Intensity-modulated arc therapy using the GATE Monte Carlo simulation platform in a grid environment.

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Introduction

Radiation therapy is constantly improved by new complex delivery techniques such as intensity-modulated arc therapy (IMAT).[1] Advanced innovations including the use of multileaf collimator (MLC) to characterize small radiation fields (< 3x3 cm^2)[2, 3] requires an accurate validation of dose calculations against measurements[4, 5]. Because the physics of small radiation fields differs from larger fields, measurements are more sensitive to the properties of the radiation detectors used. Some papers[6, 7] have reported that diodes are the best detector to use and studies[8, 9] have shown good agreement between Monte Carlo (MC) calculations and dose measurements with diodes.

MC modeling of linear accelerators is well established[10, 11, 12, 13, 14, 15], allowing users to define the exact geometry, composition and position of the various components in order to have an accurate MC model[16]. To estimate the incident electron beam energy and radial intensity distribution, depth-dose and profiles curves are compared with experimental measurements.

Due to their complex design, the MLC5 [17, 18, 19, 20] are among the most challenging geometrical structures to implement in a linac model to perform MC simulations. Modeling the details of the MLC using MC methods is considered of primordial importance to fully account for various features which have a significant impact on the penumbra and ultimately on patient dose calculations[5].

Based on the Geant4 (Geometry and Tracking) Monte Carlo toolkit[21], the GATE platform (www.opengatecollaboration.org)[22, 23] offers the possibility to a large community of users (~3500 users) to perform simulations in medical imaging and radiotherapy. Since the GATE v6.0 release, new tools and modalities are proposed for dosimetry, including features to make possible the simulation of intensity-modulated radiation therapy treatment[22]. Some studies[24, 25, 26] have already demonstrated the feasibility of modeling a linear accelerator with GATE v6. However, the majority of small-field dosimetric papers is almost universally conducted at 6 MV[17, 18, 19, 27, 28, 29]. The MC methods have demonstrated their ability to accurately perform dose calculations for radiation therapy applications, especially for IMAT [2, 16, 17, 29, 30, 31, 32, 33, 34] but they remain time consuming compared to analytic treatment planning systems[35, 36]. To overcome this problem, the openGATE collaboration proposes a distributed computing facility to execute GATE simulations on a grid infrastructure, the GATELab web platform which offers a user friendly application that can reduce by a factor 50[36] the computing time of simulations.

This present work focuses on the validation of the GATE 6.2 platform for IMAT, considering complex field shape configurations obtained using the MLC. To reach this objective, a complete modeling of Novalis Tx linear accelerator (6MV and 15MV photon modes) is necessary. A first validation has been performed in liquid water by comparing dose measurements with diodes and calculations. In a second stage, the MLC geometry implementation enabled the simulation of realistic treatment plans (head-and-neck patient IMAT plans) compared with iPlan (Brainlab clinical treatment planning software) calculations.

Material & Methods

The first stage was to model the Novalis Tx head in 6 and 15 MV modes with the GATE MC platform. All the head characteristics of this linac, in terms of shape, dimensions, density and material, were defined using the manufacturer data (Figure 1: Head geometry of the Novalis Tx on GATE). Some geometry remains complex to model as for the flattening filter where 13 cones are needed (Figure 2). The most important components of the linac are the target and flattening filter which the geometry and composition strongly influence the accuracy of the model together with the initial electron beam. These elements are adjusted in order to fit simulation calculations with dose measurements. The energy is determined by the matching of calculated and measured depth doses while the determination of electron radial intensity is done by matching calculated and measured cross-field profiles of large field 10x10cm². The reference measurements are performed in the PTW MP3 water tank at a 100 cm source surface distance for several field sizes ranging from 1×1 to 10×10 cm². A waterproof LA48 LINEAR chamber ARRAY was placed at 10 cm depth for dose profiles and a PTW 31013 Semiflex ionization chamber was used for depth dose for fields of 4x4 and 10x10cm². For the smaller fields, measurements were performed with a PTW 60012 Diode E coupled to a TANDEM electrometer.

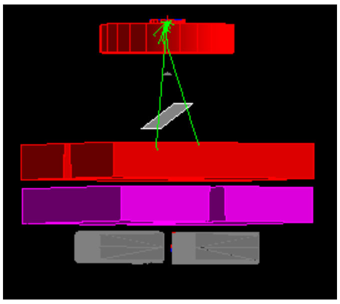


Figure 1: Head geometry of the Novalis Tx on GATE

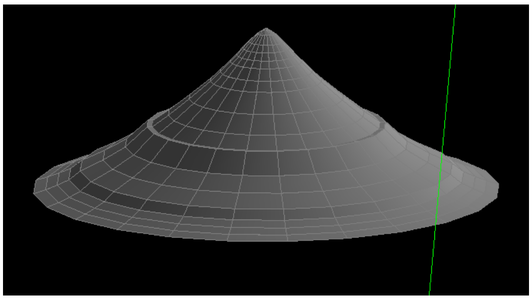


Figure 2: Flattening filter modeling

In a second stage, the MLC geometry implementation enabled the simulation of clinical IMAT treatment plans compared with the iPlan (BrainLab) treatment planning software (TPS) calculations. The strategy to fully model the MLC consists in dividing the leaves into geometrical regions. MLC positions for each segment of each beam of head-and-neck IMAT treatment plans were obtained from iPlan and adapted to allow GATE simulation.

In order to reduce the computing time of GATE calculations, the simulations are executed on a distributed infrastructure using the GATElab (http://vip.creatis.insa-lyon.fr/) platform. The application is parallelized automatically and a dynamic partitioning can also be used for further reducing the execution time and improving the robustness to job failures.

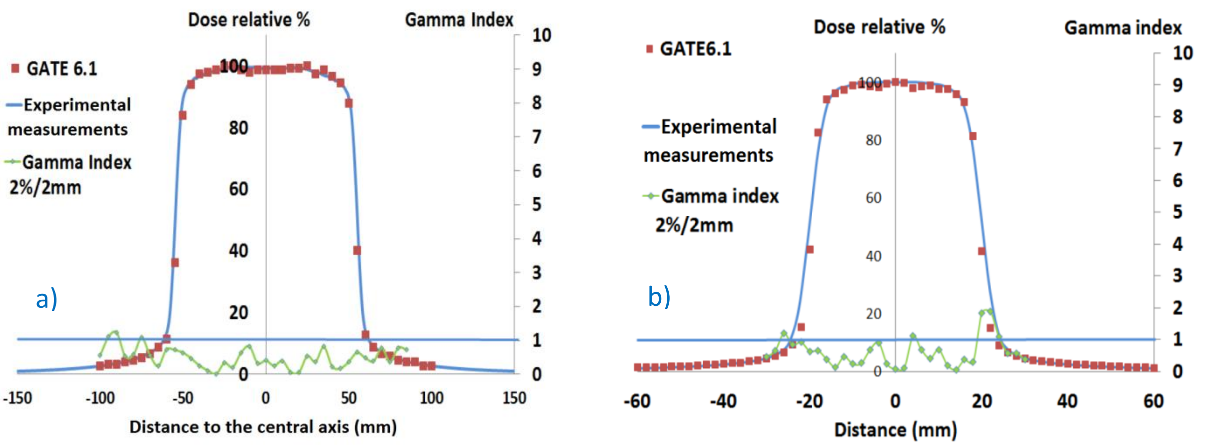
Results

1) Comparison between GATE v6 and measurements in a water phantom

An electron spot with full width at half maximum (FWHM) of 0.05 cm and a mean energy of 7.2 MeV was found to fit measurements in 6MV photon mode. The conditions of simulations for the various fields are described in Table 1: Conditions of the simulation in 6MV.

Photon energy	6 MV			
Field size	10x10 cm²	4x4 cm²	2x2 cm²	1x1 cm²
Number of primaries	5.10^8 electrons	1.10^9 electrons	1.10^9 electrons	2.10^9 electrons
Uncertainty	< 1%			
Voxels size	5x5x5 mm^3	2x2x5 mm^3	2x2x5 mm^3	1x1x5 mm^3
Gamma index	92% of points < 1	89% of points < 1 for profiles 100% of points <1 for PDD	80% of points < 1	
Detector	Ionization chamber with a volume of 0.125 cm^3		Diode E with a volume of 0.03 mm^3	
Electron source	E = 7.2 MeV and FWMH = 0.05 cm			

Table 1: Conditions of the simulation in 6MV



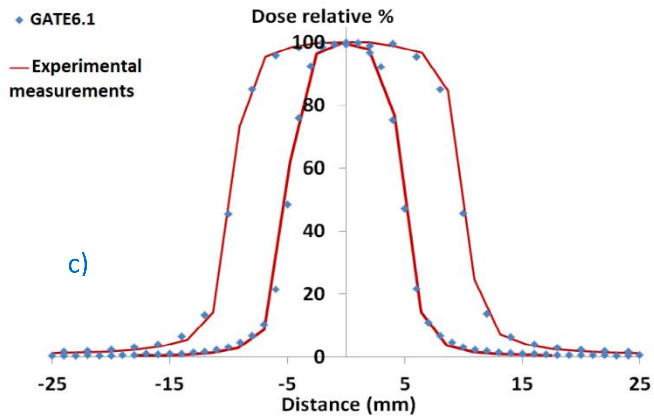


Figure 3: Results of the comparison between GATE.v6 calculations and measurements in 6 MV, a) 10x10 cm² field size, b) 4x4 cm² field sizes, c) 2x2 and 1x1 cm² field size

We show a good agreement between measurements and simulated depth dose profiles in liquid water for the fields size ranging from 1x1 to 10x10 cm² and a good respect of the gamma index of 2%/mm (Figure 3: Results of the comparison between GATE.v6 calculations and measurements in 6 MV, a) 10x10 cm² field size, b) 4x4 cm² field sizes, c) 2x2 and 1x1 cm² field size.

2) Comparison between GATE v6 and iPlan

An intracranial treatment plan was studied for the comparison between GATE and iPlan in presence of heterogeneity which is the ethmoid in this case. The characteristics of the simulation are described in the Table 2: Characteristics of the simulation of an intracranial treatment plan and the details of the treatment are shown in the Figure 4: Comparison between iPlan and GATE.

Photon energy	Field size	Number of primaries	Uncertainty	Voxels size	TPS / algorithm	Electron source
6 MV	1x1 cm²	$2,5.10^9$ electrons	< 1%	1x1x2 mm^3	Isogray / Pencil Beam	E = 7.2 MeV FWMH=0.05 cm

Table 2: Characteristics of the simulation of an intracranial treatment plan

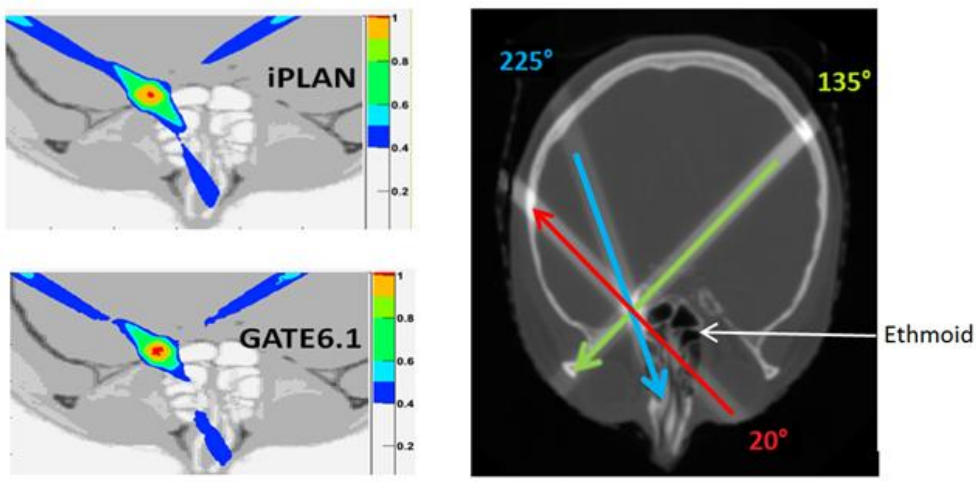


Figure 4: Comparison between iPlan and GATE

GATE and iPlan normalized treatment plans were compared using a gamma index of ±2%/mm. The ongoing work concerning treatment plan comparisons demonstrates limits of the iPlan Pencil Beam algorithm close to heterogeneities. Indeed, the Figure 5: Dose profile for beam at 135°
Figure 6: Dose profile for beam at 225° reveals a strong divergence between GATE and iPlan in the cavities of the ethmoid. However, good agreement is shown in zones of homogeneity (Figure 5: Dose profile for beam at 135° Figure 6: Dose profile for beam at 225°).

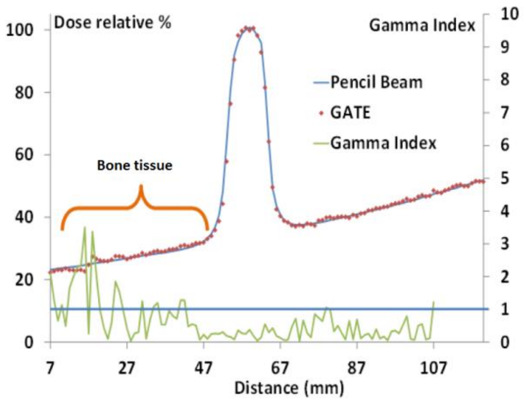


Figure 5: Dose profile for beam at 135°

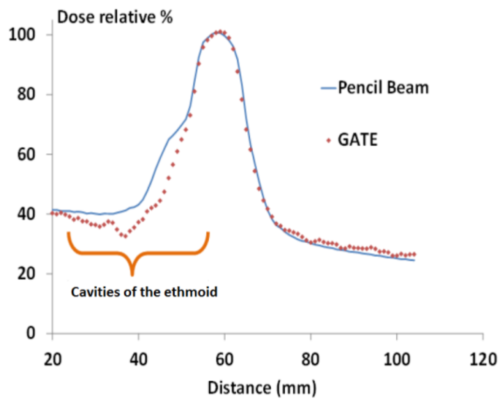


Figure 6: Dose profile for beam at 225°

Using the GATElab distributed infrastructure, outputs were produced in 14 hours for one billion primary photons generated reaching a gain of a factor 50 comparing to calculations performed on a single CPU.

Conclusions

This study demonstrates that GATE offers efficient tools to make possible IMAT applications. The accurate GATE modeling of the incident electron beam parameters and the head geometry of a Novalis Tx is particularly important for accurate dosimetry of MLC-shaped fields and small fields, especially to simulate IMAT treatments. In a subsequent work a micro-dosimetry study should be performed for a complete validation.

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