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Strategies for accurate response assessment of radiochromic film using flatbed scanner for beam quality assurance

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Abstract Radiochromic film is a useful tool for beam quality assurance, but accurate response assessment of the film is still a problem. In this study, the response uncertainties of HDV2 film were investigated using a flatbed scanner from both the scanning settings and interscan variability. Scanning settings are fixed conditions for scanning, including scanning resolution and focus setting. In this study, multipeak distributions of pixel values were found under some dots-per-inch values, which should be avoided, and the optimal setting of 2000 dpi without this problem was selected. By changing the focus setting, the relative standard deviation of pixel values was reduced by 36–50%. The influence of the interscan variability induced by three factors was investigated, including the outside illumination intensity, film homogeneity, and operating temperature. Scanning the film before and after irradiation at the same position was recommended. Moreover, the suitable operating temperature range for the scanner was found to be 15–24 °C, which results in stable film responses. Regarding the studied factors, correction methods and strategies were proposed, and the accurate response assessment of HDV2 film was realized. Finally, a standard operating procedure for response assessment of films was introduced. It can help other researchers study more scanners, films, and particle types.

Keywords Radiochromic film · Response assessment · Scanning setting · Interscan variability · Standard operating procedure

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1 Introduction

Beam quality assurance plays an important role in applications of accelerators and rays [1]. As a tool of quality assurance of beams, radiochromic film has more advantages compared with conventional silver halide films [2–4]. Examples are high spatial resolution, free postexposure processing, near tissue equivalence, insensitivity to visible light, and low dependence on energy [5]. In addition, radiochromic film has the advantages of robustness and allowing permanent recording. A recent model of radiochromic film, Gafchromic film HDV2, can be used for high doses, and it can also be used as a tool for 2D profile measurement of ion beams [6, 7]. HDV2 was designed for use with beams of photons, electrons, protons, ions, and neutrons, and it is available covering a wide range of charged-particle energies down to 5 keV or lower.

Accurate response assessment of HDV2 film is the basis of its role as a tool of quality assurance and is of great significance.

The most common method of measuring the response of radiochromic films is using flatbed scanners to capture images [8, 9]. Flatbed scanners can produce images with three color channels that provide rich information on the film response. However, special attention needs to be paid to several characteristics during film response assessment using flatbed scanners. These include postexposure changes, the orientation of the film on the scanner bed, and the nonuniformity of the lateral response [10]. When these factors are not considered, a great deal of uncertainty in response assessment is introduced. To date, many studies have addressed various factors that affect the film response [8, 11–15]. However, various film types and scanners own different optical properties and dose dependences. Research on the response characteristics of the HDV2 film has not been sufficient. In addition, previous investigations have mostly focused on the influence of the interscan variability induced by various factors, and few studies have investigated the impact of scanning settings. A scanning setting is a fixed condition for scanning, such as the scanning resolution of the scanner. Comprehensive and systematic research on the factors influencing the response is still necessary.

In this study, the response uncertainty of HDV2 film was investigated using the Epson flatbed scanner from both the scanning settings and the interscan variability. In this work, scanning settings, including the scanning resolution setting for dots-per-inch (dpi) value and the focus setting, were investigated. The influences of the interscan variability induced by various factors on the film response, such as the outside illumination intensity, film homogeneity, and operating temperature, were also investigated. Suggestions and strategies for accurate response assessment of films were developed to minimize the uncertainty caused by these factors. Then, the accurate response assessment of HDV2 film was realized. A standard operating procedure for response assessment of radiochromic films using flatbed scanners is proposed. This procedure can be used by other researchers to assess the response of other films accurately using other scanner models for more particle types.

2 Materials and methods

2.1 Radiochromic film samples

The structure of the HDV2 film (Ashland Inc., Covington, KY, USA) consisted of an 8-μm (ρ = 1.2 g/cm^3) active layer and 97-μm polyester substrate. The active layer of HDV2 was not laminated with a surface protection layer. Detailed chemical compositions of HDV2 are shown in the supplementary materials [16]. According to the manufacturer, the HDV2 film is suitable for use in the dose range of 10–1000 Gy.

In this study, Gafchromic film samples (Lot 11171601) were irradiated uniformly using an industrial ^{60}Co source (Radiation Center of Nanjing University of Aeronautics & Astronautics, 0.9 kGy/h). All film samples were cut into 1-cm × 1-cm sizes. Five types of HDV2 film with different irradiation doses (0, 450, 900, 1350, and 1800 Gy) were used to investigate the effect of dose on the film response. The last two doses were used to investigate the response of films to irradiation with high doses [17]. Film samples were exposed before being scanned for approximately five months, at which time there was no significant change in the optical density (OD) of the films. This minimized the effect of postexposure changes.

To avoid introducing unnecessary errors during the film response assessment, the preservation and handling of films received special attention [16–19]. Except for the exposure and readout, films were kept in an opaque box to avoid ultraviolet absorption. The storage temperature of the film was controlled below 25 °C. Films were handled carefully using nitrile gloves to avoid contamination with oil and mechanical damage of the surfaces. Before scanning, the films were carefully checked for scratches or smudges to ensure that they were of good quality.

2.2 Digitalization and data processing of films

Films were read in the transmission mode using the Epson 12000XL flatbed scanner. The Epson scan2 software was used to conduct the scanning, and all color correction of the software was turned off. Red, green, blue (RGB) positive images were captured at a depth of 16 bits per color channel and saved as tagged image file format (TIFF) files. The dynamic response range for each color channel was from 0 to 65,535, where 0 represented no transmitted light reaching the charge-coupled device (CCD) detector and 65,535 represented detector saturation. Each film was scanned five times to avoid the effect of accidental fluctuations. According to a previous study, the OD of HDV2 film had a negligible dependence (on the order of 10^{-3}) on the film orientation; hence, the orientation for scanning was not differentiated [12]. To avoid the influence of scanning positions on the film response, films were scanned at the same position, especially in the lateral direction.

Scattered light from the surrounding areas has an effect on the pixel values at the edge of the film and may result in a mistake in dose estimation [9]. To solve this problem, a 0.5-mm black polypropylene mask was used. It had a square hole in which to place film samples. The hole size was the same as the film sample size, and the mask turned out to be effective to prevent the influence of the scattered light (not shown). In addition, a mask with a square hole can also fix the position of the film and prevent the film from curling. To avoid the effect of the edge of the film, pixel values were obtained at a square size of 0.64 cm in the film center.

The mean value and standard deviation of all pixel values for a single film were used to represent this film. It was assumed that the same piece of film was scanned m times and each scan involved n pixels. For scanning time i, there were corresponding mean and standard deviation values ($\bar{x}_i$ and σ_i, respectively). The standard deviation of this film after scanning m times can be calculated as follows:

$$\sigma_x = \sqrt{\frac{1}{m^2}\left(\sum_{i=1}^{n}\sigma_i^2\right)}. \quad (1)$$

For m times scanning results from different films or the same piece of film under different conditions, the standard deviation should be calculated as follows.

$$\sigma_x = \sqrt{\frac{1}{nm-1}\left\{\sum_{i=1}^{m}(n-1)\sigma_i^2 + \sum_{i=1}^{m}n[\bar{x}_i - \bar{x}]^2\right\}}, \quad (2)$$

where $\bar{x}$ is the mean of all of the pixel values for scanning m times. The standard deviation results from the differences in the mean values and standard deviations of each scanning. The raw data were first exported from the software Epson Scan2 and then postprocessed by MATLAB.

2.3 Uncertainty study of response assessment of HDV2 film

Two types of scanning setting were investigated. (a) Scanning resolution: The same piece of irradiated film (0, 450, and 1800 Gy) was scanned from 50 to 2400 dpi, corresponding to the lowest and highest optical resolutions of the Epson 12000XL. Then, the relative standard deviation (RSD), full width at half maximum (FWHM), and pixel-value distributions were determined to investigate the influence of the dots-per-inch setting. The FWHM was obtained by subtracting the minimum from the maximum pixel value at the half-maximum counts in the pixel-value distribution. Gaussian fittings were conducted at some dots-per-inch settings for unirradiated film to select the optimal resolution. (b) Focus setting: The focus setting decides where the optics of the scanner focuses and can affect the mean pixel values and standard deviations of films [20]. The influence of the scanning settings was investigated by changing the focus settings from − 2 to 6 by two-step increments for the same piece of unirradiated film. Irradiated films were also examined with the same steps.

Interscan variability can be caused by various factors, three of which were investigated in the present study. (a) Outside illumination intensity: The external lighting conditions of the scanner were controlled by turning the lamps on/off, and illumination intensity was measured using a digital illuminometer (PM6612). The pixel values of irradiated films (i.e., 0, 450, and 900 Gy) with light (> 0 lx) were compared with those without light (0 lx). (b) Film homogeneity: Two sheets of unirradiated films were selected. For each sheet, 18 pieces of 1-cm × 1-cm film samples were cut evenly, as shown in Fig. 1. The homogeneity of HDV2 film was represented by the ratio of the standard deviations calculated using Eq. (2) to the mean pixel values [21]. (c) Operating temperature: The operating temperature of the scanner was measured using an infrared thermometer (563, FLUKE) when the room temperature reached thermal equilibrium. The probable slight temperature increase during scanning was ignored, because each piece of film was scanned five times. During scanning, the irradiated film samples (i.e., 0, 450, 900, 1350, and 1800 Gy) were placed at a fixed position on the scanner bed, keeping the scanner lid closed.

3 Results and discussion

3.1 Influence of the scanning setting on HDV2 response assessment

3.1.1 Scanning resolution setting

When the number of pixels is high enough, the mean value and standard deviation of the pixel values of the film represent more realistic results. Figure 2 shows the RSD and FWHM of the pixel values of films with different doses as a function of the scanning dots per inch. The RSD gradually increased with dots per inch and finally reached a stable value. Although the RSD was lower at a low dots-per-inch value, the results may not be reliable because of the low number of data points. This phenomenon was

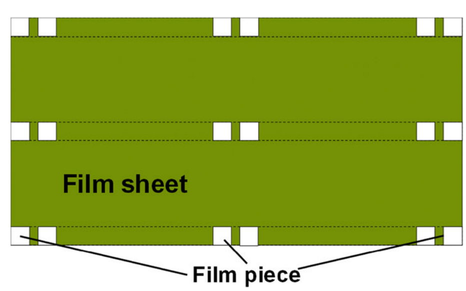

Fig. 1 Diagrams of cutting position for film homogeneity study

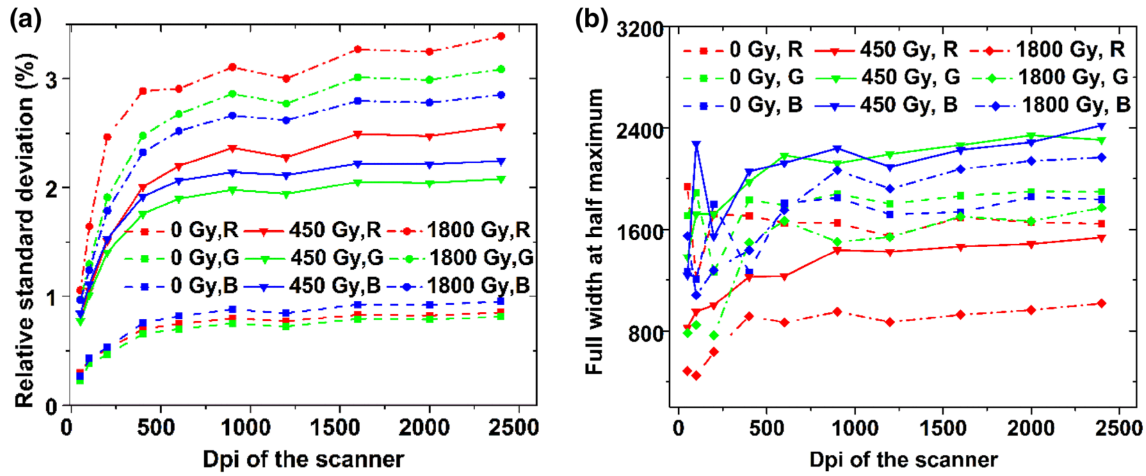

Fig. 2 (Color online) **a** RSD and **b** FWHM of the pixel values of films with various radiation doses in red (R), green (G), and blue (B) channels as a function of the dots per inch of the scanner

observed but not further investigated. Moreover, with an increase in dots per inch, the FWHM also becomes more stable. The present study asserts that the results at a high dots-per-inch value are closer to real results. The mean pixel value of films fluctuates within one standard deviation, and it is not discussed here.

Assuming that the film was completely uniform, a frequency chart of pixel values in the region of interest with a normal distribution and a small standard deviation could be obtained [22]. The distribution of the pixel values for unirradiated films at different scanning dots-per-inch values is plotted in Fig. 3 (for dots-per-inch values of more than 600). The figure shows multipeak pixel-value distributions at specific dots-per-inch values, and the distributions for other dots-per-inch values are in good agreement with the normal distribution for the same film. To exclude possible scanner problems, the authors contacted Epson (China) and conducted tests on another scanner of the same model in Shanghai, China. The pixel-value distributions of films obtained from both scanners showed multipeak problems at specific dots-per-inch values, and their distributions were alike at the same values. This demonstrates that the multipeak problem is an inherent phenomenon for the Epson 12000XL scanner. In addition, the reflection and transmission modes were tried for the same scanner, and multipeak problems existed in both modes. This emphasizes the importance of performing an accurate response assessment. Detailed results are shown in the supplementary materials.

Two possible causes of the appearance of multipeak problems are (1) the sensor used by the scanner does not work normally at specific dots-per-inch values, and (2) the scanner internally addresses the image as it is being scanned. Although the real cause of the appearance of multipeak problems is vague, this phenomenon must be considered and avoided as much as possible when radiochromic films are used. This problem is essential for assessing the film response accurately. Figure 3 only lists the pixel-value distributions at high dots-per-inch values, because the distribution of pixel values at low dots-per-inch values is difficult to see. However, multipeak problems of pixel-value distributions at low dots-per-inch values are suspected to exist. The multipeak question for low dots-per-inch values may also exist in other scanner models and other film models, but it has not been found in previous investigations. Further study on the multipeak distribution of pixel values is necessary.

Gaussian fitting of the pixel-value distributions of the film was conducted at the dots-per-inch values without multipeak problems, as shown in Fig. 3b, d, and e. At the three selected dots-per-inch values, the pixel-value distributions of the film scanned at 2000 dpi fit best with Gaussian distribution. The fixed 2000-dpi setting was used for scanning in later studies.

3.1.2 Focus setting

In addition to the scanning resolution, the focus setting of a scanner may influence the pixel values of the film. The effect of focus settings on the pixel values of unirradiated films in three color channels was investigated, as shown in Fig. 4. In Fig. 4a, the transverse line represents the average pixel values of the films for five focus settings. As the focus setting increased, the pixel value of the film remained constant, fluctuating within the error range. For films that have been irradiated, the focus setting has the same influence as for unirradiated films. Therefore, the focus setting of a scanner can be considered to have no effect on the pixel value of the films. However, the RSDs of the pixel values of the films first increased and then decreased with

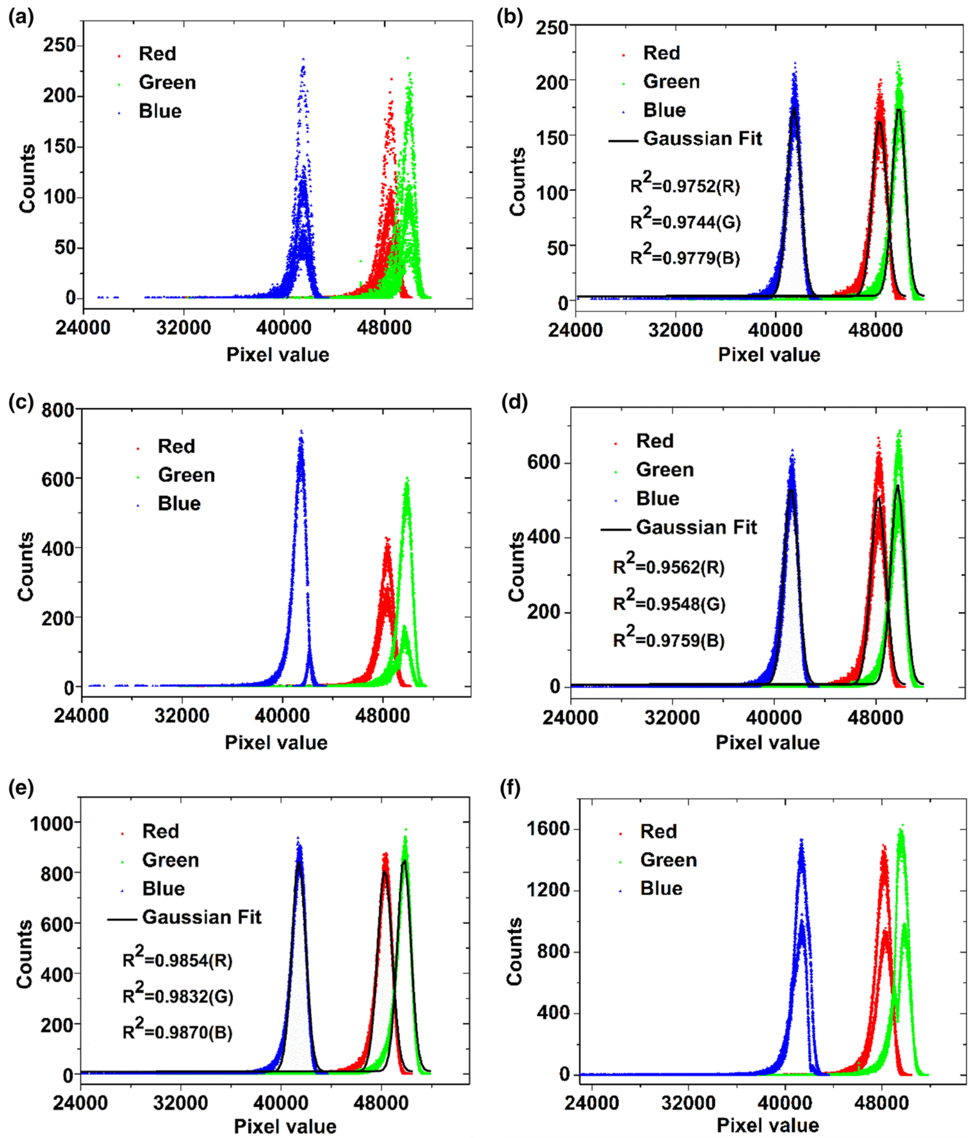

Fig. 3 (Color online) Pixel-value distributions of unirradiated films at **a** 600, **b** 900, **c** 1200, **d** 1600, **e** 2000, and **f** 2400 dpi

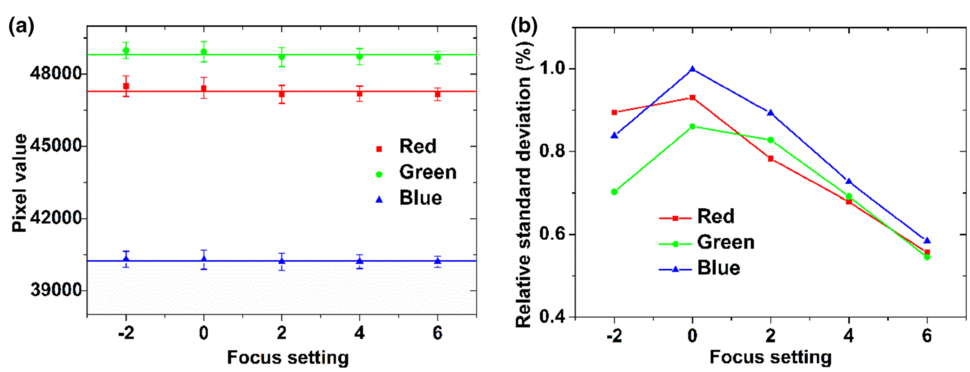

Fig. 4 (Color online) **a** Pixel value and **b** RSD of unirradiated films as functions of the focus setting

an increase in the focus setting, as shown in Fig. 4b. The RSD reached its maximum and minimum values at focus settings of 0 and 6, respectively. The RSD under a focus setting of 6 decreased by 36–50% in the three color channels compared with the RSD under a focus setting of 0. Therefore, a focus setting of 6 was selected as the experimental focus setting.

3.2 Influence of interscan variability on HDV2 response assessment

In addition to the scanning settings of a scanner, such factors as outside illumination, scanning position, and operating temperature can also induce interscan variability and affect the film response.

3.2.1 Outside illumination intensity

The scanner is not completely enclosed during scanning; hence, changes in outside illumination may affect the film response. Differences in the pixel values of films that received various doses were investigated under four illumination conditions in three color channels, as shown in Fig. 5. Outside illumination conditions had a small effect on the pixel values of unirradiated and irradiated films because of the presence of the mask. This observation demonstrates that the use of the mask can shield the films from surrounding scattered light, which can now be neglected when scanning.

3.2.2 Film homogeneity

Even if a film is scanned at the same position, its inhomogeneity may affect its response assessment. Table 1 shows the calculated homogeneity of the two sheets of films. The RSD for the entire sheet of film in three color channels is between 0.99% and 1.43%. The ratios of the two sheets of films in the red, green, and blue channels are 99.71% ± 1.95%, 99.85% ± 1.41%, and 99.86% ± 1.55%, respectively. According to the data from the 36 film species, the uniformity of the sensitometric response from the mean value was calculated and was also within the manufacturer's specification (3%). These results show the good quality of the films used. Even so, individual films were significantly different from other films. The difference was more than one standard deviation for another piece of film. Therefore, the influence of film inhomogeneity should not be ignored.

Table 1 Calculated homogeneity of two sheets of films in three color channels

Film sheet	Color channel	Mean pixel value	SD	RSD (%)
Sheet 1	Red	47,689.691	684.109	1.43
	Green	49,230.394	495.140	1.01
	Blue	40,703.868	478.929	1.18
Sheet 2	Red	47,826.752	636.318	1.33
	Green	49,306.440	487.590	0.99
	Blue	40,759.979	411.871	1.01

By position correction, differences from the scanning position of multiple films can be eliminated, but the errors introduced by film inhomogeneity cannot be excluded. Identifying the differences between the optical densities of the same film before and after irradiation, i.e., the net optical density (netOD), is the best practice. Each piece of

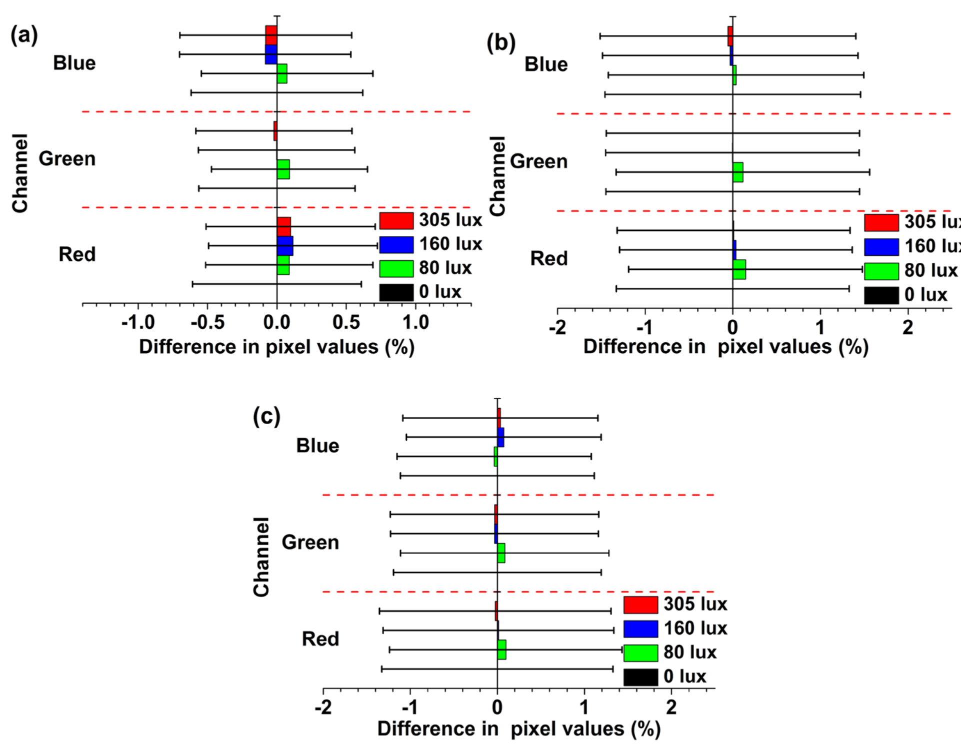

Fig. 5 (Color online) Differences in the pixel values of films irradiated with **a** 0, **b** 450, and **c** 900 Gy under four outside illumination conditions in three color channels

film should be scanned before and after irradiation at the same position. Through this cumbersome procedure, the probable errors caused by the inhomogeneity of the film or the scanning position can be completely eliminated. The use of this method is recommended to establish the dose calibration curve of films and to measure the absorbed dose of films.

3.2.3 Operating temperature of the scanner

Figure 6 shows the normalized pixel values of films irradiated with different doses as a function of the operating temperature in three color channels. The pixel value of the film scanned at the lowest temperature in the experiment was regarded as the normalized standard value. For different irradiation doses and different color channels, the effects of the working temperature on the film response were different. However, as the operating temperature increased, "stable stage" and "descent stage" were observed in the film response. When the operating temperature increased, the pixel value of the films first remained stable and then gradually decreased. Once the scanner worked in the stable stage, the effect of the operating temperature on the film response did not need to be considered. However, when the scanner worked in the descent stage, the effect of the temperature had to be corrected. Controlling the operating temperature of the scanner at 15–24 °C is preferable to achieve an accurate evaluation of the film response.

3.3 Standard operating procedure for film response assessment

Through the studies above, the accurate response assessment of HDV2 film using an Epson 12000XL scanner was realized. Similar qualitative behaviors between the proposed scanner and other scanner models are expected, because of the similar structures among different models of flatbed scanners. The conclusions above are not only applicable to the HDV2 film, but are also useful in assessing the response of other radiochromic films. However, the quantitative effects of the influencing factors on the film response cannot be determined, because they are influenced by different response characteristics and by the specific scanner model. Therefore, a standard operating procedure is proposed for other researchers to achieve an accurate response assessment for other scanners and films, as shown in Fig. 7.

The proposed standard operating procedure is primarily based on the research performed in this study and previous studies by other researchers. The influencing factors involved are enough to perform an accurate response assessment of films with acceptable uncertainty (2–4%). To achieve more accurate response measurements, or for use

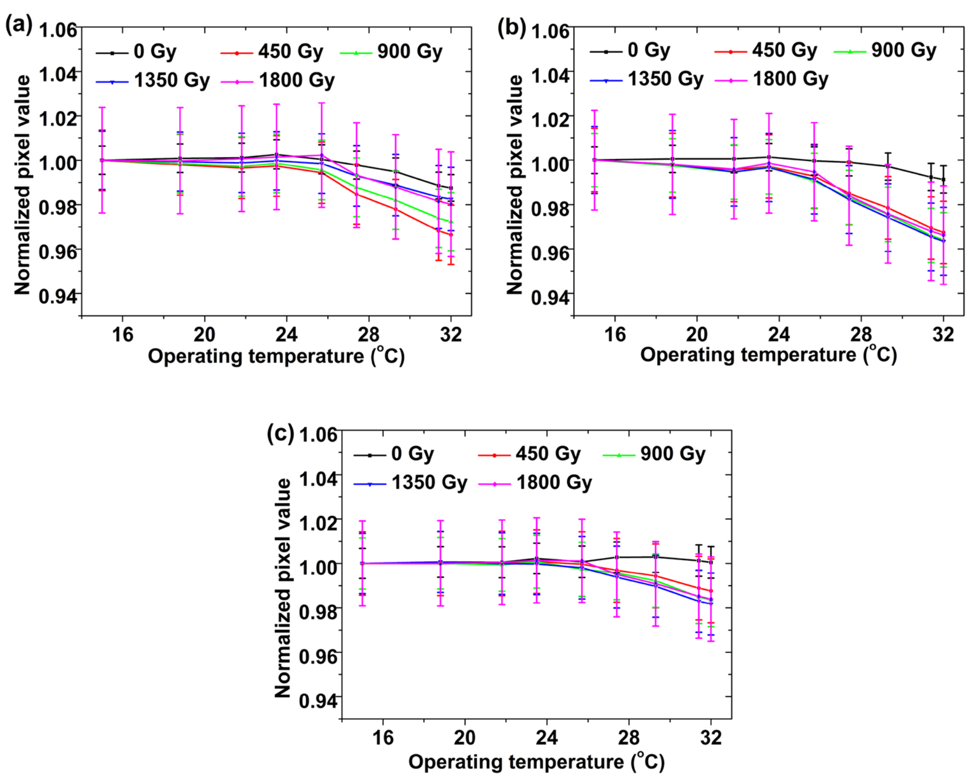

Fig. 6 (Color online) Normalized pixel values as a function of operating temperature in the **a** red, **b** green, and **c** blue channels

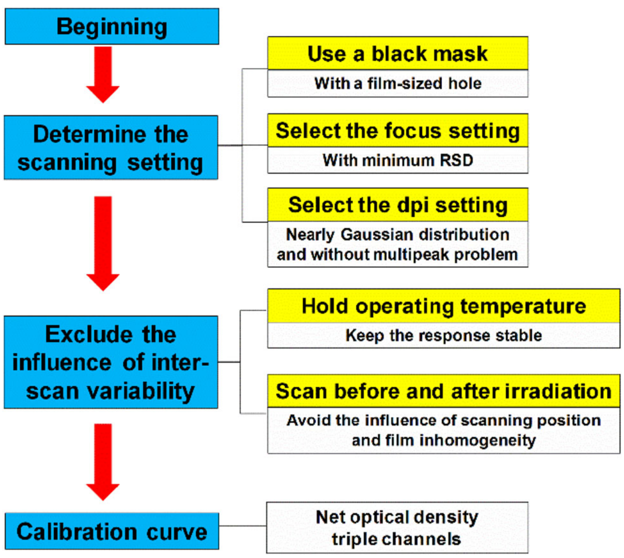

Fig. 7 (Color online) Diagram of the standard operating procedure

in other fields, other factors can be investigated based on the results presented here.

4 Conclusion

To realize accurate response assessment of radiochromic films for beam quality assurance, the influence of scanning settings and of the interscan variability on the film response of HDV2 was investigated using a flatbed scanner, and corresponding collection strategies were proposed.

In the study of scanning settings, it was found that (a) 2000 dpi was suitable as the scanning resolution, because its pixel-value distribution had a nearly Gaussian distribution and did not have the multipeak problem and (b) increasing the focus setting decreased the RSD of the pixel values of the films by 36% to 50% but did not affect the mean pixel value. The impact of interscan variability induced by three factors on the film response was also investigated. The outside illumination intensity had little impact on the film response, and it can be ignored. Scanning the same film before and after irradiation at the same position was recommended to avoid the influences of the scanning position and film inhomogeneity. Controlling the scanner working temperature to 15–24 °C was also suggested, because the film response was independent within this operating temperature range. Otherwise, there would be a 4% variation in pixel values at 32 °C. This phenomenon provided a proper operating temperature range for the scanner to work. According to these investigations, the accurate response assessment of HDV2 film using a flatbed scanner was realized.

Finally, a standard operating procedure for film response assessment that can help other researchers investigate other scanners and film models was established. This procedure was based on γ-rays from a ^{60}Co source, but it can be extended to other particles, such as neutrons, protons, and other particle types. This study can be used in beam quality assurance for boron neutron capture and proton therapies [17, 23–25]. The findings can serve as a reference for other researchers to achieve accurate response assessment of radiochromic films as a tool for quality assurance of beams.

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