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Original Paper

An effective calibration technique for radiochromic films using a single-shot dose distribution in Gamma Knife®

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Purpose: A method of calibrating radiochromic films for Gamma Knife® (GK) dosimetry was developed. The applicability and accuracy of the new method were examined.
Methods: The dose distribution for a sixteen millimeter single-shot from a GK was built using a reference film that was calibrated using the conventional multi-film calibration (MFC) method. Another film, the test film, from a different set of films was irradiated under the same conditions as the reference film. The calibration curve for the second set of films was obtained by assigning the dose distribution of the reference film to the optical density of the test film, point by point. To assess the accuracy of this single-film calibration (SFC) method, differences between gamma index pass rates (GIPRs) were calculated.
Results: The SFC curves were successfully obtained with estimated errors of 1.46%. GIPRs obtained with the SFC method for films irradiated using a single-shot showed differences less than one percentage point when dose difference criterion (ΔD) was 2% and the distance to agreement criterion (Δd) was 1 mm. The GIPRs of the SFC method when the films were irradiated following a virtual target treatment plan were consistent with the GIPRs of the MFC method, with differences of less than 0.2 percentage points for ΔD = 1% and Δd = 1 mm.
Conclusion: The accuracy of the SFC method is comparable to that of conventional multi-film calibration method for GK film dosimetry.

Introduction

The Gamma Knife® (GK, Elekta AB, Stockholm, Sweden) is a minimally-invasive stereotactic radiosurgery (SRS) device that delivers lethal radiation to intracranial lesions by directing many collimated ^{60}Co gamma rays to a single focal point. GK treatment plans should be verified with great care because a high irradiation dose, usually between 10 Gy and 40 Gy, is delivered in a single session. Thus, accurate measurement of the absorbed dose distribution is a critical requirement and the proper calibration of radiochromic films is essential.

A conventional multi-film calibration (MFC) of radiochromic films begins with a dose rate measurement using a standard radiation detector, such as an ionization chamber, to determine the irradiation time. The films are then irradiated at several pre-selected doses. The irradiated films are scanned using a scanner, and the pixel values of the scanned images are converted into optical density values after color channel decomposition. A calibration curve is then obtained to correlate the optical density with the absorbed dose by fitting the scatter plot of the optical densities and irradiated doses.

The entire calibration process for a set of films typically requires a great deal of time, effort and care to complete because several tens of films must be evaluated. Furthermore, the entire procedure must be repeated for sets of films with different lot numbers, even if they are of the same type. Therefore, it would be desirable to develop a simple method of building a calibration curve for a new set of films using previous data without needing to repeat the entire calibration procedure. In this study, we developed and verified such a simple but novel method of film calibration for GK dosimetry using an existing calibrated film with a reference dose distribution. Once a calibration curve has been obtained for one set of films, we can

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obtain a calibration curve for another set by irradiating only a single new film under the same conditions as the reference film.

Methods

Single-film calibration method

Fig. 1a illustrates the concept of the single-film calibration (SFC) method using a reference film. Here, the 'Reference film' is a film with a given dose distribution obtained using the MFC method, and the 'Test film' is the film to be calibrated. If the two films are irradiated under identical conditions, then the dose distributions on the two films will be identical. The conditions that must be matched include the dose distribution, irradiation time, position, radiation source, and phantom shape, among others. Then, even when the two films have different optical density values at a given point ($OD_{ref}(x,y)$ and $OD_{test}(x,y)$), it is known that the two films were irradiated with the same dose at that point. Once the dose–response function of the reference film has been well defined at each point, $D_{ref}(x,y) = f_{MFC}(OD_{ref}(x,y))$, it can be assigned to the optical density of the test film at the same point, $OD_{test}(x,y)$. Using pairs of data of the form ($OD_{test}(x,y)$, $D_{ref}(x,y)$), we can generate the dose–response curve for the test film, $D_{test}(x,y) = g_{SFC}(OD_{test}(x,y))$.

Fig. 1b illustrates the procedure used to verify the accuracy of the SFC method. In this case, we have an irradiated film and two calibration curves, namely, an MFC curve and an SFC curve. We obtain two dose distributions from this single image, one by applying the MFC curve and one by applying the SFC curve. We can then calculate the gamma index pass rates (GIPR) for each dose distribution and compare them. If the GIPR values are equivalent for both dose distributions, then we can conclude that the two calibration methods are equivalent, at least for the GIPR calculation. The definition and physical meaning of the GIPR are presented in the following sections and have also been described in reference [1].

Study flow

In this section, we summarize the experimental procedures to provide a general outline of the study. The detailed information regarding each procedure is presented in the following sections. First, a set of films (Set I) was calibrated using the MFC method. A non-irradiated film from Set I was irradiated at 60 Gy using the 16 mm collimator of a GK Perfexion. The dose distribution of the reference film was constructed by applying the MFC calibration curve. This film was used as the 'reference film' in the SFC procedure. Then, a 'test film' was selected from the second set of films (Set II) and irradiated at 60 Gy under the same conditions as the reference film, such that the dose distribution of the test film would be identical to that of the reference film. The test film was calibrated by correlating the optical density distribution of the test film with the dose distribution of the reference film. The GIPR of the reference film dose distribution and the GIPR of the test film dose distribution were compared with each other to assess the validity of the SFC method.

The accuracy of the SFC method was also verified using several other sets of films. In order to reduce bias, the SFC curve calculation and the other processes such as the irradiation of films, MFC calibration, and GIPR calculations were performed at separate sites. Two sets of films, Set III and Set IV, were calibrated following the MFC method using the 16 mm collimator of a GK Perfexion at Seoul National University Hospital (SNUH), Seoul, Korea. Then, all images from the Set III films used in the MFC method and three films from Set IV, which were irradiated at 33 Gy simultaneously with the MFC procedure, were sent to the Korea Research Institute for Standards and Science (KRISS). KRISS performed its own MFC for Set III and built a reference dose distribution for the 33 Gy irradiation. By assigning this dose distribution to the three 33 Gy images in Set IV, KRISS generated an SFC curve for Set IV and sent the results to SNUH. To assess the accuracy of the SFC method, an SNUH member calculated the GIPRs of the films that were irradiated following a virtual target treatment plan using both the SNUH MFC curve and the KRISS SFC curve.

Multi-film calibration at KRISS (Set I)

GafChromic® MD-V3 films (Lot No. A03051201) were selected for use in Set I. The films were calibrated using a ^{60}Co irradiation system in the dosimetry laboratory at KRISS. Before irradiation, all films were scanned to obtain the non-irradiated film images. Individual films were irradiated at doses ranging from 5 to 60 Gy in increments of 5 Gy. Two films were irradiated at each dose, and the average optical density values were used in the MFC curve fitting. The irradiation time was determined by the dose rate, which was measured using the standard absolute dose measurement procedure at KRISS. A PTW TN31010 ionization chamber (PTW, Freiburg, Germany) and a Keithley 6517B electrometer (Keithley Instruments Inc., Cleveland, OH, USA) were used for the dose rate measurements. The calibration of the PTW 31010 was traceable to the International Bureau of Weights and Measures (BIPM). A Model 2105 precision barometer (MENSOR Corp., San Marcos, CA, USA) was used for pressure measurements, and an ASL F250 precision thermometer (Automatic Systems Laboratories, Croydon, UK) was used for temperature measurements. This barometer and thermometer are calibrated annually at the Center for Thermometry and the Center for Mass and Related Quantities, KRISS. The temperature and pressure measurements were performed simultaneously with the measurements of the ionization current and dose distribution.

The irradiated films were scanned using a commercial flatbed scanner, the EPSON Expression 10000XL (Epson America Inc., Long Beach, CA, USA), 48 hours after irradiation. The scanned image was in TIFF format, with a resolution of 300 DPI and a 48-bit color depth (16 bits/channel). Each film was scanned ten times, and the average values were used to reduce errors introduced during the scanning process. The color channels were separated using ImageJ (National Institutes of Health, USA) and the red channel was used because it exhibits the most sensitive response in terms of optical density, as indicated by the manufacturer [2,3]. The relation between the optical density and the irradiated dose was determined by fitting the data to a third-order polynomial. The dose distribution images of the irradiated films were constructed by converting the optical densities into absorbed doses using this fit curve.

Single-film calibration of Set II

To irradiate the films in a Gamma Knife, we fabricated a phantom (KRISS phantom) using PMMA (poly methyl methacrylate). It was designed to measure the dose rate and dose distribution of a GK at a water equivalent depth of 8 cm (Fig. 2). The phantom was firmly fixed to a Leksell G-frame, as shown in Fig. 2c, and its center was verified through computed tomography imaging. The phantom was installed on a GK such that the center of the phantom, and thus the center of the film, was located at the radiation center of the GK. The films were cut into an octagonal shape using a stainless steel cutting jig (60.1×60.1 mm^2) to cut them into the same shape and size. Then, the films were set into the film nest of the phantom, as illustrated in Fig. 2b. PMMA sheet spacers were used at the front and back of each film such that the film was sandwiched by the spacers and there was no air gap between the film and the nest. We marked the film, the spacer, and the film nest to keep track of the film's orientation. The films were irradiated in the xy-plane of the GK, i.e., the plane perpendicular to the craniocaudal axis.

A film from Set I (MD-V3) was irradiated to 60 Gy using the 16 mm collimator of the GK Perfexion at Yonsei University

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