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Evaluation of triple channel correction acquisition method for radiochromic film dosimetry

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The purpose of this study was to evaluate the triple channel correction acquisition (TCCA) method for radiochromic film dosimetry performed with a flatbed scanner. The study had two parts: a fundamental and a clinical examination. In the fundamental examination, we evaluated the accuracy of calibration curves for Gafchromic EBT2 (EBT2). The films were calibrated using a field-by-field method with 13 dose steps. Seven calibration curves obtained by TCCA were compared with those produced by a single channel acquisition (SCA) method. For the clinical examination, we compared relative dose distributions obtained by TCCA and SCA for four cases of intensity-modulated radiation therapy (IMRT) and intensity-modulated arc therapy (IMAT). The fundamental examination showed that the consistency of the calibration curves was better for TCCA than for SCA, particularly for the dose range between 0.25 Gy and 1.00 Gy. The clinical examination showed that the dose differences between the measured and calculated doses in high-gradient regions were smaller with TCCA than with SCA. The average pass rates in gamma analysis for the TCCA and SCA methods were $97.2 \pm 0.8\%$ ($n = 20$) and $93.0 \pm 1.2\%$ ($n = 20$), respectively. In conclusion, TCCA can acquire accurate average dose values when creating the calibration curve. The potential advantage of TCCA for EBT2 film dosimetry was seen in high-gradient regions in clinically relevant IMRT and IMAT cases. TCCA is useful to verify dose distribution.

Keywords: Triple channel correction; film dosimetry; radiochromic film; dose verification; intensity-modulated radiation therapy

INTRODUCTION

Modern radiotherapy techniques such as intensity-modulated radiation therapy (IMRT) or intensity-modulated arc therapy (IMAT) can provide better dose distribution for planning the target volume and sparing normal tissue [1, 2]. However, these techniques require dosimetric quality assurance in every patient (patient-specific quality assurance: SQA) before treatment because of the very complex radiation delivery procedures required. According to the Japanese guidelines, SQA is divided into two categories [3–8]: absolute dose measurement and dose distribution validation. In general, an ionization chamber is used for absolute dose measurement, whereas film is a standard dosimetric tool for validating dose distribution. There are two types of films: radiographic and radiochromic. Radiographic films based on the silver halide reaction have been widely used for validation of the relative dose distribution in IMRT phantom plans. However, the film processors are becoming obsolete because digital imaging technology now predominates in many hospitals. Therefore, radiochromic films have recently been marketed as self-developing films that do not require a processor. These films have spatial resolution as high as radiographic films, are nearly tissue-equivalent, and have a well-defined dose response; they can accordingly be used to accurately measure relative dose distributions. Many investigators have reported the characteristics of radiochromic films and the scanning procedures for their use in therapeutic photon beam dosimetry. In particular, it is important to avoid systematic

artifacts and dose uncertainty during the scanning procedure [9–13].

The Gafchromic EBT2 (EBT2, ISP (Wayne, NJ, USA)) film is a transmission-type radiochromic film consisting of four layers, including a polyester substrate base. Most users of EBT2 films measure the optical density of the film with a single channel acquisition (SCA) technique [5]. SCA is the standard technique for measuring the film optical density using a color flatbed scanner. With this method one chooses a specific color range within the visible light spectrum transmitted through the film; we normally use red because it best suits the characteristics of EBT2 film. On the other hand, the triple channel correction acquisition (TCCA) technique is a model-based method for obtaining the characteristic curve of EBT2 film. The algorithm and fundamental characteristics of this method have already been reported by Micke *et al.* [14]. TCCA has the benefit of separating the dose-dependent and dose-independent parts of the scanned signals, to compensate for a variety of anomalies, artifacts and other disturbances such as variations of film thickness (e.g. active layer thickness), scanner non-linearity and process noise, and to allow entire available sensitivity range of the film to be used. In this study, we compared TCCA with SCA in performing EBT2 film dosimetry for IMRT and IMAT.

MATERIALS AND METHODS

This study was composed of two parts: a fundamental evaluation and a clinical evaluation. The evaluation procedures are illustrated in Fig. 1. A Clinac iX medical linear accelerator (Varian Medical Systems, Palo Alto, CA, USA) and a Novalis Tx medical linear accelerator (BrainLAB, Feldkirchen, Germany) were used in this study. For the fundamental evaluation, EBT2 films were calibrated by irradiating the films in 13 dose steps. An entire sheet of EBT2 film (10 inch × 12 inch (25.4 cm × 30.48 cm)) was divided into a 3 × 4 grid of 6 × 6 cm pieces in the central part of the sheet. The remaining pieces were used to obtain the optical density of unirradiated film. Each film piece was inserted into a 30 × 30 × 30 cm solid-state water-equivalent phantom (ToughWater; Kyoto Kagaku Co. Ltd, Kyoto, Japan). The calibration depth was 10 cm. The films were irradiated with 0.25, 0.50, 0.75, 1.0, 1.25, 1.50, 1.75, 2.00, 2.50, 3.00, 3.50 and 4.00 Gy using a 10-MV photon beam; they were then scanned using a customized scanning protocol [5, 16], summarized in Table 1. Films were scanned with a flatbed scanner (V700, Seiko-Epson Corporation, Nagano, Japan) 3 h after the irradiation. The spatial resolution was 150 dpi, with landscape orientation and the film positioned at the center of the entire scanning area, and a median (5 × 5) image processing filter was used (see Fig. 1). The calibration curves for three color channels using seven dose-steps (including five batches) were then obtained by TCCA and SCA. We calibrated the monitor chamber of the linear accelerator according to the Japanese Standard Measurement Protocol before acquisition of the first calibration curve. We defined the first calibration curve as the reference data. After this process, we obtained all calibration curves under the same conditions, and curves were compared to evaluate their consistency. With TCCA, the calibration curves were created using FilmQAPro 2010 software (Version 0; ISP Co. Ltd, Wayne, NJ, USA). The data were then exported in American Standard Code for Information Interchange (ASCII) format using an in-house program (created using Visual C language). On the other hand, the calibration curves for SCA were created using OmniPro software (IBA, Bartlett, IL, USA), and the data were exported as an ASCII-format file via a function of this software. Both ASCII-format files were imported into Excel software (Microsoft Corporation, Redmond, WA, USA) to compare the calibration curves generated by the two methods. All calibration curves were plotted for analogue-to-digital conversion ADC) value against dose.

For the clinical evaluation, we compared the planar dose distributions of IMRT and IMAT (RapidArc) plans using TCCA and SCA. We chose two IMRT plans and two RapidArc plans for prostate cancer. The IMRT plan was designed using an i-plan ver.4.2 treatment planning system (TPS) (BrainLAB) and the RapidArc plan using an Eclipse ver.8.9 TPS (Varian Medical Systems). The films were scanned using our customized scan protocol. We chose two programs (FilmQA Pro 2010 prototype and OmniPro-I'mRT) for the analyses. However, the FilmQAPro 2010 prototype did not have enough functionality to allow a quantitative dose comparison. To compare the dose distribution obtained by TCCA with that by SCA with the same program, we therefore created an in-house program (using Visual C language) to export the dose distribution data in ASCII format from FilmQAPro. The ASCII-file for TCCA was exported to OmniPro I'mRT via this in-house program. The agreement between the TPS-created plan and the film dose distributions was quantitatively assessed on OmniPro I'mRT software. The gamma analysis method was used with a tolerance level of 3% dose difference and 3 mm distance-to-agreement as criteria [3, 4, 7]. The gamma evaluation was done for above 20% isodose level.

RESULTS

The calibration curves for ADC value vs. dose are shown in Fig. 2. These curves were obtained by seven curves with 13 dose-steps for Gafchromic-EBT2 film: a total of five batches were irradiated between May 2010 and July 2011. The solid and dashed lines in the figure indicate the calibration curves obtained by TCCA and SCA, respectively. The error standard deviations (1 SD) of the ADC values among the five batches at each dose step are shown in Fig. 3.

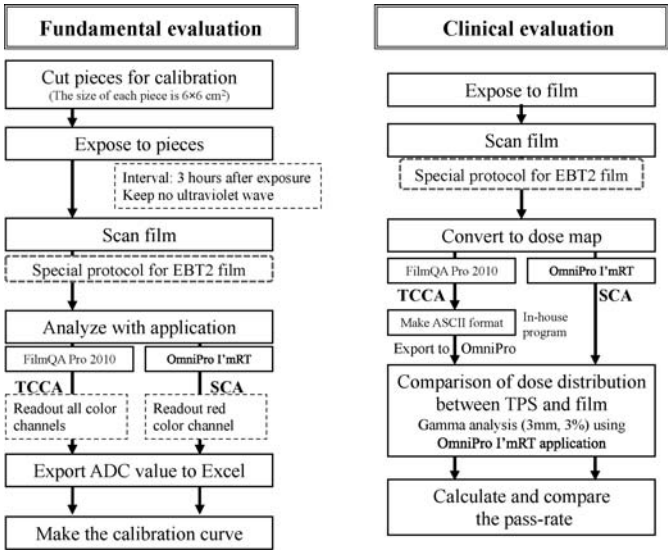

Fig. 1. experimental flowchart for this study.

Table 1. Summary of our customized protocol for film scanning

The details of scan setting	
The film size of each piece for a field-by-field method	6 × 6 cm
The film position on the glass plate of scanner	Center position of entire scanning area
The scan orientation of film	Landscape direction
The spatial resolution of scan image	150 dpi
The gradation scale	48 bit/RGB
The smoothing filter	Median filter (5 × 5)
The interval time between irradiation and scanning	3 h
The pass of transmission light	Opposite to surface side of film

Table 2. Comparison of pass rates for gamma analysis in SQA

	Pass rate: gamma analysis (3 mm, 3%)	
	TCCA method	**SCA method**
Plan 1 (RapidArc) (n= 5)	96.2 ± 0.8%	92.6 ± 1.7%
Plan 2 (RapidArc) (n= 5)	96.8 ± 0.7%	92.9 ± 1.2%
Plan 3 (7beams IMRT) (n= 5)	97.9 ± 0.8%	93.6 ± 1.1%
Plan 4 (7beams IMRT) (n= 5)	97.3 ± 0.7%	92.4 ± 0.9%

The optical density measured for SCA was higher than that for TCCA in all color channels. The maximum standard deviation was 11.1% at 0.25 Gy with SCA compared with 5.1% at this radiation dose with TCCA. For doses from 0.25 to 1.00 Gy, all SDs were smaller for TCCA than for SCA, indicating that the consistency of the TCCA calibration curves was superior. The most significant difference in the calibration curves between the two methods was observed in a low dose range (0.25–1.00 Gy).

The results of the clinical evaluation are shown in Table 2 and Fig. 4. The dose differences between the measured and planned doses in high-gradient regions were smaller with TCCA than with SCA. In fact, the average pass rates for gamma analyses were 97.2 ± 0.8% (n = 20/four cases) for TCCA and 93.0 ± 1.2% (n = 20/four cases) for SCA.

Figures show the comparison of dose distribution between TCCA and SCA.

DISCUSSION

We evaluated the usefulness of TCCA for radiochromic film dosimetry with EBT2 film. TCCA balances the color channel with the highest sensitivity because the component with the highest derivative value is the dominant factor. The use of multiple wave ranges when scanning EBT2 film enables us to use the most sensitive range in the absorption spectrum of this film. The present results indicate that TCCA allows us to reduce the systematic dose disturbance of EBT2 film in each batch [12]. In the fundamental test, the consistency of the calibration curves among several batches was better for TCCA than SCA. We believe this relates to an advantage of TCCA: subtraction of dose disturbance due to the film. Because dose disturbance is

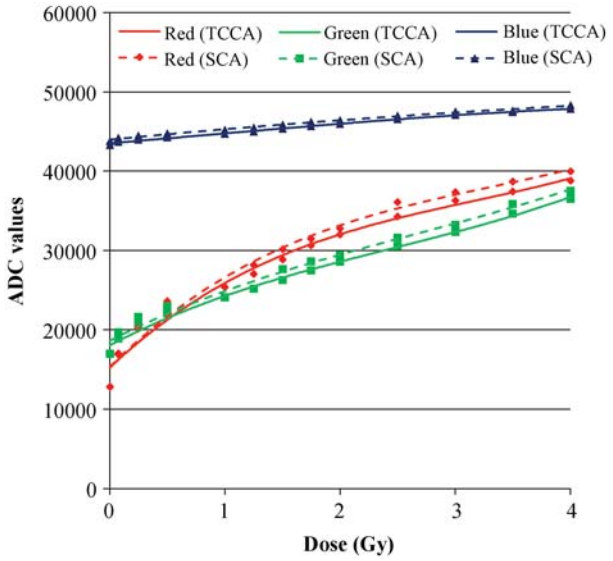

Fig. 2. Comparison of the calibration curves between TCCA and SCA.

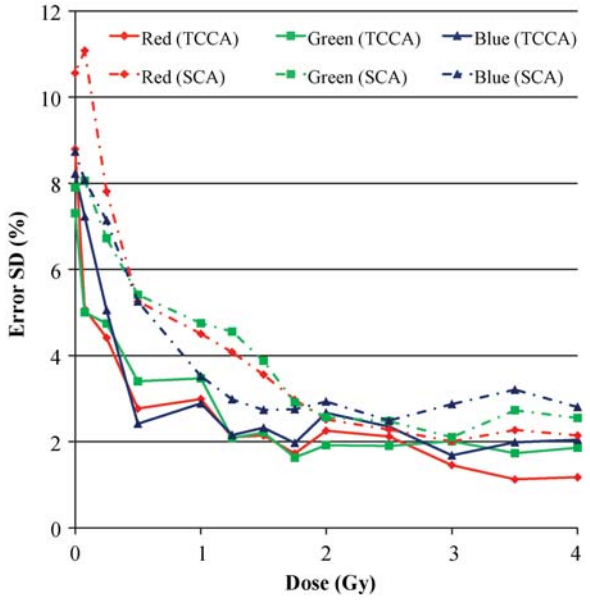

Fig. 3. Comparison of the standard deviation (1 SD) of the calibration curve between TCCA and SCA.

subtracted, TCCA resulted in not only a smaller standard deviation for each dose, but also a lower optical density on the calibration curve when compared with SCA. Although the consistency of the dose response in SCA was worse than that in TCCA, a calibration curve can be obtained with SCA using a protocol suitable for clinical practice, to evaluate the dose distribution of IMRT. In radiochromic film dosimetry, it is important to scan film accurately, and many investigators have reported methods to reduce uncertainty related to radiochromic film dosimetry. For example, Moral *et al.* compared the fitting algorithm for Gafchromic-EBT (EBT) film among four theoretical models [16]. He concluded that the gamma-distributed single-hit model based on the percolation theory was suitable for fitting and smoothing of the calibration curve of EBT film. However, this algorithm is not able to account for density differences due to film thickness variation and/or scanner-dependent variation. In addition, the accuracy of this method was better in the dose range from 0 to 2 Gy In radiochromic dosimetry, it is necessary to characterize the average relationship between the dose to which the film is exposed and the response of film. TCCA can ensure the average value of the dose to which EBT2 films are exposed by means of a mathematical equation. Hence, when creating a calibration table, TCCA appears to have an advantage in obtaining the average relationship between the dose to which the film is exposed and the film response.

In radiochromic film dosimetry, there are many uncertainties in the handling procedure [9–11]. Saur *et al.* reported the absolute non-uniformity correction method for radiochromic film dosimetry using a flatbed scanner [10]. They estimated the total 2-sigma dose uncertainty at within 4% for doses between 1 and 3 Gy and reaching a minimum at approximately 2 Gy. Their method might consequently reduce uncertainty and disturbance due to the film scanner; however, it is limited to portrait orientation during scanning. Battum *et al.* reported the overall accuracy of EBT film absolute dosimetry in water [11]. According to their evaluation, the overall random uncertainty in absolute dose with EBT film was in the order of 1.8% (1 SD). This result was obtained by scanning a limited area of film, and they recommended that a similar customized protocol for scanning of radiochromic film is important to avoid systematic artifacts. Masi *et al.* reported a comparative study of different dosimetric tools in SQA for volumetric arc therapy [17]. Their results (pass rate) showed that EBT2 film had the highest associated uncertainty when compared with several other tools. However, they used EBT2 film with the EBT film protocol, and considered that the large difference (uncertainty) might have been caused by an inappropriate scanning protocol for EBT2 film.

We previously established a customized protocol for scanning EBT2 film to reduce systematic uncertainty [13, 14], the details of which are given in Table 1. This protocol not only reduces uncertainty but also helps minimize inconsistency between handling operators. Furthermore, this protocol is compatible with TCCA, allowing the overall accuracy of EBT2 film dosimetry to be improved further.

In SQA for IMRT or other complex technologies, the composite validation of dose distributions is required to evaluate the doses both in the prescribed dose range and for organs at risk. Inconsistency between the calibration

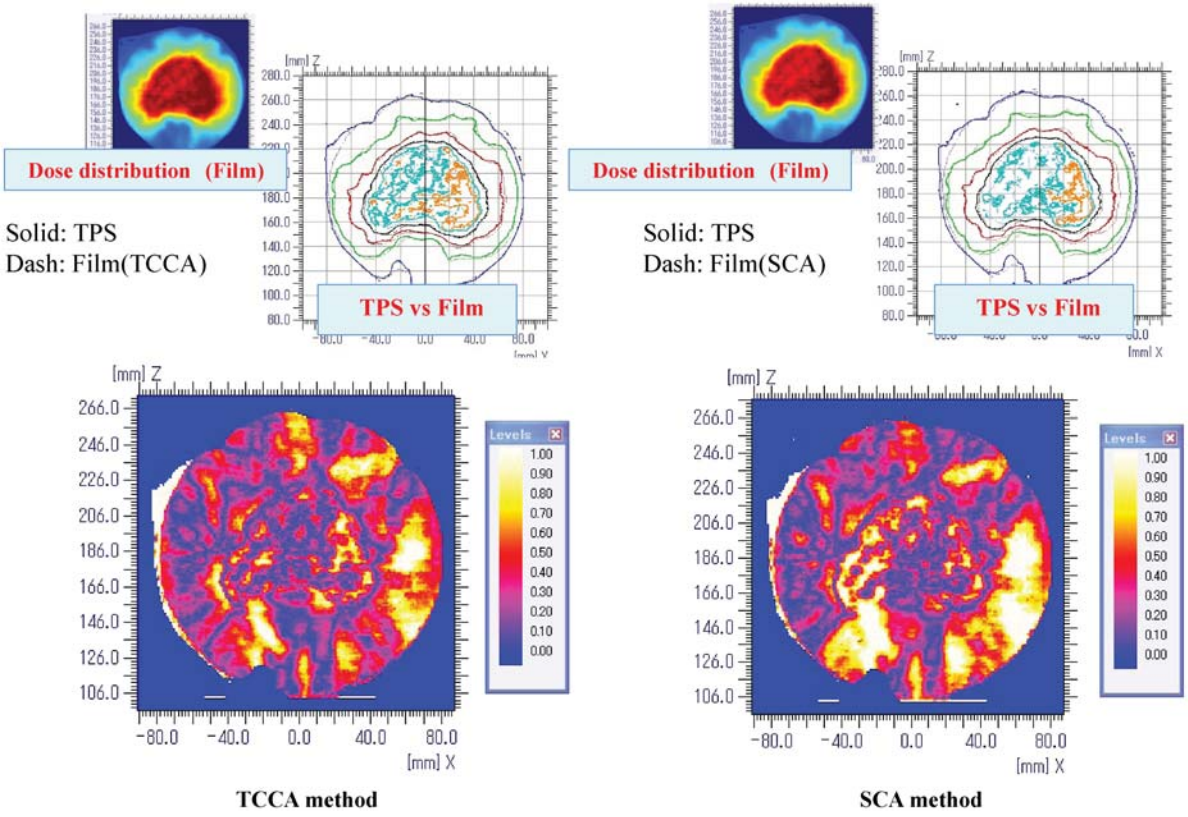

Fig. 4. A case of patient-specific quality assurance for RapidArc® delivery in a patient with prostate cancer.

curves might make it difficult to match the dose distribution in both dose ranges. In particular, if we normalize the dose distribution indicated by film so that it falls within the prescribed dose range, the dose difference from the organs-at-risk range might be unacceptable for SQA. TCCA allows us to avoid significant dose difference due to non-uniformity of films in a low dose range because this method can accurately obtain the average film response even at such dose ranges. This enables us to compare doses even in a high-dose gradient region. We therefore believe TCCA is suitable for EBT2 film dosimetry to perform dose validation when the distribution has a high-gradient region, such as in IMRT or RapidArc deliveries.

On the other hand, we suggest that those performing radiochromic dosimetry with TCCA should ensure that they evaluate slight differences such as those due to MLC leakage and the tongue and groove (T&G) effect. In particular, the T&G effect is noteworthy in terms of IMRT dose distribution, and can generally be measured using film. The total transmission factor for the T&G effect (T_{TG}) consists of the product of the transmission factors of tongue (T_T) and groove (T_G) structures (Eq. 1). If T_T is equal to T_G, it is assumed that the tongue and groove are of equal thickness. By considering the transmission factors separately for T&G structures, the T&G effects on the dose distribution will be correctly included in the process of dose calculation.

$$T_{TG} = T_T \times T_G \tag{1}$$

However, these values are normally expressed as slight differences in small regions. TCCA requires a considerable area for smoothing (at least 2.5 × 2.5 cm in 150 dpi), and if the area incorporating the T&G effect is much smaller than this large region in each color channel, the T&G effect will be sometimes ignored because of smoothing by TCCA. Hence the density difference due to T&G cannot be corrected accurately for this large a region. In SQA, the dose comparison in the coronal plane includes a T&G evaluation. However, if the dose distribution has a high-gradient area in a small region, the slight density deviation due to T&G will be ignored as a noise area with TCCA. Physicists should therefore consider these characteristics when using the TCCA method in SQA.

CONCLUSION

We showed that calibration curves obtained by TCCA have better consistency than those produced by SCA, particularly

in the low-dose range. In the clinical evaluation, the potential advantage of the TCCA method was observed in high-dose gradient regions in clinically relevant IMRT and RapidArc cases. Hence, EBT2 film dosimetry in combination with TCCA could be useful in clinical practices such as SQA. It is noteworthy, however, that the correct handling procedure for EBT2 films is important to achieve accurate SQA results, even if TCCA is used. In addition, the characteristics of TCCA mean that this method sometimes ignores small deviations such as leaf transmission. We conclude that while TCCA is useful for SQA, physicists should consider both its merits and demerits carefully.

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