CBCT-based dose calculation with Monte Carlo simulation

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Monte Carlo dose calculation system

A Monte Carlo dose calculation system called Monte Carlo verification system (MCVS) has been developed for clinical treatment plan verification, especially for routine quality assurance of intensity-modulated radiation therapy (IMRT) plans. Six MV photon beam from a Varian Clinac 23EX was implemented using BEAMnrc and DOSXYZnrc codes. The treatment head components and the Millennium MLC were modeled based on the specification provided by the vendor. In order to verify the accuracy, the MC dose calculations were compared with measurement data. The calculated PDDs, OCRs, and output factors agreed with the measurements within the accuracy of 2%. Dosimetric effects derived from the MLC structure, such as MLC leaf transmission and tongue-and-groove effect, were properly reproduced with the MCVS. Intensity-modulated (IM) beam delivery was implemented by sampling a MLC segment from a MLC leaf sequence file every one incident particle. The IM beam delivery was simulated and compered with film measurements. The IM dose distributions was reproduced properly and the calculated points more than 95% agreed with the measurements within the accuracy of 2%.

Phase space data (PSD) obtained by our initial IM beam simulation don't have time-dependent parameters and this results in static IM beam delivery. If IMRT for a moving target is simulated, dynamic IM beam delivery must be accounted for. Therefore, new PSD which holds a time-dependent parameter based on the MLC segment has been implemented. The dose distributions were calculated in the static phantom using the new PSD. The dynamic change of the dose distributions due to the dynamic IM beam delivery was observed. Also the dose distributions were calculated using the conventional and the new PSD in the moving phantom. The dose distribution calculated using the new PSD was distorted due to the interplay effect although the dose distribution calculated using the conventional PSD was only blurred. The dose calculations were performed in the moving phantoms built from 3DCT images w/ motion and 4DCT images, and compared with the film measurements. The both calculations showed good agreement with the measurements.

CBCT-based dose calculation

CBCT-based image guidance is usually performed periodically, for example weekly. This repeated imaging during treatment course reveals anatomical change such as tumor shrinkage and weight loss and these anatomical changes may result in dosimetric variation. If dose distributions can be calculated using CBCT images, delivered dose distributions can be evaluated.

The accuracy of the dose calculation is doubtful because the CBCT images have bad image quality. Therefore, we attempted to create virtual CT image, which holds similar image quality to CT images at treatment planning and similar patient anatomical information to CBCT images at treatment. Also dose distributions were calculated using its image. Using deformable image registration based on B-splice function, the virtual CT image at treatment is created by calculating a displacement vector field between the planning CT image and the CBCT image at treatment and applying the resultant displacement vector field to the planning CT image. To validate the virtual CT image at treatment, the image was visually and dosimetrically compared to the CBCT image at treatment. Compared with the CBCT image at treatment, the virtual CT image reflected the comparable patient anatomy and slightly improved the image uniformity. Also the dose calculation using the virtual CT image slightly improved the accuracy.

CBCT-based dose calculation
with Monte Carlo simulation

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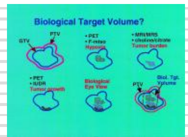
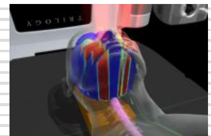
Treatment concept

- As technology progresses, it is possible to clinically implement various treatment concept.

Biological target volume



Intensity-modulated arc therapy



Dose painting

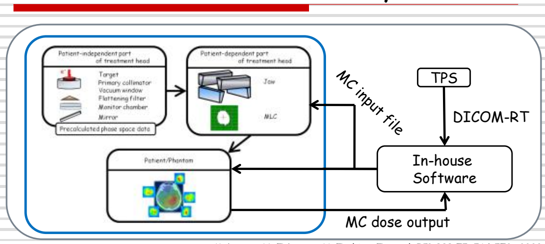
Adaptive Radiation Therapy (ART)

- ART is a closed-loop radiation treatment concept.
- Image-guidance makes it easy to clinically implement this concept.
- Dose calculation accuracy becomes important if ART is performed based on dose distributions.

- MC dose calculation system
- CBCT-base dose calculation

- MC dose calculation system
- CBCT-base dose calculation

Monte Carlo Verification System (MCVS)

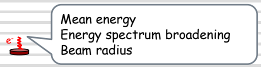


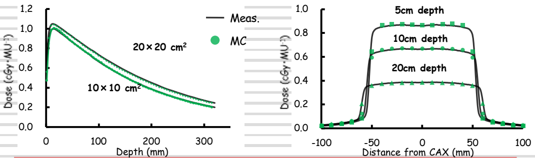
Mukumoto N, Takegawa H, Teshima T, *et al.*, IJROBP 75, 564-570, 2009

Monte Carlo dose calculation system called the MCVS has been developed in our institute.
6 MV photon beam from a Varian Clinac 23EX was implemented using BEAMnrc/DOSXYZnrc MC codes.

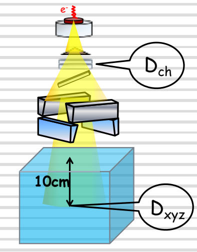
Incident Electron Commissioning

Incident electron parameters were adjusted to agree with measurement data.

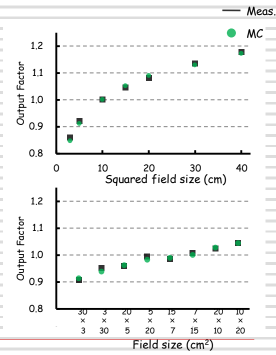




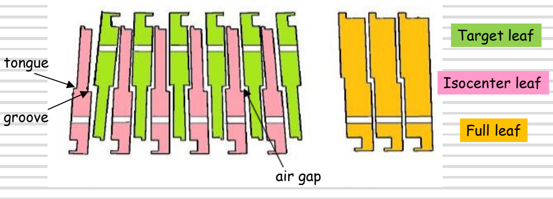
Output Factor



$$\text{OutputFactor} = \frac{D_{ch(10x10)}}{D_{ch(r)}} \times \frac{D_{xyz}}{D_{xyz}^{cal}}$$



Millennium MLC modeling

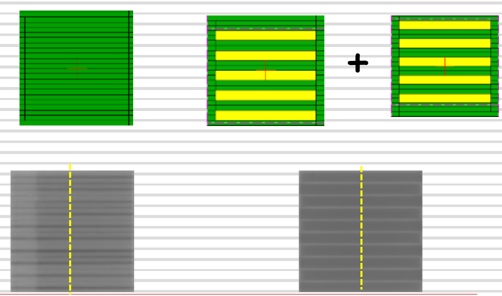


- The leaf structure was modeled based on the specification provided by the vendor.
- The width of air gap and the mass density of the leaves were adjusted to agree with measurements.

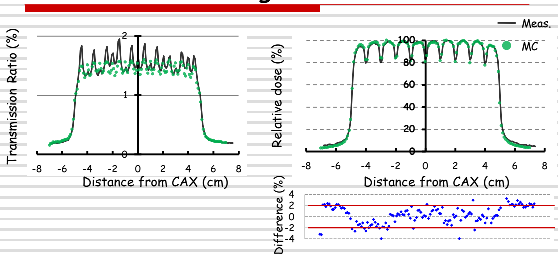
MLC commissioning

Leaf transmission

Tongue & Groove effect



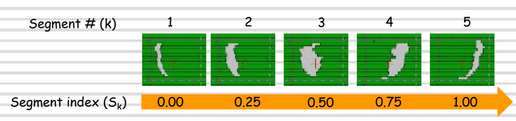
MLC commissioning



- Though MC peak values were slightly lower than measurement values, the valley and peak positions were reproduced properly.
- Dose reduction due to tongue & groove effect was reproduced.
  Almost points agreed with the measurements within the accuracy of 2%.

Intensity-modulated beam simulation

The MCVS simulates intensity-modulated (IM) beam delivery based on the method reported by Liu et al. (2000) with some modifications.



$$MU_k \le \gamma < MU_{k+1}$$

$$Pos_x = \frac{Pos_{k+1} - Pos_k}{MU_{k+1} - MU_k}(\gamma - MU_k) + Pos_k$$

γ : Randam number (0 ~ 1)

k : Segment number

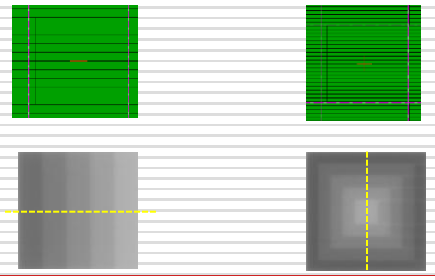
MU_k : MU index

Pos_k : Leaf position

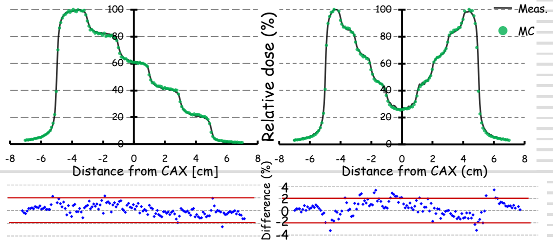
* MU index and corresponding leaf positions specified in a DICOM-RT Plan file

Verification of IM beam simulation

X-Wedge | Inverse Pyramid



Verification of IM beam simulation



- IM dose distributions were reproduced properly.
- Almost points agreed with the measurements within the accuracy of 2%.

Issues of IM beam simulation

- Phase space data (PSD) obtained by our initial IM beam simulation don't have time-dependent parameters.
- If simulating IMRT for thorax and abdomen, interplay between dynamic IM beam and respiration must be considered.

⇩

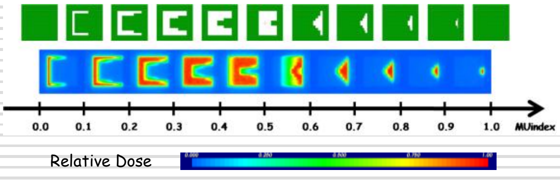
New phase space data which holds a time-dependent parameter based on MUindex has been implemented.

Conventional PSD

PSDnew = (*q, E, X, Y, Z, u, v, w, weight*, γ)

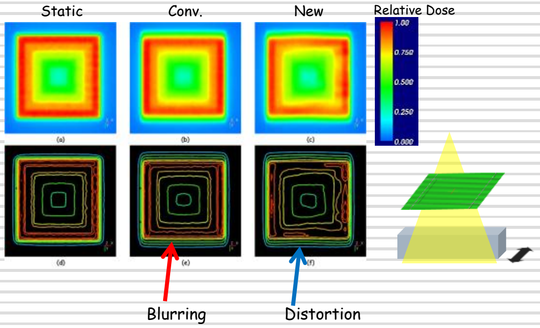
γ: sampled random # (MUindex)

Dynamic IM beam simulation

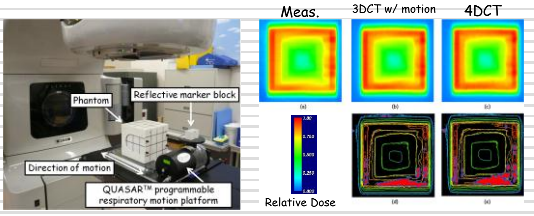


The dynamic change of dose distributions due to dynamic IM beam delivery was observed.

IM beam simulation for a moving target



Dosimetric verification



γ analysis (Criteria: 3% dose difference, 3 mm dose to agreement)

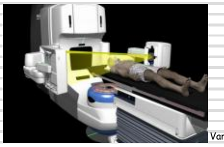
Pass rate	3DCT image w/ (continuous) :	93.5%
	4 DCT (discrete) :	91.7%

□ MC dose calculation system

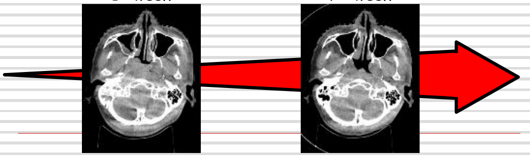
□ CBCT-base dose calculation

CBCT-based image-guidance

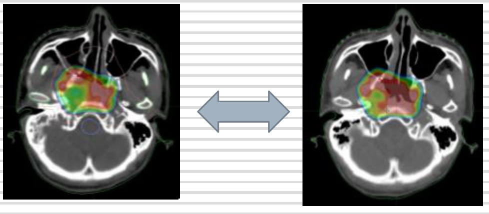
Cone-beam CT (CBCT)



Varian Medical Systems



Dosimetric variations due to tumor shrinkage

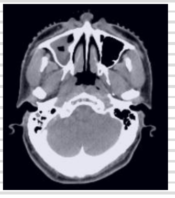


Planning CT image

CT image acquired
during treatment course

Planning CT image vs CBCT image

Planning CT image



CBCT image

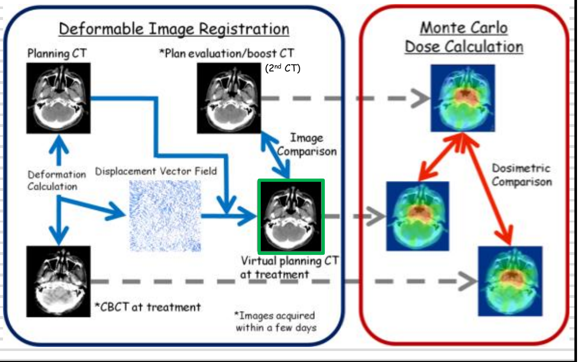
☺ Good image quality

☹ Bad image quality

☹ Patient anatomy at treatment delivery

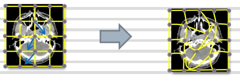
☺ Patient anatomy at treatment delivery

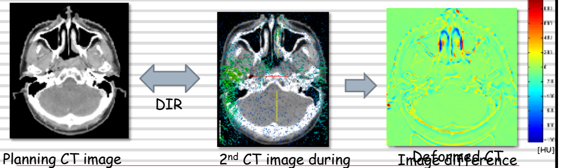
Creation & Verification Schema of Virtual planning CT at treatment



Calculation of a DVF between CT images

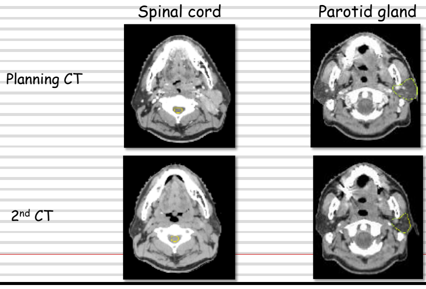
Calculate a displacement vector field (DVF)
using deformable image registration (DIR) based on B-spline function



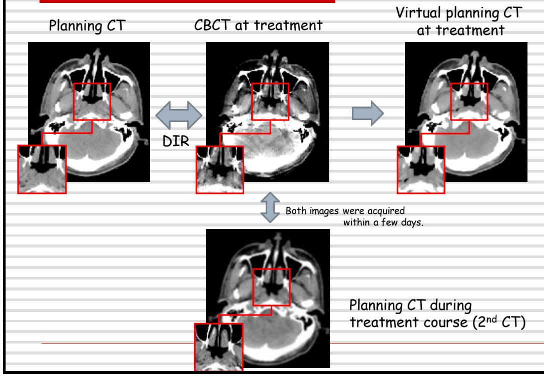


Validation of DIR

Adapting the resultant DVF to OAR contours on the treatment planning CT and then the positions of deformed contours on the 2nd CT were visually assessed.

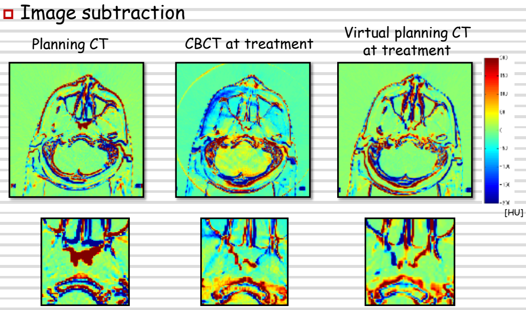


Creation of virtual planning CT at treatment



Validation of virtual planning CT

- Image subtraction

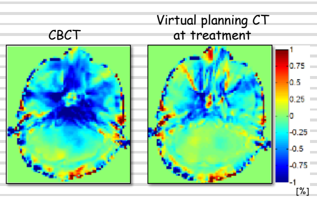


Reference image: 2nd CT

Dosimetric comparison

- IMRT (6 MV X-ray, 7-port)
- Dose distributions were calculated using same planning data with Varian Eclipse.

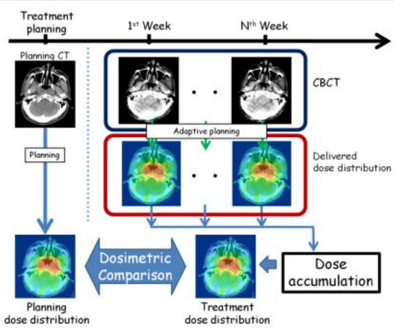
Dose difference



Dose Difference (%)	CBCT (%)	Virtual CT (%)
≤ 1	71.7	80.8
≤ 2	89.9	91.5
≤ 3	94.5	94.5

Reference image: 2nd CT

Future plan



Summary

- The MC dose calculation system has been implemented and has good dose calculation accuracy.
- Our system can calculate accurate dose distributions of IMRT for thoracic and abdominal cancers and can be extended to simulation of volumetric arc therapy.
- Compared with dose calculation using original CBCT image, that using virtual planning CT image slightly improved the accuracy.
- Our method can be extend to proton therapy and may have more improvement effect than photon therapy.