Evaluation of Kodak EDR2 film for dose verification of intensity modulated radiation therapy delivered by a static multileaf collimator

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A new type of radiographic film, Kodak EDR2 film, was evaluated for dose verification of intensity modulated radiation therapy (IMRT) delivered by a static multileaf collimator (SMLC). A sensitometric curve of EDR2 film irradiated by a 6 MV x-ray beam was compared with that of Kodak X-OMAT V (XV) film. The effects of field size, depth and dose rate on the sensitometric curve were also studied. It is found that EDR2 film is much less sensitive than XV film. In high-energy x-ray beams, the double hit process is the dominant mechanism that renders the grains on EDR2 films developable. As a result, in the dose range that is commonly used for film dosimetry for IMRT and conventional external beam therapy, the sensitometric curves of EDR2 films cannot be approximated as a linear function, OD$=c*D$. Within experimental uncertainty, the film sensitivity does not depend on the dose rate (50 vs 300 MU/min) or dose per pulse (from 1.0×10^{-4} to 4.21×10^{-4} Gy/pulse). Field sizes and depths (up to field size of 10×10 cm^2 and depth$=$10 cm) have little effect on the sensitometric curves. Percent depth doses (PDDs) for both 6 and 23 MV x rays were measured with both EDR2 and XV films and compared with ion chamber data. Film data are within 2.5% of the ion chamber results. Dose profiles measured with EDR2 film are consistent with those measured with an ion chamber. Examples of measured IMRT isodose distributions versus calculated isodoses are presented. We have used EDR2 films for verification of all IMRT patients treated by SMLC in our clinic. In most cases, with EDR2 film, actual clinical daily fraction doses can be used for verification of composite isodose distributions of SMLC-based IMRT. [DOI: 10.1118/1.1493781]

Key words: Film dosimetry, EDR2 film, IMRT, QA

INTRODUCTION

In recent years, there has been increased interest in implementing intensity modulated radiation therapy (IMRT) in external beam radiation therapy. IMRT employs nonuniform beam intensity to deliver highly conformal radiation to the targets while minimizing doses to normal tissues and critical organs.[1] One of the approaches to create nonuniform beam intensity is the use of a static multileaf collimator (SMLC). A key element for a successful clinical implementation of IMRT is establishing a dosimetric verification process that can ensure the delivered doses are consistent with calculated doses for each patient.[2,3] Dose verifications, in general, include three types of measurements. The first is absolute point dose measurements using detectors such as ion chambers. The second is relative two-dimensional (2-D) dose distribution measurements using detectors such as radiographic or radiochromic films or three-dimensional (3-D) measurements with polymer gels. The third type of measurement is the verification of a fluence pattern perpendicular to the incident beam using devices such as charge coupled device- (CCD) based imaging systems[3] or electronic portal image devices (EPID)[4] or radiographic films.

X-OMAT V (XV) film from Kodak is the most common radiographic film for relative dose distribution measurements for IMRT,[2,3] probably due to its wide availability and extensive clinic use. In addition to its energy-dependent response,[5] the main limitation of XV film is its limited dose range for IMRT applications. At optical densities (OD) above 2, the reading accuracy of a 12-bit CCD-based commercial film digitizer is limited by noise.[6] It requires about 80–90 cGy, which is approximately one-half of a typical daily fraction dose (e.g., 180–220 cGy), to produce an OD of 2 for the XV film.[7] One approach to overcome this limitation is to use a more expensive 16-bit film digitizer. The second approach is to create the patient plan with the normal daily fraction dose and then to scale the maximum daily fraction dose to 80–90 cGy for film dosimetry. The problem with this approach is that there is about a 20% chance that MLC segments for the plan with a reduced dose may differ from those for the original plan with the normal daily fraction dose. This is due to rounding errors with integer monitor units.[8] When different MLC segments are used, dose verification with film becomes less meaningful. In this work, Kodak EDR2 film, originally developed for radiation therapy portal localization and known as EC film,[9] is evaluated for dose verification of IMRT delivered by a SMLC.

MATERIALS AND METHODS

EDR2 film (Kodak, Rochester, NY) is the ready-pack form of the original EC film used for portal localization and has recently become available from Kodak. EDR2 film is a very slow speed, fine grain film. It uses very fine monodispersed grain cubic microcrystals. Double emulsion layers are coated on a 0.18 mm Estar base, which allows processing in a conventional rapid-process film processor.[9] X-ray beams, 6 and 23 MV, from a Primus linear accelerator (Siemens, Concord, CA) were used in this work. For measurements performed with the original EC film, a solid water film phantom (Gammex RMI, Middleton, WI) was used. After EDR2 film became available, the ready-pack films in the paper envelopes were used. In the remaining text, we will use EDR2 to refer this new type of radiographic film.

The reproducibility of the optical density of EDR2 film was tested by irradiating three films under the identical conditions using the 6 MV x-ray beam. Each film was placed at the depth of 1.6 cm in a solid water phantom with the target to detector distance (TDD) of 100 cm. The OD was read using a manual densitometer (Macbeth, model TD932, Newburgh, NY) with an aperture of 2 mm. All films from each experiment were processed at the same time after the processor (ALPHATEK, AX700LE) was warmed up with several scrap films. The average and standard deviation of the net OD were calculated from the three readings. The student's t distribution[10] was used to estimate the 95% confidence intervals of the measured OD. With the same setup, the effect of the dose rate on the net OD was also tested. The number of pulses produced by the linear accelerator in an irradiation was determined by the pulse counter of a diode array detector (Profiler Model 1170, Sun Nuclear, Melbourne, FL). The pulse period was determined by dividing the total time of irradiation by the number of pulses counted. The pulse width was determined by measuring the time duration of the target current with an oscilloscope (Model 2247A, Tektronix, Beaverton, OR). The effect of dose pulse period on film sensitivity was determined by using two different dose rates available for the 6 MV beam, 300 and 50 MU/min. The effect of dose per pulse (instantaneous dose rate) on OD was checked by irradiating the films at three different TDDs, 70, 100, and 140 cm.

Depth doses were measured with the film oriented perpendicular to the x-ray beam at the target to surface distance (TSD) of 100 cm. Percent depth doses (PDDs) were also obtained with XV film for comparison. A sensitometric curve was obtained for each experiment. Optical densities for sensitometric curves and PDDs were determined by the Macbeth densitometer. The background of each film was subtracted using the reading of an unexposed film. Optical densities were converted to relative doses using the measured sensitometric curve. Depth doses in the solid water phantom were also measured with a parallel plate ion chamber (PTW TN23343, Markus). Two-dimensional isodose distributions of IMRT were measured with one or more films loaded into a film phantom (NOMOS, Sewickley, PA). A Vidar film digitizer (VXR-12 plus, Vidar Systems Corp., Herndon, VA) was used to scan the film. The film scanner was operated with a resolution of 75 DPI (0.34 mm/pixel) and a depth of 12 bits. The default translation table, OD, was used. OD distributions were converted to dose distributions using the sensitometric curve obtained by the Vidar film scanner for each study. Two-dimensional images were then transferred to Wellhofer software (WP700 version 3.51) for analysis. The measured isodose lines were normalized to the calculated maximum dose.

TABLE I. Reproducibility of the optical density of EDR2 films irradiated by a 6 MV x-ray beam. The net OD represents the average with three measurements. Errors represent 95% confidence level based on the student's t distribution.

Dose (cGy)	Net OD[a]	Percent error with 95% confidence level
94	0.52±0.01	2.7
188	1.09±0.02	1.8
281	1.74±0.05	2.8
375	2.29±0.11	4.6

[a] $Error = s \times t/\sqrt{N}$, where s is the standard deviation, t is the critical value equal to 4.303 for $n=2$ (number of degrees of freedom $n=N-1$) with 95% confidence level; $N=3$ is the number of measurements (Ref. 10).

IMRT plans were generated with the Corvus planning system (NOMOS, Sewickley, PA) with five-level intensity modulation. To facilitate a direct comparison with measurement, hybrid plans were generated from patient plans recalculated for the NOMOS film phantom. The recalculation involved calculating new TSDs for the phantom while keeping the fluence the same. IMRT treatments were delivered by a SMLC approach on a Siemens linear accelerator.

RESULTS

Sensitometric curves

The reproducibility of measurement was performed at four dose levels, as listed in Table I. Three out of four measured net ODs were found to be reproducible within ±3% and the other one was within ±5%, as shown in Table I. These errors represent a 95% confidence interval based on

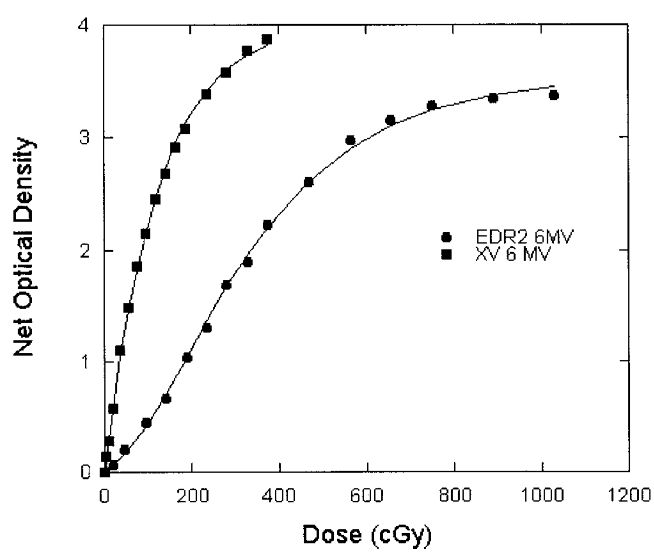

FIG. 1. Sensitometric curves for EDR2 and XV films irradiated by a 6 MV x-ray beam with a field size of 5×5 cm^2 at d_{max}, 1.6 cm. Solid lines are calculated by Eq. (1). For XV film, $OD_1 = 4.02 \pm 0.03$ and $\alpha_1 = 0.008\,05 \pm 0.000\,14$, and $OD_2 = 0$. For EDR2 film, $OD_1 = 0.07 \pm 0.05$, $\alpha_1 = 0.05 \pm 0.03$, $OD_2 = 3.45 \pm 0.04$, and $\alpha_2 = 0.005\,57 \pm 0.000\,14$.

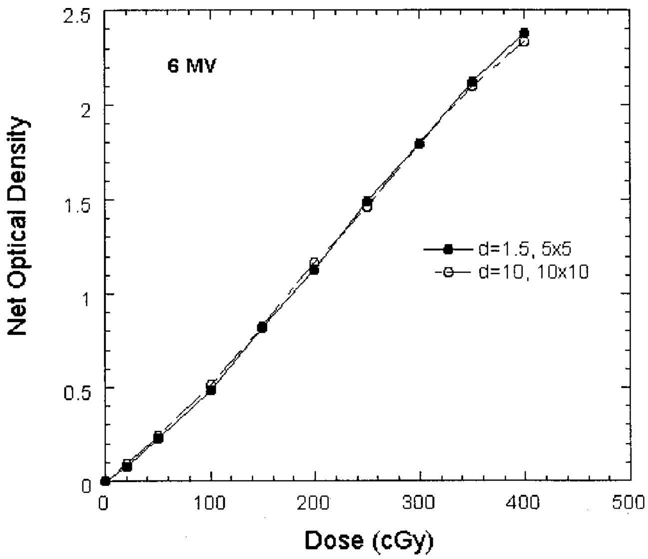

FIG. 2. Sensitometric curves for EDR2 film irradiated by a 6 MV photon beam with field size 5×5 cm^2 at the depth of d_{max}, 1.6 cm, and 10×10 cm^2 at the depth of 10 cm.

the student's t distribution, which is about 2.5 times the standard deviation for a quantity determined by averaging with three measurements.

An example of sensitometric curves for EDR2 and XV films irradiated by the 6 MV photon beam is shown in Fig. 1. It is clearly shown that EDR2 film is much less sensitive than XV film. Shown in Fig. 2 are sensitometric curves for EDR2 films irradiated by the 6 MV photon beam with the field size of 5×5 cm^2 at the depth of d_{max}, 1.6 cm and with the field size of 10×10 cm^2 at the depth of 10 cm. There is little difference between these two sensitometric curves.

ODs for EDR2 film irradiated with 188 cGy by the 6 MV beam with dose rates 300 and 50 MU/min were 1.19±0.05, and 1.21±0.03, respectively. The outputs of 300 and 50 MU/min beams were verified to be within 0.5% of each other. Again, the errors represent a 95% confidence interval based on the student's t distribution and indicate that no significant difference occurs. At 300 MU/min, 188 cGy was delivered by 9650 pulses and at 50 MU/min by 11 590 pulses. This corresponded to pulse periods of 4 and 21 ms, respectively. A change in pulse period in this range has no effect on EDR2 film sensitivity. ODs for EDR2 film irradiated with 300 cGy by a 6 MV beam with dose rate 300 MU/min at three different TDDs are shown in Table II. Within experimental uncertainty the dose per pulse in the range shown in Table II also has no effect on the resulting OD of EDR2 film.

TABLE II. Optical density of EDR2 films irradiated with 300 cGy by a 6 MV x-ray beam as a function of the target to detector distance. The net OD represents the average with three measurements. Errors represent 95% confidence level based on the student's t distribution.

TDD (cm)	Number of pulses[a]	Dose per pulse (Gy)	Net OD[b]
70	7189±39	4.2×10^{-4}	1.53±0.05
100	14475±78	2.1×10^{-4}	1.52±0.05
140	28757±155	1.0×10^{-4}	1.51±0.05

[a]Error represents one standard deviation.
[b]See the note for Table I.

TABLE III. A comparison of percent depth doses for the 6 MV photon beam measured with EDR2 and XV films to that measured with the ion chamber as a function of depth for the field size of 5×5 cm^2.

	Percent Depth Dose			% Difference Relative to Ion Chamber	
Depth (cm)	Ion chamber	EDR2 film	XV film	EDR2	XV
2.0	99.0	99.0	99.0	0.0	0.0
5.0	84.6	85.4	85.6	0.9	1.2
10.0	62.9	63.4	63.7	0.8	1.3
15.0	46.4	46.2	46.6	−0.4	0.4
20.0	34.4	35.0	34.5	1.7	0.3

Percent depth dose

Tables III and IV show the PDDs for 6 and 23 MV beams measured with EDR2 and XV films and an ion chamber in the solid water phantom for the field size of 5×5 cm^2. It is found that PDD obtained with both types of film are consistent with the ion chamber data. In most cases the agreement is better than 1.5%, with the worst case being 2.5%.

Relative dose profiles

Plotted in Fig. 3 are relative dose profiles for a 6 MV beam measured with EDR2 in a solid water phantom. Also included in Fig. 3 are dose profiles measured with an ion chamber in a 3D scanning water phantom. There is excellent agreement in dose profiles between measured with EDR2 films in a solid water phantom and measured with an ion chamber in a scanning water phantom. In the low dose gradient area, the maximum difference is within 1% and in the penumbra region is less than 2 mm.

Dose Distributions of IMRT

Intensity pattern verification

Both EDR2 and XV films were used to measure the fluence distribution of individual intensity modulated fields. These measurements were performed in a plane perpendicular to the incident beam. Shown in Fig. 4 is an example of the fluence distribution calculated by the treatment planning

TABLE IV. The same as Table III, but for the 23 MV photon beam.

	Percent depth dose			%Difference Relative to Ion Chamber	
Depth (cm)	Ion chamber	EDR2 film	XV film	EDR2 film	XV film
3.5	100.0	100.0	100.0	0.0	0.0
5.0	97.8	97.9	97.9	0.1	0.1
10.0	80.0	80.0	81.6	0.0	2.0
15.0	64.3	64.8	65.3	0.8	1.6
20.0	52.0	52.3	50.7	0.6	−2.5

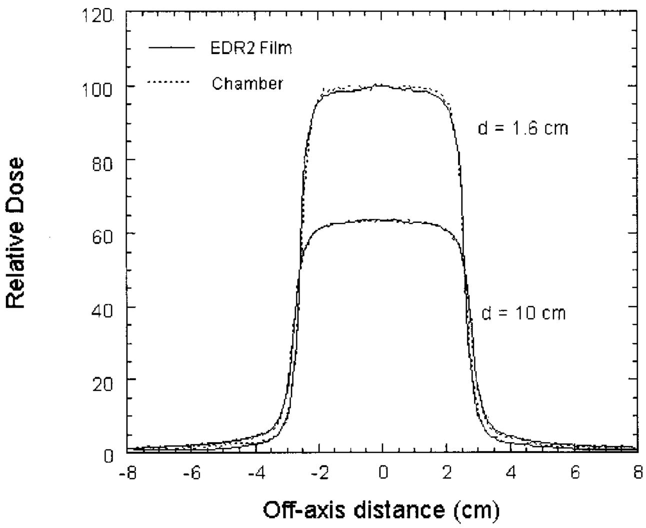

FIG. 3. Relative dose profiles measured with EDR2 and an ion chamber irradiated by a 6 MV photon beam with field sizes 5×5 cm^2 at the depths of $d_{\max}$, 1.6 cm, and 10 cm.

system and the dose pattern measured by EDR2 and XV films, respectively. This dose pattern was created by a 6 MV x-ray beam with 9 MLC-defined segments and total 151 monitor units. EDR2 or XV films were placed at the depth of $d_{\max}$ in a flat solid water phantom with the TDD of 100 cm. Both films show good agreement between measured and calculated intensity patterns.

Isodose distribution—A phantom study

The phantom used for this example was the film phantom from NOMOS. CT images in axial and sagittal planes containing the target and structure definition are shown in Fig. 5. The target defined was a C-shaped contour on each CT image. The thickness, width, and length of the target were approximately equal to 1.8, 8, and 5 cm, respectively. The critical structure was a cylindrical-shaped volume with a diameter of 1.8 cm and a length of 5 cm. The goal dose to the target was 1.8 Gy per daily fraction and the limit dose to the critical structure was 0.72 Gy per daily fraction. A 6 MV x-ray beam was directed at five gantry angles, 256°, 308°, 0°, 52°, and 104°. The optimized plan called for a total of 41 MLC segments and 1147 monitor units. Shown in Fig. 6 is a comparison of the isodose distribution measured with EDR2 film and calculated by the planning system in an axial plane. The measured and calculated isodose distributions are qualitative consistent with each other.

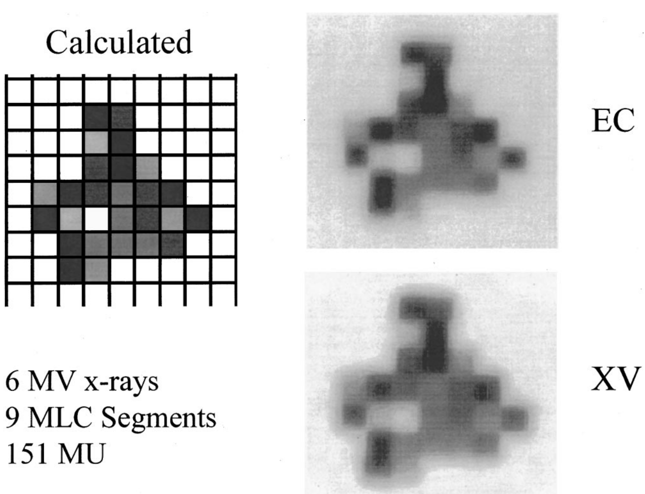

FIG. 4. An example of a qualitative comparison of the calculated fluence distribution in a plane perpendicular to the incident beam for an intensity modulated field with the measured distribution at the depth of 1.6 cm, $d_{\max}$ for a 6 MV photon beam, with EDR2 and XV films.

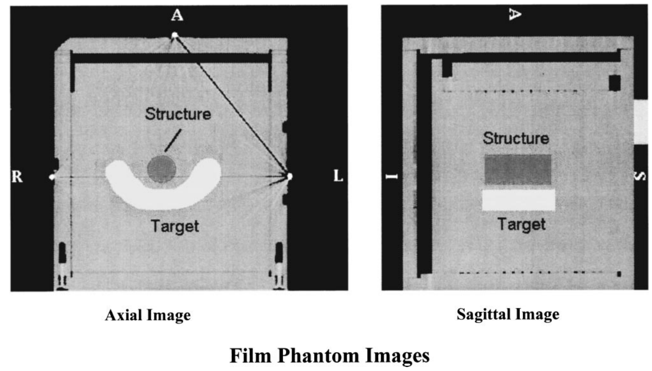

FIG. 5. CT images for a commercial film phantom in axial and sagittal planes with a target and a structure defined.

Isodose distribution—A clinical case

A 34-year-old male patient with a right nasal sinus chondro sarcoma was treated using an IMRT approach. Both CT and MR images for the patient's head and neck region were acquired for treatment planning. Targets and structures were defined on the fused CT and MR images. The prescription called for the goal dose of 64.8 Gy in 36 fractions to the gross target, and the limit dose to the spinal cord was 40.0 Gy with the maximum limit dose of 45 Gy. An optimized plan was developed, which consisted of 9 evenspaced gantry angles with total of 80 MLC segments and 986 MU. A hybrid plan was then computed for the film phantom based on the optimized plan for the patient. Shown in Fig. 7 is a com-

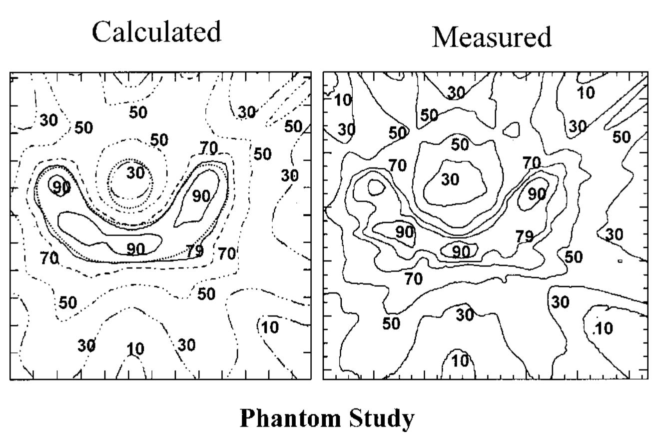

FIG. 6. A phantom study of the comparison of isodose dose distributions calculated by the treatment planning system and measured by EDR2 film.

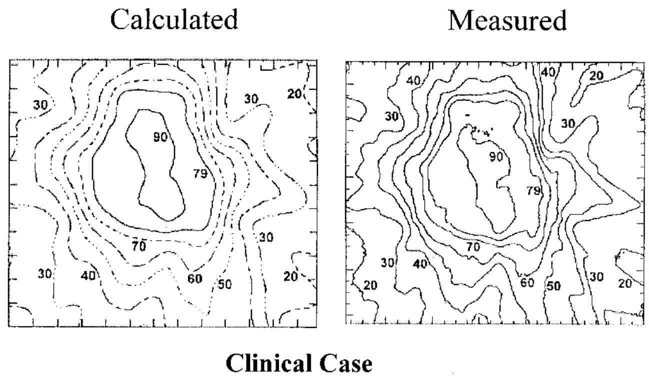

FIG. 7. A clinical case of comparison of isodose dose distributions calculated by the treatment planning system and measured by EDR2 film.

parison of isodose distributions measured with EDR2 film and calculated by the planning system for the hybrid plan. It is demonstrated that the calculated and measured isodoses are consistent with each other.

DISCUSSION

Sensitometric curve

The EDR2 film is less sensitive than XV film. As shown in Fig. 1, while the saturation level is about 200 cGy for XV film, the saturation level of the EDR2 film is approximately equal to 700 cGy. These values are consistent with the data provided by Kodak as a package insert in each box of film. The lower sensitivity of EDR2 film is a clear advantage over XV film for composite isodose verification of IMRT. We also found that the 6 and 23 MV (not shown) photon beams have very similar sensitometric curves for both EDR2 and XV films.

Figure 2 demonstrates that within experimental uncertainty the response of EDR2 film is independent of depth and field size, up to 10 cm depth and $10\times10\ \mathrm{cm}^2$ field size, which is confirmed in a separate experiment for depth dose measurements with films (see the discussion on percent depth doses). No dose rate effect was observed either in milliseconds (4 ms, 300 MU/min, vs 21 ms, 50 MU/min), or in microseconds (the dose per pulse from 1.0×10^{-4} to 4.2×10^{-4} Gy/pulse) time scales.

The solid lines in Fig. 1 are calculated by the following the equation for mixed single and double hits:[11]

$$\mathrm{OD}=\mathrm{OD}_1(1-e^{-\alpha_1 D})+\mathrm{OD}_2[1-e^{-\alpha_2 D}(1+\alpha_2 D)], \quad (1)$$

where OD is the optical density, OD_1 and OD_2 are the maximum optical density by single hit and double hit processes, respectively, α_1 and α_2 describe the film sensitivity (in units of reciprocal dose) for the single and double hit processes, respectively, D is the dose. It is assumed that a grain can be rendered developable either by single or double hit in Eq. (1). For XV film, only the single hit is involved,[5] $\mathrm{OD}_2=0$, Eq. (1) is simplified to $\mathrm{OD}=\mathrm{OD}_1(1-e^{\alpha_1 D})$; only OD_1 and α_1 are fitting parameters. For EDR2 film, additional fitting parameters are OD_2 and α_2. Parameters used for calculating the solid lines for both types of films are given in the caption of Fig. 1. In general, the shape of the optical density versus dose curve depends largely on the grain size and its distribution, on the intrinsic sensitivity of the grains, on the quality of the radiation applied for a given development condition.[12] The details about Eq. (1) are discussed in another work.[11] For EDR2 film, the double hit is the dominant process contributing to optical density. In this case, Eq. (1) predicts that the sensitometric curve has a very limited linear region. As shown in Fig. 1, for doses above 10 cGy, useful for convention external beam film dosimetry and IMRT dose verification, the sensitometric curve of EDR2 film cannot be approximated by $\mathrm{OD}=c*D$, where c is a proportional constant. In this case, the ratio of OD cannot be equated to the ratio of doses. On the other hand, for XV film that is governed by the single hit process, for doses less than 40 cGy, the sensitometric curve shows good linearity.

Percentage depth doses

There is a good agreement between PDDs measured with both types of films and with an ion chamber in the solid water phantom, as shown in Tables III and IV. Such a comparison suggests that energy dependence for both EDR2 and XV films is not significant for both 6 and 23 MV beams with the field size of $5\times5\ \mathrm{cm}^2$ and depths up to 20 cm. The result for the 6 MV beam is also consistent with the result in Fig. 2, which shows nearly identical sensitometric curves obtained at different depths and field sizes. Tsai *et al.*[2] have reported similar results for XV film in a 6 MV photon beam with the field size of $10\times10\ \mathrm{cm}^2$. In a recent study, Danciu and Proimos[13] have found for XV film for small to moderate field sizes (up to about 15 cm$\times$15 cm) and moderate depths (up to about 15 cm) no considerable variation in film sensitivity for perpendicular exposure. These results[2,13] are consistent with the present work for the depth dose measured with XV film. Our results of percent depth doses and sensitometric curves at different depths and field sizes measured with EDR2 films also justify the use of a single sensitometric curve measured at $d_{\max}$ for converting OD to dose for IMRT dose verification. It should be pointed out that the PDDs reported in Tables III and IV were measured with films perpendicular to the beam incidence direction. When a film is parallel to the central axis of the beam, there is a tendency of over-response due to the airgap introduced by the film. It was reported that this over-response was eliminated for XV films by angling the beam by 2° to the plane of the film.[14]

Dose distributions

Qualitatively, there is an excellent agreement between the measured dose pattern and the calculated fluence pattern for an intensity modulated field at a fixed gantry angle, as shown in Fig. 4. A strict comparison of these two distributions could not be made, unless the fluence distribution is converted to dose distribution. A correlation method was reported to compare a beam imaging system (BIS) measurements with the calculated fluence pattern.[15] This method could be applied to film measurements as shown in Fig. 4 for a quantitative comparison.

Not only is the EDR2 film much smaller in grain size, but also its distribution of sizes is much narrower.[9] This much smaller-grain-size emulsion results in much less sensitive film, as shown in Fig. 1. The narrower distribution in grain sizes results in higher contrast, contributing to lower noise.[9] Although they are not obvious in qualitative comparison, as shown in Fig. 4, the higher contrast and lower noise are clear advantages for any imaging-based measurement.

The low sensitivity is only an advantage in the verification of a composite isodose of all IMRT fields. The use of EDR2 film is unnecessary when verifying the fluence distributions of individual intensity-modulated fields, because small doses are usually associated with individual fields. For example, for a typical IMRT delivery with 5–9 intensity-modulated fields, the average dose per field is typically between 20 and 50 cGy. XV film can be used for this dose range without any difficulty.

For composite isodose verifications, EDR2 film has a clear advantage, being less sensitive than XV film. Standard clinical daily fraction doses can be used for the verification of composite isodose distributions with a common 12-bit film digitizer. It is not necessary to scale the daily fraction dose to a smaller value for film dosimetry, which can potentially introduce different MLC segments for film dosimetry from actually being used for the patient. If this occurs, the isodose distribution verification with film dosimetry would be less direct and meaningful.

We have used EDR2 film for every patient treated by IMRT using SMLC at our institution. The composite isodose distribution in at least one axial or coronal plane was measured. The measured isodose distribution was normalized to the calculated maximum dose so that the isodose lines with the same percentage between measured and calculated can be compared. Film dosimetry has been used only for qualitative comparison, while measurements with an ion chamber have provided quantitative point dose verification. The EDR2 films were used for daily fraction doses ranging from 1.64 to 3.0 Gy. Composite isodose distributions for all patients treated so far in our clinic were verified with the actual daily fraction doses, except one patient, who was treated to 30 Gy in 5 fractions, i.e., 6 Gy per fraction. As shown in Fig. 1, 6 Gy would produce OD approximately equal to 3. At this level of density, a 12-bit film scanner is limited by noise. For this patient, we scaled the phantom plan so that only 3 Gy was used for film dosimetry.

CONCLUSION

We have evaluated Kodak EDR2 films for IMRT dose verification. Representative sensitometric curves for 6 MV are presented. The EDR2 film is much less sensitive than Kodak XV film due to its much smaller grain size. In high-energy x-ray beams, the double hit process is the dominant mechanism that renders the gains on EDR2 film developable. As a result, in the dose range that is commonly used for film dosimetry for IMRT, the sensitometric curves of EDR2 films cannot be approximated as a linear function, $\mathrm{OD}=c^*D$. From percentage depth doses and sensitometric curves at different depths and field sizes, we conclude that for both EDR2 and XV films there is no significant field size and depth dependence for field sizes up to $10\times10\ \mathrm{cm}^2$ (at 10 cm depth) and depths up to 20 cm (at field size $5\times5\ \mathrm{cm}^2$). No dose rate effect was observed in the ranges studied in this work. In most cases, the EDR2 film can be used to verify IMRT dose distributions using clinical daily fraction doses delivered by SMLC.

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