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Radiochromic Film Dosimetry

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Radiochromic film dosimetry: Recommendations of AAPM Radiation Therapy Committee Task Group 55

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Recommendations of the American Association of Physicists in Medicine (AAPM) for the radiochromic film dosimetry are presented. These guidelines were prepared by a task group of the AAPM Radiation Therapy Committee and have been reviewed and approved by the AAPM Science Council. © 1998 American Association of Physicists in Medicine. [S0094-2405(98)00211-9]

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I. INTRODUCTION

In radiation dosimetry there are numerous problems associated with the measurement of isodose curves and depth-dose distributions in high-gradient regions of beams using conventional measuring systems such as ionization chambers, semiconductors, thermoluminescent detectors (TLDs), and radiographic films. Ionization chambers and semiconductors do not provide sufficient spatial resolution for many treatment planning needs. Thermoluminescent dosimeters, even with small dimensions, are cumbersome and time consuming when one- or two-dimensional dose distributions are required. Dosimetric data cannot be stored for archival purposes by using conventional TLD readout procedures. The evaluation of an ionizing photon beam is difficult by using silver-halide radiographic film, because of large differences in sensitivity to photon energies in the l0-200 keV region, even though its relatively high spatial resolution offers an advantage over most other radiation measuring systems. Energy absorption and transfer properties of radiographic films do not match those of biological tissues. Radiographic films also have the disadvantages of being sensitive to room light and requiring wet chemical processing.

These difficulties have resulted in a search for a radiation dosimeter with high spatial resolution which does not require a special developmental procedure and gives permanent absolute values of absorbed dose with an acceptable accuracy and precision and ease of handling and data analysis. Some of these features have been achieved with the introduction of radiochromic dosimeters. These dosimeters, with very high spatial resolution and relatively low spectral sensitivity variation, are insensitive to visible light, thus offering ease of handling and preparation in room light. Radiochromic dosimeters color directly and do not require chemical processing-- a color change (colorless to blue, red, green, etc.) indicates exposure to radiation. Image formation occurs as a dye-forming or a polymerization process, in which energy is transferred from an energetic photon or particle to the receptive part of the leuko-dye or colorless photomonomer molecule, initiating color formation through chemical changes.

Since 1965, detailed studies have been performed by McLaughlin *et al.* [1,2] and other investigators to determine the dosimetric properties of various forms of radiochromic media. Much of the effort has been carried out at the U.S. National Institute of Standards and Technology (formerly the National Bureau of Standards), initially with support from the Division of Isotopes Development, U.S. Atomic Energy

Commission, and with the assistance of the inventor of ultraviolet sensitive systems, L. Chalkley.[3] With the recent improvement in the accuracy and precision of film manufacturing, as well as the ruggedness and ease of use, radiochromic dosimeters have become increasingly popular in medical and nonmedical applications. Over the past several years the dosimetric properties of radiochromic dosimeters have been evaluated by many investigators and extensive literature on various aspects of radiochromic dosimetry has appeared. At present, various radiochromic dosimeters in the form of thin films, thick films, gels, liquid solutions, and liquid-core waveguide, are used for routine dosimetry of ionizing radiation over a wide range of absorbed doses (10^{-2}-10^{6} Gy) and absorbed dose rates (up to $\approx 10^{12}$ Gy s^{-1}).[4] In recent years, various radiochromic dosimeters have also been used for nonclinical applications such as blood irradiation,[5] radiation processing,[6] and reference standard.[7]

At this time, there are no comprehensive guidelines on the use and calibration of radiochromic films and the densitometry systems for clinical use. This report has been prepared by Task Group 55 of the Radiation Therapy Committee of the American Association of Physicists in Medicine, AAPM, primarily to fill the needs of a hospital physicist in utilizing radiochromic films for medical applications. The development of radiochromic dosimeters and the methodology of their applications is an ongoing process. This report intends to reflect on the current state of scientific understanding and technical methodology in clinical radiochromic dosimetry. As such, it is not final but is offered as an up-to-date aid to the clinical physicist. The scope of this report has been limited to:

(1) characteristics of available radiochromic films,
(2) procedures for using radiochromic films for dosimetry,
(3) characteristics of scanning systems and densitometers,
(4) medical applications of radiochromic detectors, and
(5) future directions.

Tasks related to the dosimetry of other forms of radiochromic detectors, such as gels, are separate subjects and are not part of this task group report.

II. HISTORICAL BACKGROUND AND CHEMICAL MAKEUP

A. Historical background of radiochromic dosimeters

Radiochromic effects involve the direct coloration of a material by the absorption of energetic radiation, without re-

quiring latent chemical, optical, or thermal development or amplification?[2,8-13] The radiochromic process, described in this section, involves the production of immediate permanent colored images of a radiation exposure pattern in a solid, with or without "fixing" of the sensor medium against further change. Typical films, protected from further irradiations, can serve as archival radiographic imaging and data-storage media.

One of the first commercially important direct-imaging reactions involved papers and gels impregnated with potassium dichromate, which was known to undergo photoreduction. This led to daguerreotype, collotype, photogravure, and photolithographic prints in the mid-1800 s. This process is the inverse of radiochromism, in that the brownish color is left in the unreduced portions of the image. A very early radiochromic process, first demonstrated in 1826 by Niepce,[8] involved an unsaturated hydrocarbon polymeric mixture based on bitumen that cross links upon irradiation, leaving a light-scattering pattern. Many radiation cross-linking organic systems have subsequently been used for radiographic imaging.[8-11]

One type of organic free-radical imaging medium can combine photopolymerization with leuco dyes that produce color upon irradiation. Typical of such processes is the pairing of free radicals to form radiation cross-linked carbon-chain materials, resulting in covalently bonded growing chains. Other direct-imaging effects include radiation-induced vesicular films giving light-scattering properties,[14] and the radiation-induced changes in the hardness of polymeric microcapsules containing diffusible dyes, inks, and pigments that are released mechanically.[15,16]

Some radiochromic organic image-forming systems involve *cis-trans* isomeric conversions, or dissociations resulting in enolic, ketonic, and anilic bonds and other molecular rearrangements. Such tautomerizations lead to double-bonded coloration of spiropyrans, anils, organic acids, stilbenes, and other polycyclic compounds.[10,17]

Colorless transparent radiochromic thin films giving permanently colored images have been widely used for 30 years as high-dose radiation dosimeters (10^4-10^6 Gy).[11,12,18] These are mainly hydrophobic substituted triphenylmethane leucocyanides, which upon irradiation undergo heterolytic bond scission of the nitrile group to form highly colored dye salts in solid polymeric solution. The host material for such films is generally nylon, vinyl, or styrene-based polymer. They have also been used to register high-resolution, high-contrast radiation images and to map radiation dose distributions across material interfaces.[19] This kind of radiochromic system is not sensitive enough to be used for clinical or radiological applications.

Some triphenyl tetrazolium chloride (TTC) salts can be used as direct-imaging biological stains for botanical specimens and for characterizing normal and malignant mammalian tissues.[20-22] These salts are colorless in aqueous solution but upon irradiation are reduced to the highly colored, insoluble formazans. For radiographic imaging in hydrocolloids and other aqueous gels, and for mapping ionizing radiation dose distribution directly in animal tissues,

hydrophilic TTC salts[23,24] and triphenylmethane leucocyanides (e.g., formyl violet nitrile)[25] have been used.

Recently, another form of radiochromic film based on polydiacetylene has been introduced for medical applications.[26-32] These films were previously supplied in two types, GafChromic DM-1260 (also known as HD-810)--see Sec. III for nomenclature designation--and single-layer GafChromic MD-55 for the absorbed dose ranges 50-2500 and 10-100 Gy, respectively.[28,33,34] [The single-layer GafChromic film will be designated as "MD-55-l" in this report. (See Sec. III).] A new double-layer GafChromic MD-55 film has now replaced the other two for medical applications (useful dose range 3-100 Gy).[35,36] [This currently available double-layer GafChromic film will be designated as "MD-55-2" in this report. (See Sec. III).] Each of these film types is colorless before irradiation, consisting of a thin, active microcrystalline monomeric dispersion coated on a flexible polyester film base. It turns progressively blue upon exposure to ionizing radiation. The radiochromic radiation chemical mechanism is a relatively slow first-order (k $\cong$ 10^3 s^{-1}) solid-state topochemical polymerization reaction initiated by irradiation, resulting in homogeneous, planar polyconjugation along the carbon-chain backbone.[33,34]

The characteristics of these most relevant and sensitive radiochromic films, i.e., MD-55-l and MD-55-2, are given in Sec. III.

B. Physical-chemical behavior of radiochromic dosimeters

McLaughlin *et al.* [35] have studied the radiochromic films MD-55-l by pulse radiolysis and flash photolysis, in terms of the kinetics of their response to ionizing radiation and ultraviolet light.[33,34] The radiochromic reaction is a solid-state polymerization, whereby the films turn deep blue proportionately to radiation dose, due to progressive 1,4- *trans* additions which lead to colored polyconjugated, ladderlike polymer chains. The pulsed-electron-induced propagation of polymerization has an observed first-order rate constant on the order of 10^3 s^{-1}, depending on the irradiation temperature (activation energy $\approx$50 kJ mol^{-1}). The UV-induced polymerization is faster by about one order of magnitude (k_{obs} = 1.5 $\times$ 10^4 s^{-1}). In the case of the electron beam effect, the radiation-induced absorption spectrum exhibits a much slower blueshift of the primary absorption band (λ_{max} = 675 -660 nm) on the 10^{-3}- 10^{+1} s time scale. This effect is attributed to crystalline strain rearrangements of the stacked polymer strand units.

C. Radiochromic films

The new proprietary radiochromic films MD-55-2 consist of double-layer radiochromic sensors dispersion coated on both sides of a polyester base[34,38] (see Sec. III A). The colorless, transparent film responds to ultraviolet light and to ionizing radiation by turning blue, with two nominal absorption bands (λ_{max}~670 and 610 nm) which depend on the absorbed dose, temperature during irradiation, as well as

postirradiation reading time. The radiation-induced color change is formed directly without thermal, optical, or chemical development and the original blue image is stable at temperatures up to about 60 °C, above which the color of the image changes abruptly from blue to red. This film has very little dependence on relative humidity during irradiation, but there is a marked temperature dependence, the degree of which varies with radiation dose and temperature level.[37-39] For example, at a dose of 10 Gy, the new radiochromic film (GafChromic MD-55-2), read at a wavelength of 670 nm, shows a 5% increase in response when the irradiation temperature is increased from 20 to 40 °C. [35] At higher temperatures (between 40 and 50 °C), the response increases due to a rise in irradiation temperature by ~ 1.6% per °C. The γ – ray and electron response shows negligible dose-rate dependence.[38] When the films are irradiated with photons at dose rates between 1.0 and 30 Gy/min or with electron beams at an average dose rate of $\approx 10^6$ Gy/min, the values of radiation-induced absorbance increase per unit dose agree to within the specified uncertainty of the dosimetric response ($\pm 5\%$ at 95% confidence level).[38] Response curves for MD-55-2 are presented in Fig. l(a).[35] The radiation-induced absorption spectra, shown in Fig. l(b), are similar to those obtained for earlier versions (e.g., DM-1260) of these films.[33] All spectrophotometric measurements given here were taken at 22 $\pm$ 1 °C. The estimated combined uncertainties for these measurements are $\pm 5\%$ at two standard deviations.[38] Higher dose levels can be measured by judicious selection of spectrophotometric wavelength. It has been demonstrated that the earlier DM-1260 film provided very high spatial resolution images. For ionizing photons and electrons in the energy region 0.1-10 MeV, the sensor simulates the radiation absorption properties of water and muscle, in terms of ratios of photon mass energy-absorption coefficients and electron mass collision stopping powers, within $\pm 2\%$.[35,40,41] However, experimental studies of the dependence of the film response on photon energy show that, in terms of absorbed dose in water, the response to photons in the 0.03-0.04 MeV range is about 60% of that at photon energies >0.1 MeV.[35] (See Sec. III.)

Two radiochromic systems that have been developed for radiographic imaging and dosimetry at absorbed doses greater than those used for radiation therapy are thin films containing either amino-triphenylmethane leucodyes or tetrazolium salts as the colorless radiation sensitive ingredients which are changed to deep colors upon irradiation. Historical details and the results of radiation chemical kinetics studies of these systems can be found in a series of publications by McLaughlin *et al.*[2,11-13,18,35,42-47]

III. RADIOCHROMIC FILM DOSIMETRY

A. Radiochromic film dosimeters

The chemistry and dosimetry of radiochromic dosimeters have evolved very rapidly over the past few years. Various types of radiochromic films (such as HD-810, DM-1260, DM-100, MD-55, and NMD-55), referred to as GafChromic films, have been identified by the catalog number of a sup-

plier, Nuclear Associates. The sensitivity and, possibly, the dependence on environmental parameters, differ from type to type. Over the past few years, the sensitive structure of the GafChromic films has been changed, more than once, without the changes being known to the users. In some instances the manufacturer's film designation remained unchanged even though its structure was altered. To avoid confusion and to be able to compare results it is useful to recognize the manufacturer's stated lot number for a given film type.

At the time of the writing of this report the two commercially available radiochromic films for medical applications are:

(1) GafChromic HD-810 film (formerly this film was supplied as a GafChromic DM-1260 and was only available in 12.5 cm × 15 m): This film can be purchased from the manufacturer [International Specialty Products (ISP), Wayne, NJ] and is available in 20 cm × 25 cm clear sheets.

(2) Double-layer GafChromic MD-55-2 film (in this report, the double-layer GafChromic films are designated as MD-55-2): This film can be purchased from the manufacturer [International Specialty Products (ISP), Wayne, NJ] as well as other vendor(s) (Nuclear Associates, Carle Place, NY) and is designated as model No. 37-041. In addition to model numbers, lot numbers may provide useful information. From September 1994 to December 1995, the manufacturing lot number for this film was 940818. In January 1996, the lot number for this film was changed to 941206. More recently, since 1997, this film has been manufactured with the following lot numbers: 970116, 37051, 37175, and 38055. This film is currently available in 12.5 cm × 12.5 cm clear sheets. Some publications have referred to this (new) double-layer GafChromic film as NMD-55 (viz. "new" MD-55). [Before September 1994, a less sensitive single-layer GafChromic film also designated as MD-55 (model No. 37-041), was available from Nuclear Associates. The manufacturing lot number for this film was 920813. In this report this single-layer film is designated as MD-55-1.]

Radiochromic MD-55-2 films are suitable for dose measurements in the range of 3-100 Gy; whereas HD-810 films are mainly used for dose mapping in the range of 50-2500 Gy. The present physical dimensions of these films limit their clinical application for large-field dosimetry of linear accelerators.

Although the production of some of these films has been discontinued, investigators may have purchased a large quantity of HD-810 (formerly DM-1260 rolls) and MD-55-l films which are still in use in their department. Specific information for all types of radiochromic dosimeters is not available. Therefore, data related to these three types of radiochromic films are presented here. Radiochromic dosimeters, in general, have many advantageous characteristics as well as some limitations which are discussed in the following sections.[28,35,37,47] A summary of these characteristics, as they

apply to various types of radiochromic films, is provided in Sec. III P.

B. Structure and atomic constituents/tissue equivalence

The HD-810 dosimetry film has a nominal 7-μm-thick radiation sensitive layer on a 100 μm polyester base. The MD-55-1 and MD-55-2 is a film composed of a (single or double) layer(s) of highly uniform transparent coating, sensitive to ionizing radiation, on (one or two) piece(s) of a polyester base. See Table I and Fig. 2 for details.[48] The thin radiosensitive layer is made of colorless organic microcrystals of a radiation-sensitive monomer uniformly dispersed in a gelatin binder.[26-28,33-35] The sensor layer of these films has atomic constituents with various proportions (Fig. 2).[28] The radiation absorption properties of radiochromic dosimeters can also be adjusted by changing film composition. The dosimeter materials can be made to simulate the material of interest undergoing irradiation (e.g., tissue, bone, various insulating materials).[4,49] The effective Z of these films is within the range 6.0-6.5. The energy dependence of film response to electrons, as well as the range of electrons in the dosimeter sensor and its substrate (polyester), has been determined by computation of mass collision stopping powers and continuous-slowing-down approximation ranges for electrons.[28] The energy dependence of this film to photon energies has been calculated by considering mass attenuation coefficients and mass energy absorption coefficients.[28] The sensor material is similar in its electron stopping powers to water and muscle.[28] It is also similar to water and muscle in terms of mass energy-absorption coefficients for photons of energies greater than 100 keV.[28,38] For the photon energy range of 0.1-1.33 MeV, and for secondary electrons from 0.1 to 1.0 MeV, photon mass energy absorption coefficients and electron mass collision stopping powers, for the sensor, are within 2% of water and skeletal muscle.[35]

C. Irradiated and unirradiated absorption spectra

The radiosensitive layer(s) in GafChromic film contain microcrystals of a monomer. As described in Sec. II, the radiosensitive layer undergoes partial polymerization when irradiated with ionizing radiation, such that the blue color of the polymer becomes progressively darker as the dose increases.[34] Figure 3(A) shows the optical absorption spectrum of MD-55-2 from 600 to 700 nm, before and after a dose of 6 Gy.[50] As shown a small shift in peak position occurs with dose [675 nm at 0 Gy (unirradiated film) to 676 nm at 6 Gy]. Similarly, for the weaker peak, there is a small shift from 617 nm for 0 Gy to 618 nm at 6 Gy.[50] Figure 3(B) shows the spectrum of an unirradiated film from 700 to 720 nm taken with a bandpass of 1.0 nm.[50] The interference fringes looked about the same with a bandpass of 0.25 nm but were ten times smaller when a bandpass of 3.5 nm was used. Using a bandpass of 3.5 nm, the optical density (OD), measured at 676 nm for a dose of 6 Gy, would differ by 0.2% at an adjacent peak and valley of the fringes.[50] The spectrum of unirradiated film [Fig. 3(A)] shows the presence
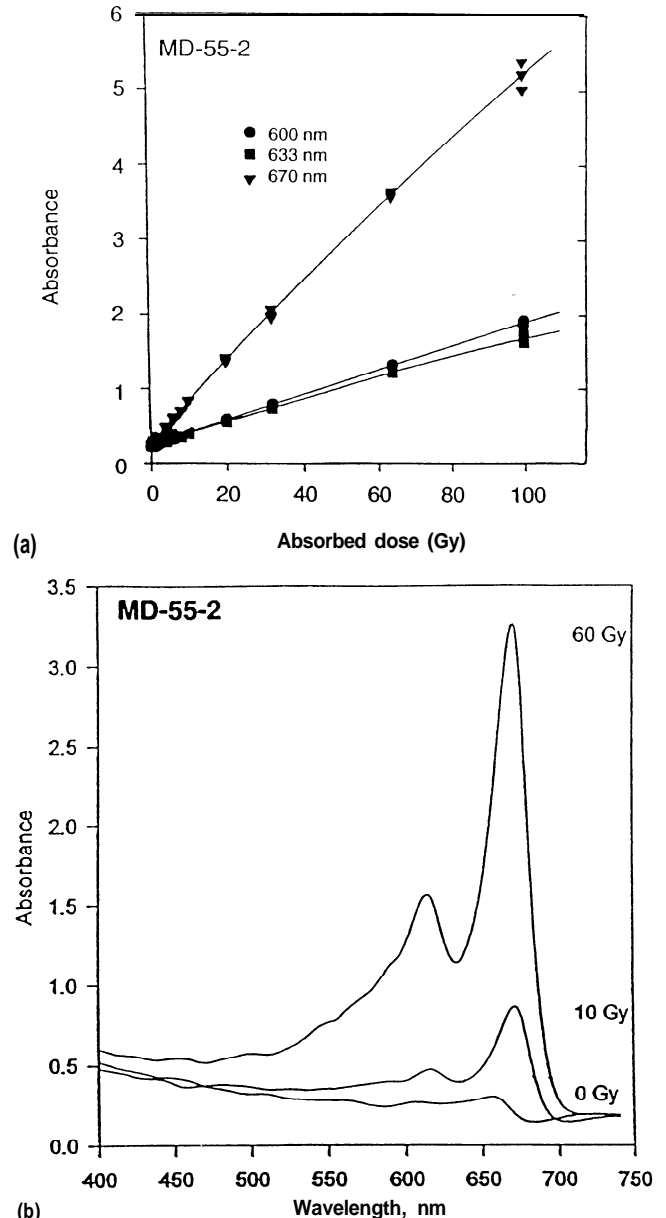
FIG. 1. (a) Increase of absorbance at three wavelengths as a function of ^{60}Co γ-radiation dose, for MD-55-2 radiochromic film; (b) radiation-induced absorption spectra of MD-55-2 radiochromic film (Ref. 35).

of some polymer plus an "underlying absorption." Assuming that the "underlying absorption" is featureless and unchanged by irradiation, Klassen *et al.*[50] conclude that in Fig. 3(A), it accounts for 0.20 OD units between 618 and 676 nm. They argue that some of the apparent absorption is actually a loss of light due to reflection, not absorption.[50]

D. Processing

Exposure to ionizing radiation results in a change from a colorless state to shades of blue due to a solid state polymerization reaction.[28,33,34] No physical, chemical, or thermal processing is required to bring out this color and relatively little change in color density occurs following the initial 24 h after the exposure.[28,39] The increase in color of radiochromic films is usually measured at a narrow spectral wavelength

TABLE I. Structure/dimensions of radiochromic films.

Film type	HD-810 (DM-1260)	MD-55-1	MD-55-2
Nuclear Assoc. No.	—	37-041	37-041
Standard size	20×20 cm^2 (12.5 cm $\times 15$ m roll)	12.5×12.5 cm^2	12.5×12.5 cm^2
Nominal thickness (μm)	107 (Fig. 2)	82 (Fig. 2)	278 (Fig. 2)
Sensitive layer(s) (μm)	7±1	15±1	30± 1
Base material (μm)	9 9	6 7	159

band with a spectrophotometer or a densitometer. These measurements are expressed in terms of the increase in absorbance A (i.e., optical density) or transmittance, T, of the light, where

$$A = -\log_{10} T.$$

E. Postirradiation color stability with time

Nearly full color development of all radiochromic formulations is very rapid, generally occurring in a few milliseconds.[33,34] However, several radiation chemical effects in plastics systems require some time, minutes and even hours, after irradiation to reach chemical completion. Therefore, with some dosimeters, a slow spontaneous development effect occurs after irradiation to different degrees depending on whether the irradiation time was long or short.[51] Most plastic dosimeters tend to be unstable in their response during the storage period between irradiation and analysis.[52-54]

The color formation in the irradiated radiochromic film types (e.g., MD-55-1 and MD-55-2) is not complete at the end of the irradiation. It continues at an ever decreasing rate.[28,33,34,50,55] Absorbancies of such films were measured at 400 nm at different times after irradiation, showing a continuous rise in relative absorbance.[28,56] During the first 24 h after the irradiation, the absorbance can increase by up to 16%, with only a slight rise (4%) thereafter, for up to about two weeks.[28] The time effect was found to depend on the absorbed dose.[28,50] No appreciable postirradiation changes of absorbance, at 400 nm, of the film occurs over the period from 40 to 165 days. Color stability is enhanced for absorbance readings made at either of the two main absorption peaks (nominal 610 and 670 nm).[28] It has also been noted that the greatest increase in absorbance occurs at higher storage temperatures, near 40°C.[27] Such an effect may require attention under typical storage conditions. Generally, at certain wavelengths of the main absorption band (e.g., nominal 670 nm), the radiation effect is relatively stable following the first 4 h after irradiation.[57] To minimize dosimetric variations due to the instability effect, spectrophotometric or densitometric readings should be made consistently at a certain wavelength.[34,35]

F. Response to polarized light

The analyzing light in most spectrophotometers and densitometers, whether the light source is a lamp or a laser, is linearly polarized to some extent. Klassen *et al.* [50] have extensively investigated the response of various layers of MD-55-2 film to polarized light. Scanning electron micrographs

suggest that the microcrystals in the radiosensitive layers of MD-55-2 have a preferred orientation, i.e., they are lying flat. As explained by Klassen *et al*,[50] if in addition, the monomers in the microcrystals have a preferred orientation in the same plane of the film, this could lead to dichroism such that the OD would vary with the plane of polarization

HD-810 (DM - 1260)

Sensitive Layer - 7 μm
Adhesive Layer - 1.5 μm
Conductive Layer - 0.05 μm
Polyester Base - 99 μm

MD - 55-l

Sensitive Layer - 15 μm
Polyester Base - 67 μm

MD - 5 5 - 2

Polyester Base - 67 μm
Sensitive Layer - 15 μm
Pressure Sensitive Adhesive - 44.5 μm
Polyester Base - 25 μm
Pressure Sensitive Adhesive - 44.5 μm
Sensitive Layer - 15 μm
Polyester Base - 67 μm

Approximate Composition

Polyester Base :	Carbon	45 Atom %
	Hydrogen	36 Atom %
	Oxygen	19 Atom %
Sensitive Layer :	Carbon	31 Atom %
	Hydrogen	56 Atom %
	Nitrogen	5 Atom %
	Oxygen	8 Atom %
Adhesive Layer :	Carbon	33 Atom %
	Hydrogen	50 Atom %
	Oxygen	17 Atom %
Conductive Layer :	Indium Tin Oxide	

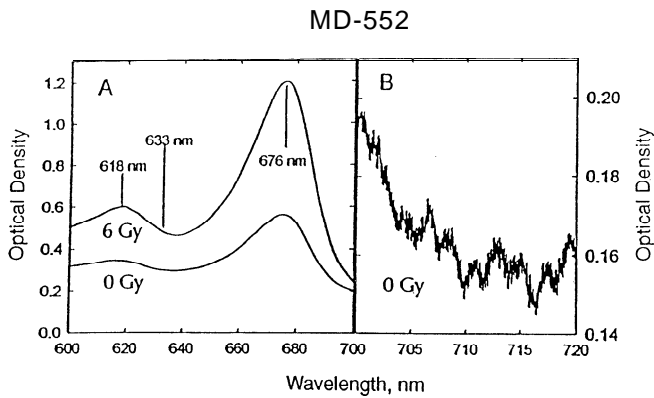FIG. 2. Diagram of radiochromic (GafChromic) film structure/dimension.

MD-552

FIG. 3. (A) The optical absorption spectrum of unirradiated GafChromic MD-55-2 (lower spectrum) and GafChromic MD-55-2 several weeks after a dose of about 6 Gy (upper spectrum). The bandpass used was 3.5 nm. Some useful wavelengths are indicated. (B) The spectrum of unirradiated GafChromic MD-552 taken using a bandpass of 1 nm and displayed at a higher sensitivity than in (A) in order to demonstrate the periodic fluctuations due to interference fringes (Ref. 50).

of the analyzing light and, hence, would change as the film was rotated or turned back to front in the spectrophotometer. Klassen *et al.* [60] found that the outer polyethylene terephthalale (PTP) layer of MD-55-2 had little effect on the polarization of the analyzing light, but the middle layer strongly rotated the plane of the light in the fashion of a 1/2 wave plate. The result is that the plane of polarization of the light is different for the two sensitive layers. They concluded that the measured OD of MD-55-2 (as presently fabricated) may change substantially due to the polarization of the analyzing light if the film is rotated or turned back to front in the spectrophotometer.[50] Therefore film orientation and alignment should be consistent with the ones used for calibration.

G. Response and energy dependence

Uniformity of the coating and reproducibility of individual polydiacetylene film sample measurements have been reported by Saylor and McLaughlin.[27] The HD-810 film responses per unit absorbed dose to water (or simply film responses) in the dose range 50-2500 Gy were studied using visible spectrophotometry, color photometry, densitometry, and scanning densitometry. The film was found to be essentially insensitive to light at wavelengths above 300 nm; however, it is sensitive to ultraviolet light at lower wavelengths. It has been suggested that the film be stored in the dark, at temperatures below 25 °C and relative humidities below 50% to optimize the useful life of the film. In addition, all optical densities should be measured at the same temperature (to within ±2 °C) and postirradiation delay (to within ±2 h) to obtain optimum reproducibility, as absorption spectrum peaks shift with temperature and time.[28] The climate inside a typical modern medical facility easily meets these temperature and humidity requirements.

The first available film (DM-1260) was not sensitive enough to measure typical clinical doses, and it required doses on the order of 50 Gy or greater for ±2% precision. The more sensitive MD-55-2 film, with double sensitive

coatings (nominal 30 μm), has become available for measuring doses as low as about 3 Gy with similar precision.[35]

Several investigators have studied the energy dependence of the radiochromic film response.[35,38,39] Muench *et al.* [39] have compared the variation of the low-sensitivity radiochromic film HD-810 (formerly DM-1260) response with those of LiF TLD chips (Fig. 4) in the effective photon energy range of 20-1710 keV. The HD-810 film response is observed to decrease by about 30% as effective photon energy decreases from 1710 keV (4 MV x rays) to 28 keV (60 kV x rays, 2 mm Al filter). This variation is similar but in the opposite direction to that of LiF TLD chips. In contrast, over this range of photon energies, the sensitivity of verification silver halide film (Kodak X-Omat V film) increases by 980%.[39]

Chiu-Tsao *et al.*[58] have measured the variation of the MD-55-1 film response with energy for the dosimetry of brachytherapy sources (Fig. 5). Their results indicated that, for these films, the sensitivity is about 40% lower for ^{125}I than [60]Co. The experimental studies of McLaughlin *et al.* [35] with photon beams show a response of MD-55-2 to be about 40% lower for photons of 20-40 keV than with ^{137}Cs or ^{60}Co gamma radiation when absorbed dose in water is measured (see Fig. 6). Meigooni *et al.*[59] have compared the characteristics of MD-55-2 with those of MD-55-l. They have shown MD-55-2 to be approximately 40% more sensitive than MD-55-l for megavoltage photon beams. Sayeg *et al.* [60] have suggested that the lower response of the radiochromic film for energies lower than 100 keV is due to the larger carbon content in the film relative to that in soft tissue. The measurement precision is limited primarily by the uniformity of the film thickness and the instrumentation used for densitometry. Photometric analysis, with three replicates per dose point, gives a reproducibility (±2 SD) of well under 5%.[28] With care reproducibility of 1% is achievable.[50] The dependence of the absorbance spectrum of MD-55-l film upon dose has been documented (Fig. 7), where doses were delivered using [90]Sr+[90]Y beta particles at the surface of a calibrated ophthalmic applicator.[30,61]

H. Dose fractionation

The possible effect of dose fractionation for HD-810 film has been studied in two ways. In the first, the irradiation was interrupted four times for 12 min before being continued. In the second, the irradiation was interrupted for 24 h before being continued. The total absorbed dose in the first case was 5 kGy so that each fraction was 1 kGy. In the second case, the absorbed dose range was from 5 to 35 kGy. In both cases the absorbance values of the unfractionated and the fractionated dosimeters were within 1% for HD-810 film.[56] Dose fractionation effect information, for the MD-55-l or MD-55-2 film, was not available at the time of this report.

I. Dose rate independence

The MD-55-l film was tested for dose rate dependence using calibrated ^{60}Co sources with dose rates of 0.020, 2.6, 71.0, and 198 Gy/min, for total doses up to 1.5 kGy. Analy-

sis was performed at wavelengths near the maximum of the two peaks ($\approx$670 and $\approx$610 nm) of the absorption spectrum (see Fig. 7). Results show that, within an uncertainty of approximately 5% ($\pm$ one SD), there is no rate dependence.[27] A more recent study by McLaughlin[35] using the double-layer MD-55-2 film, irradiated at three absorbed doses, 20, 40, and 60 Gy in the absorbed dose rate range 0.08-80 Gy/min, shows no rate dependence of response within the same uncertainty as that of MD-55-1, except at the highest dose of 60 Gy. At this relatively high dose there is about a 10% greater response at the lowest dose rate than at the highest dose rate (see Fig. 8). In general, radiochromic film is independent of dose rate effects at the clinically relevant dose rates of 2-4 Gy/min.

J. Environmental stability

The responses of radiochromic dosimeters are usually influenced by temperature and relative humidity and in some cases by ambient light and gases. Since conditions may be different between calibration and practical use, variations of response with the surrounding conditions must be determined and corrected. In the following sections, outlines of presently known effects on the response of radiochromic film to temperature, humidity, and ambient light conditions are described.[28,37,59,62]

1. Temperature and relative humidity during storage and readout

In general, a 24 h period between irradiation and readout has been suggested for the radiochromic films until relative stability is achieved.[28] However, the relative change of OD due to the postirradiation coloration after irradiation may be influenced by both temperature and relative humidity during postirradiation storage. The effect of humidity on HD-810 film during irradiation and storage has been reported to be less than $\pm$2% over the relative humidity range 6%-94%.[27,37] The effect of temperature differences during spectrophotometry of the same film shows a shift of the absorption bands to shorter wavelengths and an increase in the absorption band amplitudes with increase in readout temperature.[28,50]

2. Temperature during irradiation and postirradiation

McLaughlin *et al.*[28,35,54,63-65] have studied the irradiation temperature effects on most current and proposed solid-state dosimetry materials applicable to high dose measurements. They found the dye cyanide radiochromic materials to be the least affected by temperature variation.[64] However, temperature dependence may contribute large errors to the dose readings for many of the high-dose dosimeters, particularly if the calibration is performed under conditions different from those in practical applications. By calibrating the response precisely under the conditions of use (corresponding fractionation of dose, elevated temperatures, radiation time, etc.), these errors can be minimized.
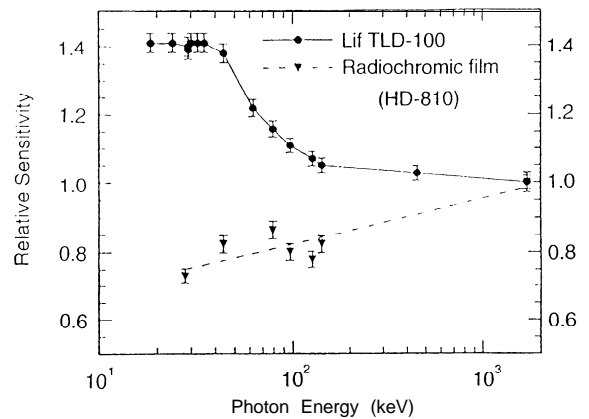
FIG. 4. Dosimeter sensitivity of HD-810 film as a function of x-ray quality (equivalent photon energy) for LiF TLD chips and radiochromic film (Ref. 39).

There is a marked dependence of the response of radiochromic (polydiacetylene coated) films on temperature during irradiation and postirradiation.[65] This dependence varies with dose level as well as the wavelength of analysis.[28,35] Figure 9 shows the temperature dependence of MD-55-1 and MD-55-2 films during irradiation with gamma rays at a dose of 40 Gy, measured at four different wavelengths, for temperatures in the range 10-50 °C.[35] Relative sensitivity is often expressed as the value of net absorbance per unit absorbed dose, relative to that when the irradiation was made at 20 °C. As irradiation temperature reaches $\approx$50 °C, in most cases, there is an erratic variation in relative sensitivity, which suggests that this dosimeter should not be used at such elevated temperatures. The effect of even greater temperature, >60 °C, on the exposed films results in the blue dye changing to red.[34] Prolonged exposure of the unexposed film to temperature >60 °C may cause a significant change in sensitivity.[28] The postirradiation temperature dependence has been described in detail by Reinstein *et al.*[65]
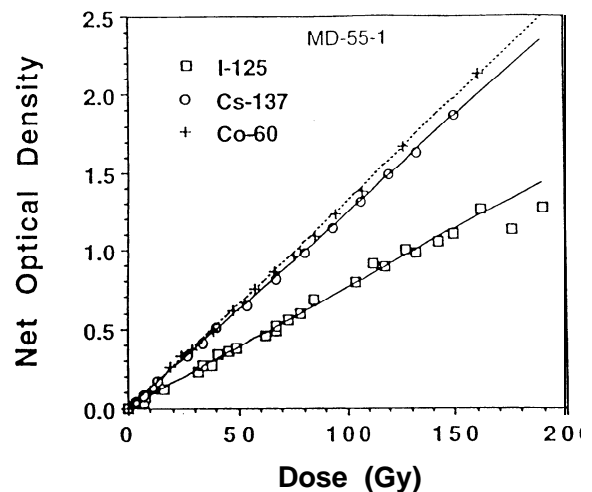
FIG. 5. The dose-response curves of MD-55-1 film measured by a laser densitometer (632.8 nm) for three radionuclides. The square, circle, and plus symbols are for ^{125}I, ^{137}Cs, and ^{60}Co, respectively. The dotted and solid lines near the symbols indicate the plot for the corresponding function fit (Ref. 58).
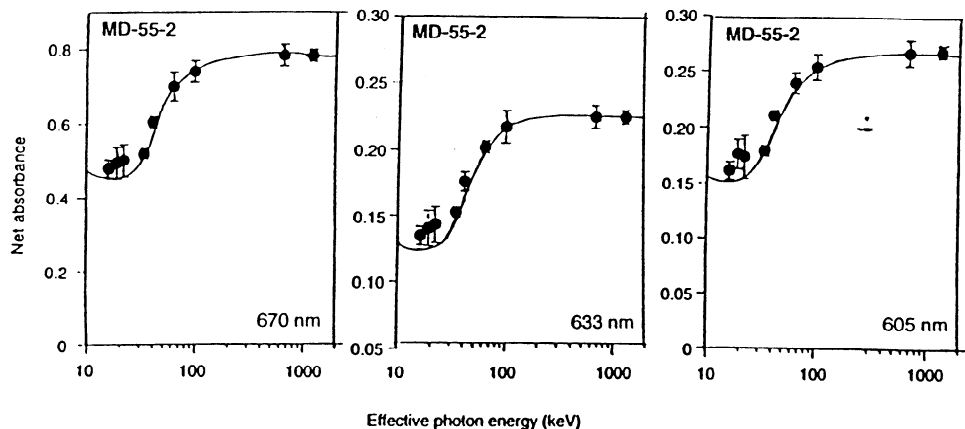
FIG. 6. The experimental photon energy dependence (points) of MD-55-2 film irradiated to an absorbed dose in water of 20 Gy by x and gamma radiation. The solid curve represents the calculated ratios of the mass energy absorption coefficients, MD-55-2 film sensor material-to-water, for photons from 10 to 1250 keV, normalized to the experimental value at 1250 keV. The vertical bars on the experimental points represent uncertainty limits based on five replicates at each point (Ref. 45).

3. Ultraviolet light

Most radiochromic films are sensitive to ultraviolet radiation, which spontaneously colors the film; they must be protected from sunlight or continuous white fluorescent lights.[57,64,65] Proper care and handling can eliminate ultraviolet exposure. The dosimeter may be stored in an opaque container, carton, or envelope; removed from the containers; a background reading taken as needed; and immediately used for exposure.[28] Qualitative studies of radiochromic film MD-55-2 have been shown it to be insensitive to ultraviolet and visible light at wavelengths above 400 nm.[57]

K. Image resolution

Image resolution of HD-810 dosimetry film with 20 keV electrons in a vacuum has been studied by McLaughlin *et al.*[28] The modulation transfer function was plotted against the spatial frequency of test patterns. An 80% response was observed at 100 cycles/mm and a 50% response at 200 cycles/mm. In addition, a series of line images was recorded with a 0.1-μm-wide electron beam. Resolution in excess of 1200 lines/mm (600 cycles/mm) was obtained. This is due to the micrometer size of the sensitive crystals in the film coating.

The radiochromic films can be analyzed with submillimeter resolution by using a scanner such as a He–Ne laser

scanning densitometer.[66] Choosing a laser of appropriate wavelength, high intensity, and low power consumption is important. The characteristic 632.8 nm line of a He–Ne laser is between the maxima of the two radiation induced absorption bands. For MD-55-2 films, the most sensitive reading is made at the primary radiation induced absorption peak (~670 nm); therefore a dedicated light emitting-diode (LED)/charged-coupled device (CCD) microdensitometer may be more useful at such wavelengths. While the spatial resolution for the polydiacetylene film is known to be better than 600 cycles/mm, the practical resolving power for dose profiles or isodose contours registered by a scanning laser densitometer using computer software depends on the pixel size chosen for the measurement routine.[38] The characteristics of scanning densitometers are discussed in detail in Sec. IV.

L. Film uniformity

Radiochromic films are being used as two-dimensional (2D) dosimeters by several investigators in various types of applications.[27,28,33,36–39,47,51,53,56,58,59,63,67,68] An ideal 2D dosimeter gives rise to a uniform (constant) response when it is exposed to a uniform irradiation field. For radiochromic films two aspects of uniformity (or nonuniformity) are of concern. The first is the nonuniformity arising from *local* fluctuations of film response (reading), q_i, with respect to

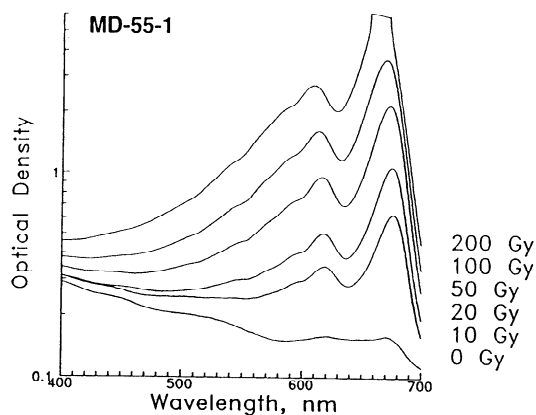FIG. 7. The dependence of the absorbance spectrum of MD-55-1 film on the irradiation level. Doses were delivered using ^{90}Sr$+^{90}$Y beta particles at the surface of a calibrated ophthalmic applicator (Ref. 27).
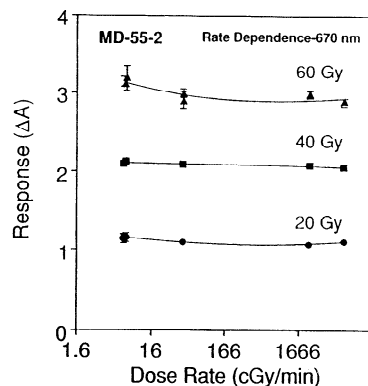

FIG. 8. Rate dependence data for MD-55-2 film response when irradiated with ^{60}Co gamma rays to different doses and dose rates, measured at a wavelength of 670 nm (Ref. 35).
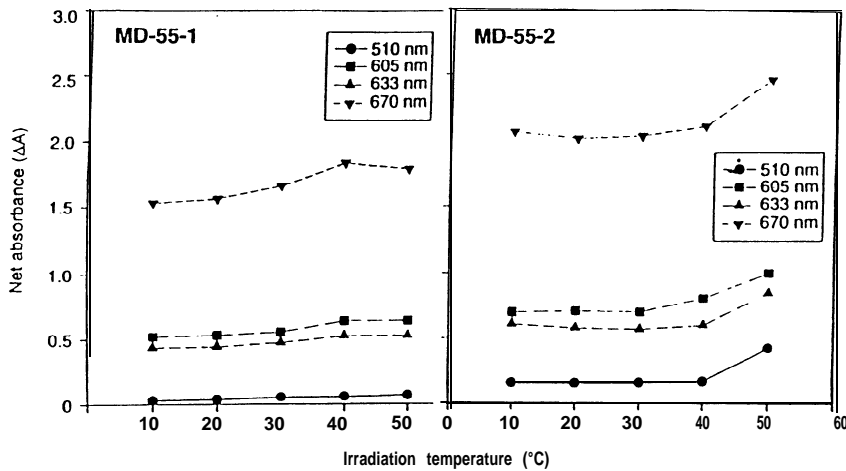
FIG. 9. The temperature dependence of the response of MD-55-1 and MD-55-2 films over the temperature range 10-50 °C during irradiation to a gamma-ray dose of 40 Gy, read at the indicated optical wavelengths (Ref. 35).

the mean response, q, in the region of interest. Hence relative (percent) standard deviation of the film response with respect to the mean provides information about *local* fluctuations in the film response. Local fluctuations are small scale and are related to such variables as the film grain size, spatial and signal resolution of the film scanner, pixel size, pixel depth, as well as electronic noise. The degree of nonuniformity caused by these *local* fluctuations, i.e., "spikes," is best assessed by comparison with the mean response and its relative (percentage) standard deviation in the region of interest. The second aspect of nonuniformity is *regional* variations produced by a systematic problem in the scanner or large scale nonuniformity in the film emulsion layer(s). Assessment of *regional* nonuniformity is perhaps best examined graphically but can be characterized by considering the differences (or ratios) of the maximum-minimum responses in the region of interest, provided *local* fluctuations are omitted. Both aspects of film uniformity, *local* and *regional,* are needed to completely characterize it.

Zhu *et al.* [36] have reported 15% *regional* nonuniformity of a particular film batch of MD-55-l. The variations in film response did not appear to have predictable pattern(s). Meigooni *et al.* [59] have also reported *regional* nonuniformity up to 15% for the ratio of the maximum-minimum responses of a certain batch of radiochromic film, model MD-55-l. Moreover, they have compared the *regional* variations of a single-layer film, MD-55-1, and a double-layer film, MD-55-2, along two central orthogonal directions, and have concluded that they both had similar nonuniformity in each direction, -4% in longitudinal direction that is parallel to the direction of the coating application, and -15% in the transverse direction that is perpendicular to the direction of the coating application.[48],[59] (See Fig. 10) To distinguish these two directions, recently the manufacturer, ISP, clips one corner of the film. The long side of the clipped corner is parallel to the direction of the coating application.[48]

Acceptable tolerances for film uniformity vary with application. Nevertheless, in a multi-institution investigation of the film uniformity of MD-55-2, the relative (percent) standard deviation of the film response with respect to the mean response did not exceed ±3% for high dose range (above >20 Gy) and ±5% for low dose range (below <l0 Gy).[69]

Therefore, for most teletherapy applications it may be reasonable to assume that film nonuniformity may not exceed these values. Film response should be evaluated using a large flat radiation field. Film should be placed on the central portion of a large photon beam (preferably 40×40 cm) at the depth of interest (preferably ≥5 cm). The flatness of the radiation beam must be determined by some other dosimeter (preferably an ionization chamber).

Furthermore, the results of a multi-institution investigation indicate that the amplitude of **local** and **regional** responses varied considerably with different instrumentations. Figure 11 is an example of responses of a MD-55-2 film exposed to a uniform dose (~20 Gy) and scanned with five different densitometers at five institutions."" The film responses, at each institution, are relative to the mean response of the film in the direction of scan. A set of fiduciary marks, located at -1.5 cm from the film edges, are used for identification of scan direction and alignment. As shown in Fig. 11, the film response is affected not only by the type of scanning equipment, but also by other instrumentation factors such as wavelength of analyzing source, step size, and sampling size. A highly coherent light source is more apt to give an interference pattern across a uniform beam than a broad band diffused light source. As evident from Fig. 11, high resolution scanners such as the ones used at Georgetown University, GU, and Washington University, WU, have given more noise which should not be attributed to film nonuniformity. For further discussion regarding scanning equipment and factors affecting dosimetry, readers are referred to Sec. IV.

Double-exposure technique: If evidence of nonuniformity should appear, the double-exposure technique is a method to improve film uniformity to an acceptable tolerance. Zhu *et al.* [36] have proposed this technique which is applicable to all radiochromic films. In the double-exposure technique a matrix of correction factors is obtained from the relative film response exposed to a uniform irradiation field. The size of this correction matrix depends on the size of the aperture of the densitometer, desired spatial resolution, and mode of the scanning system (linear versus image scanner). One may use an average of several pixels (e.g., 4×4 or 10×10) to generate the correction matrix. In practice, a layer of film is first

marked with at least three fiducial marks and then exposed to a uniform dose of D_1 (normally about 15-20 Gy for MD-55-1 film or about 10 Gy for MD-55-2 film). The mean optical density of the film, $\langle OD_1(i,j)\rangle$, in the area of interest can be determined after 24 h. Then the film is exposed to an unknown dose of D_2 in the desired irradiation field. The film is scanned, again after 24 h, and the two images are correlated using the three fiducial marks. The optical density from the first exposure, $OD_1(i,j)$, and the second exposure, $OD_2(i,j)$, can be used to obtain a nonuniformity corrected net optical density, $OD_{net}(i,j)$, using the following relations:

$$OD_{net}(i,j) = \frac{OD_2(i,j) - OD_1(i,j)}{f (i,j)} \tag{1}$$

where

$$f(i,j) = \frac{OD_1(i,j)- OD_0(i,j)}{\langle OD_1(i,j)-OD_0(i,j)\rangle}, \tag{2}$$

and $OD_0(i,j)$, which represents the background (i.e., fog) readings, is the film optical density prior to the first exposure. The double-exposure technique may require writing a computer program for image handling and data analysis. Note that the double-exposure technique has some limitations. For instance, the accuracy of matching the fiducial marks in the two exposures is limited and should be evaluated by the user. Therefore, improvement of the film uniformity by the manufacturer is necessary in order to explore further the full application of radiochromic film.

M. Film calibration and sensitivity

Radiochromic film should be calibrated using a large well-characterized uniform radiation field. Film should be placed on the central portion of a large photon beam (such as a 40×40 cm) at depth of interest (preferably ≥5 cm). The characteristics of the calibration beam should be determined by some other dosimeter (such as an ionization chamber). This would allow direct film calibration in terms of absolute dose within the dose range of interest.

The relationship between absorbed dose and film response should be determined. This relationship can be plotted as a curve, often known as a calibration curve. The slope of the calibration curve decreases as dose increases [Fig. 12(A)]. The calibration curve can provide information for conversion of film response to dose and vice versa.

The relationship between dose and film response can also be tabulated. The change in film response per unit absorbed dose can be represented by a single number for a net optical density up to 1.0. This number, defined here as film average sensitivity, is the average change in response (i.e., readout) per unit absorbed dose calculated over the lower, most linear portion of the calibration curve. This number depends on one or more of the following: (1) the wavelength used for readout, (2) the particular densitometer used for readout, (3) film batch, (4) the delay between irradiation and readout, (5) beam quality of the calibration source, and (6) other factors (such as temperature and humidity) previously discussed. Table II is an example of a film sensitivity calculation for
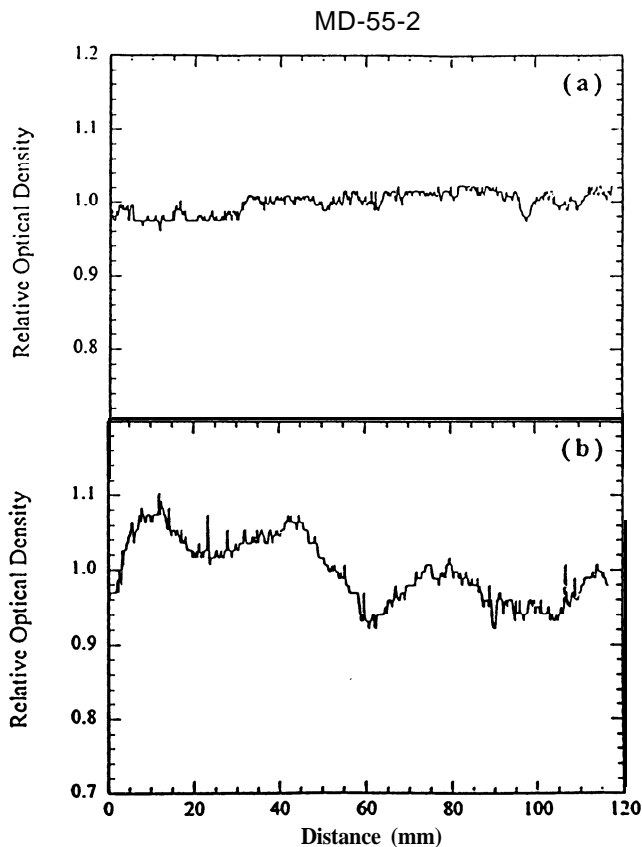
FIG. 10. Comparison of relative optical density for MD-55-2 film exposed to uniform radiation fields with ^{60}Co gamma ray beam in (a) longitudinal and (b) transverse directions, respectively (Ref. 59).

MD-55-2 (lot No. 941206), exposed to uniform ^{60}Co doses and scanned after a week delay with a 633 nm LKB densitometer at NIST. The average sensitivity (net OD/Gy) for this combination, for the dose range 0-30 Gy, from the data above the line is 0.0223±0.0007 (3.2%). Figure 12 is a plot of (A) net OD and (B) net OD per unit absorbed dose measured two days postirradiation. Figure 12(A) has two fairly linear portions, one from 0 to 30 Gy, and the other from 30 to 100 Gy. The average sensitivity for the dose range 30-100 Gy drops about 15% as compared to the one for the dose range 0-30 Gy. This average sensitivity can be used for conversion of film response to dose for *these* conditions and is clearly inappropriate for higher doses or other conditions. Each user should determine film response and sensitivity for the specific conditions.

N. Dose calculation using a double-exposure technique

Klassen *et al.* [50] used a double-exposure technique to evaluate MD-55-2 as a high precision dosimeter using a Cary 210 (Varian) Spectrophotometer with 676 nm wavelength. Unknown doses, in the range 5-7 Gy, were given to a set of films and the increase in OD was measured. Then a known dose of 6 Gy was given to each film and the increase in OD was measured. In order to measure the change in sensitivity of the films between the first and second exposures, control

Response of Radiochromic Film MD-55-2
(Dose ~2000 cGy)
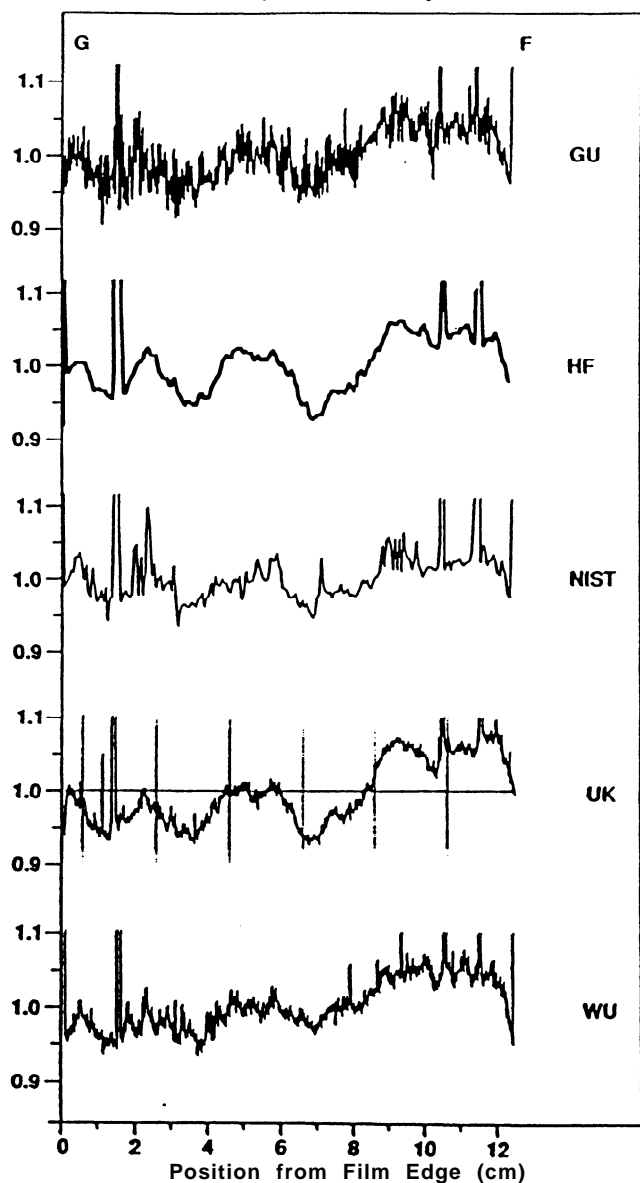
FIG. 11. Responses of MD-55-2 film exposed to a uniform dose, 20 Gy, and scanned with five different densitometers at Georgetown University (GU), Henry Ford Hospital (HF), National Institute of Standards and Technology (NIST), University of Kentucky (UK), and Washington University (WU) (Ref. 69).

films were given a known first dose of 6 Gy followed by another, known, dose of 6 Gy. The unknown dose to a film was calculated using its sensitivity to the second dose and the ratio of sensitivities derived from the control. Calculated in this fashion, the uncertainty in the unknown dose was less than 1% between 5 and 7 Gy. The uncertainty is further reduced when the unknown dose is close to the known dose, i.e., when the ratio of the increase in OD for the first dose to the increase in OD for the second dose is the same as that of the control. Figure 13 is a representation of the increase in OD with time of a first dose of 6 Gy followed by a second dose of 6 Gy. The dashed lines indicate the increase in OD in the absence of exposure.[50] The difference between the net

optical density 0.50 for the first dose of 6 Gy and the net optical density of 0.46 for the second dose of 6 Gy is caused by the slight decrease in sensitivity of the film as the total accumulated dose increases, as well as the choice of wavelength used for analysis.[35]

O. Shipping and handling

Any physical damage of the radiochromic films during shipping or handling will introduce erroneous data in dosimetric measurement. The color of the film will turn from clear to a milky white at the damaged location. Normally, the vendors provide the film between two layers of cardboard, securely placed in an additional box. However, occasionally the film may be damaged during the packing and shipping and users should carefully examine the films when they are received and store and handle them very carefully. The films have a slight tendency to pick up dust, probably due to static charges on the outer layers, so before use the film should be wiped clean with a lintless paper.[50] The cut edges of the film may be stressed and should be avoided for dosimetry analysis. It is recommended to keep the light analyzing beam about 1.5 mm away from the cut edge.[50]

P. Summary characteristics of radiochromic films

Characteristics of the most commonly used radiochromic films: HD-810 (DM-1260), MD-55-1, and MD-55-2 are summarized in Table III.

Q. Summary procedures for radiochromic film dosimetry

The following is a summary outline of considerations for radiochromic film dosimetry.

(1) Prior to use, films should be visually inspected and handled with care. (See Sec. III O.)

(2) Films should always be kept in a dry and dark environment at the temperature and humidity at which they will be utilized for clinical purposes. (See Sec. III J.)

(3) Since the radiochromic films are sensitive to fluorescent light and to sunlight, they should be read and handled in normal incandescent light. If necessary, fluorescent lights and laboratory windows can be covered with commercially available UV filters.[57] (See Sec. III J.)

(4) The film lot number and model number should be noted. This will allow the user to verify any variation in the manufacturing of the film. (See Sec. III A.)

(5) The film orientation and alignment should be noted. This will allow the user to minimize the polarization effect if necessary. (See Sec. III F.)

(6) Since the film response changes with time, especially during the first 24 h after irradiation, the exposure time and readout time for all the films should be documented and, if necessary, appropriate correction factors for instabilities should be applied. The recommendation is to read the films at least 24 h[28] (preferably 48 h) after the exposure. (See Sec. III E.)
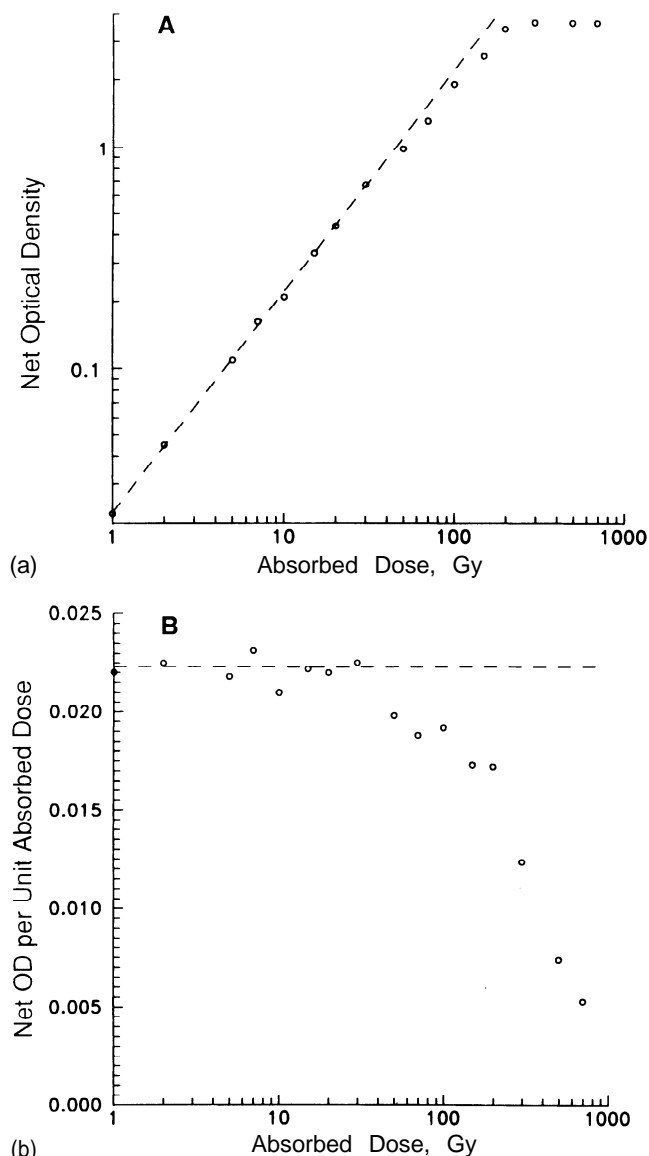
TABLE II. Film sensitivity calculation for MD-55-2 film exposed to Co-60.

Dose (Gy)	Optical density	Net OD dose
0	0.312	...
1	0.334	0.0228
2	0.357	0.0229
5	0.421	0.0218
	0.474	0.0232
10	0.522	0.0210
15	0.645	0.0222
20	0.752	0.0226
30	0.988	0.0225
50	1.303	0.0198
70	1.630	0.0188
100	2.233	0.0192
150	2.910	0.0173
200	3.759	0.0172
300	4.012	0.0123
500	3.998	0.0074
700	3.993	0.0053

FIG. 12. Log plot of (A) net optical density and (B) net optical density per unit dose as a function of dose for MD-55-2 film.

certain circumstances, in order to extend film range, lower wavelengths for readout (at the expense of contrast) are desirable. (See Sec. III K.)

IV. SCANNING DENSITOMETER SYSTEMS

Characteristics pertaining to various aspects of scanning densitometers are described in the following sections.

A. Techniques of two-dimensional data acquisition

There are two distinct approaches to the problem of how to perform two-dimensional densitometry. The more traditional approach is to use a small light source and detector and then to translate the object being scanned. A slight variation to this approach is to translate the light source-detector instead of the object being scanned. Common to both variations of this approach is that only a single point is measured at a time. As with manual, single-point densitometers, this single point consists of a light transmission measurement averaged over the area of the defining aperture of the light source, and also averaged over the absorbance spectrum of the object being measured weighted by the wavelength spectrum of the light source and the efficiency of the light detector. The resolution of such translational (moving) systems is thus governed by the size of the light source used, and by the distance between successive measurements.

A second approach to this measurement problem is the use of two-dimensional imaging systems. In this approach, a uniform light source illuminates the object being scanned from the rear, and an imaging system (like a camera) is used to measure light transmission from many points on the sample simultaneously. The resolution of the scan is primarily governed by the pixel size of the imaging system only. Such systems have a speed of measurement advantage over traditional systems since data are acquired from all points on the sample simultaneously.

(7) Film uniformity should be examined. If necessary the double-exposure technique should be considered to improve film uniformity. (See Sec. III L.)

(8) Radiochromic film should be calibrated using a large well-characterized uniform radiation field. (See Sec. III M.)

(9) The dose response curve and film sensitivity should be obtained in the dose range and conditions of interest. (See Sec. III M.)

(10) The characteristics and/or limitations of your scanning densitometer should be considered. Several laser scanning systems and CCD microdensitometer cameras are commercially available for scanning radiochromic films. (See Sec. IV).

(11) The wavelength of the light in the densitometer should be nominally between 600 and 670 nm, which are the wavelengths of the two main absorption peaks, thereby maximizing the signal obtained from the system. However in
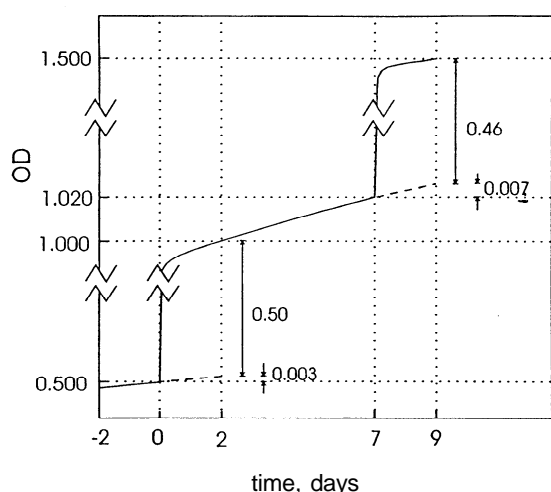
FIG. 13. A schematic of how the OD of a dosimeter changes as the result of a first dose of 6 Gy, given at 0 days, and a second dose of 6 Gy, given at 7 days. The sensitivity drops 8% at 7 days. In each case, the OD is read 2 days after irradiation. The dashed lines indicate the change in OD which would have taken place in the absence of the irradiation (Ref. 50).

B. Characteristics of light sources

Having introduced these two densitometry data acquisition techniques, we now examine the common characteristics of such systems. Of primary concern on all types of densitometry systems is the light source used for the absorbance measurements. The important characteristics for light sources are (1) emission spectrum; (2) size (for moving systems); (3) uniformity (for imaging systems); (4) output strength; and (5) polarization. For maximum sensitivity, the light source spectrum should peak at the peak of the absorbance spectrum of the sample being measured. However, for minimum pixel size, laser sources are often used which have sharply defined wavelengths. Alternatives to lasers are filtered white-light sources; fairly narrow (on the order of 10

nm full width at half-maximum) emission spectra are possible using interference filters. The disadvantage of using filtered sources is the loss of light source strength which limits the ability to make measurements at higher optical densities. For imaging systems, the uniformity of the light source is also a very important parameter. In principle, non-uniformity of the light source in such systems can be accounted for by making images of the bare light source and digitally correcting sample images for observed light source nonuniformities. A typical approach to making large-area uniform light sources is to use a bank of light-emitting diodes (LEDs) behind a light-diffusing surface. Use of LEDs has the advantage that a number of narrow emission spectra centered at different wavelengths are available. When laser sources are used, it is necessary to have the sample mounted on a light-diffusing surface so as to avoid interference fringe artifacts caused by reflections on plate and sample surfaces.[70]

C. Characteristics of light detectors

Important characteristics for light detectors are (1) sensitivity; (2) spectral efficiency; (3) linearity; and (4) signal resolution. The most sensitive light detectors for absorbance measurements usually employ some sort of transmitted photon counting. For single-point (and moving) systems the traditional detector is the photomultiplier tube (PMT) operated in the current mode for low absorbance/high signal measurements or in the pulse counting mode for high absorbance/low signal measurements. Spectral efficiencies for most common PMTs are well known and easily obtainable from product literature. Of greater concern is the linearity of these systems. Factors which affect PMT detector linearity are counting losses at high pulse rates (low absorbance levels), and possible nonlinearities at changeover points from pulse counting to current modes.

Other, though generally less sensitive detection systems, employ solid state detectors. The most sensitive imaging sys-

TABLE III. Characteristics of radiochromic films.

	Radiochromic film		
Characteristic	HL-810 (DM-1260)	MD-55-l	MD-55-2
Nuclear Assoc. No.	——	37-041	37-041
Nominal dose range (Gy)	50-2500	10- 100	3-100
Effective Z	6.0-6.5	6.0-6.5	6.0-6.5
Postirrad. color stability with time	24 h (Sec. III E)	24 h (Sec. III E)	24 h (Sec. III E)
40 keV response relative to ^{60}CO	0.7 (Sec. III G)	0.6 (Sec. III G)	0.6 (Sec. III G)
Dose fraction effect	< 1%	< 1%	<1%
Dose rate effect	<5% (Sec. III I)	<5% (Sec. III I)	>60 Gy 10% <60 Gy None[a]
Humidity effect	<2% (Sec. III J 1)	<2% (Sec. III J 1)	<2% (Sec. III J 1)
Temperature effect	Yes (Sec. III J 2)	Yes (Sec. III J 2)	Yes (Sec. III J 2)
Ultraviolet sensitivity	Yes (Sec. III J 3)	Yes (Sec. III J 3)	Yes (Sec. III J 3)
Image resolution	>600 cycles/mm (1200 lines/mm)	>600 cycles/mm (1200 lines/mm)	>600 cycles/mm (1200 lines/mm)
Uniformity (RSD)	7% (Ref. 39)	3%-5%	3%-5%

[a]Reference 35.

terms utilize banks of charge-coupled device (CCD) detectors. Quite high densities of such devices are obtainable, and sensitivity is comparable to PMTs. In considering such devices for densitometry, one needs to be aware of the spectral efficiency relative to the light source used.

Finally, an important consideration for all types of detector systems is the signal resolution. It is generally specified in terms of the number of discrete density steps (shades of grey) that the detector is capable of. Signal resolution is also often specified in terms of the number of bits of information per pixel. Thus, for example, an 8 bit device is capable of resolving only 256 shades of grey.

D. System response spatial resolution linearity

The overall light source/detector linearity is generally investigated in the course of preparing a calibration curve for the system. This process involves applying known doses of radiation to individual samples, and looking at the function of measured optical density versus delivered absorbed dose. Since the properties of the dosimetry medium may influence the shape of the calibration curve, a better way to investigate detector system linearity is through the use of calibrated neutral density filters. Such filters have a relatively flat absorbance spectrum and are uniform in density over fairly large areas. They can be calibrated using high-quality spectrophotometers, and generally consist of a stable metal evaporated onto quartz or glass.[71] By comparing the density read with the system under test with the density as indicated by a spectrophotometer, one can have a reliable method of determining system linearity independent of the imaging medium. This is useful since it may indicate that it is the reader system rather that the imaging medium that causes a calibration curve to flatten at higher dose levels. Also one may find that there is an optimal density region in terms of relative standard deviation of measured densities. Generally this will not be at a low density because of "background" density of the nonirradiated medium, or at high densities because of lack of transmitted light causing poor signal-to-noise ratios.

E. Spatial resolution

The spatial resolution of any imaging system is generally quantified by the number of resolvable line pairs per millimeter. Factors which govern resolution for moving systems are (1) light source size and (2) minimum space between successive readings. For imaging systems, resolution is governed by (1) pixel size and (2) amount of "dead" area between sensitive elements of the imaging array. Resolution in both types of systems is also limited by (1) light diffusion in the sample and (2) stray light in the reader. Spatial resolution for any system is best evaluated by reading a standard line pair pattern and determining the maximum number of resolvable line pairs/mm. An interesting feature of imaging densitometers is the possibility to vary the pixel size by changing the position of the imaging detector relative to the light source/sample plane. Thus, while the moving systems make single measurements which are basically only samples over the light source size, the imaging systems provide samples

averaged over the pixel size, with the only information that is lost being that in the "dead" area between pixels. Another important consideration for moving systems is the range of position steps available. Obviously, step increments much smaller than the size of the light source are not of much use. On the other hand, one does not want to be unduly limited in the largest stepping increment made available, since this would produce prohibitively large data files for modest sized samples.

F. Positional accuracy

An important parameter in any two-dimensional densitometer is the positional accuracy of the resulting image. For moving systems, this is effected by the accuracy of the stepping increment between measurement points. For imaging systems, the regularity of the imaging grid affects the resulting accuracy of the image. For both types of systems, positional accuracy may be determined by scanning regular grid patterns and comparing the resulting images to the known grid dimensions.[31,72] A significant caveat for systems which translate the sample and/or the light source/detector system is whether the motion is bidirectional or not. While bidirectional motion increases readout speed, it may introduce positioning errors in alternate scanning rows due to effects such as gear backlash when the direction is reversed. Examples of this effect are shown (unintentionally) in the jagged isodose contours of Soares,[30] which could subsequently be corrected to make smooth isodose contours viewed both topographically and orthographically.[38]

An unavailable feature in many scanning systems is the ability to position samples in a reproducible manner on the scanning bed. This is an important consideration when a series of films that have been irradiated simultaneously in a stack are to be read. Since the scanning system returns coordinates based on the scanning bed and not on the film itself, the user is left with the problem of registering the various images (coordinate systems) of the stack of films. In the worst case this involves both translational and rotational coordinate transformations. Similar problems arise when multiple readings of the same sample are desired, such as pixel by pixel sensitivity corrections based on readouts before and after irradiation.[36] Either fiducial marks on the film or images which include the edges of the film are necessary to make such registration corrections.[38] On the other hand, if the scanning bed has provisions for positioning samples with high reproducibility, these difficulties can be largely avoided. One suggestion has been to include small pegs on the sample bed that fit into prepared holes in each sample.[72] Since in medical dosimetry one is very often interested in three-dimensional dose distributions, such a consideration for reassembling a stack of two-dimensional images is an important one. Another important parameter associated with the scanning bed is the size of the sample that can be read. For imaging systems this is limited by the size of the uniform backlighting surface. Most moving systems are designed to accept at least a 20 cm × 25 cm (8 in. × 10 in.) sample, with conventional x-ray film in mind.

G. Acquisition time

A very practical consideration in sample reading is the time necessary to acquire the scan data. Obviously there is a speed advantage when an imaging system is used since all the data are acquired simultaneously. Other factors which affect data acquisition time for moving systems are (1) the time necessary to make an individual measurement, (2) the time necessary to step to the next position, and for systems which transfer data to a host computer, (3) the time necessary to transfer the data.

H. Control software

It is often the case that the software supplied with the scanning system for manipulating the image data limits the user to only those operations anticipated by the software designer. In practice, users may need operations that are not supported by the software supplied. For this reason, software should be as flexible as possible, but even more importantly, it is essential that the user be able to access the optical density data in a format that can be transferred to other software packages. Documentation supplied with the scanning system should clearly indicate how to do this operation. The most universally acceptable form (although probably the bulkiest as well) is an ASCII format of the *x* and *y* coordinates followed by a quantity proportional to the measured optical density. In any event, supplied software should be capable at least of displaying the scanned image, preferably in color. The ability to produce isodensity contours is also desirable. It is also important to be able to convert the density data to absorbed dose using a user-generated calibration curve. This feature is essential in nonlinear systems to avoid confusion between isodensity plots and isodose plots.

I. Environmental factors

Finally, it is important to consider several characteristics which may best be described as "environmental" factors. Chief among these is the temperature that the sample may reach in the course of readout[28] as well as postirradiation.[65] If the temperature of the sample becomes significantly above room temperature, the user should make a note of the amount of time taken for this to occur as well as the time that has elapsed since the beginning of the scan. This is a very important parameter for some dosimetry media such as polydiacetylene thin-coated film, which exhibits a temperature dependence in its absorbance spectrum.[28] For certain wavelengths, a modest change in temperature can be magnified into a significant change in optical density because the wavelengths lie on a steep portion of the absorption spectrum. Another important factor is the type of interior lighting employed during sample loading and positioning. Some systems use fluorescent lights that contain a significant ultraviolet component; some dosimetry media are sensitive to this component and spurious optical density changes can occur during sample setup.

J. Specifications of some scanning densitometer systems

Specifications of some scanning densitometers are summarized in Table IV.

V. MEDICAL APPLICATIONS OF RADIOCHROMIC FILMS

The radiochromic films are relatively insensitive to radiation compared to commonly available detectors used in medical applications. This lack of sensitivity makes them ideal for dosimetry where high doses are utilized. An example of such a situation is the dosimetry in the immediate vicinity of brachytherapy sources. Because of the inverse square law, radiation doses at points close to the source can be very high, which becomes a problem with conventional detectors. Another important characteristic of radiochromic films is that they have an elemental composition close to that of water, which reduces their sensitivity to photon energy for applications dealing with determination of dose delivered to water. Finally, the radiochromic films are available in the form of a two-dimensional dosimeter. These dosimeters need to be calibrated prior to use (see Sec. III). Some of the applications in medicine which are based on the abovementioned features of radiochromic films are described in this section.

A. Ophthalmic applicator dosimetry

Although ^{90}Sr ophthalmic applicators have been used for decades, problems with their dosimetry have been resolved only recently. Until recently, there was no standardized method for calibration of the dose rate at a reference distance in a medium; discrepancies of up to 50% were reported by Goetsch[73] in 1989. Subsequently, this discrepancy was resolved and a standardized method for the calibration of these applicators was reported by Soares.[30, 74] During this development, it became clear that the calibration of ophthalmic applicators should be based on the determination of surface absorbed dose rate to water averaged over an appropriate area, and that relative dose profiles should also be determined to completely specify the two-dimensional dose distributions produced by these applicators. Because of the extremely high dose rates produced by these applicators, the radiochromic film proved to be an ideal detector for the determination of dose profiles, as demonstrated in a series of papers from NIST by Soares.[30,75]

In 1991, Sayeg and Gregory[61] described a technique which enables them to obtain detailed dose characteristics of ^{90}Sr beta-ray ophthalmic applicators. A radiochromic radiation detector was used to determine the surface dose rate and dose distribution of these sources. The detectors were found useful for this application due to the high surface dose rates [0.10-1.0 Gy/s] and their low sensitivity (approximately 10^4 Gy for an optical density of 1.0). The films were evaluated on a He-Ne scanning laser densitometer with a resolution of 0.3 μm. Comparison with NIST extrapolation ionization chamber measurements indicated surface dose-rate agreement within 6%.

Also in 1991, Soares[30] described the use of radiochromic film for source profiling. The films were used to map dose-rate variations at applicator surfaces. The films were read using a scanning laser densitometer (LKB Pharmacia model 2222-020) at 633 nm, which is near one of the peaks in the film absorbance spectrum. The spot size of the laser was 100 μm in diameter, and the step size for scanning was adjustable in 40 μm increments in both dimensions. The accuracy of the stepping increment was checked by scanning a microscope stage micrometer and a NIST glass scale. The absolute linear accuracy of the system was found to be accurate to less than 1 μm. Soares[30] calibrated these radiochromic films using well-characterized ^{60}Co gamma-ray beams. To check this, calibrations were performed using both ^{60}Co gamma rays and ^{90}Y beta particles. The latter was done using the protection-level sources used at NIST for instrument and source calibrations. There is agreement between NIST and the National Standard Laboratory of Germany, Physikalisch-Technische Bundesanstalt (PTB) on the dose rate from these sources at the prescribed distances. Furthermore, it has been shown that radiochromic film response to electron beam irradiation is the same as the response to Co-60 gamma rays within the estimated uncertainty of measurement (±5% at 95% confidence level).[28,76]

B. Brachytherapy dosimetry

Because the dose gradients around brachytherapy sources are steep, the high spatial resolution offered by film dosimetry is an advantage over other detectors such as thermoluminescent dosimeters (TLDs). In 1991, Muench *et al.*[39] explored applications of radiochromic film for dosimetry near brachytherapy sources. Dose distribution in the immediate vicinity of a high activity (370 GBq) brachytherapy ^{192}Ir source was mapped using radiochromic film. They compared the photon energy dependence of the sensitivities of GafChromic film, silver halide verification film (Kodak X-Omat V Film), and lithium fluoride TLDs (Harshaw) over the photon energy range 28 keV-1.7 MeV, which is of interest in brachytherapy. For more discussion on the energy dependence, see Sec. III.

C. Interface dosimetry

Dose perturbation at tissue-metal dental interfaces has been studied by several investigators.[77-79] In 1991 Farahani *et al.*[77] used radiochromic films to investigate the enhancement of dose to soft tissue (or water) close to high electron-density materials and to measure the detailed lateral and depth-dose profiles in soft-tissue-simulating polymer adjacent to planar interfaces of several higher atomic-number materials of interest in dental restoration: 18 carat gold dental casting alloy; Ag-Hg dental amalgam alloy; Ni-Cr dental casting alloy: and natural human tooth structure. Interleaved stacks of calibrated thin radiochromic dosimeter films and tissue-simulation polymer were used for these measurements. Assemblies of these polymer-dosimeter stacks on both sides of the dental materials were irradiated in one fixed direction by collimated ^{60}Co gamma-ray or 10 MV x-ray

beams directed perpendicularly to the material interfaces. In another test, designed to simulate more closely therapeutic treatment conditions, a phantom constructed on both sides of a row of restored and unrestored whole teeth (restoration materials; gold alloy crown; Ni-Cr alloy crown; Ag-Hg mesial-occlusal-distal (MOD) amalgam filling; unrestored tooth) was irradiated in one fixed direction by the collimated photon beams. Their results indicated that the dose-enhancement in "tissue" is as great as a factor of 2 on the backscatter side adjacent to gold and a factor of 1.2 adjacent to tooth tissue, but is insignificant on the forward-scatter side because of the predominant effect of attenuation by the high-density, high atomic-number absorbing material.

D. Stereotactic radiosurgery dosimetry

In 1990, Bjarngard *et al.*[80] used radiochromic film to investigate the effects of electron disequilibrium for small fields used for irradiation of intracranial lesions. For radii < l.0 cm the dose on the central axis was shown to progressively diminish due to electron disequilibrium. This leads to measurement artifacts when the detector is too large, as was readily observed with ionization chambers. Radiographic and radiochromic films were used with densitometric evaluation to provide the resolution necessary to measure absorbed doses for the narrowest beams. The contribution by phantom-scattered photons was significant even at small field sizes, and scatter factors were determined from the experimental results. Photons scattered by the auxiliary collimator did not add appreciably to the dose on the central axis. The data were used to characterize the dose-to-kerma ratio as a function of beam radius.

In 1994, McLaughlin *et al.*[38] addressed similar problems related to the dosimetry of small fields. As a demonstration of suitability, the calibrated radiochromic film was used to measure the dose characteristics for the 18, 14, 8, and 4 mm fields from the gamma-ray stereotactic surgery units at Mayo Clinic and the University of Pittsburgh. Intercomparisons of radiochromic film with conventional methods of dosimetry and vendor-supplied computational dose planning system values indicated agreement to within ±2%. McLaughlin *et al.*[38] concluded that the dose, dose profiles, and isodose curves obtained with radiochromic film can provide high-spatial-resolution information of value for acceptance testing and quality control of dose measurement and/or calculation.

E. Dosimetry in the penumbra region of radiotherapy beams

During the commissioning of a multileaf collimator system, Galvin *et al.*[81] used radiochromic film to investigate any potential distortions of the dose distribution at an edge due to changing energy sensitivity of silver bromide film. Standard radiographic film was used for the penumbra measurements and separate experiments using radiochromic film and thermoluminescent dosimeters were performed to verify that distortions of the dose distribution at an edge due to changing

TABLE IV. Specifications of some scanning densitometer systems.

Maker	Model	Scan mode	Light source Type	Wavelengths	Size
LKB Pharmacia	UltroScan XL	Translational	HeNe laser	633 nm	100 μm spot or 50×800 μm rectangle
Molecular Dynamics	Personal densitometer	Translational	1 mW HeNe laser	633 nm	50 μm (FW2 σ) Gaussian spot
Zeineh	Soft laser scanning densitometer		HeNe Laser	635 nm	50 μm
Vision Ten	V SCAN	Imaging	Filtered white light	670 nm	···
Bio-Rad	GS-670	Translational/imaging	Filtered fluorescent light bed	400-750 nm	···
Photoelectron Corporation	CMR-604 CMR-608	Imaging	LED light bed	665 nm (20 nm FWHM) 470-940 nm available	···
Vidar Systems Corporation	VXR-12	Translational/imaging	Standard fluorescent light	Broadband	168 μm
AGFA	Arcus II	Translational/imaging	Standard fluorescent light	Broadband	168 μm
Lumisys	Lumiscan 75/ Lumiscan 150	Translational/imaging	Laser	633 nm	100 μm spot/ 2 K=l00 μm/ 1 K=175 μm/ variable l00-420 μm/ high resolut. 50-420 μm

Maker	Detector type	Resolution Spatial	Signal	Pixels	Density range
LKB Pharmacia		20 μm and 40-600 μm in 40μm steps	12 bit (4096 shades of grey) over 0-10 OD	Variable	0-4 OD
Molecular Dynamics	PMT	50 or 100 μm	8 or 12 bit selectable	Variable	0-4 OD
Zeineh		100 μm	8 bit		
Vision Ten	CCD	50, 87 or 105 μm	12 bit	843 × 1280 to 4096 × 5000	0-3.5 OD
Bio-Rad	Linear CCD	58 μm (variable)		4000 × variable	0-2.5 OD
Photoelectron Corporation	Cooled CCD	minimum 27 × 23 μm (variable)	16 bit	242 × 375	0-2.4 OD
Vidar Systems Corporation	Linear CCD	85, 168, 339, or 423 μm	12 bit	Variable	0-2.6 OD
AGFA	Linear CCD	21, 28, 42, 85, 168, 353 μm	12 bit	Variable	0-2.5 OD
Lumisys	Linear CCD	l00- 175 μm/variable	12 bit	2048 × 2500/variable	0-3.5 OD

Maker	Bed type	Bed size	Scan speed	Acquisition time
LKB Pharmacia	White diffused fluorescent during setup	22 × 25 cm	42 mm/s	100 × 100 pixels in 40 m (ASCII) 200 × 200 pixels in 40 min (binary)
Molecular Dynamics	Low fluorescent clear glass	20 × 25 cm	7 lines/s	20 × 25 cm sample in 6-12 min
Zeineh		Line scanner 15 cm × 5 mm		10 s per scan line
Vision Ten		35 cm width, any length > 7.5 cm	100 lines/s	
Bio-Rad		30 × 43 cm		1-15 min
Photoelectron Corporation	White diffused	9.6 × 12.2 cm or 19.6 × 24.6 cm		0.5 min
Vidar Systems Corporation	Vertical feed	35 × 43 cm		51 s for 36 cm × 43 cm film at max resolution
AGFA		21 × 35 cm	250 lines/s	25 × 20 cm film at 352 μm digital resolution ~50 s
Lumisys	Vertical feed	17 × 35 cm	115 lines/s	21.5 × 27.8 cm film at 200 μm pixel size -15 s

TABLE IV. *(Continued.)*

Maker	Interfaces	File formats	Price	Users	
LKB Pharmacia	Serial RS232 (9600 bODd), parallel (Centronics)	Coded Binary, ASCII	$15 K	NIST Vanderbilt Henry Ford Hospital	
Molecular Dynamics	Serial, parallel, thin wire ethernet	8 and 16 bit TIFF	$20 K	Washington Univ. Univ. of TX MD Anderson Univ. of WI Calib. Lab. Univ. of KY	
Zeineh Vision Ten Bio-Rad	IBM IBM AT Bus, SCSI PC, GPIB		$12 K	Henry Ford Hospital	
Photoelectron Corporation	Serial RS232 (115.2 kbODd maximum)	TIFF, FITS		NIST	
Vidar Systems Corporation	SCSI	TIFF, BMP	$16 K	Pennsylvania Hospital York Cancer Center	RIT 113
AGFA	SCSI	TIFF, BMP	$22 K	Loma Linda Univ.	RIT 113
Lumisys	PC, SCSI	TIFF-Binary	$30 K	Georgetown Univ. NIH	RIT 113

energy sensitivity of silver bromide film are negligible. Films were analyzed with a scanning laser densitometer with a 210 μm spot size.

F. Hot particle dosimetry

In 1990, Soares *et al.* [82] presented preliminary results of the measurement of the distribution of skin doses from hot particles which are micron size particles containing radioactive materials, in this study of ^{60}Co. Hot particles are a concern in the environment of a nuclear reactor because they represent a potential source of harmful radiation exposure to nuclear workers. This work was also a first demonstration of the high resolution dosimetry that is possible with radiochromic film.

The two-dimensional dose profile was obtained in the following manner. A particle of suitable nominal size and activity was selected. The ^{60}Co activity was measured at NIST using Ge(Li) spectrometry as 62 μCi. The diameter was measured with a traveling stage microscope as 277 μm. The radiochromic film was then taped to a polystyrene block and a tape strip containing the particle was stretched over the film, and the edges were taped down to keep the particle in contact with the sensor film. For measurements at 7 mg/cm^2 (the tissue depth of interest in nonpenetrating radiation protection), additional layers of Mylar^{TM} were inserted between the hot particle and the sensor film. For these measurements, exposures were made for various times between 1 and 168 h. For depth dose profiling, a stack of 12 films was exposed for 120 h. The film was then read out with a 40 μm step size. The optical absorbance for the scan file was then converted to absorbed dose rate using the exposure time and the film dose-calibration curve based on the NIST ^{60}Co standard pool source. The data files, typically 2500 x-y points, were transferred to a PC for plotting using a three-dimensional graphics routine.

In a subsequent study reported in 1991 at the same institution by a team led by McWilliams,[83] an attempt to standardize hot particle dosimetry was made through the generation and characterization of ^{60}Co spheres. An electron arc, rapid solidification process was used to produce uniform co-balt alloy spherical particles of various diameters ranging from 50 to 300 μm. Neutron activation of selected particles yielded essentially pure ^{60}Co in the MBq range. The particles were characterized by physical size and activity. Dose rates were determined using extrapolation chamber and radiochromic dye film measurements. Having simple geometries, these particles were found to be ideal for the development and testing of calculational methods and benchmarking of computer codes designed to assess shallow dose. Some of the experiments performed at NIST dealing with precision source profiling using radiochromic film were also presented in a 1993 review by Walker *et al.* [84] and another by Soares and McLaughlin.[31] A dosimetry intercomparison of hot-particle dosimetry has recently been reported on which involved two groups using radiochromic film.[85]

G. Dosimetry for radiation inactivation and target size analysis

Large doses in the range of hundreds of kGy are necessary for the inactivation of some proteins active in cellular metabolism. From a knowledge of accurate dosimetry in this high dose range and the shape of the inactivation dose response curve, it is possible to ascertain the molecular size of putative proteins (or other targets). One such application using radiochromic detectors was reported by Van Hoek *et al.* [86] in 1992. Dosimetry was performed using 1×1 cm pieces of "radiochromic nylon," 50 μm thickness film dosimeters, of which the optical density change at 510 nm, after irradiation, was measured using a Far West Technology FWT-92 radiochromic reader.[86] The dose received was determined from the difference in optical density. The calibration was checked against irradiation in a ^{60}Co gamma-ray beam and found to agree within 1% with the source calibration using Fricke ferrous sulphate dosimetry. The functional unit size of the water channel in rabbit erythrocytes was assessed using target size analysis following radiation inactivation. Using radiochromic nylon dosimetry, accurate values of accumulated dose yielded an absolute target analysis, leading to direct determination of molecular size.

H. Intravascular brachytherapy dosimetry

A special application which is ideally suited for radiochromic film dosimetry is the characterization of the dose distributions around intravascular brachytherapy sources. The dimensions of these sources are comparable to "hot particles" (see Sec. II F) and dosimetry information is needed at distances of 2-5 mm from the source axis, which are smaller than those encountered in conventional brachytherapy. Soares *et al.* [87] have reported on the use of radiochromic film dosimetry in conjunction with extrapolation chamber measurements for the calibration and characterization of $^{90}Sr + ^{90}Y$ catheter-based intravascular brachytherapy sources. Duggan *et al.* [88] are using films to perform dosimetry measurements on ^{32}P coated stents for permanent implant. Other groups are in the process of similar studies on catheter-based ^{32}P sources[89] and activated Ni-Ti stents.[90]

I. Proton dosimetry

The radiochromic films have been found to be a useful detector for dosimetry measurements in clinical proton beams.[76,91,92] The DM-1260 has been used by the National Institute of Standards and Technology, NIST, in the US and the Institute for Theoretical and Experimental Physics, ITEP, in Moscow, to investigate the dosimetric characteristics of a pulsed proton beam (0.1 μs pulse, 2.5 s interval, 7 $\times 10^6$ Gy/s peak intensity, 10 Gy/min average dose rate) for clinical applications.[91] The results of this investigation indicate that the response of DM-1260 film to a proton beam, as scanned with the NIST LKB HeNe laser scanner, was linear (~4.4% for one standard deviation) within the dose region 50-170 Gy.[91]

More recently, the more sensitive MD-55-2 film has been used for clinical proton dosimetry.[76,92] The studies of the MD-55-2 film in different beams have shown a similar linear response within the dose region l0-100 Gy for high energy photon, electron, and proton beams, except when they are irradiated in a proton beam at the Bragg peak location.[76] The MD-55-2 film exhibits an apparent suppression of the dose (5%-10%) in the Bragg peak region, however, the difference in penetration of the beam at the depth of 80%-50% distal dose fall-off measured with the MD-55 film and the ionization chamber is within 0.1-0.2 mm.

The MD-55-2 film was also used to measure complex dose distributions in an irradiated phantom, thus enabling verification of dose delivery of proton Bragg peak stereotactic radiosurgery with multiple noncoplanar beams.[92] The radiochromic film dosimetry validated the prescribed dose delivery to within ±5% (one standard deviation). The spatial resolution of the phantom verification technique was such that possible misalignments greater than 2 mm, could be detected. The radiochromic films were evaluated with the RIT 113 film dosimetry scanner system (RIT, Denver, CO). Included in this system was an AGFA Model Argus II scanner with daylight fluorescent lamp, and a CCD array and software for film analysis. To eliminate noise in the film and to improve film uniformity to ±2%, films were scanned with a digitized resolution of 85 μm and larger.

VI. PROCEDURE SUMMARY FOR RADIOCHROMIC FILM DOSIMETRY

The following summarizes the recommended procedure for radiochromic film dosimetry

(1) When selecting a scanning densitometer, the signal to noise ratio of the scanning equipment should be kept in mind. An 8 bit densitometer only provides 256 shades of grey, which may not be enough to give good images at low dose levels. (See Sec. IV.)

(2) The characteristics and/or limitations of your scanning densitometer should be considered. Several laser scanning systems and CCD microdensitometer cameras are commercially available for scanning radiochromic films. (See Sec. IV.)

(3) The maximum optical density for which the densitometry system will provide a reading should be known. This should be verified and acceptable for intended use.

(4) The sensitive emulsion layer(s) of radiochromic films absorbs most strongly in the red wavelength (about 660 nm) region. Thus the densitometer response is optimized at these wavelengths. (See Secs. II and IV.)

It is desirable to have the wavelength of the light source in the densitometer between 600 and 670 nm, which are the wavelengths of the two main absorption peaks, thereby maximizing the signal obtained from the system. However, it should be kept in mind that in certain circumstances, in order to extend film range, lower wavelengths for readout (at the expense of contrast) are desirable. (See Sec. III K.)

(5) It must be kept in mind that the measured optical density is determined by the absorption spectrum of the sensitive emulsion layer(s) of the film as well as the spectrum of the readout (scanner) light source. Thus the use of a broadband light source, such as white light, may not yield the desired contrast levels, especially when used with an 8 bit pixel depth.

(6) Prior to use, films should be visually inspected and handled with care. (See Sec. III O.)

(7) Films should always be kept in a dry and dark environment at the temperature and humidity at which they will be utilized for clinical purposes. (See Sec. III J.)

(8) Since the radiochromic films are sensitive to fluorescent light and to sunlight, they should be read and handled in normal incandescent light. If necessary, fluorescent lights and laboratory windows can be covered with commercially available UV filters.[57] (See Sec. III J.)

(9) The lot number and model number of the film should be noted. This will allow the user to verify any variation in the manufacturing of the film. (See Sec. III A.)

(10) The film orientation and alignment should be noted. This would allow us to minimize the polarization effect if needed. (See Sec. III F.)

(11) Since the film response changes with time, especially during the first 24 h after irradiation, the exposure time and readout time for all the films should be documented and, if necessary, appropriate correction factors for instabilities should be applied. The recommendation is to read the films

at least 24 h[28] (preferably 48 h) after the exposure. (See Sec. III E.)

(12) Film uniformity should be examined. If necessary, the double-exposure technique should be considered to improve film uniformity. (See Sec. III L.)

(13) Radiochromic film should be calibrated using a large well-characterized uniform radiation field. (See Sec. III M.)

(14) The dose response curve and film sensitivity should be obtained in the dose range and conditions of interest. (See Sec. III M.)

VII. FUTURE DIRECTIONS

This report documents the considerable effort that has gone into the development of radiochromic film as a valuable dosimeter for both medicine and industry. It is clear that this work is not finished, and further improvements in the characteristics of the films presently available can be expected. For example, producing radiochromic films with greater sensitivity could open the possibility for using these materials for diagnostic imaging and personnel dosimetry. It was pointed out in Secs. II and III that the manufacture of radiochromic film with an increased thickness of the sensor layer, and hence an increased sensitivity to radiation, has been accomplished in the past few years. This change in sensitivity is about a factor of 4 for an optical density of 2.0. This still leaves more than a tenfold difference compared to even the least sensitive radiographic films. Standard radiotherapy verification (Kodak XV) film is some 30 times more sensitive than the most sensitive radiochromic film. However, improved sensitivity for radiochromic film may be possible in the future.

Additional effort must be focused on improving the homogeneity of the distribution of the dye layer for the radiochromic films. The double-exposure technique described in Sec. III is a clever way of compensating for any irregularity in the sensor layer, but it lacks both the efficiency and practicality needed for routine utilization of this dosimeter. Homogeneous distribution of the dye layer is a technical problem that should be solvable by the manufacturer, but increased use of radiochromic film may be needed to serve as a stimulus for pursuing an acceptable solution.

Two improvements in the software and hardware design of scanning densitometer systems were suggested in Sec. IV. The first was a recommendation that scanner manufacturers provide easy file transfer to an alternative software package capable of analyzing raw scan data. Ideally, a selection of transfer file formats should be provided so that the user does not have to rewrite the information. As mentioned in Sec. IV, the preferred format is a string of ASCII data consisting of x and y coordinates coupled with an optical density value. The second suggestion was improvement in the spatial indexing of films in scanning densitometer system. A few flatbed scanners have a raised border along the top and one side of the sensitive scanning area. This feature can be used for indexing by pushing film against the two edges before scanning. Hopefully, more manufacturers will adopt this simple innovation in the future. For scanners where the film is

dropped in a bin, the use of fiducial markers of some sort may be necessary.

Section V discussed a number of applications where certain features of radiochromic film have been used to an advantage. These features can be listed as follows. First, the reduced sensitivity of radiochromic film can be helpful when measurements are made in regions with an extremely high dose rate. Second, the importance of being able to handle radiochromic film in normal room light should not be underestimated. This feature overcomes a major disadvantage of radiographic film. Handling the film in room light allows easy cutting of the material to conform to irregular shapes, and the film can be neatly wrapped around curved surfaces. Third, compared to radiographic film, radiochromic film has a relatively small change in response as photon or electron energy changes. Utilizing this feature it is possible to obtain high-resolution measurements in regions where the energy spectrum of a radiation beam is changing. Fourth, the very small volume of this dosimeter (dye thickness multiplied by the area of the spot size of the densitometer used for analysis) makes it valuable for measurements where other devices are not suitable. Given these unique features and the possibility of combining them in various ways, it is anticipated that there will be an explosion of new and interesting uses of radiochromic film.

Instead of two-dimensional imaging on thin films, it is also possible to produce high-resolution three-dimensional radiographic registration on clear gels or block polymers containing leuco dyes, [11] acid-forming halogenated hydrocarbons containing indicator dye,[12] or a gel solution of ferrous sulfate in the presence of benzoic acid and an indicator dye that upon irradiation forms a highly colored ferric-ion complex with the dye.[93] Although a detailed description of this new technology is not included as part of the current report, it is creating considerable excitement in the medical community and is mentioned in this section on future developments to provide the reader with a few key references. Enthusiasm about the use of gels seems to center on the possibility of measuring three-dimensional (3D) dose distributions without the problem of having to accurately register a series of films in 3D space. Instead, a solid gel can be irradiated and cut into thin sections for analysis, or analyzed in 3D with a MRI system. There is also an effort underway to develop an optical CT-type system for 3D readout.[94,95]

In summary, medical physicists have already developed a number of important applications for radiochromic film. However, since this dosimeter possesses a number of unique features, it is anticipated that with use of this dosimeter in water, we will see an explosion of new and interesting uses of radiochromic films.

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