TECHNICAL NOTE

Software tool for portal dosimetry research*

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Abstract

This paper describes a software tool developed for research into the use of an electronic portal imaging device (EPID) to verify dose for intensity modulated radiation therapy (IMRT) beams. A portal dose image prediction (PDIP) model that predicts the EPID response to IMRT beams has been implemented into a commercially available treatment planning system (TPS). The software tool described in this work was developed to modify the TPS PDIP model by incorporating correction factors into the predicted EPID image to account for the difference in EPID response to open beam radiation and multileaf collimator (MLC) transmitted radiation. The processes performed by the software tool include; i) read the MLC file and the PDIP from the TPS, ii) calculate the fraction of beam-on time that each point in the IMRT beam is shielded by MLC leaves, iii) interpolate correction factors from look-up tables, iv) create a corrected PDIP image from the product of the original PDIP and the correction factors and write the corrected image to file, v) display, analyse, and export various image datasets. The software tool was developed using the Microsoft Visual Studio.NET framework with the C# compiler. The operation of the software tool was validated. This software provided useful tools for EPID dosimetry research, and it is being utilised and further developed in ongoing EPID dosimetry and IMRT dosimetry projects.

Key words amorphous silicon, EPID, portal dosimetry, intensity modulated

Introduction

Intensity modulated radiation therapy (IMRT) beams created by inverse treatment planning techniques can deliver a more conformal dose distribution to complex shaped target volumes than conventional conformal radiation therapy¹. The improved treatment delivery with IMRT comes at the cost of added complexity. Traditional methods of verifying dose are limited and new methods are being developed for IMRT². The adaptation of electronic portal imaging devices (EPID) for dosimetry has coincided with the introduction of IMRT into clinical use. EPIDs were originally designed to be a patient alignment tool³ but their potential for routine quality assurance (QA) tests⁴ and dose verification^{5,6} has since been demonstrated. The current model of amorphous silicon (aSi) EPIDs have properties well suited to IMRT dosimetry, including high

spatial resolution⁷ and linear dose response⁸.

IMRT beams contain energy variations due to the beam hardening affect of the multileaf collimator (MLC) that is used to modulate the beam intensity⁹. The aSi detectors have an energy dependent response¹⁰ that results in a different dose response to radiation produced from open beams and MLC transmitted beams^{11, 12}. Accounting for MLC beam hardening in IMRT beams requires a method to incorporate changes in EPID dose response based on open beam and MLC transmitted beam components. This can be achieved by creating a Monte Carlo computer simulation of the radiotherapy source and the resultant signal produced in the EPID detector for each IMRT beam¹³. Simpler alternatives based on empirical data have also been proposed^{11, 14, 15}. Implementing these empirical methods still requires the development of new software tools.

This paper presents details on software developed to:

- i) read measured and predicted EPID images and MLC files for IMRT fields,
- ii) calculate 2-dimensional matrices of open [$O_{i,j}$] and MLC transmitted [$T_{i,j}$] beam fractions from IMRT MLC files,
- iii) make corrections to the predicted EPID images based on the EPID response to MLC transmitted radiation for IMRT beams,
- iv) analyse and compare images.
- v) write the output data to file.

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Background

Dynamic MLC files

Varian MLC leaves (Varian Medical Systems, Palo Alto, CA) move in the plane perpendicular to the beam axis. The MLC file describes the trajectory over time for each MLC leaf using a series of discrete leaf positions. Each sample of leaf positions is called a control point. Each control point contains the incremental fraction of beam-on time (the index). The index for the first and last control points are 0.000 and 1.000 respectively. The position of each leaf relative to the collimator central axis is described by the leaf number and the distance from the collimator central axis in the direction of leaf motion. Dimensions are in centimetres projected to the isocentre distance. The MLC controller software communicates with the linear accelerator and determines the leaf position versus monitor unit (MU) trajectory. In the case of dynamic MLC fields, the index increases at each control point and the leaf position versus MU is linearly interpolated between control points.

MLC transmitted fraction (T)

Methods of creating an intensity matrix from MLC files have been described elsewhere^{12,16-19}. The same basic approach was used in this work except that the fraction of beam time that each matrix element is blocked by an MLC leaf was also calculated.

Firstly, the intensity matrix was calculated from the open fraction using:

$$O_{i,j} = I_{B(i,j)} - I_{A(i,j)} \quad (1)$$

Where $O_{i,j}$ is the fraction of beam time the element $[i,j]$ is exposed to primary radiation (open beam). $I_{B(i,j)}$ and $I_{A(i,j)}$ are the beam indices when the trailing leaf (leaf B_j) and the leading leaf (leaf A_j) cross over the middle of the element $[i,j]$ respectively¹⁹. $I_{B(i,j)}$ and $I_{A(i,j)}$ are calculated from the MLC file at each element along row j by reading through the MLC positions of the leaf pair corresponding to row j , and finding the control points where the MLC leaves cross over column i . The index $I_{i,j}$ for the trailing and leading leaves are then linearly interpolated from the index of the control points on either side of the element $[i,j]$. The fraction of beam-on time that primary radiation to the element $[i,j]$ is blocked by an MLC leaf is called the MLC transmitted fraction ($T_{i,j}$). Since the total cumulative index is equal to 1.0 at each element, $T_{i,j}$ can be calculated using:

$$T_{i,j} = 1 - O_{i,j} \quad (2)$$

Separating the beam intensity into components of open (O) and transmitted beam (T) is an important step in IMRT dose calculations. It has also been used to model the EPID dose response to open and MLC transmitted beams separately^{11,12,14,15,20}.

Portal dosimetry – the varian method

The Portal dosimetry system implemented by Varian's EclipseTM (Varian Medical Systems, Palo Alto, CA) TPS and aSi EPID detector is in clinical use for pre-treatment verification of IMRT beams at Royal North Shore Hospital, Sydney²¹. EclipseTM calculates EPID images for IMRT beams absorbing material in the beam (non-transit portal dosimetry) and no additional build-up on the detector. The EPID image calculated by EclipseTM is called a portal dose image prediction (PDIP). Further details of the Eclipse portal dosimetry model can be found elsewhere⁶. In dosimetry mode, the EPID integrates frames to produce a frame-averaged image of the entire IMRT field exposure. The resultant image is reported in calibrated units (CU). CU is calibrated to dose using a scaling factor. The image acquisition software calculates the scaling factor from a reference exposure (Portal Imaging and Portal Dosimetry Reference Guide – Version 8.0, Varian Medical Systems, Palo Alto, CA). The PDIP and the acquired EPID image can be compared to each other using analysis tools in the dosimetry workspace of the VARiSTM Review computer application (Varian Medical Systems, Palo Alto, CA). The EPID CU calibration and the PDIP model assume that the EPID response to MLC transmitted radiation is the same as the EPID response to open beam radiation.

Software tool design, implementation and testing

Software tool design

The original motivation for developing this software tool was to create a corrected PDIP that accounted for the various effects of MLC transmission on EPID response. The measurement, derivation, and implementation of PDIP correction factors was described previously by Vial *et al*¹⁵. The software tool applies the PDIP correction factors according to the following equation (modified from equation 1 in Vial *et al*¹⁵).

$$\text{PDIP}_{corrected}^{i,j} = \text{PDIP}_{TPS}^{i,j} \times CF_{T(i,j)} \times CF_{T(i,j),r(i,j)} \times CF_{T,f_s} \times CF_{norm} \quad (3)$$

Where $\text{PDIP}_{corrected}^{i,j}$ is the modified CU value at the image element $[i, j]$. $\text{PDIP}_{TPS}^{i,j}$ is the original CU value calculated by the TPS at the image element $[i, j]$. $CF_{T(i,j)}$ is a correction factor based on the change in EPID response due to T at the collimator central axis of $10 \times 10 \text{ cm}^2$ fields. $CF_{T(i,j),r(i,j)}$ is a correction factor for the change in EPID response with radial distance from the central axis, r , due to T . CF_{T,f_s} is a correction factor for the change in EPID response with field size, f_s , due to T . $CF_{T(i,j)}$, $CF_{T(i,j),r(i,j)}$, and CF_{T,f_s} are interpolated from look-up tables. CF_{norm} is a user-defined integer that scales the CU value at each image element in $\text{PDIP}_{corrected}$. CF_{norm} is necessary to scale the raw PDIP data according to the field MU. The user may

Figure 1. Schematic flow diagram of the processes executed by the software tool. The objects with dashed borders are input files to the software. The objects with a grey background are calculated by the software tool. The objects with bold borders are look-up tables used for the PDIP correction process. The objects with double line borders are user-defined inputs specified for each IMRT field to be processed. The open beam fraction $[O_{i,j}]$ and MLC transmitted fraction $[T_{i,j}]$ are calculated from the MLC file. Each pixel of the $PDIP_{TPS}$ is modified according to correction factors interpolated from the CF look-up tables. A corrected image, $PDIP_{corrected}$, is written to a file that can be imported back into the VARiSTM database. Images may be compared using a difference image or profiles.

choose to apply CF_{norm} only (independent of the other correction factors) so that the original image is simply scaled. CF_{norm} can be used to correct for day-to-day changes in EPID sensitivity, or the linear accelerator's calibrated dose output, or to normalise $PDIP_{corrected}$ to either $PDIP_{TPS}$ or EPID CU at a desired position in the image. The software automates the large number of operations necessary to modify $PDIP_{TPS}$ images (512×384 pixels) according to equation (3). Figure 1 shows a schematic flow diagram of the software tool (modified from figure 1 in Vial *et al*¹⁵).

The operational flow of the software tool begins by reading the matrix dimensions from the $PDIP_{TPS}$ file header. The pixel dimensions are then scaled from the projected distance to the isocentre distance (100 cm). The projected distance has been set to 105 cm in the software tool as the standard distance for portal dosimetry but this may be made variable for other distances. The software tool identifies the MLC model details from the MLC file header so that the correct number of leaves and leaf widths are used in the construction of the intensity matrix, $O_{i,j}$, from which $T_{i,j}$ is calculated using equation (2). Current Varian MLC designs have leaf widths varying from 1 cm to 0.5 cm and the number of leaves may be 52, 80, or 120 depending on the

model. The matrix $T_{i,j}$ is created with the same total size and pixel dimensions as $PDIP_{TPS}$. The pixel width and pixel height sets the resolution in the directions parallel and perpendicular to leaf motion respectively (for zero collimator rotation). The intensity is considered as constant across an individual leaf width (perpendicular to leaf motion) and so the pixels in the same column under a given leaf may be combined for the calculation of $T_{i,j}$. The collimator central axis is fixed at the centre of $T_{i,j}$ and $PDIP_{TPS}$. Therefore $T_{i,j}$ and $PDIP_{TPS}$ can be spatially registered to overlay each other pixel-by-pixel. $PDIP_{corrected}^{i,j}$ is written to the original pixel dimensions of $PDIP_{TPS}$ using equation (3).

Leaf trajectories in the MLC files contained position offsets incorporated by the TPS to correct for the difference between the geometric leaf position and the radiation field edge^{22,23}. This leaf offset effects the calculation of $O_{i,j}$ and $T_{i,j}$. Because the leaf offset was inherent in the measurement of PDIP correction factors¹⁵ it was not applied when implementing the correction factors using equation (3). Nevertheless the ability to offset the MLC leaf positions by a user-defined distance was added to the

Figure 2. The graphical user interface (GUI) for the portal dosimetry software tool. The input MLC and PDIP_{TPS} files and the output PDIP_{corrected} filenames and locations are selected using a standard windows browser. By selecting the 'Normalise only' box the input PDIP or EPI image is re-scaled according to the multiplier entered by the user. An MLC leaf offset and equivalent square field size may also be entered by the user.

software tool. If an MLC offset is entered by the user, the position of each leaf at each control point are offset accordingly prior to the calculation of $O_{i,j}$ and $T_{i,j}$. Criteria for permissible leaf positions were set in the software code to ensure that leaf positions remain physically possible and within the manufacturers specified constraints. Offset leaf positions that violate this criteria were truncated to the largest permissible offset.

IMRT fields are normally delivered at collimator zero degrees (IEC) but sometimes fields are too long to fit onto the detector and it is necessary to obtain verification images at collimator angles of 90 or 270 degrees to take advantage of the wider detector dimension in the cross-plane direction. The software tool was designed to recognise orthogonal collimator angles from the MLC file. IMRT fields that are too wide for the MLC to deliver in one field are split by the TPS into two or three separate overlapping sub-fields. The MLC files, PDIPs, and measured EPID images of sub-fields were delivered and analysed separately as individual fields in the same manner used by the Varian portal dosimetry system. The ability to combine sub-fields may be added to the software tool in the future.

Additional functions for analysing the various types of images were added to the software tool. These functions included:

- The ability to read and display both PDIP and EPI images as colour or greyscale bitmaps. Images may be saved as bitmap files for convenient documentation or presentation of the images.

- A plotting routine that can generate profile comparisons from two different datasets. The plotting routine overlays profiles across any two of the following datasets; the intensity matrix $[O_{i,j}]$, the PDIP_{TPS}, the PDIP_{corrected}, or the EPI. The user can toggle between horizontal and vertical profiles and scroll the profiles across the images. These profiles can also be exported as data files for further analysis.
- An image subtraction function that displays a 2-dimensional image of the absolute difference between two images (e.g. PDIP_{TPS} and EPI) in CU.
- The intensity matrix, $O_{i,j}$, can be saved in a separate data file. MLC leaf offsets and the resolution of $O_{i,j}$ are adjustable from the graphical user interface (GUI). This data can potentially be used as an input for the calculation of dose in water¹⁸ or fluence maps¹⁶ of IMRT fields.

Implementation

The software tool was developed with Microsoft Visual Studio.NET 2002 using the C# compiler. The software structure enables an object-oriented approach that allows for further functionality to be added as required. The compiled program can be executed from any computer with a Microsoft Windows operating system with the .NET framework installed. The software tool operation is controlled using GUIs. The dialogue box that runs the PDIP correction process is shown in figure 2. This dialogue is selected from the toolbar menu of a main GUI.

Figure 3. Cross-plane profiles across a test IMRT field. Profiles of CU across $PDIP_{TPS}$, $PDIP_{corrected}$ and of the open fraction were exported from the software tool. Manually calculated $PDIP_{corrected}$ values (*) validated the software tool CU corrections.

The $PDIP_{TPS}$ and dynamic MLC files read by the software tool are ASCII files. The $PDIP_{corrected}$ files were saved in the same Varian file format as the $PDIP_{TPS}$ to be compatible with VARiSTM. This software tool was developed specifically for the Varian file format, but the method is applicable to other systems.

Software tool tests

The calculation of $O_{i,j}$ and $T_{i,j}$ was validated using sliding window test fields with fixed leaf gaps. $O_{i,j}$ and $T_{i,j}$ from these test fields can be manually calculated²³ for comparison with the software tool's calculations. The correct implementation of the leaf offsets was also validated in the same manner.

A series of simple test fields were designed to validate the PDIP correction process. Manual calculation of the corrected CU were compared to those calculated by the software tool for test IMRT fields. The test IMRT field shown in figure 3 was 30 cm × 10 cm field size and contains areas of maximal MLC transmission fraction ($T = 1.0$, $O = 0.0$) and small MLC transmission ($T = 0.284$, $O = 0.716$). The cross-plane profiles of $PDIP_{TPS}$, $PDIP_{corrected}$, and O shown in figure 3 were exported from the software tool. The CU for $PDIP_{corrected}$ was manually calculated in the middle of areas of large and small O to test the software CU calculations. The manually calculated CU agreed with the software calculated CU to within 1%. Visual inspection of the profiles in regions with steep intensity gradients is a sensitive test for detecting errors in the registration and scaling of $O_{i,j}$ and the corresponding PDIP images.

Additional tests verified that the software tool modifies CU correctly at orthogonal collimator angles and that CU profiles of $PDIP_{corrected}$ were smooth in high gradient regions in directions both perpendicular and parallel to the direction of leaf motion. Initially artefacts were observed in

the form of unexpected bumps in the $PDIP_{corrected}$ profiles. This was identified as partial volume effects because the pixel size in $O_{i,j}$ and $T_{i,j}$ was larger than in the PDIP matrix. Re-sampling $O_{i,j}$ and $T_{i,j}$ with the same pixel dimensions

as $PDIP_{TPS}$ corrected the problem. $PDIP_{corrected}$ images were also imported into VARiSTM and the correct display of $PDIP_{corrected}$ CU in the dosimetry workspace of VARiSTM was validated.

Figure 4 shows a screen capture of the software tool output displayed after processing the $PDIP_{TPS}$ of an example head and neck IMRT field. Figure 4 includes six colour image frames of the following data related to the IMRT field; $O_{i,j}$, $PDIP_{TPS}$, $PDIP_{corrected}$, the measured EPI, a difference map between $PDIP_{TPS}$ and the EPI, and another difference map between $PDIP_{corrected}$ and the EPI. The difference map indicates some large local differences in CU at the field edges. Reviewing these images in VARiS indicated a small misalignment in the EPI image. The ability to offset images for manual alignment shall be included in a future version of the software. Analysis of results for clinical IMRT fields is the subject of an ongoing project.

Discussion

Research and development of new technology in radiotherapy often requires the development of specialised software in order to process large quantities of data. Software tools developed in-house may also be useful in the clinical setting for testing of vendor systems. In particular the complexity of the data related to IMRT treatment fields and the size of image datasets requires the use of computer software for processing within a realistic time frame. The ability to produce a compiled program at relatively low

Figure 4. A screen capture of the software tool display after processing the portal dose image prediction (PDIP) of an IMRT field using the PDIP correction factor algorithm. Top left is $[O_{i,j}]$, bottom left is the measured EPI, top middle is the $PDIP_{TPS}$, bottom middle is the $PDIP_{corrected}$, top right is the difference between measured EPI and $PDIP_{TPS}$, bottom right is the difference between EPI and $PDIP_{corrected}$.

cost, that can be executed on any computer with the Microsoft .NET framework was an added advantage of our method. The .NET framework used in this work significantly enhanced the rapid development of the GUI.

Quantitative analysis of the improvements achieved by the PDIP correction algorithm was previously reported for test IMRT fields¹⁵. Further development of the algorithm is being investigated and the significance of any improvements in portal dosimetry results for clinical IMRT beams is the subject of an ongoing project.

This software tool provides a platform for developing a comprehensive suite of IMRT and imaging applications. Possible future applications of this software tool include IMRT dose in water calculations, further development of 2-dimensional analysis tools such as the gamma index²⁴, the ability to handle DICOM data, and transit dosimetry using back-projected data from EPID images onto 3-dimensional computed tomography datasets.

Conclusion

A software tool for viewing, manipulating, and analysing EPID images and image predictions of IMRT fields has been described and validated. The software tool is suited to expansion with additional functions for IMRT research and clinical QA tools.

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