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Intensity-modulated radiation therapy dose maps: the matchline effect

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INTENSITY-MODULATED RADIATION THERAPY DOSE MAPS: THE MATCHLINE EFFECT

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Certification

I, Puangpen Tangboonduangjit, declare that this thesis, submitted in fulfillment of the requirements for the award of Doctor of Philosophy, in the Department of Engineering Physics, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

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Abstract

In 2002 when this research started the brief of the project was to produce streamlined checks of planar dose maps delivered by IMRT fields to film.

At this time no other centre in Australia had a protocol for checking accuracy of RTP planned RT dose distributions. While many US centers have been checking IMRT distributions, there is still no standard protocol for these checks.

By the end of this project in 2005, 13 IMRT patient treatments had been successfully checked and this centre remains the only centre to have treated IMRT patients in Australia using the pinnacle RTP planning computer platform.

Early film dose maps revealed dose spikes due to MLC matchline effects. These matchlines were due to Varian MLC leaf ends sometimes matching other segment neighbors and were not predicted using pinnacle RTP until version 7.4 available about 2 months prior to the end of this project cycle.

Verifying a radiation treatment planning (RTP) computer's IMRT calculation was the first task for this thesis. Planar dose maps (dose in water perpendicular to the beam [cGy/MU]) were compared with beam dose distributions measured using films (XV and EDR) at various depths. The RTP computer and film measurements agreed within ±3% within the inside field region. In addition, the XV film had a lower linear dose response range than the EDR film, the efficacy of each film type depends on dose

range, the XV being used predominantly for planar dose maps and EDR for combined axial dose maps.

High dose lines (matchline effect) were studied with film measurement. Matchlines were caused by a contribution of extra penumbral dose from MLC transmission due to curved leaf ends. An MLC bank leaf stepping program was used with various minor overlap values (0, 0.06, 0.1, 0.14, 0.2 cm) of MLC position. With confirmation by BEAMnrc Monte Carlo simulations, a dosimetric overlap value due to collective effect of scatter and the rounded leaf end transmission equivalent to 0.09 cm leaf overlap was found for a particular weighting of each segment. Note the physical offset value set to avoid leaf collision is an additional 0.05 cm.

An overlapping co-incident field technique was used to extend field size, this also showed a small jaw-leaf matchline effect at both edges of an overlap region.

An aSi-EPID combined with Varian dosimetry software also showed matchline resolution similar to film. The aSi-EPID, XV film, Pinnacle RTP (version 7.0g and 7.4) and BEAMnrc Monte Carlo were all compared for a 25 segment step and shoot IMRT distribution. IMRT doses in the axial plane were further verified with an I'mRT phantom (Scanditronix-Wellhofer) using the EDR and a new low dose radiochromic film (Gafchromic® EBT, Lot no. 34267-004). For the irradiated perpendicular calibration setup, dose agreed to within ±5% (1 SD) for EDR and ±4% (1 SD) for Gafchromic® EBT film with RTP and an ionization chamber.

The conclusions based on this thesis are the following;

- The matchlines represented a potential overdose to some small volumes within the target dose delivery.
- The matchline patterns produced by moving leaf banks in known sequences helped reveal the physics properties of the rounded leaf end.
- Appropriate physical leaf gaps were found to mask the matchline, however due to differences in segment weights these were not recommended.
- A Monte Carlo model of the Varian 120 MLC was developed using Beam NRC and this model predicted matchline effects.
- EPID dosimetry revealed an a-Si detector array had sufficient spacial resolution to show matchlines.
- Late in cycle Version 7.4 of RTP computer leaf model did predict matchlines of smaller magnitude than experimental results.

Preface

The aims of the thesis

1. In order to verify the TPS system for IMRT technique dose calculation as a pilot study.
2. In order to study the dosimetric leaf end design of MLC which leads to the matchline effect.
3. In order to create benchmark of IMRT dose calculation using Monte Carlo simulation.
4. In order to make a streamline for quality assurance of IMRT technique, EPID and I'mRT phantom need to be verified.

Intensity Modulated Radiation Therapy (IMRT)

Intensity-modulated radiation therapy (IMRT) is an advanced 3D conformal radiation therapy technique in which small non uniform dose segments are used to avoid critical organs close to the treatment volume. With the aid of a computer optimization algorithm, a planner specifies dose objectives to the normal tissues and tumour target volumes. Currently the beam energy, field size and beam angle are pre-selected, then the computer iterates until a dose solution is met. The non uniform dose solution is converted to an MLC leaf sequence which would deliver a dose which closely matches this solution. Sometimes a final more accurate calculation proceeds to ensure an accurate final MU which accounts for MLC transmission etc. An overview of

different IMRT delivery including some issue used in this thesis (step & shoot technique, *k*-means clustering algorithm, CC convolution, Monte Carlo simulation) is described in chapter 1.

IMRT dose verification

Normally a manual calculation is used to check uniform radiation therapy planned treatment fields before the first fraction of dose is going to the patient. However, as mentioned above, IMRT consists of at least several small non uniform dose segments per fields, combined with 7 to 9 fields per fraction to complete an IMRT treatment. As a result a manual calculation for each segment multiplied by each field is time prohibitive. Hence several alternate IMRT dose verification techniques have been developed and there are reviewed in the first section of chapter 2. Because film is the most common for measuring dose in two dimensions, film is the main dosimeter in this thesis. Therefore a few types and the limitations of film dosimeters were reviewed. Moreover the key point of this thesis is studying the dosimetric characteristics of curve leaf end design which leads to the matchline effect, the review of MLC including pros and con of having MLC, the physical leaf end MLC position, and the leaf end transmission was referred in section 2.3. The benchmark of this thesis for IMRT dose verification is using Monte Carlo simulation so various investigations employing Monte Carlo for IMRT modelling were reviewed such as the code types of Monte Carlo simulation, the methods and the code's limitations of modelling curved leaf end MLC. The last section of chapter 2 reviewed the using of electronic portal imaging device (EPID) for IMRT verification. Due to its superior improvements

compared with film dosimeter such as real time imaging and no processing and routine calibration required, it could replace film for IMRT verification in the near future.

Two dimensional dosimeter

When IMRT dose verification first started for patients at Illawara Cancer Care Centre (ICCC) in mid 2002, radiographic film dosimetry was the only method available to compare 2D dose maps with dose predicted from the Pinnacle RTP. Hence film dosimetry is a major part of this thesis. It provides a 2 dimensional high resolution image. It is suitable to verify IMRT fields by visual inspection (qualitative) and dose beam profile (quantitative) measurement. Three types of films were used for this thesis. XV film had the highest sensitivity. The approximate linear dose response range is between 0-100 cGy. EDR film had a linear dose response range between 0-400 cGy. The XV film was mainly used for checking dose per field. The EDR as predominantly used for checking composite field doses. Section 3.2 shows a comparison of results between the XV and EDR film.

Radiochromic film is a more tissue equivalent material (Z=6.0-6.5) than radiographic film. There is no processing required. The use of Gafchromic® MD-55 is reported in chapter 4 in order to expect the better predicted dose in the region of the MLC penumbral tail due to its linear low energy response characteristics. The results show in section 4.2. Late in 2004, a new Gafchromic® EBT film became available, the usage shown in chapter 8. At the same time an Art phantom (Scanditronix-Wellhofer)

became available. This phantom had a better fit and could be clamped tighter than the solid water stacks. So EDR film and Gafchromic® EBT were compared for the perpendicular and parallel calibration orientation to the radiation beam. See results in section 8.2. Gafchromic® EBT has higher dose sensitivity than MD-55 in order to suit to the clinical radiotherapy dose range (0.01-8 Gy versus 2-100 Gy; www.ispcorp.com).

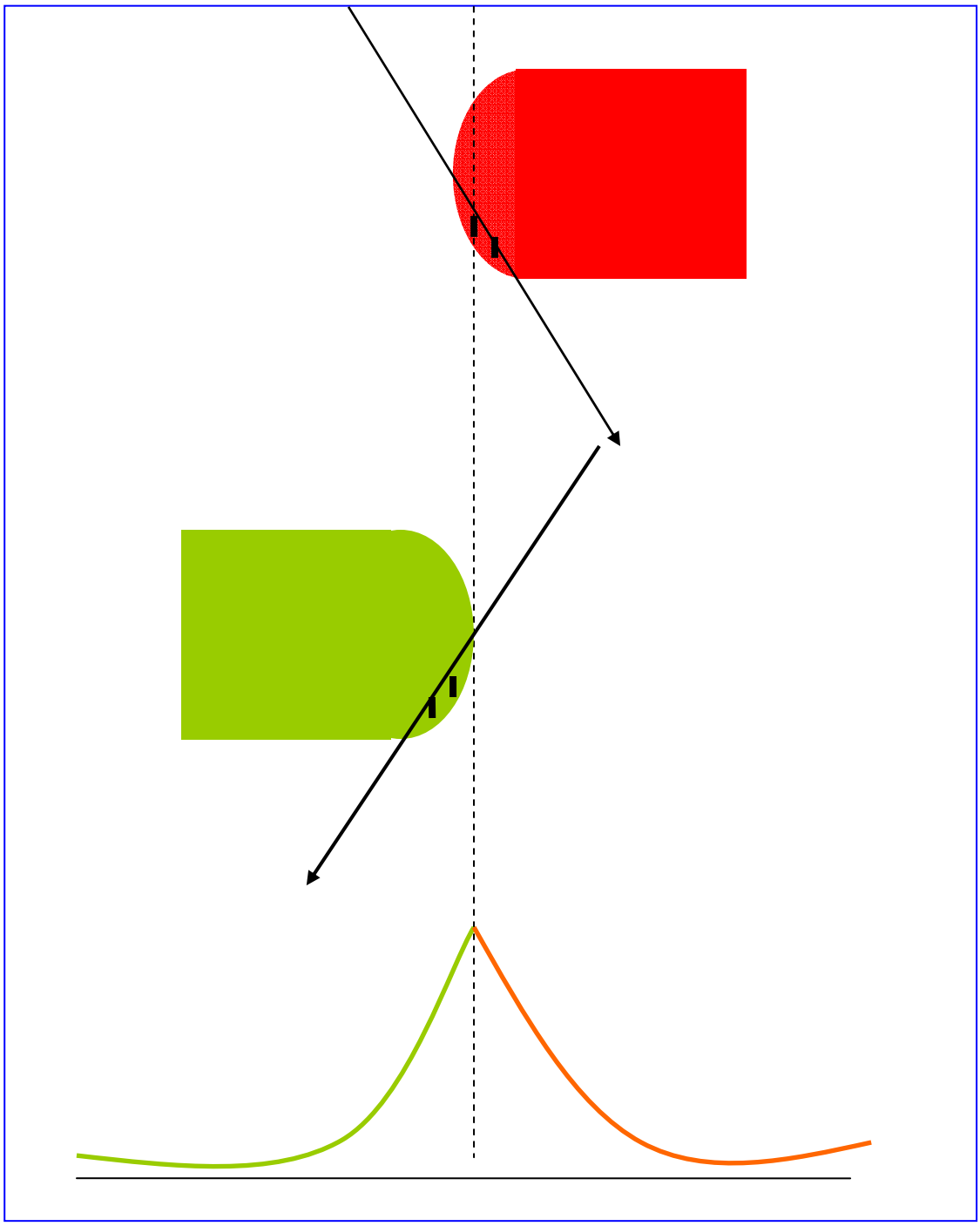
Film analysis was obtained by using a Vidar 12+ scanner for all experiments correspond with Scion analysis program or ImageJ program. The scanner program (Osiris) was calibrated to the OD unit before film scanning therefore the tiff image obtained from the scanner program was automatically related to the OD unit.

In 2005 close to the end of the project time limit, an electronic portal imaging device (EPID) was installed at ICCC with a commercial dose assessment tool. IMRT verification with this device was attractive due to no processing required, online image, and reliability. The aSi-EPID was tested compared with EDR film and BEAMnrc Monte Carlo simulation. The results are discussed in section 7.2.

Matchline effect

During verification of step-and-shoot IMRT fields using the Varian MLC, matchline effects were frequently observed and the detection of these narrow dose lines became a recurring of this thesis. Matchline effects appear due to the curved leaf end design of

this MLC. Extra transmission leads to a combined penumbra (matchline) of extra dose.



The matchline definition: the hot dose line which caused by the combination of the transmission dose (penumbra) through the curved leaf end (tiny vertical lines as shown at the above picture) of MLC pair.

During experiments suitable overlap values of MLC are discussed. An in-house adapted from Hoban P (2002) was used to generate the MLC overlap files. With a confirmation using Monte Carlo simulations, this thesis found an optimal value of MLC overlap which is presented in section 4.2 and 6.2.

In chapter 5, the overlapping co-axial modulated field measurements (film and EPID) and calculation (RTP computer) were compared. Also the effect of matchline appearing between jaw-MLC is discussed. During head and neck IMRT treatment at ICCC, six out of eight head and neck patients treated have had large enough target volumes to require split overlapping co-incident fields (Metcalfe *et al* 2004). Because of the limitation of MLC traveling distance up to 14.5 cm, one field was split into 2 subfields with an overlap set at 4 cm.

In chapter 9, the demonstration of the RTP version 7.0g and 7.4 to produce the matchline situation was discussed with a comparison of the clinical IMRT technique with the XV film and MC simulation.

Internationally refereed publications directly related to this work which the author has published during the course of this thesis include the following:

Tangboonduangjit P., Wu I., Butson M., Rosenfeld A., and Metcalfe P., 2003 Intensity modulated radiation therapy: film verification of planar dose maps. ***Aust. Phys. Eng. Sci. Med. 26***: 194-200.

Tangboonduangjit P., Metcalfe P., Butson M., Quach K.Y., and Rosenfeld A., 2004 Matchline dosimetry in step and shoot IMRT fields: a film study. ***Phys. Med. Biol. 49***: N287-N292.

Associated papers in this area which the candidate has had significant input into include:

Metcalfe P., Chapman A., Arnold A., Arnold B., Tangboonduangjit P., Capp A., and Fox C., 2004 Intensity-modulated radiation therapy: Not a dry eye in the house. ***Australasian Radiology 48***: 35-44.

Metcalfe P., Tangboonduangjit P., and White P., 2004 Intensity-modulated radiation therapy: overlapping co-axial modulated fields. ***Phys. Med. Biol. 49***: 3629-3637.

Parts of this work have also been presented by the author at the following conferences:

Tangboonduangjit P., Metcalfe P., Butson M., Quach K.Y., and Rosenfeld A. Intensity-modulated radiation therapy (IMRT) dose verification: measuring the match line effect. **World congress on Medical Physics and Biomedical Engineering conference, Sydney Australia,** 24-29 August 2003.

Tangboonduangjit P., Metcalfe P., Butson M., Quach K.Y., and Rosenfeld A. Intensity-modulated radiation therapy (IMRT) dose verification: measuring the match line effect. **Experimental Radiation Oncology, St.George Hospital, Sydney Australia,** Dec, 2003.

Tangboonduangjit P., Metcalfe P., Takacs G., and Rosenfeld A. Monte Carlo simulation of a linear accelerator for a 6 MV photon beam. **Experimental Radiation Oncology, University of Newcastle, Collaghan, NSW,** 6 Dec, 2004.

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