Dosimetric performance of an enhanced dose range radiographic film for intensity-modulated radiation therapy quality assurance

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Film-based quality assurance (QA) is an important element of any intensity modulated radiation therapy (IMRT) program. XV2 film is often used for IMRT QA, however, it has saturation and energy response limitations which hinder accurate film dosimetry. A new commercially released ready-pack film has been introduced that has an extended dose range (EDR2), reportedly allowing measured doses above 600 cGy without saturation. Also, this film may have less energy dependence due to its composition. The purpose of this paper is to study and compare the two types of film with respect to absolute dose accuracy for IMRT plans, percent depth dose accuracy for square fields between 2 and 20 cm, ability to measure composite plan isodoses and single beam fluence maps for IMRT cases, and sensitivity to processor variations over time. In 19 IMRT patient QA tests, the EDR2 film was able to achieve an absolute dose accuracy of better than 2% vs over 4% for XV2 film. The EDR2 film was able to reproduce ionization chamber and diode-measured percent depth doses to 20 cm depth generally to within 1% over the range of field sizes tested compared to about 10% for the XV2 film. When compared to calculations, EDR2 film agreed better than XV2 film for both composite plan isodoses and single beam fluence intensity maps. The EDR2 film was somewhat more resistant to processor changes over time than the XV2 film, with a standard deviation of dose reproducibility of less than 2% compared to 6%, respectively. [DOI: 10.1118/1.1500398]

Key words: film dosimetry, intensity modulated radiation therapy, quality assurance

INTRODUCTION

Intensity modulated radiation therapy (IMRT) is a relatively new delivery technology in which, for a given beam direction, many small fields are delivered, each potentially with differing monitor units (MU), to produce the required variations in intensity throughout the volume of interest. In combination with other beam directions, these intensity-modulated fields are expected to produce the prescribed dose to the target while not exceeding the specified doses to the organs-at-risk. Because of the added complexity of this type of delivery, patient specific quality assurance procedures are employed to assure that the calculation of the 3D-dose distribution determined by the treatment planning computer agrees with the dose distribution actually delivered. Although these quality assurance procedures are still developing, the typical set of measurements involves irradiating a phantom with the entire beam-set of each patient plan. One obtains an absolute dose measurement with an ionization chamber at one or more points and at least one isodose distribution measurement using films. These measurements are then compared to the treatment planning system's calculations in the same phantom. Ideally, the phantom irradiation should deliver the same MU as the patient treatment for one fraction to accurately test the ability of the planning system to correctly calculate and the delivery system to accurately deliver the treatment.

A commonly used film for two-dimensional photon beam dosimetry, XV2 film (Eastman Kodak Co., Rochester, NY), is available in ready-peak form and has been used for film dosimetry purposes for many years. However, it suffers from several serious limitations that can hamper the accuracy of the measurements made for IMRT QA.[1–7] Most importantly, it will begin to saturate at doses of less than 100 cGy, or about one-half the full fraction dose typically used in radiotherapy. Although one can scale down the dose and thus the monitor units of a plan to stay within the sensitive range of XV2 film, the multileaf collimator leaves will be required to move faster for the QA test of the dynamic plan than when the patient is actually treated. Also, for the Siemens linear accelerator, only integral MU values are permitted. When the MU are scaled down, nonintegral MU will be rounded off to integers, causing a potentially large percentage difference in the MU for each segment used for QA compared to that used to treat the patient. For example, if 4.4 MU are required for one segment, but the system rounds off to 4 MU, 10% less dose will be delivered through that segment. Finally, linear accelerators can have stability problems when delivering less than 2 MU per segment, which may be required if MU reduction is employed.[8–10]

One of the limitations of photon beam film dosimetry exhibited by XV2 film is the overestimation of percent depth dose, especially for depths greater than 10 cm and field sizes greater than about 7 cm×7 cm. This is due to the silver content in the film, which causes an increase of photoelectric interaction for the low energy scattered radiation in the field, producing an enhanced film response.[1–7] Depending on the degree of error caused by this energy dependence, the ability to accurately measure isodoses for IMRT QA will be affected. XV2 film has also been used for absolute dose measurements as a supplement to ion chamber or thermoluminescent dosimeter (TLD) measurements. Reports in the literature are contradictory as to whether XV2 film can be used to make absolute dose measurements for treatment plan evaluation with an accuracy of better than 5%.[1,3,7,11,12]

Using XV2 film for parallel photon irradiation (the film plane is aligned with the central axis) to obtain percent depth dose data, one is required to calibrate the film in this geometry to correct for the known over response as a function of depth.[2,3] If the beam to be measured were directed perpendicular to the film, as for studying beam profiles, then the calibration film set would typically be acquired in this same geometry.[2,5,6,7] To be precise, one would have to create a calibration data set for a range of fields sizes, depths and film orientations as the energy dependence effect varies with all these parameters.[4–7] The dilemma facing the physicist performing IMRT plan QA is that beams from noncoplanar plans irradiating a film in any orientation and coplanar beams irradiating a film oriented other than in an axial plane are incident on the film at oblique angles. For XV2 film, neither calibration geometry is optimal. If a film were found to have minimal energy dependence, then instead of the current practice of needing to acquire both perpendicular and parallel calibration films sets to be applied depending on the geometry of the tests to be analyzed, one set could be used for all tests regardless of field size, depth, or beam angle. Although radiochromic film is insensitive to the presence of low energy scattered radiation in megavoltage photon fields, its accuracy is hampered by the approximately 6–15% dose nonuniformity which must be corrected for, the relative insensitivity requiring a large MU multiplication for IMRT QA in order to produce readable optical densities, the need for special handling, and it is 15 times as expensive as XV2 film.[13,14]

In the first half of 2001, Eastman Kodak released a new ready-pack film with enhanced dynamic range called EDR2. The composition of this film as reported by Kodak is different than XV2 film in that the EDR2 AgBr grains are 1/10 the size and more uniform in shape than the XV2 grains. In addition, the silver content of EDR2 is about one-half that of XV2, significantly lowering the sensitivity of the film.[15] The result is that the EDR2 film can be exposed to doses of at least 300 cGy, the highest dose tested in this study, without becoming saturated. Due to the reduced silver content and smaller grain size, the energy dependence problem might be reduced as well.[15] These two improvements together could make for a superior film medium for IMRT QA.

In addition, it is generally accepted that XV2 film dosimetric accuracy is a strong function of the stability of the film processing used.[16,17] The ability to impose processor QA standards that exceed that required for imaging in order to improve film dosimetry results may be impractical at many institutions.

The ideal film for QA of fractionated IMRT treatments would be able to measure absolute dose with an accuracy of less than 2%, register dose independent of photon energy, be sensitive to doses between 5 and 250 cGy, be linear in this dose range, and be relatively insensitive to variations in film processing. The purpose of this paper is to report on the comparison between XV2 and EDR2 film with respect to these dosimetric features when used for IMRT QA.

MATERIALS AND METHODS

Dose delivery

A Varian 2100C linear accelerator with the 120 leaf multileaf collimator (MLC) operated in 6 MV x-ray mode using step and shoot delivery at 400 MU/min was used for all irradiations. The mean equivalent square field jaw size (stationary during MLC leaf motion) was 8 cm, with a range of 3 cm to 13 cm. Between 5 and 9 coplanar (4/19 cases) and noncoplanar (15/19 cases) beams were used. When monitor units were reduced for XV2 film irradiation, the monitor units per segment were never less than 2. The Varian accelerator control software permits delivery of nonintegral MU's.

Film dosimetry

The same batch of 10 inch×12 inch EDR2 and XV2 film and their calibration files were used throughout this study. A Kodak X-omat film processor in the Radiology department was used throughout following the manufacturer's suggested daily QA procedures.[18] These procedures allow a daily variation in the speed and contrast index of up to 0.15 units from nominal values of 1.2 and 1.75, respectively. A Vidar 16 bit Dosimetry Pro film scanner was used to scan all films with a resolution of 0.178 mm and the RIT (Radiological Imaging Technology, Colorado Springs, CO) 3.11 software was used to analyze them. A calibration data set for each film type was acquired by placing a sheet of each film under a 1.5 cm thick slab of solid water, with 20 cm of solid water underneath. In preliminary testing of both EDR2 and XV2, it was determined that the film dose 1.5 cm outside the beam edge of a 10 cm×10 cm field at 1.5 cm depth (d-max) was only 1% higher than the water scanner data, suggesting that at this depth low energy photon contamination from head scatter is no more than that from phantom scatter at 10 cm depth, which for XV2 film produced a 5% over response. The films were perpendicularly irradiated at each of the four corners of each film with a 7 cm×7 cm field. The MU's required to deliver a given dose was calculated by dividing the desired dose by the output factor for the 7 cm×7 cm field. First a single corner was irradiated with 100 cGy and the dose to the other three corners measured. The approximately 1% dose contribution from irradiation of each corner to the others corners was used to correct each measured dose. Each corner was given a different dose so that 16 to 20 dose points were obtained using 4 or 5 films. For each type of film, the doses were incremented by 5 or 10 cGy starting from 0 up to about 100 cGy followed by approximately 20 cGy increments ending at 300 cGy for the EDR2 film and 177 cGy for the XV2 film. This perpendicular irradiation geometry was chosen for two reasons: (a) so that subsequent parallel irradiation percent depth dose over estimation would not be hidden by the film calibration process, and (b) the IMRT plans studied would use either coplanar or noncoplanar beam sets, so that neither parallel nor perpendicular calibration geometry would be correct in all cases.

Ionization chamber dosimetry

A PTW N30001 0.6 cc ionization chamber with Keithley 35040 digital electrometer was used for all isocenter absolute dose measurements. RMI 457 (Gammex, Inc., Middleton, Wisconsin) solid water was used for phantom material.

Treatment planning

The Nucletron Plato treatment planning system with inverse treatment planning (ITP) module for IMRT using 15 level step and shoot intensity modulation was used for all cases. During commissioning, the Plato treatment planning computer was found to accurately calculate the penumbra across an MLC edge for single 2 cm$\times$2 cm fields to within 0.5 mm, the depth dose at 10 cm depth within 1%, and the absolute dose at 10 cm depth to within 1%. Also, for IMRT plans, the ion chamber-measured isocenter dose agreement with Plato was 0.999 ± 0.153. This excellent calculation accuracy persuades us to believe that plato isodoses for IMRT plans are accurate.

The following tests were made to compare the performance of the two types of film:

(a) Energy dependent tests using parallel irradiation.
(b) Absolute dose accuracy for 19 IMRT patient plans.
(c) Relative dose agreement with the planning system for 8 IMRT patient plans.
(d) Low dose accuracy and intensity map agreement with that calculated by the planning system for 6 IMRT fields.
(e) Changes in absolute dose accuracy over time that may be caused by variations in film processor conditions.

Energy dependence

In order to study the energy dependence of each film, a phantom made of 30 cm$\times$30 cm slabs of solid water were laid flat and parallel to the couch top. The edge of the ready-pack envelope was folded over carefully after feeling for the edge of the film. The film was then taped down on top of a 14 cm thickness of solid water with the folded edge over the front edge of the phantom and another 14 cm of solid water was then placed on top of the film. The weight of the solid water on the film provided sufficient uniform compression. All the slabs of solid water were aligned with each other and the front edge was aligned with the sagital room laser. The entire phantom was leveled and the couch was positioned so that the isocenter was in the plane of the film at its front edge. The gantry was rotated to a lateral position (gantry 270 ± 0.5 degrees) so that the beam entered the phantom at the front edge of the film. Field sizes of 2 cm$\times$2 cm, 4 cm$\times$4 cm, 7 cm$\times$7 cm, 10 cm$\times$10 cm, and 20 cm$\times$20 cm were used to irradiate each film separately. For the EDR2 film, a dose of 200 cGy to a depth of 1.5 cm (d-max), about the dose for one fraction of an IMRT treatment, was used for each irradiation. For the XV2 film, d-max doses of both 40 and 90 cGy were used. Forty cGy gives about the same optical density as 200 cGy to EDR2 film while 90 cGy was chosen because this dose would be obtained if a twofold MU reduction were applied to the IMRT plan. This monitor unit reduction factor was chosen as a trade-off between the desire to obtain an optical density below 2.5 in the QA test and the benefit of minimizing the change to the patient plan that would be used to QA the treatment. Even at 90 cGy, an optical density of 2.4 is obtained for XV2 film, which is not on the linear portion of its H and D curve and is therefore susceptible to larger variations in inferred dose due to varying processor and scanner conditions than for smaller doses. The calibration film set described above and the energy dependence film set were irradiated, processed and scanned at the same time. After the films were scanned, the calibration data were applied to convert the film scanner units to dose. Doses were normalized to the maximum for each film. The locations of the maxima were verified to be within 1 mm of the known location. Central axis depth doses was calculated by the RIT software for each film up to a depth of 24 cm and compared to the known percent depth doses acquired with an ionization chamber or diode scanned in a water phantom.

Absolute dose accuracy

19 IMRT plans used for patient treatment were used to compare absolute dose accuracy of the two films to that calculated by the Plato treatment planning system. The prescribed doses were 180 or 200 cGy. Each plan was applied to a 30 cm$\times$30 cm$\times$10 cm solid water phantom within the Plato treatment planning system, with the isocenter at the geometric center of the phantom. Mean absolute isocenter dose was calculated over the volume of a 0.6 cc ionization chamber for each plan and compared to the ion chamber dose measurement. Plato also calculated isodoses in a coronal plane in the phantom 1 cm anterior to the isocenter.

This same phantom was irradiated with each plan with the ion chamber at the isocenter at the same time that either a sheet of XV2 or EDR2 film was placed inside the phantom in the Plato-calculated coronal plane 1 cm anterior to the isocenter (Fig. 1). In this way, the absolute dose to isocenter is found from the ionization chamber reading during each film irradiation, avoiding potential 0.5–1.0% dose delivery differences which can occur between repeat irradiations. The isocenter and the film absolute dose reference point 1 cm anterior to isocenter were always in the same nearly homogeneous dose region. The open-field cross-hair image was marked by pinpricks on each film to serve as registration marks for later comparison to the plan isodoses. The monitor units from the plan were reduced by a factor of two for the XV2 film irradiation while there was no monitor unit reduction for the EDR2 film.

To determine the degree of perturbation of the film dose due to the presence of the chamber, a single PA open field was used to irradiate the phantom with chamber and film in place. Because there was less than a 2.5% variation in the uniformity of the film dose in the shadow of the chamber, the net effect from 5 or more well spaced fields would be less

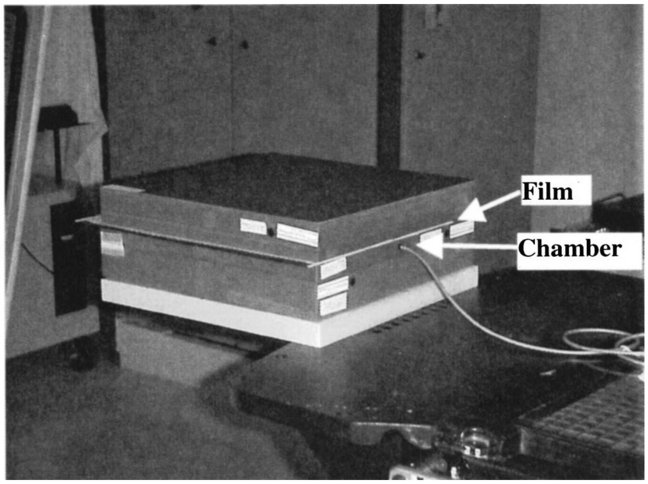

FIG. 1. Solid water phantom used for absolute and relative dose measurements with ionization chamber and film present.

than 0.5% over an area less than 1 cm wide for each beam first passing through the chamber before striking the film. This small perturbation is equally present during testing of both films types and is no more than the potential repeat-irradiation dose constancy error which would be obtained if separate chamber and film irradiations were used.

For every phantom irradiation, a separate sheet of each type of film was given a dose within 10% of the calculated isocenter dose for that plan through a 10 cm×10 cm open field with the film at 1.5 cm depth with full backscatter provided. These absolute dose reference films were processed and scanned together with the IMRT plan QA films. The ratio of the known dose to the RIT calculated dose from the reference films was then multiplied by the RIT calculated absolute dose at the reference point on the plan films. This process was intended to correct the reference point absolute dose on the plan films for processor and scanner variations between the time of film calibration and IMRT QA plan tests. In the 19 plans tested, the mean and standard deviation of the ratio of the ion chamber-measured to Plato-calculated volume-averaged isocenter dose was 0.999 ± 0.0153. Because of this excellent isocenter dose agreement, the Plato-calculated dose at 1 cm anterior to isocenter, corrected by this ratio, typically within 1.5% of unity and separately determined for each case, was taken as the reference absolute dose for comparison to the two films tested. This chamber-corrected planning system coronal plane calculated dose was compared to the XV2 and EDR2 film measurements of dose to the same point. The dose difference for each case is $(D_{\text{film}} - D_{\text{calculated}})/D_{\text{calculated}} \times 100\%$.

Relative dose agreement with Plato

In 8 of the 19 cases, the isodoses calculated from the planning system and the RIT software were normalized to the same value, plotted with sufficiently many levels to resolve 3 mm spatial differences and scaled identically so that they could be overlaid using the registration marks for visual comparison. A 1 cm×1 cm determination grid was used to

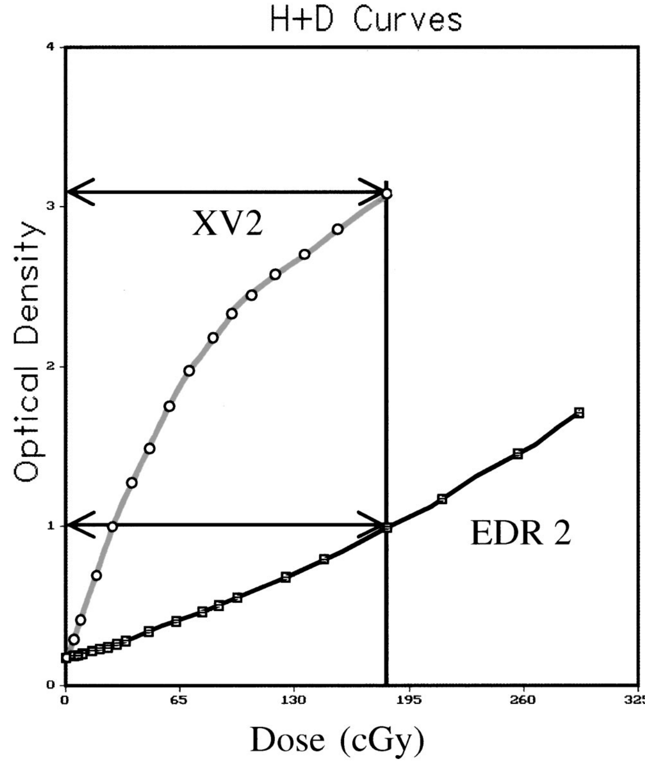

FIG. 2. Optical density vs dose curves with calibration data pints for XV2 and EDR2 film.

compare the isodose values from the planning system and the film measurement in the 20–90% dose region over at least one-half of the irradiated area. This method provided 15–35 comparison points.

Low-dose accuracy and intensity map agreement with Plato

When more than five beams are being used in a plan, each beam may contain intensities ranging from a few cGy to over 50 cGy. At the upper end of the range, either film should be capable of accurately measuring the dose based on the optical densities for these doses found on their respective dose vs optical density curves (Fig. 2). However, with less than 0.1 net optical density units at 30 cGy, the EDR2 film/scanner combination may be unresponsive at these and lower doses, unlike XV2, potentially because of a high signal-to-noise ratio. In order to determine how well the two films perform at very low doses, two tests were performed. First, both films were given 3, 5, 7.9, and 11.8 cGy doses at *d*-max in a phantom by 7 cm×7 cm fields irradiated perpendicular to the films. The films were processed and scanned together, and the dose determined by the RIT software. Second, for two of the patient plans, calculated and measured fluence map profiles from six of the beams were compared. The doses within the single beams ranged between 3–100 cGy and were from 5–9 beam plans where total fraction dose was 180 cGy. A film of each type was placed on top of a 0.3 cm thickness of solid water with 1.5 cm of solid water on top of the film. The film was positioned at isocenter and the full monitor units for each beam were delivered perpendicular to the films. This setup was used to reduced phantom scatter yet provide full buildup, which is a close approximation to conditions under which the fluence maps are calculated. The Plato-calculated fluence maps were imported into the RIT software for direct comparison to the films taken for each beam. Profiles were calculated from the film measurements and compared to Plato-calculated fluence map profiles for the six cases. Each profile was normalized to the Plato maximum dose. The second-to-highest peak and the two lowest troughs were used as comparison points.

Effect of film processor variation

Over the period of this study, starting with the day the calibration films were obtained, seven measurements were made about one weak apart with each film type in which doses of 100%, 75%, 50%, and 25% of either 90 cGy or 180 cGy for the XV2 film and the EDR2 film, respectively, were given, matching the doses used in the IMRT QA tests, using the same setup as for the calibration films. Each film was processed and scanned together and the calibration file from the beginning of the study was applied to correct optical density to dose. Constancy of scanner output was tested with a step wedge filmstrip and found to be within 1.0% over the duration of the study. The average difference between the known and measured dose at each level is the mean error.

RESULTS

Film dynamic range

Figure 2 shows the sensitivity of EDR2 compared to XV2 in terms of optical density vs dose. One can see that at the typical radiotherapy fraction maximum dose of 200 cGy, the optical density of EDR2 film is close to 1 while it is about 3, or near the saturation level, for XV2. One can also see that the EDR2 curve only diverges slightly from linearity over the entire range plotted. At the other end of the EDR2 curve, the average net optical density for a typical single beam fluence map is only about 0.1 units while for XV2 film, an optical density close to 1 is obtained. However, due to the ability of the Vidar 16 bit scanner to resolve over 65 000 shades of gray, 50 000 of which are in the region below optical density of 1.0, these small optical density differences on the EDR2 film are interpretable as seen in Fig. 3. Here, the depth dose curve for a 10 cm×10 cm parallel film given 10 cGy at *d*-max is compared to the ion chamber-in-water measurements, shown as dots. Although noisy, the EDR2 film measurement gives a good approximation to the known values, down to about 3 cGy.

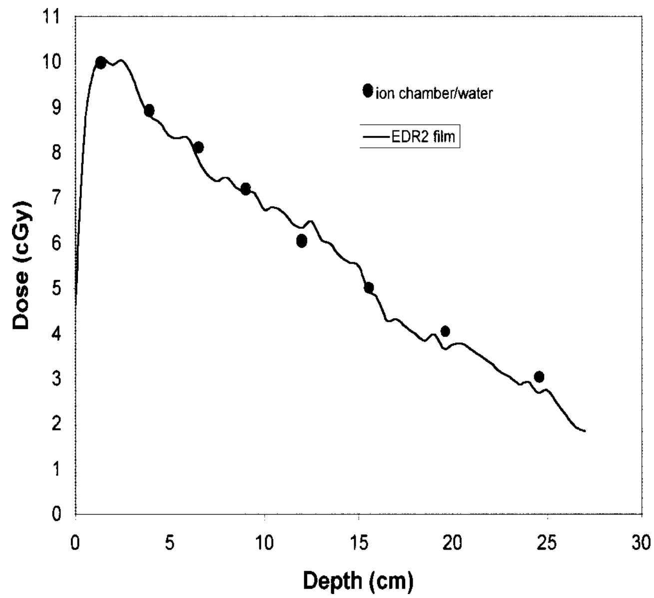

FIG. 3. Percent depth dose curve for EDR2 film for a 10 cm×10 cm field size with 10 cGy given at *d*-max. Solid line is film measurement and dots are ion chamber measurement.

Energy dependence

The comparisons of percent depth dose for square fields of 2, 4, 7, 10, and 20 cm are shown in Figs. 4(a)–4(e). The data for XV2 film for both 40 cGy and 90 cGy to *d*-max are shown together with the EDR2 and water-scanned data. For the XV2 film, there is a trend towards diverging above the water-scanned data at ever-shallower depths as the field size increases. The 40 cGy XV2 films agreed slightly better with the water-scanned data than the 90 cGy dose for all field sizes tested which might be explained by the lower optical density of the former being less susceptible to processor and scanner variations. For the 2 cm×2 cm field size, the 40 cGy XV2 film matched the diode-in-water data within 2% to a depth of about 15 cm and was within 5% up to a depth of about 19 cm, after which the film data diverges above the diode data by more than 10%. The EDR2 film data was within 2% for all depths measured. The 90 cGy XV2 data was within 5% of the diode data to a depth of 7 cm, after which it further diverges to 15% above the diode data. The 4 cm×4 cm curves show that both XV2 dose curves are within 5% of the ion chamber curve up to a depth of about 17 cm and by 20 cm depth, they are about 10% above the ion chamber curve. The EDR2 film data was within 1% for all depths. For the 7×7, 10×10, and 20×20 cm field sizes, both dose curves for the XV2 film are within 5% of the ion chamber curve up to 13 cm, 11 cm, and 8 cm, respectively. The EDR2 film data is within 1% for all depths for the 7×7 and 10×10 cm fields sizes. For the 20×20 cm field size, except for a region between 8 and 14 cm where the difference is less than 4%, the EDR2 film data is within 2% of the chamber data for all other depths.

Absolute dose accuracy

In 19 plans measured with EDR2 film, the mean difference between the measured and calculated dose to the point 1 cm anterior to the isocenter was $-1.88\%\pm1.81\%$. In 11 of the 19 plans where XV2 film was tested, the mean difference was $-4.15\%\pm4.37\%$ (Fig. 5). For the XV2 film measurements where the MU from the plan were halved, the ionization chamber reading was always within 0.3% of one-half the reading obtained with the full MU.

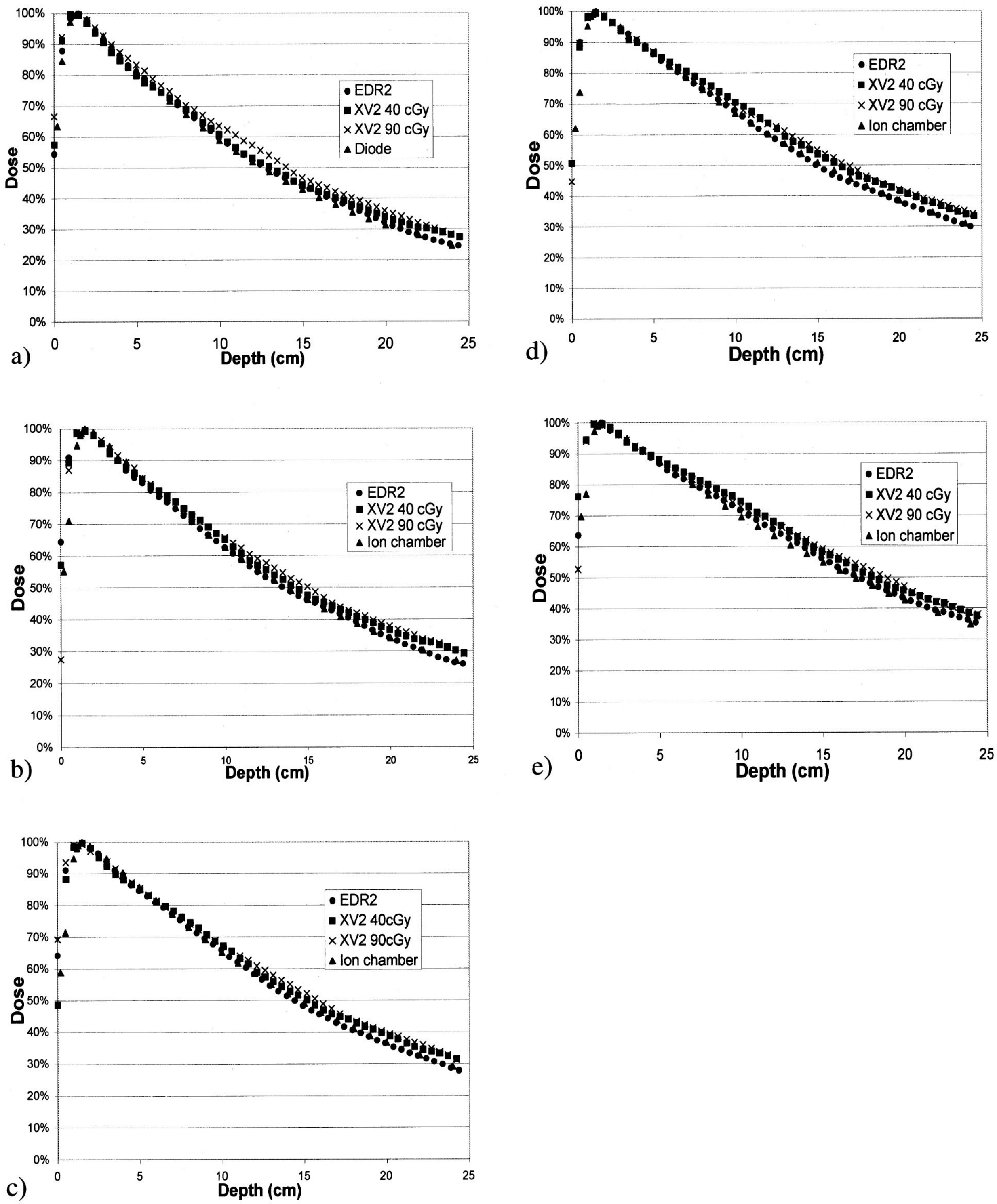

FIG. 4. (a)–(e) Percent depth dose curves measured with EDR2, XV2 and ion chamber for square fields with side, (a) 2 cm, (b) 4 cm, (c) 7 cm, (d) 10 cm, (e) 20 cm.

Relative dose agreement with Plato

In eight cases, the isodoses for each film type were compared to the calculated isodoses and distance to agreement was measured for the 20%–90% of isocenter dose region. The eight-patient mean distance between the EDR2 measured and Plato-calculated isodoses was 1.39 mm±0.23 mm, while for the XV2 film the mean distance was 2.33 mm

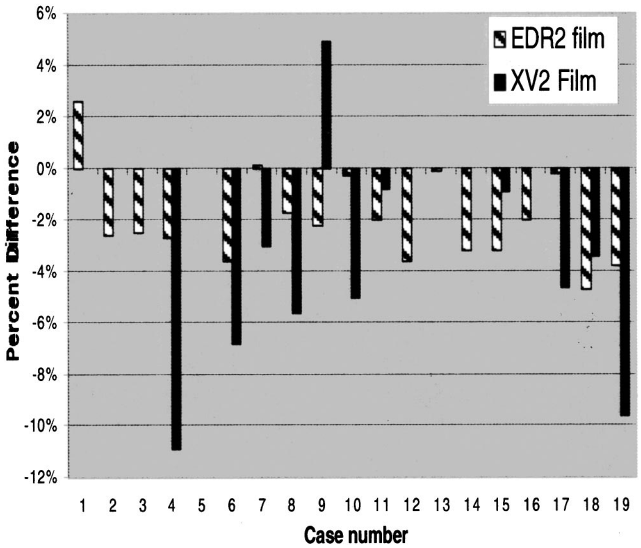

FIG. 5. EDR2 and XV2 film measurement of absolute dose as compared to an ionization chamber. The mean ±SD for EDR2 film is −1.88%±1.81% and −4.15%±4.37% for XV2 film.

±1.01 mm. Using an analysis of variance test, the EDR2 film result was significantly different than the XV2 film result in five out of the eight cases (Table I).

Low-dose accuracy and intensity map agreement with Plato

Each film type was given 3, 5, 7.9, and 11.8 cGy. The film dose errors were +0.5, −1.6, +1.1, and −0.5 cGy and +1.7, +2.1, +3.1, and +3.1 cGy, respectively, for EDR2 and XV2 film.

Table II shows the comparison of the two films against the calculated profiles at three low-dose points—averaging about 39 cGy, 28 cGy, and 6 cGy for six IMRT fields. The absolute doses in cGy are shown for the Plato calculation and for each film. The mean difference between the EDR2 film and calculation was consistently less than for the XV2 film. The EDR2 film agreed better with the calculation than the XV2 film at the 39 cGy and 28 cGy doses by 5% and 10%, respectively. At the 6 cGy average calculated dose, the measured dose difference ranged from 1 to 6 cGy and 2 to 11 cGy for EDR2 and XV2, respectively.

Effect of processor variation

Table III shows the effect of processor variations on the readings from each type of film for 7 weekly measurements. The maximum dose given to each film is normalized to 100%. The 75% dose level is faithfully reproduced for both types of film to within about 1%, however, the 50% and 25% doses have mean errors of 5.6 and 8.4%, respectively, for the XV2 film. The EDR2 film exhibited no error at the 50% does level, and a 5.9% mean error at the 25% dose level. In terms of absolute dose deviation at the 100% dose level, the XV2 film had a mean error of +6.6%±6.0% while the EDR2 film error was −3.7%±1.8%.

DISCUSSION

IMRT QA demands that film dosimetry be able to accurately measure dose between about 5 and 250 cGy over a wide range of depths, beam directions and irradiated areas. The 5 cGy region corresponds to cold regions near critical structures found on single beam fluence maps and the 250 cGy region corresponds to maximum doses associated with typical prescription doses in the composite of all beams in a plan. In between are the doses that are found on isodose plots measured for the composite plan where doses of 10%–130% of the prescription dose are of interest. In addition, both coplanar and noncoplanar beams may deliver these doses. Accuracy for composite plan film dosimetry has been found adequate for radiosurgery field sizes.[11] Isodoses for single larger fields, IMRT or conventional, have been measured perpendicular to the beam with reasonable accuracy.[17,19] Accuracy over the remarkably large range of conditions present for IMRT QA has eluded physicists performing film dosimetry.[1–6]

In this study, the new EDR2 film was compared to a commonly used film, XV2, over the range of measurements done for IMRT QA. Due to the smaller, more uniform grain size and lower siver content, EDR2 has the potential to perform better in terms of energy response. Also, because of its higher saturation dose, EDR2 could be used without monitor unit reduction, providing for a measurement made under exactly the same conditions as for actual patient treatment. This eliminates uncertainties introduced by forcing the MLC leaves to move faster (for dynamic treatments) during QA than for patient treatment, rounding off nonintegral MU to integers, as well as using less than two monitor units per segment, which may not provide time for some linear accelerators to fully stabilize the dose output and uniformity.[8–10] In this work, step and shoot rather than dynamic MLC delivery was used and dose differences measured for full versus half-monitor unit irradiations (never less than 2 MU per segment) were found to be less than 0.3%. It has been shown that the beam flatness and symmetry for the Varian 2100C is affected by less than 1% for 2 MU exposures.[20] Thus, because of the IMRT delivery hardware used in this study, the beam instability effect of small MU for the XV2 film was

TABLE I. Distance to agreement between EDR2 and XV2 film isodoses compared to Plato calculated isodoses for eight patients. Mean ±SD in mm.

	Patient 1	Patient 2	Patient 3	Patient 4	Patient 5	Patient 6	Patient 7	Patient 8
EDR2	1.35±0.89	1.32±0.74	1.21±0.73	1.68±0.64	1.72±1.04	1.75±.127	1.41±1.01	1.18±0.99
XV2	1.48±0.90	2.38±1.87	1.24±0.86	2.11±1.15	4.48±4.65	2.19±1.15	2.89±2.11	1.91±1.05
p value	0.512	0.003	0.840	0.004	0.009	0.225	0.005	0.002

TABLE II. Dose agreement between EDR2 and XV2 film profiles compared to Plato profile calculation for six fluence maps (fields irradiated perpendicular to beam). The comparison is shown for one relatively high (2nd peak) and two relatively low doses (troughs 1 and 2) in each profile. The last row is mean percent deviation of film to plan except for trough 2, which is the range of the film-plan deviation.

		Second peak			Trough 1			Trough 2		
		Plato cGy	EDR2 cGy	XV2 cGy	Plato cGy	EDR2 cGy	XV2 cGy	Plato cGy	EDR2 cGy	XV2 cGy
Patient 1	Field 1	29	28	28	22	22	23	9	9	11
	Field 2	21	21	27	18	18	22	4	9	11
	Field 3	51	54	54	29	33	36	4	10	13
Patient 2	Field 1	41	45	45	36	38	41	11	11	14
	Field 2	62	56	62				5	10	16
	Field 3	27	28	31	35	36	39	3	4	9
Mean % dev.			0	+5.1		+3.6	+14.3		1–6	2–11

negligible so that differences seen between the two film types is substantially due to their intrinsic features. XV2 film dose measurement error would be expected to worsen when MU reduction is required for other linear accelerators that are less stable at low MU and/or when using dynamic delivery.

The suite of tests performed on the two film types were designed to indirectly determine and compare their energy response as seen by their ability to reproduce depth dose data, their ability to accurately measure absolute dose, isodoses, and very low doses in an IMRT QA setting, and sensitivity to processor variations over time. No special film processor QA was performed beyond the standard QA recommended by Kodak for diagnostic radiology films. The dose vs optical density data set obtained at the beginning of the study was used throughout on the same batch of film of each type. To attempt to remove processor variation in the determination of absolute dose accuracy, a reference film was taken for each film type for each plan evaluation.

The EDR2 film did in fact reproduce percent depth doses generally to within about 1% for a wide range of field sizes and depths despite the fact that its calibration dataset was obtained in the perpendicular geometry with a single field size. The XV2 film percent depth dose data rose about 10% above the ionization chamber data for field sizes less than 10 cm square and depths of about 12 cm, in agreement with other reports.[1,3,7,16] Although the 40 cGy at *d*-max percent depth dose data agreed somewhat better with chamber data for the smaller field sizes, using this dose for IMRT QA would require about fivefold MU reduction, which may introduce dose delivery errors due to beam instability, dose nonlinearity, leaf velocity errors, and MU round-off.

TABLE III. Mean percent dose differences between EDR2 and XV2 and the known dose at 25, 50, 75, and 100% of a reference dose for 7 weekly measurements. The 100% dose was 180 cGy for EDR2 and 90 cGy for XV2. The percent dose difference and standard deviation for the 100% doses are given in the last two columns.

	% Normalized dose differences					
Dose level	25%	50%	75%	100%	100% dose deviation	SD
EDR2	−5.90	0.00	−1.10		−3.7%	1.80%
XV2	8.40	5.60	0.90		6.6%	6.00%

For the IMRT QA plans, the absolute dose difference between the ionization chamber measurement and XV2 film was found to be over 4% with a greater than 4% standard deviation compared to less than 2% dose difference and standard deviation for EDR2 film. The XV2 film performance in this study is as expected based on reports of others in the literature.[1,3,7,11,12] The high fidelity of percent depth dose along with the more consistent dose readings despite the processor variations occurring over time are probably responsible for the excellent absolute dose performance of EDR2, about as good as TLD. For both EDR2 and XV2, the mean film-measured dose was less than the ionization chamber-corrected calculated dose. The increased percent depth dose and the negligible film dose enhancement just outside the field at *d*-max measured with XV2 relative to data taken with a water-scanner suggest that low energy scatter and, therefore, film over-response, is higher at depth than at *d*-max. That the measured XV2 film-to-chamber dose deficit was over 4% cannot be explained by the fact that the calibration depth was 1.5 cm rather than 10 cm. If the calibration films had been taken at 10 cm depth, the higher response to the low energy radiation would have resulted in any given dose being associated with a higher optical density. The resultant calibration curve would produce lower doses for a given optical density, thus lowering the film-measured coronal plane IMRT plan dose and further widening the film-chamber dose difference. One possible explanation for the systematic negative film-chamber dose differences is that to the extent the reference film field size of 10 cm×10 cm was larger than the irradiated area of the IMRT plan, the reference film measured dose is too large. For XV2 film, the difference between the measured dose at *d*-max for a 10 cm×10 cm field and a 7 cm×7 cm or 2 cm×2 cm field given the identical dose is about +3% and +5%, respectively. For the IMRT plans in this study, the range of field sizes was 3 to 13 cm, however, it is not clear to what irradiated area the film is responding. Dividing the raw XV2 film IMRT plan dose by a value that is 3–5% lager than necessary can explain the systematic underreading seen with this film type. The relative differences based on these field sizes are less than 2% for EDR2 film. Although the performance of any film can theoretically be optimized by carefully choosing the conditions for irradiation that favor the particular type of film and performing a film dosimetry system calibration along with each test session, for many physicists, this may not be practical. For testing noncoplanar beam plans, the optimal choice of film calibration geometry is unclear. In this study, a practical and consistent calibration and irradiation methodology was employed for both film types that was designed to demonstrate differences between them with regard to dynamic range, energy response, and sensitivity to processor variations. Note that the performance of XV2 film used with other delivery systems may be worse than in this study which used the Varian linear accelerator that can deliver fractional MUs and has good dose linearity and beam uniformity at low MUs and where IMRT deliver was by step and shoot rather than dynamic mode.

There is no gold standard dosimeter for measurement of isodoses produced by IMRT fields. TLD chips and rods have dimensions of 1–3 mm, which are similar to the size of the distance-to-agreement discrepancies one looks for in high dose-gradient areas and can only give the dose at a limited number of points. The fastest radiochromic film (GAFCHROMIC HS, International Specialty Products, NJ) requires monitor unit multiplication by a factor of 2–5 that, for dynamic plans, means one is testing a different plan than that used to treat the patient.[14] Because there is no commercial software available to make the necessary corrections for radiochromic film nonuniformity, most physicists would not be able to accurately use this type of film for IMRT QA. In this study, the isodose comparison between the two films showed that the EDR2 film agreed significantly better with the treatment planning computer than XV2 film in five out of eight cases.

While the low sensitivity of EDR2 film is an advantage at high doses, it may be a disadvantage at very low doses, as are found in fluence distributions for single beams from multibeam plans. Here, doses close to zero are sometimes desired to protect normal structures. Film dosimetry can provide proof that the treatment planning computer is correctly creating MLC segments and the MLC/linac control system is correctly operating to produce these low doses. To determine the applicability of EDR2 and XV2 film to this QA test, doses between 3 and 12 cGy were given to each film, and the measured doses determined. Here, the EDR2 film performed better than the XV2 despite the lower optical densities produced on the EDR2 film. In addition, when EDR2 film was irradiated parallel to the beam with 10 cGy at d-max, the percent depth dose curve generated approximated the ionization chamber data down to 3 cGy. Perhaps the superior ability of the 16-bit scanner to resolve low optical densities can partially explain this finding. In the actual comparisons of beam fluence maps delivered to the films, the EDR2 film overestimated the low doses in profiles by less than the XV2 film, and was in better agreement with the Plato calculation. Although the films were irradiated to minimize scatter (to approximate the conditions under which the PLATO system calculates fluence), filling-in of the calculated low dose troughs on the films can be expected. Looking at Table II, we see that the EDR2 film could measure doses in single beam fluence maps below 10 cGy with mean absolute dose differences of 3 cGy compared to 6 cGy for XV2 film. Taken together, these data indicate that EDR2 film scanned by a 16-bit scanner is capable of providing useful dosimetric information over the very broad range of doses encountered in IMRT plans.

One important practical matter in film dosimetry is that it, like any dosimeter, requires efforts to assure the stability and continued accuracy of its readings. Ideally, the calibration of dose vs optical density data is performed at the time of each patient's QA study. However, this is time consuming and not practical for many physicists. In this study, the film processor QA was performed as recommended for diagnostic radiology, and the film scanner QA was done monthly to check that the step wedge continued to produce the same density, within 1%, as the day the study started. Having performed only these simple procedures, a determination was made as to how variable the film dose readings were for 25, 50, 75, and 100% of a reference dose (matching the IMRT QA plan dose) given repeatedly to each film type over the duration of this study. The optical densities produced by these doses ranged from 0.7–2.4 for XV2 and 0.2–1.0 for EDR2. The EDR2 film dose reproducibility was equal to or better than that of the XV2 film at every dose level. Normal day-to-day processor variations that are otherwise acceptable can produce an increase in the high optical density region and a decrease in the low optical density region.[18,21] That there was a systematic error for each film and in different directions indicates that there were processor variations occurring over the course of this study and that each film, being exposed to doses at different ends of their sensitometric curves, responded differently to them. One can apply a correction factor to the measured film dose to compensate for the mean error due to processor variation as long as this factor is constant within user-specified limits. Over the course of 7 weeks, for the EDR2 film as tested in this study, one could simply increase its isocenter dose by 3.7% instead of performing and correcting by the reference film irradiation each session, and only incur an error of 1.8% (standard deviation of the mean error). The XV2 film's 6.0% standard deviation, consistent with other reports of effects of interval processing, is large enough to not warrant this simplification.[22] For the highest degree of dose accuracy for any radiographic film, one should re-establish the sensitometric curve for each measurement session.

CONCLUSION

The QA procedures routinely required for each IMRT patient are more demanding than for any other radiotherapy special procedure. At the same time, tumor and morbidity control still require the same high standard of dosimetric accuracy as for conventional radiotherapy. The most practical and useful dosimeters for IMRT QA remain the ion chamber for absolute dose and radiographic film for relative dose. The commonly used XV2 film has distinct and well-known limitations. A new film, EDR2, was tested and compared to XV2 film in a battery of tests and was found to be superior in all respects. EDR2 is about as good as TLD for absolute dose, nearly unaffected by the presence of low energy photons present in large fields at great depths, and is less sensitive to processor variations. Based on our findings, we believe that EDR2 is the film medium of choice for IMRT QA.

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