TG-69: Radiographic film for megavoltage beam dosimetry

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TG-69 is a task group report of the AAPM on the use of radiographic film for dosimetry. Radiographic films have been used for radiation dosimetry since the discovery of x-rays and have become an integral part of dose verification for both routine quality assurance and for complex treatments such as soft wedges (dynamic and virtual), intensity modulated radiation therapy (IMRT), image guided radiation therapy (IGRT), and small field dosimetry like stereotactic radiosurgery. Film is convenient to use, spatially accurate, and provides a permanent record of the integrated two dimensional dose distributions. However, there are several challenges to obtaining high quality dosimetric results with film, namely, the dependence of optical density on photon energy, field size, depth, film batch sensitivity differences, film orientation, processing conditions, and scanner performance. Prior to the clinical implementation of a film dosimetry program, the film, processor, and scanner need to be tested to characterize them with respect to these variables. Also, the physicist must understand the basic characteristics of all components of film dosimetry systems. The primary mission of this task group report is to provide guidelines for film selection, irradiation, processing, scanning, and interpretation to allow the physicist to accurately and precisely measure dose with film. Additionally, we present the basic principles and characteristics of film, processors, and scanners. Procedural recommendations are made for each of the steps required for film dosimetry and guidance is given regarding expected levels of accuracy. Finally, some clinical applications of film dosimetry are discussed.
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I. INTRODUCTION

Radiographic films based on silver halide (AgH) emulsions are widely used for relative dosimetry of external radiation treatment beams in the megavoltage energy range. These films are convenient to use, providing permanent records of integrated spatial dose distributions. By using different film types, the dose distributions can cover a broad range of doses from just a few cGy up to several Gy. Film dosimetry provides an attractive method for measuring dose distributions in phantoms for dose characterization and/or verification, or to perform quality control tests of radiation beams (e.g., correspondence between light field and radiation treatment field, field flatness and field symmetry). In recent years, film dosimetry has become even more popular and is indispensable for verifying advanced irradiation technique dose distributions such as produced from a soft wedge, intensity-modulated radiotherapy (IMRT), and stereotactic radiosurgery. These new radiotherapy technologies make complex-shaped tumor conformal irradiation feasible and clinically deliverable. Prior to clinical implementation of these advanced technologies, measurement-based validations of the planned dose distributions are required.[1,2] Radiographic film is a preferred tool for this purpose due to its unrivaled spatial resolution, low cost, wide accessibility, and ability to be placed inside a variety of phantoms without perturbing charged particle equilibrium. Large differences in dose (as determined by the measured optical density) can occur between two neighboring points positioned in steep dose gradient regions, found, for example, in IMRT dose distributions. The large dose differences can be more accurately measured using film dosimetry than by other methods such as thermoluminescent dosimetry (TLD) or ionization chamber measurements. The two-dimensional nature of film offers the option of selecting the orientation of the film relative to the dose distribution and, because it is an integrating dosimeter, aids in the measurement of dynamically delivered dose distributions.

A. Background

Film dosimetry offers a convenient and quick method of obtaining a two-dimensional dose distribution from which a set of isodose curves can be obtained in the film plane. Its use for measuring electron beam dose distributions is well established. The energy independence of some types of film may be explained by the fact that the ratio of collision stopping power in emulsion and in water varies slowly with electron energy.[3]

Although film is well established as a straightforward method of measuring electron beam dose distributions, its application for megavoltage photon-beam dosimetry is more complex. This results from the fact that film sensitivity varies because the photon energy spectrum in phantoms varies as a function of field size and depth.[4] The existing data concerning the influence of irradiation geometry on the sensitometric

curve are conflicting.[3–12] In spite of this, there has been a renewed interest in radiographic film dosimetry for modern radiotherapy technologies such as IMRT and intensity-modulated stereotactic radiotherapy.[13–20] These technologies employ time-dependent dose delivery and therefore require an integrating dosimeter to quantify the integrated delivered dose.

The main challenges for using radiographic film as a megavoltage beam dosimeter is the dependence of optical density (OD) on

(a) photon beam energy and field size and depth in the phantom;[21,22]
(b) film plane orientation with respect to the beam direction;[23]
(c) emulsion differences amongst films of different batches, films of the same batch, or within the same film;
(d) processing conditions;[24] and
(e) method of densitometry and related artifacts.[25–27]

The implication of the above issues is that the same optical density is not always associated with the same dose, making the conversion of OD to dose potentially difficult.

Over the past few decades, there have been numerous technical notes, papers, and textbook references describing film dosimetry techniques for megavoltage therapy; however, these are scattered throughout the literature and are thus not easily found and are often contradictory. Insufficient guidance exists for the medical physicist on the selection and use of radiographic films and the issues listed above.

B. Scope and purpose of document

The primary mission of the task group is to develop guidelines for film selection, irradiation, processing, scanning, and interpretation to allow accurate and precise external beam dose measurements. A variety of densitometers are discussed with specific recommendations for acceptance and QA checks in order to obtain consistent and reproducible optical density measurements. Different film phantoms, different film orientation in phantoms, and the precautions one should take are also discussed. In addition, a complete film calibration protocol is presented for quick reference. Finally, film dosimetry for specific applications of radiotherapy is discussed. The report also recommends the precautions that should be taken when using film as a quantitative dosimeter and indicates the limitations inherent in this form of dosimetry.

Throughout this report, certain commercially available films, phantoms, linear accelerator modalities, and other commercial products are referred to by name. These references are for informational purposes only and do not imply that these are the best or only products available for the purpose. This report does not endorse any particular film or product dealing with the film, but only the technical and scientific merits of these products as published in literature are discussed.

In this report, the words "*shall*" and "*should*" are italicized in places to emphasize that they are being used in the special sense conveyed by the definitions given here:

Shall indicates a procedure that is essential for either (1) establishment of uniform practices or (2) the most safe and effective result and/or maintaining established standards of practice.

Should indicates an advisory recommendation that is to be applied when practicable. The task group favors the indicated procedure but understands that there are other procedures, which can accomplish the same goal. Deviations from the recommended procedure should only be carried out after careful documentation and analysis demonstrates that an equivalent result will be produced.

II. CHARACTERISTICS OF SILVER HALIDE FILMS

Typical radiographic film consists of a radiation sensitive emulsion coated on a transparent polyester base. The emulsion consists of silver halide crystals (typically 95% silver bromide and 5% silver iodide suspended in gelatin, in the case of Kodak XTL and XV films). The specific emulsion composition and manufacturing process varies with the manufacturer and is often a closely guarded industrial secret. When the emulsion is exposed to ionizing radiation, ionization takes place in the silver halide crystals that result in the formation of a latent image. The relative composition of iodine, bromine, and some traces of chlorine yield the film's unique sensitivity characteristics. Electron micrographs of some commonly used films reveal large differences in grain size and uniformity within the different film types. Although there are many manufacturers (including Agfa, CEA, DuPont, Fuji, Kodak, Konica, etc.), Kodak films account for the majority of the radiographic films used for dosimetry in the United States. Currently, the most commonly used Kodak films for megavoltage beam dosimetry are the therapy verification (XV) and the relatively new extended dose range (EDR) films. The properties of these films will be described in a later section. The XTL, therapy localization film, had been widely used but production was discontinued in 2003. Even though Kodak films are stated in this report by name, this report does not endorse any product dealing with film, but only the technical and scientific merits of films as published in literature are discussed. The polyester film base is typically 0.2 mm thick and free from significant optical defects or impurities. Most x-ray films are coated on both sides of the polyester base. The emulsion, which is the sensitive component of the film, consists of gelatin and silver halide grains, which are typically $1-3$ μm in dimension. The silver halide grain is a light sensitive material. The presence of silver iodide produces an emulsion of much greater sensitivity than the pure silver bromide emulsion. The typical crystal of silver halide consists of a cubic lattice of both silver ions and halide ions. The lattice spacing dimension of silver halide crystals is approximately $20-30$ nm. There are approximately 10^9-10^{12} grains/cm^2 in a typical x-ray film.[28] Most silver-bromide grains in film contain impurities such as io-

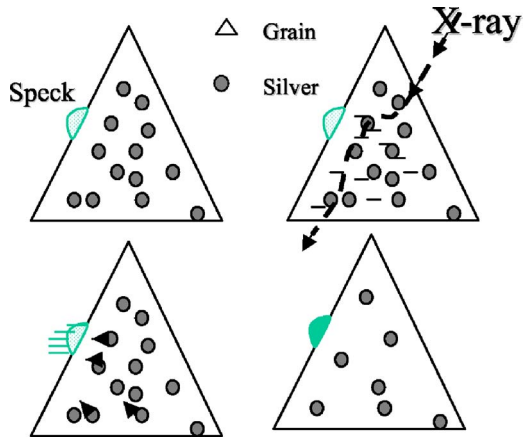

FIG. 1. Gurney and Mott model of latent image (Ref. 29). AgBr remains in ionic form (Ag^+Br^-) in the crystal of the grain. Radiation produces ionization of Br^- to $Br+e^-$. These electrons make the speck negatively charged. The Ag+ migrate to neutralize the speck and forms a lump of Ag (aggregate) on the speck.

dine and chlorine that modify their sensitivity. The sensitivity typically increases with these imperfections or sensitivity specks.

A. The latent image and Gurney and Mott mechanism

There is a significant change that takes place in silver halide grains when the photographic emulsion is exposed to light, x rays, or charged particles. It is known, however, that only adequately exposed grains will be developed and the remainder are left largely undeveloped with the exception of a small fraction that creates a low level darkening on the film referred to as "fog." While the mechanism that permits the formation of latent images is not fully understood, some indirect processes (the transformation of silver bromide to atomic silver) indicate that the latent image is a formation of silver atom aggregates inside the grain. While various theories have been proposed, the most widely accepted is the Gurney and Mott theory[29] proposed in 1938. Herz[28] has described in detail the controversy of this theory. It was noted that, for UV light, these aggregates consists of 4–10 silver atoms per quanta of light and approximately 1000 silver atoms aggregate with each x-ray quanta. A typical film grain contains 10^{10} silver atoms and only a few atoms constitute the latent image that renders the grain developable. Through the film development process, a significant multiplication of silver atoms takes place, which is 10^6–10^9 times that of the original latent image.[28,30,31]

A description of the Gurney and Mott mechanism of latent image formation[29] is shown in Fig. 1. It shows a silver grain with silver bromide molecules in the Ag^+Br^- ionic state. A speck is also noted that represents the sensitive center of the grain. These specks are the impurities of silver halides or other impurities in the crystal. When the grain is ionized by radiation, the Br^- ions are split into Br and electrons:

$$(Br^- \rightarrow Br + e^-).$$

These electrons migrate towards the specks, making the speck negatively charged, which, in turn, attracts Ag^+ ions toward the speck, forming a latent image. Once the grains are developed, those grains comprising the latent image are converted to metallic silver, producing the dark regions on the film.

B. The principles of processing a film

Film developing is a complex process, which includes four steps: developing, fixing, washing, and drying. In the development process the latent image is reduced to metallic silver grains. The details for the processing can be seen in Sec. III.

C. Optical density

The value of film opaqueness is quantified through the light transmission factor, T, and is measured by a quantity called optical density (OD). The OD is a value describing the darkness of a film and is measured by a device known as a densitometer:

$$\mathrm{OD} = -\log_{10}(T) = \log_{10}(I_0/I), \tag{1}$$

where I_0 is the incident light intensity measured in absence of film and I is the intensity transmitted through the film perpendicular to the film plane. Thus, an OD of 3 is 100 times more opaque than an OD of 1. Dainty and Shaw[30] provided extensive descriptions of the relationship between optical density, grain size, and mechanism of photon interactions that relates to the optical density. If α is the average area (cm^2/grain) of a developed silver grain and if there are n developed grains/cm^2 of film, then T can be written as

$$T = e^{-\alpha n}, \tag{2}$$

$$\mathrm{OD} = -\log_{10}(e^{-\alpha n}) = 0.4343\alpha n. \tag{3}$$

It is difficult to know the number of electrons needed to develop a grain. However, if we assume that a single electron is responsible for developing one grain, then one can correlate the electron fluence, ϕ, passing perpendicular to the film, to the optical density.[31] If N is the number of silver bromide grains per unit area of the unexposed film, then n and OD can be written as

$$n = \alpha N \phi, \tag{4a}$$

$$\mathrm{OD} = 0.4343\alpha^2 N\phi. \tag{4b}$$

While this assumption is simplistic, it provides useful insights in OD film response. There are numerous models dealing with OD including single-hit and multiple-hit models.[30–32] Because the OD is proportional to the number of silver grains per unit area and the photon fluence, and because the photon or electron fluence is directly related to the radiation dose, the optical density should be a function of dose. The relationship between dose and optical density is known as the sensitometric curve.

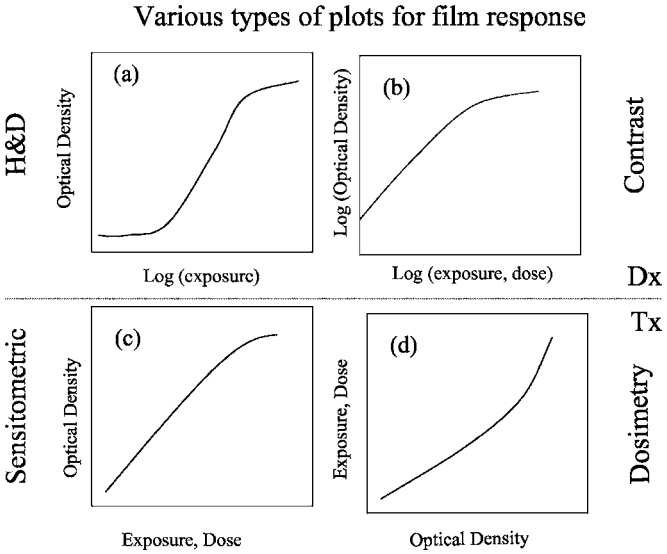

FIG. 2. Different representation of the film response and radiation dose. Upper panel is used in diagnostic radiology, whereas lower panel is useful in radiation therapy.

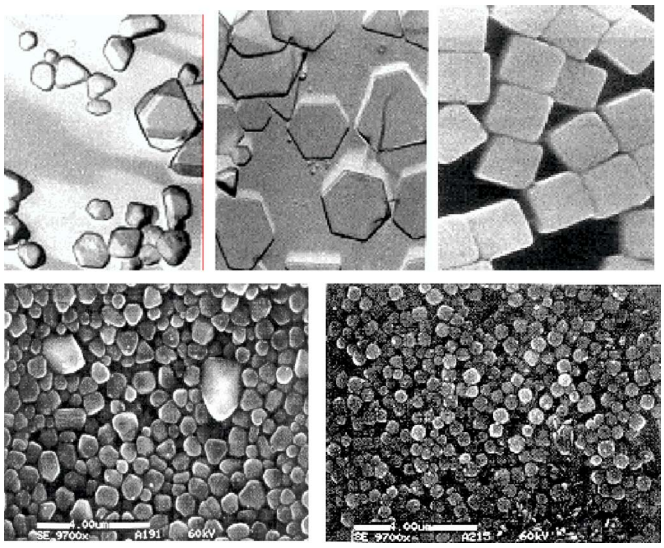

FIG. 3. Grain morphology: 3D, tubular, cubic, and others found in radiographic films. Adopted from Haus (Ref. 24) and Cheng and Das (Ref. 33). The upper panels of the figures have different magnification than the lower panels.

D. Characteristic curves

Hurter and Driffield introduced the sensitometric curve in 1890 and it is now referred to as the H&D curve.[30,31] The H&D curve is the film response curve of a film where the log (exposure) is plotted on the X axis and the OD on the Y axis. H&D curves are important for quantifying contrast and dynamic range of a radiographic film. The characteristics of film response can be plotted in various ways such as dose vs. OD, log (dose) vs. OD, or log (dose) vs. log (OD) as shown in Fig. 2. There are advantages to each of these plots, but in radiation oncology the dose versus OD presentation is most-often used and called the sensitometric curve. The OD is a function of several parameters:

$$\mathrm{OD} = f(D, D_r, E, \gamma, d, \mathrm{FS}, \theta, \tau), \tag{5}$$

where D is the radiation dose, D_r is the dose rate, E is the energy, γ is the type of the primary radiation (x rays, electrons, etc.), d is the depth of measurement, FS is the field size, θ is the relative film orientation (parallel or perpendicular), and τ refers to the processor conditions (e.g., development time and developer concentration). While, in principle, the OD depends on all of the factors in Eq. (5), the sensitivity of OD on some of the factors can be ignored for specific applications, including the clinical use for megavoltage photon and electron dosimetry. This will be discussed in detail later.

The H&D curve provides the characteristics of a film. It typically has three sections: toe, gradient, and shoulder. In diagnostic radiology, this type of graph shows the optical density range that provides optimal diagnostic information. A good optical density for visualization in radiology is 2; however, the useful OD range in radiation oncology typically ranges from 0 to 3. Most Kodak films do not have a linear response outside narrow dose ranges. Examples of sensitometric curves for various types of films can be found in various publications.[5,23,33,34] Roberts[35] has provided a table with a list of common films, showing their wide range of *slope and latitude* (range of exposure where OD is linear). Becker[32] provided similar information for some films used for dosimetry. Two films that are in common use for megavoltage beam dosimetry are Kodak XV film and the recently introduced EDR film. The response of all films to radiation is mainly due to their crystal size and the variation is significant. Some typical film crystal sizes are shown in Fig. 3.

E. Dependence of optical density on processing conditions

The relationship between OD and dose depends strongly on the processing conditions, including developer temperature. In general, for a given dose, OD increases as the developer temperature increases, as shown in Fig. 4. Bogucki *et al.*[36] showed that the optical density can be approximated as a function of temperature, τ:

$$\mathrm{OD} = K_0\tau + K_1\tau^2, \tag{6}$$

where K_0 and K_1 are constant for a specific film. While Fig. 4 shows data for diagnostic films, therapy films (e.g., XV and EDR) will have similar responses. Figure 5 shows other important film properties, including the relationship between developer temperature and fog, and contrast and film speed. In general, these properties are functions of developer temperature. Hence, the processing condition has to be carefully maintained. It can be seen in Fig. 5 that processor temperature changes can affect the slope of the H&D curve.

F. Dynamic range

For radiation oncology applications, the required dynamic range will depend on the specific application.[37–40] The dy-

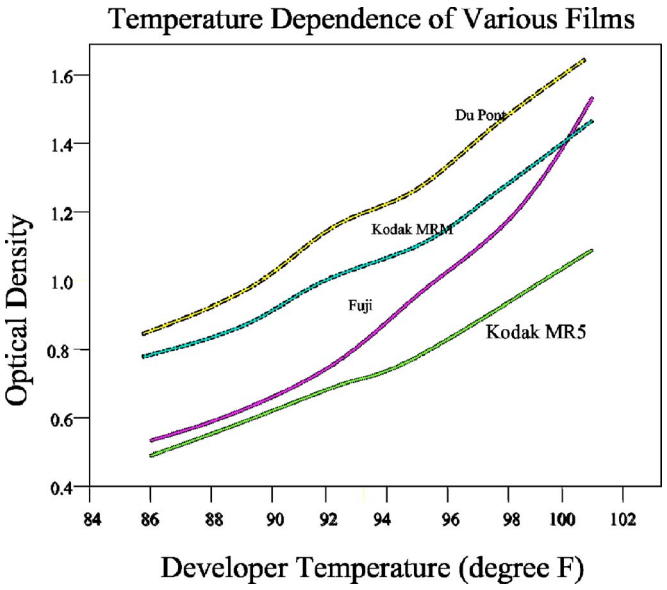

FIG. 4. Effect of temperature on OD of various films used in radiology adopted from Haus (Ref. 24).

namic range requirement for IMRT, for example, can be 0.2–3.0 Gy, larger than what Kodak XV film would allow. To overcome this problem, Kodak recently introduced an extended dose range film. There are several publications that investigate the sensitivity and quality of EDR film.[41–50] Because of its wide useful dynamic range, EDR film has become an important tool for IMRT quality assurance.

The typical dynamic range for XV and EDR film are 0.05–0.8 Gy and 0.1–5.0 Gy, respectively as shown in Table I.

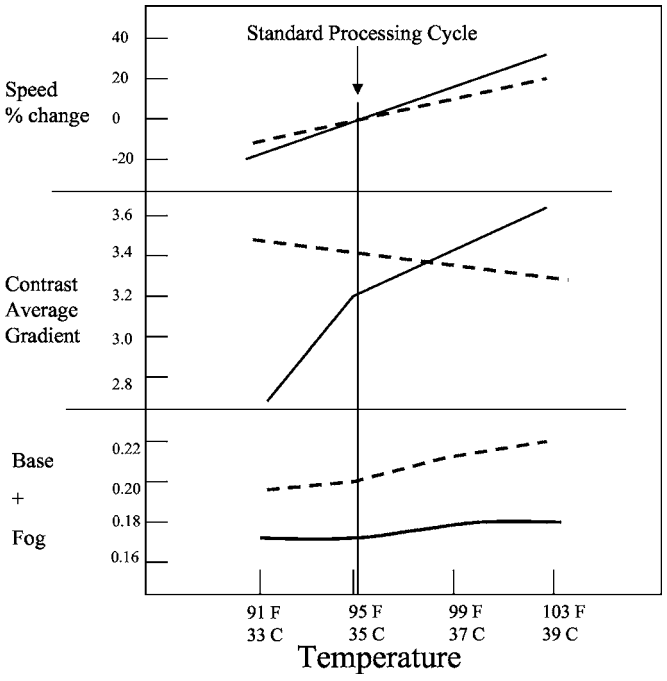

FIG. 5. Effect of developer temperature on various properties of the films. Solid line for 3D grain film and dashed line for the cubic grain (Ref. 24).

TABLE I. Physical properties of Kodak films.

Description	XV2	EDR2
Grain crystal	AgBr and AgI	AgBr
Total silver density (g/cm^2) (both sides of the film)	4.2	2.3
Effective thickness (μm)	0.4	0.2
Grain size distribution	Variation in size and shape	Monodisperse
Base thickness (μm)	180	180
Gelatin coating thickness (g/cm^2) (per side)	3	5
Double sided	Yes	Yes
Dynamic range	0.05–0.80 Gy	0.1–5.0 Gy
Dynamic OD range	0–4	0–4
Approximate Dose (Gy) for OD 1	0.4	2.0
Maximum recommended dose (Gy)	0.8	5.0

G. Energy dependence

Film contains silver bromide grains and both silver and bromine are high atomic number materials. X-ray interactions within these high atomic number materials are going to differ from those within materials of low atomic number such as soft tissues or water. Hence the film's relative dose response will depend strongly on the relative contributions of photoelectric interactions, and thus on the x-ray beam energy. There are various publications on energy dependence in different context.[5,11,31,51–53] Typical photon dose or exposure response curves are shown in textbooks such as those by Herz[28] and Attix.[31] It is known that for photon energies below 100 keV, the dose response increases and peaks up to 40-fold compared to ^{60}Co and then drops rapidly for megavoltage beams. This response increase is due primarily to the photoelectric absorption process in the silver bromide grains. The energy dependence also causes dose-measurement artifacts in megavoltage beam dosimetry where the ratio of primary to low-energy scattered photons varies, e.g., for large photon fields at deep depths.[5,54] This effect can yield dose-measurement errors that should be carefully evaluated by the medical physicist. Further discussion and clinical examples where energy dependence is an issue can be found in Sec. VII.

The dose response of Kodak XV film to low-energy kilovoltage beams and a high-energy x-ray beam is shown in Fig. 6 from a recent publication (adopted from Ref. 51). The beam energy in the figure is the equivalent photon energy derived from measured half-value-layer data. Figure 6 shows that the OD increases dramatically as the photon energy decreases.

H. Dose rate

Reciprocity law failure, known as the Schwarzschild effect,[50,56,57] relates to the nonlinearity of the optical density when exposed to various dose rates. The OD of a film is directly related to dose, which is a product of dose rate and time [$\mathrm{OD} \Rightarrow f(D)$; $D = D_r^* t$]. Hence for a given OD, dose rate and time are inversely proportional. When the system obeys

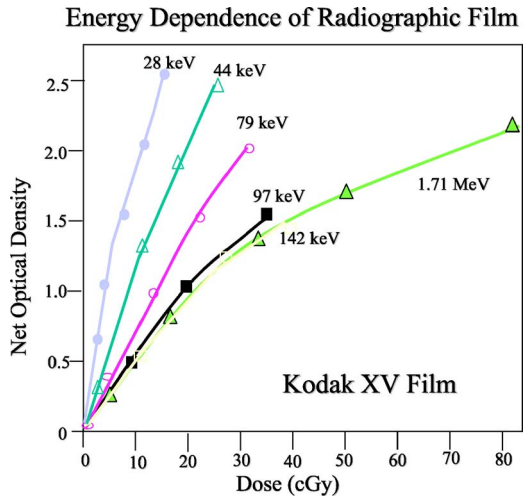

FIG. 6. Energy dependence of the optical density of XV film. Adopted from Muench *et al.* (Ref. 51).

reciprocity law, OD should be independent of dose rate. However, photographic films are shown to fail the reciprocity law. The dose rate effect is related to the grain composition and processing condition. For low energy and low dose experiments conducted during the middle of the 20th century, significant dose rate effects were observed. Ehrlich[55] showed dose rate dependence of x rays and gamma rays for Dupont 502 films (Fig. 7). Figure 7 indicates that for low exposures (<10 R), Dupont 502 film did not exhibit a dose rate effect. However, for high doses (>10 R), a significant dose rate effect was observed indicating solarization at extremely high dose rates. This steep dose rate dependence is often noted in the literature,[32] however such experiments have not been clearly demonstrated for megavoltage beams. Recently several publications[50,56,57] showed that, in general, reciprocity law does fail in megavoltage beams. For Kodak EDR and XV films, 5% and 9% reductions in OD, respectively, were observed when the dose rate was decreased by a factor of 12. Typical time-averaged dose rates in modern linear accelerators vary from 0.80 to 10 Gy/min and also the dose rates change from central axis to the beam penumbra.

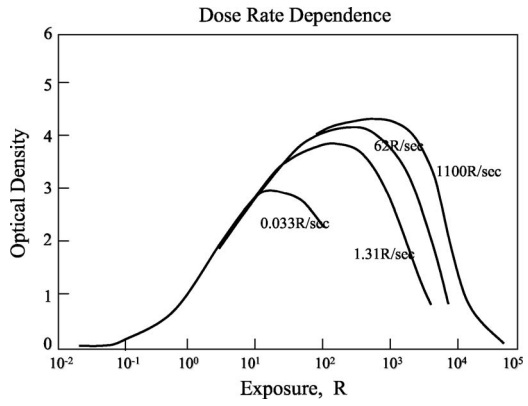

FIG. 7. Exposure-rate dependence of DuPont 502 film with 50 KV x rays. Adopted from Ehrlich (Ref. 55).

Djougela *et al.*[56] explained why the dose rate effect may not be observed when measuring the IMRT dose distributions and also provided a theoretical model to explain the Schwarzschild effect. In general, the reciprocity law may not hold for all films and processing conditions hence the user should consider this as a potential source of error in the film dosimetry.

I. Spatial resolution

The small grain size of radiographic film allows the film to have extremely high spatial resolution for dosimetry measurements. The spatial resolution of film-based measurements is typically limited by the optical densitometer aperture size and not the developed grain size in the film. Spatial resolution limits will be discussed in detail in Sec. IV.

J. Summary

In summary, silver halide films used for radiation dosimetry provide a practical dosimetric tool for the evaluation of relative dose, and with more care may be capable of sufficient accuracy for absolute dosimetry. However, every type of film should be evaluated for its linearity, stability, dynamic range, and response to various processing conditions before use. A comparison between the user's results and those in the published literature is recommended. As new films become available, some of the response data for these films may not yet be published and, in such situations, users are cautioned to proceed carefully.

III. PRACTICAL ASPECTS OF FILM PROCESSING

A. The principles of film processing

1. Developer

Film developing is a complex process, which includes four steps: developing, fixing, washing, and drying. In the development process the latent image is reduced to metallic silver grains. The development process does not affect the unexposed silver halide grains. The chemicals in the developer solution consist of Hydroquinone, Metol, or Phenidone in basic solution that convert the exposed grains to metallic silver. The developer also contains several other chemicals such as *accelerator* (alkali) to increase the rate of reaction by increasing the *p*H, *preservative (potassium and sodium sulfite)* to maintain the high *p*H by slowing oxidation, *restrainer (potassium and sodium bromide)* to keep unexposed grains from being converted, and *hardener* to prevent excessive absorption of water by the gelatin, which could damage the film. Excessive amounts of impurities like iron, copper, and tin in water can cause excess amounts of fogging. Hence, the water solutions used for making developer have to be free from impurities. Temperature also affects the development process, which is discussed later in this section.

2. Fixer

The process of fixing the film consists of rinsing off undeveloped silver halide crystals, which are still present in the

emulsion, by converting them into soluble components without damaging the silver in the emulsions, and neutralizing the alkaline solution from the developer that was transported from the developer tank. The chemicals in the fixer are also dissolved in water and consist of *fixing agent* (sodium and ammonium thiosulfate, also known as hypo) to remove undeveloped silver halide grains, *preservative (acetic acid)* to prevent decomposition of the fixer, *hardener* (potassium alum) to prevent excessive absorption of water by the gelatin, and *acidifier* and *buffer* to maintain the optimal *p*H.

3. Washing and drying

All remaining chemicals, except the silver aggregates, which are permanently affixed to the film, are removed in the rinsing step. Filtered water is used for washing the films. The final stage is to dry the film with heated air.

B. Factors affecting consistency in film processing

1. Darkroom

The darkroom requires particular attention because it is an important part of the film processing system and is usually custom-designed to meet the needs of each site. For example, there should be adequate amount of storage space so that a clean counter area dedicated for film handling is available. The accumulation of dust, dirt, and chemicals can introduce dose measurement artifacts. The counter area should be open and flat so that it is easy to keep clean. The wattage and type of safelight should be designed so that it will not introduce significant fogging of the employed film types. Adequate ventilation for removing the moist hot water vapor emitted from the processor should be provided. A dedicated area for cleaning the racks during maintenance should be provided to allow proper service of the system.

2. Processor

Most modern automatic processors have a microprocessor or microcontroller that monitors and implements its functions. It is common for modern processors to support multiple developer cycles so that the user can select the cycle time. For example, some processors may support extended, regular, and rapid processing at different combinations of developer replenishment rates, processing times, and developer temperatures. An important requirement for film processing is consistency. The response of film to radiation dose changes rapidly with variations in the processing conditions. Because measurement sessions often expose large numbers of films, it is important that the processor provides consistent film development for as many films as the user expects to process in a single session. There are multiple factors that will affect the development of the latent image. The major ones are (a) chemistry activity level, which depends on developer concentration, developer oxidation, developer contamination, replenishment rate, and the use of special chemistry (i.e., starter) during startup of the processor; (b) processing time; and (c) developer temperature. Processors are designed to control these factors and keep the variations within specified limits.

3. Chemistry control

Chemistry activity level of the processor is an important factor affecting film dosimetry. However, chemistry activity is a dynamic quantity that depends on many factors. The processor replenishes developer as films are processed. Modern processors determine the replenishment according to the area of the film fed through the processor rather than the older method based on the length of film fed. This provides greater stability in processing conditions when films of different sizes are used in the clinic. The developer in the developer tank slowly oxidizes between replenishments at a rate depending on the developer temperature. The replenishment chemical is usually stored in a replenishment tank where the ambient temperature determines its oxidation rate. The volume of developer in the replenishment tank relative to the volume of films per day determines the loss of chemistry activity while the developer is stored in the replenishment tank. As a result, the cycle selected, the volume of film processed per day, the pattern of film processing during the day, the ambient temperature of the darkroom area, and the replenishment rate setting affects the chemistry activity that produces the latent image. Rapid developing cycles usually have a higher developer temperature than regular cycles and consequently faster oxidation rates. The selection of developing cycle may depend on the volume of film used and amount of developer oxidation that can be tolerated. A large volume of chemicals in the replenishment tank with a low film volume will experience more loss of chemistry activity level of the replenishment developer and consequently a change in the OD film response. It is thus preferable to have a consistent pattern of usage and conditions so that the processor reaches an equilibrium state. Most processors require a minimum volume of film to attain stable developer activity level during the day. An accepted criterion is about 40 films of 14×17 in.^{2} size processed at regular intervals per day.

A constant flow of film processed over the day will help in achieving an equilibrium chemistry activity level. Unfortunately, it is common for film dosimetry projects to have a relatively large number of films to be processed in a short period of time. This change in pattern of processing can affect the equilibrium and a new equilibrium should be established for consistency. Processing five to ten blank (unexposed) films before processing films containing measured data is effective in such situations. When the volume of film processed is less than about 25 films per day, it may be advantageous to use flood replenishment. In this mode the processor will replenish the developer regularly, in addition to the area of film processed. During initial installation, fresh developer with starter solution may be used to reduce the effect of using fresh chemistry instead of seasoned chemicals.

TABLE II. Film processor tests.

Test	Procedure	Frequency[a]
Darkroom cleanliness	Check cleanliness under white light	W
Processing protocol	Determine frequency of sensitometry checks from reproducibility of processing	C
Ventilation	Check dark room ventilation	C
Artifacts	Process two identically exposed films in different directions of film transport and check visually	C, W
Developer temperature	Measure with body temperature thermometer	C, W
Immersion time	Measure film transport time	C, W
Sensitometry	Expose film with sensitometer and measure "base and fog," mid density and density difference	C, W, E
Replenishment rate	Check sensitometric stability	C
Fog Level	Cover half of exposed film in darkroom, check optical density difference	C

[a]C=commissioning, W=weekly and E=each time the processor is used for dosimetry.

4. Processing time control

Some processors have a selection of processing cycles. The standard cycle has a typical drop time, the time it takes for a film to go through the processing cycle, of 90 s. The developer immersion time should be consistent during the life of the processor. A baseline developer immersion time should be recorded after installation for future reference.

5. Developer temperature control

As discussed in Sec. II, the developer temperature affects the response of the film and its magnitude depends on the film type. In a typical film processor, the developer circulates within an internal circuit consisting of heaters and heat exchangers to control the temperature. Due to the sensitivity of the film OD on developer temperature, most processors have a tight tolerance ($\sim$0.3 °C) for developer temperature and temperature gradient within the developer tank. Some processors provide a temperature readout, which can be compared periodically with measurements using a thermometer.

C. Commissioning a film processor for dosimetry

1. Acceptance and commissioning tests on a film processor

When a processor is installed, a group of tests (Table II) should be performed once to verify that the processor operates within specifications and to establish a process for film dosimetry. These tests do not have to be done regularly. After a major repair, a subset of the tests related to the repair can be performed to confirm that the repair is acceptable.

a. Ventilation. After installation or repair involving the ventilation system, the operation of the ventilation of the dark room and the processor should be confirmed.

b. Artifacts. This check is performed to identify artifacts such as roller marks, scratches, and optical density variations within a relatively uniform film exposure. During acceptance testing, this test is performed to verify that the installed processor is within specifications. This test also establishes a baseline for future reference. In this test, two films are exposed with a field size that covers the surface area of the films. The film size for this test is the largest that will be used at the site for film dosimetry. The two films are stacked and exposed at the same time at a depth of maximum dose with appropriate buildup and backscatter material. The orientation of the film is identified by placing a radio-opaque object at one of the corners of the radiation field. An exposure to achieve an OD of about 1.5 is given. The two films are then processed by feeding the short side towards the processor for the first film and the long side towards the processor for the second film. After processing, the films are evaluated visually for artifacts. If artifacts are found, those due to the processor will appear at perpendicular orientations on the two films.

c. Developer temperature. A digital body-temperature thermometer can be used to measure the developer temperature. A mercury thermometer should never be used because, if the thermometer breaks, the mercury can contaminate the developer tank. To ensure consistent results, the temperatures should be measured at the same location in the developer tank. The developer temperature should be measured over a period of 10 days. The standard deviation of the temperature is compared with the manufacturer specification as part of the acceptance testing. The average and standard deviation are used as baseline commissioning values for weekly QA.

d. Developer immersion time. For a specific processor model, the time between when the rollers catch the leading edge of the film to the time when the film comes out of the processor is used as a relative measure of the developer immersion time. A stopwatch is started when the film is felt to contact the rollers and it is stopped when the film drops into the film exit slot of the processor. This relative immersion time is measured over the same 10 days as the developer temperature check above. The average and standard deviations of the relative immersion time are computed as baseline values.

e. Sensitometry. Sensitometry is an effective method to monitor the condition and quantify the stability of the processor. In sensitometry, a film is exposed by a sensitometer, which is an instrument designed to expose different areas on a film to very precise amounts of light, with typical specifi-

cation of ±0.02 OD. A sensitometer that meets the IEC 61223-2-1 requirements should be used. The exposed film is processed by the film processor being tested. The optical densities of the exposed areas are measured using a densitometer. A densitometer should be calibrated to ±0.01 OD with a NIST traceable optical density tablet (see Sec. IV).

In order to ensure consistency of the sensitometry test, the films used should be selected from a single batch of film, identified by the manufacturer-supplied batch number. When a batch of film is exhausted, the standardized procedure described in Sec. III D below is followed to transition to a different batch. The sensitometer step wedge should be exposed in a consistent orientation and the film processed in a consistent direction. These tests should be performed during the same time of day that most of the dosimetry films are processed.

Sensitometers designed for diagnostic screen film systems may be used to expose the films used for film dosimetry. The exposure may be adjusted to accommodate the film sensitivity. If the largest sensitometer exposure level cannot expose the film to optical densities above 2.0, multiple sensitometer exposures at the same location may be used to provide ODs beyond the limit of a single exposure. The sensitometers may require a minimum recovery time to reach their calibrated exposure levels, so for multiple exposures a delay between successive exposures as specified by the manufacturer should be employed. A sensitometer is used to expose step wedges on all four sides of the film. The darkest steps on opposite edges of the film should orient in the same direction on the film. The color (blue or green) and exposure time are specified.

The film is fed with the lightest step on the short edge first and the lightest step on the long edge towards the right. This method allows the detection of a gradient in film processing along and perpendicular to the direction of film transport as well as the overall variation of the processing. If a film dosimetry protocol requires extra films to be processed before the films with data are processed, the same numbers of films should be processed before the sensitometry film.

After processing, the optical densities of four predetermined steps on each sensitometer exposure at the four film edges are measured. The following procedure can be used to select these four steps and establish control limits. After installation, the processor is operated for a period of time until it is seasoned. This means that the developer in the processor has turned over two to three times with the replenisher under normal operation. For 10 consecutive days on a seasoned processor, the relationship between optical density and x-ray exposure for the most often used film type is measured according to the selected film dosimetry protocol (Sec. III B). The processor should be stable enough so that the variations of the optical densities for the same x-ray exposure are within the acceptable limits for film dosimetry. On the same 10 days, films are exposed with a sensitometer on four sides as described above. These ten films are processed at the same time as the other ten films exposed to x rays. The optical densities of each step on the sensitometer strips are measured. The average optical density of the lightest step (step one) is taken to be the "base and fog" level (BF). The step with average optical density closest to 0.25+BF is taken to be the low-density step. The step closest to 1.0+BF is the "mid-density" step. The step closest to 2.0+BF is the high-density step. The difference between the high and low density steps is an index for the mean gradient of the sensitometric characteristic curve. The "density difference" is used for quality control of the processor. During commissioning, baseline values *shall* be established for QA of the processor. The averages and standard deviations of the "base and fog," "mid-density," and "density difference" are computed from the 10 days of measurements as baseline values.

f. Replenishment rate study. After installation, repair, or change in processor load, it is important to perform a replenishment rate study for film dosimetry. Since inappropriate replenishment rate has the maximum effect on the last few films for a batch of films processed consecutively, it may not be apparent if only a small number of films are processed. In order to evaluate the effectiveness of replenishment for film dosimetry, a number of films corresponding to the maximum number of films used for each dosimetry run are exposed with x rays using a typical field size. They are exposed with identical settings to approximately 1.5 OD. Sensitometric strips are exposed on the four edges of each film. The films are processed according to the film dosimetry protocol (Sec. III B) with the lightest step on the right and towards the processor. The x-ray exposure, mid-density, density difference, and base and fog are evaluated to determine if chemical equilibrium is maintained through all the films processed as required by the film dosimetry protocol. The study should be done for all film sizes used in film dosimetry.

g. Fog level test. After installation or repair that may introduce light leak, a fog level test is performed to evaluate the level of light leakage. This test is also used to check the light leakage from the safelight after installation or repair. Since the response of film to light is nonlinear, the test should be done using an optical density of about 1.5 (the condition at which film dosimetry is most sensitive to leakage of light in the darkroom) and not at the optical density of the base. To account for this variation in sensitivity at nominal x-ray exposure levels, a film is preexposed to x rays to give an expected optical density of about 1.5. In the darkroom, half of the film is covered by thick black paper and left to be exposed to light leakage at a location where most of the film handling is done. It is exposed in this manner for duration ten times the typical film handling time. The film is processed and the optical densities on the covered side and the exposed side are measured. The difference should be less than the uncertainty in film dosimetry established according to Sec. III C 2 below.

2. Establishing a film processing protocol

As detailed in Sec. II above, since there are many variables affecting the consistency of film processing, and there are factors such as film processing load that are specific to each clinic, it is not possible to have one protocol that will meet the needs of all clinics. It is important to evaluate the

processing practice in each clinic to determine if a different film processing protocol should be implemented for film dosimetry as part of the commissioning procedure. It needs be done only one time before the processor is used for film dosimetry. We will describe a procedure to determine a film processing protocol for consistent film dosimetry that will meet the accuracy and precision requirements.

The first step is to decide on a limit in the variation in optical density that is acceptable to the film dosimetry application under consideration. For example, the accuracy requirements for film dosimetry in patient QA of IMRT treatments may be ±3% and that for checking head leakage may be ±10% in dose. For the determination of absolute dose, there *should* be quantitative requirements. For illustration, the requirements could specify ±0.05 OD at 1.5 OD, ±0.03 OD at 1.0 OD, and ±0.02 OD at 0.5 OD applied simultaneously. These should be based on the sensitometric curve of the film used. For example, if the accuracy requirement is ±5% at 40 cGy (or ±2 cGy) and the OD at 40 cGy is 1.5 with a slope of 0.025 OD per cGy, the requirement in OD will be ±0.05 OD (0.025 OD/cGy × 2 cGy) at 1.5 OD with two standard deviation limits. The specific requirements applied at a particular clinic should correspond to the uncertainty in the measurement of dose that is acceptable for the dosimetric application.

The second step is to identify the processor that has the steadiest film processing load. It may be useful to investigate the possibility of sharing a film processor with the radiology department. It may be helpful to discuss with the processor maintenance personnel whether the variations can be reduced by adjusting the replenishment rate, selecting an appropriate cycle time, or running the flood replenishment mode.

The third step is to quantify the reproducibility of the film processor. To quantify its reproducibility, films of the same batch are exposed with x-ray doses that yield optical densities specified in the quantitative requirements. It is useful to expose several areas of different dose on the same film. An example of this was reported by Childress *et al.*[43] where the exposure was delivered using a dynamic MLC. If a dynamic MLC is not available, the exposures can be performed with radiation fields defined by asymmetric jaws as long as the total dose from all areas to the center of each area is measured with an ionization chamber. During different times of the day and on different days, groups of ten films are processed in each session. The optical densities of the x-ray exposed regions are measured. The variations in OD among the films show the film processor reproducibility. The results can be classified into one of the following categories:

(i) If the variations meet the requirements set forth in step 1, OD of processed films can be converted to dose using the x-ray sensitometric curve of the same batch of film obtained on a different day.

(ii) If the variations do not meet the requirements set forth in step 1, and the differences between the OD measured on films processed in the same session meet the requirements without any noticeable time trend in the OD measured within a session, the x-ray sensitometric curve of the same batch of film obtained in the same film processing session can be used to convert OD to dose, that is, a calibration film should be exposed for each film processing session.

(iii) If the differences between the OD measured on the first film and the tenth film do not meet the requirements, and there is observable trend within a processing session, it is necessary to evaluate whether the trend stabilizes for the last several films of a processing session. If there is indication that the trend stabilizes after a number of films are processed in a session and the variations in OD after the stabilization has been reached meet the requirements set forth in step 1, that particular number of films should be processed before dosimetry films are processed. A sensitometric curve of the same batch of film obtained in the same film processing session after stabilization has been reached can be used to convert OD to dose.

(iv) If there is no indication that the trend stabilizes, multiple calibration films from the same batch should be processed within a session and the OD is converted to dose using the calibration film processed at a time closest to the film to be analyzed.

After a film processing protocol is found that meets the limits on variations, the control limits of sensitometry will be established according to the procedure described in Sec. III A above.

D. Quality control of processors

1. Weekly checks

These checks are similar to the daily processor QA in a diagnostic radiology department. They are a simplified subset of the tests in Sec. III C above. These checks take less than half an hour to complete.

a. Darkroom cleanliness. Counters, the film feeding tray of the processor, and floor of the darkroom should be kept clean to avoid contamination and dust settling on the emulsion. This should be checked with white room light and not with the safe light. The counter should also be kept tidy so that there is a clear and clean area for handling dosimetry films and performing sensitometry tests.

b. Artifacts. The test described in Sec. III above is performed weekly to monitor artifacts due to film processing.

c. Developer temperature. The developer temperature is measured with the method described in Sec. III above once a week using a digital body temperature thermometer. The developer temperature is considered in control if it is within two standard deviations of the average value established during commissioning.

d. Developer immersion time. The relative immersion time is measured during the processing of the artifacts test films with the method described in Sec. III above. The relative immersion time is considered within specifications if it

is within two standard deviations of the average value established during commissioning.

e. Sensitometry. Sensitometry should be done according to a well-controlled procedure. A specific batch of film is specially set aside for sensitometry. When the batch of film runs out, a new batch of film is then commissioned for sensitometry using a crossover procedure that will be described below. A film from the commissioned batch is exposed with a sensitometer on four sides according to the procedure described in Sec. III. The "base and fog," "mid-density," and "density difference" are measured. The processor is considered in control during weekly checks if these control values are within two standard deviations of their baseline average values.

To crossover film batches for sensitometry, a film from the old batch and a film from a new batch are exposed with a sensitometer and processed in the same session every time during weekly checks for 5 or more consecutive weeks. The processor is confirmed to be in control with "base and fog," "mid-density," and "density difference" from the old batch of films as above. New averages and standard deviations of these values from the new batch of films are used as the revised baseline values.

2. Daily sensitometry check

On days that film dosimetry is done, the sensitometry check described above is performed to confirm that the processor is operating within specifications. This takes less than 10 min to complete. If the scattered radiation from the x-ray exposure is insignificant at the edge of the film, e.g., for small fields, the edge of the film can be exposed with a sensitometer and analyzed to monitor the consistency[58] of the process.

IV. DETECTION EQUIPMENT

A. Point densitometers

1. Characteristics and specifications

Point densitometers are straightforward devices used for determining the OD at a few points in a film. These devices are easiest to QA for absolute OD and are therefore often used as the local standards in OD measurements. Point densitometers use a silicon photodiode to measure the transmitted flux of light passing through a film. The International Organization for Standardization (ISO) has developed standards for the geometric and spectral conditions for the determination of optical density (ISO 5). Diffuse illumination is achieved by a broad-spectrum incandescent lamp whose spectral properties (Illuminate A) conform to CIE (International Commission on Illumination) standards. The collimated light passes through the film and the transmitted component passes through a detecting aperture that usually can be from 1 to 3 mm in diameter. This light flux passes through a "V_λ" filter (555 nm peak, 380–780 nm range) and is then detected by a silicon photodiode with amplifier electronics capable of measuring signals spanning several orders of magnitude.

FIG. 8. Typical point densitometer.

These systems consist of a backlit tablet with light aperture on which one places the film sample, an arm which extends over the film and has at its end the light source aligned with the aperture, and a digital readout of optical density (Fig. 8). The operating characteristics of four of these devices are shown in Table III.

2. Acceptance testing, calibration, and QA

These devices *shall* undergo acceptance testing. The following *should* be tested as described in Table IV:

- zero drift,
- OD range,
- calibration,
- reproducibility, and
- linearity.

Test the zero drift by turning on the unit and letting it warm up for 10 min or the amount of time recommended by the manufacturer. Null the unit, wait an hour, and take a null reading. The unit should still read 0 to within 0.01 OD. For routine use, one should check the null reading prior to each reading session. Calibration and determination of useful OD range of the unit is typically accomplished by using a NIST-calibrated step wedge that provides optical densities from about 0.05 to about 4.0 OD, including a zero value. After sufficient warm-up time and with the unit in calibration mode, two steps from the calibrated step wedge are used, the zero OD step and a higher OD, typically about 3, to create a two point calibration. To determine the usable optical density range, use the NIST-calibrated step wedge to sample steps at the low and high OD end of the step wedge and compare the readings to the known OD value. OD differences greater than 1.5% of the OD value or 0.01 OD, whichever is greater, indicate the limits of the sensitive range of the unit is being reached.

TABLE III. Vendor supplied specifications of some point densitometers.

Manufacturer	Density range	Accuracy	Zero drift	Apertures	Spectral response	Detector illumination	Detector	Measuring geometry	Resolution	Reproducibility
Nuclear Associates 07-443 (clamshell)	0.0–4.0 OD	0.02 OD	negligible	1 or 2 mm	Centered on 540 nm	Incandescent lamp with spectral compensation filter	Silicon photodiode	Diffuse	0.01 OD	0.01 OD
Nuclear Associates 07-424	0–4.5 OD	0.02 OD	negligible	1,2 or 3 mm	500–550 nm	Incandescent lamp with spectral compensation filter	Silicon photodiode	Diffuse	0.01 OD	0.01 OD
GretagMacbeth D 200-II	0–6.0 OD	0.01 OD	negligible	1,2 or 3 mm	Peak at 555 nm 50% transmission 100 nm	Tungsten lamp 3000° Kelvin	Silicon photodiode blue enhanced	Specular light source. Received light passes a diffuser	0.01–0.001 OD	0.01 OD or 1%
X-Rite 301	0–4.0 OD (1 mm), 0–5.0 OD (2,3 mm)	0.02 OD or 1.5% (whichever is greater)	negligible	1,2 or 3 mm	560 nm	Tungsten 2800° Kelvin	Gas filled silicon photodiode	Diffuse	0.01 OD	0.01 OD

Reproducibility and linearity can be tested by taking a reading of ten of the step wedge steps distributed across the full wedge OD range (be sure to include a very low and a very high OD step) and then repeating this several times a few minutes apart. Record the readings at each step and calculate the mean and standard deviations. The mean OD reading should be within 0.02 OD of the calibrated value, and standard deviation of each step should be within 0.02 OD or 1.5%, whichever is greatest, up to an OD value of 4.0. The user may limit the tests to the maximum OD that will be used clinically. The degree of deviation of the reading from the known OD value as a function of the OD value is a measure of the instrument linearity. Typically the absolute value of the reading error is largest at the highest OD value, where the percentage error should be less than 1.5%.

These same tests performed for acceptance of the unit

TABLE IV. Acceptance tests and QA of point densitometers.

Tests described in text	Procedure	Tolerance	Frequency[a]
Zero drift	Warm up unit and take series of null readings separated by at least 10 min. Check that unit reads zero	0.01 OD	A,e
Calibration	Use NIST calibrated step wedge to adjust unit to the correct OD at an OD value of about 3.0 (or the value recommended by the manufacturer). Zeroing the unit constitutes a second data point for the calibration.	0.02 OD	A,e
Optical density range	Sample low and high density steps of the calibrated step wedge and record the readings. Readings within 0.01 OD or 1.5% of the reading indicate the limit of the sensitive range of the unit.	0.01–4.0 OD	A,q
Reproducibility	Take reading of 10 step wedge steps from 0.1 to 4.0 OD. Repeat each step several times and record values.	Standard deviation of step reading within 0.02 OD of mean OD	A,q
Linearity	Same procedure as Reproducibility	Mean of ten readings at each step should be within 0.02 OD or 1.5% of known reading, whichever is greatest	A,q

[a]A=acceptance and yearly (annual), q=quarterly, e=each time.

should be repeated quarterly or at a frequency consistent with the documented stability of the instrument as noted in Table IV.

3. Practical recommendations for film dosimetry

Once the film has been calibrated for optical density to dose, one can determine the dose at any point on the film. This may be useful for dosimetry measurements where the film has an area of uniform density representing an unknown radiation dose. An example of this application is the estimation of surface dose for photons or electrons. Irradiate a phantom with one piece of film in ready-pack on the surface and another at d_{max}. After calibration of optical density to dose, the ratio of measured doses represents an approximation of surface dose. One can expect film to give a surface dose value about 10% absolute above that measured with an extrapolation chamber (personal communication, A. Olch). Another application is determining output factors for small or heavily blocked fields. Here a film can be exposed to a 5×5 cm^2 reference field for two doses about 30% apart (within a known linear region of the film's dose-response curve) and then to the small test field at the same monitor units as the reference field's higher dose, each at an appropriate depth. This should provide a dose for the small test field that is between the two reference field doses. The differential film response to fields less than 10 cm square has been found to be within 2% (for both XV and EDR) so that the 5 cm square reference field can be used to directly calibrate a 1 cm square field.[59] All films are processed together. The doses to the reference field are known and the optical densities can be measured with the point densitometer. The small test field optical density can be measured and its dose inferred from interpolation of the optical density-to-dose calibration data for the reference field. Also, simple percent depth dose or profile measurements can be made if the measurement locations on the film are carefully marked in a way which can be seen through the backlit tablet but do not interfere with the measurement.

B. 2D scanners: Mechanical scanners, CCD scanners, and other scanners

1. Characteristics and specifications

a. General characteristics. Two-dimensional (2D) film scanners or digitizers rapidly measure film OD planar distributions or profiles with high spatial resolution. When properly calibrated and characterized, these devices allow the study of the steep dose gradients found in brachytherapy as well as conformal external photon and electron beam radiotherapy.[26] The film response is quantified by high-resolution measurement of the 2D OD distribution contained in a film. This OD distribution is then converted to dose using an experimentally determined H&D curve. To date, 2D scanners that provide precise quantitative results are based on transmission optical densitometry, i.e., the light source illuminates one side of the film and is detected on the opposite side. 2D scanners that use reflection densitometry (where light is detected on the same side of the film as the light source after reflection back through the film) have a limited OD range and problems related to the uniformity of the reflecting surface. It is assumed in this report that the user has the access to software for viewing and interrogating any image data provided by these devices. A discussion of film analysis software is outside the scope of this report.

b. Light source and detector geometry. In general, there are four mechanisms for acquiring a 2D OD distribution from a film that can be categorized by the dimensionality of the light source and detector configuration. The first technique involves the translation of a point source over the film, typically by translating a collimated beam of light in concert with a confocal detector over the film (e.g., commercial systems include DynaScan Model 1710 Laser Densitometer, Computerized Medical Systems Inc.; FDM-300 Scanditronix Wellhöffer; CRS Laser Film Scanner, Med-Tec; and 9721 Film Densitometer, Multidata Systems Intl. Corp.). The second type of scanner simulates a linear light source by rastering a laser beam in one dimension while stepping the film in the orthogonal direction. A temporally gated linear detector or linear-detector array is employed in laser rastering systems [Personal Densitometer, Amersham Pharmacia (formerly Molecular Dynamics Inc.); LS50, LS75, and LS50 Kodak (formerly Lumysis)]. The third type of scanner employs a linear light source with a linear detector array (MultiRAD 860 and MultiRAD 460, Howtek, Dosimetry Pro Advantage/ Dosimetry-Pro 16, Vidar). The fourth type of scanner illuminates the entire film while detecting the transmitted light in a 2D detector array (CCD Microdensitometer, PeC). Higher quality scanners, which translate the film, do so either with high spatial resolution rollers or by translating a platen while holding the optics fixed to minimize any vibrations to the light source and detectors. Another important feature of 2D scanners employed for film dosimetry is a "split-beam" measurement where some type of measurement of the incident light intensity in coincidence to the transmitted light is performed. Devices without a measure of light output assume constancy of the light-source output during measurement. As OD measurement depends on knowledge of the initial light intensity, a split beam configuration is used to correct fluctuations in the light output of the device.

c. Spatial resolution. Commercially available 2D scanners typically have pixel dimensions that depend on the light source and detector geometry. Confocal point-source scanners typically have the lowest spatial resolution with beam spot sizes between 0.25 and 0.8 mm. Sample spacing for these devices can be typically adjusted between a fraction of the spot size and several centimeters. The higher dimensional light source (line scanning and 2D light sources) and detector geometry devices typically have much higher resolution with pixel dimensions between 0.34 and 0.042 mm. In principle, this small pixel size affords the spatial resolution to accurately image OD distributions band limited below spatial frequencies as high as 1.43 to 11.9 mm^{-1} by the Nyquist-Shannon sampling theorem.[60]

d. Dynamic range. The detectable OD for these devices typically ranges between 0 OD and upper limits of 2.5 to 4.0 OD, depending on the light source and detector technology.

Recent innovations in radiographic film technology have produced films that have nearly linear responses for ODs of up to 3.0 and possibly higher (ODs greater than 4, requiring a measurement of more than 1 part in 10 000, are difficult to measure accurately with these devices).[34] Dosimetry *shall* be performed inside the OD dynamic range specified by the scanner manufacturer to ensure that reliable results are attained.

e. Film format, readout time, and handling. The devices described in this section typically have the ability to rapidly acquire data from large format films at high spatial resolution in a matter of a few minutes. Films are typically mounted in one of two ways. Either the film is placed on a scanning platen or it is fed into a slot that grasps the film with elastic rollers. Scanners that employ rollers have typically been designed for digitizing diagnostic radiographs and a large number of films can be placed into a feeder slot for sequential scanning. These scanners have typically been designed to accept the largest clinical film formats and can accept films as large as 14×17 in.^{2}, allowing scanning of radiation field sizes of up to 30×30 cm^2 with a 5 cm border. Scanners that employ a scanning platen allow for more delicate handling of dosimetry films but typically limit the maximum size of the film to 10×12 in.^{2} and can only accept one of these films at a time. It is recommended that film be handled carefully with clean hands, or preferably using light cotton gloves, to prevent the transfer of oils from the hands to the film. Bending, stretching, or scratching a film should be avoided as this can permanently damage the film substrate or denature it, changing the opacity of the film. The film handling system and the film itself should be kept dry and clean. If dust is seen to accumulate, it should be removed with pressurized dry air. Do not attempt to clean either with liquid solvents. Glass platens for flat bed scanner can be cleaned with commercial glass cleaners unless they have an antireflective coating. Antireflective coated glass *should* be cleaned with pressurized dry air or using manufacturer-recommended procedures.

f. Discretization, scanner output, and software format. The 2D film scanners either directly measure OD or transmission (T). Devices that directly measure OD employ logarithmic and differential amplifiers to obtain low noise OD measurements. Scanners without a logarithmic amplifier measure light transmission, which can be subsequently converted to OD. The discretization of the signals produced by the scanner *should* be of sufficient dynamic range such that discretization error is below the desired measurement precision. For example, 12 bit analog-to-digital converters (ADCs) can provide 0.001 OD resolutions for systems with logarithm amplification and an OD range between 0 and 4.0 OD (0–4096 levels). Scanners that measure T typically have more bit resolution for discretization to provide the desired dynamic range, commonly employing 14 or 16 bit ADCs. Despite the fact that OD scanners logarithmically compress the signal compared with transmission, yielding a larger relative discretization error, transmission scanners require greater dynamic range because the signal spans four orders of magnitude while OD signals span a factor of 5 (OD 0–4 corresponds to T $1.0-10^{-4}$). Scanners that measure OD, or use less than a 12-bit ADC to measure T, may compromise the quality of measured data through discretization errors. It is very important to know whether a scanner's output is representative of OD or T. An OD is the quantity for film dosimetry that will be directly related to dose and use of T requires application of a nonlinear transformation in the sensitometric curve. Many scanners that measure T will allow for a direct conversion of the discrete level of measured T into OD using a look-up-table (LUT). Often, 2D scanners provide many LUTs from which a negative base 10 logarithm is one option. If LUTs are used, care has to be taken to ensure that an appropriate and consistent LUT is always applied; otherwise data corruption can take place.

Confocal scanning point densitometers do not typically support the output of data in standard image file formats and may have limitations on the size of the data that can be scanned limiting high-resolution scans to small regions. For higher dimensional light-source and detector geometry source scanners data can typically be exported as common image file formats such as the tagged image file format (TIFF), graphic interchange format (GIF), joint photographic experts group (JPEG), or Window's bitmap. Care should be used if the image format is compressed. For example, even selecting "no compression" in a JPEG does result in some compression. Since some compression schemes can lose information, compressed images should not be used in film dosimetry.

For transmission type scanners, e.g., Vidar scanners, the output is ADC units. There are $2^{12}=4096$ (12 bit) or $2^{16}=65\,536$ (16 bit) possible values. Thus, the primary calibration relationship is ADC units to the known dose. This relationship is logarithmic, so that for the 16 bit scanners, for example, there are about 50 000 ADC units between OD 0–1 and the other 15 536 units for the rest of the OD range. Thus, the OD resolution is much higher for low OD than for the higher ODs. These scanners do not output OD directly. Film calibration is most directly performed in terms of ADC units to dose. One does not need OD output to perform film dosimetry with these units. However, if one scans an OD step wedge, one can calibrate ADC units to OD if desired and one can use the constancy of scanner ADC units converted to OD as a way to check the long term stability of the scanner.

2. QA and acceptance testing

a. Acceptance testing

Table V provides a summary of the procedures for acceptance testing.

(1) Scanning procedure. The first step of scanner characterization is to establish a procedure of operation so that results are measured consistently. If provided, the manufacturer warm-up procedure should be adopted. If no guidance is given for scanner warm up, the consistency of scanner readout can be evaluated by performing repeated scans of a film with sufficient OD range to span the dynamic range of the scanner. Image subtraction of repeated measurements of the same film every 5 mins

TABLE V. Acceptance tests and QA of 2D scanners.

Tests described in text	Procedure	Tolerance/Recommendations	Frequency[a]
Warm up	A consistent warm up procedure and the determination of consistency of scanner readout by performing repeated scans of a film and performing image subtraction of repeated measurements of the same	The scanner gain should be constant to within 2% and the noise of the system should be <2% of the OD of the measurement in the range of operation.	A and Y
Geometric accuracy	The spatial integrity of 2D scanners shall be independently validated in both dimensions using a known test pattern that spans the scanning plane.	Local distortions should be <1 mm. For distortions >0.5 mm over 10 cm a spatial correction to dimensions should be applied.	A and Y
Calibration	Measurement of the characteristic curve s using neutral OD films with known nominal values of OD and uncertainty.	A least squares curve fit can be applied to a reasonable set of calibration points, and then used to supply intermediate points necessary for accurate conversion of measured OD to calibrated OD.	A, Y and Q
Characterization of possible interference pattern artifacts	Scanning nearly uniform films (described in Sec. IV B of varying OD (between 0.1 and 1.0) to assess the magnitude of the error introduced by interference artifacts as a function of OD.	Interference patterns should be < 2% of the OD of the measurement in the range of operation.	A
Characterization of possible light scatter artifacts	The light scatter artifact can be detected by scanning a nearly uniform high OD film (described in Sec. IV B), used in clinical dosimetry, and then scanning the same film with a hole cut in the center.	If loss of OD is <5% within 1 mm of the edge of the hole, then the film in question can be scanned without artifact otherwise a more careful study is warranted	A
Evaluation of effective resolution	The light scatter artifact can also degrade the effective resolution of the system.	A line pair test should be performed with black lines printed on a transparency film with line spacing down to a least 1 mm. The resolution limit of the system is found where the valley between lines increases >5% OD of transparent background.	A
Characterization of scanner uniformity	Taking the small film cut from the center of the film in the previous test scan it at different locations in the scanning line or bed.	If OD from different locations changes <5% and profile width if within 1 mm, then scans are invariant to location, otherwise care shall be taken to reproduce film positions and sizes.	A

[a]A=acceptance, Y=yearly (annual), Q=quarterly.

for 1 h after power-on can be used to empirically determine if the noise or gain of the system is changing with time. Image subtraction of images taken after warm up can be used to determine the noise introduced by the scanner to the measurements and check for gain drift as zero offsets in the subtracted images, which should contain only noise for a stable system.[25] The scanner gain should be constant to within 2% and the noise of the system should be less than 2% of the OD of the measurement in the range of operation. If a scanner demonstrates significant noise or gain changes at times longer than 30 mins the device may be unsuitable for film dosimetry. In particular, devices that do not have "split-beam" measurement geometry or some technique for correcting the measurement of the incident light intensity in coincidence to the transmitted light may require frequent recalibration. Once a warm-up protocol is established it should be adhered to for all characterization and dosimetry measurements.

(2) Characteristic curve and linearity. The characteristic or sensitometric curve of the scanner *should* be determined, i.e., relationship between the measured OD or T and the actual diffuse OD or T, where diffuse OD or T refers to transmitted light that is collected for all angles. In principle, the relationship between the measured and the actual OD or T should be linear. However, most scanners

exhibit nonlinearities near the maximum and minimum of their ranges. Measurement of the characteristic curve should be performed using neutral OD films (i.e., OD that does not depend on the wavelength of the light employed) with known nominal values and uncertainties of OD (preferably traced to a NIST standard). Either large format films (e.g., an OD step tablet where the steps extend across the entire field of view for the scanner) or a small film with high OD masks that extend over the entire field of view should be employed to separate out the device's inherent OD measurement characteristics from any artifacts that may exist in the presence of large OD gradients or steps. It is recommended that the OD steps should be spaced linearly in OD with a step size of at most 0.5 OD. The measured values of OD or T and their estimated noise should match the tolerances specified by the scanner manufacturer. An appropriately measured characteristic curve will be a monotonic increasing function.

(3) Geometric accuracy. The spatial integrity of 2D scanners *shall* be independently validated in both dimensions using a well-characterized test pattern. Ideally, the spatial test pattern films should be validated by an independent laboratory and made available by the manufacturer. If a spatial test pattern is unavailable, a 2D grid of lines or dots can be printed with 1 cm spacing on an overhead transparency sheet using a laser printer and independently validated by measuring the spacing between the points with a ruler. This transparency grid should be affixed to a piece of unexposed and developed radiographic film if used in a scanner that employs film rollers to transport the film. The scanned positions of the spatial grid can then be compared with the known values. The grid positions should be checked for pair-wise accuracy at increasing distance intervals until the field of view is spanned in both dimensions. It is recommended that local discrepancies should be sub-millimeter for neighboring lines or points. Small discrepancies that accumulate over increasing distances may be due to a difference in the pixel dimension from those reported by the manufacturer.[25] Ideally, a spatial correction that scales the measured to the physical dimensions *should* be applied in the horizontal and vertical pixel dimensions if such accumulating distortions exceed 0.5 mm over 10 cm.

(4) Spatial frequency limits on quantitative results. Ideally, acceptance testing criteria of spatial resolution should be based on reported line-spread functions (LSF), point-spread functions (PSF), and modulation transfer functions (MTF) for measured light-transmission values of the film scanner.[61–63] Unfortunately, these measurements require considerable resources that are not widely available, though some results have been reported for older model scanners.[61,62] Therefore, we recommend that scanner manufacturers take on the responsibility of acquiring and providing such data for all systems intended for quantitative film-dosimetry applications. The use of MTF data for evaluating scanner performance is further discussed in the Appendix.

(5) Characterization of possible interference pattern artifacts. Interference pattern artifacts have been reported for systems that employ a scanning platen or transparent film support in the optical path of the scanner.[26,64–66] This artifact is caused by multiple reflections due to variations in the index of refraction along the light path between the film and its support. Air gaps between the film and the digitizer platen can give rise to "Newton's Rings" interference artifacts due to multiple reflections between the air, glass, and film materials. While less severe, variations in film thickness and internal film structure can also lead to multiple reflections to produce intrafilm interference, though this has only been reported in radiochromic film.[26] This artifact produces a high frequency fluctuation pattern that gives rise to errors as large as 7% in low OD regions. In principle, aliasing of a high frequency OD distribution can produce an artifact[67] with a similar appearance known as a "Moiré pattern." Such artifacts have been observed in digital radiography films where a high spatial resolution antiscatter grid was employed with spatial frequencies of 3–4 lp/mm.[67] It is unlikely that such high frequency signals would be present in routine dose distribution measurements.

For platen-based densitometers, the optical interference pattern shapes are strong functions of the distance between the film and support platens. The interference pattern is therefore, for practical purposes, irreproducible.[26] This makes artifact removal by image subtraction impractical for these scanners. Recent studies have shown that some scanners that use film rollers can produce reproducible artifact patterns that can be eliminated by image subtraction.[66] Several techniques to eliminate this artifact have been suggested. They use material placed in the optical path of the scanner to break the coherence of the light source and prevent interference from multiply reflected light. Fortunately, these techniques, which include diffusing ground glass,[66] vellum paper,[27] and antireflective coated glass,[65] have all been used to successfully abate this artifact. It should be noted that this artifact is most significant ($>2\%$) at OD values of less than 0.5 and should not affect measurements at high OD values. It is recommended that scanner manufacturers incorporate an appropriate solution to this artifact into devices intended for use in film dosimetry. It has also been recently reported that some commercially available scanners are free from this artifact due to the use of an incoherent light source.[66]

(6) Characterization of possible light scatter artifacts. Several publications have reported the existence of light scatter artifacts in 2D scanners that employ higher dimensional light source and detector geometries.[25,26,65,68,69] This artifact has been observed to significantly corrupt OD measurements in the presence

of high gradient and high OD distributions. This artifact behaves nonlinearly for OD measurements, being essentially nonexistent for measurements of low-gradient low-OD distributions and incurring errors of up to 30% of lost OD in high-gradient high-OD distributions. Dempsey *et al.*[26] have demonstrated that this artifact can be removed using linear-systems signal processing techniques after the interference pattern artifact had been removed from a commercial 2D laser scanner system (Personal Densitometer, Amersham Pharmacia, formerly Molecular Dynamics Inc.). This technique has also been successfully applied by Low *et al.*[65] to a fluorescent lamp and linear CCD array scanner. An important point made by these works is that the artifact can only be properly assessed from the transmission data (e.g., a MTF displayed for scanner transmission values would demonstrate it). Measured *transmission* LSF and MTF provided by the scanner manufacturer would allow medical physicists to assess the potential impact of this artifact on the dose distributions that are intended for measurement. An alternative technique using a LUT for scanners that measure T has also been proposed to eliminate this artifact.[68] More work is called for in the detailed investigation of light scatter artifacts in 2D scanners and their potential impact on film dosimetry. While confocal point light source and detector 2D scanners are the slowest and lowest resolution devices of all those described, they are typically free of light scatter artifacts that have been reported for systems with higher dimensional detectors and light sources. Therefore, we recommend that caution be used when attempting to measure dose in the steep-dose gradient regions found near brachytherapy sources and in the penumbrae of external beam dose distributions. Existing characterizations of scanners indicate that restricting the max OD<2 should help avoid this error.[25,26,65,68] When dealing with high ODs and/or gradients where this artifact can be important, care is taken to ensure that measurements are not being corrupted. Repeated measurements, with a lower dose and hence a lower OD, which should diminish any potential artifact, are suggested to determine whether such an artifact is significantly affecting the measurement.

b. Calibration. Measurement of the characteristic curve *should* be performed at least quarterly using neutral OD films with known nominal values of OD and uncertainty (preferably traced to a NIST standard). This measurement *should* be tracked over time to ensure consistent operation of the scanner. A curve fit that is forced to go through the measured data can be applied to a reasonable set[61,63] of calibration points, and then used to supply intermediate points necessary for accurate conversion of measured OD to calibrated OD. A least squares curve fitting can be useful in smoothing out noise but the user *should* carefully inspect the fit compared to the measured data to determine if any of the measurements points are suspect and need to be repeated.

c. Protocols and practical recommendations. Practical clinical film dosimetry can be practiced with all of the devices described in this section. While the slowest, oldest, and lowest resolution devices, confocal point light source, and detector 2D scanners are somewhat cumbersome to use, they appear to have the fewest issues with regards to possible measurement artifacts. A single unfortunate, yet important, exception to this is that they often are not split beam devices and can suffer from long time gain drifts in their measurements requiring frequent recalibration. Additionally, they are often limited in data size and data digital export format for 2D dose mapping applications. More modern 2D scanners with higher dimensional light sources and detectors can rapidly image 2D OD distributions with very high resolutions and provide data in modern imaging formats. While this appears as a more attractive alternative, care *shall* be taken to ensure that the results from such devices are quantitative for the intended application; considering both the OD or T range and the spatial gradients that exist in a measurement film. While MTF data provide the best method for this assessment, there are some simple tests that can be applied to determine if a 2D scanner suffers from the artifacts described above.

To perform these tests, nearly uniform films of varying OD values are required. To produce such films we recommend that films oriented perpendicular to the beam axis be exposed by a large area field (30×30 cm^2 or greater) at depth (typically 5 to 10 cm) in a large water-equivalent phantom (30×30 cm^2 or greater) using the lowest available megavoltage photon beam energy (to provide the sharpest penumbra). Clinical ion-chamber beam profile data can be used to select a beam quality and depth with a high degree of flatness. Typically, a central region of approximately 20 $\times20$ cm^2 or greater can be found where the beam has a uniform dose and, hence, OD to within 2%. A point densitometer, as described in Sec. IV A, can be used to accurately spot check the film for OD uniformity. Interference artifacts are found by preparing and scanning a uniform OD film with an OD between 0.1 and 0.5. The artifacts will appear as a high frequency pattern.[26] Scanning uniform OD films at several intervals between 0.1 and 1.0 will provide an assessment of the magnitude of the error introduced by this artifact as a function of OD. The effective resolution of the scanner can be determined using a black and white line pair test generated by printing lines with a 600 dpi or higher resolution laser printer on transparency films. Lines should be printed with varying widths down to at least 1 mm with 1 mm spacing. The resolution limit is taken as the width where the transparent valley increases in OD by 5% above the OD of the transparent background (Note that scalable pdf line spread test films can be purchased from SINE PATTERNS LLC, http://www.sinepatterns.com/index.htm). The light scatter artifact can be detected by scanning a uniform high OD film and then scanning the same film with a hole cut in the center as described by Messerman and De Wagter.[68] A significant drop of OD near the edge of the hole will indicate the existence of this artifact. If an artifact is observed, then cutting the hole to a larger size should then increase the observed effect upon rescanning. If the OD of the film used

TABLE VI. Expected film dosimetry accuracy under ideal conditions (optimal processor and densitometer performance).

Procedure	Relative dose
Photon beam data acquisition and QA	2% or 2 mm for field sizes $\leq 10\times 10$ cm^2 and depths $\leq$15 cm (Ref. 74)
Electron beam data Acquisition and QA	Distance to agreement for PDD is $\leq$1 mm at depths greater than 10 mm (Ref. 33)
Composite plan IMRT	2% or 1.5 mm EDR2 film, 4% or 3 mm XV2 film (Ref. 73)

in this test is near the maximum OD used for film dosimetry, then the potential for this artifact to affect a clinical dosimetry film can be assessed. If there is no significant effect, then the scanner can be used without scatter artifacts for high dose distributions containing steep gradients; otherwise a more careful study is warranted. Finally, the uniformity of the detector response *should* also be tested. The small film(s) cut from the uniform film(s) can be scanned at different locations in the scanning line or bed. The central OD and the profile of the small film should be invariant with scanning location.

V. DOSIMETRIC CHARCTERISTICS OF COMMONLY USED FILMS AND PHANTOMS

A. Relative vs. absolute dose measurements

As mentioned in earlier sections, the sensitometric curve *should* be established for the same energy, batch of film, type of film, film orientation, and processing conditions under which the film is to be used. The sensitometric curves relating OD to dose in a phantom may be linear or nonlinear depending on the film type and dose range. If one operates in the region where the OD is linearly related to dose,[7] and a valid calibration curve is applied, then accurate relative dosimetry may be obtained. If one requires absolute dose, then one *shall* establish the relationship of dose to pixel value[12,70] or OD to dose.[38,71,72] By processing a new calibration film dataset at the same time as that of the experimental films, then accurate absolute dosimetry may be obtained. Typically second or third order polynomials provide the best fit to calibration data.

Reports in the literature are contradictory as to whether XV2 film can be used to make absolute dose measurements with an accuracy of better than 5%.[4,33,34] With EDR2 film better accuracy may be achieved.[73] Chetty and Charland[74] have described in detail the method to minimize potential experimental errors with film dosimetry. They also provide uncertainty estimates, which in part form the basis for achievable accuracy (Table VI) with film dosimetry for clinical photon and electron beams.

B. Types of film and range of optical density

Film response is highly energy dependent below photon energies of 400 keV[5,72] because the photoelectric mass attenuation coefficient varies with the cube of atomic number. Since the relative number of low energy scattered photons increases with both depth and field size for megavoltage beams, it is thought that film sensitivity is significantly influenced by both parameters.

A depth dependence of the sensitometric curve has been observed for both the parallel and perpendicular film orientation for photon beams from ^{60}Co to 23 MV[5,6,11,12,21,75,76] and has been summarized by Danciu *et al.*[4] There is a large difference in the magnitude of the effect reported by the different investigators. While some authors indicate minimal depth dependence and a decrease in depth dependence with photon beam energy, Anderson and St. George[77] report a significant depth dependence of the sensitometric curve for 25 MV. A sensitivity dependence on radiation field size is also reported although it is $<3\%$[9,12,76,78] for fields up to 20×20 cm^2. For fields smaller than 4 cm in diameter, as are used in radiosurgery, the depth dependence has been found to be insignificant.[12]

There are no significant energy dependent effects for small fields and shallow depths, where the scatter tends to be a small fraction of the total dose inside fields, i.e., the energy spectrum is not changing rapidly. Because this may not be true outside fields, where scatter is a large portion of a small dose, film dose accuracy is greatly diminished when used to measure doses outside fields. For larger fields and depths, the scatter dose increases and so energy dependent effects become more pronounced, especially in the low-dose primary regions.

The most commonly used film for dosimetry is the Kodak X-Omat V (XV2). It is a low-speed film with emulsion coating on both sides of the plastic base.[4] The silver halide crystals in the emulsion are nonuniform and of tublar grain type.[33] The Kodak film can be irradiated to doses up to 0.8 Gy and still maintain an optical density of less than 2. The sensitometric curve is generally curved, with the derivative of OD to dose decreasing with increasing dose.

Kodak has developed a new therapy film (EDR2). Its advantage is that there is a greater linear OD range, a smaller microcrystalline structure, lower silver content, and a response, which extends to higher doses and is reported to be nearly linear up to 3.5 Gy.[74] The response and accuracy of the EDR2 film has been compared to the XV film. Variations in response with changes in radiation field size have been reported to be less than 2% for both XV and EDR2 film for radiation fields smaller[7,59,73,74,78] than 10×10 cm^2. But variations of 5%–7.5% have been reported for field sizes greater than 24×24 cm^2; however, these variations also included depth dependence.[59,77,79] One way of overcoming the problem of overresponse of the film at deeper depths is to use a sensitometric curve at deeper depth for the dose conversion. Another way is to normalize measurements made with film with spot measurement made with a more accurate dosimeter such as an ion chamber. Changes in sensitivity as a function of depth have been observed, although less than with XV film. For example, Dogan *et al.*[59] reported a decrease in sensitivity with depth of 0.5% at 20 cm and 6×6 cm^2 field size for EDR2 film but 2.5% for the XV film. At the larger field size of 24×24 cm^2 increased film sensitivity was observed and was 4.2% for the EDR2 film and

7.2% for XV2 at the same depth. Olch[73] reported a maximum depth dependence of 2% for EDR film up to field sizes of 20×20 cm^2 but 10% changes for XV film at 20 cm depth in all field sizes. The energy dependence was shown to be less for EDR film than XV film in the range ^{60}Co to 18 MV.[40,59,79–81] To overcome depth dependent effects a method has been described by Williamson *et al.*[5] in which an equation is derived from a single field percentage depth dose and is fitted to a depth dependent sensitometric curve.

C. Measurement geometry

Most commonly radiographic film is used in either parallel or perpendicular orientation placed between slabs of a polystyrene or water-equivalent phantom.[5,6,23,33,34,39] The surface of the phantom that lies in contact with the film *should* be flat and the film tightly clamped between the phantom slabs so as to avoid air gaps.[23,78] If the film is kept in its light-tight packaging, air holes should be punctured in the packet to reduce the formation of air pockets between film and phantom. Because of potential undesired film exposure due to Cerenkov radiation,[82] it is suggested that the film should be kept in its packet. If paper wrappers are used for both film calibration and isodose curve measurements, any effect that the paper wrappers have on film sensitivity will be included in the sensitometric curves. In this case extreme care is taken to ensure a smooth match between the edge of the film and the entrance of the phantom edges where the film is used in parallel to the beam axis. The edge of the film should be carefully folded over the edge of the phantom. Making sure that the film edge aligns with the phantom edge, the folded edge of the film should be secured to the phantom slab with the tape. Recent statements by Kodak indicate that the film jacket was meant to be light resistant not light tight. Care should be taken when jacketed film is left exposed to room light, particularly after exposure to radiation.

When the film is placed horizontally, the phantom slabs will tend to compress the film package. In other orientations, the film and slabs *should* be compressed by a mechanism or clamps,[6,77] which provide even pressure and good contact between the phantom and the film. Registration marks on the film (made with pinpricks) are often helpful to define the film location with respect to the beam. Suchowerska *et al.*[22] noted that an air gap produced an apparent over response of 10% with XV film. It is recommended that, unless otherwise indicated, for parallel irradiation with single beams, the film and phantom be laid horizontally so that gravity can compress the film. The gantry is then rotated laterally to perform the irradiation. When the film is aligned parallel to the beam, it is important that the film edge in the film jacket is found and aligned carefully with the surface of the phantom or that the proximal end is positioned against the phantom material. A method proposed by Danciu *et al.*[4] is to detect the film edge and mark it on the paper. Then align these marks to the phantom edge and fold excess paper and tape to phantom.

For the parallel irradiation geometry, there is a controversy as to whether it is necessary to angle the beam 1–2 deg from the exactly parallel beam-film alignment. Suchowerska *et al.*[22] gave an explanation in support of this angulation, based on increased forward scattering electrons in the silver halide. Another reason given for the over-response is simply that no matter how well one clamps the phantom to the film to reduce air gaps, a small gap may be present that served to reduce attenuation of the beam. Suchowerska's calculation[22] showing that 0.6 deg is necessary assumes a 2 mm phantom gap across the film and its envelope. A more typical gap with good compression of the phantom is 1 mm or less, which would give a needed 0.3 deg beam angle to the film to avoid any over-response. For film parallel to the couch top, the weight of a $30\times30\times5$ cm^3 thick solid water slab on top of the film is sufficient to provide good compression. Suchowerska *et al.*[22] had a 1 mm gap, yet a 5% over-response was observed for XV film oriented at 0.5 deg and a 7% over-response was observed for radiochromic film at a 1 deg angle. Others have not found an over-response when setting the beam angle to be parallel to the film.[4,11,74] Gantry angle readouts are typically calibrated to an accuracy of 0.5–1.0 deg, so at least this small misalignment angle may have been present in many of the published dosimetry studies. Also, for megavoltage photon beams, the fraction of the dose to the film from electrons generated more than 0.5 mm from the film at even medium depths is very large. Although this task group cannot demonstrate a benefit from angling the gantry by up to 1 deg in the presence of the typical (less than 1.5 mm) gap between the phantom slabs compressing the film, we feel that this small gantry tilt does not jeopardize the measurement except for very small field sizes where the beam may diverge from the film at the deeper depths.

D. Phantoms

A water-equivalent commercial film phantom that holds bare film has been described by Bova. This phantom design provides a system that is light proof, is free of air gaps, offers good alignment, and allows rapid loading and unloading. Cheng and Das[33] report that the CEA film packets (manufactured in Sweden and marketed in the US by CEA America Corporation, Houston, TX) would be suitable for immersion in water. Other solid phantoms used are Temex (polyisoprene, density$=1.015$ g/cm^3) by Anderson and St. George,[77] and water-equivalent slabs by Suchowerska *et al.*[22] and Masonite by Danciu *et al.*[4]

Film is suitable to insert in any custom made phantom constructed for specific purposes, cubic or curved, e.g., between slices of an anthropomorphic phantom. A special purpose film cassette fitted into a water enclosed head phantom was constructed in order to verify stereotactic radiosurgery dose distributions.[12,70] Special water-equivalent phantoms are also commercially available for IMRT dose verification and most of these are in a slab geometry while one is cylindrical and holds the film in a spiral configuration. Most phantoms for film dosimetry consist of water equivalent material, however some contain non-water-equivalent plugs with elec-

tron densities equivalent to a variety of human tissues. Charland *et al.*[80] investigated EDR film dosimetry in lung equivalent heterogeneous media.

A cubic high-impact polystyrene film phantom is provided with the Peacock IMRT system.[65] High-impact polystyrene has a density of 1.044 g/cm^3 and is usually opaque. Unlike clear polystyrene, opaque polystyrene usually contains high atomic number ingredients. Thus the scattering of such phantoms compared with water may be different depending on the beam, and caution is advised. A correction for the higher density can be made. However, phantoms made of Lucite (or PMMA) of density 1.18 g/cm^3 are not recommended because of the greater density correction and the possibility of Cerenkov radiation in the clear plastic.[82]

Films *should* be exposed in tissue simulating material (water equivalent plastic). It is recommended that several centimeters of water-equivalent material be placed above and below the film to be exposed. Burch *et al.*[11] developed an experimental setup of a tissue-equivalent phantom and thin lead foil to be used with XV film. This publication reported that the lead filter removed low energy photon scatter. The polystyrene blocks including the film and filter were compressed in an aluminum compression box to remove any air cavities. The filters were placed on either side of the film at 6 mm distance. By removing the low energy scatter, the dependence of the sensitometric curve with depth in phantom is removed. Yeo *et al.*[38,39] explored this idea further and reported with Monte Carlo modeling to determine the ideal setup and distance of the Pb foil filter. Utilization of lead filters has resulted in very good agreement between film dosimetry measurements and ion chamber measurements.[40] Burch *et al.*[11] maintain that this is due to the proper utilization of tissue-equivalent phantom and the effect of the foils to reduce the scatter in the energy range where film is supersensitive. However, some researchers maintain that the improved results are due to the film being well compressed in the tissue-equivalent phantom, which minimizes the air gap.[22] Several commercially available phantoms have been developed to make film exposure in water-equivalent plastics easier and more repeatable. If one needs to use the lead filter to eliminate very low energy photons, it *should* be used with caution.

E. Recommendations

Films *should* be exposed in tissue simulating material (water-equivalent plastic). It is recommended that several centimeters of water-equivalent material be placed above and below the film to be exposed. If film is used inside an envelope, the phantom in contact with the film *should* to be compressed so that air pockets are removed. While using non-water-equivalent phantoms, the user needs to make appropriate density corrections compared to water.

VI. FILM CALIBRATION PROTOCOL

There are many factors that contribute to an accurate calibration including the type of scanner, the type of film, the type of delivered radiation, the exposure conditions, the type of film processor used, the conditions under which the film is processed (chemical mix, temperature, etc.), and the settings or configuration of the film scanner. Due to this large mixture of conditions, it is not possible to have a generic calibration procedure that applies to all or most circumstances.

There are several steps of calibration and each one is critical to the success of film dosimetry. There are two common methods of calibrating film to dosimetric values: either the beam axis is parallel or perpendicular to the film.

A. Calibration geometries

1. Parallel calibration geometry

Parallel film calibration is performed by having the central axis of the radiation beam in the same plane as the sheet of film. The film orientation for the calibration film and the film to be analyzed are the same, the depth dependence is effectively calibrated out by using this technique. The film *should* be exposed to radiation levels that are similar to those that span the range expected to be delivered to the patient and in addition have at least one dose point that exceeds the maximum level expected on the patient film. Use the same field size as for subsequent irradiations that will be corrected by this calibration data. To get the low dose part of the calibration curve, longer films (35×43 cm^2) may be used if that size film can also be used for the subsequent QA images (and phantoms sufficiently large are available). In cases where only smaller films are available, the more typical 24×30 cm^2 film should be used where the 30 cm dimension is along the increasing depth direction. With this geometry, doses down to about 25% of maximum dose can be directly measured. Doses below 25% can be interpolated to zero dose by a fitting routine, typically automatic in commercial film dosimetry software. If very accurate doses below 25% are required, then two films may be necessary to sample enough points for the high and low dose levels. If a large phantom is available, then the two films can be irradiated one behind the other. In this case care must be taken to properly identify the depths on each film by means of fiducials or pin pricks in the phantom away from the central axis. If the more standard 30×30 cm^2 size phantom is to be used, then the films will be irradiated one at a time, with the highest dose needed given to d-max on the first film, and a dose of about 50% of that dose given to d_{max}on the second film. Note that with either method, the depth of any dose may be different than that within the QA image to be analyzed. To the extent there is energy (i.e., depth) dependence of the film, there will be some error in using these calibration data.

The processed film is scanned into the computer and smoothing or filtering may be applied to the pixel values. A depth density profile or several profiles are then taken through the image from the point of highest dose to the point of lowest dose. Once the acquisition software has extracted this data, the user designates the dose at various depths. The corresponding depth dose information is readily available from standard ion chamber measurements taken during commissioning of the accelerator. The software then develops a

calibration curve to correlate the values from the film scanner and the measured dose points. Prior to using the parallel calibration method, one *should* characterize the influence of field size and depth on the constancy of OD with dose for each film type to be used by measuring the OD or scanner ADC value for a given dose and field size for the range of relevant depths. One may find that, depending on energy for smaller field sizes, a dose given at 5 cm and one given at 20 cm give nearly the same OD or ADC value while this may not be true for larger fields.

2. Perpendicular calibration geometry

Perpendicular film calibration is performed by exposing one or more films to a series of dose levels. If multiple dose levels are exposed on a single film, care shall be taken to ensure that there is no dose overlap between the exposed areas. Ideally a separate film should be irradiated for each dose point with an equivalent field size as the test irradiation. If test irradiation uses smaller field size (such as 7×7 cm^2), then one can position these fields in the corners of the film. In this case, the user *shall* determine the dose at each square accurately and include the scatter contribution from other squares. A calibration exposure can also be made with a known dose pattern[109] (e.g., a step wedge in dose generated with a MLC, couch movement, or compensator) if the dosimetry software is capable of accurately calibrating with this pattern (e.g., in a step wedge, only the uniformly exposed areas *should* be used for calibration). The use of dose patterns may considerably reduce the physics time and number of films needed to expose a complete calibration curve, thus enabling more frequent calibrations resulting in higher accuracy. It is critical that each film in the calibration set is exposed under the same experimental setup conditions (e.g., at the same depth). Each film is scanned into the computer, the user designates a uniform area for each dose level, and the average reading in this area is correlated to a measured dose value to create the calibration curve.

B. General considerations

The decision to use either parallel or perpendicular irradiation for film calibration depends on the degree of energy dependence of the film used and the geometry that will be used for actual test measurements. One *should* use the same geometry for the calibration film as for the test film. This tends to match the scatter characteristics of the calibration and test film environments. For example, use perpendicular geometry for film calibration when the measurements are for beam profiles or fluence map evaluation at a constant depth, and parallel calibration geometry if the test film is irradiated parallel to the beam axis to get isodoses and profiles at various depths. When the film is oriented vertically and irradiated by all the beams of a coplanar plan, the film should be calibrated using the parallel geometry. Where one irradiates the test film with a combination of beam directions, such as for a coronal film plane in a composite IMRT plan QA test, no one calibration geometry is applicable. The physicist *shall* choose a film orientation for calibration based on the above recommendations and validate the particular type of film for the mixed angle of incidence used for IMRT QA.

Before exposing films in either the parallel or perpendicular configuration, the experiment *shall* be carefully constructed to ensure accurate and reproducible results. First, if the film is to be exposed in the film package (optical jacket), the package *should* be punctured at a minimum of two locations (outside the film area or at the edge of the film). This will allow trapped air, from within the optical jacket, to be pushed out during film fixation in tissue simulating material (phantom). Air gaps between the film and the phantom can result in incorrect and widely varying dose readings over the area of the film as discussed in Sec. V.[22] Having the phantom slabs and film stacked parallel to the couch top is recommended for either parallel or perpendicular irradiation condition.

Independent of the calibration method utilized, the user *should* ensure that the calibration value for zero dose (base plus fog) be obtained from a completely unexposed film rather than from an apparently unirradiated area of an irradiated film. This practice will eliminate scattered radiation in the zero dose calibration value.

In order to minimize the effect of the variation in the film processor, all of the calibration films *should* be developed in the same session. A temperature change of just one degree within the film processor can have a dramatic effect on the density of the film. Similarly, a change in the processing chemicals will also affect the density of the film, as explained in Sec. III. A simple technique of running a previously irradiated film through the processor can check the processor functionality and cleanliness, in addition to saving time and trouble if processor malfunction occurs.

Film-based and ionization-chamber based dose measurements are often compared. Caution is advised while doing this comparison. In high dose gradient regions, depending on the volume of the chamber, such a comparison will be inaccurate because the effective point of measurement within the chamber is not the center and its true location is generally unknown. Comparing beam profiles in a gradient region, the chamber will, depending on its volume, show a smaller gradient due to volume averaging than the film. In low dose gradient regions produced by beams from multiple directions, the effective point of measurement of the chamber can be taken to be near the center of the chamber. For single beams, the point of measurement is upstream of the center of the chamber. In either situation, depending on the degree of dose homogeneity, a valid comparison between the chamber dose and the film dose can be made. The film dose *should* be obtained by filtering and averaging over an appropriate region to reduce the impact of noise in the film data.

It is recommended that the film be calibrated at doses that span the portion of the film dynamic range that will be encountered in the measurement. The user *should* make sure that there is a zero-dose point (base and fog) and one calibration point beyond the maximum expected measured dose to prevent the requirement for dose extrapolation. The number of calibration points will depend upon various factors:

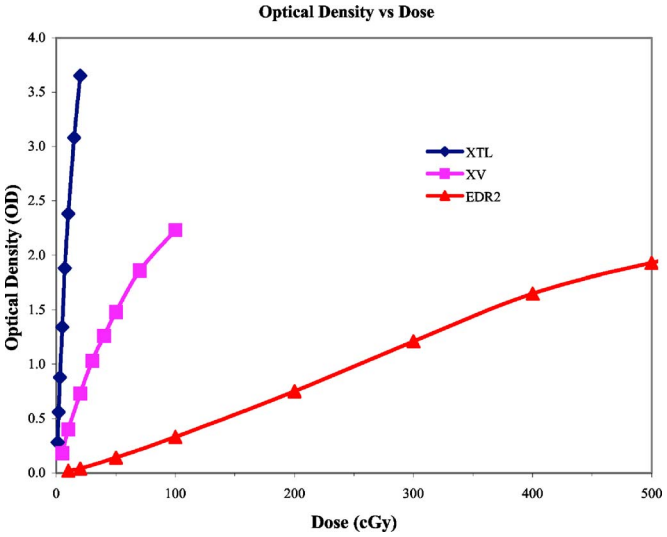

FIG. 9. Film response curves.

(a) The dose values and their spacing of the calibration points are critical to accurate film dosimetry.
(b) The next most critical factor is the type of curve fitting algorithm that is used by the film calibration software. If linear interpolation is used for films with a nonlinear response, more calibration points will be required. Some other types of fit may yield good results with fewer calibration points.
(c) The type of film also influences the decision. (e.g., XV versus EDR2)
(d) The type of scanner also makes a significant difference. If the scanner uses only a 12 bit digitizer rather than a 16 bit digitizer, for example, the number and value of the calibration points will be more critical.
(e) Importance of measurements where the dose-response curve is nonlinear. More points will be needed in the nonlinear region to accurately determine the dose.

For both XV and EDR2 films, approximately 13 equally spaced points well define the curve across their respective useful dose range. The calibration curve *shall* be measured for the modality, electron or megavoltage photon, and beam energy. Typical film response curves for silver halide films are shown in Fig. 9.

The user *shall* develop a calibration curve for each type of film to be analyzed. If the film to be used is very expensive or if the experimental setup requires a small film (to fit within a phantom), it may be necessary to expose and analyze small films. These *should* be handled in accordance with the steps mentioned in Sec. IV. If the film is smaller than the scanner can accommodate, then the film to be analyzed is to be placed within a plastic jacket and the calibration films shall also be placed within a plastic jacket. In this manner, the data values sent from the scanner will reflect both the exposed film and the transport media, and the effect of the transport media can be compensated for in the calibration curve.

Some types of scanners allow the user to adjust the integration time for each pixel or for each row of pixels. The integration time is the amount of time that light is collected for that pixel or for that row of pixels. If the integration time is adjustable, the user *shall* ensure that each of the calibration films and the films to be analyzed are scanned with the same integration time.

C. Summary of calibration procedures

- Ensure that the film scanner is warmed up according to the manufacturer's recommendations.
- If the film will be exposed in a jacket, puncture the jacket in two locations to allow any trapped air to escape.
- Some types of film can be sensitive to room light, even in their film jackets according to the KODAK recommendations. Therefore, minimize the time that the jacketed film is in room light to lessen any potential affect.
- Place the film between slabs of the phantom. Good compression is critical to reducing or eliminating any air effects.
- Use the films from the same batch for both calibration and the subsequent QA measurements.
- Keep one unexposed piece of film separate from the rest for the "zero dose" (base plus fog) value.

1. Calibration methods

a. Parallel calibration method

- Place the film parallel to the radiation beam.
- Ensure that the front edge of the film is precisely aligned with the front edge of the phantom.
- Uniquely identifiable pinholes or registration marks can be made.
- Phantom depth *should* be at least 3 cm deeper than deepest point needed for the lowest dose point on the film.
- Place sufficient phantom material above and below the film.
- Expose the film to a dose level that exceeds the maximum level expected on the patient film or film to be analyzed. Use the same field size as for subsequent irradiations that will be corrected by this calibration data. Longer films (35×43 cm^2) may be optimal for large dose ranges with sufficiently large phantom. In cases where only smaller films are available two films may be necessary to sample enough points for the high and low dose levels.
- Extract at least 13 depth dose points distributed evenly across the full depth of the film (except for the last 3 cm) to be used for the calibration curve. If

the calibration points are optimally selected from the film characteristic curve, fewer points may be sufficient.

b. Perpendicular calibration method

- Typically 13 dose points can be calibrated uniformly over the dose range expected to be utilized. Also expose the film to a dose level that exceeds the maximum level expected on the patient film or film to be analyzed.
- Choose a depth and field size that is the same as that to be used for subsequent irradiations.
- It is recommended that the dose delivered to the calibration film be independently checked using an ionization chamber.
- Expose one dose level to each film to minimize the dose contamination from one dose level to the next.
- For multiple exposure calibration films, make sure that there is no dose overlap between exposures (i.e., carefully shield each area of the film). By using fields of 7×7 cm^2 in the corners of the film one can avoid dose overlap within 1%.
- It is critical that each calibration film is exposed under the same experimental setup conditions (i.e., the same amount of solid water and the same depth).
- Mark each exposed film with the dose level for later reference.
- A calibration exposure can also be made with a known dose pattern (e.g., a step wedge is dose generated with a MLC, couch movement, or compensator) if the dosimetry software is capable of accurately calibrating with this pattern.
- The transition area between steps should not be used in the calibration process (e.g., in a step wedge). Only the areas with uniform exposure should be used for calibration.
- The use of dose patterns may considerably reduce the physics time and number of films needed to expose a complete calibration curve, thus permitting more frequent calibrations resulting in higher accuracy.
- Since some dose overlap may occur, careful ion chamber measurements *should* be made for each area in the pattern to accurately account for the actual delivered dose.

(1) If the film manufacturer recommends a time interval between exposure and processing, wait the suggested interval. The paper by Childress *et al.*[43] suggests that while for XV no delay between exposure and processing is necessary, for EDR film dosimetry one should wait 1 h.
(2) To minimize variation in the film processor, all of the calibration films should be developed in the same session.
(3) Ensure that the film processor is maintained to the recommendations of the manufacturer. Processor QA enumerated in Sec. III should be performed on a regular basis.
(4) To prevent excessive film processor temperature rise, pause after several films to allow the processor to return to its original temperature.
(5) Mix constant dose films with the experiment films to keep track of processor chemistry and temperature change and their effect on OD.
(6) If the film scanner can be commanded to perform an internal calibration (without film), calibrate the scanner just before scanning a batch of films.
(7) Calibrate the scanner to known OD values by scanning a NIST calibrated step wedge. This may not be necessary for dose conversion but is always helpful for the proper generation of a correct H&D or sensitometric curve and for tacking the performance of the scanner.
(8) Scan the film into the computer following the recommendations of the film dosimetry software that is being used.
(9) Some amount of filtering is always recommended to reduce dose artifacts caused by lint, dust, and fingerprints on the film.[83,84] Use a filter size $\geqslant 1$ mm^2 to reduce the dose artifact.
(10) When comparing against ionization chamber doses, choose a region of interest that is appropriate based on the ionization chamber that is used.
(11) The software will produce a calibration curve to correlate the values from the film scanner to the measured dose points.

VII. CLINICAL APPLICATIONS

Film dosimetry is a useful tool for commissioning, routine quality assurance (QA), and verification of special procedures.[5,8,9,12,59,71–74,76,81] The high resolution of radiographic film combined with modern film density digitization is often the reason for choosing radiographic film as a dosimetric tool, particularly for periodic QA, SRS, and IMRT applications. Its ability to provide a reasonably accurate and precise 2D distribution from a single exposure, avoiding labor and equipment intensive scanning procedures at the treatment machine utilizing point detectors or linear detector arrays, is beneficial for commissioning soft wedges and IMRT applications. When the film is used with tissue equivalent phantoms, the measured dose distribution is what would be present in the absence of the film, allowing multiple films to be irradiated simultaneously. These features make film a very attractive dosimeter for external beam dosimetry measurements as long as its response to radiation (optical density versus dose) is completely characterized in the clinical beams.[4,5,11,12,33,75]

A. Photon beam data acquisition and QA

The basic dosimetry data for commissioning clinical photon beams include central axis depth dose, cross beam profiles, and isodose distributions. As explained earlier, film do-

simetry is quite useful for measuring cross beam profiles, which have a steep dose fall-off in the penumbral region. This is because the ion chamber measurements in the penumbral region are prone to volume averaging effects and the higher spatial resolution of the film provides more accurate measurements. The film is shown to be reasonably accurate within 2% or 2 mm for fractional, central axis depth doses, and profiles over a range of field sizes (up to 10×10 cm^2) and depths (up to 15 cm) in the phantom. Moreover, the film sensitivity is not significantly influenced by the off-axis variation in the energy spectrum that results from increased scattering in the cross beam profile penumbrae and tail region.[74,76] As described in Sec. V, the films do have a problem of relative over response (3%–5%) relative to ion chamber for large field sizes and deeper depths greater than 15 cm. This is attributed to an increase in film sensitivity of approximately 4% due to laterally scattered low energy photons and increase in scatter to primary dose ratio with depth and field size.

Even with all the limitations described above, film is an ideal dosimeter for quick relative QA measurements of depth doses and cross beam profiles. It can be used to verify the flatness and symmetry of the beam as well as the light and radiation field coincidence. For a rapid check of radiation parameters such as flatness and symmetry, the user can select a dose and subsequent OD in the linear region of the response curve without the use of a calibration curve. It is also an ideal dosimeter for measuring the beam quality change of the clinical photon beams. A small change in the photon beam quality manifests itself into a dramatic change in the off-axis ratio measured at shallow depths with a film. A single film exposure can quantify and verify all of these parameters.

B. Electron beam data acquisition and QA

The advantages of film dosimetry (high spatial resolution and short beam time) for electron beam data acquisition over ion chamber dosimetry could be much more obvious because a large amount of measured electron beam data are often required to commission a treatment planning system. Data are required for many field sizes at each nominal electron energy and sometimes it is repeated for multiple collimation systems (for example, different applicators). It may be impractical to measure all of the electron beam data with ion-chamber/water phantom system as it will require a substantial amount of accelerator beam time.

Radiographic film can be reliably used for electron beam dosimetry as long as proper attention is paid to the film emulsion (same manufacturing batch), processing conditions, linear dynamic range of optical density, and setup conditions. The Kodak XV silver halide films have little energy response for clinical electron beams.[23,85] However, the new EDR2 films exhibit an apparent energy-dependent enhancement for electron beams.[42] While this film has shown to excel at x-ray dosimetry applications such as IMRT dose verification, it should be used with care when performing electron beam dosimetry. The film dosimetry setup conditions are critical in electron beam dosimetry because of sharp dose fall-off. Therefore, electron beam dosimetry measurements with film *should* be made with a cassette that is made of near-tissue-equivalent solid and opaque phantom material. These cassettes are commercially available and are very useful in removing some of the major systematic errors arising from air gaps adjacent to the film and the misalignment of the top edge of the film with the surface of phantom when the film is positioned parallel to the beam axis.

The film cassette, described above, can be used to measure electron beam depth dose, cross beam profiles, isodose distributions, and output factors. The expected distance to agreement (DTA) for the central axis depth dose is typically within 1 mm at depths greater than 10 mm. The underestimation of dose near the buildup region from film measurements is partly attributed to the high atomic number of the film emulsion, which produces more electrons scattered out by the film than are scattered in from the solid phantom. Due to this potential difference, it is recommended that the central-axis buildup depth dose be measured with either a diode or a parallel plate chamber. The expected accuracy of the high dose region of cross beam profiles measured with film is typically of the order of 2% and 2 mm in the penumbral region. Therefore, film in an electron water-equivalent phantom can be used for the measurement of the isodose distribution by aligning the film parallel to the beam axis. The most efficient and accurate method of measuring isodose distributions for clinical electron beam is still a hybrid technique, in which the central-axis depth dose measurements with either an ion chamber or a diode detector are combined with the cross beam data measured using film in a solid-water phantom. This technique not only provides the same degree of accuracy as the ion-chamber/water-phantom measurement, but also reduces the amount of beam-on time on the linear accelerator. Finally, the film is an ideal dosimeter for quick relative QA measurements of depth doses and cross beam profiles. It can be used to verify the flatness and symmetry of the beam as well as output factors.

C. Commissioning dynamic (soft) wedge

The idea of producing wedge-shaped dose distributions by controlling collimator motion was first reported in 1978.[86,87] Soft wedges became available in the late 1980s. One-dimensional intensity modulation, wedged fields up to 20 cm wide and asymmetric fields up to 30 cm wide (10 cm across the axis), is currently achieved via modulation of jaw motion and dose rate. Wedge angles varying between 10 deg and 60 deg are preprogrammed and delivered under computer control. Commissioning these wedged profiles and collection of a large data set are facilitated by methods that allow simultaneous acquisition of multiple points. Radiographic film suits this application as a single exposure can provide integrated data in single or multiple planes, perpendicular or parallel to the beam. In this way commissioning can be accomplished in a relatively short time.

Film (Kodak XV) was used to evaluate the feasibility of soft wedged fields as early as the 1978 publication.[86,87] The

use of automatic processing, computer controlled densitometry, and dose density conversion referenced to ion chamber dosimetry claimed ±5% accuracy at that time. The implementation of soft wedges through the mid 1990s found film to be the most practical method in terms of accuracy, spatial resolution, and cost effectiveness, compared to ion chambers, TLD, and radiochromic film, for measuring cross profiles.[13,88–90] Although film is still a popular method, its accuracy is affected by variations in calibration and processor conditions, and it is relatively slow compared to commercial linear detector arrays. The detector arrays have been decidedly more efficient and accurate for primary data acquisition for soft wedges.[58,90–93]

The OD to dose conversion accounts for the influence of the softening energy spectrum with increasing depth, especially for larger fields. These corrections are more pronounced for 6 MV, ~0.2% per cm, than for 18 MV x rays, for which corrections were negligible.[93] Data acquisition procedures should correct for the variation of photon scatter with field size as well as depth by a series of measurements relating film and ion chamber response over the clinical range. However, film response corrections for variations of primary and scattered photons within the phantom across the wedged field cannot easily be resolved by such a strategy and are often ignored. One can expect that energy dependency of film will cause an apparent decrease in the measured wedge angle, particularly for lower x-ray energies, and larger fields and depths. The significance of this radial energy dependency *should* be quantified by cross-checking a few points with an ion chamber, especially for large fields.

D. Stereotactic radiosurgery

Precise spatial registration of the prescribed doses with the target volume and critical structures is the crucial factor in accurate stereotactic radiosurgery (SRS) and stereotactic radiotherapy (SRT). This is achieved by well-designed and carefully aligned hardware to assure the registration of the imaging modalities and linear accelerator coordinate systems, dedicated treatment planning software modeled for the specific delivery system, and an exclusive data set focused on small, highly collimated fields. This applies to γ-knife units and to linear accelerators equipped with fixed circular collimators or mini-multileaf collimators (mMLC).

As the practical upper limit for using SRS is 4 cm diameter fields (slightly greater for SRT), the treatment planning data set is relatively small compared to conventional radiation therapy. Data acquisition requires tissue maximum ratios (TMRs), off-axis factors (OAFs), and output factors (OFs) for this range of collimator size. Once again, emphasizing that the spatial registration is potentially the largest source of dose uncertainty in such small fields, then it is the OAFs that require careful attention. Lateral electronic disequilibrium and steep dose gradients exist in a large portion of these fields, requiring the use of high-resolution measurement techniques. For this reason and the availability of film dosimetry technology in most radiotherapy departments, radiographic film is useful for both commissioning the SRS system and verification of patient dosimetry. In fact, Task Group 42 on SRS[94] recommends film dosimetry for measurement of profiles for γ-knife units and linear accelerators. Film is particularly beneficial for the measurement of irregular dose distributions generated with multiple isocenters and mini-MLC that conform the dose to the target shape.

Evaluations of measurement techniques specific to the needs of SRS have been reported.[12,95] These studies compared Monte Carlo (MC) calculations with measurements to examine the impact of photon and electron energy spectra at different depths and field sizes on detector response. Spectral variation is particularly important when the detector is not tissue equivalent and when lateral equilibrium does not exist. In these regards, the pros and cons of radiographic film relative to ion chambers, radiochromic film, diodes, and diamond detectors are discussed. Films were used in plastic phantom to measure TMRs and OAFs. Heydarian *et al.*[95] showed a ~5% over-response of film at 10 cm depth compared with MC and tissue equivalent detectors. In contrast, Robar and Clark[12] measured the variation in film sensitivity for fields for radiosurgical fields; for a 2.5 cm diameter field, a maximum error of 1.5% was observed at 20 cm depth for a sensitometric curve established at a depth of 1 cm. Others have found that energy dependence varies with the type of film used, though this is not a major concern over the range of field size for SRS fields.[4] In general, it may be concluded that variation of phantom scatter within fields less than or equal to 10×10 cm^2 does not have a significant impact on the overall film response.

Heydarian *et al.*[95] showed ~1 mm wider penumbra with radiographic film relative to MC, but comparable to penumbra measured with small diode and diamond detectors for 6 MV x rays. Penumbra delineation for SRS justifies the use of film dosimetry. Detector size will adversely affect measurement accuracy in regions where the gradient is varying across the detector.[96] The error introduced by larger diameter detectors always tends to reduce the gradient, thereby broadening the penumbra. When film is the detector, the scanning system is usually the resolution-limiting component. TG 42[94] reported that detector diameter of 3.5 mm or less could reproduce penumbra to within 1 mm; detector dimensions of 2 mm or less are recommended. Commercial film scanners designed for dosimetry applications *should* exceed this specification.

Output factors for small SRS fields also depend upon the spatial resolution of the detector. For 6 MV x rays, the absence of lateral electron equilibrium affects the dose at the central axis for beam radii less than 1 cm. In these small fields, the detector integrates over a region of varying electron fluence, even at the center of these fields. As the field size increases, the flat region can accommodate larger detectors. For this reason for fields less than 2 cm in diameter, the detector resolution *should* be matched with that used for the cross-plane profile scans; only then will the output factors be consistent with and complementary to the data in the profiles. Thus if radiographic film is used to acquire profiles, using the same film and scanner for both profiles and output measurements will provide good results. With careful con-

trols to detect and eliminate dose uncertainties due to variations in emulsion and processing, radiographic film can be used to obtain scatter correction factors for even the smallest SRS fields, based upon the film response measured for larger reference fields.

Internally scattered light in CCD-based digitizers may contaminate the film transmission signal within the scanned region. Optical scatter will increase the apparent transmission in the high density region of the film proportional to the area and proximity of the low optical density regions. Therefore, this scanner artifact may broaden the penumbra and reduce the measured output factor significantly, especially for the smallest fields. Internal collimation in the scanner design is the best approach to minimize this problem; however, user provided opaque masking that defines the region of interest is helpful to minimize artifacts. Laser film digitizers are susceptible to temporal and spatial distortions near steep density gradients due to the response of electronics to sudden changes in signal and to the size and shape of the laser beam spot, respectively. Methods for evaluating CCD-based and laser film digitizers[25,26,68] are discussed in Sec. IV B.

E. Intensity-modulated radiation therapy

The availability of IMRT via multi-leaf collimation and treatment planning optimization software is enticing to many therapy centers. IMRT provides the means for improved conformal treatment for a wide variety of cancers. However, interest in IMRT is often subdued by concern that these technical methodologies are more obscure to the user compared with three-dimensional conformal radiation therapy (3DCRT).[97] Verification of treatment plans is helpful to allay these concerns, and, in fact, dosimetric verification of the intensity map is required in the new IMRT codes in the American Medical Association CPT manual. Though not a simple task, radiographic film is currently best suited for much of the 2D dosimetry involved in IMRT commissioning and verification. As such, IMRT is the principal reason for the recent renewed interest in film dosimetry and the timing of this task group report.

IMRT presents new challenges to verification dosimetry. Since the intensity variation within the field is potentially different from field to field, one cannot presume to know the dose at an arbitrary point based upon the dose at any other point. Therefore, the premise for ion chamber dosimetry verification at a single point, useful for fixed fields with or without standard wedges, is invalid for IMRT. Dose verification in IMRT fields requires the acquisition of dose at multiple points sufficient to ensure that the correct distribution is delivered with reasonable certainty. This can be accomplished with point detectors, but only very inefficiently since each individual point would require the delivery of the entire treatment. Linear detector arrays provide more efficient data sampling, though limited to one dimension. EPIDs have been tested for this purpose with some success, but EPIDs measure intensity patterns more similar to exit fluence, optimized for image quality, rather than patient dose.[98–100] Two-dimensional tissue equivalent detector arrays developed specifically for IMRT purposes (PTW and SunNuclear) are enormously beneficial for routine IMRT verification; however, their resolution, which depends upon detector size and spacing, is a limiting factor for commissioning these highly modulated fields. Furthermore, EPIDs and detector arrays, limited to measuring normal to the beam axis, are not suitable for composite plan dosimetry.[101–105] Radiochromic film is manufactured to be relatively tissue equivalent, avoiding the energy dependence restriction of radiographic film, but it has suffered from insensitivity at clinical doses, nonuniformity across the film, and cost for routine applications, although recent advances in radiographic films have alleviated these problems somewhat. For these reasons there is resurgence in interest for radiographic film, specifically for verification dosimetry of IMRT.

The consequences of the energy-dependent sensitivity response of radiographic film provide unique challenges when film is used for IMRT verification. The effects of low-energy photon over-response of radiographic film is similar in one regard to the above discussion for soft wedges as in all megavoltage photon applications, i.e., variation in film sensitivity increases for larger field sizes and depths. However, the over-response is both slowly varying and predictable in dynamic-wedged fields, wherein it can be nearly eliminated by an appropriate calibration technique. Because of the nature of IMRT delivery, the primary photon component varies in proportion to the degree of intensity modulation, while the low energy scatter is relatively uniform across the field.[106] This means that a simple technique to compensate for the sensitivity variation cannot be developed. For small IMRT treated volumes, requiring fields smaller than 10×10 cm^2, the variation in scatter-to-primary is not sufficiently large to modify the sensitivity across the treated field. However, for large IMRT fields, the low energy scatter component is large, and so the variation in the scatter to primary ratio can produce a large film response variation within the field. One method to correct for this variable over-response is high-Z filtering, as is described in Sec. V D.[11,39,53,52]

While spatial distortions introduced by film scanning will negatively impact all dose measurements, they are more critical when measuring IMRT dose distributions. Often the film measurements are intended to localize steep dose gradient regions near critical structures, so a spatial distortion may yield inaccurate conclusions regarding the accuracy of the delivered dose distribution. For conventional treatment fields, the spatial distortions would only affect the field edges, where spatial accuracy tolerances are often relaxed due to errors in beam aperture definition and patient alignment.

The CCD-based digitizers and laser film digitizers introduce OD artifacts associated with steep density gradients into dose distributions contaminating the film transmission signal as explained in Sec. IV B. MLC leaf alignment tests have been proposed by a number of clinical users of MLC to check the alignment of the leaves.[16,107] Sub-millimeter leaf positioning precision is particularly important if the MLC is to be used for IMRT purposes, where errors in the leaf posi-

tion can significantly influence the dose delivered throughout the target volume. Most treatment planning systems do not model the variations in dose caused by interleaf transmission; nevertheless, it is advisable that the range of these perturbations be documented for each MLC.[108] A common test uses radiographic film placed in the isocenter plane and exposed using MLC patterns of designed to generate narrow bands of varying density formed by the gap between opposing banks of leaves. Misalignment of individual leaves by as little as 0.2 mm can be visually detected relative to neighboring leaves. While these film patterns may be evaluated by the naked eye, a more objective approach uses deviations in net optical density measured with a high-resolution film scanner. Interleaf transmission variation is easily measured with film dosimetry.

VIII. CONCLUSIONS

Medical physicists working in radiation oncology departments have been using radiographic film for ^{60}Co and linear accelerator beam dosimetry for more than half a century. It is difficult to imagine a radiation oncology physicist who has not relied on film dosimetry for checking dose distributions for special patient treatment techniques, or for regular linear accrelerator QA measurements.

Recently, the use of film dosimetry has increased dramatically with the development and popular implementation of advanced megavoltage radiotherapy delivery techniques such as IMRT, tomotherapy, dynamic conformal therapy, etc. As a two-dimensional integrating dosimetry medium, radiographic film is nearly ideal for use with dynamic treatment delivery techniques, which, because of their complexity and our relative lack of familiarity, make individual patient dose validation essential. Alternative methods for patient dose validation have been introduced. Large scale 2-D ion chamber or diode arrays as well as the development of an improved radiochromic film (EBT) are now available for IMRT dosimetry. However, perhaps because of its familiarity and apparent simplicity, radiographic film (and EDR2 in particular) remains the most common means for validating patient IMRT treatments through dose measurements.

Given the overall importance of film dosimetry in radiation oncology for so many decades, one might ask why there has not been a Task Group report published on this topic until now? Why are there no comprehensive review articles, monographs, or practical guides to megavoltage film dosimetry? Perhaps the answer is contained in the phrase "familiarity and apparent simplicity." Medical physicists use film for dosimetry because they are familiar with it—and this familiarity typically derives from the oral (i.e., unwritten) tradition of on-the-job-training. Film dosimetry is also apparently simple since the film can be easily irradiated and then automatically processed, scanned, calibrated, and analyzed using modern, reliable commercial systems. What could be simpler?

The answer is that radiographic film dosimetry can achieve the accuracies of ±2% required for meaningful IMRT QA, but achieving such highly accurate results is by no means simple. As with any form of dosimetry, accurate film dosimetry requires a thorough understanding of the fundamental mechanisms, which comprise the entire process. It requires knowledge of the sensitivities of these mechanisms to variations, which are likely to be encountered during irradiation, processing, and scanning. And, it requires an awareness of potential problems and pitfalls, which can lead to unacceptable systematic errors.

We hope that this Task Group report is able to provide the reader with this understanding, knowledge, and awareness. Besides theoretical background, we offer the reader practical and useful recommendations wherever possible. And, we suggest a specific protocol for radiographic film calibration and dosimetry, which, if properly followed, will lead to consistent accurate results.

APPENDIX: MTF FOR SCANNER PERFORMANCE

MTF data allow the medical physicist to evaluate the transmission frequencies at which the scan remains quantitative, i.e., MTF has a value near unity. Attempting to measure OD distributions with significant frequency components where the MTF of the device is significantly below unity results in nonquantitative results. This is largely thought to be due to the artifacts discussed in Sec. IV B above. Because of the nonlinear relationship between T and OD, it has been observed that OD signal is lost in the measurement, resulting in underestimations of the OD in steep gradients. For a specific scanner MTF, the impact of the scanner performance on a measured dose distribution can be determined using the Fourier transform of the actual T distribution. If the Fourier transform of the actual T distribution is band-limited by frequencies in the MTF that are near unity, then the measurement will be accurate. If there are significant contributions at frequencies where the MTF falls below unity, a worst case estimate of the error can be deduced using the following inequality, which is based on the definition of the inverse Fourier transform:

$$T(\mathbf{r}) = \int_{-\infty}^{+\infty} d^2\boldsymbol{\varpi}\,\tilde{T}(\boldsymbol{\varpi}) \times e^{-2\pi i \boldsymbol{\varpi}\cdot\mathbf{r}} \leqslant \int_{-\infty}^{+\infty} d^2\boldsymbol{\varpi}\,|\tilde{T}(\boldsymbol{\varpi})| \tag{A1}$$

where $\mathbf{r}$ is a spatial coordinate in the film plane, $\boldsymbol{\varpi}$ is a corresponding spatial frequency coordinate, $T(\mathbf{r})$ is the T distribution in the film, and $\tilde{T}(\boldsymbol{\varpi})$ the Fourier transform of the T distribution in the film. The inequality follows from the fact that the term the $e^{-2\pi i \boldsymbol{\omega}\cdot\mathbf{r}}$ in the inverse Fourier transform can at most return the absolute value of $\tilde{T}(\boldsymbol{\varpi})$ when all of its components are in phase. Weighting the integral in the last part of Eq. (A2) with the MTF of the device, MTF ($\boldsymbol{\varpi}$), will select out the lost frequency components where signal is lost in the correct proportion. Thus, we obtain an expression for estimating the worst-case error introduced by the device:

$$T(\mathbf{r}) = T^{\mathrm{Meas}}(\mathbf{r}) \pm \int_{-\infty}^{+\infty} d^2\boldsymbol{\varpi} |\tilde{T}(\boldsymbol{\varpi})| \times [1 - \mathrm{MTF}(\boldsymbol{\varpi})], \tag{A2}$$

where $T^{\mathrm{Meas}}(r)$ is the measured T distribution in the film. Note that this analysis shall be with T and not OD, as the imaging system will only approximate a linear system for light transmission. [Note that standard transparency films and analysis software can be obtained from the International Imaging Industry Association (I3A) at their website http://www.i3a.org/about.html]

[a]Conflict of Interest: President, of RIT, Inc.

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