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CyberKnife® M6™: Peripheral dose evaluation for brain treatments

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ABSTRACT

Purpose: This study evaluates the peripheral dose (PD) delivered to healthy tissues for brain stereotactic radiotherapy treatments (SRT) performed with a CyberKnife M6™ Robotic Radiosurgery System and proposes a model to estimate PD before treatment.
Method: PD was measured with thermoluminescent dosimeters. Measurements were performed to evaluate the influence of distance, collimator type (fixed or Iris™) and aperture size on PD for typical brain treatment plans simulated on an anthropomorphic phantom. A model to estimate PD was defined by fitting functions to these measurements. In vivo measurements were subsequently performed on 30 patients and compared to the model-predicted PD.
Results: PD (in cGy) was about 0.06% of MU at 15 cm for a 20 mm fixed collimator and 0.04% of MU for the same aperture with Iris™ collimator. In vivo measurements showed an average thyroid dose of 55 mGy (σ = 18.8 mGy). Computed dose for thyroid, breast, umbilicus and gonads showed on average a relative difference of 3.4% with the in vivo dose (σ = 12.4%).
Conclusion: PD at the thyroid with Iris™ was about a third lower than with a fixed collimator in case of brain SRT. Despite uncertainties (use of anthropomorphic PD to estimate patient specific PD, surface PD to estimate OAR PD) the model allows PD to be estimated without in vivo measurements. This method could be used to optimise PD with different planning strategies.

1. Introduction

During radiotherapy, organs located outside the treated volume receive a fraction of the dose delivered to the target volume. Estimating this peripheral dose (PD) is important especially for healthy structures with low tolerance to radiations [1,2], for peadiatric patients [3] and pregnant women [4]. Several reports have evaluated the risk of second primary malignancies associated with radiotherapy. In 2009, Tubiana indicated that "second primary malignancies (SPM) occurring after radio-oncologic treatment have become a major concern during the past decade ... and it was found that the cumulative incidence of SPM could be as high as 20% of patients treated by radiotherapy" [5].

Stereotactic radiosurgery (SRS) and stereotactic body radiotherapy (SBRT) deliver high doses per fraction to the target volume (up to 30 Gy in a single fraction), and require a larger number of monitor units (MU) compared with conventional treatments. The corresponding PD may be a limiting parameter which generates late toxicity. Stereotactic treatment can be performed with the CyberKnife Robotic Radiosurgery System (Accuray Incorporated, Sunnyvale USA). It is equipped with a 6-MV accelerator mounted on a robotic arm designed to deliver non-isocentric non-coplanar beams arrangements under continual image guidance. Peripheral doses have been measured for the older G4 and VSI CyberKnife system versions [6,7]. Petti et al. showed that PD in the lower thorax and pelvis delivered by intracranial treatment was up to 4 or 5 times larger than for Gamma knife or co-planar IMRT treatments (with PD normalized to the number of delivered MU) [6]. Subsequently, the vendor added shielding outside the beam aperture in the primary collimator. Further studies showed PD was reduced by a factor of two for distances within 30 cm from the field edge [7,8]. The latest CyberKnife M6 system version includes a new design for the primary, secondary and tertiary collimators, and also a different range of non-coplanar beam orientations compared with older version. To our knowledge, no studies of PD with this system version have been performed previously.

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Peripheral dose is typically defined as the dose outside the therapeutic radiation beam [9] and is generated by two sources: accelerator and patient. Peripheral dose from the accelerator is composed of scatter radiation from the collimators and leakage radiation from the accelerator head. Accelerator contributions depend on the treatment plan characteristics (e.g. collimator type, aperture size, MU number, number of beams and beam orientations). Patient scattered radiation within depends primarily on distance from the target volume and morphology of the patient [10–12].

The purpose of this study was to evaluate PD to organs such as thyroid and gonads for SRS/SRT brain treatments performed with a CyberKnife M6 system by combining phantom and in vivo measurements. In addition we aimed to compare these results with those obtained using older CyberKnife versions, and to define a predictive model that would allow PD to be estimated for subsequent patient treatments.

2. Material & methods

2.1. Dosimetry protocol

Peripheral doses were measured using a batch of 75 GR 200A (LiF:Mg, Cu, P) thermoluminescent dosimeters (TLD). The useful dose range of these dosimeters was 1 μGy to 10 Gy according to the manufacturer's specifications, with several studies confirming this range [13–15]. Dosimeters were calibrated using a 6MV photon beam with $TPR_{10}^{20} = 0.678$ (Synergy, equipped with Agility multileaf collimator, Elekta AB, Stockholm, Sweden). The TLD chips were placed in an RW3 solid phantom (PTW, Freiburg, Germany) and irradiated with a nominal 100 mGy dose, at the maximum depth of 1.5 cm (SSD = 130 cm) in a 15 cm × 15 cm field. TLD were calibrated by intercomparison with a semiflex M31003 0.3 cm^3 ionization chamber (PTW, Freiburg, Germany), with individual calibration factors determined for each chip. A PCL3 automatic TLD reader (FIMEL) was used for the readout. This equipment had two isothermal heating zones, one for preheating (155 °C) and one for readout (260 °C). After 10 stabilization cycles (irradiation with calibration protocol and readout), only TLD showing reproducibility levels within ±3.5% were kept.

During dose measurements, five TLD were used to correct the measurements for background signal and five reference dosimeters (irradiated at 100 mGy) were used to correct for the daily variation of signal sensitivity.

2.2. Uncertainties

As TLD sensitivity depends on photon energy, one of the uncertainties lies in the spectral difference between calibration and measurement [15–17]. LiF TLD over-respond with low energy (+2.5% for photon under 0.1 MeV) [15]. A recent study [18] conducted for Elekta linacs with a 6 MV photon beam reported that within the beam the 0.1 MeV photon fluence represents about 2.5% of 1.5 MeV fluence (spectrum max fluence). For CyberKnife, this proportion may be about 3% [19]. As these components of low energy for Synergy and CyberKnife are very low and in the same order of magnitude, the uncertainty for TLD response variation between energy calibration and measurements within the beam was considered negligible.

Out of field radiation is known to have a softer energy spectrum than inside the primary beam, owing to the higher proportion of scattered photons [12,20]. A recent CyberKnife M6 study showed that the mean photon energy for a 5 mm beam decreases from 1.7 MeV within the beam to 1.5 MeV at an off-axis distance of 2.5x the beam radius. For a 60 mm beam the corresponding decrease is from 1.5 MeV within the beam to 0.2 MeV at 2.5x radius, indicating the higher fluence of scattered radiation generated by the larger beam [21].

Given these considerations, the uncertainty related to the TLD over-response with low energy was estimated to be up to 2% for dose measurements outside the field. Other uncertainties considered were: readout (reproducibility, repeatability and fading) (2.3%) [22,23] and calibration with ionization chamber [24] (1.8%). The global uncertainty was evaluated at 3.5% (k = 1).

2.3. Phantom measurements

Measurements were performed with a CyberKnife M6 system for simulated intracranial treatment. Treatment plans were calculated with the Multiplan v.5.1.2 treatment planning system using a Ray Tracing dose calculation algorithm. A reference treatment plan was created using a male anthropomorphic ATOM 701-c phantom (CIRS, Norfolk, Virginia, USA), using 172 non-coplanar beams focused a target in the brain centre and with 100 MU per beam (Fig. 1). Several reference treatment plans were realized, with varying collimator type and aperture diameters:

- Fixed cylindrical collimators: 5, 7.5, 10, 12.5, 20 and 60 mm
- Iris™ variable aperture collimator: 7.5 and 20 mm

Doses were measured at 24 points distributed on the median line of the phantom surface, from thyroid to gonads. The TLD were placed on a graduated pattern between 15 cm and 82.5 cm from the PTV centre. Reproducibility of TLD placement was evaluated to be about 2 mm. Ten additional TLD were inserted into the phantom: 5 in the thyroid slice and 5 in a pelvic slice, with a 0 to 15.2 cm depth range. At each point, 5 measurements were carried out for each treatment plan. The results were expressed as the average and standard deviation (SD) of these 5 measurements.

To quantify the scattering volume influence on PD, we compared measurements on anthropomorphic phantom with "in air" measurements (measured on a same sized polystyrene phantom with the same graduated pattern). As the influence of scattering volume increased with field size, we measured this component with the largest fixed collimator diameter (60 mm).

2.4. In vivo measurements

The study included 30 patients (19 men and 11 women) who underwent intracranial CyberKnife treatment. Patient

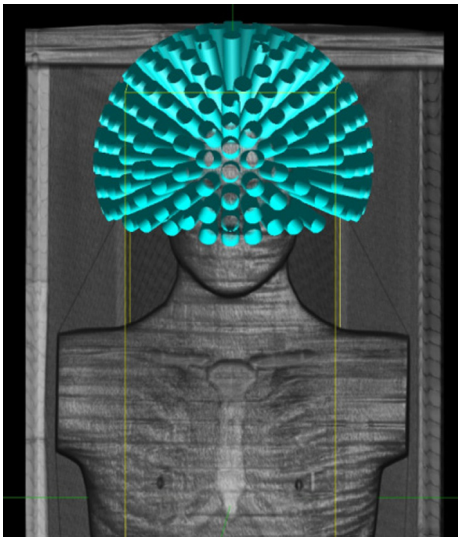

Fig. 1. Beam geometry for the reference phantom treatment plan.