Film planar dose verification of "step and shoot" intensity modulated radiation therapy fields

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Abstract

The aim of this study was to quantify the rounded leaf end effect of multileaf collimator (MLC) from a sequence of segmented fields within an intensity modulated radiation therapy (IMRT) delivery by the step and shoot technique. This field sequence was designed to highlight and quantify the match line effect. The observation of this study included: (1) The dosimetry characteristics of MLC (2) Match line effect (3) Dose verification of MLC segmented fields. The Kodak X-Omat V film was used as a dosimeter in this study.

During this study, all the films were orientated perpendicular to the beam central axis. In the determination of optical density-dose calibration curve, the film was placed between solid water slabs at $d_{\text{max}}$ under a 6MV photon beam which was produced using a Clinac 2100C (Varian Medical System). The dosimetry characteristics of MLC were divided into two parts: interleaf transmission/leakage measurement and rounded leaf end transmission/leakage measurement. Also two sequences of small MLC fields with different offset distances were customised to produce multiple match lines. Then film and computed planar dose maps were compared for five, seven and ten segment step and shoot IMRT fields.

The results showed that the total leaf transmission/leakage component was 1.5%. The amount of rounded leaf end leakage at the central axis was 28.7% with a FWHM of 4.9mm. In the sequence fields irradiation for the match line effect, a 2cm leaf gap with 1cm leaf offset and 1cm leaf gap with 0.5cm leaf offset were used, the average dose in
the match line was 11.88cGy (6.55%) and 2.27cGy (4.14%), respectively. In the dose verification for clinical IMRT plans, a match line was observed with the seven-segment plan. The FWHM of match line peak obtained from the dose curve of the film at the dose level of 30cGy was 6.5mm with a dose increase about 2cGy or 6.6% (2cGy/30cGy). In the five and ten segmented plans, the average difference between the normalised computed and film dose maps was about 6.7% and 11%, respectively.

In conclusion, it is noted that the dose along the match lines tended to increase, as the width of gap between leaves was decreased. The dose increased by match line effect was 4% to 6.5% in the experiment of the small gap with short distance offset sequence and was 6.6% in the clinical sequence. However, the match line effect could be minimized by offsetting the leaf position (LoSasso et al 1998) or avoiding the leaf driving to the area where a match line may occur. The dose contributed from match line in a multiple field delivery may only contribute to a less than 1% difference in treatment dose delivered to the target.

Key words: film dosimetry, IMRT dose verification, MLC, multileaf transmission, match line effect, rounded leaf end effect, step and shoot technique
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Chapter 1.

Introduction

X-rays were discovered by Roentgen in 1895. In the early days radiation scientists mainly focused on the production of satisfactory radioactive sources. The result of discovering x-ray emission from the radiative decay of Radium made progress in radiation therapy possible.

Following developments in the understanding of tumour control and normal tissue complication, radiation therapy has played a major role in cancer treatment. There are three methods in clinical application of radiation in common use today (Williams et al 1993):

(1) External beam radiation therapy (Cobalt-60, linear accelerators).

(2) Brachytherapy.

(3) Unsealed source therapy.

Since the 1940s development particularly with regard to linear accelerators has seen this technology dominate as a radiotherapy delivery device.
The result of the combination of radiation therapy with computer technology has had a major influence on the dose/target prescription practices of radiation oncologists. The development of three dimensional radiotherapy treatment planning systems has led to an advanced treatment technique, called three dimensional radiation treatment planning (3DRTP).

A 3DRTP system usually contains the following components:

- Images of target/tumour and organs/normal tissues that are near the target/tumour taken from CT or with MRI and PET fused images
- Real or virtual simulation of linear accelerator movements such as changing the angles of gantry, couch and collimator.
- A dose calculation module which models three dimensional x-ray and charged particle dose deposition.

As a result, the accuracy of beam delivery and dose calculation is improved by such a system.
1.2 Conformal Radiation Therapy

In this study, conformal radiation therapy (CRT) is defined as the treatment that conforms a three dimensional dose region to the target volume but delivers a low dose deposition to the tissue outside the target volume. This requires configuring the treatment fields according to the target shape that is viewed from each beam angle. When CRT combines with the use of computer controlled treatment devices which includes multileaf collimator (MLC) and 3DRTP, it is then called computer-controlled conformal radiation therapy (CCRT) or 3D-CRT. (Fraass, 1995)

1.3 Intensity Modulated Radiation Therapy

Intensity modulated radiation therapy (IMRT) is described as treatment delivery that is capable of varying the beam intensity across the treatment field and produces not only a conformal dose distribution to the target volume but also minimizes the dose deposition in the normal tissue around the target (Carol, ch2 1997). It is also considered as a specialized procedure within CCRT as commonly delivered by MLC-based techniques.
1.4 Dose Verification

Remarkable improvements in radiotherapy have been made due to MLC and inverse treatment planning systems which enable IMRT planning and treatment delivery. Nevertheless, detailed investigations of the treatment accuracy are in their infancy. Such investigations need to compare the dose delivered to the patient with the planning system dose. This is particularly important for IMRT since the delivery technique is more complex. Several subjects about dose verification, such as the dose distributions in vivo dose and monitor unit required at each treatment field, have been studied by medical physicists (Boyer et al 1999, Ling et al 1996, Burman et al 1997, LoSasso et al 1998). In those studies, the verification process was demonstrated by using the traditional tools for radiotherapy quality assurance (QA) check such as film, ion chamber and TLD. In addition, the result of dose distributions in IMRT also can be influenced by the patient positioning, internal organ movement and localization of target (Booth et al 2001, ICRU 50 and 62). The dose verification under these influences becomes more challenging.

1.5 This Study

The MLC studied in this thesis has rounded leaf ends. This gives an even penumbra at all leaf positions. The aim of this study was to quantify the rounded leaf end effect of MLC from a sequence of segmented fields within an IMRT delivery by the step and shoot technique. This field sequence was designed to highlight and quantify the match
line effect. Clinical port verification film (ie. Kodak X-Omat V film) was used as a dosimeter during this study. The observation of this study included:

(1) The dosimetry characteristics of MLC: it contains the determination of mid-leaf, interleaf and rounded leaf end transmission, commonly also defined as leaf end and interleaf leakage. The terms “rounded leaf end” and curved leaf end are interchangeably used in this study.

(2) Match line effect: is indicated as more than two irradiated fields with one of the leaf pairs driving to where the other leaf pair was for a prior segment. Several researches have observed this phenomenon (LoSasso et al 1998, Mohan et al 2000)

(3) Dose verification of MLC segmented fields was sought by comparing planar dose maps predicted by an inverse planning and leaf sequencing method with film placed between solid phantom slabs. The dose profiles were compared.
Chapter 2.

Literature Review

2.1 Intensity Modulated Radiation Therapy (IMRT)

2.1.1 Concept of IMRT

One advantage of IMRT is that radiation can be delivered to re-entrant target shapes close to critical organs. For example, the spinal cord if surrounded by a concave shaped tumour (see figure 2.1). The best unmodulated 3D-CRT plan is virtually always a less acceptable than a modulated IMRT plan. The treatment planner may be given a choice of MLC delivery known as “step and shoot” or “sliding window” or field compensator technique. These techniques will be described later in this chapter.

Figure 2.1 The concave shape of tumour around the spinal cord
2.1.2 3D-CRT vs. IMRT

Although 3D-CRT and IMRT have many similarities, there are differences in their concept, the treatment planning sequence and outcomes. In 3D-CRT, each treatment plan is constructed from three-dimensional (3D) image and multiple beams from different directions are usually required. The planners can then see clearly the shapes of targets through their beams-eye-view (BEV) and select the beams that fully cover the target site but not the critical organs or normal tissue. In addition, through the calculation with a forward dosimetric algorithm, it presents a 3D dose distribution. The optimisation of the plan is done by varying the beam weights, wedge angle and beam directions. Whether or not the treatment plan is acceptable depends on whether the dose is distributed uniformly in the target while the surrounding normal tissue receives the dose well below their tolerance.

In IMRT and 3D-CRT, the dose planning CT images are processed using the same method as in 3D-CRT. Image fusion from computed tomography (CT), magnetic resonance imaging (MRI) and positron-emission tomography (PET) may be used to increase the accuracy of contouring the target site as well as reducing the area of normal tissue exposed to the radiation field.

An inverse treatment planning system with computerised optimisation is essential for in IMRT. In this application, the meaning of “inverse” refers to an inverse process of determination of the optimal intensity pattern (Verhey, 1999). As previously mentioned, there are two main delivery techniques: “step and shoot” and “sliding
window”, applied in IMRT. “Step and shoot” described the delivery of several discrete in field segments whereas “sliding window” described treatment delivery as the MLC leaf pairs move dynamically across the field. Because sliding window creates a better spatial dose resolution maps, it may become the method of choice. The delivery method depends somewhat on design of the MLC device and computer planning system.

2.1.2.1 Case Study

The following describes some clinical cases, prostate and nasopharynx carcinoma, that have been treated with IMRT and 3D-CRT in some cancer centres. The treatment plans analysed using by dose-volume histograms (DVHs).

Prostate Treatment

- Study 1.

Verhey (1999) has used DVH to compare the prostate treatment results in three different techniques: simple IMRT, which was also called 3D-CRT that there were forward planned and in-field segments and weighting were defined by the planner; inverse-planned SMLC-IMRT and dynamic IMRT with the Peacock MIMiC. In simple IMRT and SMLC-IMRT, the treatment was completed within two phases. The first phase was delivered the entire prostate gland up to 73.8Gy with 1.8Gy/fraction/day. In
the second phase the tumour region, which was specifically identified by MR spectroscopy, was boosted up to 90Gy with 2.2Gy/fraction/day. The patients were treated in supine position with seven beam angles in the directions of right/left laterals; right posterior oblique/left anterior oblique, left posterior oblique/right anterior oblique and anterior inferior oblique (see figure 2.2) The total segment of treatment was 18 for simple IMRT and 60 for SMLC-IMRT.

The observation in DVHs in these three plans showed that the highest conformal dose to the target and the lowest dose to organ at risk, such as rectum could be achieved by dynamic IMRT. It also indicated that with increasing the number of intensity level and beams, more conformal dose plans were obtained. Moreover, the results showed that there was higher dose to the rectum in SMLC-IMRT plan than in simple IMRT plan but not much difference was found at 60Gy or above. The Study also recorded the setup error and internal movement of patient. It was found no major difference of setup error in all three techniques. However, the internal organ movement was a concerned for dynamic IMRT.

![Figure 2.2 Beam orientation of prostate treatment](image-url)

*Figure 2.2 Beam orientation of prostate treatment*

*Indicates the beam direction*
Study 2.

Burman et al (1997) also compared the 3D-CRT and dynamic IMRT in prostate treatment. There were six beam angles applied in 3D-CRT and five for dynamic IMRT. The patients were treated in prone position. The dose prescribed to the planning target volume (PTV) was 75.6Gy for 3D-CRT and 81Gy for dynamic IMRT. The comparison of DVHs showed that 5% PTV had received 85.5cGy in dynamic IMRT. The tumour control probabilities (TCPs) were 90% for the IMRT plan and 83% for the 3D-CRT plan. In 3D-CRT, 20 to 30% of rectum received 75.6Gy or higher. The volume receiving dose from 70 to 75Gy in 3D-CRT plan was slightly higher and was lower from 20 to 40Gy in comparison to the IMRT plan. The normal tissue complication probability (NTCP) in both plans was about 2%.

Nasopharynx Treatment

Study 1.

The case of nasopharynx addressed by Verhey (1999) was planned with eight beam angles in simple IMRT and 5 beam angles with 5 intensity levels in SMLC-IMRT. The total dose prescribed to the gross tumour volume (GTV) was 70.2Gy delivered by 1.8Gy/faction/day. The dose constraints to critical organs were described as follows: less than 45Gy to the spinal cord, less than 50Gy to the brainstem and less than 35Gy to 50% of the parotid glands.
The DVHs showed that dynamic IMRT gave a better result by reducing critical organ dose. The majority of critical organs received dose slightly higher than or close to their constraints in simple IMRT plan with increased dose to the target. The study also found that increasing the number of beam angles and intensity levels could improve the dose uniformity to GTV. Unfortunately, it increased the dose to the critical organs as well.

- *Study 2.*

Wu et al (2000) have also compared the DVHs of both 3D-CRT and IMRT plans of head and neck cases. In 3D-CRT, to avoid xerostomia, the tumour was first treated with 5 factions of 2Gy and then increased the faction size to 2.25cGy. As the treatment dose in tumour volume reached to 46Gy, the treatment fields of target would be reduced and multiple entry portals were applied with 2.25Gy/fraction until the total dose was reached about 73Gy. The total dose to the lymph node area, spinal cord and brainstem were limited to 46, 45, and 55Gy, respectively.

In IMRT, the treatment was done by using a “sweeping window” technique. The total dose to the tumour and dose constraints to the critical organs remained the same as for 3D-CRT. However, the IMRT plan was designed based on “simultaneous integrated boost” (SIB) that was to treat volumes of regional, suspected and gross disease simultaneously. The entire treatment region was irradiated by a single weep of MLC leaves in each intensity modulated field.
Their results showed that the IMRT plan had better conformity to the tumour volume than 3D-CRT. It was found that less than 40% of the parotid gland volume received more than 32Gy. The study also concluded that in most of the head and neck cases, the IMRT plans were satisfied with 9 intensity modulated beams.
2.1.3 Inverse Planning

Forward planning requires users to predefine beam parameters. The dose distribution in treatment plan is then calculated based on those conditions. Users often need to change and readjust the beam parameters and weighting in order to achieve the desirable dose distribution. This process is repeated until the result is satisfied. On the other hand, inverse planning is designed to work in reverse order. Commonly, it starts with defining the desirable dose distribution and setting the dose constraints for the organs at risk. Through the dose calculation and optimisation process, the planning system produces the beam intensity profiles which are able to deliver such an optimised dose distribution, as described by Nutting et al (2000).

2.1.3.1 Calculation Model

In dose calculation, several calculation models have been implemented in commercial treatment planning systems. Rosen (ch3, 1997) supposed that the pencil beam and kernel convolution approaches were more accurate than other models in dose calculation.
Since this study also involves the ADAC Pinnacle radiotherapy treatment planning system, which uses the collapsed cone convolution model. This model then is reviewed as follows.

**Collapsed Cone Convolution**

Collapsed Cone (CC) convolution is one of the convolution methods that has been implemented in a commercial treatment planning systems. In convolution algorithm, there are two main components included in the calculation: (1) total energy released per unit mass (Terma), which is the total energy transferred to the medium by the interactions of primary photons (2) energy deposition kernel, which is the energy deposited about a photon interaction site. It is often divided into a primary kernel that scores interactions caused by the primary photons and a scatter kernel that scored the energy deposition from scatted photons. In some studies, the energy deposition kernel is also called as dose spread array, a differential pencil beam or a point spread function.

In Metcalfe et al (ch7, 1997), terma was given as:

$$T(r) = \frac{-1}{\rho(r)} \nabla \cdot \Psi(r) \quad \text{------------------ (2.1)}$$
Where \( \rho(r) \) is the density at a point \( r \) in the medium. \( \Psi(r) \) is the energy fluence of primary photon. Since the energy fluence is decreased exponentially with depth, the equation 2.1 can also be represented as:

\[
T(r) = \frac{\mu}{\rho}(r) \Psi(r) \quad \text{--------- (2.2)}
\]

Where the \( \frac{\mu}{\rho}(r) \) is the mass attenuation coefficient at a point \( r \)

For the energy deposition kernel, it was given as (Metcalfe et al 1997):

\[
H_p(\Delta r) = \frac{E_p(\Delta r)}{E_{\text{tot}}} \quad \text{--------- (2.3)}
\]

Where \( E_p(\Delta r) \) is the primary energy deposited in a voxel at vectorial displacement \( \Delta r \). \( E_{\text{tot}} \) is the total energy transferred by primary photons in the selected interaction voxel. For the scatter kernel, the subscript “p” is replaced by “s”. However, equation 2.3 can be written in Cartesian coordinate as:

\[
H_p(\Delta x, \Delta y, \Delta z) = \frac{E_p(\Delta x, \Delta y, \Delta z)}{E_{\text{tot}}} \quad \text{--------- (2.4)}
\]

With a polyenergetic primary kernel, equation 2.4 can be represented by an analytical function (Ahnesjo, 1989, Metcalfe et al 1997):

\[
H(r, \theta) = h(r, \theta) = \left( A_{\theta} e^{-a_{\theta} r} + B_{\theta} e^{-b_{\theta} r} \right) / r^2 \quad \text{--------- (2.5)}
\]
Where $A_\theta, a_\theta, B_\theta, b_\theta$ are functions of the scattering angle $\theta$. $(A_\theta e^{-a_\theta r} / r^2)$ is the primary kernel and $(B_\theta e^{-b_\theta r} / r^2)$ is the scatter kernel.

For the absorbed dose at $r$, Ahnesjo (1989) defined it as:

$$D(r) = \frac{1}{\rho(r)} \int \int \int T_E(s) \rho(s) h(E,s,r) d^3s dE \quad \text{(2.6)}$$

Where $T_E(r)$ is the differential term. $h(E,s,r)$ represents the energy deposition kernel, which is a fraction of the radiant energy released by the primary photons at $s$ that has energy transferred per unit volume at $r$, monoenergetically.

The equation 2.6 is rewritten with a polyenergetic kernel as:

$$D(r) = f(r) \frac{1}{\rho(r)} \int \int \int T_E(s) \rho(s) h(s,r) d^3s \quad \text{(2.7)}$$

Where $f(r)$ is the depth hardening correction factor.

However, Ahnesjo (1989) described that the cc convolution algorithm was based on the assumption as follows:
"All energy released into coaxial cones of solid angle $\Omega_{m,n}$ from volume elements on the axis is rectilinearly transported, attenuated and deposited in elements on the axis" (see figure 2.3)
Figure 2.3 The assumption of collapsed cone is (a) all energy released into coaxial solid angle $\Omega_{m,n}$ from volume elements on the axis is rectilinearly transported, attenuated and deposited in element on that axis. $\Sigma_{mn} \Omega_{m,n} = 4\pi$. In (b), it shows that the energy from Cartesian voxels, $A$ and $A'$ will only be deposited into the voxels, $B$ and $B'$, respectively. (From Ahnesjö (1998) figure 4.)
Consider an energy receiving voxel which was located at the intersection of collapsed cone lines, the solid angle covered by the corresponding cone was $4\pi$. Each radial line, was considered as an axis of a cone with a polar angle and also represents the result of the energy deposited with the entire cone at particular radius. The interaction site was defined as a point in a Cartesian voxel array. Each interaction voxel could also generate a lattice of lines that passes through the dose calculation array. Terma was obtained from each point at each cone axis throughout the array. During the dose calculation, the voxel array was radiated through by a lattice of line in each of direction of the cone axis. One line of each direction only passed through each voxel once. Only the voxels that have the energy radiated through along the cone axis would be taken into account in the calculation.

This reduction in computation points means that the collapsed cone convolution method demonstrates a comparable computation time to Fourier convolution and the accuracy of the result is satisfied. (Metcalfe et al ch.7 1997 and ADAC Pinnacle Manual)

2.1.3.2 Optimisation Algorithms

These algorithms are employed during inverse planning to compare the solution calculated with the objective solution being sought. Webb (2001) also mentioned that
Bortfeld et al (1999) has summarised the optimisation techniques in two classes: deterministic and stochastic. The gradient-descent technique, which is also known as the steepest-descent technique, was a typical example of deterministic algorithm. Simulated annealing was classed as a stochastic algorithm. The difference is that the deterministic approach is done by using an intelligent estimate of how to approach a minima. On the other hand, the stochastic approach is performed by a random method. However, in both approaches, it requires a “cost function” operator to determine if sufficient iterations for the optimisation process before have occurred achieving the goal.

**Inverse back Projection, Radiation Kernel and Iterative Reconstruction**

Rosen (ch3, 1997) has reviewed the inverse back projection, radiation kernel and iterative reconstruction methods. For inverse back projection, they divided each treatment beam cross-section into a two-dimensional array of pencil beams. The fluence from each pencil beam was combined into an one-dimensional fluence profile. The two-dimensional fluence profile was a result of summation of all fluence profiles from one dimension. A projection operator, which was similar to the back projection operator of image reconstruction, was required for the calculation of the dose distribution. As the conditions for both target and normal tissues were given, the dose along each beam ray onto the incident beams was added up by the projection operator. After the inverse transformation, the intensity profile was produced from the dose distribution and the fluence profile was normalized to the desirable dose on the isocentre. He also pointed
out that the resultant dose distribution could be improved with a filtering function in the calculation. But this could also result in negative beam weight being calculated that often was set as zero rather than the negative.

**Simulated Annealing**

Simulated annealing was one of stochastic algorithms which requires interactive process, as described by Webb (2001). By applying a “hill climbing” and “tunnelling” technique, it was possible to obtained the optimum solution in global minima rather than being trapped in local minima. The cost function operator that has been applied in simulated annealing was based on the importance-weighted quadratic dose or dose-volume constraints. In the optimisation process, the solution was usually accepted when the value of cost function was less than the previous one. There also was some exception of accepting the variable that had the cost value higher than the previous one.

**Gradient-descent Method**

The Gradient-descent method was classed as one of deterministic algorithms by Bortfeld et al (1999). The optimised solution generated from the gradient technique was
faster than from simulated annealing but could be trapped in local minima easily. Webb (2001) addressed that the intensity beam fluence could be optimised based on dose-volume constraints, soft or hard constrains in the gradient technique iteratively. Using dose-volume constraints, the maximum and minimum dose constraints to the normal tissue and the target, respectively were determined by users. In each iteration step, the controlled variables or parameters were allowed to be readjusted. In a soft constraint approach, a penalty was usually followed in the dose constraints variation. With a hard constraint, it simply would not allow the dose constraints to be contravened.
2.1.4 Delivery of IMRT

2.1.4.1 Multi-leaf Collimator (MLC)

While MLC's were initially used as static field blocking devices, they have been adapted for cone beam IMRT application (Boyer et al 1998). Due to accuracy and mechanical tolerance Siemens and Elekta MLCs have been used for "step & shoot" techniques while the Varian (Millennium) was designed for both "step & shoot" and "sliding window" techniques. Several studies have investigated the dose characteristics of MLC within different delivery techniques. This section will review some studies of MLC dosimetry that have been done in past few years.

MLC Transmission

Klein et al (1995) have investigated clinical implementation of a commercial MLC (Varian Medical System). The MLC with 26 pairs of leaves was mounted to a Varian Clinac 2100C. The leaf transmission was measured using films which were placed at $d_{\text{max}}$ between a set of solid water phantom slabs and irradiated through a jaw defined field size of $20 \times 20 \text{cm}^2$ for each energy. The resultant images were scanned in both perpendicular and parallel directions to the leaf movement. The difference of dose profiles between leaf retracted and open fields were used to define the transmission and leakage of the MLC.
The observation showed that the maximum and minimum transmission at 6MV was 1.5 and 2.0% and for 18MV, it was 1.5 and 2.5%. However, the total transmission of MLCs was less than that of conventional alloy blocks but was greater than that of jaws. The maximum transmission through the leaf end in the closed field at 18MV was 28% at the central axis but could be decreased to 12% while the junction of opposing leaves was offset as a function of distance.

Georg et al (1997) have compared MLC dosimetry with that of conventional collimators. Both MLCs with 32 pairs of leaves and conventional collimators were manufactured by GE. This leaf has an excellent design to minimize interleaf leakage. Although this manufacturer has no linacs in Australia, the design is of academic interest in that the leaves were interlocked within a "wave" shape (see figure 2.4), which was unlike the "Tongue and Groove" design in the Varian MLC. The measurement of transmission and leakage of leaves was done by exposing film at a depth of 2cm for 6MV and 4cm for 18MV and 25MV between solid water phantom slabs. The films were irradiated while the leaves were completely closed at the central axis and also at 5cm off-axis. All resulting images were then scanned in a parallel direction as well as a perpendicular direction to the leaf movement. All the resulting data was normalized to both 4×4cm² and 10×10cm² open fields. The mid-leaf transmission measured for all setups and at all energies was less than 0.5% with both normalization fields. Reported interleaf leakage results, after normalizing to 4×4cm², the maximum value was 1.28% and 1.15% for 25MV and 18MV, respectively at the position of central axis with the leaf closed at 5cm away from the central axis. For the energy of 6MV, the maximum was recorded as 1.18% at the point of 5cm off-axis when the junction of closed field was at the beam's central axis. The average interleaf leakage in the case of off-axis was
Figure 2.4 The leaf design from (i) GE (from Georg et al (1997) figure 1.b) and (ii) Varian (from Chen et al (2000) figure 2.)
0.66% and 0.6% for 25MV and 18MV. For 6MV, it was 0.5% found again in the on-axis case. For the leaf end leakage, the maximum was 20% obtained from the junction at the central axis and 10% at the 5cm off-axis.

**MLC Transmission Calculation**

Chen et al (2000) obtained the transmission of MLC (Varian Medical System) by using a ray tracing based method. The calculation started with determining the path length of a ray line in the MLC from the exact geometry of leaves. The path length was then substituted in a numerical equation and simulated using a Monte Carlo method. From the result of this, they generated a fluence distribution for IMRT fields. The assumption of the fluence distribution was based on a point source and extended source model that was calculated by a convolution method.

The result of the study showed that, there was no significant difference in the penumbra caused by the rounded leaf ends in both the point and extended source model. However, a region that was caused by interleaf transmission in both cases was clearly indicated (see figure 2.5). In the path length calculation, a minimum was observed in the region of leaves overlapping, which was a result of the tongue and groove effect (see figure 2.6).

Since the study was designed for verification of beam delivery and dose calculation, the authors believed that such calculation models could also be applied in
Figure 2.5 Comparison of calculation fluence profiles in the direction of (a) parallel and (b) perpendicular to leaf movement: point source (thin lines) and convolution method with extended source (thick lines). (From Chen et al (2000) figure 6.)

Figure 2.6 The tongue and groove effect was showed as the minimum in the path length profile. (From Chen et al (2000) figure 7.)
dynamic MLC verification and these results agreed with the experimental measurement from film and a beam image system, details of that are available in their paper.

**MLC Transmission and Leakage Reduction**

The "tongue and groove" (T&G) design is commonly used by most manufacturers. The researchers also show that such a design can also cause an underdose region during the movement of leaves. Balog et al (1999) investigated the effect in the MIMiC MLC which was designed for the purpose of IMRT by NOMOS Corporation. The NOMOS device is a one dimensional pneumatic MLC for tomotherapy, which is used during arcs. Note conventional motor driven MLCs are deemed too slow for this binary (on/off) mode of operation. In figure 2.7, the T&G effect is shown in schematic representation. The effect is obtained when an open and closed movement between two contiguous leaves occurred, which then causes an underdose region at the intersection of T&G. Penumbral blurring was also considered as a cause of underdose. It occurred when two adjacent leaves were opened simultaneously due to an incomplete irradiation through the leaves. The aim of the study was to determine the dose characteristic of leaves with and without T&G design from the film and ion chamber measurement and calculation modelling (analytic model and Monte Carlo simulation).
Figure 2.7 The tongue and groove effect: a underdoes region was observed at the centre. (From Balog et al (1999) figure 2.)
During the experiment, the measurement of with and without T&G was processed by using the tungsten plates to setup as the real leaf size. The dose detected from the experiment was described in a normalized profile integral dose (NPID) that was the dose integrated under the dose profile curve and divided by the number of MU which was used.

\[ \text{NPID (cGy-mm/MU)} = \int \frac{D(x)}{\text{MU}} \, dx \] 

In the film detection, the maximum transmission from a closed field was 0.33%. It was considered insignificant to the overall leaf transmission. A 38% difference was noted in the dose profiles between a simultaneous opening of adjacent leaves, i.e. penumbral blurring, and sequential opening, i.e. T&G effect with 2.1mm in the FWHM (see figure 2.8). In the case of non-T&G design, there was no substantial reduction observed from the result of analytical modelling. But from the experimental results, it showed that the dose transmitted through the region between two adjacent leaves was increased by the increment of separation between the leaves. A 1.5% NPID increase of a fully opened leaf in the region with 0.2mm separation was recorded.

In the case of the T&G design, there was a large fluence decrease in the region between the leaves while a 0.5mm space was applied in analytical modelling. From the experimental measurement reported the transmission through the T&G region was proportional to the separation of T&G plates. When the separation was up to 0.2mm, the transmission increased to 0.34% in NPID of a fully opened single leaf.
Figure 2.8 The fluence profile comparison of simultaneous (penumbral blurring) and sequential (T&G effect) opening of adjacent leaves. (From Balog et al (1999) figure 6.)
The study concluded that T&G design had been a benefit in the reduction of interleaf leakage. The only benefit of increasing the overlapping region in T&G was to avoid leakage due to the MLC manufacturing tolerances. Although the underdose region caused by T&G seemed also to have influence on the dose homogeneity, it could be limited by operating the leaf control programme correctly. In addition, such effect might be negligible if the patients setup variation was also considered. Furthermore, a decrease in leaf transmission was recorded in the case of the less separation between two adjacent leaves without T&G, which appeared more effective than in the case with a wider T&G. However, the leakage of interleaf was significantly affected by the thickness of the leaf.

**MLC in Sliding window technique**

The MLC characteristics in dynamic (sliding window) mode have been investigated by LoSasso et al (1998). They mentioned that the accuracy of dose delivery in dynamic mode was mainly influenced by the precision of the field or gap between the opposing leaves. Thus, the stability of leaf step and the positioning accuracy of leaves and the leaves performance during their acceleration and deceleration were critical to the outcome in such a technique. Moreover, although the majority of normal tissue was shielded by the leaves during the treatment, the transmission and leakage of the leaves could still cause a substantial contribution in the dose delivery.

In order to ensure the accuracy of MLC, they believed that the mechanical check of MLC was even more important to the sliding window technique. In the study, a
narrow gap between the opposing leaves with a different width was used to examine the positioning accuracy, reproducibility and stability of leaves. The results were recorded by either a verification film or parallel plate ion-chamber. In-house design software was used to compare the leaf positions during the operation with their prescription position in every 55 ms. The tolerance of leaf position was defined by users from 0.1 to 5mm. The experiments could be interrupted if the leaf was moving out of its defined tolerance.

The result of this study showed that at energy of 6MV, the leaf transmission was increased relative to open field dose at a given depth as the depth of measurement was increased. Such a phenomena could be due to the beam hardening. But it was observed at energy of 15MV. However, the transmission was decreased while the size of MLC field was increased in both energies (see figure 2.9). The average transmissions of mid-leaf and interleaf were 2.0% in 6MV and 2.1% in 15MV (see figure 2.10). The values were varied between 1.7 to 2.7%. The study stated that since it was believed that the tissue remained under the leaves in dynamic mode was longer in comparison to time of exposure though the window, the effective transmission should be counted as typically 4 to 6% of total dose in-field for the treatment planning calculation. Of course, this also depends on the leaf opening width.
Figure 2.9 Transmission vs. Depth in 6MV and 15MV (From LoSasso et al (1998) figure 3.)
Figure 2.10 Interleaf transmission measured at the centre axis (From LoSasso et al (1998) figure 4.)

Figure 2.11 The rounded leaf end transmission based on the calculation. (From LoSasso et al (1998) figure 6.)
In the study of LoSasso et al (1998), the rounded leaf end effect was observed when a sequence of static MLC fields with gap width varied from 0 to 10cm was irradiated. The integrating dose profile from this demonstration was recorded on the film. The value of field offset determined from the film was then compared with the value based on the calculation. The irradiated field size tended to be enlarged by the dose contributing from the leaf end due to a larger attenuation of rounded leaf end.

Figure 2.11 shows the leaf end transmission calculation gives result which are approximately equal to a 1 mm leaf offset, as was determined from the width of the rectangular area that is equivalent to the area under the transmission curve. Thus, for a MLC field, the transmission was counted as a 2mm offset in 6MV. In addition, the results of experimental measurements in field offset were 2 and 1.7mm for 6MV and 15MV, respectively, which agreed with the calculation results. However, the study concluded that the total transmission of MLC in dynamic mode could cause an extra 5% of target dose for typical 4cm leaf gaps and up to 20% for typical 1cm leaf gaps.

Papatheodorou et al (2000) also mentioned the rounded leaf end effect. In their study, the rounded leaf end transmission became significant when the small gap size was occupied in the sliding window technique. The reason given for such a technique was that the leaves moved with a constant speed and were exposed with continuous radiation while they were driven across the defined target area. If the gap or slit size was reduced, the time the leaves remained under the radiation was increased. Hence the leaf end transmission effect became significant. Furthermore, since the attenuation at the
rounded leaf end was larger than in the mid-leaf, it was important to quantify and taken into account the dose that contributed from the leaf end transmission during the dose calculation.

In Papatheodorous' study, a constant mid-leaf transmission of 2% was included during the dose calculation. The rounded leaf end transmission was taken into accounted by using the method proposed by LoSasso et al (1998). That is, the leaves covered under the irradiation window were moved inward 1mm each so the width of the nominal gap was reduced by 2mm. Comparing the results before and after considering both the mid-leaf and leaf end transmission, they found that the dose difference between the calculations and the measurements before including the leaf end and mid-leaf transmission could be up to 26% different. However, after taking into account both transmissions, the difference dropped to less than 2%.

Ling et al (ch15, 1997) particularly considered the effect of rounded leaf ends from Varian's MLC. They accounted for the effect by offsetting each leaf by 0.75mm. As a result of this, they reported that an accurate intensity profile was obtained in both the in-house design and the clinically used inverse treatment planning system.
2.1.4.2 Techniques

*Step & shoot*

The step & shoot technique has been commonly used for IMRT plan delivery. For each static gantry angle the treatment field is divided into a number of segments or sub-fields according to the preset intensity level in the target. During the irradiation, no MUs are delivered while MLC leaves "step" to the next segment configuration. When the leaves reach their prescribed position, the beam is set to "on" ("shoot") again. This process is then repeated for a number of segments at the set gantry position. The idea of the technique is to create a three-dimensional dose fluence map relative to the shape of the target by varying the dose transmission through a different number of sub-fields. However, the smooth field edge is often difficult to achieve by MLC due to the limitation of the leaf width and shape. Chang et al (2000) described the intensity modulated map from "step & shoot" as a series "skyscrapers" representing the height of each discrete intensity level.

*Multi-Segments Vs. Compensator*

Chang et al (2000) have investigated the characteristics of static field delivery techniques: step & shoot MLC auto-sequence and a compensator like intensity modulator. They stated that the main difference between these two techniques was the resolution of intensity modulation. In the step & shoot, the intensity modulation (IM) maps tended to perform as a "skyscraper" due to the discontinued IM map. In contrast, a
smooth continuous IM map was obtained with the compensator technique. In addition, the study also evaluated the dose optimisation of two clinical cases: a three-field sinus tumour treatment and a six-field nasopharynx tumour treatment by using the technique of conventional open/wedge, compensator and step & shoot with different IM levels. In both treatments, the observation recorded that the number of segments was proportional to the number of IM levels. In nasopharynx tumour treatment, the results of DVH comparison in normal structures recorded that the compensator technique was deemed to preserve more normal tissue. The difference between both techniques was not varied significantly by increasing the IM levels.

Moreover, the treatment time in the step & shoot was raised rapidly as the IM level was increased. On the other hand, there was no indication of a difference in treatment time in both compensator and conventional treatment techniques. In fact, the average treatment time required for the step & shoot was longer than the other two techniques. Furthermore, the time of preparation for the compensator was longer in comparison with the step & shoot. However, the study also found that a reasonable dosimetric quality and treatment time could be achieved by using five IM levels. For a further investigation, both Sharpe et al (2000) and Chang et al (2000) considered that since the small field size (less than 4×4cm²) was often applied in the step & shoot technique, the study of dose verification of the small field sizes needed to be carried out.
Sliding Window is another technique used in IMRT delivery. It is also known as a dynamic MLC (dMLC) technique. In the Varian system, such a technique is performed by driving both banks of leaves with leaf gaps determining the output. The beam intensity is modulated through a sequence of MLC leaf movements. The speed of each leaf pair is defined by the interpreter from the dynamic MLC software that consists of a series of check points. Once the intensity distribution from the treatment planning calculation is satisfied, it then creates the speed profile for each leaf pair according to the distribution, as described by Nutting et al (2000). In addition, they mentioned that the leakage and transmission of MLC must be included during the dose calculation.

The verification of the sliding window technique is more complex than the static field technique. For the dose distribution examination, Ling et al (ch15, 1997) compared the resulting dose distribution determined by importing the dMLC fields into an integrated 3D conformal treatment planning computer, with the dose patterns from the original inverse plan. In mechanical checking, the leaf speed and the position accuracy should be included as a part of routine QA. For the pre-treatment checking, a computer controlled interface system was used to evaluate the initial position of MLC leaf, gantry angle and MU setting. For on-line MLC examination, they designed a computer controlled electromechanical system to record the real time leaf position and compare that with the prescribed position in each 55msec of continuous irradiation. If the difference in the position was greater than the defined tolerance, the treatment would be interrupted.
Intensity Modulated Arc therapy (IMAT)

Intensity modulated arc therapy using conventional motor driven MLCs is one technique requiring dMLC functionality in IM plan delivery. Yu (ch7, 1997) is the first one proposing this technique. The ideal of IMAT is to combine the dMLC function with the arc function in gantry rotation. It is believed that a highly conformal dose distribution could be achieved without increasing the treatment time. Hence the dose distribution in this technique is then modulated both spatially and temporally.

While the gantry is rotating, the field shape is varied from one angle to another. Since one arc can only deliver one level of intensity, to construct a desirable dose conformity, a number of superimposing arcs is required. The number of sub-fields in each beam angle depends on the number of intensity levels. After a preferable dose intensity distribution is defined from the treatment planning system, the distribution is divided into a number of intensity levels and decomposed into multiple uniform intensity sub-fields. Yu (ch7, 1997) pointed out that there was a number of decomposition patterns that could be produced from the same intensity level at the same gantry angle. These patterns were also relative to the leaf position of all sub-fields and the order of delivery. Since the gantry rotation and radiation delivery were in the continuous process, the distance of the leaf travelling needed to be minimized, which was also a registration criteria set in the process of decomposition patterns selection. If the long distance travel for the leaves could not be avoided, a lower dose rate could be required for the dose delivery.
Furthermore, Yu (ch7, 1997) compared the IMAT with tomotherapy. He found that in IMAT, there was no consideration of hot and cold spots associated with the beam abutment between slices as in tomotherapy because the target was completely covered by each sub-field. In addition, the couch movement and patient motion between slices was considerable and critical in the tomotherapy but not in IMAT.
2.2 Verification of IMRT

Since IMRT plans are often more complex than conventional 3DCRT and the plan delivery techniques are different from one to another, the treatment verification can be quite complicated. For mechanical verification, especially for MLC, Elekta has developed an on-line video camera, which is mounted above the MLC, inside the treatment head. Therefore, the MLC leaf motion and positioning can be monitored while the treatment is proceeding. Megavoltage electronic portal imaging (EPI) has also been commonly used for the leaf positioning and field configuration verification in IMRT, particularly for dMLC technique, stated by Ma et al. (1997). James et al (1999) also proposed that the correlating portal snapshot image could be an alternative method of verification in dMLC. For step & shoot, the mechanical check can be done by the regular method used in conventional 3DCRT such as EPI or port films. However, Nutting et al. (2000) pointed out that as the field size became smaller, the difficulty of beams-eye view verification increased since the internal structure under the field could not be clearly identified on either EPI or port film.

2.2.1 Dose Verification

There are several devices that have been used for dose verification of IMRT fields: Kodak XV film, thermoluminescent dosimeters (TLD), polyacrylamide gel and MOSFET semiconductor detectors. Since this study is designed for verifying the dose
distribution from regular verification film, this section will review mainly the film
dosimetry that has been done in past. In addition, the utilising of MOSFET detectors has
been extended to the radiation therapy field. Several institutions, including the medical
physics centre of University of Wollongong, and manufactures have been carrying out
the research in MOSFET and commercialised the relative products.

2.2.1.1 Film

Film response in Low dose

Evans et al. (1992) have used film to compare the dose distribution of the
treatment with and without a tissue compensator. They also studied the film response
within low energy (Cobalt-60) and high energy (6MV and 10MV) of photon beams.
During the experiment, Kodak XV2 film sandwiched by two sections of opaque
polystyrene phantoms was irradiated in the direction parallel to the beam's central axis.
The dose converted from the optical density from the film was compared with the
measurement from ion chamber. For all energies of photon beams tested, a linear
response curve was observed while the given dose was less than 50cGy. There was a
good agreement between the readout from ion chamber and the converted dose from
film density while such a low dose range was used. (See figure 2.12). Hence, they
Figure 2.12 Depth-dose data comparison of film and ion chamber
(From Evans et al (1992) figure 1(a))
concluded that there was no correction required for the optical density-dose conversion within a low given dose.

Film Calibration for Megavoltage Photon

Hale et al. (1994) have determined the film response curve in various depths with three different photon energies: Cobalt-60, 4MV, 18MV. The film was placed parallel to the beam central axis between slabs of polystyrene phantom with an adjustable aluminium frame. They also introduced two methods of dose determination from the film response curve: single depth and multiple depth conversions. In the single depth method, the optical density obtained from specific depth was converted into the corresponding dose from the selected calibration curve. In the multiple depth method, a series of calibration curves was produced in a depth range (0.5-12cm). The dose was converted from the suitable depth curve or calculated from the depth curves in between. The difference of the calibration curve measured at difference depth was recorded. In addition, the dose obtained from both the single and multiple conversion method was compared with the result from TLD.

The observation recorded that when the optical density was 0.8, the difference of the corresponding dose determined from the calibration curves with depth of 0.5 and 12cm was about 9% in Cobalt-60 (See figure 2.13). In figure 2.14, the difference
Figure 2.13 Calibration curve in Cobalt-60 γ-rays
(From Hale et al (1994) figure 1)

Figure 2.14 Calibration curve in 4MV photon beam
(From Hale et al (1994) figure 2)
increased to 15% in between the 1 and 12cm curves at 4MV. It was varied from 3.5% to 7% in between the 3 and 12cm curves at 18MV.

Moreover, comparison of two depth conversion methods showed that the dose obtained from the multiple depth conversion had a good agreement with the result from TLD. In the single depth conversion, the difference to TLD measurement increased while the depth was increased (see figure 2.15). The study concluded that for the optical density-dose conversion, a series of calibration curves determined in a range of depth was recommended while the film was oriented parallel to the beam’s central axis. A new calibration curve for each experiment was essential.

**Latealr Scatter Filtering of Film**

Burch et al. (1997) have proposed a lateral scatter filtering method to increased the accuracy in film dosimetry. The study was done by applying the high atomic number foils, lead (Pb), to both sides of film which was oriented in vertical direction during the exposure. Hence, the majority of low energy photon due to the Compton scattering could be filtered out by the foils. The effect of foil thickness and separated distance between film and foil was investigated. In order to observe a maximal change in the film response sensitivity, a 4MV photon beam was used for the study. The film calibration was done by irradiating the films that were placed horizontally and perpendicular to the
Figure 2.15 Percentage depth dose curve comparison of TLD, single depth and multiple depth conversion. 
(From Hale et al (1994) figure 4)
beam direction. The film sensitivity with field size and depth were also noted. Measurement from an ion chamber were used as a reference for the experiments.

The results of the film calibration recorded a significant change in film sensitivity while the depth of measurement was varied from 5 to 15cm within a field size of 25×25 cm² but not within a 6×6 cm² field size. They also observed that the difference of dose obtained from film and ion chamber was varied proportionally to the field size. In the percentage depth dose, the result with a 46mm thickness of lead foil and a 1.2cm of film/foil distance had a good match with the ion chamber measurements. A dramatic improvement in the accuracy and sensitivity of film from such combination was apparent when field size was increased up to 25×25 cm² (see figure 2.16). In addition, without the later filters, a maximum difference between film and ion chamber readout was 65% measured at d_{max} in the central beam axis. On the other hand, it could be reduced to 4% when the filter was applied. The study concluded that the lateral scatter filtering technique had a benefit for the improvement of film accuracy and sensitivity in low energy photon beams.

**Variation of Sensitometric curves in Perpendicular and Parallel Geometry**

Danciu et al (2001) have investigated the variation of sensitometric curves for two types of radiographic films, Kodak X-Omat V film and Agfa Structurix D₂ film in two different film orientations, parallel and perpendicular to the beam centre axis Their
Figure 2.16 The comparison of percentage depth dose data in film and ion chamber with and without the filter. A great improvement of film sensitivity showed in (b) field size 25×25cm² while the filter was applied. (From Burch et al (1997) figure 8)
study was particularly interested in the variation of optical density (OD) with field size and depth in phantom. Photon beam energies used for the study were Cobalt-60, 6MV, 15 MV, 18MV and 45MV. The curves for Kodak films and Agfa films were determined by using a wood phantom with density of 0.965 g/cm$^3$ and a polystyrene phantom with a density of 1.04g/cm$^3$.

The film arrangements for both orientations were shown in figure 2.17. In order to avoid any penetration of unattenuated primary beam through the plan between two slabs of phantoms and to remove the effect of any air gap in the film, the arrangement for parallel geometry was done by either setting the film 1.5 above the beam central axis or creating a angle of 2° between the beam central axis and the film plan.

For the Kodak film, it was found that there was not significant variation in the OD when the field size was changed at $d_{\text{max}}$ but it was found a small variation in the Agfa film. Figure 2.18 showed that the sensitometric curve from the perpendicular irradiation in Kodak films were independent to the depth in phantom in high energy of photon beam but a difference of 3.7% at the depth of 9g/cm$^3$ was noted in Cobalt-60. A simular result was also recorded in Agfa films. For the parallel geometry, the maximum difference of OD to the perpendicular geometry in the Kodak and Agfa films at $d_{\text{max}}$ with the same dose were 4% and 6%, respectively. (See figure 2.19)

For the influence of beam attenuation in the parallel geometry, two films that were irradiated independently with an inclination of 2° and a displacement of 1.5cm to
Figure 2.17 Film orientation in (a) perpendicular geometry and (b) parallel geometry (From Danciu et al (2001) figure 1.)

Figure 2.18 Sensitometric curves of the Kodak film in perpendicular geometry with a field size of 15×15 cm² at three different depths in phantom (From Danciu et al (2001) figure 2.)
Figure 2.19 Comparison of sensitometric curves in perpendicular and parallel geometry for the Kodak and Agfa films. (From Danciu et al (2001) figure 6.)
the beam central axis were compared with a film irradiated on the same level as the beam central axis. The results showed that a deviation of 3% was indicated between the curves obtained from the central plan and other two arrangements at $d_{\text{max}}$. The difference of the curves between 1.5cm displacement and 2° inclination was less 2%, which was within the experimental uncertainty. A summary of result with the experimental condition from the study was shown in Table 2.1.

**Clinical Case Evaluation**

In the study of Burman et al (1997), the dose verification for IMRT plans was done by comparing the dose distribution from the treatment plan with the measurement from Kodak X-Omat V (XV2) film. The film was placed between the phantom at the same depth as the treatment plan and perpendicular to the beam central axis. The dose-OD conversion curve was also obtained at the same depth with a similar field size as the plan. The scatter contribution to the film from such setup was believed more comparable to the film from the patient. Hence, the conversion curve was deemed more accurate and reliable.

The results showed that the dose distribution from both calculation and measurement was in a good agreement. Their cross-field dose profiles in both X and Y direction at the selected points also corresponded with one to another. (See figure 2.20)
Figure 2.20 Comparison of dose distribution in (a) IMRT plan (calculated) and the film image (measured) and (b) the cross-field dose profiles in X and Y direction. (From Burman et al (1997))
3.1 Verification Film

Verification film as used in a clinical radiation oncology departments consists of two protective coatings, silver bromide emulsion layers, adhesive coatings and one polyester base (see figure 3.1).

Figure 3.1 Components of medical X-ray film
3.1.1 Polyester Base and Emulsion Layer

The polyester base is designed to support and provides a surface for the emulsion. The thickness of such a base is approximately 180µm. It can tolerate the high temperature in an automatic processor. Moreover, the base is often dyed with colour (e.g. blue colour in KODAK film) which is to prevent eye fatigue while the film is examined on viewing boxes. In general, the image information in the film would not be changed by the dye. However, the base dye has significant effect on the radiographic density. Adding too much dye can cause an increment in the density. Thus, for a processing film, the radiographic density is the sum of remaining silver on the film and the base density.

The image after radiation exposure is contained in the emulsion layer that includes crystals of silver bromide within a gelatine medium. The shape, size and distribution of the crystals can cause a change in the characteristics of the emulsion. (Donaled 1996, Thompson et al 1994)

3.1.2 Formation of an Image

The image of radiographic film after radiation exposure is also called a latent image since the image is formed and is visible after processing. According to the Gurney-Mott hypothesis, when the film is irradiated, the electrons in silver bromide crystals will transit from their original orbit and move around in the crystals randomly. As those electrons are trapped or captured by sensitisation specks. It then neutralizes the
specks that have negative charges initially and forms metallic silver. The size of speck after neutralization is based on the amount of energy absorption. During the film processing, the specks are transformed to metallic silver and this produces the visible image. The blackness in the radiographic image is the result of silver appearance. The degree of darkness, which represents the amount of metallic silver, is described as the “density” of the image. (Donaled 1996, Thompson et al 1994)

3.1.3 KODAK X-Omat V film

KODAK X-Omat V film (Ready Pack, RP), which is also called XV-2 film, was used for all experiments in the study. According to the description from the KODAK company, it is a relatively low speed film and can be processed manually or through an automatic processor. The manufacturer recommends that unexposed films require storage at a temperature between 10°C and 20°C (50-70F) at 30 to 50 RH within a proper radiation shielded environment. For processed films, it is recommended to store at 16°C to 27°C (60-80F). The characteristics of film are shown in figure 3.2 whereby optical density is plotted against relative log exposure.

XV-2 film is designed for the purpose of verifying patient orientation and approximating treatment dosage. It is suitable to detect the dose in between 25 and 175 rad (cGy). Hence, this is a relatively dose insensitive film which is designed to stay in the field for the whole treatment (unlike sensitive portal film 2-4cGy). This is good for detection of patient movement and potentially for IMRT portal verification. Additionally, to increase image contrast, reduce film density and absorption of scatter
radiation, it is suggested to place a 0.03 inch thickness of galvanized steel or 0.01 inch lead plate between patient and film. For quantitative analysis, this is not done in this study.

Figure 3.2 the characteristics of RP X-Omat V film
3.2 Film Processor

During this study, a Kodak RP X-Omat processor was used to develop all the films. Sprawls (1993) stated that accuracy and consistency were the two main goals of processing. Film processing generally consists of four phases:

1. Development
2. Fixing
3. Washing
4. Drying

The processing cycle time of most medical film processors is approximately 90 seconds. In the stage of development, the chemicals in developing solution, hydroquinone and metol, cause a reduction to silver halide molecules and this results in metallic silver. If the film remains in the solution for a long time, the reduction will continue and eventually all silver halide will be turned into metallic silver. Therefore, to exclude the unnecessary metallic silver production to the image, a time setting is required. However, concentrations of the solution and temperature during this stage also have an influence on the quality of image.

During the fixation stage, the fixer solution acts on unexposed and undeveloped silver halide. It then makes the latent image become visible and fixes it on the film base. After washing by water, the remaining chemical on the film from the previous stage is removed and the film is dried at a temperature of about 57°C. There is some variability in film response due to processor variability. This has been quantified elsewhere (Suchowerska et al 1999).
3.3 Film Scanner and Image software

The film scanner used for these experiments was called a “VXR-12 plus film digitizer” (VIDAR System Corporation). It is a charge coupled device (CCD) digitizer. Hard copy film images of medical image can be converted by the system to digital images with a resolution of 0.427mm/pixel. The image software attaché to the system is called “Osiris”. It allows users to view and store the images as digital files. The software provides not only general functions for image enhancement and editing but also some functions for quantitative analysis such as dose profile determination, and image fusion.

3.4 Multi-leaf Collimator

Multi-leaf Collimator (MLC) development was begun in Japan in the 1960s. In conformal radiation therapy, there has been a great improvement in treatment technique and planning design since MLC was introduced. Generally, most treatment fields can be shaped by MLC such that they can replace traditional custom blocks and save time and labour during treatment. They also remove the occupational health and safety issues with regard to manufacture and lifting of blocks. The MLC requires shape design software and a computer control system. Using software, the treatment field can be designed in an irregular shape with a digitizer, from keyboard or by planning computer file transfer. After that, the shape of each field is saved as a file and can be recalled while the treatment is processed. During the treatment, the MLC is fully controlled by
its computer system and the leaves then reproduce the field shape, when the file is opened.

However, the leakage and transmission of the MLC needs to be considered in the treatment planning dose calculation. The speed of leaf movement and MLC position accuracy needs to be ensured especially for IMRT applications. LoSasso (1998) et al. mentioned that a small error in leaf position could lead to a large error in dose for IMRT fields.

### 3.4.1 Millennium MLC-120

The Millennium MLC-120 (Varian Medical System) was used in this study. It has 120 leaves (60 pairs) with maximum field size of 40×40cm². In the central 20cm of field, the width of each leaf is 5mm at isocentre and 10mm for the outer 20cm of the field i.e. 5mm width for 80 leaves and 10mm width for 40 leaves. According to information from the manufacturer, Varian MLCs are designed as single focused which refers to the leaves diverging in one axis and aligning perpendicular in the other axis. Thus, the leaf movement direction does not correspond to the beam divergence. In addition, all leaf-ends are curved. The leakage of millennium MLC-120 is less than or equal to 2% and the resolution across the central leaves is 0.5cm. This MLC has the capability to perform ‘step and shoot’ and ‘sliding window” operation for IMRT.

The field shape is usually transferred from the planning computer to the “shaper” leaf planning software and editor workstation. The shaper work station allows
users to modify the field shape with a digitizer or using keyboard and mouse functions. After the field shapes are saved in files, these files are read so the leaf shapes can be reproduced with the MLC just prior to treatment. (See the flow chart in figure 3.3) In general, the files of conformal and IMRT leaf sequences contain the $X_1$ and $X_2$ position of each leaf. These files are created on the planning computer and transferred to the shaper. The files for a step and shoot sequence resemble a series of $X$ and $Y$ leaf positions (see Appendix 1). However, in the files for a sliding window, the leaves are simulated in a dynamic movement under continuous irradiation.

![Figure 3.3 Flow chart of MLC system](image-url)
3.5 Linear Accelerator

The linear accelerator (linac) used in this study is a Clinac 2100C (Varian Medical System). It can produce two photon energies (6 and 10MV) and 6, 9, 12, 18, 22 MeV electron energies. The dose rate of the photon beam can be varied from 80 to 400MU/min. A linac, in general, can be divided into four sections: gantry, stand, control consol and treatment couch (see figure 3.5).

In the Varian system (Karzmark et al 1989 and Metcalfe et al 1997), the major components included in the gantry are accelerator structure, electron gun, bending magnet, treatment head and sometimes a beam stopper. The stand consists of a klystron, waveguide, circulator and cooling water system. The control console holds the linac operating parameters such as timing pulses and prescribed Monitor Units. The treatment couch has height, lateral, longitudinal and rotational movements. The hand pendant controls are attached to the couch and allow the therapist to vary couch ordinates and gantry parameters according to the patient's treatment plans. Moreover, the linac with Millennium MLC-120 system with dMLC controller software is capable of delivering an IMRT plan.
Figure 3.4 Schematic view of medical linear accelerator set-up (Karzmark et al 1989)
Chapter 4.
Method

4.1 Introduction

The main purpose of this study is to determine the dosimetry of IMRT x-ray beams with dose being delivered by a step and shoot technique. The verification film (Kodak, X-Omat V-film) was used to record the experimental results. The data from a treatment planning computer (ADAC Pinnacle, Version 6.0) are referred to here as calculation results. The calculation model was collapsed cone convolution. The study was divided in three parts: (1) calibration of radiographic film, (2) an investigation of dosimetry characteristics of MLC eg. match line effect, (3) dose verification of segmented fields with the MLC leaf sequence produced by the Pinnacle K-means clustering method (Hartigan 1975, ADAC manual).

4.2 Calibration of Radiographic film

The aim of this experiment is to determine the relationship between film optical density (OD) and the corresponding dose delivered at both $d_{\text{max}}$ and $d_{10}$ (depth = 10cm). The films were placed between solid water phantoms and perpendicular to the beam incident direction. Source to surface distance was set at 100cm and jaw field size was

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set at 10×10cm² (see figure 4.1). Under such conditions, the linear accelerator is calibrated to deliver 1cGy per 1MU at $d_{\text{max}}$. In order to estimate the relationship of OD to dose, a dose range from 10MU to 70MU was given to the films. The processed film images were then scanned through a VXR-12 plus film digitizer (Vidar systems corporation). OD values of the images were recorded from image analysis software (Osiris) and a Microsoft Excel spreadsheet was used to generate the curve of OD vs. dose with an equation that corresponded to the curve. The same procedures were repeated at $d_{10}$.

4.3 Dosimetry Characteristic of MLC

4.3.1 MLC Transmission and Leakage

Since most IMRT uses MLC delivery, it is important to know the dosimetric characteristics of the MLC. The aim of this experiment is to measure the leakage and transmission of the Varian Millennium 120 leaf MLC. The experiment set-up was the same as the previous section. For inter-leaf evaluation, one bank of leaves was driven 14cm across midline and end-leaf leakage was avoided by collimation, i.e. hiding the leaf ends under a jaw. Then 1000MU was given through the leaves to analyse leaf transmission and interleaf leakage.
Figure 4.1 Set-up for film calibration
For the end-leaf leakage, both sides of the MLC were driven to the centre with MLC field size = 0×0cm² with the jaws providing 10×10cm² collimation and irradiated with 100MU. All dose was detected by the films at d_max and the average dose of inter-leaf leakage, leaf in centre for this with the MLC closed and leaf transmission of MLC was analysed from their dose profiles (see figure 4.2 and 4.3).

### 4.3.2 Match line Effect

The aim of this experiment is to determine if the dose along a “match line” has a significant effect to overall results for a simple segmented field arrangement. Match line is indicated as more than two irradiated fields with one of the leaf pairs being driven to where the other leaf was for a prior segment. In this experiment, it is essential to understand the penumbral difference of dose produced by leaf end and jaw edge. To do this, centre driven jaw and leaves were used. A 5×10cm² asymmetric field was designed by jaws and MLC separately and irradiated each with 50MU. The dose profiles in both cases were compared.

For match line observation, independent jaws, MLC or combination of both constructed a 10×10cm², which was composed of 2 sets of 5×10cm² asymmetric fields (see figure 4.4.). Each set received 30MU. In addition, a collimated field size of 10×10cm² was covered by a sequence of 1×15cm² fields from MLC with 1cm leaf gap and 0.5cm offset irradiated in each portion with 30MU and then repeated for a sequence of 2×15cm² fields with 1cm of step size and gave 20MU in each segments (see figure...
Figure 4.2 Set-up for inter-leaf leakage measurement
Figure 4.3. Set-up for end-leaf leakage measurement
Figure 4.4. Field arrangement of match line

Figure 4.5. Sequence fields

Figure 4.6. Leaf position (2cm gap and 1cm offset)
4.4 Dose verification of segmented fields for clinical delivery

The experiment was designed to verify dose of clinical delivery according to the beam data from a treatment plan by using the films. The clinical case, which was chosen for simulation, was a prostate carcinoma treatment. The treatment was designed using the Pinnacle 6.0 IMRT planning system. Seven gantry angles (0°, 45°, 90°, 135°, 225°, 270°, 315°) were user defined and K means clustering parameters were selected to produce 5, 7, and 10 segmented plans. A step and shoot technique was simulated to deliver the treatment. However, the experiment would focus on verifying the beams eye view (BEV) dose in one of segmented fields only. The dose data was calculated by Pinnacle at any plane for the individual field. This tool was known as the planar dose tool and dose data was transferred to an Excel file along with film dose profile data for comparison on the same graph axis.

4.5 Dynamic MLC Controller Modelling

The dynamic MLC (dMLC) controller was not available as it had not yet been purchased. The dMLC files from Pinnacle were run through a conversion process and transformed from dynamic to static (see Appendix 1). A check sum was then
recomputed at the bottom of each file to enable acceptance by the static MLC controller. Hence each step and shoot sequence was delivered as a separate set of static in field segments. Monitor Units for each were reduced to integers and manually set and delivered. This was a temporary method of delivering multi-segments from dMLC files.

The use of this method meant the verification dosimetry study could be continued. However, the use of this system is not recommended for patient treatment as it is too slow and cannot be fully integrated into the Varis verification check sequence.
Chapter 5.
Results

5.1 Introduction

The following sections describe the experimental results that were recorded according to the methods in chapter 4.

5.2 Calibration of Radiography

There were three sets of measurements done at \(d_{\text{max}}\) and two sets were taken at \(d_{10}\). Experimental error was also calculated and presented in the graphs (see figure 5.1 and 5.2). Observation showed that at both depths the films density to dose response was non-linear. Optical density (OD) values that corresponded to dose values from 0cGy to 70cGy in steps of 20cGy were chosen, then using excel a polynomial equation which fitting the calibration data was used. A typical data fit equation is given below:

For \(d_{\text{max}}\),

\[
D_i = 1.2025 \times 10^{-2} OD_i^2 + 1.69378 \times 10^{-1} OD_i - 1.21847 \quad \ldots \quad (5.1)
\]
Figure 5.1 Dose vs OD (dmax)

\[ \text{Dose} = 1.20250 \times 10^{-3} \text{OD}^2 + 1.69378 \times 10^{-1} \text{OD} - 1.21847 \times 10^0 \]
Figure 5.2 Dose vs OD (d10)

Dose = 1.393206E-03 OD^2 + 1.320299E-01 OD - 8.191290E-01

the curve for the Dose-OD conversion equation

the experimental curve
For $d_{10}$

$$D_2 = 1.39321 \times 10^{-3} OD_2^2 + 1.32023 \times 10^{-1} OD_2 - 8.19129 \times 10^{-1} \quad \ldots \ldots \ldots (5.2)$$

The dose values, $D_1$ and $D_2$, were calculated while their corresponding optical density, $OD_1$ and $OD_2$, were submitted into the equations. Both equations were later applied in experiments. Since the study was divided in several sessions on different days, it was essential for each experiment to have its own calibration curve and corresponding equation which was done by exposing a set of standard films and plotting an equation fit prior to each subsequent film experiment. Hence the coefficients quoted in equation 5.1 and 5.2 changed for each calibration run to fit the calibration data. If the calibration data did not fit into the error range for the calibration curve, then the experiment and its calibration curve would be repeated again.

5.3 Dosimetry Characteristic of MLC

5.3.1 MLC Transmission and Leakage

An image of end-leaf leakage is shown in figure 5.3. The amount of leakage at the central axis was 28.7% with a FWHM of 4.9mm (see figure 5.4). During the inter-leaf leakage measurement, the curve from 100MU in figure 5.5 indicated that there was low noise generated during the experiment and OD or the amount of leakage was below or at the lower limit of the calibration curve range.
The end-leaf leakage is recorded as the dark horizontal line.
Figure 5.4 Dose vs Distance (end leaf leakage)
FWHM=4.9mm
Therefore the uncertainty during such measurement was considerably large. To improve determination accuracy, the experiment was repeated with 1000MU instead of 100MU (see figure 5.6). The resulting profile curve was smoother and presumed more accurate as dose fell within the calibration range. In figure 5.7, leakage between each leaf could vary from 0.09% to 0.471% and its average was 0.27%. The maximum and minimum transmission through leaves was 1.339% and 1.149% and the average was 1.23%. Hence, the total inter-leaf leakage with the transmission component was about 1.5%.

5.3.2 Match line Effect

Figure 5.8 and 5.9 shows the dose profiles of asymmetric fields with one end of the MLC and an edge of jaw at the central axis. The shapes of profiles in both cases were similar but the tail to 55mm at MLC edge seemed longer than at the jaw edge in figure 5.8. Its gradient was larger than that of the jaw. In figure 5.10, it showed that using the combination of jaws and MLC a match line is not visible with the MLC alone a match line is clearly visible. Quantitative analysis shows there was a maximum peak with 29cGy at the position of match line recorded using the MLC only. The width at 80% was 5.9mm found in the peak.

In figure 5.11 and 5.12, the images from films recorded a sequence of match lines. The dose profiles of images then were produced from "Osiris" and the maximum peaks in the curves of gap 1cm and 2cm indicated the match lines (see figure 5.13 and
Figure 5.6 Image of inter-leaf leakage (1000MU)
The interleaf leakage are recorded as the dark lines in horizontal on the film
Figure 5.7 Dose Profile of Inter-leaf Leakage with 1000MU delivered
Figure 5.8 Image of asymmetric fields $5 \times 10 \text{cm}^2$
constructed by (a) jaws and (b) MLC
Figure 5.9 Dose Profile Comparison of Asymmetric field
(Leaf end and Jaw edge at center axis)
Figure 5.10. Dose Profile of Matchline of Jaw+MLC, MLC, Jaw
Figure 5.11 Match-line image of 1cm gap and 0.5cm offset
(Dark lines indicated match-lines)

Figure 5.12 Match-line image of 2cm gap and 1cm offset
(Dark lines indicated match-lines)
Figure 5.13 Dose Profile of 1cm gap 0.5cm offset (Osiris)
Figure 5.14 Dose Profile of matchline 2cm gap 1cm offset (Osiris)
To reduce the noise and smooth out the curves, a graphical software called "Scion image" was applied and the results were shown in figure 5.15 and 5.16. A 2cm leaf gap with 1cm leaf offset and 1cm leaf gap with 0.5cm leaf offset were used, the average dose in the match line was 11.88cGy (6.55%) and 2.27cGy (4.14%), respectively. The reason for less noise in using Scion was a pixel averaging utility in Scion not available in Osiris. The offset distances determined from the experiment for 2cm gap and 1cm offset were 1.02cm using the peak of the film profile plots and 0.51cm for 1cm gap and 0.5cm offset. Therefore, the difference in set distance versus measurement was between 1.6% and 1.7%, respectively (see figure 5.17). The overall width of film was 10.2cm a difference from 10cm, which still needs to be resolved.
Figure 5.15 Dose Profile of Match line 1cm gap 0.5cm offset (Scion)
Figure 5.16 Dose Profile of Match line 2cm gap-1cm offset (Scion)
Figure 5.17 Dose Profile Comparison of Match line
1cm gap-0.5cm offset, 2cm gap-1cm offset (Sicon)
5.4 Dose verification of segmented fields for clinical delivery

The beam orientation of the treatment plan was shown in figure 5.18. The sequence of MLC shapes with gantry set at 0° angle and its beams-eye view (BEV) were presented in figure 5.19 and 5.20. In figure 5.21 and 5.23, the images from these films with 5 segments and 10 segments respectively were similar to the planar dose map in figure 5.20 by general eye vision. Note that dose conversion has not yet been applied to the film maps. The shapes of profiles from both treatment plan and films agreed with each other but were slightly different in their magnitudes. Because the BEVs were normalized to dose/MU, it was essential to apply a normalization factor to treatment planning profiles. The normalization equation used is shown below:

\[ F = \frac{\text{total MU of beam}}{\text{total weight (\%)} \text{ of beam}} \]  \hspace{1cm} (5.3)

All the dose values from the treatment plan were multiplied by the factor “F”. Figure 5.24 and 5.26 presents the results of dose profile comparisons generated by the treatment planning system versus film.

For the five segmented plan (figure 5.24), there was only a slight magnitude difference between film and planned planar dose at the peaks in the field edges but at the central axis, the dose from treatment planning after normalization was still approximately 2cGy greater than in the film measurement. In the distance from -40mm to +40mm, the average difference between two curves was about 6.7% as referred to the normalised ADAC curve. In figure 5.26, with ten segmented plan, the dose at two peaks
from the planning were 3 to 4cGy greater than from film but the dose at central axis in both did not record a significant difference. The average difference between two curves was about 11% as referred to the normalised ADAC curve from -40mm to 40mm.

The seven segmented experiment was actually the first beam tested. This consisted of using the Beta test software supplied by Pinnacle prior to the clinical release version with a different step and shoot intensity pattern. Though the same patient was used there is no guarantee the code for optimisation and K-means clustering did not include some change in the clinical release. The film image is shown in figure 5.22. A match line was recorded and could be easily observed on the film.

Figure 5.25 showed a dose profile comparison. The FWHM of the match line peak obtained from the dose curve of the film at the dose level of 30cGy was 6.5mm with a dose increase about 2cGy or 6.6% (2cGy/30cGy).

There is a considerable shift in alignment between the 2 curves. This was attributed to not using an alignment method which was independent of field exposure. Therefore, to get a better match between ADAC and film, a new alignment method was introduced. It was done by irradiating the segmented fields with positions marked by using the cross hair from the linac light field to mark the centre, and the light projected jaw edges and four corners with a pen and ruler before irradiating the film. If the pen is pressed heavily on the film, a clear mark with less optical density after processing is
visible. Hence the centre, width and length of exposure field are indicated. (See the diagram below)

It was assumed that the area of light field was the same as the area of exposure field as this is checked routinely with film QA. A slight difference in light field to irradiation field of 0.25mm is expected due to the curved leaf ends. As a result of this, the alignment in five and ten segmented fields between films and ADAC showed a great improvement. Note the dose profiles of the film in these three clinical cases were the result of the average dose in five closely spaced horizontal lines close to the centre of exposed field. The average of the pixel values at each point were then taken to produce a smoother profile. It would have been preferable to be able to re-test the new alignment method against the first example that showed the match line. Unfortunately the data for this beta test sequence had been lost prior to the new alignment process being developed.
Figure 5.18 Axial 2D IMRT beam orientation of clinical case: prostate carcinoma
Figure 5.19 BEV of MLC
“step and shoot” segments at gantry angle 0°
Figure 5.20 Grey scale representation of planar dose map produced by Pinnacle for the seven segment case. (White area represent less dose)
Figure 5.21 Film image of the five segmented plan (IMRTSL)
Figure 5.22 Indication of match line in the seven segmented plan (IMRT7L)
Figure 5.23 Film image of the ten segmented plan (IMRT10L)
Figure 5.24 Dose Profile Comparison of IMRT5L

- film
- normalized ADAC

Dose (cGy) vs. Distance (mm)
Figure 5.25 Dose Profile Comparison of IMRT7L

- Red line: film
- Blue line: normalized ADAC
Figure 5.26 Dose Profile Comparison of IMRT10L
Chapter 6.
Discussion

6.1 MLC

In the experiment of MLC characteristics, a FWHM of 4.9mm (figure 5.4) and a nominal 80% of 5.9mm width (figure 5.10) were recorded from the end-leaf leakage and match line effect, respectively. It is mainly due to the rounded leaf end design. The other component effecting the result of the end-leaf dose is the initial distance setting for collision prevention of opposing leaves in closed field. As the prevention distance is increased, the value of FWHM becomes larger. LoSasso et al (1998) stated that the transmission at the leaf end with curved shape was expected to be larger off axis than near the central axis and a slight increase in penumbra was also identified. The results from this study seem to agree with their observation. However, the result of LoSasso et al (1998) concluded that it was possible to provide an approximate correction for the larger transmission and the increased at penumbra if the leaves were offset by 1mm towards the irradiation centre.

In the measurement of interleaf leakage, the average of interleaf leakage from the experiment was about 1.5%, which is comparable to the 1.7% quoted in LoSasso et al (1998) and other studies.
6.2 Match line Effect

In figure 5.8, a longer tail and slight increase in dose in the tail of the penumbra curve for the MLC dose profiles was expected due to the rounded-leaf end effect. This explains the effect of maximum value at the match line in figure 5.10, which was the dose summation of the rounded leaf end transmission from two contiguous fields. (See figure 6.1)

![Figure 6.1 the end leaf dose profile in asymmetric fields](image)

The experiment of small gap with offset is a simulation of what might happen in a step and shoot sequence. It is noted that the dose along the match lines tended to
increase, as the width of gap was decreased. Hence, the uncertainty of the dose delivery in smaller gap or small field was larger, which agrees with LoSasso et al (1998).

6.3 Clinical Case

Considering the match-line effect in the 7 segments case, the dose contributed from match line, which was the dose difference between film and ADAC at the same position, was about 2cGy in 200cGy per fraction. That is, an extra 1% of treatment dose was delivered to the target. If the match line only appeared in one gantry direction, it may not then represent a significant change to the treatment dose delivered. However, a dose correction factor may be required if it is noted in more gantry directions. Alternatively, the match line effect may be resolved by varying the modulated levels, which will reconstruct the segment arrangement. Although the same patient planned field was converted to discrete dose levels in the five and ten segmented plans, there was a difference in their dose profiles due to the changes in dose constraints and shapes of segments but no match line was observed.
6.4 Film Dosimetry

In the dose verification for clinical cases, the dose variation between the film and ADAC was 2 to 3cGy in most profile portions. In some cases differences of 8% were observed. The qualitative film images in both plans seem to similar to their individual dose BEVs. Hence, the XV film has potential to become a useful tool in single field dose verification for IMRT. The film did provide the information such as dose profile, field configurations and dose distributions efficiently. Several studies in the past tended to use the film for their routine checking and dose verification or for the experimental result comparison.

However, according to Evans et al (1992), the calibration curve of XV film was only accurate while the given dose was under 50cGy. From this study, the calibration curve was considered to be usable up to 70cGy. Thus, the XV film usage for dose verification in IMRT may be limited by such consideration as the calibration curve flattens out and dose resolution is reduced. To increase the reliability of calibration curve, a correction factor is required when the given dose is over 70cGy. Furthermore, although according to Danciu et al (2001), the sensitometric curve was not varied by the film orientation in either perpendicular or parallel to the beam central axis in photon beam with energy over 6MV, in order to exclude the error causing by different film orientation, the films for all calibration curves were orientated perpendicular to the beam central axis, which was in the same orientation as all experiments in this study.
6.5 Conclusion

This report shows that the curved leaf ends may lead to a small increase in dose for a clinical step and shoot sequence. The dose increased by match line effect was 4% to 6.5% in the experiment of the small gap with short distance offset sequence and was 6.6% in the clinical sequence. However, the match line effect could be minimized by offsetting the leaf position (LoSasso et al 1998) or avoiding the leaf pair driving to an overlap position where a match line may occur. The use of multiple fields will also reduce the impact of the match line on the integral multiple field dose map.

In addition, in the clinical cases without match line effect, the planar film dose agreed with the computed dose within an average of 6% to 11%. This error seems quite large but is low when the actual magnitude of the dose differences is considered. The total error in target dose required for radiotherapy depends on the steepness of the tumour control probability (TCP) curve but generally is -5% to +7% (ICRU 50). However, as the dosimetry error is only one component of this error, more images need to be analysed to see if a better match can be achieved.

More analysis of the error from combined fields is required. One other qualitative benefit of the planar film maps is that a general eye observation comparison with the computed planar dose maps will immediately show any geometry mismatch that may have occurred in the leaf conversion process.
6.6 Future Projects

This study has demonstrated that the XV film can be used for dose verification in IMRT. The accuracy of dose measurement from XV film was not particularly mentioned in this study but it can be obtained by comparing the results with the measurements from other devices such as MOSFET and ion chamber. The dose along the match line measured by MOSFET detector is currently under investigation. The match line effect has been observed from one beam direction in clinical case. Nevertheless, how the match line effect from one beam influence to overall dose of the treatment has not been clearly understood. This could be carried out in a further investigation. In addition, a better dosimetry match between film and Pinnacle may be achieved by comparison with other dosimeters such as small volume ion chambers and diode profile devices.

A new verification film called Kodak EDR2 has just become available in Australia. It has a range of up to about 400cGy. The study of this film to analyse IMRT fields at axial plane will be the focus in future. The development of future time saving methods such as an MU check code for IMRT fields would also be a useful future project.
Reference


ICRU Report 62 (1999), "*Prescribing, recording and reporting Photon Beam Therapy (supplement to ICRU 50)*", International Commission on Radiation Units and Measurements, Bethesda, Maryland.


VIDAR systems Corporation MEDICAL IMAGING, VIDAR systems donates film digitizer to Armenian telemedicine project, News Releases.


Appendix 1.

An example of MLC leaf file generated from ADAC is shown below. To access the leaves in this study, the changes are presented within the following text boxes.

File Rev = G
Treatment = Dynamic Dose
Last Name = PROSTATE 3
First Name = IMRT
Patient ID = 003640
Number of Fields = 20
Number of Leaves = 120
Tolerance = 0.5

Field = Beam_1-0a
Index = 0.0000
Carriage Group = 1
Operator = p3rtp
Collimator = 0.0
Leaf 1A = 0.50
Leaf 2A = 0.50
Leaf 3A = 0.50
Leaf 4A = 0.50
Leaf 5A = 0.50
Leaf 6A = 0.50
Leaf 7A = 0.50
Leaf 8A = 0.50
Leaf 9A = 0.50
Leaf 10A = 0.50
Leaf 11A = 0.50
Leaf 12A = 0.50
Leaf 13A = 0.50
Leaf 14A = 0.50
Leaf 15A = 0.50
Leaf 16A = 0.50
Leaf 17A = 0.50
Leaf 18A = 0.50
Leaf 19A = 0.50
Leaf 20A = 0.50
Leaf 21A = 0.50
Leaf 22A = 3.25
Leaf 23A = 3.75
Leaf 24A = 4.25
Leaf 25A = 4.25
Leaf 26A = 4.75
Leaf 27A = 4.75
Leaf 28A = 4.75
Leaf 29A = 4.75
Leaf 30A = 4.75
Leaf 31A = 4.75
Leaf 32A = 4.75
Leaf 33A = 4.75
Leaf 34A = 4.75
Leaf 35A = 4.75
Leaf 36A = 4.75
Leaf 37A = 4.75
Leaf 38A = 4.25
Leaf 39A = 3.75
Leaf 40A = 0.00
Leaf 41A = 0.00
Leaf 42A = 0.00
Leaf 43A = 0.00
Leaf 44A = 0.00
Leaf 45A = 0.00
Leaf 46A = 0.00
Leaf 47A = 0.00
Leaf 48A = 0.00
Leaf 49A = 0.00
Leaf 50A = 0.00
Leaf 51A = 0.00
Leaf 52A = 0.00
Leaf 53A = 0.00
Leaf 54A = 0.00
Leaf 55A = 0.00
Leaf 56A = 0.00
Leaf 57A = 0.00
Leaf 58A = 0.00
Leaf 59A = 0.00
Leaf 60A = 0.00
Leaf 1B = -0.50
Leaf 2B = -0.50
Leaf 3B = -0.50
Leaf 4B = -0.50
Leaf 5B = -0.50
Leaf 6B = -0.50
Leaf 7B = -0.50
Leaf 8B = -0.50
Leaf 9B = -0.50
Leaf 10B = -0.50
Leaf 11B = -0.50
Leaf 12B = -0.50
Leaf 13B = -0.50
Leaf 14B = -0.50
Leaf 15B = -0.50
Leaf 16B = -0.50
Leaf 17B = -0.50
Leaf 18B = -0.50
Leaf 19B = -0.50
Leaf 20B = -0.50
Leaf 21B = -0.50
Leaf 22B = 2.25
Leaf 23B = 2.75
Leaf 24B = 3.25
Leaf 25B = 3.75
Leaf 26B = 4.25
Leaf 27B = 4.25
Leaf 28B = 4.25
Leaf 29B = 4.75
Leaf 30B = 4.75
Leaf 31B = 4.75
Leaf 32B = 4.75
Leaf 33B = 4.75
Leaf 34B = 4.75
Leaf 35B = 4.75
Leaf 36B = 4.75
Leaf 37B = 4.25
Leaf 38B = 4.25
Leaf 39B = 3.75
Leaf 40B = 0.00
Leaf 41B = 0.00
Leaf 42B = 0.00
Leaf 43B = 0.00
Leaf 44B = 0.00
Leaf 45B = 0.00
Leaf 46B = 0.00
Leaf 47B = 0.00
Leaf 48B = 0.00
Leaf 49B = 0.00
Leaf 50B = 0.00
Leaf 51B = 0.00
Leaf 52B = 0.00
Leaf 53B = 0.00
Leaf 54B = 0.00
Leaf 55B = 0.00
Leaf 56B = 0.00
Leaf 57B = 0.00
Leaf 58B = 0.00
Leaf 59B = 0.00
Leaf 60B = 0.00
Note = 13
Field 0 Start
Shape = 0
Magnification = 1.00
Field = Beam_1-0b
Index = 0.1414
Carriage Group = 1
Operator = p3rtp
Collimator = 0.0
Leaf 1A = 0.50
Leaf 2A = 0.50
Leaf 3A = 0.50
Leaf 4A = 0.50
Leaf 5A = 0.50
Leaf 6A = 0.50
Leaf 7A = 0.50
Leaf 8A = 0.50

 CRC = 8EDA

Re-generate a new CRC cord after changing “Dynamic Dose” to “Static”.

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