Fast and accurate leaf verification for dynamic multileaf collimation using an electronic portal imaging device

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A prerequisite for accurate dose delivery of IMRT profiles produced with dynamic multileaf collimation (DMLC) is highly accurate leaf positioning. In our institution, leaf verification for DMLC was initially done with film and ionization chamber. To overcome the limitations of these methods, a fast, accurate and two-dimensional method for daily leaf verification, using our CCD-camera based electronic portal imaging device (EPID), has been developed. This method is based on a flat field produced with a 0.5 cm wide sliding gap for each leaf pair. Deviations in gap widths are detected as deviations in gray scale value profiles derived from the EPID images, and not by directly assessing leaf positions in the images. Dedicated software was developed to reduce the noise level in the low signal images produced with the narrow gaps. The accuracy of this quality assurance procedure was tested by introducing known leaf position errors. It was shown that errors in leaf gap as small as 0.01–0.02 cm could be detected, which is certainly adequate to guarantee accurate dose delivery of DMLC treatments, even for strongly modulated beam profiles. Using this method, it was demonstrated that both short and long term reproducibility in leaf positioning were within 0.01 cm (1σ) for all gantry angles, and that the effect of gravity was negligible. © 2002 American Association of Physicists in Medicine. [DOI: 10.1118/1.1501141]

Key words: intensity-modulated beams, QA, dynamic multileaf collimation, electronic portal imaging device

I. INTRODUCTION

Intensity modulated radiotherapy (IMRT) is a powerful tool for delivery of conformal dose distributions. There are several ways of producing IMRT fields by compensators,1 tomotherapy,2 segmented multileaf collimation (“step and shoot”),3,4 or dynamic multileaf collimation (DMLC).5–12 The first DMLC treatment was performed in 1995 for a prostate cancer patient at the Memorial Sloan-Kettering Cancer Center, NY.11 At the Daniel den Hoed Cancer Center (DDHCC, Rotterdam, The Netherlands), we started using DMLC in 1999 for patients with head and neck cancer who were treated on the MM50 Racetrack Microtron (Scanditronix Medical AB, Uppsala, Sweden).12 Due to the complexity of these treatments, rigorous quality assurance (QA) is mandatory. An important aspect of the QA procedure is related to the mechanical accuracy of the multileaf collimator (MLC) in DMLC mode, including leaf calibration, stability of leaf speed, and effects of acceleration and deceleration of leaf motion.

To perform leaf verification for DMLC, Chui et al.13 proposed the use of a sliding slit beam of 0.1 cm width, which was stopped at several equally spaced control positions. At these positions, film measurements showed straight dark lines, if the leaves were positioned correctly. Using this method, they could detect errors in leaf position of about 0.02 cm. To monitor the stability in gap width, LoSasso et al.14 measured the dose in the center of a uniform 10×10 cm² field, realized by a 0.4 cm slit beam, using an ionization chamber. The dose delivered within this DMLC field is highly sensitive to the actual leaf gap sweeping across the field; a deviation of only 0.01 cm in a 0.4 cm leaf gap width, results in a dose difference of about 2.5%. Both tests were also used in our institute as part of a quality assurance procedure for DMLC treatments on the MM50 Racetrack15 and on the Varian 2300C/D (Varian Oncology Systems, Palo Alto, CA).16 Several groups have used Electronic Portal Imaging Devices (EPID) for geometrical approaches to verify leaf motion while delivering a DMLC treatment.17 A difference of about 0.1 cm between prescribed and realized leaf positions, as assessed from the EPID images, could be detected.

The above-mentioned methods for QA on leaf positioning have some drawbacks. The procedure developed by Chui et al.13 using film is accurate but allows leaf verification to be performed only at the control positions where the sliding gap stops, by comparing leaf pairs relative to each other. In our experience, to quantify leaf gap deviations with an accuracy of 0.02 cm, the film should be scanned, which is time consuming. The ionization chamber method used by LoSasso et al.14 can measure the reproducibility of a leaf gap accurately, but offers the possibility to perform this check for one leaf pair and one point at a time only. Moreover, for this method quite some set-up time at the treatment unit is required. On the other hand, the reported accuracy of 0.1 cm, encountered by monitoring leaf positions with an EPID,17 may not be sufficient if highly modulated beams are used.18

In DDHCC, we are using fluoroscopic EPIDs for dosimetric verification.19–22 Since 1994, these systems are applied
for daily verification of the beam output and beam flatness of static fields on the MM50 Racetrack Microtron. Recently, we started using the EPID to perform pretreatment dosimetric verification of each clinically used IMRT field realized with DMLC. Based on this experience with EPIDs, we have extended the method described by LoSasso et al. to a full 2D, fast and accurate QA procedure for leaf verification. This procedure overcomes the drawbacks of the previously mentioned methods. In this paper, the method is described in detail and its level of accuracy is assessed. The reproducibility in gap width of a sliding slit beam is investigated by examining short and long term variations, and variations under gantry rotation.

II. MATERIALS AND METHODS

A. The MLC

In this study, all measurements were performed on a Varian 2300C/D. This linac is equipped with a 40 leaf pair MLC (Mark II), each leaf having a width of 1 cm at the isocenter plane. The maximum field realized with the MLC is 40×40 cm². The leaves have a maximum overtravel across the beam axis of 16 cm. The maximum distance that one leaf can be extended beyond another on the same carriage is 14.5 cm. The maximum leaf speed is 3 cm s⁻¹.

A DMLC treatment field is divided in a number of segments; each segment contains a fraction of the number of monitor units (MU) to be delivered and the prescribed leaf positions at that time. The leaf positions are transferred from the treatment planning system to the MLC controller of the treatment unit head, generating a light beam perpendicular to the direction of leaf motion. The calibration of each leaf can be assessed because the distance between the leaf carriage and the infrared beam is known.

B. The EPID

A fluoroscopic Theraview NT EPID (Cablon Medical, Leusden, The Netherlands), low elbow type, is attached to the Varian linac. The EPID is equipped with a CCD camera (Adimec MX12), which detects the optical signal, originated from a fluorescent screen and reflected by a 45° tilted mirror. The fluorescent screen (FS), positioned for this study at 150 cm from the focus, contains a layer of gadolinium oxysulphide coated onto a 2 mm thick brass build-up plate. An additional buildup layer of 1 mm stainless steel is used for dosimetric purposes. This extra layer hardly affects image quality. The CCD camera is connected by means of an optical fiber to a PC containing a frame grabber. Image acquisition is performed using the EPID software running on a Windows application. In the EPID image, pixel (or gray scale) values can range from 0 to 1023 ADC units. Each EPID image is the sum of a number of individual frames, acquired with a given integration time. The summed image, divided by the total number of frames, is then corrected for the dark current, which is measured just prior to the start of the irradiation. In the clinical software version, only the resulting EPID image is stored. For this study, a research version of the EPID software was used, which made possible to store not only the summed EPID image but also the individual frames. This feature was used to enable noise reduction (Sec. II D).

The EPID system has three characteristics most relevant to our measurements: (i) the signal is integrated simultaneously in 1024×1024 pixels, each measuring 0.025×0.025 cm² at the isocenter plane, (ii) the CCD read out time for a measured frame (during which no signal is accumulated) is only 2 ms, and (iii) an excellent short and long term stability.

C. Description of the sliding gap measurements

All measurements were performed using a 6 MV photon beam, running at a dose rate of 600 MU/min. Except for the measurements described in Sec. II E, a uniform 10.5×20 cm² field was delivered dynamically by sweeping a prescribed 0.5×20 cm² slit across the field with constant velocity (0.3 cm s⁻¹). The blocks were set to 10.5×20 cm² in order to minimize transmission through the leaves outside the field. During each measurement, a total of 30 EPID frames were acquired, one of these frames is shown in Fig. 1(a). The integration time for each frame was 1.4 s. The total acquisition time was always longer than the time required for the DMLC field delivery. The field center in the EPID images was derived from the borders of a static 20×20 cm² field image, acquired for the same gantry angle. This static field is also used to verify the performance of the EPID on the day of measurement.

In this paper, the x and y position coordinates are defined in the direction of leaf motion, and perpendicular to this, respectively (Fig. 1). Unless mentioned otherwise, all dimensions are measured in the isocenter plane. For coordinates measured in the EPID plane, (x_{FS}, y_{FS}) are used.

D. Image processing

In the sliding gap measurement, most points in the EPID plane receive primary radiation during one camera frame only, due to the applied narrow leaf gap; for these points, the other camera frames are only filled with signal resulting from leaf transmission and camera noise. Consequently, when simply summing the individual frames, as is done in the clinical version of the EPID software, noise significantly contributes to the signal in the resulting EPID image. Due to the poor signal-to-noise ratio, small deviations in leaf gap width cannot be detected.

In order to reduce this noise level, four steps were performed for each individual frame, after subtracting the dark current and prior to adding the frames. First, a median filter was applied within a region of 0.075×0.075 cm² to remove isolated high or low values resulting from damage to the CCD chip. Second, for each leaf pair, j, the middle 13 gray scale value profiles, g_j,raw(x), were averaged in the direction
perpendicular to the leaf motion [Fig. 1(b)]. In this direction, only minor variations in pixel values were observed for these 13 middle profiles, but for adjacent lines, $g_{j, raw}(x)$ was increasing due to the influence of leaf leakage between adjacent leaves, as observed in the measured $y$ profiles. Third, transmission through the leaves and the blocks was subtracted, as shown in Fig. 1(c) by the horizontal line. The transmission was determined by averaging the pixel values at a distance larger than 3 cm (at the EPID plane) from the peak. After transmission subtraction, all negative pixel values were set to zero. Finally, and most importantly, the pixel values at all points within the frame, located at a distance larger than 3 cm (at the EPID plane) from the peak center, were set to zero [as indicated by the vertical lines in Fig. 1(d)]. By setting the pixel values to zero beyond 3 cm from the peak center, where the signal reached a plateau, all primary and scattered radiation were still included in the signal of the frame, while minimizing the contribution of noise. Cross-talk within the EPID images was also removed by performing this step. Figure 1(e) shows the resulting frame image after these four steps. Next, the frames were summed to get the final gray scale profile, $G_j(x)$, for each individual leaf pair. In the end, a smoothing filter was applied within a distance larger than 3 cm from the peak center, where the signal reached a plateau, all primary and scattered radiation were still included in the signal of the frame, while minimizing the contribution of noise. The above-mentioned image processing was performed by means of a routine developed in our institute and programmed using the Interactive Data Language 5.3 (Research Systems, Boulder, CO). The total amount of time required for the acquisition of the static field and the IMRT field, and for the succeeding image processing, is 3 minutes.

E. Relation between leaf gap width and measured EPID signal

In order to establish the relation between the nominal leaf gap width, $w$, and the EPID signal for our measurements, the procedure described in Sec. II C, was performed for a uniform 10×20 cm$^2$ field realized by sweeping a 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 cm nominal gap, respectively. All leaf gaps traveled at the same velocity (0.3 cm s$^{-1}$). After image processing (Sec. II D), the gray scale values of the resulting profiles, $G_j(x)$, were averaged in the direction of leaf motion over 8 cm, therefore neglecting the penumbra, yielding $G_{j,c}$. These average gray scale values were then normalized to the average value of the uniform field realized by the 0.5 cm gap. This gap width was chosen because it is used in all our QA measurements. In this way, for a given QA check, differences in EPID signal can directly be related to differences in leaf gap width.

F. Detection of leaf position errors

To assess the accuracy of our method, we simulated leaf position errors, $\Delta w$. Each simulated error was introduced in one leaf pair only. In the DMLC file sent to the treatment unit, the sliding leaf gap was programmed to have a nominal width of 0.5 cm at the start of the irradiation, 0.5−$\Delta w$, halfway, and again 0.5 cm at the end of the treatment. These images were compared with an EPID image acquired using a dynamic field of 0.5 cm width, without simulated errors in leaf positions.
G. Reproducibility of QA measurements

In order to establish the short term reproducibility of the QA measurements performed on our linac, four EPID images were successively acquired, as described in Sec. II C, within a short time interval. After performing image processing in each image, the gray scale values in the resulting profile of each leaf pair, \( G_j(x) \), were averaged in the direction of leaf motion, yielding \( G_{j,c} \) (Sec. II E). The short time stability was defined as the standard deviation, \( \sigma \), of these values in the four images. This standard deviation was determined separately for gantry angles 0°, 90°, and 270°.

Differences in leaf calibration between different leaf pairs were assessed, by calculating the average gray scale values over a region of \( 0.25 \times 0.25 \text{ cm}^2 \), at the central axis of each leaf pair. These values were then divided by the gray scale values measured in a static centered field of \( 1 \times 20 \text{ cm}^2 \), to correct for variations in the \( y \) direction, in EPID response and shape of the dose profile, as delivered by the treatment unit.

To study the long term reproducibility, a sliding gap field was measured 21 times over a 50 day period, for gantry angles of 0°, 90°, and 270°. To overcome the limitation that leaves have a limited range of travel with respect to their corresponding carriage, and to be able to verify the reproducibility of the sliding leaf gap over the maximum field that can be detected with the EPID, two, 1 cm overlapping, fields (left and right) with dimensions of \( 10.5 \times 20 \text{ cm}^2 \), were used. On the first day, the measurements were repeated three times. For each field, image processing was performed for the four EPID images and the average image was calculated, which was then defined as the reference. On the same day, a film was irradiated following the method proposed by Chui et al.\(^{13} \) to ensure that the reference images were acquired in currently acceptable conditions of leaf calibration. In the following days, one EPID image was acquired for each field. The percentage differences between these gray scale values and the gray scale values in the reference image were calculated, for each gantry angle and for each field. The long term stability was defined as the standard deviation of this percentage differences averaged over all leaf pairs, in the 50 days study period.

The EPID images used to assess the long term stability for each gantry angle, were also used to investigate the influence of gravity on gap motion in the same period of time. The influence of gravity was derived by the percentage difference in \( G_{j,c} \), between the images at 90° and 270° gantry angles, and the image at 0° gantry angle, averaged over all measurement days and all leaf pairs.

III. RESULTS

A. Image processing

To show the effects of our image processing routine, two profiles in the direction of leaf motion are compared for one EPID measurement (Fig. 2). In the leaf profile [Fig. 2(a)], all individual EPID frames were summed and corrected for dark current but no extra noise reduction steps were performed, yielding \( G_{j,\text{raw}}(x) \). This image would be obtained with the clinical version of our EPID software, after filtering isolated high and low pixel values. For the same measurement, frames were processed as described in Sec. II D before summing them [Fig. 2(b)]. While in Fig. 2(a) the noise exceeds the ±5% level, it could be reduced to about 1% by our image processing. Because in our QA measurements, EPID images are analyzed relative to a reference measurement, deviations of the order of 2% should be detectable. By comparing the profiles in Figs. 2(a) and 2(b), a difference in height is observed, which is mainly due to the subtraction of leaf transmission in the second step of the image processing.

B. Relation between leaf gap width and measured EPID signal

By performing the measurements for nominal leaf gap widths of 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 cm, a calibration curve could be made. As shown in Fig. 3, the EPID signal, \( G_{j,c} \), changes linearly with the leaf gap width, \( w \). According to this calibration curve, a change in EPID signal of 3% corresponds to a change in gap width of 0.02 cm, when using a sweeping leaf gap of 0.5 cm as a reference. Due to the fact that the leaves of the Varian MLC have rounded edges, the nominal leaf gap width is smaller than the effective leaf gap. By performing regression analysis to the data in Fig. 3, a difference of 0.18 cm between both values was found, which is in agreement with results obtained by others.\(^{14,16} \)
C. Detection of leaf position errors

The relative differences between the measured gray scale value profiles, \( G_j(x) \), with and without introduced nominal errors, \( \Delta w \), are shown in Fig. 4, for two leaf pairs. In the center of the field, differences in signal of \(-9\%\) and \(-3\%\) were detected by the introduction of a 0.05 cm and 0.02 cm error in the 0.5 cm nominal leaf gap, respectively. The fact that an error in gap width of 0.02 cm can easily be detected, indicates that the accuracy of our method is 0.01–0.02 cm.

D. Reproducibility of QA measurements

The short term reproducibility of the measured gray scale values was 0.3\% (1\sigma), at gantry angles of 0°, 90°, and 270°. This value found is similar to the EPID short term reproducibility of 0.2\% (1\sigma) already reported by others for gantry angle 0° using a static field.\(^{19,23}\)

No significant variation could be observed in the gap widths of the different leaf pairs. As shown in Fig. 5, the difference between the measured gap width for each leaf pair and the average width over all leaf pairs did not exceed 0.02 cm, being within the accuracy of our method.

The long term stability of the measured leaf gap widths at gantry angle 0° is depicted in Fig. 6, for one leaf pair. For all leaf pairs, a variation of 0.01 cm (1\sigma) was detected, in the 50 days study period, for all gantry angles. At one day, a significantly higher deviation was observed, not only for the particular leaf pair shown in Fig. 6, but also for the other leaf
pairs and for the different gantry angles. A possible explanation for this deviation might be a calibration error of all leaves for that particular day, resulting in a deviation in gap width of 0.04 cm. It is unlikely that this deviation would be due to the performance of the EPID on that day, because no significant deviations were found between the static field acquired at the same day and the other days of measurement. Although this deviation is within the required tolerances for DMLC delivery,\textsuperscript{18} it indicates the importance of this QA check.

The mean gap width differences with respect to gantry angle 0°, over a period of 50 days, were $\pm 0.01\pm 0.02$ cm (1σ) and $0.00\pm 0.01$ cm (1σ) for the gantry angles 90° and 270°, respectively, indicating that gravity has a negligible effect.

**E. Gap width variations with high spatial frequencies**

By closely examining the peaks in individual frames, signal variations may be observed (Fig. 7), that cannot be attributed to noise. For each leaf pair, there is a common signal pattern for the 13 central gray scale profiles, $g_{j,1}(x)$, which are averaged in step 2 of the image processing. In Fig. 7, two of these lines are shown. Different leaf pairs have different patterns. Static EPID images acquired at the same day do not show these local signal variations. Probably, the signal variations arise from short and minor variations (less than 0.02 cm) in the leaf gap width, while the leaves are traveling across the field.

**IV. DISCUSSION**

The leaf verification method described in this paper is being used for constancy checks, where deviations in leaf gaps are measured relative to a 0.5 cm nominal leaf gap width as selected for acquisition of the reference images (Sec. II G). In order to allow absolute leaf gap width verification, a feeler gauge could be used to measure the actual leaf gap width when the reference images are acquired. Actually, these absolute measurements need to be performed for one leaf pair only, because the leaf calibration for different leaf pairs does not differ significantly, as seen from Fig. 5.

The proposed QA method has been tested for one particular MLC. Probably it can be implemented for multileaf collimators with other leaf widths as well. Some alterations in the image processing procedure should then be performed in order to achieve the same signal-to-noise ratio as stated in this paper. For instance, the number of the middle gray scale value profiles chosen for averaging, as performed in step two of the image processing (Sec. II D), has to be determined for another multileaf collimator.

This leaf verification method is used as a quick morning check of the calibration and the performance of the MLC, prior to the start of patient treatments. In addition to this daily check of the treatment unit, also patient specific dosimetric tests are performed with the EPID, both prior to the start of the fractionated treatment (pretreatment verification),\textsuperscript{22} and weekly during the treatment. For pretreatment verification, the treatment planning system is used to calculate for each IMRT field an absolute, two-dimensional dose distribution in the plane of the EPID, based on the leaf sequences that will be used for treatment of the patient. Prior to the first treatment fraction, these dose distributions are measured with the EPID and compared with the prediction. Deviations may point to problems with the leaf sequencing algorithm or with data transfer between the treatment planning system and the treatment unit. The weekly dosimetric measurements during the treatment are used to check constancy.

**V. CONCLUSIONS**

Our QA measurements using the EPID can detect differences in leaf gap width of 0.01–0.02 cm. In one single measurement, 2D information is obtained, verifying the reproducibility of the leaf gap width for all leaf pairs at the same time. In this method, constancy of the absolute measured gray scale values is required. This is in contrast, in one hand, with the use of EPIDs for patient setup verification, where high contrast between anatomical structures is important (i.e., high relative differences between the gray scale values).

**Fig. 7.** Variation in measured gray scale values, $g_{j,1}$, on the top of the peak in a single frame image. Four top peak profiles are shown in the direction of leaf motion, two, measured under the same leaf pair (line 1 and line 2), and two under different leaf pairs (pair 18 and pair 19).
and, on the other hand, with dosimetric verification,\textsuperscript{22,24,25} where dosimetric calibration of the EPID is required. The method is fast, due to the fact that the EPID is already attached to the accelerator and no extra setup time is required. By using the EPID, leaf verification can easily be performed for different gantry angles. Presently, this QA procedure is in daily use.

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