

[9] C. X. Yu, "Intensity-modulated arc therapy with dynanic multileaf collimation: an alternative to tomotherapy," Phys. Med. Biol. 40, 1435-1449 (1995).

[10] T. R. Mackie, T. Holmes, S. Swerdloff, P Reckwerdt, J. O. Deasy, J. Yang, B. Paliwal, and T. Kinsella, "Tomotherapy: A new concept for the delivery of dynamic conformal radiotherapy," Med. Phys. 20, 1709-1719 (1993).

[11] S. Webb, "Conformal intensity-modulated radiotherapy (IMRT) delivered by robotic linac - testing IMRT to the limit?," Phys. Med. Biol. 44, 1639-1654 (1999).

[12] S. X. Chang, T. J. Cullip, K. M. Deschesne, E. P. Miller, and J. G. Rosenman, "Compensators: An alternative IMRT delivery technique," J. Appl. Clin. Med. Phys. 5, 15-35 (2004).

[13] S. Chang, "Compensator-intensity-modulated radiotherapy – A traditional tool for modern

application," Radiotherapy & Imaging 82-86 (2006).

[14] E. D. Ehler, B. E. Nelms, and W. A. Tomé, "On the dose to a moving target while employing different IMRT delivery mechanisms," Radiother. Oncol. 83, 49-56 (2007).

[15] F. C. P. du Plessis, and C. A. Willemse, "Monte Carlo calculation of effective attenuation coefficients for various compensator materials," Med. Phys. 30, 2537-2544 (2003).

[16] L. Weber, and F. Laursen, "Dosimetric verification of modulated photon fields by mean of compensators for a kernel model," Radiother. Oncol, 62187-62193 (2002).

[17] M. K. Yu, R. S. Sloboda, and B. Murray, "linear accelerator photon beam quality at off-axis points," Med. Phys. 24, 233-239, (1997).

[18] E. Papież, and G. Froese, "The calculation of transmission through a photon beam attenuator using sector integration," Med. Phys. 17, 261-266 (1990).

[19] B. E. Bjärngard, and H. Shackford, "Attenuation in high-energy x-ray beams," Med. Phys. 21, 1069-1073, (1994).

[20] Animesh, "Advantages of multiple algorithm support in treatment planning system for external beam dose calculations," Journal of Cancer Research and Therapeutics 1(1), 12-20 (2005).

[21] CMS, ",decimal Commissioning Guide," .decimal, Inc. U.S.A, (2005).

[22] T. Bartrum, M. Bailey, V. Nelson, and M Grace, "Linear attenuation coefficients for compensator based imrt," Australasian Physical & Engineering Sciences in Medicine, 30(4), 281-287 (2007).

[23] D. M. Dimitriadis, and B. G. Fallone, "Compensators for intensity- modulated beams," Med. Dosim. 27, 215-220 (2002).

[24] T. R. Mackie, A. Ahnesjo, P. Dickof, and A. Snider, "Development of a convolution/superposition method for photon beams," In *Proceedings of the 9th International Conference on Computers in Radiotherapy*. Elsevier Science, Amsterdam 107-110 (1987).

[25] D. A. . B. Harms, S. Mutic, and J. A. Purdy, "A technique for the quantitative Low, W evaluation of dose distributions," Med. Phys. 25, 656-661 (1998).

[26] F. C. P. du Plessis, and C. A. Willemse, "Radiological properties of a wax-gypsum compensator material," Med. Phys. 32, 1246-1255 (2005).

[27] T. R. Mackie, A. F. Bielajew, D. W. O. Rogers, and J. J. Battista. "Generation of photon energy deposition kernels using the EGS Monte Carlo code," Phys Med Biol. 33, 1-20 (1988).

[28] J. Olofsson,T. Nyholm, A. Ahnesjö, and M. Karlsson "Dose uncertainties in photon pencil kernel calculations at off-axis positions," Med. Phys. 33, 3418-3425 (2006).

[29] H. H. Liu, T. R. Mackie, and E. C. McCullough, "Calculating dose and output factors for

wedged photon radiotherapy fields using a convolution/superposition method," Med. Phys. 24, 1714-1728 (1997).

[30] P. Xia, and L. J. Verhey, "Multileaf collimator leaf sequencing algorithm for intensity modulated beams with multiple static segments," Med. Phys. 25, 1424-1434 (1998).

[31] F. C. P. du Plessis, and C. A. Willemse, "Inclusion of compensator- induced scatter and beam filtration in pencil beam dose calculations," Med. Phys. 33, 2896-2904 (2006).

[32] P. Huang, L. M. Chin, and B. E. Bjärngard, "Scattered photons produced by beam-modifying filters," Med. Phys. 13, 57-63 (1986).

[33] Y. Mejaddem, S. Hyödynmaa, and A. Brahme, "Photon scatter in intensity modulating filters evaluated by first compton scatter and Monte Carlo calculations and experiments in broad beams," Phys. Med. Biol. 45, 2747-2760 (2000).

[34] M. K. Isiam, and J. Van Dyk, "Effect of scatter generated by beam-modifying absorbers in megavoltage photon beams," Med. Phys. 22, 2075-2061 (1995).

[35] S. X. Chang, T. J. Cullip, and K. M. Deschesne, "Intensity modulation delivery technique: "Step & shoot" MLC auto-sequence versus the use of a modulator," Med.Phys. 27 (5), 948-959 (2000).

[36] J.Lian, S. Chang, T. Cullip, K. Deschesne, E. Schreiber, W. Gardner, L. Potter, and W. Euliss, "Implementation of the Tungsten-Compensator Based Intensity-Modulated Radiotherapy (IMRT)," Med. Phys. 32(6), 1973 (2005).

[37] F. C. P. du Plessis, and C. A. Willemse, "Inclusion of compensator-introduced scatter and beam filtration in pencil beam dose calculations," Med. Phys. 33(8), 2896-2904 (2006).

[38] H. Salz, T. Wiezorek, M. Scheithauer, M. Schwedas, J. Beck, and T. G. Wendt, "IMRT with compensators for head-and–neck cancers" Strahlentherapie und Onkologie, 181, 665-672 (2005).

[39] J. Meyer, J. A. Mills, O. C. L. Haas, E. M. Parvin, and K. J. Burnham, "Some limitations in the practical delivery of intensity modulated radiation therapy," Br. J. Radiol. 73, 854-863 (2000).

Figure caption

Figure 1

(a) Photograph of the floor-type computer-aided numerically controlled milling machine (CNC-mill). (b) Photograph of the Blass modulator for geometric pattern A (oblique intensity distribution in the cross-field direction), mounted on the accessory slot of the linear accelerator gantry head.

Figure 2

(a) The intensity map for the two-tone pattern geometry designed by the XiO treatment planning system. (b) Cross-line dose profile in an intensity map of the two-tone pattern geometry. The solid line is calculated from the XiO treatment planning system, and the open circles indicate measured data.

Figure 3

Schematic diagram of the setup used to measure the change in attenuation characteristics with the distance from the beam axis.

Figure 4

The linear attenuation coefficient ratio (LADR) as a function of the off-axis position for various brass modulator thicknesses for 4-MV photon beams. The linear attenuation coefficient (LAC) was normalized using the reference value, which was 0.3819 cm^{-1} (the brass thickness was 5.08 cm and the OAP was 5 cm).

Figure 5

Relative dose profiles for geometric pattern A. The solid line represents data calculated by XiO. The symbols indicate measured data. The dose profiles have been calculated with (closed circle) and without (open circle) correction using the 2D-LACR.

Figure 6

Relative dose profiles for geometric pattern B. The solid line represents data calculated by XiO. The symbols indicate measured data. The dose profiles have been calculated with (closed circle) and without (open circle) correction using the 2D-LACR.

Figure 7

Relative dose profiles for geometric pattern C. The solid line represents data calculated by XiO. The symbols indicate measured data. The dose profiles have been calculated with (closed circle) and without (open circle) correction using the 2D-LACR.

Figure 8

Comparison of dose distributions of the calculations and the measurement results using the gamma-value map. The levels of evaluation criteria were 3 mm 3%, 4 mm 4%, and 5 mm 5%. (a) is geometric pattern A (an oblique intensity distribution in the cross-field direction), (b) is pattern B (a pyramidal pattern), and (c) is pattern C (a reverse pyramidal pattern). The red parts indicate under- or overestimated areas.

Figure 9

(a) Schematic image of the pharynx model phantom. This phantom includes a pharyngeal target (red), neck lymph nodes (magenta), parotid glands (white), and the spinal cord (blue). The gamma-value map over the transverse plane (b), coronal plane (c), and sagittal plane (d) for 4 mm 4% criterion. The red parts indicate under- or overestimated areas.

Table 1

The linear attenuation coefficient (LAC) as a function of the brass modulator thickness for six different off-axis positions for 4-MV photon beams.

Table 2

Values of a_i, b_i, c_i, and d_i determined by cubic polynomial fitting of the linear attenuation coefficient ratio (LACR) as a function of the off-axis position and brass modulator thickness using Eq. (5).