Quality assurance for dynamic multileaf collimator modulated fields using
a fast beam imaging system

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A quality assurance procedure was developed for x-ray beam intensity modulated conformal radiotherapy (IMCRT) using dynamic multileaf collimators (MLC). The procedure verifies a prescribed intensity modulated x-ray beam pattern in the beam eye’s view (BEV) before the treatment procedure is applied to a patient. It verifies that (a) the leaf sequencing computer files were transferred correctly to the linac control computer; (b) the treatment can be correctly executed without machine faults. A fast beam imaging system (BIS) consisting of a Gd$_2$O$_2$S scintillation screen, a charge-coupled device (CCD) camera, and a portable personal computer (Wellhöfer Dosimetrie, Schwarzenbruck, Germany) was commissioned for this purpose. Measurements for the BIS performance are presented in this work. Reference images were derived from MLC leaf sequencing files that were used to drive a dynamic MLC system (Varian Oncology Systems, Palo Alto, CA). A correlation method was developed to compare the BIS measurements with the calculated reference images. A correlation coefficient calculated using 26 correct intensity modulated fields was shown to be a reliable threshold to identify inaccurate treatment delivery files. The study has demonstrated the feasibility of using the BIS and the correlation method to carry out on-line quality assurance tasks for IMCRT treatment fields in the BEV. © 1997 American Association of Physicists in Medicine. [S0094-2405(97)01708-2]

Key words: quality assurance, portal image, intensity modulation, conformal therapy, multileaf collimators

I. INTRODUCTION

Intensity modulated conformal radiotherapy (IMCRT) using dynamic multileaf collimators (MLC) aims to improve dose distributions and increase local tumor control by conforming several x-ray beams to a specific tumor shape. The techniques of using MLC in IMCRT have been actively studied and reviewed.1–5 To implement IMCRT on a Varian linear accelerator equipped with a MLC system, we adopted the commonly used “sliding window” technique.6–8 The leaf sequencing file produced by the leaf sequencing algorithm was saved by the MLC control computer to control the motion of the MLC leaves during a treatment delivery. It is essential to verify a leaf sequence before an IMCRT treatment procedure is applied to a patient.9,10 Our goal was to develop a reliable and convenient procedure to ensure that the beam fluence patterns in the beam eye’s view (BEV) match those specified by an IMCRT plan. A fast beam imaging system (BIS) consisting of a metal/phosphor detecting screen and a CCD camera was employed for this purpose.

The BIS is a video-optical electronic portal image device (EPID). Various EPID devices have been reviewed.11 For megavoltage x rays, theoretical modeling of the metal/phosphor system has been investigated by several authors.12–14 Advantages of using a metal/phosphor portal image device for IMCRT lies in its high data acquisition rate, easy handling, high detecting efficiency, good signal-to-noise ratio, high image resolution, and its resistance to radiation damage. The metal buildup layer that precedes the phosphor screen serves as a signal enhancer. The metal is thick enough to allow incoming x rays to interact and to generate Compton electrons within the layer. These Compton electrons, in turn, produce the majority of the detected light output from the phosphor. Since the light output monotonically corresponds to the energy fluence carried by the incoming x rays, the energy fluence under BEV can be measured by the system.

In the present work, an image correlation method was developed for comparing the measured fluence distribution with a reference fluence distribution calculated from the leaf-sequence file. A similar correlation method was employed to compare digitally reconstructed radiographs (DRR) with electronic portal images for detecting patient setup errors.15

II. INSTRUMENTS AND TECHNIQUES

A. Wellhöfer Beam Imaging System (BIS)

The schematic of the Wellhöfer BIS device is shown in Fig. 1. The device consists of a Gd$_2$O$_2$S fluorescent phosphor screen preceded by a Cu screen.16 The Cu sheet is 1.0 mm thick. The Gd$_2$O$_2$S phosphor is 0.6 mm in thickness. A charge-coupled device (CCD) video camera captures the phosphorescent beam image viewed through a 45° mylar mirror. The CCD camera has an array of $512 \times 512$ light sensitive elements, which produce a digital image using a charge integration time adjustable from 120 ms to 1 s. The camera can view an image on the screen up to 30.1 cm $\times 30.7$
cm. Through a two-way data line, the control unit of the BIS is interfaced with a frame-grabber board within a personal computer. The frame-grabber board is capable of acquiring a fixed number of image frames, averaging them, and then generating a ten-bit beam image on the computer monitor. The total number of the summed image frames is between 1 and 2000 and is user selectable prior to each measurement.

To obtain a BEV image for an IMCRT treatment, the BIS is fastened to the blocking tray holder of the linear accelerator. Once secured, the BIS rotates together with the gantry without detectable shifts in its position. We found that the BIS position is repeatable within 1.0 mm.

The measured BIS image was calibrated against a standard background image to compensate for the image inhomogeneity that may have been caused by nonuniformities in the thickness of the Gd$_2$O$_2$S phosphor layer, warps on the mirror surface, or other imperfections in the imaging system. A calibrated image was also a background-subtracted image. The calibration formula for a measured image was

$$P(x_i,y_j) = \frac{P_0(x_i,y_j) - P_b(x_i,y_j)}{\rho(x_i,y_j)}, \quad i = 1, 2, ..., 512, \quad j = 1, 2, ..., 512,$$

where $P(x_i,y_j)$ is the calibrated pixel value at the position $(x_i,y_j)$ on the detection screen, $P_0$ is the measured pixel value, $P_b$ is the background or dark current pixel value at the same position $(x_i,y_j)$, $\rho$ is a calibration factor measured from a well-designed, uniform x-ray beam geometry. The $\rho(x_i,y_j)$ value was provided by the manufacturer. Typically, the $P_0$ value was obtained by averaging more than 100 image frames for a measurement.

**B. Output and spatial linearity**

Output linearity is a prerequisite for converting a BIS-measured image into an x-ray beam fluence distribution. It is important for real-time monitoring of beam images in the BEV. Measurements of output response were made using exposures delivered by a linear accelerator (Clinac 2300 C/D, Varian Oncology Systems, Palo Alto, CA) through square and rectangular 6 MV x-ray fields at 100 cm SSD. The linearity of the transmission ionization chamber and associated electronics that controlled the exposures was verified independently. Background images were measured before and after x-ray irradiation. The calibration dark-current image was the average of these two measurements. For each radiation field, an average pixel value within a fixed region of interest (ROI) was determined. The ROI was defined around the center of the field, such that the statistical error of the total counts within the region was less than 0.5%. A plot of averaged pixel values within the ROI versus irradiating monitor units is shown in Fig. 2. The result of a linear regression fit is also shown. The errors for the fitting parameters were evaluated at the 95% confidence level and all fitted lines exhibited $r^2 > 0.99$. From the slopes of the fitted lines, the BIS output per monitor unit increases from a 10 cm$^2$ field to a 10 × 10 cm$^2$ field. This indicates that the BIS output is directly related to the beam energy fluence, as is typical for a metal/phosphor system.\textsuperscript{13}

To measure spatial linearity, standard field sizes ranging from $1 \times 1$ cm$^2$ to $25 \times 25$ cm$^2$ at 100 cm SSD were measured using the BIS. A small $0.6 \times 0.6$ cm$^2$ ROI was defined symmetrically around the center of a calibrated image. The average pixel value within the ROI was calculated. This value was taken to be the 100% fluence value. Using this value, field edge positions corresponding to the 50% fluence value for the entire field image were determined. From the edge positions, radiation field sizes in image pixels were plotted against their nominal physical sizes. The result is given in Fig. 3. The error bars on the data were computed from error propagation of the standard deviation of the 100% fluence value. The error on the data was typically 0.5 pixel. A least-square fit was performed on the data. The spatial resolution in the object plane of the BIS CCD camera lens was determined from the slope of the fitted line. The spatial resolution was determined to be $0.602 \pm 0.014$ mm for a horizontal di-
where MU \(_1\) was the total monitor units, a 20 cm \(^2\) field image was measured. The measurement was carried out by starting the BIS frame grabber before the initiation of x-ray beam irradiation of the BIS phosphor screen.

C. BIS response deadtime

BIS response deadtime is the time lapse between two successively captured images by the frame grabber. It is mainly caused by electronic switching processes associated with storing and transmitting images. A correction for a large response deadtime would be necessary when converting image pixel values to beam fluence values across a radiation field.

To measure the BIS deadtime \(\tau\), a monitor unit, MU \(_{1}\), was first selected for beam irradiation, such that

\[
\text{MU}_{1} = m \cdot DT < n \cdot DT, \tag{2}
\]

where MU \(_{1}\) was the total monitor units, \(\dot{D}\) was the averaged dose rate in MU/min, \(T\) was the BIS integration time, \(n\) was the total frame counts for the BIS measurement, and \(m\) was an arbitrary integer that satisfied Eq. (2).

Using these values, an averaged pixel value \(C'\) for a 20 \(\times\) 20 cm \(^2\) field image was measured. The measurement was carried out by starting the BIS frame grabber before the initialization of x-ray beam irradiation of the BIS phosphor screen.

The total time for the BIS picture-capture process was kept longer than the total beam-on time from Eq. (2). Typically, \(m = 0.75n\) was selected.

After the above measurement, a second measurement was carried out to acquire \(C''\) by setting the total beam-on time much larger than the total BIS capture time. For the second measurement, the BIS frame grabber was started after the initiation of the x-ray beam irradiation.

To carry out data analysis, one identical region of interest (ROI) was set within the two images from the two measurements. The average pixel value, together with its standard deviation, was calculated for the ROI.

From the first measurement, we obtained

\[
C' = FD\left[mT - (m - 1)\tau\right]/n = FDT \left(\frac{m - m - 1}{n} \frac{\tau}{T}\right)
\]

\((n > m \geq 2), \tag{3}\)

where \(T\) was the BIS integration time, i.e., \(mT\) was the total beam-on time. \(C'\) was the average pixel value within the ROI, \(\dot{D}\) was the dose rate for the beam, \(F\) was the dose to pixel value conversion factor, \(n\) was the chosen frame count for the measurement, and \(\tau\) was the BIS deadtime.

From the second measurement, we obtained

\[
C'' = n'F \cdot DT/n' = F \cdot DT, \tag{4}\)

where \(C''\) was the average pixel value and \(n'\) was the BIS frame count for the measurement. Combining Eqs. (3) and (4), the BIS deadtime \(\tau\) was computed using

\[
\tau = \left(\frac{m - C'}{n - C''}\right) \frac{n}{m - 1} T \ (n > m \geq 2). \tag{5}\)

The statistical error on \(\tau\) was calculated by error propagation, i.e.,

\[
\Delta \tau = \sqrt{\left(\frac{\partial \tau}{\partial C'}\right)^2 \Delta C'^2 + \left(\frac{\partial \tau}{\partial C''}\right)^2 \Delta C''^2}
\]

\[
= \frac{nT}{(m - 1)C''} \sqrt{\Delta C'^2 + \left(\frac{C'}{C''}\right)^2 \Delta C''^2} \ (n > m \geq 2), \tag{6}\)

where \(\Delta C'\) and \(\Delta C''\) were the standard deviations (s.d.) of \(C'\) and \(C''\), respectively. By substituting \(n, m, T, C',\) and \(C''\) values into Eqs. (5) and (6), the deadtime and the statistical error of the BIS were calculated. The measurements of \(\tau\) were carried out at two dose rates of 400 MU/min and 600 MU/min.

The measured deadtime for the BIS was 0.7±3.7 ms at the dose rate of 600 MU/min, and 4.1±5.3 ms at the dose rate of 400 MU/min. Therefore, within a 3σ confidence level, \(\tau\) was smaller than 20 ms, which agrees with the manufacturer’s estimated value of zero.
III. METHODS

A. BIS image registration

To correlate a BIS image with a calculated image, the center and the orientation for the reference coordinates were determined from a measured ‘‘cross-hair’’ radiation field. The field pattern is presented in Fig. 4a. The photon jaws were used to form six narrow 0.5 × 20 cm² fields centered at 0, 1, and −1 cm from the field center along the horizontal and vertical directions. The accuracy of the digital controls used to set the jaws was verified by mechanical measurements. The maxima points at the nine intersecting locations of the six narrow fields were extracted from the integrated BIS image. The reference center was calculated as the center of the mass of the nine maxima positions. Once the BIS was attached to the blocking holder, positional errors for the reference center were determined within ±0.6 mm in translational shift and ±0.1° in rotational shift.

The MLC leaf width was measured in units of pixels in order to determine each MLC leaf pair’s position in a BIS image. The field pattern in Fig. 4b was measured using the same BIS setup. Leaf-edge positions separated by different leaf widths were determined within the field. The edge positions corresponded to the 50% pixel values of the field maxima. The results for the average leaf width was given in Fig. 5. The leaf width was determined to be 12.43±0.23 pixels at 74.5 cm SSD, which agreed with the mechanical calibration of 1 cm at 100 cm SSD for the Varian MLC systems.

To obtain the beam fluence distribution modulated by the MLC leaves, the BIS image was represented as a series of vectors 

\[ C_k(x_i) \] at \( x_i \) along the leaf motion direction, where \( k \) denotes the \( k \)th leaf pair, and \( i \) represents the \( i \)th element of the \( C_k \) vector. \( C_k(x_i) \) was determined by averaging three beam profiles along the middle line of the \( k \)th leaf pair plus two adjacent ones, i.e.,

\[ \Psi_k(x_i) = \frac{1}{4} \left[ \Psi_k(x_1 + d) + \Psi_k(x_0) + \Psi_k(x_1 - d) \right], \]

where \( \Psi_k(x_i) \) is the pixel value scanned along the middle line of the \( k \)th leaf pair, and \( d \) is the separation between two adjacent scans. Typically, \( d \) was selected to be 0.6 mm, and \( \Psi_k(x_i) \) was normalized to the pixel maximum across the image.

B. Reference image calculation

Reference images for BIS measurements were calculated from dynamic MLC leaf sequencing files that dictated MLC leaf motion through the MLC controller computer interface. We define a reference fluence vector \( F_k(x_i) \) for the BIS measurements at a given position \( x_i \) along \( k \)th leaf pair motion, i.e.,

\[ F_k(x_i) = \int_{0.0}^{1.0} \Phi_k(x_i, f) df, \]

where \( \Phi_k(x_i, f) \) was the calculated fluence at position \( x_i \) for the \( k \)th leaf pair when cumulative-fraction-dose (CFD) values specified in the leaf sequencing file changed from \( f \) to
The CFD value is taken to be proportional to the accumulated monitor units, and increased from a normalized value of 0.0–1.0.

The $F_k(x_i, f)$ in Eq. (8) was modeled as the convolution between a source distribution function in the target plane $S(x, y)$ and a collimator transmission function $T(f; x, y)$.

The whole expression was corrected by the off-axis factor OAR($x, y$). It is given as

$$F_k(x_i, f) = OAR(x, y) \int \int S(x', y') T(f; x - x', y - y') dx' dy'.$$

In Eq. (9), the OAR($x, y$) was directly measured by the BIS using a large 40 × 40 cm$^2$ MLC open field. It was obtained by normalizing each pixel at position ($x, y$) with the pixel value of the reference center. The measured OAR varied as much as 15% at the outer edge of the field.

$T(f; x - x', y_k - y')$ in Eq. (9) is the fluence transmission function when CFD = $f$ in a leaf moving sequence. It was calculated as

$$T(f; x - x', y_k - y') = \{H(f; x_L - x') - H(f; x_R - x')\} \times T(y_k - y'),$$

where $H$ is the Heaviside step function, $x_L$ is the left-side leaf-tip position of the $k$th MLC leaf pair, $x_R$ is the right-side leaf-tip position of the $k$th leaf pair. $T(y_k - y') = 1$, when $y'$ falls within the projection of the $k$th leaf pair centered at $y_k$ and is zero otherwise. This is because MLC intensity modulation is realized along the horizontal leaf motion in the $x$ direction. Over the vertical $y$ direction, $F_k(x_i, f)$ is approximated to be the same across the width of a leaf.

$S(x', y')$ in Eq. (9) was calculated as a linear combination of two Gaussian distributions, i.e.,

$$S(x', y') = A_1 \exp \left(-\frac{x'^2 + y'^2}{2\sigma_1^2}\right) + A_2 \exp \left(-\frac{x'^2 + y'^2}{2\sigma_2^2}\right),$$

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where $A_1$, $A_2$, $\sigma_1$, and $\sigma_2$ are empirical parameters. The first Gaussian represents the focal distribution of the x-ray source. The second Gaussian represents extrafocal scattering components from the source plus other contributions such as electron transport uncertainties associated with the BIS image processing. The empirical parameters were determined from the minimized-$x^2$ fitting of the penumbra region of a BIS-measured MLC open field using Eq. (9). The fitting results are shown in Fig. 6 for a penumbra region and Fig. 7 for an open field profile. The best-fitting parameters are tabulated in Table I.

C. Global correlation coefficient

A global correlation coefficient $r$ was used to compare calculated reference image $F_k(x_i)$ from Eq. (7) with the BIS measurements $\Psi_k(x_i)$ from Eq. (8). The correlation coefficient $r$ is defined as

$$ r = \frac{\sum_{i,k} (F_k(x_i) - \bar{F})(\Psi_k(x_i) - \bar{\Psi})}{\sqrt{\sum_{i,k} (F_k(x_i) - \bar{F})^2} \sqrt{\sum_{i,k} (\Psi_k(x_i) - \bar{\Psi})^2}}, $$

(12)

where $\bar{F}$ is the average of $F_k(x_i)$ over $i$ and $k$, and $\bar{\Psi}$ is the average of $\Psi_k(x_i)$ over all $i$ and $k$. For a fixed value $k$, Eq. (12) becomes

$$ r_k = \frac{\sum_i (F_k(x_i) - \bar{F}_k)(\Psi_k(x_i) - \bar{\Psi}_k)}{\sqrt{\sum_i (F_k(x_i) - \bar{F}_k)^2} \sqrt{\sum_i (\Psi_k(x_i) - \bar{\Psi}_k)^2}}. $$

(13)

The resulting $r_k$ represented the correlation between the reference image and the BIS measurements for the $k$th leaf pair.

Calculation of the correlation coefficient $r$ was suited for our purpose because it tested the linear predictability of a BIS measurement from its reference image, and vice versa. In practice, if the global correlation coefficient $|r|$ in Eq. (12) or the minimum of the $|r_k|$ in Eq. (13) failed to satisfy a preset quality assurance value, the location of the faulty leaf motion will be flagged to diagnose the cause.

IV. RESULTS

A typical BIS measurement for an intensity modulated field is shown in Fig. 8. The isovalue contours for the field and the calculated reference image are given in Fig. 9. The fluence distribution patterns in the beam eye’s view were conveniently identified from the figures. The global correlation coefficient between the reference image and the BIS measurement was 97% for this case. It confirmed that the MLC control file for driving the leaf motion had been correctly transferred and loaded into the linear accelerator’s control unit. Moreover, the leaf sequencing program for generating the MLC control files had also functioned correctly.

The above correlation procedure was carried out for 26 intensity modulated fields for different cancer sites such as prostate, head and neck, and cervix. A scatter plot of the global correlation coefficients is shown in Fig. 10(a). For all
cases, the global correlation coefficients were above 95%.

To demonstrate the effectiveness of the procedure for detecting simple errors in leaf sequencing files, global correlation coefficients between BIS images and the mirror reflection of their reference images were calculated. The result was presented together with the original \( r \) value in Fig. 10(b). For all cases, global correlation coefficients were reduced to between \(-10\%\) and \(-15\%\). For each individual MLC leaf pair, the correlation coefficients \( r_k \) in Eq. (13) was also consistently within \(-10\%\) to \(-15\%\).

To demonstrate the sensitivity of the procedure, random errors were intentionally introduced into the MLC leaf motion sequence. The \( x_i \) in \( \Phi(x_i, f) \) of Eq. (8) was replaced by a random variant following the Gaussian distribution whose centroid was \( x_i \). The magnitude of the error was governed by the standard deviation \( \sigma \) of the Gaussian distribution. The error distribution for each leaf motion instance was generated subject to conditions of continuous and valid leaf motion. Continuous leaf motion forbade discontinuity in a leaf’s travel path. Valid leaf motion ensured no leaf collision.

The calculated global correlation coefficients as a function of \( \sigma \) for various intensity modulated fields are given in Fig. 11. With a threshold \( r \) value of 92% in the figure, \( \sigma \) was screened to less than 1 mm. Such a threshold \( r \) value could be used to detect faults in a leaf sequencing file for the QA procedure.

V. CONCLUSIONS AND DISCUSSION

A simple and convenient quality assurance procedure was developed to verify intensity modulated conformal therapy. The procedure employed a fast beam image system (BIS) capable of measuring and examining intensity modulated beam fluence patterns in the beam eye’s view (BEV). In the procedure, a comparison was made between BIS measurements and reference images generated from the MLC leaf sequencing files. A parametric test employing correlation coefficients was developed and demonstrated to score the comparison results.

The procedure was carried out for 26 intensity modulated fields. It was found that the global correlation coefficients were above 95% for all cases. By introducing random errors into the reference image calculation, the global correlation coefficient was able to detect uncertainties of less than 0.5 mm in the MLC leaf motion. A gross error such as a flipped reference image from an erratic leaf sequencing file was readily detected by the procedure.

Further improvements in the agreement between the reference image and the BIS measurements are anticipated by including photon transport effects in the optical system, a more realistic MLC transmission function, and a more accurate extrafocal scattering model. A compromise between precision and calculation speed was also considered in the approximations made in this work. Presently, a reference image took, on average, 40 s to calculate on a Sun SPARC10 workstation. The whole procedure could be performed on site with other quality assurance tasks.

Since the global correlation technique is insensitive to the absolute normalization between the BIS measurements and the reference images, this technique can be applied to the verification of dose distributions in an optically transparent medium that provides clinically equivalent scatter conditions.

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