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Independent dose validation system for Gamma Knife radiosurgery, using a DICOM-RT interface and Geant4

Hyun Joon Choi[a], Hyun-Tai Chung[b], Jason W. Sohn[c], Chul Hee Min[a,*]

[a] Department of Radiation Convergence Engineering, Yonsei University, Wonju, South Korea
[b] Department of Neurosurgery, Seoul National University College of Medicine, Seoul, South Korea
[c] Department of Radiation Oncology, Case Western Reserve University, Cleveland, OH, United States

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ABSTRACT

Leksell GammaPlan was specifically designed for Gamma Knife (GK) radiosurgery planning, but it has limited accuracy for estimating the dose distribution in inhomogeneous areas, such as the embolization of arteriovenous malformations. We aimed to develop an independent patient dose validation system based on a patient-specific model, constructed using a DICOM-RT interface and the Geant4 toolkit. Leksell Gamma Knife Perfexion was designed in Geant4.10.00 and includes a DICOM-RT interface. Output factors for each collimator in a sector and dose distributions in a spherical water phantom calculated using a Monte Carlo (MC) algorithm were compared with the output factors calculated by the tissue maximum ratio (TMR) 10 algorithm and dose distributions measured using film, respectively. Studies using two types of water phantom and two patient simulation cases were evaluated by comparing the dose distributions calculated by the MC, the TMR and the convolution algorithms. The water phantom studies showed that if the beam size is small and the target is located in heterogeneous media, the dose difference could be up to 11%. In the two patient simulations, the TMR algorithm overestimated the dose by about 4% of the maximum dose if a complex and large bony structure was located on the beam path, whereas the convolution algorithm showed similar results to those of the MC algorithm. This study demonstrated that the in-house system could accurately verify the patient dose based on full MC simulation and so would be useful for patient cases where the dose differences are suspected.

1. Introduction

Gamma Knife (GK) radiosurgery is used to treat small intracranial lesions by focusing hundreds of small gamma beams on the target area [1]. It is recognised to offer high-precision radiotherapy with accuracy better than 0.3 mm [2–4]. Leksell GammaPlan software (Elekta Instrument AB, Stockholm, Sweden) is specifically designed for the treatment planning of stereotactic GK radiosurgery in clinical practice, predicting patient dose distributions using fast mathematical algorithms [5,6], including the tissue maximum ratio (TMR 10) and convolution algorithms [6]. TMR 10 is a water-based dose calculation algorithm based on the assumption that the patient's head solely comprises homogeneous water-equivalent materials, without taking into consideration materials with different electron densities, such as bone structures and air cavities in the skull. The magnetic resonance images usually used with TMR 10 do not provide information about bone structures, so the skull shape has to be defined manually using a ruler that measures the distance to the scalp. In addition, patient information can be lost due to image distortion caused by the presence of paramagnetic or ferromagnetic materials. For these reasons, a convolution algorithm for dose calculation based on CT images has recently been developed and included in GammaPlan software version 10 [6]. This convolution algorithm takes account of electron density differences and provides a more accurate dose prediction than the TMR algorithm. For example, Rojas-Villabon et al. reported that the patient dose calculated using the convolution algorithm was about 7% lower than that calculated with the TMR algorithm and that there was a 6% difference in the beam on time (BOT) in ipsilateral cochlea treatment cases [6]. However, the accuracy of patient dose calculations made by this semi-empirical and simplistic algorithm can be limited in some special cases, such as the embolization of arteriovenous malformations [7] and lesions near air cavities. This is because an inaccurate assumption of the scatter radiation at the interface between two materials with significantly different densities can increase dose uncertainty, especially if the beam size is very small [8,9].

The Monte Carlo (MC) method has been used as the 'gold standard' for radiotherapy treatment planning [10–19]. Many groups have used the MC method to calculate standard dosimetric parameters as an

* Corresponding author.
E-mail address: chmin@yonsei.ac.kr (C.H. Min).

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alternative to small field dosimetry, which has physical limitations such as a lack of electronic equilibrium [20–22]. When applying MC simulation to GK modelling, Battistoni et al., Best and Pipek et al. used FLUKA, PENELOPE, and Geant4, respectively, while focusing on detailed source modelling of the GK [23–25]. Recently, Yuan and Machtay presented a methodology for the clinical application of a GK MC model to patient dose validation; this used a virtual source model based on film measurement [26]. Their study using a heterogeneous phantom composed of multilayer materials showed that there was still a discrepancy of up to 10.7% between the target doses calculated by the MC and convolution methods [26].

Among the many MC packages available, Geant4 has been shown to be applicable to diverse fields of research and to provide effective dose evaluation using computational human phantoms based on a tetrahedral mesh and DNA strand damage simulation [27–29]. In particular, Geant4 is capable of four-dimensional simulations including the dynamic motion of a multi-leaf collimator (MLC), the patient's respiratory movement and moving scanners [30,31].

The aim of this study was to develop an independent patient dose validation system using a DICOM-RT interface based on Geant4. Here, we describe the methodology of GK modelling, MC commissioning, patient model construction, dose scaling factor calculation and patient dose calculation, as well as a dose comparison with the commercial treatment planning systems (TPSs).

2. Materials and methods

2.1. Source modelling

Leksell Gamma Knife Perfexion (LGK-PFX) was modelled using Geant4.10.00 based on the manufacturer's information of 72 sources and beam channels (Fig. 1). The LGK-PFX model comprises 576 channels with beam sizes of 4, 8 and 16 mm. Eight sectors consisting of 24 channels move independently to open or close beam channels to achieve the pre-planned beam size. Each channel is designed as five layers with different hole sizes to control beam divergence. To reduce the computational burden, 1.17 and 1.33 MeV gamma radiation beams biased at an angle of 10 degrees relative to the direction of the beam were generated from the cylindrical volume of the cobalt-60 source. Phase space files of particle information (position, direction, kinetic energy and particle type) were recorded on the surface of a very thin spherical cap near the exit of the channels. Having a phase space file for every beam size allows a reduction in the time to calculate dose distributions through eliminating the calculation time related to particle transport in the LGK-PFX model. The number of primary particles per channel was 10^8; this ensured the recorded number was greater than 10^8 to take account of statistical error in the simulation, and it facilitated the determination of a dose scaling factor based on the relationship between the dose and the number of primary particles used for the simulation. The final numbers of particles recorded in the phase space file for beam sizes of 4, 8 and 16 mm were 1.5×10^8, 5.1×10^8 and 1.8×10^9, respectively. The 24 cobalt-60 sources in each sector were arranged in five rings with a different number in each ring. The manufacturer provides 15 dose profiles for the TMR 10 algorithm unique to each ring. To validate the LGK-PFX geometrical model, the output factors from these 15 dose profiles were compared with those calculated using our system. The output was determined at the central region of the dose profile. The dose distributions were calculated in a spherical water phantom 16 cm in diameter, with a grid resolution of $0.5 \times 0.5 \times 0.5\ \mathrm{mm}^3$.

2.2. Development of the DICOM-RT interface

MC simulations for patient-specific radiotherapy plans should consider the many patient-dependent parameters, such as the patient model, the special volume control, the many isocenters and different beam size settings for the eight sectors. A DICOM-RT interface is therefore essential for the clinical application of MC simulation while reducing or even eliminating transcription errors in setting each parameter. There are four types of DICOM files for radiotherapy planning: CT images, radiotherapy (RT) structures, RT plans and RT doses. The DICOM example using Geant4 provides methods for constructing a patient model from CT images and using this to calculate the dose distribution. However, this example is unable to access other types of DICOM files than CT images and it does not provide a user-friendly interface.

We developed an algorithm for extracting patient-specific parameters stored in RT plan files, modelling special volumes using contour data stored in RT structure files, generating sources from pre-recorded phase space files and setting the position and rotation of patient models. Fig. 2 illustrates the patient dose validation process using this system. The system constructs a patient model based on CT images using the G4PVReplica class. A lookup table for converting Hounsfield units (HU) into electron densities (EDs) is used to assign the appropriate material EDs to each voxel of the patient model. A mass density and an elemental composition are then determined using the conversion method proposed by Schneider et al. [32]. If there is a special volume that has to be considered in dose calculation, the system allows this volume to be virtually constructed from the contour data and the physical property information stored in the RT structure file. The RT file provides the beam conditions, including the isocenter, BOT and dose rate; however, it does not include sector-by-sector beam size data. We therefore added

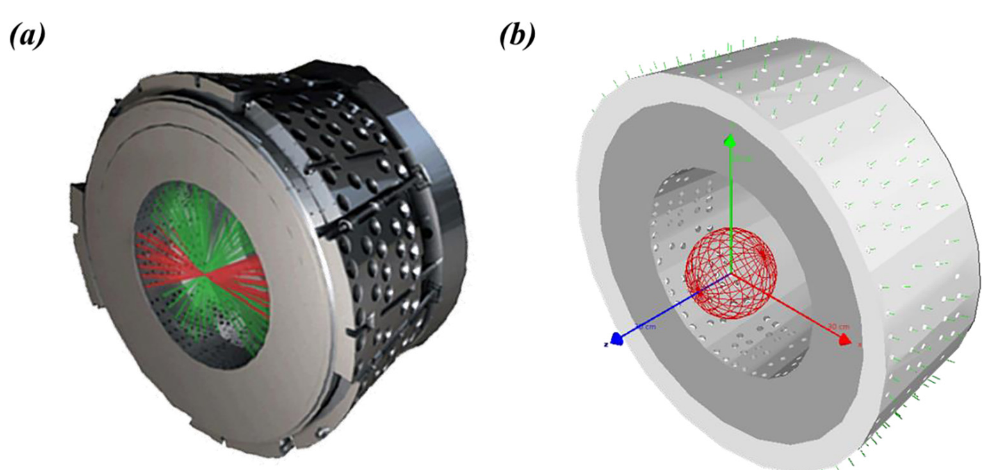

Fig. 1. a) The Elekta LGK-PFX. b) The LGK-PFX modelled in Geant4.