Original Article

Backside Irradiation of Ultraviolet-A for Correcting Nonuniformity Error of Gafchromic XR-QA2 Films

Nobuyoshi Tanki, Sachiko Goto[1], Toshizo Katsuda[2], Rumi Gotanda[3], Tatsuhiro Gotanda[3], Tadao Kuwano[4]

Department of Radiological Technology, Graduate School of Health Sciences, Okayama University, [1]Department of Radiological Technology, Faculty of Health Sciences, Okayama University, Okayama, [2]Department of Medical Radiation Technology, Shizuoka College of Medicalcare Science, Hamamatsu, Shizuoka, [3]Department of Radiological Technology, Faculty of Health Science and Technology, Kawasaki University of Medical Welfare, Kurashiki, [4]Department of Radiology, Osaka Center for Cancer and Cardiovascular Diseases Prevention, Osaka, Japan

Abstract

Purpose: Radiochromic film is used for quality assurance and quality control of X-ray equipment in the diagnostic radiology. In addition, three-dimensional dose distribution of computed tomography (CT) is measured. To correct the nonuniformity and uncertainty of radiochromic films for dose measurement of CT, the films are preirradiated ultraviolet (UV)-A rays. There is a difference in the UV protection strength of radiochromic films. A concern exists about the effects of the UV-A irradiation intensity. We thus irradiated with UV-A rays from the backsides of the films to assess if backside irradiation was possible. **Materials and Methods:** Gafchromic XR-QA2 and RTQA2 were used in this study. The UV-A rays were simultaneously irradiated on the front and backsides of each film for 12 h. The yellow layer of each film was scanned and imaged. The average pixel values ± standard deviations (SDs) were compared. In the statistical analysis, a paired t-test was performed. To compare, the active-layer densities engendered by the UV-A rays. Calibration curve was created with 48 h of preirradiation of UV-A. **Results:** The mean pixel values ± SD for Gafchromic XR-QA2 on the front and backsides were 130.776 ± 0.812 and 81.015 ± 1.128, respectively. On the other hand, the mean pixel values ± SD for Gafchromic RTQA2 on the front and backsides were 62.299 ± 1.077 and 133.761 ± 1.365, respectively. The statistical results of the paired t-test were significantly different ($P < 0.01$) between both films. Fitting equation of the calibration curve is shown below. y = -390.47 ± 200 + (443.45 ± 10x80).5068 ± 0.0434. **Conclusion:** Based on the relationship between the sensitivity of the active layer to UV-A rays and the strength of UV protection on the surface, we concluded that backside irradiation is recommended for Gafchromic XR-QA2, and frontside irradiation is recommended for Gafchromic RTQA2.

Keywords: Backside irradiation, computed tomography, reflective type radiochromic film, ultraviolet radiation

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Introduction

Radiochromic film is used for quality assurance and quality control of X-ray equipment in diagnostic radiology. For example, it is used to measure the half-value layer to obtain the effective energy of X-rays[1] and to measure the three-dimensional dose distribution of X-ray computed tomography.[2,3]

Radiochromic films are divided into two categories: transmissive scan type and reflective scan type. Gafchromic EBT3 film is a typical transmissive scan-type film. The features of this film are typically applied for the measurement of therapeutic high-energy X-rays, which enable large-dose measurements and low-energy dependence. As a structural feature, the high-energy X-ray has no ultraviolet (UV) protection layer. Scanning is usually performed by employing the transmissive method; however, in some cases, it is performed using the reflective scan method.[4] Experimentally, it can be used to measure X-rays in the diagnostic area.[4]

Gafchromic XR-QA2 (XR-QA2) and Gafchromic XR-RV3 (XR-RV3) films are typical examples of the reflective

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Address for correspondence: Dr. Nobuyoshi Tanki, Department of Radiological Technology, Graduate School of Health Sciences, Okayama University, 2-5-1 Shikata-Cho, Kita-Ku, Okayama 700-8558, Japan.
E-mail: i.nobu44.tanki@mail-me.com

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scan types that are used in diagnostic applications. The front surfaces of these radiochromic films are opaque, yellow, and UV-protected. The backside surface is white. Therefore, the reaction of the active layer is not affected by ambient room UV rays. Gafchromic XR-SP2 (XR-SP2) film is more sensitive to X-rays than XR-RV3.[5] However, the degree of UV protection differs depending on the film type. For example, the UV protection of XR-SP2 is stronger than that of RX-RV3.[5] It is thus used to measure diagnostic energy X-rays and is a relatively low-dose measurement.

There are two types of nonuniformity errors in a reflective type radiochromic film. One is the nonuniformity error of the yellow surface layer. The unevenness of the yellow layer has been expressed as a density difference of color. It is expressed when it is acquired as an image by a scanner. The other is the thickness inhomogeneity of the active layer. The active layer is sandwiched between the yellow layer on the frontside and the white layer on the backside. Thus, no difference in thickness is expressed before the density increases owing to the X-ray. The uneven reaction due to the nonuniform thickness of the active layer engenders the uneven density change of the active layer. Therefore, it is necessary to irradiate with uniform X-rays or UV-A to increase the density of the active layer and to express the uneven thickness of the active layer. The nonuniformity error of the yellow layer can be corrected by subtracting it before and after X-ray irradiation images. In this case, it is possible without UV-A irradiation. The subtraction method corrects only the nonuniformity error of the yellow surface layer. In addition, the subtraction method can be used after irradiating the active layer with uniform X-rays or UV-A to express the nonuniformity error of the yellow surface layer and the active layer. Accordingly, both nonuniformity errors can be corrected simultaneously.

To correct the nonuniformity error, there is a double exposure method for X-rays in the therapeutic radiology.[6] In this area, uniform X-ray irradiation is possible by sandwiching a radiochromic film in a rectangular phantom with a uniform thickness.

However, in diagnostic radiology, uniform irradiation of X-rays is not possible owing to the heel effect of nonuniform X-ray generation at the focus of the X-ray tube. It has already been clarified that the density of the active layer of the radiochromic film is increased by irradiation with UV-A.[5,7] Therefore, UV-A can be used as a substitute for double X-ray irradiation in radiology.[8]

To irradiate the radiochromic film with UV-A, a UV irradiation device using a UV-light emitting diode (LED) that can irradiate UV-A at 385 nm was developed. The irradiation area of this device is greater than the A4 size, and the maximum irradiation intensity on the surface of the radiochromic film is 12,800 μW/cm^2.

The density-dose calibration curves of the XR-QA2 and the Gafchromic RTQA2 (RTQA2) films contain uncertainty in the low-dose range.[9,10] To address this issue, UV-A irradiation with subtraction method is a useful method.[11] The RTQA2 solved this problem by performing 40 h of pre-UV-A irradiation. The uncertainty in the calibration curve of the RTQA2 was reduced ($P < 0.05$).[11] However, the UV protection of the XR-QA2 was much stronger than that of the RTQA2 in our experiences. Therefore, a longer UV-A irradiation duration was required to increase the density when UV-A was irradiated on the frontside of the XR-QA2 film. Thus, in this study, we attempted to irradiate UV-A from the backside of the film for the applied shooter irradiation duration. Thus, the calibration and fitting curves were evaluated.

To reduce the nonuniformity error and improve the immediacy and convenience for creating a calibration curve, a pre-UV-A irradiation method for the backside was applied. In this study, XR-QA2 and RTQA2 films were irradiated with UV-A on the respective front and backsides.

We compared and evaluated both side irradiations with UV-A to find that backside irradiation was possible or not. Moreover, we examined whether it is possible to create a calibration curve using the UV-A backside irradiation method.

Materials and Methods

The XR-QA2 and the RTQA2 films (Ashland Advanced Materials, Bridgewater, NJ, USA) were used to assess the sensitivity of X-rays and UV-A. Both the XR-QA2 and the RTQA2 films were cut to 40 mm × 40 mm.

The calibration curve for converting pixel value changes to dose was created using the data of irradiating XR-QA2. The size of the XR-QA2 for creating the calibration curve was 24.5 cm long and 5 cm short. The XR-QA2 was divided into 14 segments for different exposure doses in each segment. The size of each segment was 5 cm long and 1.4 cm short.

A UV-A irradiation device was developed and constructed (CCS Inc. Kyoto). The UV-LED (385 nm: NICHIA Corp., Tokushima) was used. Representative characteristics of the UV-LEDs are shown.

- LED Name: NCSU034B (T)
- Direct current order direction electric current: I_F (mA): 500 mA
- Peak wavelength: λp (nm): 385 nm
- Direct current forward voltage: V_F (V): 3.7V (I_F = 500 mA)
- Photo output: P_0.(mW): 540 mW.

The distance from the UV-A LED lamp to the radiochromic film surface was 131 mm. The relative UV-A irradiation power ranged from 2530 μW/cm^2 to 12,800 μW/cm^2 at the radiochromic film surface.

Preultraviolet-A irradiation

Four sets of the XR-QA2 and the RTQA2 films each were prepared. These films were attached to a 3 mm thick acrylic plate. Four sheets were attached on the frontside, and the other four sheets were attached to the backside [Figure 1]. A 3 mm

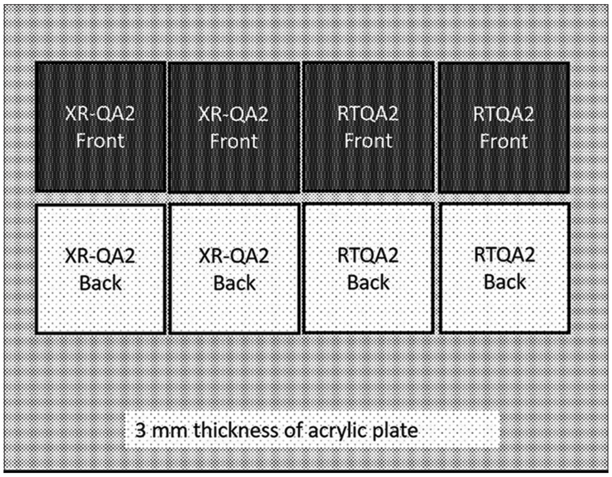

Figure 1: Diagram of Gafchromic films. Two sets of the same film type were attached on a 3 mm thick acrylic plate for irradiating with ultraviolet-A

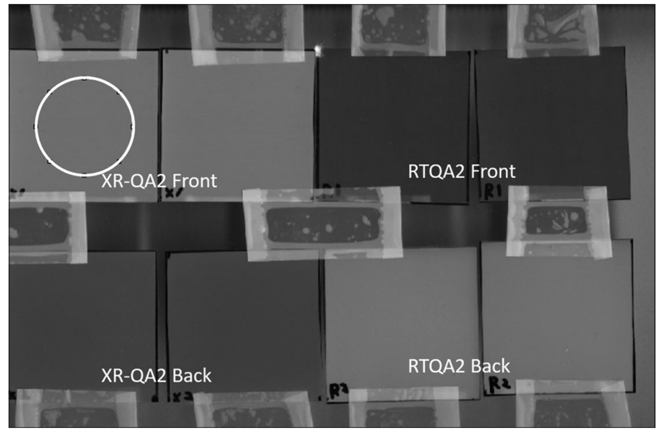

Figure 2: The position of 1″ diameter circular region of interest is shown on the film. This image is the red component of scanned red, green, and blue image

thick acrylic plate with radiochromic films was inserted into the UV-A exposure device. The XR-QA2 and the RTQA2 were irradiated with UV-A for 12 h.

Calibration curve of the XR-QA2

X-ray equipment (MRAD-A32S, Canon Medical Systems, Ohtawara, Japan) was used to irradiate the XR-QA2 film. XR-QA2 cells were irradiated with UV-A for 48 h. In addition, XR-QA2 was stuck on an acrylic plate of 3 mm thickness for easy handling and scanning. The XR-QA2 was irradiated with X-rays at 0, 2, 4, 6, 8, 10, 15, 20, 25, 50, 75, 100, 150, and 200 mGy in each segment during monitoring using a semiconductor dosimeter (ThinX RAD, Unfors RaySafe AB, Billdal, Sweden).

Image scan

The UV-A irradiated XR-QA2 and RTQA2 films were removed from the acrylic plate once. Then, the backsides of the films were reattached to the acrylic plate. An acrylic plate with frontside of the films was attached to the scanner glass. The UV-A preirradiated XR-QA2 film for creating calibration was attached to the backside on an acrylic plate. An acrylic plate with frontside films was attached to the scanner glass.

The irradiated (X-rays or UV-A rays) XR-QA2 and RTQA2 films were scanned using a flatbed scanner (EPSON ES-2200, Seiko Epson Co. Nagano), and the images were acquired using Adobe Photoshop CS2 (Adobe Systems Incorporated, San Jose, CA, USA). They were read at 150 dpi resolution, and each 16-bit red, green, and blue (RGB) mode was used. A protective film of liquid crystal (LCD-230W, Sanwa Supply Inc., Okayama) was used for the removal of moiré artifacts (Newton's rings).[1] The preparation of the radiochromic films was performed by changing the room temperature from 21°C to 25°C. To compare the density increases of the back and frontside UV-A irradiation films, 16-bit images were obtained and assessed.

Image analysis

The diameter of the 1″ circular region of interest (ROI) was set at the center of each scanned film [Figure 2]. The mean pixel values ± standard deviation (SD) were calculated using the image processing software ImageJ for Windows (version 1.45i) (National Institutes of Health, Bethesda, MD, USA). The data obtained by irradiating UV-A for the XR-QA2 and the RTQA2 were evaluated. To create a calibration curve, the mean pixel values and standard deviation were calculated in the circular ROI (diameter: 0.45″) was set at the center of each segment of the XR-QA2. The curve fitting equation was made using IGOR Pro graphic software version 6.3.6J (Wave Metrics Inc. OR, USA). A fitting curve by "power" was performed.

The sensitivity of UV-A for increasing the density of the active layer in the two irradiation directions was compared. The mean pixel values of the front and back irradiated UV-A of the XR-QA2 and the RTQA2 films were compared. The Student's *t*-test was performed using the statistical analysis software R (Free Software Foundation GNU Project).

We compared the conveniences of XR-QA2 and RTQA2 based on the difference in the reaction of the active layer after 12 h of UV-A irradiation on the front and backsides. In addition, we assessed the calibration curve and fitting curve of the XR-QA2 created with pre-UV-A irradiation for 48 h.

Results

Color and density change of radiochromic films

The scan images of the UV-A-irradiated radiochromic films are shown in Figure 3. The color change was different between the XR-QA2 and the RTQA2. The RTQA2 film is colored green. The XR-QA2 film with backside irradiation and the RTQA2 film with frontside irradiation and vice versa. The pixel values ± SD of the XR-QA2 and the RTQA2 films are shown in Table 1. By the RTQA2, the sensitivity of UV-A to frontside irradiation was high. However, by the XR-QA2, the sensitivity of UV-A to backside irradiation was high.

Comparison of front and backside ultraviolet-A irradiation

Table 1 presents the results of pixel value ± SDs of UV-A

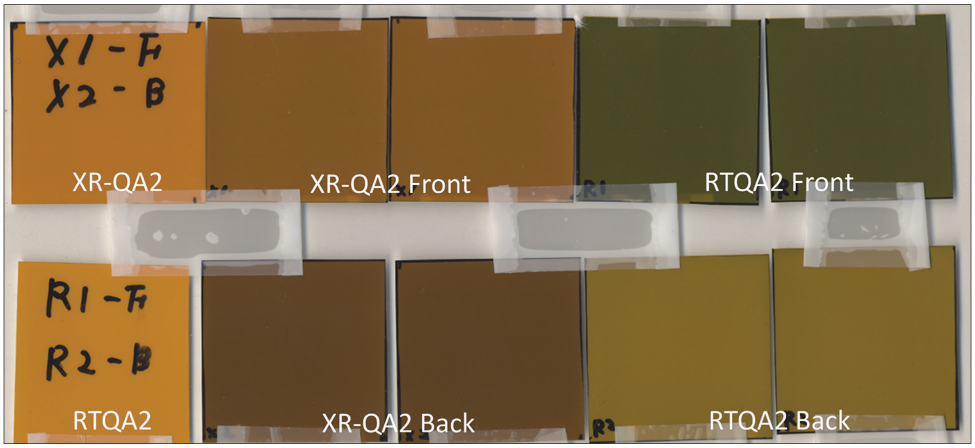

Figure 3: Scan images after 12 h of ultraviolet-A irradiation to XR-QA2 and RTQA2 films. Left side shows nonirradiated XR-QA2 and RTQA2 films

Table 1: Results of pixel values±standard deviations of ultraviolet-A irradiation on both films (16-bit)

Direction	Maximum	Minimum	Mean±SD	*P*
XR-QA2				
Front	135.500	127.500	130.776±0.812	<0.01
Back	92.000	77.500	81.015±1.128	
Without UV-A	201.000	192.000	196.452±1.014	
RTQA2				
Front	75.000	58.500	62.299±1.077	<0.01
Back	150.500	124.000	133.761±1.365	
Without UV-A	213.000	185.000	207.525±1.390	

SD: Standard deviation, UV-A: Ultraviolet-A

irradiation on both films (16-bit). The results of the paired *t*-test of the XR-QA2 between the front and backsides are statistically different ($P < 0.01$). In addition, the results of the paired *t*-test of the RTQA2 between the front and backsides are significantly different ($P < 0.01$).

Calibration curve and fitting equation

The calibration curve (solid line with markers) and fitting curve (dotted line) of the XR-QA2 are shown in Figure 4.

The dose calibration curve was fitted using the following equation:

$$f(x) = y_0 + Ax^{pow} \quad (1)$$

The fitting curve coefficients were as follows:

$y0 = -390.47 \pm 200$, $A = 443.45 \pm 108$, $pow = 0.5068 \pm 0.0434$

Usability

When using the UV-A irradiation method for the XR-QA2 and the RTQA2, the shorter the UV-A irradiation time is, the better the efficiency is and thus the more frequently it can be used. According to the results of 12 h UV-A irradiation of the XR-QA2, the density increase from the backside irradiation was significantly larger than that from the frontside irradiation. In contrast, for the RTQA2, the increase in density was greater when the irradiation was on the front surface. Therefore, when using the XR-QA2, UV-A was irradiated on the backside, and when using the RTQA2, UV-A was irradiated on the frontside. In addition, a calibration curve of the XR-QA2 with 48 h of pre-UV-A irradiation on the backside was convenient.

Discussion

It was found that the increase in the density of the active layer due to the UV-A differed between the frontside and backside irradiation. For the XR-QA2, the density changes of UV-A irradiation on the backside were larger than that on the frontside. On the other hand, for the RTQA2, the density increase was larger in the UV-A irradiation on the frontside.

The sensitivity of the active layer to X-rays was almost similar between the XR-QA2 and the RTQA2. However, when the UV-A was irradiated, the mean pixel value ± SD of frontside irradiation of the XR-QA2 and backside irradiation of the RTQA2 were 130.776 ± 0.812 and 133.761 ± 1.365. These were similar values. In contrast, the mean pixel values ± SD of backside irradiation of the XR-QA2 and frontside irradiation of the RTQA2 were 81.015 ± 1.128 and 62.299 ± 1.077. These were similar values. It seems that sensitivity to the UV-A does not differ between XR-QA2 and RTQA2. The UV protection strength of frontside of XR-QA2 and backside of RTQA2 are similar, vice versa.

Originally, the reflective type radiochromic film had UV protection on the frontside. It was constructed to prevent the influence of UV rays on the active layer. In general, the frontside always faces the light source from the ambient UV source; thus, it is considered that there is no reaction of the active layer. Therefore, very strong UV rays are necessary to increase the density of the active layer. We originally developed a UV-A irradiation device. However, even when using the UV-A irradiation equipment we developed, irradiation for 48 h was required. To increase the density that required in a shorter time, it is necessary to use UV-LEDs with strong UV-A generation intensity, or to increase the number of UV-LEDs used and to develop equipment that can irradiate more powerful UV-A rays.

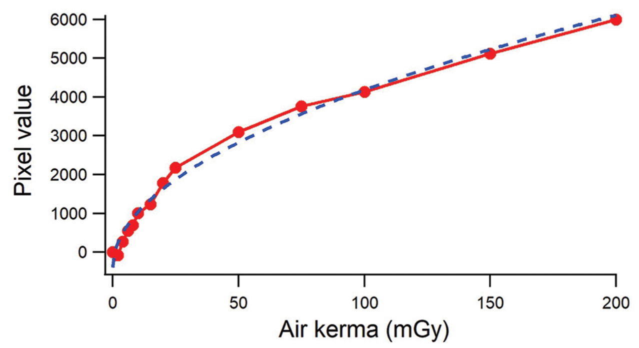

Figure 4: A calibration curve (solid line with markers), and fitting curve (dotted line) for XR-QA2

The UV-A irradiation time for creating the calibration curve in this study was 48 h. The reason for this is that when the RTQA2 calibration curve was created using preirradiation UV-A, the density change was linear at 100 mGy more, so the initial density of UV-A irradiation was set at about 100 mGy.

Although XR-QA2 is different from RTQA2, the sensitivity to X-rays is only slightly different, so the UV irradiation time was set so that the density would be equivalent to the X-ray dose of 100 mGy.

Our research has proved that the UV-A irradiation method can be applied for nonuniformity error correction of radiochromic films. Because reflective-type radiochromic films are protected from UV rays, long-term UV-A irradiation is required to increase the density to an effective level using strong UV-A rays. Therefore, we attempted to irradiate UV-A on the back-ide, which was not protected from UV rays. As a result of this study, it was found that the effect could be obtained for the XR-QA2 in a time shorter than the irradiation time on the frontside by UV-A. To the best of our knowledge, this is the first study to develop a useful method for correcting the nonuniformity error of radiochromic films to create a calibration curve of the XR-QA2.

Radiochromic films were reacted using X-ray and UV-A. One was a density change; the other was a color change. The XR-QA2 changed in density with a brownish color through the yellow layer. However, the density of RTQA2 changed in a greenish color through the yellow layer. Therefore, the density difference could not be visually estimated between the XR-QA2 and the RTQA2. In this study, the RGB channel image was split into three colors and the red channel was used. It was converted into a black and white image and evaluated by pixel values.

Conclusion

From the results, UV-A irradiation of the RTQA2 should be performed on the frontside. On the other hand, it was found that the UV-A irradiation of the XR-QA2 should be performed on the backside. The calibration curve of the XR-QA2 was easy to correct nonuniformity error and uncertainty using this method.

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Conflicts of interest

There are no conflicts of interest.

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