An Optical Common-mode Rejection for Improving the Sensitivity Limit of a Radiochromic Imaging Film

著者	Ohuchi H., Abe K.
journal or publication title	CYRIC annual report
volume	2005
page range	50-54
year	2005
URL	http://hdl.handle.net/10097/50315

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Radiochromic plastic dye films, such as the commercially available GAFCHROMIC films (International Specialty Products, USA.), have been found to be excellent two-dimensional dosimetry tools for tissue-equivalence, having good spatial response, relatively flat energy response like LiF TLD' s (with a few exceptions, e.g. XR films1), wide dynamic range of absorbed doses, dose-rate independence and long-term storage of images, allowing multiple reevaluations, etc. Investigations up to 2002 are fully reviewed in the literature[1)]. They have, however, some drawbacks, such as low-sensitivity, non-uniformity of response, post-exposure optical density growth and film cost. Low-sensitivity and non-uniformity of response are difficult to resolve owing, mainly, to the low-Z composition of the films. The films were formerly imaging materials for high-dose radiation dosimetry and high-resolution radiography[2)]. However, their use has increasingly spread to medical and industrial applications, owing to their numerous excellent qualities. Nevertheless, their low sensitivities have become a serious obstacle, especially in medical applications. For example, doses from about 10 mGy to a few Gy are valuable for monitoring patient skin dose in interventional procedures, whereas the required doses (higher than those mentioned) for the present films preclude most applications.

Various studies have reported efforts to improve sensitivity: (1) layering five sheets of film together[3)]; (2) wrapping the film with UV phosphor screens[4)], or (3) GAFCHROMIC XR film including proprietary materials (Br, Cs, Ba)[5)]. It should be noted that the latter two improvements have been achieved with the loss of tissue-equivalence, owing to the high-Z material content. Further improvements in sensitivity seem to have reached their limit.

We considered the second drawback: macroscopic and microscopic non-uniformities of film layers, including the thickness variation of active radiochromic emulsions, discussed in Ref. 1 and inferred that these non-uniformities may be the main causes of light disturbance (noises) against the lights (signals) to be measured with a densitometer, resulting in a lowering of actual film sensitivities, i.e. generating the first drawback. The most important factor is not the intensity of signals but the optical S/N (signal-to-noise ratio) in the light paths.

Among the many devices used for film dosimetry, RGB color scanners have been extensively used by researchers[1,5,7]. Fortunately, the high absorption peaks upon irradiation are at 675 nm (main peak) and 617 nm (secondary peak), both lying in the red region of the light spectra (Fig. 2) and both responsible for the same R output from color scanners. It is noted that both R and G components are a set of raw data of the lights having passed together along the common optical path, hence, suffering a common fate upon attenuation, reflection, etc., with the exception of wavelength-dependent events. The R and G components are neighboring wavebands about 100 nm apart, nevertheless, their responses to radiation exposure are quite different. The R component is highly sensitive to radiation exposure, while the G component is nearly insensitive to radiation exposure, owing to the absence of a clear absorption peak in the green waveband. These facts indicate that the common-mode rejection (CMR) scheme may be successful in distinctively recording events not common to them, i.e. irradiated effects, if applied to paired optical signals.

The optical properties of radiochromic films1 were examined, using a spectrophotometer (DU-640, Beckman Coulter, Inc., USA.), and computer-simulated experiments carried out on the obtained absorption spectra to assess the applicability and validity of an optical version of the CMR scheme to radiochromic film dosimetry. The RGB components, needed for processing, were generated by multiplying the spectra by the RGB filter functions stated below. One way to simulate the CMR is to create a ratio of the two signals, where the factors common to both numerator and denominator will automatically disappear.

We found that, in the case of GAFCHROMIC films, the detection limit is greatly improved with the optical CMR stated above and the lowest detectable dose attained was nearly 20 mGy for the HS-14 (response range for product specification: 0.5 - 40 Gy) and 50 mGy for the MD-55-2 (response range: 2 - 100 Gy). Some studies, using a single color component (red in most cases) output from RGB scanners, have been reported[5,7], but, so far, no publication has reported using the combination described above.

Experimental procedures were as follows: film specimens of 1 x 4 cm in size were placed on the sample stage in the X-ray irradiation system (MBR-1520R, Hitachi Medico Co., Japan.), exposed to X-ray beams of 100 kV with a 1.0-mm Al filter and monitored with a thimble ionization chamber (PTW-TN31003) installed inside the unit. They were analyzed, 24 or 25.5h after exposure, using the spectrophotometer over the range 450 - 1100 nm in 1.0-nm steps.

Figure 1 shows the RGB filter functions used for analysis, whose properties are similar to those of color filters for CCD photosystems. Figure 2 shows an example of the R and G components produced from an absorption spectrum for HS-14 film, multiplied by the filter functions. The vertical is expressed as light transmission in percentage, T (%).

The relationship between T and optical density (OD) used in film dosimetry can be expressed as follows:

$$OD= -\log_{10}(T/100)= 2 - \log_{10}T,$$
$$\text{net } OD= OD - OD_0= \log_{10}T_0 - \log_{10} T= \log_{10} (T_0/T)$$

where subscripts denote unirradiated background quantities and 'net' stands for the quantities after removing the background.

In the case of the optical CMR scheme, T should be replaced by Rd/Gr, where Rd and Gr are the amounts of lights for the red and green components, respectively. Thus, reduced OD (ROD) in the optical CMR scheme, is:

$$ROD= 2 - \log_{10} (Rd/Gr), \quad \text{net } ROD= \log_{10} ((Rd_0/Gr_0)/(Rd/Gr))$$

Figure 3 shows the dose⌇response curve, i.e. net ROD vs. absorbed dose, from 8.1 mGy to 1.6 Gy, for the HS-14 film 24 h after exposure. Figure 4 shows an expanded version of Fig. 3 over the range 0 - 500 mGy. The standard errors shown in the figures are less than 3.4% after repeated measurements.

Linear fits established for each of the two data sets have nearly the same slopes, demonstrating that HS-14 film is a valuable tool for monitoring doses down to about 20 mGy. Some fluctuations were observed around the lowest doses, which were, however, far lower than the normal working range of the X-ray system of 0.1- 860 Gy.

Figure 5 shows the dose-response, from 7.2 to 720 mGy, for the MD-55-2 film, 25.5 h after exposure. The lowest detectable dose was about 50 mGy. The cause of fluctuations around the doses lower than 40 mGy are unclear. However, MD-55-2 film may contain some additional causes, owing to multilayer interference and its polarization properties[1].

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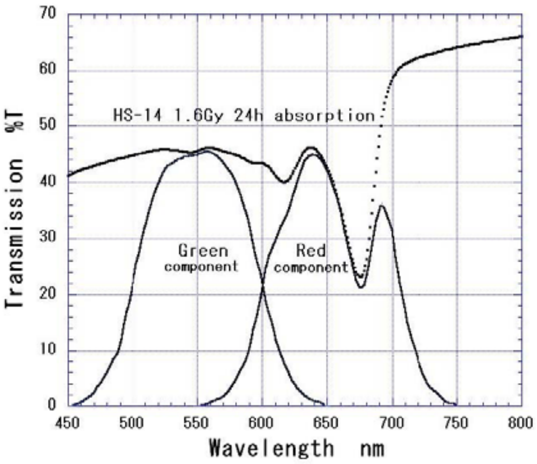

Figure 1. Filter functions for red and green wavebands used for analysis.

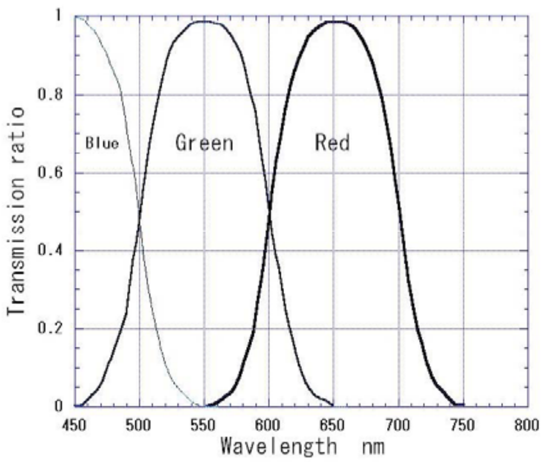

Figure 2. An example of HS-14 absorption spectrum and its color components formed with the filter functions shown in Fig. 1.

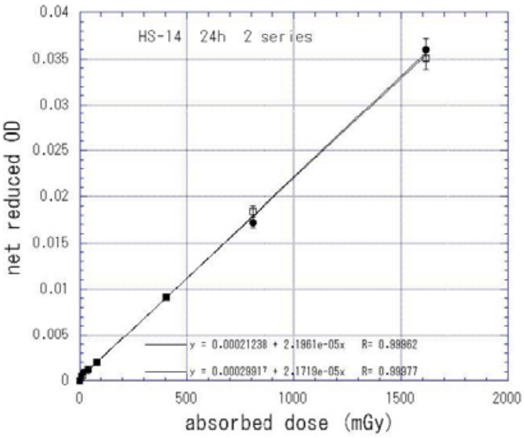

Figure 3. Net reduced optical density vs. absorbed dose for HS-14 when exposed to 100 kVp x-rays.

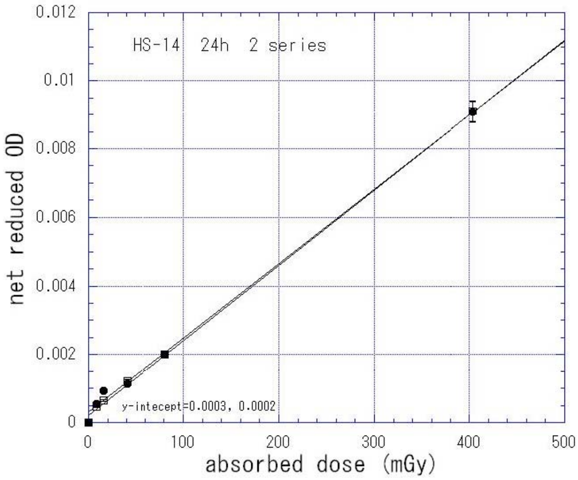

Figure 4. An expanded version of Fig. 3, net reduced OD vs. absorbed dose for HS-14.

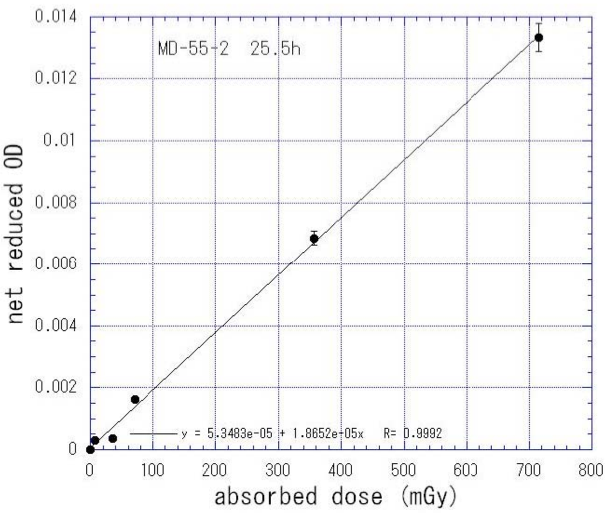

Figure 5. Net reduced optical density vs. absorbed dose for MD-55-2 when exposed to 100 kVp x-rays.