Chapter 23

Radiochromic Film

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1. Introduction

Media that turn color upon being irradiated (coloration detectors) were some of the earliest available detectors for ionizing radiation. Besides conventional silver halide photographic media, which aided in the discovery of x-rays by Röntgen, barium platinocyanide pastille discs were used along with color wheels to quantify absorbed dose. Even human skin was used as a coloration detector, employing erythema, and an early unit of radiation exposure was the "erythema dose," defined as the amount of ionizing radiation required to produce visible reddening of the skin of the hand or arm. Other materials that also turn color upon irradiation have been discovered; they all share the common property of not requiring subsequent

processing, as opposed to conventional silver halide film. For the most part these detectors are too insensitive for applications in medical dosimetry. In the last 20 years, however, a new class of coloration detectors in the form of films has been developed which are much more sensitive than previous detectors of this type, so much so that they are finding wide acceptance in the field of medical dosimetry. These "radiochromic" film dosimeters are the subject of this chapter.

Radiochromic film has been available for dosimetric applications since the mid-1980s (Saylor et al. 1988; McLaughlin et al. 1991). Initially available only in a relatively insensitive form, the product has steadily evolved into more and more sensitive models. Currently available models are suitable for therapy-level dosimetry as well as for dosimetry of diagnostic x-ray procedures. All of the advantages of conventional silver halide film are realized with radiochromic film (two-dimensional [2-D] dosimetry, thinness, ruggedness, permanent record), but without its disadvantages (necessity of processing, non-tissue equivalence, sensitivity to light). Thus radiochromic film is currently a strong contender for the replacement of conventional silver halide film as more and more clinical centers go "filmless", i.e., remove their darkrooms and film processors and seek other means for 2-D imaging.

As with conventional film, the measurement quantity is light transmission. The more radiation delivered to the film, the darker and less transmitting the film becomes. Because the dye formation in the film takes place without the necessity of chemical development procedures, the color change is immediately visible to the naked eye. Readout may be accomplished with any device that will measure light transmission. Devices that will measure light transmission as a function of position on the film are especially advantageous as they provide 2-D dosimetry information.

1.1 Description of Available Film Models

In the following sections, characteristics of some currently commercially available radiochromic film models manufactured under the brand name GAFCHROMIC®[1] by International Specialty Products (ISP), Wayne, NJ, are discussed.

1.1.1 HD-810

Initially (before 1990), the model now known as HD-810 was only available in 15 m long rolls 12.5 cm wide. It was initially known as DM-1260 and was the first product introduced which was suitable for dosimetry purposes. It is now available in

[1] Certain commercial equipment, manufacturers, instruments, or materials are identified in this chapter in order to specify the experimental procedure adequately. Such identification is for informational purposes only and is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology (NIST) and the authors of this chapter, nor is it intended to imply that the manufacturer, materials, or equipment are necessarily the best available for the purpose.

20 cm × 25 cm sheets. The film consists of a nominal 6.5 μm thick emulsion coated on to a nominal 100 μm thick polyester base. As a result of this thin emulsion layer it is rather insensitive for most clinical applications, requiring about 30 Gy to yield an optical density (OD) of 1 absorbance unit (AU) when read with a laser scanning densitometer at 633 nm. The emulsion in this early model and all models before the introduction of EBT film in 2004 are identical (referred to as GAFCHROMIC emulsion in tables 23-1 and 23-2), and exhibit absorbance spectrum maxima at about 675 nm, as shown in figure 23-1. The chief advantages of this film are the thinness of the emulsion, which specifies the position of the dose measurement well, and the lack of a covering layer, which allows measurements close to a source of radiation.

1.1.2 MD-55-2

In its current design, this film consists of two emulsion layers, each about 16 μm thick, sandwiched between 66 μm thick polyester layers and separated by nominal 25 μm thick layers of adhesive and a single nominal 25 μm center layer of polyester. Because of the greater thickness of the emulsion, the range of use for this film is usually quoted as being between 1 Gy and 100 Gy. The chief advantage of this film over model HD-810, besides sensitivity, is the ability to use the film immersed in water. This product has undergone some construction changes with time; initially it was introduced as a single-layer emulsion, similar to HD-810. To distinguish it from the later model, this single-layer model was referred to as MD-55-1. It is no longer commercially available. The current product is referred to as MD-55-2 and is available in 12.5 cm × 12.5 cm sheets. A related product, HS, was introduced to overcome some of the problems associated with the adhesive layers of MD-55-2 film, but it is also no longer commercially available. The manufacturer is in the process of modifying the construction of MD-55-2, increasing the outer layers to 91 μm thickness and improving the coating uniformity. The new product, currently referred to as MD-V2-55, will also be available in 12.5 cm × 12.5 cm sheets.

1.1.3 EBT

In its current design, EBT film consists of two EBT emulsion layers, each about 17 μm thick, sandwiched between 97 μm thick polyester layers and separated by a nominal 6 μm thick layer of "surface layer" material, as shown in table 23-1. The EBT emulsion is of a different formulation than the original GAFCHROMIC emulsion (see table 23-2) and the introduction of EBT film resulted in an order of magnitude increase in film sensitivity, as shown in table 23-3. Besides being about 10 times more sensitive, the absorbance maximum was shifted to about 633 nm, which increased sensitivity by another factor of 2 to 3 when EBT film was read with a HeNe laser at this wavelength. The GAFCHROMIC EBT emulsion is more water equivalent than the previous GAFCHROMIC emulsion, and the manufacturer claims the films have less non-uniformity and less post-irradiation signal growth. Near energy independence of response for this new emulsion over a range

Table 23-1. Radiochromic Film Types

Film type	Layer number	Description	Thickness (μm)
GAFCHROMIC HD-810	1	Surface layer	0.75
	2	Active layer (emulsion)	6.5[a]
	3	Transparent polyester	97
GAFCHROMIC MD-55-2	1	Transparent polyester	67
	2	Active layer (emulsion)	16[a]
	3	Adhesive	~20
	4	Transparent polyester	25
	5	Adhesive	~20
	6	Active layer (emulsion)	16[a]
	7	Transparent polyester	67
GAFCHROMIC HS	1	Transparent polyester	97
	2	Active layer (emulsion)	38[a]
	3	Transparent polyester	100
GAFCHROMIC EBT	1	Transparent polyester	97
	2	Active layer (EBT emulsion)	17[a]
	3	Surface layer	6
	4	Active layer (EBT emulsion)	17[a]
	5	Transparent polyester	97
GAFCHROMIC XR-RV2	1	Yellow polyester	97
	2	Adhesive	12
	3	Surface layer	3
	4	Active layer (XRQA emulsion)	17[a]
	5	Opaque white polyester	97
GAFCHROMIC XR-QA	1	Transparent polyester	97
	2	Active layer (XRQA emulsion)	25[a]
	3	Surface layer	10
	4	Active layer (XRQA emulsion)	25[a]
	5	Opaque white polyester	97
GAFCHROMIC XR-T	1	Transparent yellow polyester	97
	2	Active layer (XR-T emulsion)	18[a]
	3	Transparent yellow polyester	97
GAFCHROMIC RTQA	1	Transparent yellow polyester	97
	2	Adhesive	12
	3	Surface layer	3
	4	Active layer (RTQA emulsion)	17[a]
	5	Opaque white polyester	97

[a] Thickness of the active layer (emulsion) is adjusted from lot to lot to achieve the design sensitivity and may vary by 10% from the nominal thickness given in the table.

Table 23-2. Composition of GAFCHROMIC Detector Materials

Material	Density g/cm^3	Effective Z	Number of electrons per unit volume $10^{27}/m^3$	Elemental composition (percentage by mass)				
				H	C	N	O	Others
GAFCHROMIC emulsion	1.08	6.27	328	9.3	56.6	15.7	18.4	
GAFCHROMIC EBT emulsion	1.1	7.05	328	9.4	57.4	13.2	16.4	0.8 Li; 2.9 Cl
GAFCHROMIC XRQA emulsion	1.2	32.6	303	6.4	38.1	5.5	13.8	0.4 Li; 13.4 Br; 22.3 Cs
GAFCHROMIC RTQA emulsion[a]	~1.1	8.29	326	9.1	53.7	12.7	14.2	1.9 Li; 8.4 Cl
GAFCHROMIC XR-T emulsion[b]	~1.2	26.6	315	7.8	46.2	11.5	14.3	7.6 Br; 12.6 Cs
Surface layer[c]	~1.2	9.90	317	6.5	32.3	21.6	20.5	2.3 Li; 16.8 Cl
Transparent and yellow polyester[d]	1.35	6.64	313	4.2	62.5		33.3	
Adhesive[d]	~1.2	6.26	329	9.4	65.6		24.9	3.5 S; 15.1 Ba
Opaque white polyester[d]	~1.6	27.6	302	3.1	46.6		31.7	
Water[e]	1.00	7.42	334	11.2			88.8	

[a] Contains ~7.5% moisture. Contains gelatin, a natural product, therefore the elemental composition may vary from batch to batch. The composition is derived by calculation, not analysis.

[b] Contains ~5.8% moisture. Contains gelatin, a natural product, therefore the elemental composition may vary from batch to batch. The composition is derived by calculation, not analysis.

[c] Contains ~15% moisture. Contains gelatin, a natural product, therefore the elemental composition may vary from batch to batch. The composition is derived by calculation, not analysis.

[d] The composition is derived by calculation, not analysis.

[e] Included for comparison purposes.

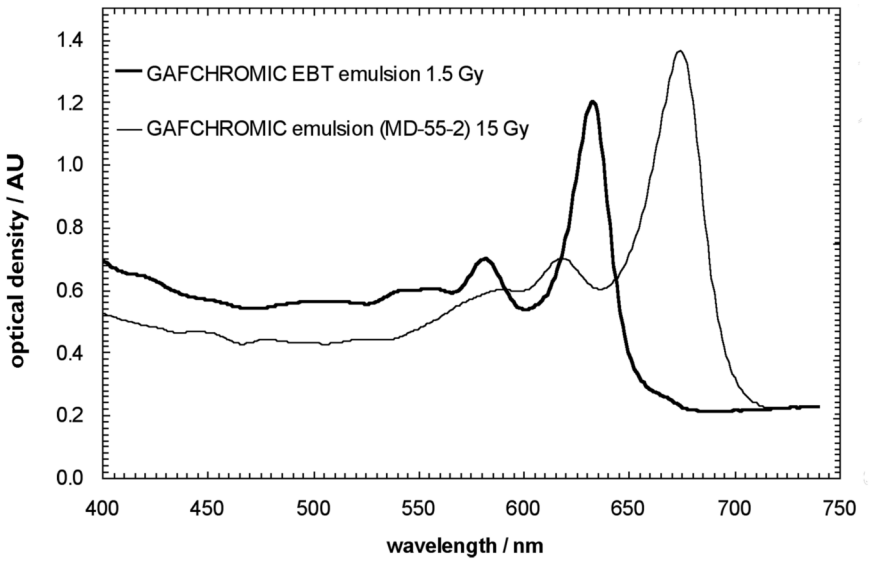

Figure 23-1. Typical absorbance spectra for GAFCHROMIC emulsion (model MD-55-2) compared to GAFCHROMIC EBT emulsion.

Table 23-3. Radiochromic Film Characteristics for Readout at 633 nm

Film Model	Emulsion thickness (μm)	Sensitivity (mAU/Gy)	Useful range (Gy)
HD-810	6.5	3	10–1000
MD-55-2	32	20	1–100
HS	38	35	0.5–50
EBT	34	400 to 800[a]	0.05–10
XR-RV2	17		0.01–5
XR-QA	50	0.001–0.2	

[a] For a dose of 1 Gy, depending on film orientation.

of photon energies from 30 keV to 30 MeV has been reported (Chiu-Tsao et al. 2005; Butson et al. 2006). The films are available in 20 cm $\times$ 25 cm sheets, as well as 36 cm $\times$ 43 cm sheets. It is also possible to obtain single layer EBT film (EBT-1) from the manufacturer. This format is especially suited for dosimetry of non-penetrating radiations, measurements in close proximity to a radiation source, and

for situations where the film has to be curled to conform to non-planar surfaces. This capability is possible due to the thinness and flexibility of the film.

A very recent development is the introduction of the EBT2 film model. This film has replaced EBT, which is no longer available. EBT2 features the addition of a yellow marker dye in the emulsion layer, which will allow corrections for variations in the uniformity of the emulsion thickness (see section 2.3.5) when using color photo scanners for film readout (see section 3.2.4).

1.1.4 XR Emulsion-based Models

GAFCHROMIC XR emulsion was developed to provide enhanced sensitivity to low-energy photons for diagnostic radiology dosimetry. There are several film models available which utilize this emulsion, the most general one being XR-RV2, which is available in 36 cm × 43 cm sheets. Other related products are XR-CT for CT scan quality assurance (QA), XR-M for mammography, and XR-QA for general radiology. All R-type films have opaque backing, making only reflection mode measurements possible (see section 3.1.8), although an earlier version of the film, XR-T (no longer commercially available) did not contain a reflective backing and could be read in transmission mode.

The various constructions and layer thicknesses are given in table 23-1, while the atomic constituents of these layers are given in table 23-2.

1.2 Clinical Applications

Film integrates the delivered absorbed dose over the irradiation time and provides spatial resolution in the submillimeter range. It is thin and can be easily sandwiched in phantoms in the preferred measurement planes. Therefore it is considered an important tool for 2-D dosimetry in intensity-modulated radiation therapy (IMRT) applications, which feature high spatial dose gradients and dose distributions that rapidly change over the delivery time. In IMRT the film is used for testing and commissioning of new treatment planning systems and algorithms, multileaf collimators (MLCc), treatment planning and delivery for new clinical sites, as well as routine QA of clinical cases. Film is also extensively used for non-dosimetric QA of linear accelerators (linacs) and HDR (high dose-rate) remote afterloaders. The above clinical applications have traditionally employed (silver halide) radiographic film, while radiochromic film was formerly used only for brachytherapy dosimetry and other special measurements, which could not be done using the bulky "ready pack" radiographic film, or which would require one to move the entire film preparation and measurement process into a darkroom.

Unfortunately, dosimetry using radiographic film is both film- and time-consuming because of uncertainties associated with film processing. A set of 10 to 15 calibration films has to be irradiated for each dosimetry case. Many institutions irradiate only one patient film, placed in a phantom, with the full dose from all

treatment fields, imitating the actual treatment delivery, while others irradiate separate films for each treatment field. The patient film (or films) has to be processed together with the calibration films, preferably by applying a sensitometric strip to each film prior to processing in order to monitor the stability of the processing. Then sensitometry results have to be densitometrically evaluated in order to generate appropriate corrections. All films have to be scanned, a calibration curve has to be generated, and finally the patient films can be analyzed. Since it is not feasible in terms of resources to perform this process for each IMRT patient in a busy clinical environment (this work would require many hours of a physicist's time per patient, as well as irradiation of 10 to 20 sheets of film), most physicists either abandoned film dosimetry, instead using various dosimetric-array instruments with low spatial resolution, or resorted to relative film dosimetry, irradiating only the patient's fields. In the latter technique the analysis creates a 2-D dose map using an existing calibration curve usually created once, when establishing the IMRT QA program. This calibration curve would not necessarily provide the correct correlation between the optical density measured from the film and the radiation dose, due to the variability of the chemical film processing, even if the film belonged to the same production lot as that calibrated. The measured dose map is compared to the treatment plan in order to compare the qualitative agreement between the two. This comparison is done in relative terms, usually expressed as some percentage, normalizing the film and the plan either at a selected dose level, or at a selected point; for example, the origin. A simultaneous ion chamber measurement at one point, carefully selected in a low dose gradient area, serves as the measure of absolute agreement between the treatment plan and actual treatment delivery. Another problem of radiographic film is its high silver content, which makes it not equivalent to human tissue. Because of this, radiographic film over-responds to low-energy photons, which are abundant in the scattered part of the accelerator beam (Muench et al. 1991). This effect becomes more pronounced in large fields and at large depths (Palm and LoSasso 2005). As already mentioned in section 1, more and more institutions are becoming filmless. Even in rare cases when a processor is kept for physics purposes, its quality rapidly deteriorates due to lack of use.

Radiochromic film as described in section 1.1 is almost tissue equivalent and does not require processing. It has been used for many years for brachytherapy dosimetry as well as for quality assurance in brachytherapy, stereotactic radiosurgery, and other small field applications. A typical example of brachytherapy dosimetry is dosimetric characterization, QA, and commissioning of miniature $^{90}Sr/^{90}Y$ (Soares 1991, 1992), $^{106}Ru/^{106}Rh$ (Taccini et al. 1997; Soares et al. 2001; Trichter et al. 2002, 2007) and ^{125}I ophthalmic applicators (Trichter et al. 2008). Radiochromic film could have been the perfect solution for IMRT dosimetry, but unfortunately, prior to the development of the EBT type, which was commercially released in 2004, radiochromic film could not replace radiographic film for IMRT and linac QA due to its limitations of low sensitivity, small size, inherent nonuniformity, and high price.

GAFCHROMIC films prior to EBT film required radiation doses of 30 Gy to 100 Gy in order to produce an image of sufficient optical density, while typical IMRT uses doses of 1.8 Gy per fraction. Delivery of such a high dose would result in IMRT QA performed at conditions very different from the normal clinical practice, resulting in suboptimal testing of the whole treatment planning and delivery systems. For example, in the DMLC (dynamic multileaf collimator) technique, the leaves would have to be slowed down to a very low speed, which is far from clinical reality. Pre-EBT GAFCHROMIC films had optical density uniformity variations of up to 15% in a single sheet, mainly due to thickness variations of the sensitive layers (Meigooni et al. 1996; Zhu et al. 1997). While this non-uniformity would be tolerable for brachytherapy dosimetry where the usual uncertainties are at the level of 15% to 20%, it is totally unacceptable for IMRT QA, where the desired agreement between the treatment plan and the actual delivery should be within 5% (Kutcher et al. 1994). The film was available in 12.5 cm $\times$ 12.5 cm sheets at $50 per sheet. Therefore at the beginning of 2002, ISP, collaborating with a group of medical physicists, started developing a new kind of radiochromic film which would be free from the above-mentioned limitations of sensitivity, small film size, inherent non-uniformity, and high cost, while retaining the advantages of high spatial resolution and tissue equivalence. In 2004 the new film was commercialized under the name EBT film. This film is available in 20 cm $\times$ 25 cm and larger sheets, produces an image with an optical density of about 0.5 at a dose of about 2.0 Gy, is significantly better in terms of uniformity (Zeidan et al. 2006), and sells at a price which makes it feasible for routine clinical work, especially if considering the cost saved when eliminating the film processor. The new film was evaluated by many groups for IMRT QA and is being widely used. The large sheets and improved sensitivity of the film enabled its use for all QA applications of linacs and HDR machines formerly reserved for radiographic film. In parallel with the EBT film, ISP released a version using the same emulsion, called RTQA, which is opaque, having a white polyester sheet as the base and a yellow polyester sheet on top. This film is specifically designed for non-dosimetric QA applications in radiation therapy.

The XR emulsion–based films described in section 1.1.4 are mostly intended for dosimetric and QA clinical work in the field of diagnostic radiology and will not be discussed in this chapter.

The use of radiochromic film for clinical applications in radiation therapy will be described in more detail in section 4 below.

2. Procedures for Measurements with Radiochromic Film

2.1 Principle of Measurement

The emulsion in the most commonly available radiochromic film models is a radiation sensitive monomer that is incorporated into a gelatin matrix and coated onto

a polyester base. The colorization process is based on radiation-induced polymerization of diacetylene molecules, causing polydiacetylene dye polymers to be formed. These are blue in color, and hence cause the film to absorb light in the red part of the visible spectrum. In GAFCHROMIC emulsion, the small dimensions of the diacetylene chromophores allow quite high spatial resolutions up to 1200 lines per mm (McLaughlin et al. 1991). GAFCHROMIC EBT emulsion differs from the original emulsion in that the chromophores are in the form of needle-like microcrystals about 1 μm to 2 μm in diameter and 15 μm to 25 μm in length (ISP 2007).

The signal information from irradiated radiochromic film is obtained from a light transmission measurement. The light transmitted by a sample is usually expressed as some percentage of the light incident on a sample. This quantity, *transmission,* is thus

$$\text{Transmission} = I_t / I_0, \tag{23.1}$$

where I_t is the light transmitted and I_0 is the incident light intensity. The relationship between transmission and delivered dose is inversely proportional and non-linear for most readout systems. As a result, it is more desirable to use a related quantity, absorbance, or optical density (OD), which is defined as the inverse logarithm of the transmission. Thus,

$$\text{OD} = \log_{10}(\text{transmission}^{-1}) = \log_{10}(I_0 / I_t), \tag{23.2}$$

where the OD is expressed in absorption units (AU). Thus an OD of 1 AU corresponds to a 10% transmission, 2 AU to 1% transmission, and so on. Optical density is the preferred measurement quantity since in many optically read systems (see chapter 31 on Fricke dosimetry) there is a linear relationship between delivered absorbed dose and measured optical density. One has to bear in mind, however, that the optical density is a function of the wavelength at which the transmission equation (23.1) was sampled. This means that the measured optical density can be considered unique for the film and delivered dose only if sampled by either a spectrophotometer at a known wavelength, or an optical densitometer that employs a monochromatic light source. In the latter case, the measured optical density depends on the wavelength of the visible light source. On the other hand, a number of optical densitometers are in use (particularly flat-bed color photo/document scanners) that employ broad band fluorescent visible light sources. For these optical densitometers, optical density change is a rather complex convolution of the film absorption spectrum, the linear CCD (charge-coupled device) array sensitivity spectrum, and the emission spectrum of the fluorescent light source of the scanner. This is a reminder that for every particular radiochromic film dosimetry system—consisting of a particular radiochromic film model, film scanner, and film dosimetry protocol—there will be a different sensitivity curve.

2.2 Handling and Calibration

Various aspects of radiochromic film dosimetry for medical applications have been covered in some detail in several excellent review articles that have appeared in the last decade (Niroomand-Rad et al. 1998; Dempsey et al. 2000; Butson et al. 2003; Soares 2006a). Much of the following information is covered in these reference works.

2.2.1 Film Handling Tips

Before discussing calibration in detail, a few tips on good practice will be offered. It is good practice not to handle the films with bare hands since skin oils transferred to the films can cause spurious absorbance measurements. Tweezers or vacuum pickup tools should be used to handle small films, while large sheets of film should be handled with gloves. Because of the effects of time and temperature on film readings, it is very good practice to control temperatures during irradiation, storage, and readout in a consistent fashion, applying the same conditions to films used for calibration as well as those irradiated in experiments. While not nearly as sensitive to light as conventional silver halide film, radiochromic film still does exhibit some sensitivity, especially to ultraviolet (UV) wavelengths. Therefore exposure to light should be minimized, i.e., film should not be left uncovered for hours at a time under fluorescent lighting or exposed to sunlight. A few minutes handling in normal lighting conditions are not a problem, however. As mentioned previously, a valuable aspect of most radiochromic film models is the ability to make measurements directly in water. The emulsion softens and turns a milky color when wet, but when dried, the clear color is mostly restored. It should be noted that prolonged immersions will cause water to seep into the film emulsion at the cut edges. For this reason, one should avoid making readings close to cut edges in films that have been irradiated in water. The manufacturer reports that the penetration of water when EBT film is immersed is about 1.5 mm in the first hour and about 3 mm after 4 hours. A great advantage of film dosimeters is the ability to cut the film into the shape and size desired for the experiment. For HD-810 and other non-sandwich types of film, the preferred method of cutting is the use of a straightedge and a scalpel. However for sandwich types and especially for MD-55-2, one should use scissors or a paper cutter to keep layers from separating unduly during cutting. Exposure of GAFCHROMIC emulsions to temperatures exceeding 60 °C must be avoided since at these temperatures the dye is rendered inactive. However, the manufacturer claims that GAFCHROMIC EBT emulsion will withstand temperatures up to 70 °C. Because of these temperature limitations, care must be taken when machining the film (i.e., drilling holes in film stacks, cutting with a lathe, etc.) to avoid exceeding these critical temperatures. The best results for sandwich and non-sandwich types are achieved using specially designed punches, which can be created in any shape and assure no separation of the layers in sandwich type

films and no rough edges which can cause air gaps in solid phantoms (see also section 4.2). Such punches can be built by companies specializing in manufacturing of tools, punches, and dies. Another advantage of radiochromic film dosimeters is the ability to place identification and fiducial marking directly on the film surface. Conventions for doing this should be established and adhered to. For example, at NIST, a sequential identification number is placed in the lower right corner of films. For HD-810 film, this is placed on the emulsion side of the film. This procedure allows the consistent placement of films relative to a source or radiation field during irradiation, and in the film reader during readout. Fine-pointed felt-tip permanent markers are suitable for writing both identifying numbers and for making fiducial markings on films, which are necessary for reading the same film more than once and registering the resulting images with each other, or for registering films with treatment plans (see section 4.1). As mentioned earlier, the emulsion turns milky when wet. Since the emulsion is essentially uncovered in HD-810 film, one need merely slightly wet a corner of one side of a film to determine on which side the emulsion is coated. The emulsion side of EBT-1 film is easily distinguishable since it is not shiny like the polyester substrate side. For applications with non-penetrating radiations such as low-energy x-rays or beta particles, this information is absolutely critical. It should also be noted that the adhesive used in MD-55-2 films is somewhat compressible and the thickness may shrink with age. Thus thicknesses of anywhere between 0.2 mm and 0.25 mm for this film model have been quoted. If the total thickness of a film sample is critical to interpreting the results of an irradiation, as, for example in a depth-dose curve using a stack of films, then the film thickness should be determined for each sample using a micrometer or other suitable device, being careful to apply approximately the same pressure during the measurement as will be applied during irradiation.

2.2.2 Film/Reader System Calibration

The film/reader system comprises the particular radiochromic film model being employed, the device on which the film is to be read, the radiation field or fields of known properties in which the film is to be calibrated, and the analysis techniques used to yield the measured film reading for each delivered dose. In principle, any radiation field in which the absorbed dose rate is known can be used to calibrate radiochromic film. In practice, however, there are often limiting criteria on the applicability of particular fields to particular films. For example, the absorbed dose rate should be sufficient to cover the range of anticipated absorbed doses in a reasonable length of time for the film being calibrated. The most common calibration field employed for medical applications is that produced by therapy linacs, which typically produce dose rates on the order of 0.05 Gy/s. This rate is sufficient for the calibration of the more sensitive film models such as MD-55-2 and EBT, but clearly calibrating the less sensitive HD-810 with this field would be impractical. A properly carried out calibration will yield information about both small- and large-scale sample reproducibility, as well as the individual

sample reproducibility as a function of signal (system characteristic curve). The latter indicates the dose level for the particular system that yields the best sample reproducibility.

The range of dose levels used for the calibration must cover the anticipated measurement range since extrapolation of these often non-linear calibration functions is dangerous and not recommended. A good choice is the use of dose levels in an approximately even logarithmic distribution, usually covering at least two decades of dose. Thus a typical range of doses for MD-55-2 film might be 0 Gy, 1 Gy, 1.5 Gy, 2 Gy, 3 Gy, 5 Gy, 7 Gy, 10 Gy, 15 Gy, 20 Gy, 30 Gy, 50 Gy, 70 Gy, and 100 Gy. This set of delivered doses will yield information at both ends of the dose range. Dose levels clustered at the low end of the range are important since non-linearities often occur here and the system characteristic curve changes rapidly here as well. Further spacing at higher dose levels is warranted by the smoother character of both the calibration curve and the characteristic curve. At the highest dose levels there is often serious non-reproducibility because of poor signal-to-noise in high-OD samples. This is reflected in the system characteristic curve and the flattening out (sometimes referred to as saturation) of the calibration curve. Dose levels high enough to achieve saturation should be used at least once for a calibration of a film batch to establish where the behavior begins for a particular system.

Small film samples may be used for film calibration, even as small as 1 cm $\times$ 1 cm pieces. However, due to the fact that radiochromic films exhibit pronounced orientational dependence of the film response (see section 3.1.7), it is very important to keep track of the initial sheet orientation when square film pieces are cut. Thus it might be preferable to cut and use rectangular pieces instead, e.g., 1 cm wide $\times$ 1.5 cm long. Another advantage of using rectangular film pieces is that one may still keep the square region for the measurement, while the rectangular extension can be used for labeling, marking, and handling film pieces. These should be numbered such that information on the coating direction and the position of the samples within the larger film sheet from which they are cut are preserved. Six films per dose point are recommended so as to provide meaningful statistics at each dose level. Also, in case a film is lost or damaged, five replicates still provide reasonably valid statistics. Films should be assigned doses in a random pattern so as to avoid trending due to possible large-scale non-uniformity in the larger film from which the samples are cut. This can be done by generating random integers between 1 and n, where n is the number of samples in the dose response study and correspond to the film sample number. The first six integers (films) are not irradiated (0 Gy), the second six are irradiated to the 1st dose level, and so on.

Calibration films should be handled and stored in the same manner as films irradiated for subsequent experimental procedures will be. This includes storage temperatures, time delays and any annealing procedures. It is recommended to precut the small films several days prior to irradiation to enable them to equilibrate to the environment in terms of moisture content. There is always a degree of moisture content in radiochromic film and it may affect the OD readout. Readouts are performed so as to include all regions of the sample that received the uniform cali-

bration irradiation, but excluding a margin at the edges of the sample, which may have been damaged in the cutting process. Resolutions should be selected such that sufficient small-scale sampling statistics are achieved. Typically for 1 cm × 1 cm samples, resolutions of 0.1 mm to 0.2 mm are quite sufficient. Histograms of the uniformly irradiated portions of the films should be formed and the result expressed as an average reading with an associated standard deviation. Many film dosimetry or image processing programs provide average reading and standard deviation for a selected region of interest. After analysis of all the calibration films one ends up with a three-column dataset consisting of delivered absorbed dose, averaged measured signal, and standard deviation of the average measured signal. An example is given in table 23-4, and shown plotted in figure 23-2. In this table and plot, the standard deviation and error bars are those associated with the replicate readings at each dose level. The calibration function is formed by least squares fitting of this dataset, either non-weighted or weighted using the inversely squared relative standard deviations of the readings of the individual films. Usually a second- or third-order polynomial yields a sufficiently accurate fit, but often better fits can be obtained using software packages that allow a choice from a large number of fitted

Table 23-4. Typical Calibration Data Table for MD-55-2 Film Read at 633 nm

Dose to water (Gy)	Average OD (AU)	SD_{OD} (AU)	Net OD (AU)	SD_{NetOD} (AU)	Net OD per dose (mAU/Gy)	$SD_{NetOD\ per\ dose}$ (mAU/Gy)
0	0.1528	0.0031	--	--	--	--
1	0.1776	0.0020	0.0248	0.0037	24.81	0.12
1.5	0.1875	0.0032	0.0347	0.0045	23.16	0.14
2	0.1971	0.0027	0.0443	0.0041	22.13	0.13
3	0.2193	0.0023	0.0665	0.0039	22.17	0.12
5	0.2620	0.0036	0.1092	0.0047	21.84	0.15
7	0.3016	0.0054	0.1488	0.0062	21.26	0.20
10	0.3588	0.0058	0.2060	0.0066	20.60	0.21
15	0.4564	0.0040	0.3036	0.0050	20.24	0.16
20	0.5449	0.0045	0.3921	0.0055	19.61	0.17
30	0.7157	0.0062	0.5629	0.0069	18.76	0.22
50	1.0382	0.0085	0.8854	0.0091	17.71	0.29
70	1.2691	0.0303	1.1163	0.0305	15.9	0.96
100	1.5459	0.0349	1.3931	0.0351	13.9	1.11
150	1.8383	0.0127	1.6855	0.0130	11.2	0.41
200	1.9325	0.0109	1.7798	0.0113	8.9	0.36

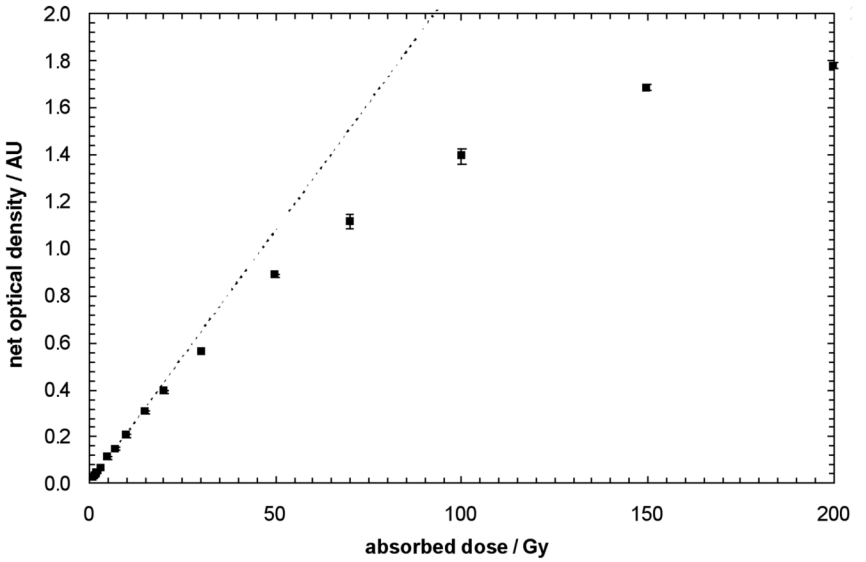

Figure 23-2. Calibration curve for MD-55-2 film read at 633 nm from data in table 23-4. The dashed line indicates the region of linearity between 5 Gy and 20 Gy.

functions. For determining an intrinsic linearity, $k_l(M_{\text{det}}(D))$, rational equations of the form

$$D = (a + b\, M_{\text{det}})/(1 + c\, M_{\text{det}} + \ldots) \tag{23.3}$$

(where D is the absorbed dose, M_{det} is the film response, and a, b, and c are fitting parameters) are particularly useful since the denominator in this function is the intrinsic linearity.

The calibration curve is a plot of measured signal (transmission or optical density) versus delivered absorbed dose. An example corresponding to the data in table 23-4 is shown in figure 23-2. What is shown in figure 23-2 should be more properly termed an "absorbed dose sensitivity" curve, since the slope at any absorbed dose point is the film absorbed dose sensitivity for that absorbed dose. However, to avoid confusion the more generally accepted term "calibration curve" will be used in this chapter. In general a calibration curve in terms of optical density will have a non-linear very low-dose region, a linear or nearly linear low- to medium-dose region, and a non-linear high-dose region. The high-dose nonlinearity is usually sublinear as the system approaches saturation. The linear region is useful for the quantization of film sensitivity in terms of net optical density (NetOD) per unit absorbed dose (see table 23-3). For the data in table 23-4, the nearly linear region (as determined from the data between 5 Gy and 20 Gy) is indicated by the dashed line in figure 23-2. Net optical density is simply the measured density less

the unirradiated film density, the latter of which may or may not include the base plate density, depending on the measurement system. Forming the NetOD and the NetOD/dose (in units of mAU/Gy) guarantees that system sensitivities can be compared in an unambiguous fashion. Table 23-4 includes the NetOD and NetOD/dose values, the latter of which are also shown plotted in figure 23-3, which indicates the nearly linear (relatively flat) region of the calibration curve. When specifying the system sensitivity it is very important to also specify the wavelength or wavelengths at which the film was read.

Since film readouts are very often performed these days with flat-bed color photo/document scanners (hereafter referred to as photo scanners), another example of calibration data is given for this class of instruments. Since the film exhibits maximum absorption in the red part of the visible spectrum, the most sensitive reading is obtained by using the red component of the pixel value, in transmission units. For photo scanners that work in the 48-bit RGB (Red-Green-Blue) mode, the reading is obtained by extracting the red component only from the resulting scanned image, such that a value of 1 corresponds to 0% transmission (infinite optical density) and a value of 65535 corresponds to 100% transmission (zero optical density). Table 23-5 shows calibration results for EBT film read in an uncorrected photo scanner. Figures 23-4 and 23-5 are generated from the data in this table. Note that the corrected optical densities in table 23-5 are obtained from an optical density scale calibration as described in section 3.3.2.

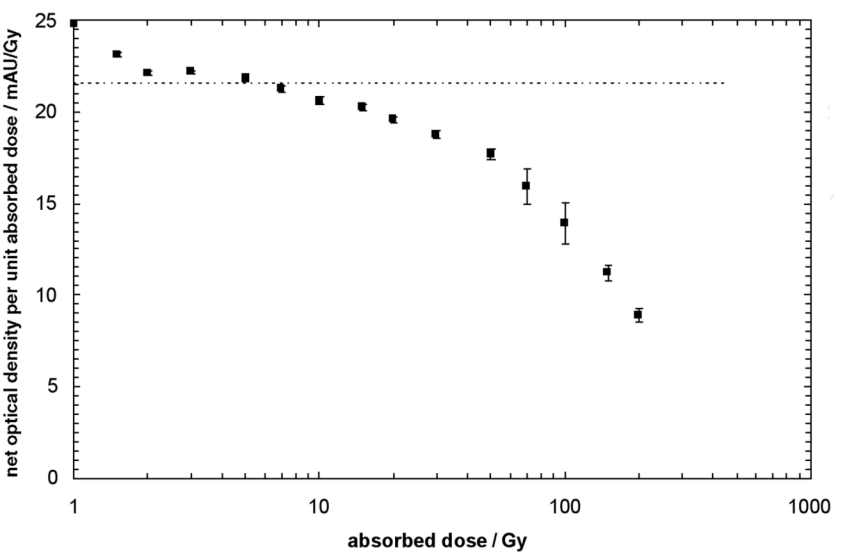

Figure 23-3. Net optical density per unit absorbed dose to water medium curve for MD-55-2 film read at 633 nm from data in table 23-4. The dashed line indicates the region of linearity between 5 Gy and 20 Gy.

Table 23-5. Typical Calibration Data Table for EBT Film Read in the Red Channel of an Uncorrected Photo Scanner

Dose to water (Gy)	Average pixel value (transmission units)	$SD_{transmission}$	Corrected optical density (AU)	NetOD (AU)	SD_{NetOD} (AU)	Net OD per dose (mAU/Gy)	$SD_{NetOD\ per\ dose}$ (mAU/Gy)
0	53326	178	0.199	--	--	--	--
0.03	52385	324	0.216	0.017	0.007	567	233
0.05	52026	70	0.223	0.024	0.004	480	80
0.07	51463	107	0.233	0.034	0.004	486	57
0.10	50941	36	0.244	0.044	0.003	440	30
0.15	49830	163	0.264	0.065	0.004	433	27
0.20	48923	224	0.282	0.083	0.006	415	30
0.30	46642	108	0.328	0.129	0.004	430	13
0.50	43832	209	0.388	0.189	0.006	378	12
0.70	39346	252	0.492	0.293	0.007	419	10
1.00	35823	245	0.582	0.383	0.007	383	7
1.50	29947	201	0.755	0.556	0.007	371	5
2.00	25873	200	0.896	0.697	0.008	349	4
3.00	18950	212	1.195	0.996	0.011	332	4
5.00	10526	373	1.764	1.565	0.035	313	7
7.00	5646	598	2.484	2.285	0.128	326	18
10.0	3238	444	3.082	2.883	0.096	288	10

It is informative to plot the relative standard deviations of the optical densities of the pixels obtained from the uniformly irradiated calibration films as a function of measured signal. The shape of this curve varies with the densitometer system and is thus characteristic of the system. An example of such a "characteristic curve" is given in figure 23-6. In general, all characteristic curves have an initial low-dose high-uncertainty portion that descends to a minimum value before rising again at high dose/high optical densities. The elevated lower dose portion of the curve is characteristic of high transmission/low absorbance measurements and is dominated by noise characteristics in the film and to a lesser extent the densitometer signal resolution. The elevated upper portion of the curve is characteristic of the poor signal-to-noise levels associated with low transmission/high absorbance measurements. The plateau region in between these indicates the region of most

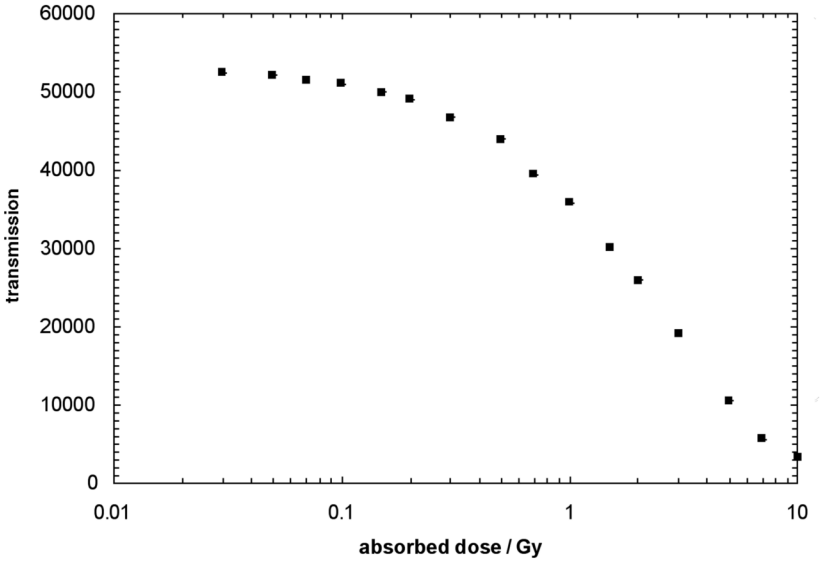

Figure 23-4. Calibration curve for EBT film read in the red channel of an uncorrected photoscanner curve from data in table 23-5.

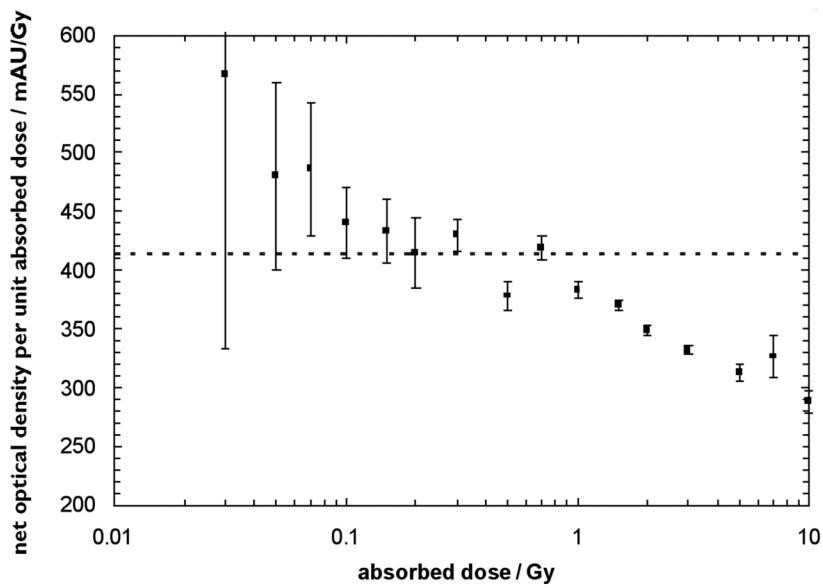

Figure 23-5. Net optical density per unit absorbed dose to water medium curve from data in table 23-5. The dashed line indicates a region of assumed linearity.

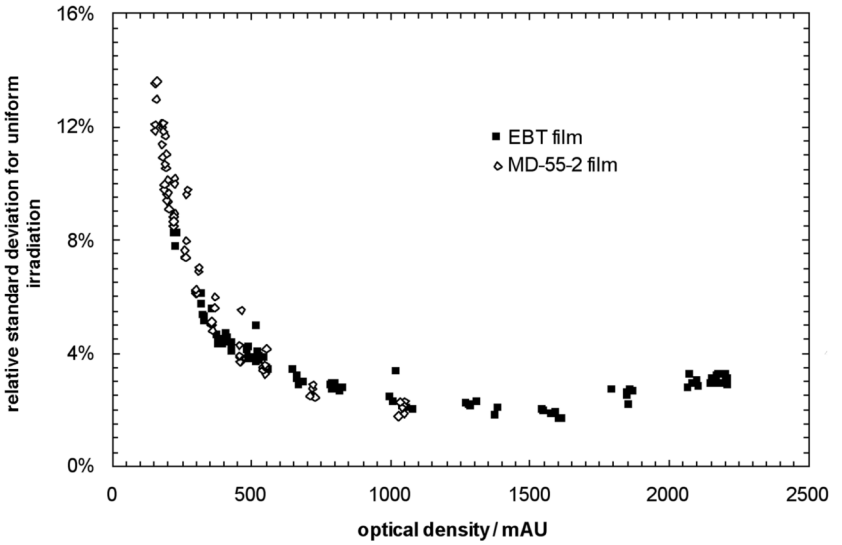

Figure 23-6. A characteristic curve for a laser densitometer. The relative standard deviation on the y-axis refers to the standard deviation of the average of the optical densities of the pixels of uniformly irradiated films.

precise (statistically) dose measurement with the particular system. It is important to record this characteristic curve for each densitometer system used. As can be seen in figure 23-6, the curve is characteristic of the densitometer and should be independent of film type.

In general, the full scale and admittedly laborious calibration procedure described in the previous paragraphs only needs to be performed once for any given film batch/densitometer system. Afterwards, the function need only be checked at a few dose levels periodically to verify that the function has not changed. It is also very important to monitor the optical density of unexposed film since this can grow slightly with time, even when film is stored in the dark at room temperature (dark reaction).

Because this calibration technique may involve too much labor for routine clinical use, it should be stressed that it needs to be done only once—when establishing the clinical film dosimetry program for a particular film type and densitometer—in order to test all system components and should periodically be repeated to verify that the system has not changed. Afterwards, for new batches of the same film type, a simpler procedure, using fewer films and dose levels, can be used to create calibration curves for the new batches. This should be done with the understanding that a somewhat higher uncertainty in dose assessment may result.

2.3 Corrections

2.3.1 Intrinsic Linearity

As indicated in section 2.2.2, intrinsic linearity, $k_I(M_{\text{det}}(D))$ can be determined from the parameters of the equation used to fit the calibration data. GAFCHROMIC emulsion exhibits an excellent linearity of response when read with a high-quality spectrophotometer, as shown in figure 23-7. Nonlinearity is introduced when instruments less well adapted to measure optical density are used. Dose/response curves for films that contain GAFCHROMIC emulsion generally have a low-dose linear region, followed by a sublinear region, which varies with the reader system. As a general rule, the less intense the light source, the earlier is the onset of sublinearity. GAFCHROMIC EBT emulsion, on the other hand, shows nonlinear behavior, even for readout with a spectrophotometer, as shown in figure 23-8. A clue to the reason for this behavior might come from an examination of the two absorption spectra shown in figure 23-1. GAFCHROMIC EBT emulsion shows much more absorbance at wavelengths shorter than those of the red region of the spectrum than GAFCHROMIC emulsion, and it has been speculated that this is due to a greater amount of light scattering in the newer emulsion. This scattering could in turn affect the intrinsic linearity of the emulsion response.

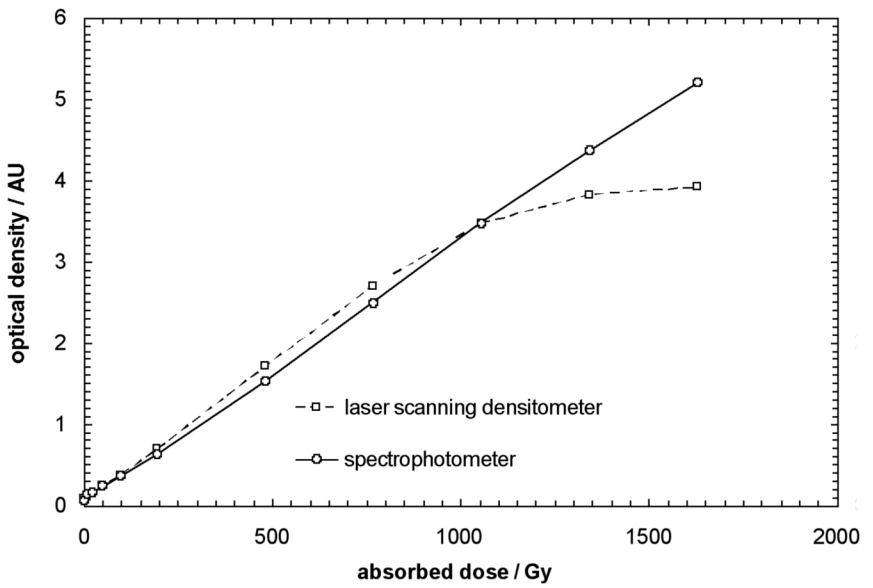

Figure 23-7. Comparison of linearity between a spectrophotometer and a laser scanner for reading HD-810 film.

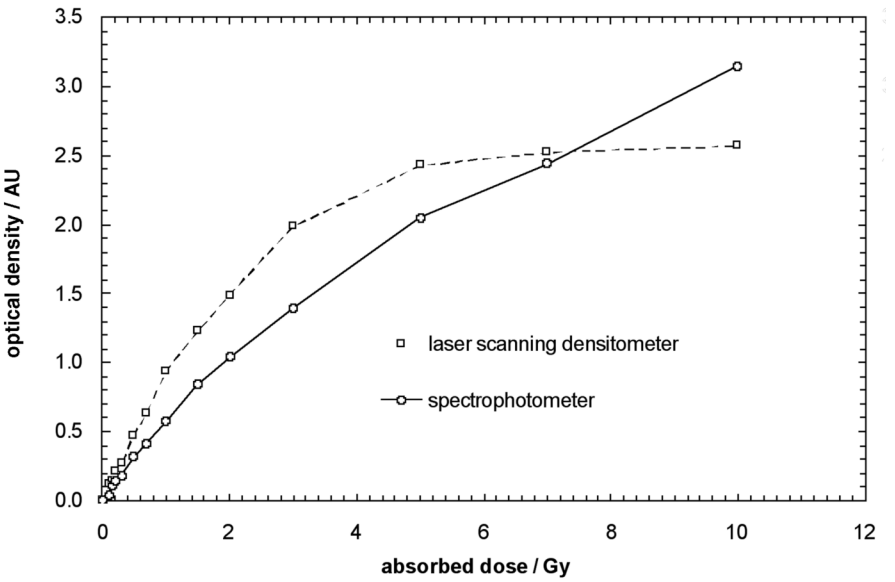

Figure 23-8. Comparison of linearity between a spectrophotometer and a laser scanner for reading EBT film.

2.3.2 Dose-Rate Dependence

The correction for dose-rate dependence, $k_{dr}(\dot{D})$, for all GAFCHROMIC emulsions is usually taken as unity, based on early work with ^{60}Co beam irradiations (Niroomand-Rad et al. 1998). It is very difficult to separate the effects of any dose rate dependence from the time effects discussed in section 2.3.8.

2.3.3 Intrinsic Energy Dependence

It is expected that the intrinsic energy dependence, $k_{bq}(Q)$, of all GAFCHROMIC emulsions is a constant independent of energy. This is due to the fact that, as with the ionization of air, there is a certain minimum energy (less than 1 eV) required to polymerize the diacetylene molecule.

2.3.4 Absorbed-Dose Energy Dependence

The data in table 23-2 can be used to calculate stopping-power ratios and mass-energy absorption coefficients for the radiation sensitive film emulsion. The results are shown in figures A-2 and A-3 in appendix A for the various GAFCHROMIC emulsions, and indicate that these media compare favorably to water, making them desirable detectors for photon and electron dosimetry. Also shown in table 23-2 are the effective Z (Khan 1994) and the electron density. For comparison, data for

water are also included. The effective Z is indicative of water-equivalence for photons below 100 keV, where the photoelectric effect dominates the photon absorption cross section, while electron density is more indicative of the Compton effect, which dominates above 100 keV.

As shown by figures A-2 and A-3 in appendix A, the absorbed-dose energy dependence, $f(Q)$, of GAFCHROMIC emulsion shows an under-response relative to water for photons below 100 keV. This must be taken into account when film types containing this emulsion are used for low-energy photon dosimetry. On the other hand, GAFCHROMIC EBT emulsion is much more water equivalent, and to a good approximation, $f(Q)$ for this emulsion may be considered nearly constant. For GAFCHROMIC XR emulsion, the addition of high-Z components to enhance low-energy x-ray sensitivity renders it very non–water-equivalent at these energies, and small values for $f(Q)$, as indicated by the data in appendix A, are necessary.

2.3.5 Corrections for Film Non-Uniformity of Response

The principle limitation of all forms of GAFCHROMIC film in performing accurate dosimetry is the variation in film sensitivity with position, which is probably a result of variation of the emulsion thickness due to the coating process. The manufacturer quotes a nominal variation of less than 0.25 μm for the 6.5 μm thick emulsion on HD-810, but admits that this variation may be higher for the thicker emulsions. There may also be variations in the bulk sensitivity of the emulsion on a given film sample, and the manufacturer states that there are variations in emulsion sensitivity from film lot to film lot which are compensated for by changing the coating thickness (see table 23-1). It appears that in some MD-55-2 film batches there are "large scale" (on the order of a few centimeters) periodic variations of up to ±15% that occur only on the axis perpendicular to the direction in which the film is coated. For this reason, the manufacturer now makes an indication (notch) on each MD-55-2 film sample indicating the coating direction. The correction to take into account the effect of film non-uniformity is denoted as $k_{nu}(x,y)$.

Several methods have been proposed to determine corrections for film non-uniformities. The most laborious employs a uniform irradiation prior to experimental use. The pre-irradiated film is read and then sensitivity corrections based on this readout are applied to the subsequent readout of the experimentally irradiated film (Zhu et al. 1997). This is done on a pixel-by-pixel basis, but it requires the exact registration of the two readout images in order to be effective. The corrections are also only effective if the non-uniformities are greater than the pixel reading noise of the film/reader system. For a good film/reader system the pixel noise is on the order of 2% to 3%. This statistical uncertainty applies both to the pre-irradiated and the experimentally irradiated film and is independent of any film non-uniformities. Thus, any combination of these two readout values to form a corrected reading will have a statistical uncertainty of 3% to 4%. If the film non-uniformity is less than this level, then the use of the double exposure technique will actually result in worse statistics than just using the single experimental exposure.

One of the major difficulties in using the above double-exposure technique is the requirement to exactly register the two exposures. In most readers it is not possible to exactly reproduce the film positioning from readout to readout, and it is necessary to use fiducial marks on the film to perform this registration. In general, precise alignment will require both translational and rotational coordinate transformations of one image relative to the other. Since the observed film non-uniformities are usually on the order of a few centimeters, a method which uses only the average pixel value of the pre-irradiated film for the non-uniformity correction has been proposed (Soares 2006b). This is recommended only for film samples of 1 cm $\times$ 1 cm or less.

If one of the double-exposure techniques given above is not used, the user should verify the uniformity of a film lot by irradiating a full sheet in a known uniform radiation field to a dose sufficient to yield an image with a density in an optimal range for the particular film/densitometer system used (see also section 3.3.1). When read, this film can quantify the degree of uniformity of a given batch, but the non-uniformity of the film response should be distinguished from read-out non-uniformity (see also section 3.3.3). Uniformity is usually expressed as a percentage deviation from the average (i.e., a range) rather than as a relative standard deviation, which would probably make more sense and is more useful statistically. Small-scale fluctuations are usually associated with image artifacts (such as dust and scratches) and noise in the film reader. These variations complicate the assessment of large scale uniformity, particularly when the range is being determined. Small-scale variations can usually be reduced by increasing pixel size, pixel averaging, or high-frequency filtering.

2.3.6 Unirradiated Film Corrections

Readings of the unirradiated films, $M_{\text{det}}(0)$, should always be performed and subtracted from those of irradiated films to a yield net signal. It is not an exaggeration to say that these measurements of "nothing" are the most important parts of the quantification process. Monitoring these readings allows control of the base density of the film batch, as well as any changes in the film reader.

2.3.7 Corrections for Effects of the Readout Non-Uniformity

Small films should always be read at the same location in the reader to avoid having to consider position sensitive corrections for variations in reader sensitivity, $k_{pos}(x,y)$. Otherwise, for large films, these corrections need to be specified using the methods given in section 3.3.3.

2.3.8 Corrections for Time and Temperature Effects

The time and temperature dependence during storage and the temperature dependence during irradiation of GAFCHROMIC film is well documented and the reader is referred to the literature in the reference list for details (Reinstein and Gluckman

1999; Ali et al. 2003, 2005; Le et al. 2006). There is a relatively complicated dependence of the position of the peaks in the absorbance spectra of GAFCHROMIC emulsions on both storage time and temperature post irradiation. These instabilities usually translate into a growth in measured absorbance with time, usually termed post-exposure growth, especially with GAFCHROMIC emulsion read with laser scanners at 633 nm. It has been shown that this growth in absorbance is roughly logarithmic; that is, there is about as much increase in signal in between 0.1 days and 1 day as between 1 day and 10 days. This slope is approximately 5% per decade. A method to rapidly stabilize the absorption growth of GAFCHROMIC emulsion involving a heat treatment of the film after the completion of the irradiation has been developed (Reinstein et al. 1998). The method specifies film storage at a temperature of 45 °C for 2 hours and will yield a film density equivalent to a film stored at room temperature for several months.

To avoid having to make corrections for variations in time and temperature, $k_{tT}(T,t,D)$, it is customary to store the films at a controlled temperature for at least 24 hours after irradiation before reading the films. Good practice dictates using controlled and consistent timing and temperature to achieve the best results, with the same regimen used both for the calibration and the experimental films.

2.3.9 Use of a Control or Unexposed Film Piece during Readout

The use of an average value for the unirradiated film, as discussed in section 2.3.6, is one way to determine net optical density. Another, more rigorous approach to this problem is given here, which involves reading a control film (unexposed film piece) along with all irradiated films. The control film represents a film piece that has not been irradiated and any change in the absorbance for this film piece reflects the film absorbance changes due to environmental conditions, e.g., temperature, visible light, humidity, scanning light, etc. To account for all the absorbance changes in the control film pieces (other than radiation-induced changes in the absorbance), this control film piece must be of the same shape and size as the irradiated film pieces that are used for the actual dose measurement. If there are many measurement film pieces of the same shape and size to be processed in the course of one single experiment (as might be the case for IMRT QA), only one control film piece need be used. It is also very important to keep in mind that the control film piece must be handled in the very same way as the measurement film pieces.

If the control film piece is used, its optical density should be subtracted from the optical density of the measurement film piece and the obtained value should be considered as the net optical density change of the measurement film caused by the irradiation only. It is also recommended to place the same fiducial markers on both measurement and control film pieces and use them to define and co-register regions of interest on both film pieces with the same image size and resolution properties prior to pixel value subtraction.

One should also keep in mind that the use of a control film piece will certainly improve the accuracy of the measured result, but at the expense of the increased

uncertainty of the measured net optical density change. The standard deviation of the transmission signal of the control film piece will be summed in quadrature with the standard deviation of the transmission pixel value of the measurement film, resulting in an overall increase in the uncertainty of the reported dose value. The use of the control film piece and the benefit of the increased accuracy should be weighted against an increase in overall processing time and increase in the uncertainty of the reported results.

A more sophisticated use of an unexposed control film which includes correction for the unflatness of the scanner response is described in sections 3.3.3 and 4.1 below.

2.4 Overall Conversion of Reading to Dose to Medium

Putting it all together, the dose to a medium in the absence of a detector arising from radiation of quality Q, from the reading of radiochromic film calibrated with radiation of quality Q_0, is given by

$$D_{med}(Q) = f(Q)k_{bq}(Q)k_{dr}(Q,\dot{D})k_{fT}(T,t,D)k_{pos}(x,y)k_{nu}(x,y) \times k_l(M_{\det}(D))\left[\frac{D_{med}(D_0,Q_0)}{\{M_{\det}(D_0,Q_0)-M_{\det}(0)\}}\right][M_{\det}^{raw}(Q)-M_{\det}(0)]. \quad (23.4)$$

The quantity in square brackets in equation (23.4) is the inverse of the absorbed-dose sensitivity.

2.5 Uncertainty

Total combined uncertainties for absorbed-dose measurements with radiochromic film vary with the application. In equation (23.4) positional uncertainties are not accounted for, and for close proximity brachytherapy measurements, these may be significant. In measurements with low-energy photon sources, the uncertainty in the absorbed-dose energy dependence tends to be large also. There also may be uncertainty added when irradiations are made in non-water media, such as water-equivalent plastic, but with absorbed dose to water being the desired measurand.

Table 23-6 gives a sample uncertainty budget for the case of a measurement of absorbed dose to water at 1 cm from a low-energy photon brachytherapy seed with GAFCHROMIC emulsion film calibrated with ^{60}Co gamma rays. Positional uncertainties are assumed to be 0.01 mm in this example.

While the uncertainty is only an estimate of the error of the measured unknown quantity and defines the precision of the measurement, the absolute error is the actual difference between the measured value and the conventionally true value and defines the absolute accuracy of the measurement. Every dosimetry protocol gives a recipe to determine the unknown dose following certain steps and has to provide

Table 23-6. Example of an Uncertainty Budget for Measurement of a Low-Energy Photon Brachytherapy Source at 1 cm in Water with GAFCHROMIC Emulsion Film Calibrated with ^{60}Co Gamma Rays

Component of uncertainty	Uncertainty (%) Type A	Type B
Net film response, $M_{\text{det}}^{raw}(Q) - M_{\text{det}}(0)$		2
Film calibration, $k_l(M_{\text{det}}(D))\left[\frac{D_{med}(D_0,Q_0)}{\{M_{\text{det}}(D_0,Q_0) - M_{\text{det}}(0)\}}\right]$		3
Absorbed-dose response, $f(Q)$	5	
Source detector positioning, $[D(r)/D(r_0)]$	0.2	
Intrinsic energy dependence, k_{bq}	0.5	
Dose rate dependence, $k_{dr}(\dot{D})$	0.5	
Time and temperature corrections, $k_{tT}(t,T,D)$	1	
Film non-uniformity correction, $k_{nu}(x,y)$	1	
Film reading position correction, $k_{pos}(_{x,y})$	0.1	
Combined uncertainty	6.4	
Combined, expanded (k=2) uncertainty	13	

the uncertainty (precision) estimation of the final outcome. For a protocol to be valid, it has to be shown that the estimated uncertainty is greater or equal to the actual absolute error. This process is performed during the calibration procedure during which it is assumed that the dose delivered to the dosimeter (film in this case) is known. To improve the accuracy of a radiochromic film dosimetry system, one may decide to employ a more complex functional form for the fitting function to convert net optical density into absorbed dose (i.e., more fitting parameters), and this will result in a smaller error (the difference between fitted value and the measured value will be smaller). However, the increased number of parameters will add to the overall uncertainty. On the other hand, one may decide not to use an analytical approach at all, but rather use a look-up-table method while claiming that there is no uncertainty on the conversion of net optical density to the dose at all (i.e., a spline fit which necessarily passes through all the calibration data). However, in this case, one will probably obtain an uncertainty that is smaller than the actual error determined during the calibration process, making the dosimetry protocol inaccurate with regard to uncertainty. [See also (Crop et al. 2008)].

3. Components of a Radiochromic Film Readout System

3.1 Radiochromic Film Readers

Techniques to quantify the absorbance of irradiated radiochromic film have changed in the last several years with traditional methods of scanning laser densitometry giving way to the use of high-resolution imaging systems typical of modern photo and photographic slide scanning systems (Devic et al. 2004). The difference in cost between these two types of systems is significant, on the order of two orders of magnitude. Thus the emphasis will be placed on photo scanner systems, which have revolutionized the field, and made the overall system very much more affordable.

3.1.1 Light Source

Traditional scanning densitometers, such as those compared in the AAPM TG-55 report (Niroomand-Rad et al. 1998) employ very small diameter HeNe lasers at 633 nm. Modern photo scanners, on the other hand, employ long white fluorescent light sources, which contain a broad spectrum of wavelengths including some in the UV range. Care must be taken with the latter as the film is somewhat sensitive to UV energies and exposure time of the film to these lamps should be minimized and controlled, even though Lynch et al. (2006) found no noticeable permanent change in optical density after 1000+ scans, but up to 7% temporary optical density increase with multiple consecutive scanning as a result of temperature increase.

3.1.2 Light Detection

Photodiodes are used in laser scanning densitometers, usually optimized for the wavelength of the light source. Photo scanners employ linear CCD arrays, which are scanned across the sample in a direction perpendicular to the array axis. It is important to remember that the signal represents the value of the absorbance averaged over the wavelength(s) and weighted by the spectral response of the detector. It is also a spatial average over the area of the light source or the detector, whichever is smaller.

3.1.3 Signal Resolution

The output signal represents a quantity related to light transmission. In most laser scanners, a quantity proportional to optical density at the laser wavelength is output for each pixel position read. In photo scanners, the output quantity is usually proportional to transmission. In both types, the number of shades of intensity is specified by the "image depth," which is the bit width of the pixel. Thus an "8-bit" scanner has 256 shades of color intensity, while a 16-bit system has 65536 shades. A distinct advantage of color scanners is the ability to capture image information for more than one wavelength range. In color mode, in a 48-bit scanner, there are 16 bits each available for red (R), green (G), and blue (B) wavelength ranges.

Looking at the absorption spectra given in figure 23-1 it is seen that, especially for EBT film, in addition to the red area, there is a significant response for the green area of the spectrum (about 520 nm) and somewhat less for the blue area (about 450 nm). What this means is that the dynamic range of the film can be extended to higher absorbed-dose readings (where the red channel signal saturates) by doing calibrations and analyses in these lower wavelength regions.

3.1.4 Spatial Resolution

Spatial resolution in all scanners is user controlled. In laser scanners one can control the spacing between readings, and to a limited extent, the reading area (laser spot size and shape). In photo scanners, resolution is specified in terms of dots per inch (dpi), which is nominally the image resolution; the pixel size is usually taken as the inverse of the dpi value. Modern photo scanners are typically capable of 2400 dpi, which corresponds to 10 μm pixels.

3.1.5 Reader Bed

All readout systems need some sort of surface on which to lay the films to be read; this is referred to as the "reader bed." The size of the reader bed determines the maximum size of the film that can be read. As a rule for photo scanners, the larger the reader bed size, the more expensive the scanner. Reader beds are usually clear glass plates in photo scanners and some laser-based systems. Other laser-based systems have employed ground-glass plates that act as diffusers (see section 3.1.6). In any system it is important to quantify the uniformity and repeatability of the reading of the system with no film in place; this is the background signal, and it is a good check of the absorbance scale stability (see section 3.3.2). When reading small films (2.5 cm $\times$ 2.5 cm or less in size), it is convenient to always read the films in the same place on the reader. This avoids having to apply reader positioning corrections. The use of markings on the reader bed, opaque masks with cutouts, or removable positioning templates with cutouts, aid in reproducibly positioning small films.

3.1.6 Interference Patterns

Interference (Moiré) patterns are possible when reading films in contact with clear glass base plates, particularly with coherent light sources. These are caused by reflections from thin and gradually varying air gaps between the film and glass surface. One way to avoid these artifacts is to use ground-glass plates (plate glass roughened by polishing with aluminum oxide lapping compound), but at the expense of a decreased spatial resolution. Another approach is to use an opaque mask with a hole cut out, over which the film is placed. This keeps the film from coming into contact with the glass base plate and avoids the small air gaps.

3.1.7 Effect of Film Orientation during Readout

Orientation effects associated with MD-55-2 were first reported in 1997 (Klassen et al. 1997). Previously discussed in section 1.1.3, the chromophores in EBT emulsion

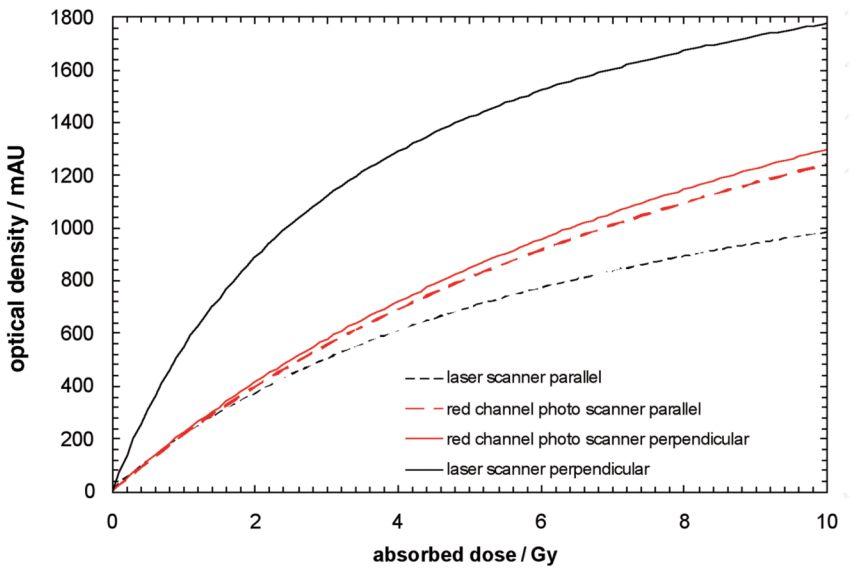

Figure 23-9. Effect of EBT film orientation relative to coating direction in two scanners.

are needlelike in structure. These needles tend to align with their long axes parallel to the coating direction of the film. Because of this alignment, more light is scattered perpendicular to the coating direction than parallel to the coating direction. Thus there is a difference in light transmission between the two film orientations in the reader for the same pixel read. An example of this difference in response is shown in figure 23-9, which shows the orientation effect for single layer EBT film in a laser scanning system and a photo scanner. In EBT film, the coating direction is parallel to the shorter side of the sheets, and it is critical for reproducible results that this orientation information is preserved when cutting films from a sheet. The manufacturer recommends that EBT film should always be scanned with the coating direction (which is parallel to the short sides of EBT film sheets) of the film coinciding with the scanning direction, i.e., orienting the short side of the film parallel to the scanning direction.

3.1.8 Other Issues

In general, radiochromic film may be read either in transmission mode or in reflection mode. Laser-based densitometers are only capable of readout in transmission mode since the light from the laser must pass through the film. Photo scanners without special "transparency" adaptors (also known as slide scanners) are only capable of measurements in reflection mode. In the latter mode, the light source and detector are on the same side of the film, and light passes through the film twice, being reflected either by the photo scanner cover, or by the opaque white polyester in some

film models (Kalef-Ezra and Karava 2008). With a transparency adaptor, which has a light source which is mounted above the reader base plate, radiochromic film without an opaque backing layer can be read in transmission mode. This allows one to make a more direct comparison between different types of readers (see figure 23-9).

The film response is sensitive to temperature during readout. Therefore it is important to allow the reader to achieve a stable temperature prior to reading films. For a laser-based device this generally takes about one hour.

It is desirable that the reader display the data as it is being acquired, so that reading times and progress can be monitored. Of course, the data from the film being read must be securely stored for later retrieval and analysis (see section 3.2.4). It is also important that there be a clear and immediate indication of malfunctions should they occur.

3.2 Other System Components

3.2.1 Calibration Sources and Fields

Any source used to calibrate radiochromic film absolutely in terms of absorbed dose to water must be well characterized in terms of field size, uniformity, dose rate, and energy. The calibration of the absorbed-dose rate at the center of the field should be traceable to national standards. The absorbed-dose rate of the calibration field should be commensurate to the film sensitivity, as mentioned in section 2.3.2. Therefore it is important to find a calibration source which possesses as close as reasonably possible the same qualities of the radiation field to be measured, and which will hence result in the same film response. Obviously, using calibration sources/beams with qualities different from the field to be measured may increase the measurement uncertainty.

A convenient source for calibration of the less sensitive HD-810 film for beta particle dosimetry is a calibrated planar beta particle ophthalmic applicator. Such sources have contact absorbed-dose rates on the order of hundreds of milligrays per second, delivering the large doses required for calibration of HD-810 film in a matter of minutes. Of course this source is not suitable for calibration of the much more sensitive EBT films because of the very high dose rate. In addition, since the calibration of these sources is generally specified only at the surface (Soares 1991), corrections have to be applied to the specified surface dose rate in order to know the dose rate at the sensitive element layer(s) of sandwich film. Since calibrated beta particle ophthalmic applicators are not readily available, it is possible to use other radiation fields for calibration (see also section 4.2), like ^{60}Co therapy beams as recommended by Niroomand-Rad et al. (1998) for electron dosimetry or linear accelerator electron beams, as long as they are properly characterized and calibrated using instruments traceable to a primary standard. The latter conditions are usually met in North America, since all photon and electron therapeutic beams are well characterized as part of the commissioning process, routinely tested as part of the monthly and annual QA, and have to be calibrated using equipment calibrated

by an Accredited Dosimetry Calibration Laboratory (ADCL), which is traceable to national primary standards.

Therapeutic photon beams produced by linear accelerators are routinely used for calibration of radiochromic films for IMRT QA and other external beam dosimetric tasks. The calibration done at the accelerator's reference depth and field size usually can be applied to other depths and field sizes, since radiochromic film does not over-respond to low-energy scattered photons. This has been specifically investigated for EBT film (Cheung et al. 2006; Todorovic et al. 2006; Fuss et al. 2007) (see also section 4.1). Calibrated ^{192}Ir HDR sources and ^{125}I brachytherapy seeds in water-equivalent plastic phantoms or in water have also been successfully used for calibration of radiochromic film for dosimetry of these brachytherapy sources, respectively (see section 4.2).

3.2.2 Phantoms and Film Mounting Jigs

One of the chief advantages of sandwich-type films is the ability to use the films directly in water with no added waterproofing material. To best take advantage of this, a mounting jig may be constructed of low atomic number materials to hold the film flat and perpendicular to the beam axis in a water phantom. Otherwise, calibrations in terms of absorbed dose to water for photon or electron beams should be performed in water-equivalent plastic phantoms, Solid Water™ (WT1), PMMA (polymethylmethacrylate), and polystyrene being the most suitable for high-energy (>1 MeV) beams. Normally, cutouts for the film are not necessary for photon beams, but it is very important to assure complete contact between the film and any adjacent phantom slab as air gaps may allow the streaming away of secondary electrons. For calibrations in high-energy electron beams, consideration should be given to shallow cutouts for film insertion in phantoms to cut down on streaming effects. In addition, for very high dose rates in charged-particle beams, consideration should be given to the use of electrically conducting water-equivalent plastics, such as A150 plastic, to prevent charge trapping which may distort measured depth-dose curves.

It is tempting to do three-dimensional (3-D) dosimetry with stacks of radiochromic film. The films can be read and the image data registered with each other using fiducial marking and 3-D images obtained. While the components of radiochromic film are fairly water equivalent, some corrections may be necessary to the film readings for non–water-equivalence (differences in absorption and scattering). It is also possible to obtain a complete depth dose profile for a radiation beam by a single irradiation of a strip of radiochromic film placed parallel to the beam axis within a phantom. The same cautions mentioned above also apply. A better method for doing this type of measurement is to tilt the film at a small angle, say 10°, relative to the beam axis, such that the film does not shadow itself in the beam. This is particularly important for XR film models since they contain high-Z components and film models on white substrates since the substrate also contains a high-Z component.

3.2.3 Scanner Control Software

It is impossible for any instrument software control designer to imagine all the possible ways a user is going to want to use an instrument and data from that instrument. The best one can hope for is that the software is sufficiently flexible to allow the user to do what is necessary to perform an analysis properly. For a radiochromic film reading device such as a photo scanner, this includes the ability to turn off all image enhancements and get the truest tagged image file format (TIFF) transmission output file possible. Other desirable features are flexibility in setting resolution and pixel depth, ease in setting scanning field dimensions, use of a standard data output format (see section 3.2.4), or at least an ASCII text data output format, and rapid data acquisition.

3.2.4 Image Data Format, Access to Data, and its Analysis

In the modern world of photo scanning for the readout of radiochromic film, the standard data output format is coming to be the uncompressed TIFF. There are a number of TIFF image viewers available. An often cited freeware package, ImageJ, is available from the National Institutes of Health website at http://rsb.info.nih.gov/ij/. A TIFF file manipulator should allow access to the data in each of the three-color channels as well as the ability to do simple averaging, standard deviations, distributions of readings, and conversions to optical density. Most packages only allow the user to manipulate and analyze one image at a time, which becomes quite tedious when hundreds of film samples are involved, such as in the calibration described in section 2.3.2. For this purpose, the ability to decode TIFF files is desirable, so that batch analysis routines can be written. In general, all binary-coded data files such as TIFFs contain a header block, which is followed by the data. The key to decoding such files is knowing where crucial information is located within the header. To aid in gaining this information, a TIFF tag viewer is invaluable. A freeware version of such a viewer is available at http://www.awaresystems.be/imaging/tiff/astifftagviewer.html. With the information from such a viewer, it is relatively straightforward to write software to decode TIFF files and extract the color channel information for further analysis. In TIFF files, the image data is stored pixel by pixel with the red channel bits, followed by the green channel bits, followed by the blue channel bits. Thus, for a 48-bit scanner, each pixel requires 6 bytes. A very desirable feature of photo scanners using TIFF output is the possibility to use data in the other, less sensitive, color channels to extend the dynamic range of the emulsion (Devic et al. 2009).

At NIST it has been found useful to establish a common ASCII text format for all image files that allows the same analysis software routines to be used independent of the readout system employed. Thus file decoders have been written which read in raw scanner output, either in binary coded or ASCII format, and write out the data in the standard text format for subsequent analysis.

Many institutions write their own propriety data analysis routines using MATLAB™ and similar software packages or even write complete film dosimetry software (for example, Memorial Sloan-Kettering Cancer Center's [MSKCC's]

Contour package). There are also several commercial film dosimetry packages mainly designed for IMRT and linear accelerator QA. These packages usually include or control the scanner control software, calculate calibration curves, convert the optical density or transmission of the films into dose, and perform various analysis functions (see also sections 4.1 and 4.3).

3.2.5 Spatial Transfer Function

It has been reported that laser scanning densitometers suffer from a light transmission artifact that tends to blur the edges of images with sharp changes in optical density. A method has been proposed to remove this artifact; it is based on a determination of the line spread function of the densitometer and the use of discrete fast Fourier transform deconvolution algorithms to recover the true optical density image (Dempsey et al. 1999). This procedure is recommended for applications with laser scanning densitometers involving very abrupt changes in optical density where accurate knowledge of dose dropoff profiles is critical.

3.3 Acceptance Tests and Quality Assurance

3.3.1 Film Batches

Film is purchased from the vendor in batches, on which the lot number is noted. This should be recorded for future reference. Film should be examined for coloration or any extraneous marks (e.g., crimping marks, dust, etc.). It is good practice to expose a single whole sheet of the film batch to a low, uniform dose and examine the uniformity of the film response to be assured that it lies within the manufacturer's specifications. This should be done with the proper understanding of the uniformity of the radiation field used to expose the film to a uniform dose, since linear accelerator beams have inherent unflatness and may exhibit asymmetry. The beam asymmetry may be corrected by exposing the film to half of the dose, rotating it 180° and delivering the other half of the dose. The non-uniformity of the reader response discussed in section 3.3.3 should not be confused with non-uniformity of film response. On first receipt of a new type of film, the film/reader combination should be calibrated using techniques outlined in section 2.2.2. Additional batches of the film need not receive this full calibration, but, as described above in section 2.2.2, it is prudent to do spot checks with fewer films and dose levels than the full calibration procedure, to assure oneself that the system response is reasonably the same as that initially obtained. Some batch-to-batch differences are to be expected, so each batch has to be calibrated for each energy, but the degree to which each batch should be calibrated should be left to good judgment.

3.3.2 Reader Absorbance Scale Calibration and Stability

Unless a comparison with other film readers is to be done, the absorbance scale of a film reader does not need to be calibrated; it needs only to be stable and reproducible. If one wishes to make comparisons with other densitometry systems, the

absorbance scale of a new film reader can be calibrated with the use of well-characterized neutral density filters or a calibrated film step wedge. Such devices are useful in any event to monitor the constancy of the reader absorbance scale, and it is prudent to make readings of both the absorbance readings with no film in the reader, as well as with one or more of the reference filters. In this way, a control can be kept on the stability of the reader absorbance scale. For very precise dosimetry a small-size calibrated film step wedge (often termed "transfer tablet") can be scanned together with each film.

It is good practice to routinely test the mechanical closure of the photo scanner cover (transparency unit), because there are situations when the lubrication of the hinges dries out and the transparency unit will not close completely. This will cause it to become non-parallel to the scanner bed, and allow stray room light penetration into the scanner.

In addition, the accuracy of the positional measurement should be checked. This can be done by scanning an artifact of known dimensions, such as a millimeter ruler, and comparing the results of the scan (with x and y measurement dimensions added) with the dimensions of the known artifact. Another possible technique is to print or copy graphing paper onto a transparency, verifying both dimensions using a calibrated ruler, and to then scan the transparency. Both x and y dimensions need to be checked, especially in systems in which one of the dimensions is in motion during measurement while the other is not. This requirement is very important when scanning large sheets of film for IMRT QA, where geometric accuracy is of great significance. A good film dosimetry software package will enable one to introduce a scaling correction for each axis separately.

3.3.3 Readout Non-Uniformity Determination and Correction

Contemporary CCD scanners used for film dosimetry that employ long diffuse light sources (see section 3.1.1) and linear array CCD detectors (see section 3.1.2) suffer from unflatness of response when scanning films along the light source, which is perpendicular to the scanning direction. This unflatness is manifested as lower sensitivity at the edges of the scanning field as compared with its center. Usually the light source and the detector are calibrated together either prior to each scan (flat-bed color photo/document scanners) or at specified time intervals (film translation devices such as the Vidar VXR-16 DosimetryPro or similar models, Vidar Systems Corporation, Herndon, VA). The calibration is performed without film, through a special section of the scanner glass plate of a photo scanner or having just air between the light source and detector in the Vidar scanners. Radiographic or radiochromic films consist of particles which scatter light (ISP 2006). The light scattering results in more photons arriving at the center of the CCD array with their number gradually decreasing toward its edges. Certain other mechanisms, like spectral changes of the light source with the light angle, and non-uniformities caused by the light source and CCD light detector may contribute to decreased sensitivity at the edges of the scanning field. Devic et al. (2006b) mention many

possible causes for this phenomenon. The unflatness of scanner response is of little importance when scanning small films which can be positioned at the center of the scanning field, but becomes very relevant for large sheets of film used for IMRT QA. The easiest way to correct for this problem is to scan an unexposed film and create a matrix of corrections relative to some reference position in the center of the readout area as suggested by ISP (ISP 2006) and implemented in their film dosimetry program (see also section 4.1). It was found later by several authors who investigated photo scanners (Lynch et al. 2006; Fiandra et al. 2006; Devic et al. 2006b; Fuss et al. 2007; Paelinck et al. 2007; Menegotti et al. 2008; Saur and Frengen 2008) that the unflatness of scanner response in the direction of the light source increases with increasing optical density, i.e., sensitivity towards the edges is decreasing with increases in optical density of the scanned film, and the unexposed film correction will provide only a partial solution. The decrease in measured optical density of a uniformly irradiated EBT film will be in the range of 3% to 5% for doses of 2 Gy, which is the clinical range of external beam radiation therapy, and becomes greater than 10% at doses of 5 Gy (Fiandra et al. 2006). In the direction of scanning (perpendicular to the light source) there are only small variations attributed to possible imperfections of the mechanical movement of the scanning assembly, which can be improved using averaging of a few scans (Fiandra et al. 2006), but which could be left uncorrected due to their small contribution to the dosimetric uncertainty. Many authors who studied the unflatness of photo scanners have suggested various techniques for the creation of correction matrices in the form of look-up tables which will account for the position of each pixel on the scanner bed as well as for its value or optical density (Fiandra et al. 2006; Devic et al. 2006b; Fuss et al. 2007; Paelinck et al. 2007; Menegotti et al. 2008; Saur and Frangen 2008).

Although being a slightly more expensive option, one could instead use a commercially available large-format photo scanner with a transmission scanning option. By positioning the film piece in the center of the large-bed scanner, the effect of scanner unflatness will be lessened and one may decide to ignore this effect in data post processing. It is still important to test the flatness of response of large-format scanners prior to deciding to abandon the unflatness correction.

4. Radiochromic Film in Clinical Use

In the following, the most common clinical uses are described, along with some that are less common. It should be noted that besides those given below, other examples are detailed in some of the other chapters of this monograph (see, for example chapter 20, Dosimetry for SRS/SRT).

4.1 Quality Assurance of IMRT

A good review of IMRT dosimetry including verification techniques and methods for analysis of the results is given in chapter 19, Dosimetry for IMRT, of this monograph.

Therefore, this section will focus only on application of radiochromic film dosimetry for this purpose. The interest in film dosimetry for IMRT QA is due to its potential to provide precise 2-D absolute or relative cumulative dose distributions having spatial resolution in the submillimeter range as discussed in section 1.2 and described in detail below.

In the suggested protocol all treatment fields are delivered to a phantom positioned on the treatment couch (or its appropriate attachments, for example, on a head and neck board) as would be the actual patient. A brief description of this approach is given in chapter 19. Placement of the phantom in a position mimicking the actual patient position assures that all treatment fields will be delivered to the phantom at the appropriate gantry angles without any obstruction from metal parts of the treatment couch. The phantom is made of water-equivalent plastic (Solid Water, polystyrene, etc.), and it can be made of a set of rectangular slabs which enable sandwiching of film between the slabs, or in any other applicable shape as long as it permits convenient and reproducible placement of the film. Many phantoms have cavities for simultaneous measurements using ion chambers or by other dosimetric means. A preferred orientation of the film is placing it in the coronal plane (the accelerator beam at "0" gantry angle is perpendicular to the plane of the film), which seems to provide easier positioning and marking of the film, but it is possible to put the film in other planes; for example, in the transverse plane. Placing several films in different planes of a phantom can verify the 3-D dose distribution (Galvin et al. 2004). It is recommended first to set up the phantom using the room lasers, the linac's crosshairs, and the Optical Distance Indicator (ODI). It is convenient to have fiducial marks on the top and sides of the phantom for this purpose. Then, carefully, without changing the position of the phantom, the upper blocks of the phantom are removed and a sheet of film is placed at the proper plane. It does not have to be the isocenter plane, as long as it is well defined for the calculation of the plan in the phantom. At this point it is necessary to put fiducial marks on the film, which will be used to register it with the calculated plan in the film analysis process. It is recommended to lightly tape the film edges to the phantom prior to marking it. There is no need to mark the film by pricking holes, like in radiographic film, but it is sufficient to use a fine-pointed felt-tip permanent black marker pen, placing tiny marks at the crosshairs, a few millimeters from the edges of the film, and marking one corner of the film in order to know its orientation on the linac. To visualize the crosshairs on the radiochromic film, it is suggested to place a white sheet of paper under the film. It can be gently removed after placing the marks. It is possible to prepare and use a fiducial template for marking the film (some commercial film dosimetry programs may require the use of a fiducial template), but using such a template is time consuming, and may add additional uncertainty, since the template has to be properly positioned and aligned with the crosshairs on top of the film, and preferably taped to the phantom or film. After pricking holes it has to be carefully removed without moving the film. After the film is marked, the upper blocks of the phantom are gently replaced without scratching the film or moving anything, and the phantom with the film can be

shifted into the final measurement position using the controls of the linac couch, a ruler, and the room lasers (this method can be more precise than using the couch readouts). Film dosimetry can be done without shifting the phantom; but if a simultaneous ion chamber measurement is done to verify the dose at a single point, the phantom may need to be shifted, bringing the ion chamber into a pre-selected point with low dose gradients. At this point the phantom with the film can be treated with all of the patient's fields, and then the film gently removed and put into a light-tight box for storage at normal room temperature prior to scanning (see section 2.2.1 for handling tips).

An exposed GAFCHROMIC EBT film representing a head and neck case is shown in figure 23-10. The pen marks of the crosshairs and the upper left corner (which is indicated by the label with the serial number of the film production lot supplied by the vendor of the film) can be clearly seen. It is good practice to write in an empty area of the film other pertinent information, like patient ID, date of exposure, linac ID, and beam energy (not shown in the figure).

This technique of delivering all treatment fields to a single film the way the patient would be treated is one of the benefits of film dosimetry, since it tests the integral dose to the plane including the uncertainties of treatment delivery at the actual gantry angles. It would also be applicable for rotational IMRT treatments described in chapter 19 of this book. Most of the 2-D detector arrays used for IMRT

Figure 23-10. GAFCHROMIC EBT film exposed to a full head and neck IMRT treatment in the coronal plane of a phantom. The film shows the fiducial marks at the crosshairs, and a label of the film lot placed at the initially marked upper left corner.

QA cannot be used this way, but can only measure single fields delivered perpendicularly to the detector. It is also possible to verify single fields using film. In this case a separate sheet of film would be used for each field, and each field treated at gantry angle "0".

Measurements in a phantom assume delivering the actual patient's treatment fields to the phantom, while the actual treatment plan has to be recalculated using the patient's fluence maps and the same monitor units to the phantom's "anatomy." For this purpose the phantom has to be CT scanned like a patient, when establishing the film dosimetry program, and imported into the treatment planning system. The plan in phantom should be done prior to irradiating the film, since it may involve shifts of the phantom if doing a simultaneous chamber measurement.

The next steps include scanning the exposed film(s) and analyzing the results. Radiochromic film has post-exposure growth of optical density (Niroomand-Rad et al. 1998). The latter results in a change in optical density of the exposed film after irradiation, which can be up to 20% in the first hour. After several hours the process slows down to a few tenths of a percent in 24 hours (see section 2.3.8). Therefore, precise film dosimetry should follow a rather strict protocol of reading out the films at the same time after irradiation as the calibration films were read. It is suggested to scan all films 24 hours after irradiation, which assures that the film is sufficiently stable. The 24-hour delay in QA results usually would be acceptable from the clinical perspective. This requirement is similar to thermoluminescent dosimetry, and even radiographic film also has a stabilization period of about 3 hours. Presently, radiochromic film dosimetry is most often done using CCD scanners, which are either flat-bed color photo/document scanners or scanners which translate the film using rollers. Most photo scanners use a white light source, but one manufacturer has introduced a scanner with a red light-emitting diode (LED) source more appropriate for radiochromic film dosimetry. When using a photo scanner it is recommended to scan the film at the highest color quality, producing a 48-bit RGB image, and save the result as an uncompressed tagged image file format (TIFF) file. The next step is to extract the red channel, which is the most appropriate for radiochromic film dosimetry. If the film dosimetry program does not extract the red channel, it can be done using a variety of standard image processing software programs (see section 3.2.4). If the scanner uses a white light source, and can only produce a 16-bit grayscale image, it is often possible to enhance the response of the scanner by scanning the EBT film sandwiched with a special orange-colored filter. Ideally the filter should have an absorbance >2.0 at visible wavelengths <550 nm and an absorbance <0.1 at wavelengths >600 nm. A filter with such characteristics is appropriately tuned for the absorbance spectrum of GAFCHROMIC EBT film in order to optimize the scanner response (there are other filters for GAFCHROMIC emulsion-based films). Obviously when using the orange-colored filter, the calibration films should be scanned with the same filter. For best results the films should be placed on the scanner in the same position on the scanner bed, preferably at its center and in the same orientation as the calibration films were scanned. The film readout is sensitive to the polarization of the scanner's light source (see section 3.1.7), which makes the

highly polarized laser densitometers less desirable. But even when using non-laser scanners, special attention should be paid to the orientation of the film on the scanner. Depending on the scanner, the film response can differ up to 19% (Trichter et al. 2005) or even 80% (Lynch et al. 2006) upon rotating the film by 90° (see also figure 23-9). Rotation by even a small angle can increase the uncertainty of the result. Photo scanners enable easy scanning of small films as compared to the moving roller-based scanners, which is convenient for brachytherapy and permits use of small calibration films. These, incidentally, have been found to be equivalent to using full sheets of film for each dose level (Trichter et al. 2005), which results in significant cost savings. Roller-based scanners also introduce specific motion-related artifacts. When scanning small films using a roller-based scanner, it is possible to tape them at the edges to a cutout of the appropriate size made in a polyester sheet (such as a single sheet of a sheet protector pocket). Placing films into a full sheet protector having polyester sheets on both sides of the film can create interference patterns on the scanned image (see section 3.1.6). On the other hand, photo scanners suffer from un-flat response due to spectral changes of the light source with the light angle, light scattering, and non-uniformities caused by the CCD light detector (see section 3.3.3). Many authors (Devic et al. 2005, 2006b; Lynch et al. 2006; Zeidan et al. 2006; Fiandra et al. 2006; Fuss et al. 2007; Paelinck et al. 2007; Menegotti et al. 2008; Saur and Frangen 2008) studied the effects of the scanner response on the film dosimetry process. The main conclusion was that each scanner used for precise film dosimetry has to be characterized and appropriate corrections worked out and applied to the results of the scanning. Some of commercially available film dosimetry software vendors have introduced scanner-related corrections. For example, the FilmQA program (ISP, Wayne, NJ) requires scanning a full unexposed film that is used for the scanner unflatness correction. In this case, the scanning resolution, scanning field (field dimensions in both directions), and position on the scanner should be identical for all films since the program uses image arithmetic functions to correct the final result. When scanning small (calibration) films, placing them at the center of the scanner keeps them in the area of flat response which does not require unflatness corrections; but if the film dosimetry program applies such corrections, they should be applied to the calibration films as well. Generally the scanning resolution for IMRT QA films should not be overly high, since the grid size of the treatment plan used for comparison with the film is usually around 0.5 mm. Therefore a scanning resolution of 75 dpi (0.339 mm) is sufficient. Using higher resolutions significantly increases the computing time for the plan and the file size of the scanned films without any significant benefit.

The calibration curves have already been discussed in section 2.2.2, but it is important to mention that since EBT film is nearly tissue equivalent, the film does not over-respond to low-energy scattered photons like conventional silver-halide radiographic film, as confirmed by a number of authors (Cheung et al. 2006; Todorovic et al. 2006; Fuss et al. 2007), who found that calibration curves of EBT film are independent of field size and depth in phantom. Therefore, calibration curves do not necessarily have to be created at a field size and depth similar to the measured

case, but can be created at a convenient field size (for example, 10 cm × 10 cm) and depth (10 cm). Since the film dosimetry programs either linearly interpolate the calibration curve between adjacent points or fit it with an analytical expression, the curve should have enough points at close separation (0.30 Gy between points for a curve which will extend to about 3 Gy is good practice). The calibration curve should extend well above the expected maximum dose in order to be able to deal with possible hot spots, but for routine clinical work there is no need to create a research grade calibration curve, extending to as high as, for example, 8 Gy.

Applying the calibration curve to the scanned film converts the pixel values or optical density into dose, resulting in a 2-D dose map. Figure 23-11 shows the dose distribution derived from the GAFCHROMIC EBT film in figure 23-10 superimposed on the plan in phantom. Simply superimposing the two demonstrates only qualitative agreement. It is also possible to visualize and quantitatively analyze the

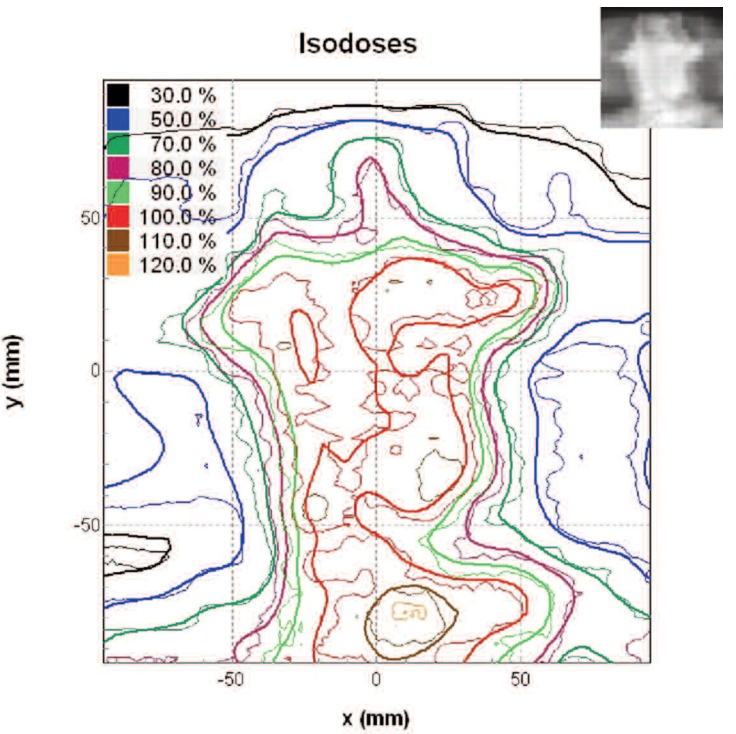

Figure 23-11. Dose distribution of film superimposed on plan. Dose distribution derived from the film in figure 23-10 using the FilmQA film dosimetry program superimposed on the dose distribution of the treatment plan computed in the same phantom plane. The dosimetry was done in absolute terms, but the isodose lines are presented in percents relative to an arbitrary normalization point in the measurement plane (these are not percents of the prescription dose!). Thick lines represent plan and thin lines film doses, respectively.

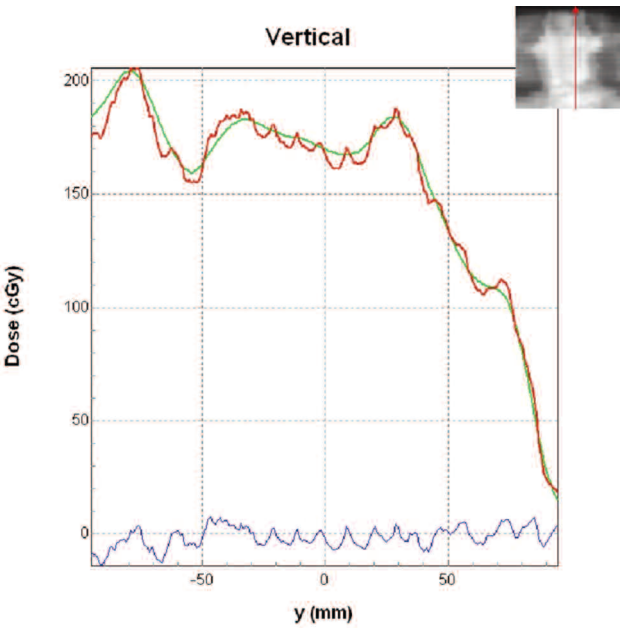

Figure 23-12. Vertical profiles through the dose distributions of the superimposed film and plan in figure 23-11 represented in absolute dose. The green line is the plan dose, the red line is the film dose, the blue line shows the difference between plan and film doses. The thumbnail picture in the upper left corner shows the location of the profile in the film plane. (FilmQA film dosimetry program).

agreement between the film results and the treatment plan, looking at profiles through the dose distributions, (for example, see figure 23-12). The question of how to compare dose distributions of the plan with the film measurements is a very important aspect of film dosimetry discussed in detail in chapter 19 of this monograph.

Exposing the patient film, including the setup of the phantom, takes about the same time as using any other IMRT QA measurement tool (30 to 45 minutes depending on the number of fields). The whole process of film scanning and analysis using an established technique (scanner + film dosimetry software) should not take more than 15 to 20 minutes per patient.

4.2 Brachytherapy Dosimetry

The use of radiochromic film for brachytherapy has evolved from early use of the relatively insensitive HD-810 film for surface dose rate measurements with relatively high dose-rate beta particle ophthalmic applicators (Sayeg and Gregory 1991; Soares 1991, 1992; Soares et al. 2001). This was followed by dosimetric characterization and calibration of concave $^{106}Ru/^{106}Rh$ beta particle ophthalmic

applicators (eye plaques) manufactured by Eckert & Ziegler (BEBIG GmbH, Berlin, Germany) (Taccini et al. 1997; Soares et al. 2001; Trichter et al. 2002, 2007] using in addition to HD-810 film, the more sensitive MD-55-2, EBT, and recently the single layer EBT-1 film. Because of their size (as small as 11.5 mm in diameter), concave shape, dose gradients as large as 30% per millimeter in the proximity of the applicator surface, and the need to collect dosimetric data starting virtually at the surface of the eye plaque, dosimetric measurements of ^{106}Ru/^{106}Rh eye plaques pose unique challenges, but the detailed example of eye plaque dosimetry to follow is typical of brachytherapy dosimetry using radiochromic film. Three types of ^{106}Ru/^{106}Rh ophthalmic applicators are shown in figure 23-13 (the company manufactures 16 different types). Some applicators have cutouts (CIA in figure 23-13), which enable their placement around the optic nerve, but add to the dosimetric challenges. The plaques are made of pure (99.99%) silver with a total thickness of 1 mm. The shape is a section of a hemisphere with an inner radius of 12 mm to 14 mm, which conforms to the typical human eye. The radioactive material, ^{106}Ru/^{106}Rh in the form of a thin film, is encapsulated between a 0.1 mm silver

Figure 23-13. Front and back views of three types of ^{106}Ru/^{106}Rh eye plaques (from left: CCA, CIA, and CCX types). These are "dummy" plaques, which are an exact silver replica of the appropriate plaque, but without the radioactive layer. They can be distinguished from the real plaque by the hole through the plaque and missing serial number.

window on the concave (facing the eye) side and the silver backing. Each eye plaque has several suture lugs used to suture it to the sclera, which can be used to register the plaque with the collected dosimetric data. Usually the measurements are done in phantoms machined from water-equivalent solid materials, which enable precise positioning of the film with respect to the plaque. Use of such materials in principle increases the measurement uncertainty since the interactions of beta radiation with the solid material differs from the interactions with water. On the other hand, it is possible to correct for the difference using Monte Carlo calculations (Mourtada et al. 2006). An RMI 457 Solid Water™ "eye" phantom (Gammex RMI, Middleton, WI) used for eye plaque dosimetry (Trichter et al. 2002, 2007) is shown in figure 23-14. The phantom mimics the main dimensions of a human eye. At each depth, a custom-cut film is sandwiched between layers of Solid Water while the plaque is placed above the film. The reproducibility of the plaque placement is assured by its suture lugs which fit into specially designed grooves cut in the phantom. A number of features of the phantom (e.g., two key structures to hold the film in place, four pinholes enabling the placing of needle marks on the film) assure accurate co-registration of the film and the plaque. The assembled phantom with open cover is shown in figure 23-14a together with an exposed film; the phantom's body and the Solid Water inserts are shown in figure 23-14b. Exposure times are adjusted as a function of depth to ensure adequate optical density on the film without overexposing it. It is good practice to achieve approximately the same optical densities (doses) on each film, thus using the same area of the calibration curve. Wide variation in exposure times limits the irradiation to one film at a time. The protocol of film scanning and conversion of pixel values to dose is similar to the one described in section 4.1, with the exception that the scanning resolution should be in the 254 dpi (0.1 mm) or better range. If films curl on the scanner bed (thin EBT-1 for example) they should be lightly taped to the scanner bed. Special care should be taken to avoid interference artifacts. The calibration curve can be created using a ^{60}Co teletherapy beam as recommended by Niroomand-Rad et al. (1998) since there are no readily available beta calibration capabilities in a clinical department. On the other hand, ^{60}Co machines are also scarce at the present time. In the absence of a ^{60}Co source, the calibration curve can be created using a 6 MeV linac electron beam in Solid Water. After converting the optical density of the exposed films to dose, the doses should be recalculated into dose rates at a specified reference date, since each film will have a different exposure time and is exposed separately, usually on a different date. An EBT-1 film exposed at a distance 2.642 mm from the inner surface of an eye plaque along with the dose rate distribution (calculated from this film) are shown in figure 23-15. It is also important to mention that films for brachytherapy dosimetry in solid phantoms often have to be cut in special shapes and very small sizes, sometimes with diameters of just a few millimeters, without damaging the integrity of the film. The edges of the films should have no protruding rough areas which could create air gaps in the phantom. The precise cutting is best achieved by using specially designed punches (see also section 2.2.1).

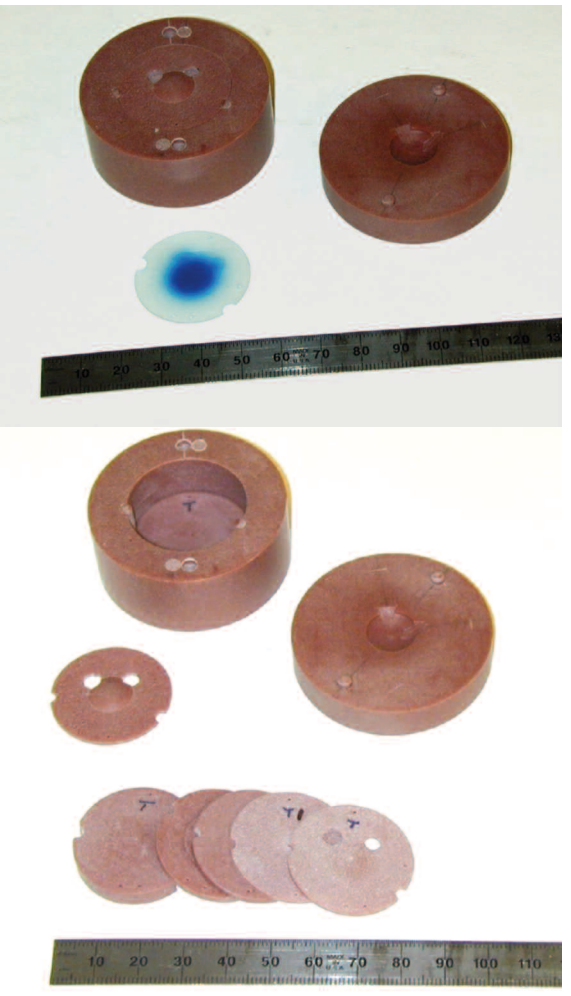

Figure 23-14. Pictures of the Solid Water™ eye phantom, which enables exact co-registration between the film and the plaque. The GAFCHROMIC film is placed between inserts of the phantom. (a) Assembled phantom with removed cover part and an exposed MD-55-2 film. (b) Body of the phantom and its various inserts.

The data collected using the above-described technique in the form of a set of films exposed in planes perpendicular to the central axis of the plaque at different distances from its inner surface (usual coordinate convention) can be used for acceptance testing and commissioning of an ophthalmic applicator, as well as treatment planning calculations, and even 3-D reconstruction of the dose rate distribution. The forthcoming ISO (International Organization for Standardization)

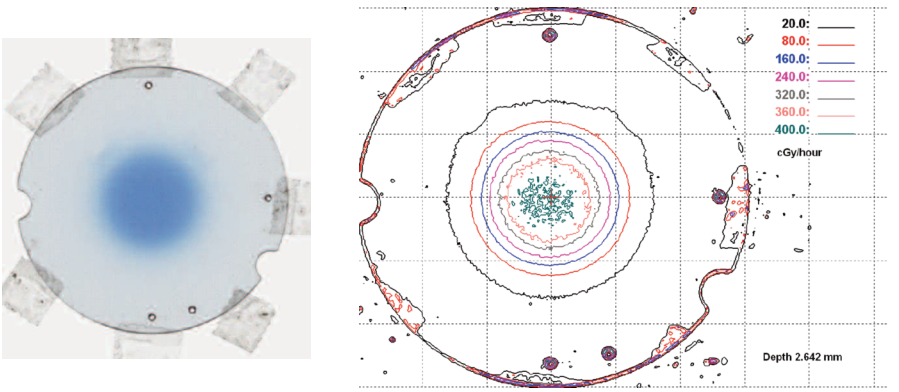

Figure 23-15. EBT-1 film exposed at a distance 2.642 mm from the inner surface of a CCX plaque and the dose rate distribution calculated from the film using MSKCC's Contour film dosimetry program.

standard "Clinical Dosimetry-Beta Radiation Sources for Brachytherapy" lists radiochromic film as a recommended detector for acceptance testing and commissioning of beta particle emitting ophthalmic applicators (ISO 2009).

Radiochromic film also found use during the short heyday of intravascular brachytherapy as one of the few methods that could match the challenges posed by this dosimetry. These are immense; the sources are very small, on the order of 0.5 mm in diameter and tens of millimeters in length, and dose rate is required at millimeter distances from the source axis. Furthermore, all sources used have very steep dose gradients near the source surfaces, on the order of 100% per millimeter. Dosimetry of these sources requires a very thin detector capable of high spatial resolution in three dimensions; radiochromic film was a natural candidate. A good review of these radiochromic film measurements for intravascular brachytherapy is contained in Chiu-Tsao et al. (2007a).

Use of radiochromic film for conventional photon seed low dose-rate (LDR) brachytherapy has not been widespread up to now, mainly due to the low dose rates from these sources (Muench et al. 1991). However with the advent of more sensitive film models such as EBT, this situation is changing. The challenge with using radiochromic film successfully for this application will be the proper accounting of the large temporal mismatch between the LDR photon irradiations and the higher dose rate calibration field irradiations (Le et al. 2006). This effect was already observed by Monroe et al. (2001) while doing radiochromic film measurements on a GliaSite™ balloon applicator, developed for treatment of brain tumor beds after surgical resection and filled with liquid ^{125}I. Chiu-Tsao et al. (2008) successfully used EBT film for dosimetry of an ^{125}I seed in a Solid Water™ phantom using a calibrated ^{125}I seed for irradiation of 25 calibration films to different doses, which may account for the temporal miss-match at low doses. Trichter et al. (2008) used

the Solid Water™ phantom shown in figure 23-14 for dosimetry of a novel ^{125}I ophthalmic applicator, initially using XR-T film and later EBT film. The calibration of both types of film was done using a calibrated ^{125}I seed in the same phantom. To account for photon scatter the "eye" phantom was inserted into a Solid Water™ "head" phantom similar to one described by Chiu-Tsao et al. (1993).

Radiochromic film was also successfully used for ^{192}Ir dosimetry. Chiu-Tsao et al. (2004) used GAFCHROMIC MD-55 film for dosimetry of LDR ^{192}Ir intravascular seeds at distances of 0.5 mm to 6.0 mm from the source exposing the calibration films to an ^{192}Ir HDR source. Poon et al. (2006) compared Monte Carlo based dose distribution calculations to film measurements by immersing EBT film in water around a novel intracavitary mold endorectal brachytherapy applicator that utilized an ^{192}Ir HDR source. The calibration films in this work were irradiated in water using an ^{192}Ir HDR source.

In addition to the work described above, there have been a number of published papers describing the use of radiochromic film in other applications of brachytherapy. Chiu-Tsao et al. (2007b) employed EBT film to determine the TG-43 parameters for a ^{131}Cs seed source, while Le et al. (2007) used EBT film to assess dose heterogeneity in intraoperative HDR brachytherapy.

It appears that the energy dependence, including the effects on film response of materials immediately surrounding the film, has largely been solved with the latest emulsion formulations, which when combined with near tissue-equivalence and other features make radiochromic film a detector of choice for most brachytherapy dosimetric applications.

4.3 Linac and HDR Commissioning and QA

Radiochromic film has been used for a long time for quality assurance in HDR radiation therapy instead of silver halide film, mainly for source position verification when the HDR source is being replaced. This is usually done by sending the HDR source to several preselected positions in a catheter taped directly to a piece of film with premarked expected dwell positions or using a Perma-Doc® Phantom (Mick Radio-Nuclear Instruments Mount Vernon, NY) and creating an autoradiograph. When using EBT emulsion-based film for this purpose, 1 second dwell time per position produces a good quality image. Evans et al. (2007) published an alternative idea of using a combination of an autoradiograph with a conventional radiograph of marker seeds inserted into the catheter after the autoradiograph using radiochromic film. Figure 23-16 shows examples comparing the use of photographic film (XV-2) with two radiochromic film models for QA measurements of HDR source positioning.

Another application is the verification of HDR treatment plans prior to first treatment. The source guide of an applicator identical to the one inserted into the patient's cavity or interstitially is affixed to a sheet of film, connected to the HDR afterloader using the same transfer tube used for treating of the patient, and the full

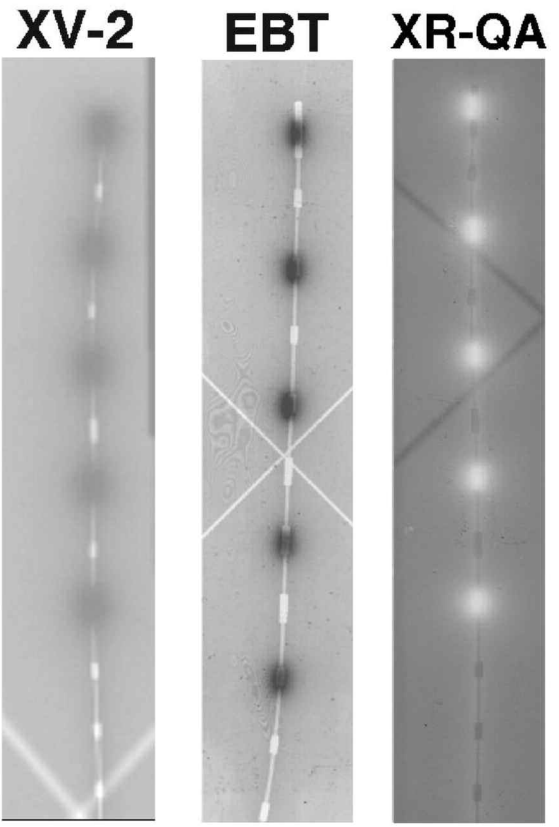

Figure 23-16. Examples comparing the use of photographic film (XV-2) with various radiochromic film models for QA measurements of HDR source positioning.

treatment is then delivered. An implementation of treatment plan verifications for vaginal cylinders is described by Steidley (1998). This technique can detect gross treatment planning errors, like wrong transfer tube or applicator length used, avoiding potential misadministrations, but also giving a good idea of the overall geometric accuracy.

Prior to the development of EBT emulsion-based films, radiochromic film was used in external beam radiation therapy only for small-field commissioning, QA, and dosimetry; for example in stereotactic radiosurgery (SRS). Introduction of sensitive EBT and RTQA models, available in large sheets, enabled the use of radiochromic film for all external beam commissioning and QA tasks formerly reserved for silver halide film, like star shots, light-radiation coincidence, beam profiles, flatness constancy and symmetry checks. Many possible applications of radiographic film have been reviewed in the report of AAPM's Task Group 69 on

radiographic film dosimetry (Pai et al. 2007). In addition to film uses already discussed here, other uses include acquisition and QA of photon and electron beam data, commissioning of dynamic (soft) wedges, commissioning and QA of MLCs in the sense of leaf and interleaf transmission measurements, as well as leaf position tests. The high spatial resolution of film gives it an advantage as compared to ionization chambers or diodes in high gradient areas, like narrow penumbral regions. Since radiochromic film is nearly tissue equivalent and the EBT emulsion-based films are almost energy independent, radiochromic film lacks the limitations of silver halide film for these kinds of measurements. These limitations include dependence on the energy spectra, over-response to low-energy photons, different electron scattering in the film and surrounding tissue-equivalent phantoms (due to high Z materials of the silver halide emulsion), and air gaps in the ready packs. When doing beam profile measurements it should not be forgotten, as mentioned by Pai et al. (2007), that film is a nonlinear detector, and a calibration curve converting optical density or pixel values to dose should be applied. Direct optical density measurements are permissible in relatively flat beam areas for routine QA only.

4.4 Other Clinical Applications

Apart from the IMRT QA measurements, for which the latest EBT GAFCHROMIC film model was specifically designed, radiochromic film has found use in a number of additional dosimetry applications. Radiochromic film is currently widely used for many clinical applications and measurements in addition to those already mentioned in the previous sections. A few of these applications are listed below.

Chung et al. (2005) used HS film in a Solid WaterTM phantom for evaluation of the dose on the surface and in the build-up region of IMRT head and neck plans. Devic et al. (2006a) did accurate skin dose measurements in external beam radiation therapy using GAFCHROMIC HS, XR-T, and EBT films.

Radiochromic film has been found to be useful in total skin electron therapy (TSET): Bufacchi et al. (2007) used EBT film to measure dose during TSET in vivo, while Lightfoot (2006) described the use of the same film model for a TSET commissioning process. Radiochromic film also shows a great potential for 2-D clinical dosimetry of electron beams (Su et al. 2007; Gerbi and Han 2006).

Owing to its high resolution measurement capabilities, EBT film has found applications in skin dose measurements: Butson et al. (2007) studied the impact of the beam angle and carbon-fiber couch tops on the skin dose, while Su et al. (2008) used EBT film for in vivo dose measurements during total body irradiation (TBI).

Radiochromic films have also been used for dose assessment in various phantom measurements: Nioutsikou et al. (2008) employed radiochromic film to investigate lung tumor motion compensation with a robotic respiratory tracking system, Wilcox and Daskalov (2007a) used EBT film to perform dose measurements in heterogeneous phantoms containing lung- and bone-equivalent materials for 6 MV

photon fields in the range of 0.5 cm to 4 cm in diameter produced by a CyberKnife®, and Polednik et al. (2007) utilized radiochromic film on an anthropomorphic breast phantom to evaluate calculation algorithms implemented in different commercial planning systems.

Radiochromic films have been used for dosimetry of small photon fields employed in stereotactic radiotherapy: Wilcox and Daskalov (2007b) evaluated the EBT film model for CyberKnife dosimetry, and the same authors (Wilcox and Daskalov 2008) also investigated the accuracy of dose measurements and calculations within and beyond heterogeneous tissues for 6 MV photon fields smaller than 4 cm produced by a CyberKnife, while Sturtewagen et al. (2008) performed multidimensional dosimetric verification of stereotactic radiotherapy for uveal melanoma using radiochromic EBT film.

Radiochromic film is being employed for dosimetry characterization of proton therapy beams: Ciangaru et al. (2007) used radiochromic film to perform the verification procedure for isocentric alignment of proton beams.

Finally, radiochromic films are being used for radiobiological and small animal irradiation experiments: Tomic et al. (2007) used the EBT film for dose verification during cell irradiation in MTT (3-(4,5-Dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) radiobiological experiments, while Wong et al. (2008) used radiochromic film for dose verification in high-resolution, small animal radiation research with x-ray tomographic guidance.

For medical research purposes, radiochromic film is used for, among other things, in vitro measurements of absorbed dose, and dose verification in radiobiological experiments and animal irradiations.

It is important to mention that radiochromic film has many more uses in the medical field than the applications discussed in this chapter, which is dedicated to radiochromic film dosimetry in radiation therapy. For example, GAFCHROMIC film has been historically used as a convenient detector of radiation in blood irradiators and is being used for this to this day. The XR emulsion-based films were specifically developed for diagnostic radiology where high response to low-energy photons is more important than tissue equivalency.

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Problems

1. Estimate the bulk sensitivity of GAFCHROMIC emulsion for 633 nm readout in units of mAU/Gy/cm.

2. An absorbed dose of 1 cGy produces an optical density of 2 on a particular type of film. What is the film sensitivity (assuming linearity) in mAU/Gy?

3. What is the file size in bytes (excluding the header) of the TIFF file resulting from a readout of a 20 cm $\times$ 24 cm film at 2400 dpi with a 48-bit photo scanner?

4. A photo scanner has a 12-bit pixel depth but the maximum corresponds to an OD of 10 and saturation occurs at an OD of 4. What is the effective pixel depth of this system?

5. A photo scanner is to be calibrated to convert 16-bit transmission signal values to corrected optical density units. For the calibration two calibrated neutral density filters are used. A 10% transmitting filter yields a reading of 25000 while a 30% transmitting filter yields a reading of 42000. By what factor must the calculated optical densities of this scanner be multiplied to yield correct values?