Evaluation of a computed radiography system for megavoltage photon beam dosimetry

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Computed radiography (CR) systems have been gaining adoption as digital replacements for film for diagnostic and therapy imaging. As a result, film processors are being removed from service, leaving a void for the medical physicists who use film and processors for two-dimensional megavoltage beam dosimetry. This is the first report to evaluate the ability of a commercial CR reader and storage phosphor plate system to accurately quantitate absolute dose and dose distributions from a 6 MV photon beam. There are potential advantages and disadvantages of current CR systems compared to film systems. CR systems inherently produce a linear dose-response over several logs of dose. However, the barium in the storage phosphor has a higher atomic number than the silver in film, resulting in significant energy sensitivity. The purpose of this work is to fully characterize the impact of these and other features of this CR system relevant to dosimetry. The tests performed and reported on in this study include uniformity of readout across a uniform field, geometrical accuracy, intra- and interday reproducibility, signal decay with time and with light exposure, dose-to-signal calibration, high dose effects, obliquity effects, perpendicular and parallel calibration results, field size and depth of measurement effects and the use of lead filters to minimize them, and intensity modulated radiation therapy quality assurance test results compared to that for film. Practical techniques are provided to optimize the accuracy of the system as a dosimetric replacement for film. © 2005 American Association of Physicists in Medicine. [DOI: 10.1118/1.2012787]

Key words: computed radiography, dosimetry, quality assurance

I. INTRODUCTION

Computed radiography (CR) systems are becoming ubiquitous as digital replacements for film for diagnostic and therapy imaging. As a result, film processors are being removed from service or are poorly quality assured, leaving a void for the medical physicists who use film and processors for two-dimensional megavoltage beam dosimetry. Alternatives to film include electronic portal imaging (EPI) and computed radiography (CR). There has been extensive work done with EPI to enable the resulting image to be calibrated and used dosimetrically, especially for intensity modulated radiation therapy (IMRT) quality assurance (QA) applications. However, a dosimetric characterization for CR has not been previously reported in the literature for megavoltage beams. There have been limited reports studying CR for kilovoltage beam dosimetry. CR systems for radiographic imaging have been commercially available for over 20 years and there have been several reports characterizing CR for imaging attributes, an area which is outside the scope of this report. Inherently, CR is more versatile than EPI in that the CR plate itself is physically film-like so that it can be placed inside a phantom and irradiated from any direction. This versatility lends itself to IMRT QA where one wants to irradiate the phantom containing the dosimeter with all the beams from a plan using the treatment beam angles. The purpose of this work is to characterize a CR system for a range of basic and IMRT dosimetry applications and to report on the suitability and potential accuracy of the system.

II. MATERIALS AND METHODS

The KODAK 2000RT CR System was tested in this study. It is comprised of a laser scanner connected to a PC running acquisition and analysis software. A single Agfa 24 cm × 30 cm CR plate, model MD10, was used for a suite of QA tests while a subset of these tests was conducted on two additional Agfa plates, each from a different batch. The active layer of the CR plate is a photostimulable phosphor (BaSrFBr:Eu²⁺) approximately 300 μm thick. This layer is coated onto a flexible plastic plate 0.9 mm thick. Although still controversial, one explanation of the mechanism by which photostimulable phosphors work is that a fraction of the absorbed energy of the photon beam ionizes Eu²⁺ ions and the electrons are liberated to the conduction band and subsequently trapped at F⁺ centers. An exposed image plate stores a latent image of the radiation dose (in a semi-stable state) consisting of trapped electron-hole pairs in the BaFBr:Eu²⁺ phosphor grains. The information readout is performed by means of a red laser beam (658 nm) that scans across the image plate as the plate is pulled across the path of the laser by rollers. This causes photo stimulated Eu²⁺ luminescence whereby trapped electrons are liberated and recombine with the trapped holes with the emission of light. The quantity of light is proportional to the density of trapped...
electron-hole pairs and thereby to the locally absorbed x-ray dose. The emitted photons are collected by a photomultiplier tube (PMT) that converts the luminescence into an electrical signal. This signal, logarithmically amplified and correlated with the scanning laser spot position, is digitized by means of a 12 bit analog-digital converter and sent to a computer for the reconstruction of the two-dimensional image. A strong fluorescent lamp erases any remaining information in the image plate so that it can be reused. The useful range of the CR system is about four orders of magnitude of dose compared to about three orders of magnitude for Kodak EDR2 film. For a detailed review of storage phosphor physics, see the paper by von Seggern.5

The Kodak 2000RT CR scanner was first recalibrated using Kodak-supplied software modified by the author to produce a uniform scanner unit (SU) readout (equivalent to analog-digital converter units) for a uniformly irradiated plate (PMT uniformity calibration). Three plates, each from a different batch, were used in tests described in this report. The CR plate was always irradiated inside a Kodak 10 in. × 12 in. ready pack envelope, not a cassette. A 0.4 mm layer of lead was placed on either side of the CR plate with 1 cm of solid water between the CR plate and the lead for some of the tests. To produce a highly uniform radiation field across the plate, the envelope containing the plate was placed at a depth of 10 cm (batch 1) or 15 cm (batches 2 and 3) in a 30 cm × 30 cm solid water phantom that had 7 cm of solid water under the plate. The phantom was placed on the floor so the plate was about 2.4 m from the source. The plate was carefully centered inside the solid water phantom. In the original PMT calibration method used for the batch 1 plate, no additional scatter material was placed around the edges of the phantom. The collimator was set to 40 cm × 40 cm and 4 monitor units (MU), less than 1 cGy, were delivered. The plate was removed from the envelope, centered on the scanner feed tray, and run through the scanning process using diagnostic mode (maximum PMT gain). In the new method, used for batch 2 and 3 plates, 5 cm blocks were placed along side each edge while 200 MU, about 30 cGy, were delivered in the same geometry as described earlier. Also, the calibration process was adjusted to allow the scan to be performed with the PMTs in port film mode (PMT gain decreased 100-fold compared to diagnostic mode). At the time of this writing, the ability to perform the PMT calibration scan in port film mode was not commercially available. In each case, the scan was then followed by a scanner calibration process that ultimately determines a PMT uniformity look up table (LUT) used by the scanner to make corrections to subsequent scans as a function of location across the plate. There are two PMTs in the scanner about 10 cm apart center-to-center. The uncorrected scan profile shows two response peaks centered at the location of the PMTs. It is the purpose of the PMT LUT to correct for this intrinsic nonuniformity, along with that of the plate itself. The author’s method used the central 1/3 of the plate’s length to average the SU at each pixel location across the width of the plate instead of the top 1 in. of the plate used by the standard Kodak method. The plate-specific PMT calibration LUT was loaded into the scanner depending on the plate to be used. Each plate was always subsequently read in the same orientation (portrait except where noted) centered within 0.3 cm of the center of the plate feed tray using the calibration LUT created from that plate.

Both the scanner and the Agfa plates are standard and commercially available. Subsequent to the PMT calibration process, the scanner was always operated in port film mode using the low resolution (1024 pixels) setting for all tests. There are 1024 pixels across the 24 cm plate width so that each pixel is 0.234 mm wide. The scanner creates square pixels of this dimension distributed across the entire length of the plate. A 2048 pixel mode was also available. Because the scanner digitizes using 12 bits, there are 4095 SU available between zero and doses of over 500 cGy; zero dose is represented by approximately 4095 SU with higher doses represented by lower SU values. Although SU values have been directly related to log of dose in these results, one could alternatively relate the log(4095/SU) to dose to obtain a more film-like dose response curve which increases with increasing dose. After each readout, the plate was automatically erased by exposure to a fluorescent lamp light source for 30 s. Multiple sequential erasures were not found to be more effective than a single erasure, either of which was found to fully erase the plate, producing a SU value of about 4080. The 15 SU difference from the nominal zero dose value of 4095 is due to an artifact of the scanner calibration process, which subtracts a small offset SU value regardless of dose applied. The scanner was kept powered on throughout this study. After irradiation, the plate was always kept inside the ready pack envelope until readout (except where noted). The readout was performed in a darkened room with the only light present coming from two computer monitors (light level at the scanner measured to be 0.2 lux using an INS DX-200 illumination meter). Plate readout was generally performed 10 min after irradiation (except where noted). In the course of this study, it was determined that a 5 SU difference corresponded to an approximate 1% dose difference at any SU level.

Where square fields were used for determining the SU reading for a particular dose, the SU were found by averaging over a 1 cm × 1 cm central region. The standard deviation of a SU reading for given dose was 2–5 SU over the range of 350–1800 SU. Kodak-supplied image analysis software was used to find average pixel values in a region of interest and Radiological Imaging Technologies V 4.1 software was used to open the unprocessed Kodak DICOM images, calibrate them, and perform profile and isodose analysis. A 16 bit Vidar Dosimetry Pro scanner was used to scan EDR2 or XV films and the RIT software was used to analyze them. In all cases, a Varian 2100C 6 MV x-ray beam was used as the radiation source. This treatment unit is equipped with a 120 leaf multileaf collimator. All IMRT irradiations were done using the step-and-shoot method. The planning system used to calculate dose for IMRT plans was the Nucletron Plato system with the ITP IMRT program. Room light intensity levels were measured with an INS model DX-200 illumination meter.
The following suite of tests were performed on a plate from batch 1:

1. Spatial accuracy
2. Spatial uniformity of response
3. Signal decay with time
4. Signal decay with light exposure
5. Dose-response reproducibility
6. Response degradation with high doses
7. Perpendicular irradiation-calibration and field size dependence
8. Parallel irradiation-calibration and field size dependence
9. CR plate response with incident beam angle
10. Dose-response from 6 to 328 cGy
11. Beam profile agreement versus EDR2 film
12. Perpendicular irradiation of IMRT beam, agreement with XV film
13. Parallel irradiation of composite multibeam IMRT plans, comparison with planning system and EDR2 film.

In addition, tests 2, 3, 4, 5, and 7 were repeated 9 months later using plates from two other batches. These tests were performed to determine the variability of plate-dependent characteristics.

1. Spatial accuracy. A grid of BBs covering a 20 cm × 20 cm area were placed on graph paper and the graph paper was placed directly on the ready pack envelope containing the CR plate. A dose of 100 cGy was given with a 24 cm × 24 cm field centered on the BB grid. The plate was scanned in both portrait and landscape orientations three times and the Kodak-supplied image analysis software was used to get X and Y coordinates of each corner BB. The mean lengths of the sides and diagonals of the 20 cm × 20 cm square were computed from the measured coordinates and compared to their actual values.

2. Spatial uniformity of response. A radiation field was created to uniformly irradiate the CR plate. A 40 cm × 40 cm field was set, the CR plate was placed on the floor at 2.4 m from the source, at a depth of 10 cm in a 30 cm × 30 cm solid water phantom for batch 1 and 15 cm depth for batches 2 and 3. For batch 1 there was no additional phantom material placed around the edges of the phantom while for batches 2 and 3, 5 cm solid water blocks were placed up against each side of the phantom, providing additional scatter to the edges of the plate. At least the central 13 cm of the field (30 cm region of the field when projected to a distance of 2.4 m) was uniform to within 1.5% at a depth of 10 cm (as determined by ion chamber and film dosimetry performed at 100 cm from the source) and fully covered the CR plate. A dose of about 100 cGy was delivered. Horizontal and vertical profiles were taken and compared to those from film for the batch 1 plate. In addition, the mean and standard deviation of SU values across the entire plate were obtained, excluding strips 0.5 cm wide along the long edges and 3 cm wide along the short edges (0.5 cm on each edge for batches 2 and 3).

3. Signal decay with time. Because the latent image is stored in a metastable state, there is decay of the signal over time. CR plate 1 was irradiated with 100 cGy and then read out after various times, including: 1, 5, 10, 20, 30, 50, 850, and 930 min. This was repeated for 1, 10, 30, 100, 850, and 930 min delay times for all three batches. Three measurements were made for all but the three longest times. The loss of SU per minute of delay time relative to the SU reading obtained with a 1 min delay was calculated.

4. Signal decay with light exposure. One CR plate from each of three batches was irradiated with 100 cGy, kept in a dark environment (0.2 lux), and then read out. The plate was re-irradiated and then read out after exposure to typical fluorescent room light for periods of 5 and 30 s. This process was also repeated for the batch 1 plate (for 30 s exposure) in the room where the lights were off but a door 1 m from the CR plate was open to a fully lit room (light level of 5.0 lux).

5. Dose-response reproducibility. A 6 cm × 6 cm field was used to irradiate each corner (centered at least 5 cm away from an edge) of one CR plate from each of three batches to doses of 6.1, 31.0, 101.5, and 226.6 cGy inclusive of dose contribution from each other. The plate was positioned at a depth of 10 cm in a solid water phantom with 0.4-mm-thick sheets of lead 1 cm above and below the CR plate (see 7 to follow). The plate was read exactly 10 min after irradiation and then erased. Thirty to 45 min later, another irradiation was performed. This was repeated for a total of three to four times per session. A 1 cm × 1 cm central region of each irradiated square was used to measure the mean SU value. For the batch 1 plate, these sessions were repeated one to two weeks apart for seven sessions. One reading session was obtained with the batch 2 and 3 plates using the same methods as for plate 1.

6. Response degradation with high doses. A dose of 200 cGy was delivered to the batch 1 CR plate and then the plate was read. This was repeated three times and the mean scanner value at a 1 cm × 1 cm central region of interest was recorded. The plate was then given 5000 cGy, scanned, and a 2 min erasure performed. The plate was then reread confirming that the plate was fully erased. Two more 200 cGy doses were then delivered to the plate each followed by readout. Another 5000 cGy dose was delivered to the plate and the same erasure sequence as before was used. Finally, another set of two 200 cGy doses was delivered to the plate each followed by readout.

7. Perpendicular irradiation-calibration and field size dependence. The CR plate from each batch was placed at a depth of 10 cm in solid water and irradiated perpendicularly with 5 cm × 5 cm, 10 cm × 10 cm, and 15 cm × 15 cm fields at 100 cm source-surface distance. From the data in test 9 demonstrating dose-response linearity for four dose points from 6 to 152 cGy, just two doses, 10 and 100 cGy, separately irradiating the center of the plate, were used for each field size.

It has been reported that lead filters placed above and below film improve their accuracy by filtering out the low energy scattered photons. It was hypothesized that these lead filters could reduce the magnitude of the energy response of CR plates whether the beam was perpendicular or parallel to the plate. Different thicknesses of lead sheet
placed on each side of the CR plate with 1 cm of solid water in between was used to minimize the difference between the SU reading for a 100 cGy to a 20 cm × 20 cm field at 10 cm depth compared to a second exposure of 100 cGy at $d_{\text{max}}$, each in perpendicular irradiation geometry. The SU value for $d_{\text{max}}$ was 625 while it was 478 at 10 cm depth without lead filters, demonstrating the increased response of the plate due to the increased presence of lower energy photons at depth. The scanner value at 10 cm depth rose for 0.2 and 0.4 mm lead thickness, 576 and 602 SU respectively, but there was no further increase in reading for 0.6 mm lead. Thus, it was determined that 0.4-mm-thick lead layers were optimal and this thickness was used subsequently whenever lead filters were employed. For perpendicular irradiation, this lead thickness caused a 4% to 5% decrease in dose (attenuation of the 6 MV x-ray beam and the low energy scatter components) that was compensated for by increasing the monitor units to obtain the stated dose. Using the lead filters, the batch 1 plate was then irradiated again with each field size as described earlier. All doses given with the lead present were corrected for attenuation. The plate was read out 10 min after irradiation. The SU values were plotted against log of dose. This was repeated for the batch 2 and 3 plates.

8. Parallel irradiation-calibration and field size dependence. The batch 1 CR plate was placed in a solid water phantom parallel to the couch-top. The gantry was rotated to 270° and the source to surface distance was set to 100 cm. Field sizes of 5 cm × 5 cm, 10 cm × 10 cm, and 15 cm × 15 cm were used to irradiate the CR plate. Sufficient phantom material was used above and below the plate to provide full coverage of each field and lead blocks were placed on top of the phantom to further compress the CR plate within the phantom. Lead filters were used as described earlier. About 48 cGy was give to 1.5 cm depth ($d_{\text{max}}$) for each field size. A 0.5%–1.5% dose decrease was measured (using an ion chamber at a depth of 15 cm in solid water with and without the lead filters) for fields between 5 and 15 cm square with the lead filters in place requiring monitor unit corrections to be made to obtain the stated dose. SU values at depths of 3–27 cm were obtained and plotted against the log of the dose at each depth.

9. CR plate response with incident beam angle. The batch 1 CR plate was placed in a solid water phantom at a depth of 10 cm. The isocenter was set to a point in the plate 10 cm from one edge of the plate. No lead filters were used. The plate was irradiated perpendicularly with a 5 cm × 5 cm field given 75 cGy and then readout. The mean SU for a 1 cm × 1 cm central region was obtained. The beam angle was sequentially rotated from this perpendicular position by 45°, 80°, and 90°, and for each angle, the phantom thickness above the plate and the isocenter lateral position was adjusted to maintain the 10 cm depth along the central axis of the beam as well as the position of the isocenter in the plate. The plate was irradiated and readout at the same location on the plate at each angle. Measurements of mean SU values were taken within a 1 cm × 1 cm area centered at isocenter for each field.

10. Dose-response from 6 to 328 cGy. The batch 1 CR plate was placed at a depth of 10 cm in solid water with the lead filters in place and irradiated perpendicularly with 6 cm × 6 cm fields to each corner of the phantom. One irradiation set used doses of 6–102 cGy, one from 102 to 226 cGy, and one from 226 to 328 cGy. The plate was read out 10 min after exposure. The SU versus log of dose was plotted for the full set of doses.

11. Beam profile agreement versus EDR2 film and ion chamber. The batch 1 CR plate was placed at the center of a stack of 20-cm-thick solid water with the lead filters in place and irradiated in the parallel geometry with 5 cm × 5 cm, 10 cm × 10 cm, and 15 cm × 15 cm fields for about 65 cGy each at 10 cm depth. This was repeated with EDR2 film without lead filters. The EDR2 film was scanned and calibrated, and profiles extracted using the RIT software. The CR data for the 5 cm × 5 cm and 15 cm × 15 cm fields were calibrated by two methods, (1) using the parallel calibration data from each irradiation or (2) using perpendicular calibration data from test 7 above. The 10 cm × 10 cm CR data were calibrated using the perpendicular geometry calibration data. Dose profiles at a depth of 10 cm through each field were obtained after CR dose calibration. CR and EDR2 profiles were normalized and superimposed. For the 10 cm × 10 cm field, water scan profile data were also used to compare to the film and CR data.

12. Perpendicular irradiation of IMRT beam, profile agreement with XV film. One beam from an 8 beam IMRT plan was used to irradiate the batch 1 CR plate followed by XV film each placed at a depth of 10 cm in a solid water phantom. Lead filters were used within the CR plate in this test. The CR plate was calibrated using the perpendicular calibration irradiation performed immediately prior to the beam fluence irradiation. The XV film was calibrated using a separate separation film irradiated with the same field size as the IMRT beam (the author’s routine procedure). The two images were registered and calibrated using the RIT software, normalized, and the profiles superimposed. Throughout this study, registration consistency was determined to be within 1 mm by using the RIT registration program’s report of the standard error of registration of each set of images. A normalized horizontal dose profile from CR versus XV film was compared. Absolute dose at the normalization point for each image and from the plan was also noted.

13. Parallel irradiation of composite multibeam IMRT plans, profile and isodose comparison with planning system and EDR2 film. The solid water phantom slabs were placed vertically on the treatment couch. Either the batch 1 CR plate or EDR2 film was placed in the center (axially) of a 12-cm-long (superior-inferior), 30-cm-wide, and 30-cm-deep stack of solid water. Lead filters were used for the CR plate but not for the EDR2 film. The isocenter was placed at the exact center of this phantom. All beams with their actual treatment parameters and monitor units from two different plans were used to irradiate the film or CR plate. Six or eight coplanar beams were used in each plan and it took 6 to 7 min to perform these treatments. The Plato planning system was used to calculate the three-dimensional dose grid for each
plan and the required axial dose plane was extracted by the RIT software. The CR plate was read out after 14 h to minimize the effect of signal decay over the time it took to perform the IMRT plan irradiation (up to 20 SU or 4% apparent dose decrease nonuniformly distributed if read out after 10 min). The plan and plate or film data were registered and calibrated using the RIT software. CR calibration consisted of pairing Plato dose points with the corresponding CR SU value and a near zero dose with the corresponding SU value. Since this was not an independent calibration, absolute dose agreement will not be reported. For the eight beam plan, vertical and horizontal profiles were inter-compared with EDR2 film and the Plato plan [Figs. 11(b) and 11(c)]. For the six beam plan, isodoses were inter-compared (Fig. 12). For both plans, in a region of interest within each image extending 3–5 cm outside the high dose region to include doses as low as 20% of maximum, the percentage of pixels exceeding a Gamma value of 1 (a composite measure of both the dose and distance to agreement) were computed for the EDR2 film and the CR dose distributions as compared to each other using 5% dose and 3 mm distance-to-agreement tolerances and to the Plato dose using 3% and 4% dose and 3 and 4 mm distance-to-agreement tolerances.

### III. RESULTS

1. **Spatial accuracy.** Table I, columns 1–4 show the mean percentage deviation from the 20 cm distance in the length and width direction measured between BBs placed at each corner of a 20 cm × 20 cm square. Columns 5 and 6 show the deviation across the diagonals of the square. In all cases, the deviation is within 1% (2 mm) and each measure shown in Table I was repeatable to within 0.1% evaluated with three scans in both portrait and landscape orientation. Row 1 shows data for the portrait feed mode while row 2 data are for the landscape feed mode. The largest variations are generally in the first two columns that are for measurements in the feed direction where roller slippage can occur. These values are similar to Vidar Corporation’s geometrical accuracy specification (1% or 2 pixels, whichever is greatest) for a Vidar Dosimetry Pro 16 bit scanner.

<table>
<thead>
<tr>
<th>Plate Feed Direction</th>
<th>0.8%</th>
<th>0.7%</th>
<th>-0.6%</th>
<th>-0.6%</th>
<th>-0.4%</th>
<th>-0.2%</th>
<th>P</th>
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<tbody>
<tr>
<td>BB</td>
<td>0.6%</td>
<td>0.9%</td>
<td>-0.3%</td>
<td>0.2%</td>
<td>0.2%</td>
<td>0.3%</td>
<td>L</td>
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</table>

Fig. 1. Original vs new uniformity calibration method, (a) horizontal profiles, (b) vertical profiles.

**TABLE I.** Percentage deviation from known dimension between BBs 20 cm apart. Bold line represents the edge (relative to the scanner) whose measurement is given in the column. The last column indicates the plate feed direction, portrait or landscape.

2. **Spatial uniformity of response.** Centrally, the batch 1 plate response uniformity was within an acceptable standard deviation of 1.5% of the mean in dose compared to film, but the 3 cm region around the edges of the plate corresponded by up to 15% of the central dose and the region 3–5 cm from the edges under-responded by up to 5%. For all other tests, the doses around the outermost 3 cm of the plate were not within the area of interest. Ideally, the PMT calibration file should be created with the same irradiation and scan conditions as the test irradiation and the calibration process should produce a flat profile across the entire uniformly irradiated plate. Scans of plates from batches 2 and 3 were corrected by the improved PMT calibration method and little fall off of signal was found at the edges (excluding the first 0.5 cm because of possible nonuniformities produced by the

Fig. 2. Rate of scanner unit decay with readout time after exposure.
plate manufacturing and handling process or by scanner readout limitations). Figures 1(a) and 1(b) compare the horizontal and vertical profiles obtained with either the original (using plate 1) or the new uniformity calibration method (using plate 2 or 3). The mean and standard deviation in SU for the evaluated region of each of the three plates were 962 ± 7, 922 ± 7, and 904 ± 12 SU for the batch 1, 2, and 3 plates, respectively.

3. Signal decay with time. Signal decay with delay time between irradiation and readout appears to follow a power law (Fig. 2), with there being a loss of 2–3 SU/min in the first 10 min, about 2 SU/min at 30 min, then plateauing at about 0.5 SU/min after about 3 h. It is therefore imperative that a consistent delay time between calibration and test irradiation is used. For situations where the radiation time is long (i.e., 10 min for an IMRT composite irradiation), one should use a long enough delay time so that the signal loss between the beginning and the end of the irradiation session is minimized. The standard deviation of three readings taken for all but the 360, 850, and 930 min time points was 2 SU (readings ranging from 616 to 857 SU). These results were consistent across all three plates (Table II).

4. Signal decay with light exposure. Signal decay with room light exposure is significant and must be carefully controlled. Approximately 70 SU are lost (SU reading increases) for each second of room light exposure (Fig. 3). About 3% of the SU are lost in 30 s of exposure to dim light. The mean and standard deviation of the SU increase for 5 and 30 s of room light were 304 ± 35 and 1018 ± 32, respectively. The reading without any room light exposure was an average of about 630 SU.

5. Dose-response reproducibility. Reproducibility of scanner unit response for four doses between 6.1 and 226.6 cGy was analyzed by finding the mean and standard deviation of the set of SU for the doses from each session (Table III). If the CR system can remain consistent within a 30–45 min time frame, then the calibration data set preceding a test irradiation data set will be compatible. Intrasession reproducibility in terms of dose was found to be typically within 2% and intersession constancy was within about 5%, with the larger variations at the larger doses. Both of these are within acceptable limits and not worse than the results reported using a typical film processor-based dosimetry system. The change in SU between consecutive irradiations within a 1.5 h session was influenced by the doses used, such that the lower SU values trended lower (higher dose) while the higher SU values trended higher (lower dose), both by an average of 10 SU (about 2% of dose). In addition to looking at the SU changes over time, the SU versus dose data for each plate irradiation were graphed using the log of dose and a log curve fit, which constitutes a calibration curve. The mean slope and y-intercept for the seven sessions were computed. The mean and standard deviation for these parameters were consistent across the three plates and the absolute value of the dose response of the batch 2 and 3 plates evaluated in the same week was within 8% of dose throughout the dose range tested (Table IV). Because the batch 1 plate was irradiated 9 months prior to the other two batches, no conclusion is drawn regarding its absolute dose-response compared to the other plates.

6. Response degradation with high doses. The mean SU values for each set of 200 cGy doses were 404, 397, and 393 (±1 SU). The SU for the erased plate after each 5000 cGy was 4080, the same value produced after erasure of any dose given to the plate. This downward migration from 404 to 393 was similar to that seen after multiple consecutive irradiation.

**Table II.** Time delay effect for three different CR plates.

<table>
<thead>
<tr>
<th>Delay time (min)</th>
<th>Mean ± std SU loss/min</th>
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<tr>
<td>1</td>
<td>0</td>
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<tr>
<td>10</td>
<td>2.25 ± 0.23</td>
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<tr>
<td>30</td>
<td>1.57 ± 0.35</td>
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<tr>
<td>100</td>
<td>1.29 ± 0.20</td>
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<tr>
<td>850–930</td>
<td>0.28 ± 0.01</td>
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**Table III.** Reproducibility data (mean and standard deviation) for four doses given over seven sessions about 1 week apart.

<table>
<thead>
<tr>
<th>Dose</th>
<th>Session 1 Ave</th>
<th>Std</th>
<th>Session 2 Ave</th>
<th>Std</th>
<th>Session 3 Ave</th>
<th>Std</th>
<th>Session 4 Ave</th>
<th>Std</th>
<th>Session 5 Ave</th>
<th>Std</th>
<th>Session 6 Ave</th>
<th>Std</th>
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<td>8</td>
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![Fig. 3. Loss of scanner units with exposure time to room light.](image-url)
tions of 200 cGy alone (see test 5 above), indicating that the plate response was not significantly altered by irradiation with 10,000 cGy.

7. Perpendicular irradiation-calibration and field size dependence. The dose versus response from each field size and with and without lead filters was graphed logarithmically for the batch 1 plate. For the case without lead filters, the three lines were found to be nearly parallel to each but separated by about 100 SU from one field size to the next (Fig. 4). Repeating the irradiation of the three field sizes using lead filters showed that the curves moved closer together, being only 30 SU apart, and also became virtually parallel (same slopes) to each other (Fig. 5). This proved that the lead filters were useful. From the data in test 5, the error bars for Figs. 4 and 5 are smaller than the symbols used as data points. This test with lead filters was repeated 9 months later for all three CR plate batches. Both the values of the slopes and its dependence on field size are consistent across the three plates (although somewhat different from the 9 month earlier values for batch 1 in Fig. 5). The separation between the intercepts for 5 cm to 15 cm fields ranges from 98 to 128 SU (a 30 SU difference represents about 6% dose) depending on the plate (Table V). These data collectively indicate that CR plates even from different batches behave similarly to field size variations.

8. Parallel irradiation-calibration and field size dependence. The effectiveness of lead filters was also determined using the parallel irradiation geometry. As for the perpendicular geometry, the slopes of the dose-response lines were virtually identical but now each line was separated by about 60 SU. The mean slope of the parallel dose-response lines was noticeably different from that of the perpendicular dose-response lines, 463 and 404, respectively (Fig. 6). The correlation coefficient for the parallel dose-response was about 0.999 over doses taken from depths in the phantom from between 3 and 27 cm. If there were significant remaining energy sensitivity in the CR plate despite the presence of the lead filters, then this correlation would be poor because of the over-response with increasing depths. Therefore, the CR dosimetry accuracy using lead filters is not limited by depth up to 27 cm. The reason for the slope difference between parallel and perpendicular irradiation geometries is under investigation. Measurements taken with a 2 degree gantry tilt gave the same results as with no intended tilt.

9. CR plate response with incident beam angle. As can be seen in Fig. 7, a progressive decrease in SU (more plate darkening) is obtained as the beam incidence changes from

| Table IV. Reproducibility of response for three different CR plates. |
|-----------------|---------------|---------------|---------------|
| Batch | 1 | 2 | 3 |
| Dose (cGy) | Mean±std SU | Mean±std SU | Mean±std SU |
| 6 | 1723±9 | 1705±3 | 1727±2 |
| 31 | 1077±5 | 1068±1 | 1082±1 |
| 102 | 635±4 | 613±3 | 583±3 |
| 227 | 411±8 | 378±4 | 341±2 |

| Table V. Dose-response for three different CR plates as a function of field size. |
|-----------------|---------------|---------------|---------------|
| Batch # | 1 | 2 | 3 |
| Field size | Slope | y intercept | Slope | y intercept | Slope | y intercept |
| 5×5 | 418 | 2572 | 420 | 2563 | 423 | 2549 |
| 10×10 | 413 | 2519 | 424 | 2547 | 416 | 2481 |
| 15×15 | 409 | 2474 | 411 | 2456 | 408 | 2421 |
parallel to perpendicular. The CR plate and phantom were well compressed so other reasons for this finding are being investigated.

10. **Dose-response from 6 to 328 cGy**. The dose-response is linear up to a dose of about 150 cGy, beyond which it flattens, with a slope about 23% lower. Fig. 8 shows the scanner reading vs dose for doses between 6 and 328 cGy. Although lines have been drawn through the data in the two dose regions, as even higher doses are added, the high dose region may be represented by a curve rather than a line as the response saturates. For situations where more than 150 cGy is required, then several more points defining the inflection and the higher doses are required for calibration. Note that in both this test and that in test 5 where regions near the corners of plate 1 are irradiated, the dose-response is somewhat different from that of tests 7 and 8, where the center of the plate was irradiated. This is likely due to the effects of nonuniformity within the first 5 cm of the edges of plate 1 prior to the implementation of the improved PMT uniformity calibration.

11. **Beam profile agreement vs. EDR2 film**. The ability of the CR system to reproduce beam profiles for 5-, 10- and 15-cm-wide fields at a depth of 10 cm irradiated in the parallel geometry was tested and compared to EDR2 film without lead filters and, for the 10 cm square field, to an ion chamber scanned in a water phantom and to a CR plate with and without the presence of lead filters (Fig. 9). The shoulder, penumbral slope, and low dose toe of the profiles were examined. The CR data were calibrated both by parallel and perpendicular calibration data sets. Both calibration methods gave nearly equivalent results except that the perpendicular calibration data applied to the CR profile gave better agreement with the EDR2 film profile for doses below about 30%. Clearly, the presence of the lead filter for the 10 cm field improved the CR agreement with the EDR2 film and ion chamber, especially in the low dose region. The EDR2 film without lead filters compared very well against the ion chamber scans. The 5 cm x 5 cm EDR2 profile showed a +3% asymmetry in the left-side shoulder that may be artifactual since it does not appear in the larger field sizes. The shoulders of the CR profiles for 5 cm x 5 cm and 10 cm x 10 cm fields were within 3% of those for the EDR2 film, while the penumbral dose between 30% and 80% matched within 1 mm. The shoulder of the 15 cm x 15 cm CR profile was about 7% lower than for the EDR2 profile. The CR dose in the dose region between 15% and 30% was in good agreement for the 5- and 10-cm-wide fields but did rise above the EDR2 dose for the 15-cm-wide field. The absolute dose at the center of each field determined by the CR plate was within 2% of the known given dose when calibrated with 10 and 100 cGy doses given using two separate exposures in perpendicular geometry to the same plate using the same field size at a depth of 10 cm.

12. **Perpendicular irradiation of IMRT beam, agreement with XV film**. The planning system dose profiles are routinely compared to those found on XV film to test fluence map accuracy for individual beams. In this study, the CR plate and XV film were placed at 10 cm depth and irradiated with the same beam (with all of its monitor units). Figure 10 shows the agreement between the CR and XV film profiles. The two profiles are nearly identical (within 2% and 1 mm) except at the lowest doses outside the field. The absolute dose agreement at a point near the center of the field between XV film and CR was 4%. 

![Fig. 6. Parallel calibration for 5 x 5, 10 x 10, and 15 x 15 cm square fields with the use of lead filters.](image)

![Fig. 7. CR plate response as a function of incident beam angle.](image)

![Fig. 8. Scanner reading vs dose for doses between 6 and 328 cGy.](image)
13. Parallel irradiation of composite multibeam IMRT plans, profile and isodose comparison with planning system and KODAK EDR2 Film. For the eight beam IMRT case, the horizontal and vertical profile dose agreement among CR, EDR2, and Plato was studied (Fig. 11). For the horizontal profile, the CR dose matches the EDR2 dose better than does the Plato dose, and all three are generally within 3% or 3 mm of each other. For the vertical profile, although the majority

![Fig. 10. Horizontal profile of an IMRT beam irradiated perpendicularly to the CR plate or XV film, at a depth of 10 cm in solid water.](image)

![Fig. 9. Profiles for EDR film and CR with lead filters at a depth of 10 cm from parallel irradiation, (a) 5 cm × 5 cm, (b) 10 cm × 10 cm (also included is ion chamber scan and CR plate without lead filter), (c) 15 cm × 15 cm.](image)
of the data points are in good agreement, there is as much as a 7% dose difference in a 2 cm portion of the high dose region, and a larger difference on one side below the 40% dose region. In the latter region, the Plato dose is between the CR and EDR2 doses. Despite this small area of dose difference, as noted in the following, the more global indicator of agreement, the Gamma function, was only marginally poorer for CR than for EDR film.

The isodose analysis was also performed on a six beam IMRT plan. This second case is representative of a prostate IMRT case where the agreement between the CR plate and EDR2 dose [Fig. 12(a)] as well as the CR plate and the Plato dose [Fig. 12(b)] appears qualitatively acceptable, especially in the steep gradient area posteriorly where the rectum is being protected. A quantitative analysis of each case using the Gamma function (with the Plato dose as the reference) with reference values of 3% dose agreement in the high dose low gradient regions and 3 mm distance-to-agreement in the high dose gradient regions reveals that in the EDR2 dose image, the number of pixels exceeding a gamma of 1 were 15% for the first IMRT case and 13% for the second. For the CR plate, the percentage of pixels exceeding Gamma of 1 were 30% and 25%, respectively. To obtain the same percent exceedence values for the CR dose images as for EDR2 film, 4% and 4 mm would have to be specified in both cases tested. When comparing CR directly to EDR using a 5% dose tolerance and a 3 mm distance-to-agreement tolerance, the eight beam plan gave 14% and the six beam plan gave 7% of pixels exceeding a gamma of 1, respectively. For both plans, the Gamma analysis was performed over a region large enough to include doses as lows as 20% of maximum.

IV. DISCUSSION

The tests performed in this study represent the first comprehensive characterization of the ability of an Agfa CR plate and the Kodak 2000RT CR scanner to be used for megavoltage photon beam dosimetry. Ultimately, IMRT quality assurance tests were performed with the CR system and compared to the results from XV or EDR2 film, the current widely used two-dimensional measurement media for this purpose, and to the Plato planning system doses. The objective of this study was to determine whether the CR system was suitable as a substitute for film and processor for dosimetry applications. Due to the high Z constituents of the active layer of the CR plate, it was anticipated that an even stronger energy dependence than film would be found, greatly limiting the accuracy of CR. To minimize this energy dependence, 0.4-mm-thick lead filters were used on each side of the CR plate with 1 cm of solid water interposed, much like the filtering of films suggested in various reports. Because the use of lead filters with film is not widely used, for most of the analysis, this study compares CR with lead filters to film without lead filters. Also, the variability of response under various conditions by plates from three batches was assessed.

Fundamental characteristics that are required for acceptability as an accurate two-dimensional dosimeter include spatial accuracy and uniformity, reproducibility, and dose-response linearity. The spatial accuracy was within about 1% for both directions and film scan orientations, not significantly different from that of a Vidar scanner. Meeder reported that a laser scanner tested has 0.8% different pixel dimensions horizontally versus vertically. One deficiency of the initially tested CR system using plate 1 was that the PMT calibration process did not properly calibrate-out non-uniformities at the edges of the CR plate. The Kodak-supplied calibration software that corrects for spatial nonuniformities was modified by the author and used to recalibrate the scanner. After the time the tests were performed with the first plate, an improved uniformity calibration method was developed and used for tests with the batch 2 and 3 plates.
which involved uniformly irradiating the CR plate including its edges and scanning the plate using therapy doses in port film mode. The results of all the tests in this study (except for the intercomparison of the three batches) were performed using batch 1 with the less optimal uniformity calibration protocol. The new protocol greatly improved uniformity, especially at the edges of the plate (Fig. 1). To the extent that this calibration process was improved, the results of the tests reported here may also improve. Film dosimetry can also suffer from nonuniformity of response. There have been reports that CCD and laser scanners produce nonuniformities at the edges of the image area due to light scatter and other effects.12,13

Repeatability of response with a given dose was generally within about 2% of dose over a 1.5 h session and within 5% over a six week period, with the larger doses having the larger long-term differences in response, an effect that deserves further study. These differences are most likely caused by PMT sensitivity variations over time rather than by changes in the CR plate itself (irradiating the plate with over 10 000 cGy in a few hour period did not significantly change the dose-response of the plate). By comparison, 12 bit Vidar film scanners are reported to have standard deviations of 15 SU units for a 2500 SU reading and repeatability of about 8 SU14 and long-term variability of a film dosimetry system was reported to by as much as 15%.10 In addition, the resistance to damage from high doses of radiation demonstrates the dosimetric durability of the CR plate.

One distinct advantage of the CR system over film is that the dose-response is highly semi-log linear up to at least 150 cGy. Further linearization might be achieved by further reducing the PMT gain. This coupled with good reproducibility of response over at least several hours means that one could produce the PMT gain. Further linearization might be achieved by further reducing the PMT gain. This coupled with good reproducibility of response over at least several hours means that one could produce

The central and penumbral region of 5 cm x 5 cm and 10 cm x 10 cm fields were well reproduced while the dose outside the edge of the field was overestimated significantly only for the 15 cm square field. The deviations between the CR plate and the film dose profiles found in this test are probably due to the inability of the lead filters to completely remove low energy scatter combined with the high atomic number of the CR phosphor.6 In addition, the perpendicular calibration data taken at 10 cm depth gave a better rendering of the dose profile at 10 cm depth within a plate irradiated in the parallel geometry than did the parallel calibration data set outside the 30% dose region. This may be due to a lack of low dose data in the parallel calibration data set; the lowest dose found in the parallel irradiation, at a depth of 27 cm, was about 50% of the dose at 10 cm depth while for the perpendicular calibration method, the lowest dose point was 10 cGy, 15% of the dose at 10 cm depth. Thus, the parallel calibration data set used requires extrapolation down from the 50% dose level that may less accurately represent the 15% dose than will the perpendicular method that actually provides that low dose. Although Fig. 6 demonstrates a high degree of linearity for SU versus dose, it is recommended that if just two doses are used to generate a calibration curve, they bracket the doses of interest in the test irradiation. Further study of this effect is warranted.

The addition of 0.4-mm-thick lead filters placed parallel to the CR plate reduced the difference between calibration curves taken for 5, 10, and 15 cm square fields for both parallel and perpendicular geometries. This makes it possible to use a single calibration curve for that range of field sizes with little error for relative dosimetry as the slopes of the curves are within 1.3% for the three field sizes. For absolute dosimetry with, for example, an 8 cm x 8 cm field size, one could interpolate the y intercept between the 5 and 10 cm field calibration curves and use the average slope of these curves to determine the 8 cm x 8 cm calibration curve as an alternative to measuring it. The spread of the y intercepts across all three field sizes, even with the lead filters, is still 69–128 SU for perpendicular and parallel calibration geometries, respectively. To compare this to the field size dependence for XV film, for the parallel geometry, CR displayed a nearly constant 30% apparent dose difference for all depths studied for fields sizes of 5 cm x 5 cm vs 15 cm x 15 cm compared to 8%–42% dose difference (varying with depth) reported by Burch for a 4 MV beam for 6 vs 25 cm square
Finally, a subset of tests performed on plates from three batches demonstrates the consistency of response indicating that the results from this study may be widely applicable to Kodak systems using Agfa plates currently in the field.

V. CONCLUSIONS

The KODAK 2000RT CR System appears to be suitable for a wide range of dosimetry applications, including IMRT QA. The results of the various tests compared well to those of film-scanner systems up to at least a 10 cm × 10 cm field size for depths of 10 cm in solid water. Lead filtration was required to minimize the response enhancement of low energy scatter, resulting in a response to field size and depth similar to unfiltered film. Also, recalibration of the scanner using a modified version of the Kodak-supplied uniformity calibration software was performed prior to testing. A further improvement of the uniformity calibration process greatly improved response uniformity in two other plate batches tested.

One must be aware of the unique properties of CR that require different handling than for film. With careful attention to methodology, the CR system accurately performed both relative and absolute dosimetry for single open beam and IMRT beam QA tests with field sizes less than 15 cm × 15 cm. Reduced accuracy was found at the shoulders and outside the 30% dose level for 15 cm × 15 cm beam profiles probably due to the presence of low energy scattered photons despite the lead filtration. For composite IMRT QA tests, relative dosimetry was performed with only slightly reduced accuracy compared to film. Because film processors will no longer be available to many physicists, CR will be an attractive alternative to film, especially for those who already have a CR system purchased for imaging or those who need both an imaging and dosimetry system.

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