Physica Medica 32 (2016) 838–846

Contents lists available at ScienceDirect

Physica Medica

journal homepage: http://www.physicamedica.com

Original paper

High resolution ion chamber array delivery quality assurance for robotic radiosurgery: Commissioning and validation

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ARTICLE INFO

Article history:
Received 6 November 2015
Received in Revised form 22 May 2016
Accepted 23 May 2016
Available online 27 May 2016

Keywords:
Delivery quality assurance
Liquid filled MicroLion ion chamber array
Stereotactic body radiation therapy
CyberKnife robotic radiosurgery

ABSTRACT

Purpose: High precision radiosurgery demands comprehensive delivery-quality-assurance techniques. The use of a liquid-filled ion-chamber-array for robotic-radiosurgery delivery-quality-assurance was investigated and validated using several test scenarios and routine patient plans.

Methods and material: Preliminary evaluation consisted of beam profile validation and analysis of source–detector-distance and beam-incidence-angle response dependence. The delivery-quality-assurance analysis is performed in four steps: (1) Array-to-plan registration, (2) Evaluation with standard Gamma-Index criteria (local-dose-difference $\leqslant$ 2%, distance-to-agreement $\leqslant$ 2 mm, pass-rate $\geqslant$ 90%), (3) Dose profile alignment and dose distribution shift until maximum pass-rate is found, and (4) Final evaluation with 1 mm distance-to-agreement criterion. Test scenarios consisted of intended phantom misalignments, dose miscalibrations, and undelivered Monitor Units. Preliminary method validation was performed on 55 clinical plans in five institutions.

Results: The 1000SRS profile measurements showed sufficient agreement compared with a microDiamond detector for all collimator sizes. The relative response changes can be up to 2.2% per 10 cm source–detector-distance change, but remains within 1% for the clinically relevant source–detector-distance range. Planned and measured dose under different beam-incidence-angles showed deviations below 1% for angles between 0° and 80°. Small-intended errors were detected by 1 mm distance-to-agreement criterion while 2 mm criteria failed to reveal some of these deviations. All analyzed delivery-quality-assurance clinical patient plans were within our tight tolerance criteria.

Conclusion: We demonstrated that a high-resolution liquid-filled ion-chamber-array can be suitable for robotic radiosurgery delivery-quality-assurance and that small errors can be detected with tight distance-to-agreement criterion. Further improvement may come from beam specific correction for incidence angle and source–detector-distance response.

1. Introduction

Comprehensive delivery quality assurance (DQA) is required for high-dose radiosurgery to ensure accurate treatment delivery and hence patient safety. Accurate and sensitive dosimetric methods and detailed procedures are needed both in daily routine QA and

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http://dx.doi.org/10.1016/j.ejmp.2016.05.060
1120-1797/

for patient-specific DQA especially when frameless image-guided radiosurgery is delivered by complex systems such as the robotically steered CyberKnife® (Accuray Incorporated, USA) [1,2]. The CyberKnife uses registration of stereoscopic X-ray images to the planning computer tomography (CT) to locate and position the patient on the treatment couch. Patient position shifts in reference to the calibrated imaging center are tracked and corrected by the robot. Inverse treatment planning is based on sequential multi-objective optimization, which generally results in an arrangement of several non-isocentric non-coplanar beams of various sizes and source–detector-distances (SDDs) generating complex dose distributions with steep dose gradients. Commissioning and performance testing of the CyberKnife have been widely reported [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 [6,7]. The commissioning and validation for film based CyberKnife DQA using various test scenarios [7] was recently reported and results confirmed that, by means of accurate film-to-plan registration, maximum Gamma-Index pass-rate search and tight distance-to-agreement (DTA) criteria, small errors in beam delivery and system miscalibration can be detected. However, some drawbacks of film based methods applied to CyberKnife, remained unsolved: (1) absolute film dosimetry requires additional ion-chamber verification and appears to have an accuracy of no less than 3% [7] and (2) film DQA evaluation is cumbersome and requires long wait times (up to several hours) after irradiation. The generally long times required both to perform and analyze patient specific film DQA may significantly reduce the number of dosimetrically verified clinical treatment plans.

On the other hand, DQA for conventional linear accelerators with Multi Leaf Collimators (MLC) is routinely performed using two-dimensional ion-chamber or diode arrays [8–11]. However, the diode or chamber spacing of these arrays (0.5–1.0 mm) is generally too large for the small CyberKnife beams. Recently, a new high-resolution liquid-filled ion-chamber array (Octavius1000SRS, PTW, Germany) with 2.5 mm chamber spacing at the center was developed purposefully for small field radiosurgery DQA. The general dosimetric properties of the 1000SRS are promising [12,13], but specific questions regarding angular and dose-per-pulse (DPP) dependences [14] originating from small non-coplanar beams with variable SDD remain unanswered for the applicability to CyberKnife DQA. Specifically, the following questions need to be addressed before validating CyberKnife treatment plans using the 1000SRS:

(1) Is the 1000SRS chamber spacing (2.5 mm at the center) appropriately sensitive for the small field sizes of the CyberKnife (5–60 mm)?
(2) Does the DPP and thus SDD dependence of the 1000SRS influence the DQA measurements for clinical CyberKnife plans with variable SDDs (typically 80–90 cm)? Liquid filled ion-chambers are subject to much larger recombination effects [14]. Specifically, the volumetric recombination, which refers to the recombination of two ions coming from different ionization events, are dependent on dose rate and therefore on the distance of the beam source and the detector [14].
(3) Are the different incident angles of a CyberKnife plan (typically 0–110°) influencing the DQA measurements performed using the 1000SRS? Array dose responses are generally dependent on beam incidence angle, especially for lateral beams passing through multiple diodes or chambers. Various techniques such as synchronously rotating the array or using angle correction factors [15,16] have been implemented in clinical routine. However, rotating the 1000SRS synchronously with the CyberKnife is non-trivial due to the six degrees of freedom of the robot.

In this study, a streamlined CyberKnife DQA process using the Octavius 1000SRS detector was developed and evaluated. The design of the study followed the scheme we had previously implemented for film based DQA [7]. The test scenarios proposed for film dosimetry were used with minor modifications to evaluate the sensitivity of the proposed 1000SRS DQA method to system delivery errors and geometric misalignments. A benchmark will be established for commissioning liquid-filled ion-chamber array-based CyberKnife DQA and the results will be compared against the current gold standard (film). Furthermore, new tests were added to address the specific issues related to the use of the array, such as DPP and angular dependence. The appropriate criteria for Gamma-Index analysis were also evaluated in reference to our previous findings with film DQA [7] and the proposed tolerance levels were validated on a large number of clinical treatment plans in multiple institutions.

2. Methods and materials

2.1. High-resolution liquid-filled ion-chamber array

The Octavius 1000SRS detector array consists of 977 MicroLion liquid-filled ionization chambers that are arranged in a square plane. The chamber has a sensitive volume of 2 mm^3 and is filled with iso-octane having a density of 0.688 g/cm^3. The size of each detector is $2.3 \times 2.3 \times 0.5$ mm (2.65 mm^3) and the spacing in the high resolution inner area (5.5×5.5 cm^2) is 2.5 mm (center to center), whereas the spacing of the detector in low resolution outer area (up to the full 11×11 cm^2 measurement area) is 5 mm (center to center). The properties and characteristics of the 1000SRS have been thoroughly investigated for conventional linear accelerators [12,13].

2.2. Dosimetric analysis of the 1000SRS specific for CyberKnife DQA

To assess the sampling distance and resolution, the *x* and *y* profiles of the 12 collimated small circular CyberKnife beams (5, 7.5, 10, 12.5, 15, 20, 25, 30, 35, 40, 50, 60 mm) were measured with the 1000SRS and compared to profiles measured in a water phantom using a synthetic diamond detector (TM60019, PTW), which was previously evaluated and validated for accurate CyberKnife beam commissioning [17]. The TM60019 has a sensitive volume of 0.004 mm^3. The water phantom axis and the 1000SRS array were positioned along the CyberKnife robotic coordinate system. The TM60019 detector was aligned to the center of the field and positioned orthogonal to the beam direction. The *x* and *y* profiles were measured at 5 cm water depth and a source–surface-distance of 80 cm. The 1000SRS measurements were performed in water equivalent RW3 (PTW) in the same setup. The output factors measured with the 1000SRS were compared to measurements with the TM60019 and with the small field diode E (TM60017, PTW). The output factors for the TM60019 were uncorrected as the TM60019 appears to require only small corrections relative to dose in water [17] and the output factors for the TM60017 were corrected by using Monte Carlo factors according to [18].

To assess the SDD response variability the array central chamber was cross-calibrated in dose-to-water against a reference SemiFlex 0.125 cm^3 ion-chamber (PTW) using the 60 mm collimator and varying the SDD from 60 cm to 120 cm, both for the chamber and the array. The phantom build-up configurations varied