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Original paper

Film-based delivery quality assurance for robotic radiosurgery: Commissioning and validation

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ABSTRACT

Purpose: Robotic radiosurgery demands comprehensive delivery quality assurance (DQA), but guidelines for commissioning of the DQA method is missing. We investigated the stability and sensitivity of our film-based DQA method with various test scenarios and routine patient plans. We also investigated the applicability of tight distance-to-agreement (DTA) Gamma-Index criteria.

Methods and material: We used radiochromic films with multichannel film dosimetry and re-calibration and our analysis was performed in four steps: 1) Film-to-plan registration, 2) Standard Gamma-Index criteria evaluation (local-pixel-dose-difference $\leq$2%, distance-to-agreement $\leq$2 mm, pass-rate $\geq$90%), 3) Dose distribution shift until maximum pass-rate (Max_{γ}) was found (shift acceptance <1 mm), and 4) Final evaluation with tight DTA criteria ($\leq$1 mm). Test scenarios consisted of purposefully introduced phantom misalignments, dose miscalibrations, and undelivered MU. Initial method evaluation was done on 30 clinical plans.

Results: Our method showed similar sensitivity compared to the standard End-2-End-Test and incorporated an estimate of global system offsets in the analysis. The simulated errors (phantom shifts, global robot misalignment, undelivered MU) were detected by our method while standard Gamma-Index criteria often did not reveal these deviations. Dose miscalibration was not detected by film alone, hence simultaneous ion-chamber measurement for film calibration is strongly recommended. 83% of the clinical patient plans were within our tight DTA tolerances.

Conclusion: Our presented methods provide additional measurements and quality references for film-based DQA enabling more sensitive error detection. We provided various test scenarios for commissioning of robotic radiosurgery DQA and demonstrated the necessity to use tight DTA criteria.

Introduction

High-dose radiosurgery demands comprehensive delivery quality assurance (DQA) for accurate treatment delivery and patient safety. Especially for frameless image-guided radiosurgery with complex systems such as the robotically steered CyberKnife® (Accuray Incorporated, USA) [1,2] accurate and sensitive methods are needed both in daily routine QA and for patient-specific DQA. CyberKnife uses registration of stereoscopic X-ray images to the planning computer tomography (CT) to locate the patient on the treatment couch. Shifts in patient position in reference to the calibrated imaging center are tracked by the robot. Inverse treatment planning is based on sequential multi-objective optimization, generally resulting in an arrangement of non-isocentric non-coplanar beams of various sizes, which generate complex dose distributions with steep dose gradients. Commissioning and

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performance testing of the CyberKnife have been widely published [3–5] and the quality assurance necessary for robotic radiosurgery was summarized in the American Association of Physicists in Medicine (AAPM) Task Group 135 report [6].

Radiochromic film measurement is the current method of choice both for routine QA as well as specific validation of patient treatment plans for the CyberKnife system [7,8]. However, to our knowledge, film dosimetry on a larger number of CyberKnife plans has never been reported. Furthermore, a meaningful analysis of any film-based DQA method with sensitivity to delivery errors and misalignments has never been performed. This is mainly due to the fact that film dosimetry has many drawbacks as the analytic accuracy strongly depends on the quality of the calibration and film scan, film and scanner inhomogeneities, and inter-scan variations between calibration and test scans [9–11]. The analysis also depends on the use of meaningful gamma criteria [12], which has not been investigated for CyberKnife DQA.

Recently developed EBT3 (Ashland Incorporated, USA) film [13] and new methods such as correction factors for the parabola effect of the scanner [14] and multichannel (red, green, blue) film dosimetry with re-calibration (film calibration at the time of DQA delivery) can reduce the uncertainties in film-based quality assurance [15,16]. Using these procedures, an improvement in error detection is likely; hence, these new methods warrant accuracy and sensitivity analysis for all radiation delivery systems [17–21]. However, due to high prescription doses, steep dose gradients, and long delivery times, their application to CyberKnife DQA is not completely straightforward and requires careful validation.

For this purpose, we sought to develop a streamlined process for CyberKnife DQA using EBT3 film with multichannel film dosimetry and re-calibration [15,16]. We then wanted to evaluate the sensitivity of our methods in different test scenarios with purposefully simulated system delivery errors and geometric misalignments in order to establish a benchmark for commissioning of film-based CyberKnife DQA similar to the work of the AAPM task group 119 for IMRT [17]. Finally, we wanted to evaluate the appropriate criteria for Gamma-Index analysis in reference to the AAPM Task Group 135 [6] and validate our proposed tolerance levels on a larger number of clinical treatment plans.

Methods and materials

Film calibration and scanning

Dose calibration of the EBT3 film was performed using a custom-made stack RW3 phantom (PTW-Freiburg, Germany) which includes gold fiducials for CyberKnife tracking and an ion chamber insert for reference dosimetry (Fig. 1). To quickly perform film calibration and avoid manual robot setup, dedicated treatment plans with various prescription doses, each with a single vertical beam (60-mm collimator) were created. To define the film calibration curve, we used six to eight dose levels (range 0–20 Gy). Film dose re-calibration [16] using three dose values, i.e. zero, median and a dose above the maximum value of the analyzed phantom plan, was performed directly after the DQA test delivery to fit the original calibration curve to additional calibration points acquired at the time of the DQA test. All films were positioned at 1.5 cm depth (D_{Max}) and simultaneous reference dose measurement using a Semiflex TM31010 ion chamber (PTW-Freiburg, Germany) was performed for all film irradiations. DQA test delivery was done on the standard CyberKnife BallCube2 Phantom (Accuray) with specially cut radiochromic EBT3 films (Ashland) orthogonally inserted into the 63.5 mm large cube (see Delivery Quality Assurance Phantoms).

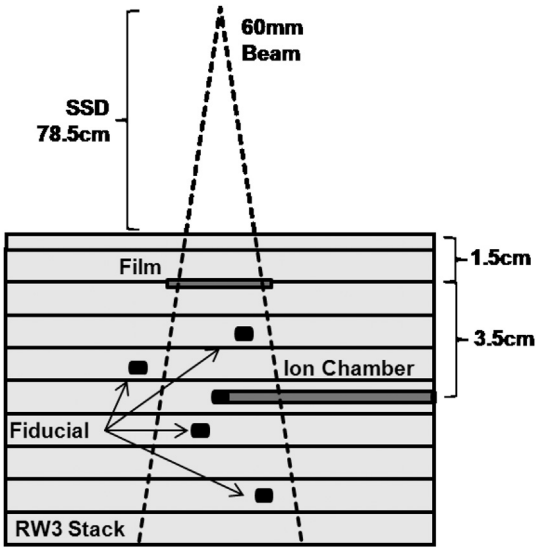

Figure 1. CyberKnife film calibration with RW3 Stack Phantom, Ion Chamber and Fiducials for Tracking. The Film is placed at D_{Max} = 1.5 cm at source axis distance (SAD) of 80 cm and simultaneous ion chamber measurement was performed at $D_{5\ cm}$, which was cross-calibrated during commissioning.

For film scanning, an Epson V700 (Epson, Japan) was used. Color scanning was performed at 48bit without color correction and with a resolution of 72 dpi. Consistency of film positioning (centered on the scanner) and orientation (landscape) was ensured, while, due to the small film dimensions (<10 cm), lateral scanning effects did not have any influence [14]. Inhomogeneity of the beam profile was accounted for by using a small region of interest (approx. $10 \times 10\ mm^2$) over the D_{Max} area of the film calibration pieces. For consistency analysis, (re)calibration and test plan films were scanned at various times after irradiation to analyze post-exposure aging of the EBT3 films, which can be up to 10% in the first 24 h. This kind of analysis has been already performed for DQA with other systems [9,10,13], but our purpose was now to investigate whether the CyberKnife's longer delivery times (generally above 30 min) would require any extra waiting time before film scanning. Films were evaluated using multichannel film dosimetry (Ashland Inc., USA) with a linear calibration function [15] and re-calibration with color scaling and dose-range stretching [16].

Gamma index analysis

Gamma index analysis was always performed using FilmQA Pro (Ashland) and a local normalization for dose difference criteria (local pixel dose difference: LPDD). The analysis was limited to isodoses above 50% following the suggestions of the AAPM TG 135 [6] and also considering that, due to the small dimensions of the CyberKnife BallCube2 films, lower isodoses are often not completely represented within the film borders. In the following, X % LPDD and Y mm distance-to-agreement (DTA) criteria will be simplified as (X%/Y mm).

Delivery quality assurance phantoms

For DQA, the BallCube2 phantom was inserted either into the head & neck phantom for intracranial targets or into the hemisphere (Accuray) for extracranial targets. The BallCube2 includes multiple fiducials for target tracking and allows orthogonal film placement in the axial and sagittal planes where each piece of film had a center slit and dedicated pin holes to fit into the phantom.