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A GATE/Geant4 Monte Carlo toolkit for surface dose calculation in VMAT breast cancer radiotherapy

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ABSTRACT

The accuracy of superficial dose calculations for breast cancer treatments with Volumetric Modulated Arc Therapy (VMAT) is of major importance. For target volumes close to the surface, the inverse dosimetric planning can lead to very high fluences in the build-up region to properly cover the volume to be treated. Various radiotherapy modalities are currently used in parallel with additional protocols to enable a better control on the dose delivery (bolus, target volume margins). One of the difficulties currently facing medical physicists is the lack of available tools to test the impact of these different solutions on the superficial dose distribution. We present a new open source toolkit to assist medical physicists in evaluating the 3D distributions of superficial dose in VMAT breast cancer treatments. This tool is based on the GATE Monte Carlo software, a Geant4 application dedicated to medical physics. A set of macros has been developed to simulate in an easy way a full VMAT plan from the information available in the DICOM-RT files (image, plan, structure and dose). The toolkit has been tested on a 6 MV Varian NovalisTx™ accelerator. The paper presents a precise comparison of 3D surface dose distributions from experimental measurements (EBT3 films), TPS (Varian Eclipse) and Monte Carlo simulation (GATE). The comparison made it possible to highlight both the TPS biases for the surface dose calculation and the good performances of the developed toolkit. The simulation of surface dose distributions on a real patient has also been performed to illustrate the potential clinical applications.

1. Introduction

Breast cancer is the most common cancer among women in France, with about 50,000 new cases and 12,000 deaths per year [1]. About 85% of patients are currently treated with radiotherapy. The reference technique is the 3D conformational radiotherapy (3D-CRT). This technique is nowadays well controlled, but the complex geometry specific to breast cancer often involves ballistic radiation fields with several junction areas. These areas may be difficult to manage because of the presence of under- and/or over- dosing regions within the target volumes. On the other hand, the doses delivered to the organs at risk (mainly the heart and the ipsilateral lung) can be relatively important [2]. For some complex cases, such as cancers with many positive nodes, breast and ganglionic treatments are more and more performed by rotational intensity modulated radiation therapy (IMRT), such as Volumetric Modulated Arc Therapy (VMAT) [3,4] or Tomotherapy [5,6]. These techniques theoretically reduce the dose to organs at risk, while ensuring better coverage of target volumes [7–9]. The advantages of rotational IMRT compared to 3D-CRT in the context of node-positive breast cancer, however, raises several questions with regard to doses delivered to contralateral organs and the impact of anatomical variations during treatment on the superficial dose distribution. A significant number of patients still suffer of burn side effects after their treatment. In breast radiotherapy, a large part of the target volume is indeed close to the surface of the patient. As a result, reactions to the skin and subcutaneous tissues are still the most common acute toxicities in breast radiotherapy [10].

The difficulties of calculating the dose distribution in the high gradient part of the build-up region, generally defined as the firsts 2–3 mm of tissues and called superficial or surface dose, have several origins: the lack of precision of the treatment planning systems (TPS) at the air-tissues interface, the strong dose gradient of the build-up region, and the unavoidable changes in patient geometry during the treatment (breathing, inflate of the breast between fractions) [11–14]. The inaccuracy of the TPS for superficial dose computation has almost no significant clinical impact in 3D-CRT, where treatment planning is

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straightforward. But for rotational IMRT, which relies on inverse dosimetric planning, this is quite more problematic. For target volumes close to the surface, the TPS can calculate very high fluences in the build-up region to properly cover the volume to be treated. Due to the high dose gradient and the large TPS uncertainties in this region, this can lead to important dose deposition in the first few millimeters of tissues.

There are already many scientific publications on the issue of surface dose in breast cancer radiotherapy, both with experimental measurements [15,16] and Monte Carlo simulation [17–19]. But there are still few practical solutions to guide the medical physicists in planning breast cancer treatments with rotational IMRT techniques. Nowadays each radiotherapy center has developed its own protocol to limit the possible side effects of an inaccurate estimate of the surface dose. Among these protocols, the most common are the modification of the patient target volume (PTV) margins (skin-to-PTV subtraction margins), the use of a water-equivalent bolus for the TPS optimization and during the treatment so that the skin is not located in the build-up zone, or the use of a "virtual" bolus only for the optimization stage (not during the irradiation). The main difficulty currently facing medical physicists is the lack of available tools to test the impact of these different solutions on the superficial dose distribution for a given patient. This is the purpose of the Monte Carlo toolkit described in this article. We present a new open source tool developed in collaboration between the Institut Pluridisciplinaire Hubert Curien (IPHC – Strasbourg) and the Paul Strauss Center (CPS – Strasbourg) to evaluate the 3D distribution of superficial dose in VMAT breast cancer treatments. This tool is based on the GATE Monte Carlo software [20], a Geant4 [21] application dedicated to medical physics. A set of macros has been developed to simulate in an easy way a full VMAT treatment plan from the information available in the DICOM-RT files (image, plan, structure, dose). The toolkit has been tested on a 6 MV Varian NovalisTx™ accelerator, using the Eclipse TPS with AAA algorithm v11. The paper presents a precise comparison of 3D surface dose distributions from experimental measurements (EBT3 gafchromic films), TPS and Monte Carlo simulation. The comparison made it possible to highlight both the TPS uncertainties for the surface dose calculation and the performances of the developed Monte Carlo toolkit. The surface dose distributions of three different VMAT plans on a real patient have also been compared to illustrate potential clinical applications.

2. Material and method

2.1. 6 MV Varian Novalis Tx™

A 6 MV Varian NovalisTx™ linear accelerator was modeled with the GATE Monte Carlo software (version 8.0). Unlike the newer versions of the Novalis accelerator (Novalis TrueBeam™), Varian does not provide phase spaces of the photon beam for this model. It was therefore necessary to perform a full modeling of the accelerator head starting from the electron beam and including the target, the primary collimator, the flattening filter, the jaws and the multi-leaf collimator (MLC). The characteristics of each piece, i.e. spatial dimension and materials composition, were precisely implemented following the manufacturer information (Monte Carlo Data Package: High Energy Accelerator, DWG NO. 100040466-02).

The Monte Carlo simulation of linear accelerator (LINAC) for radiotherapy is a well-known process since more than a decade [22,23]. Following the scientific literature, the general modeling of the Varian NovalisTx™ was validated using photon dose measurements. A PTW Semiflex 31010 ion chamber (sensitive volume of 0.125 cm^3) was used to measure the percentage depth dose (PDD) and the lateral dose profile (at 20 mm, 50 mm and 100 mm) in a water tank. The measurements were done with a Source Surface Distance (SSD) of 100 cm and a $10 \times 10\ cm^2$ field (corresponding to the most common field size for breast cancer radiotherapy) with a full opening MLC [24]. The PDD and the dose profiles were only used as a first step of the validation of VMAT simulation in order to check the general LINAC geometry and to define the optimal electron beam parameters (E = 6.0 MeV, FWHM = 1.0 mm).

2.2. VMAT treatment plan

A precise description of the Varian 120 HD multi-leaf collimator [25,26] was then implemented to reproduce as precisely as possible the experimental 3D dose distributions from VMAT plans that require movings of both the accelerator head and the MLC. The Eclipse AAA treatment planing system was used to generate DICOM-RT Plan files that contain for each control point the angulation of the accelerator head, the position of the 120 leaves and the corresponding dose fraction. A set of macros, based on the Python module PYDICOM [27], has been developed to extract the useful information from DICOM-RT Plan and transform them into a GATE software format.

For the validation step, PMMA cubic phantoms of various dimensions were used and implemented manually into the GATE software. For the application on real patient, the patient geometry was obtained from the DICOM-RT Image. A calibration curve is used in the GATE software to convert CT image into numerical phantom by attributing to each Hounsfield Unit (HU) value a given material composition and density [28]. In case of use during the irradiation, the bolus geometry can be extracted from a DICOM-RT Structure file and combined to the CT image of the patient.

By providing the DICOM-RT files (image, plan, structure), the toolkit is able to automatically produce a GATE Monte Carlo simulation of a full VMAT treatment with the corresponding 3D dose distribution. Dose maps were reconstructed using the GATE software capabilities of producing voxelized dose distributions with pre-defined resolution. The user can choose the simulation statistic (total number of primary particles) and the spatial resolution of the dose map depending on the expected dose uncertainty per voxel. Some Python macros are provided for dose maps analysis (PDD, dose profiles, …). The toolkit also enables statistical comparison, resampling and normalization options between Monte Carlo and TPS dose maps if a DICOM-RT Dose file is provided. The schematic view of the toolkit is presented on Fig. 1.

2.3. Experimental dose measurements

For the validation of the toolkit, various dose distributions in PMMA cubic phantoms were measured using EBT3 gafchromic films. The EBT3 film allows a dose measurement ranging from 0.1 cGy to 10 Gy. The original size of a film is $20.32 \times 25.4\ cm^2$. An EPSON 10000 XL multichannel color scanner (16 bits per channel (RGB)) was used for the digitization.

To obtain a precise superficial depth dose distribution, film measurements were carried out in a stack of RW3 plates (water equivalent material, PTW type 29672) of dimensions $300 \times 300\ mm^2$ with thicknesses of 1 mm, 5 mm and 10 mm. The chemical composition of RW3 is mainly polystyrene (C_8H_8) with 2% (± 0.4%) of TiO_2 in mass fraction. The calibration factor between the dose in RW3 and the dose in water varies with depth, so we used the triple-channel dosimetry method described by D. Lewis et al. and published by the AAPM in 2015 [29,30]. In order to assess the reliability and the accuracy of the full measurement process, a number of tests have been carried out. At the scanner level: uniformity, heating time, stabilization of the lamp. At the digitization level: orientation of the film. At the film level: uniformity, repeatability, stability, orientation, reading time. All the tests carried out make it possible to estimate an overall uncertainty of the measurement chain of 2.8%. Therefore a statistical uncertainty around 2–3% on the dose calculation was also targeted in the Monte Carlo simulation.

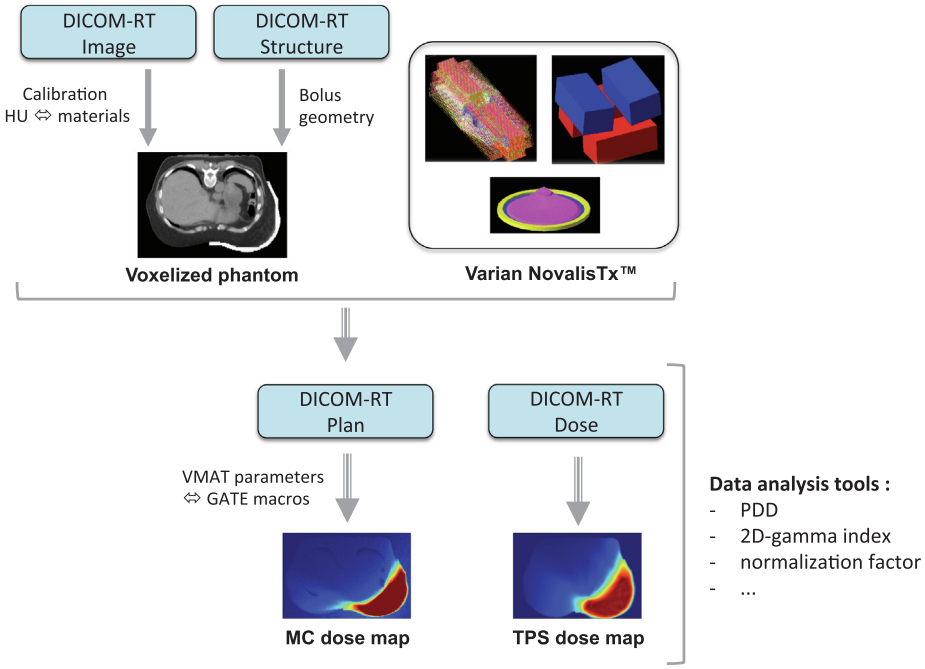


Fig. 1. Schematic view of the Monte Carlo toolkit detailed throughout Section 2.2.

3. Results

3.1. VMAT Monte Carlo simulation

In order to validate the general behavior of the toolkit, experimental and simulated 3D dose distributions were compared for a typical VMAT plan used by the medical physicists for monthly controls of the Novalis accelerator. The VMAT plan contained 180 control points. The experimental measurements were done in a $30 \times 30 \times 10\,cm^3$ PMMA phantom (build from 10 mm RW3 plates). EBT3 gafchromic films were placed at 150 mm depth in the Y axis of the phantom, in order to reconstruct a 2D depth dose distribution. The irradiations corresponded to a fixed $15 \times 15\,cm^2$ field (with SSD = 95 cm). The simulated dose map was produced with 500×10^9 electrons with a resolution of $5 \times 0.5 \times 5\,mm^3$. The voxel resolution was selected in order to get a precise depth dose distribution (Y axis) with a mean statistical uncertainty of around 2% per voxel. For comparison, the two dose maps were normalized by the mean dose value in the slice, and the experimental dose map was resampled to the MC dose map resolution (Fig. 2). 2D-gamma index [31] was used to validate the simulated spatial dose distribution with respect to the experimental data. The gamma index is a common metric for VMAT radiotherapy that enables to compare dose maps by taking into account both the dose discrepancies and spatial shifts. At the Paul Strauss Center, medical physicists consider that a treatment plan is validated if the gamma score is higher than 90% for a dose criterium of 3% and a spatial criterium of 3 mm. The gamma scores computed in global analysis from the dose maps presented in Fig. 2 were respectively 94% and 90% for 4%/3 mm and 3%/3 mm criteria.

3.2. Surface dose: percentage depth dose (PDD)

After the validation of the toolkit with a VMAT plan simulation, a more detailed study was done on the surface dose distribution. The goal of this study was to compare the dose maps computed by the Eclipse AAA TPS and the GATE Monte Carlo toolkit with experimental film measurements in the range [0–5] mm. The first test used fixed $10 \times 10\,cm^2$ 6 MV photon fields (SSD = 100 cm) on a $30 \times 30 \times 20\,cm^3$ PMMA phantom. $2 \times 2\,cm^2$ EBT3 films were placed at 0, 1, 2, 3, 4, 5, 20 and 50 mm in depth. 5 measurements were performed for each depth to compute the mean dose value and its related uncertainty (standard error of mean). The TPS dose map was computed

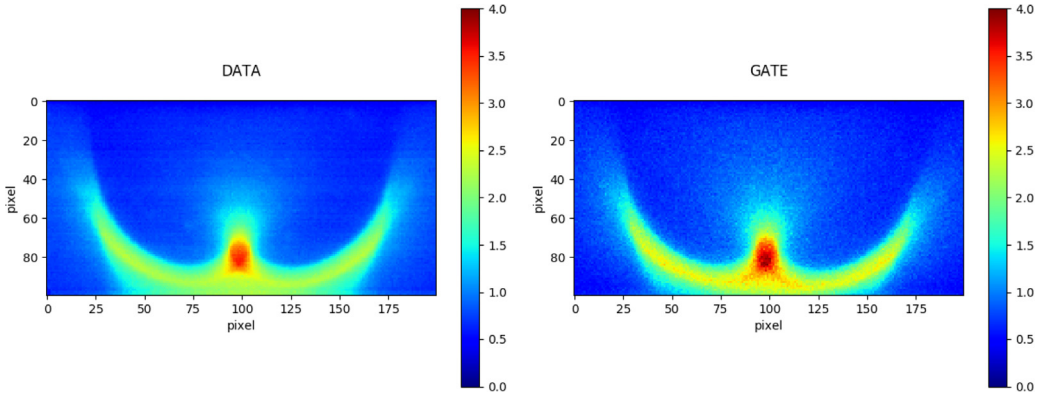


Fig. 2. Experimental (EBT3 gafchromic film - left) and simulated (GATE – right) dose maps of a VMAT plan. Dose maps are normalized by the mean dose value of the slice.

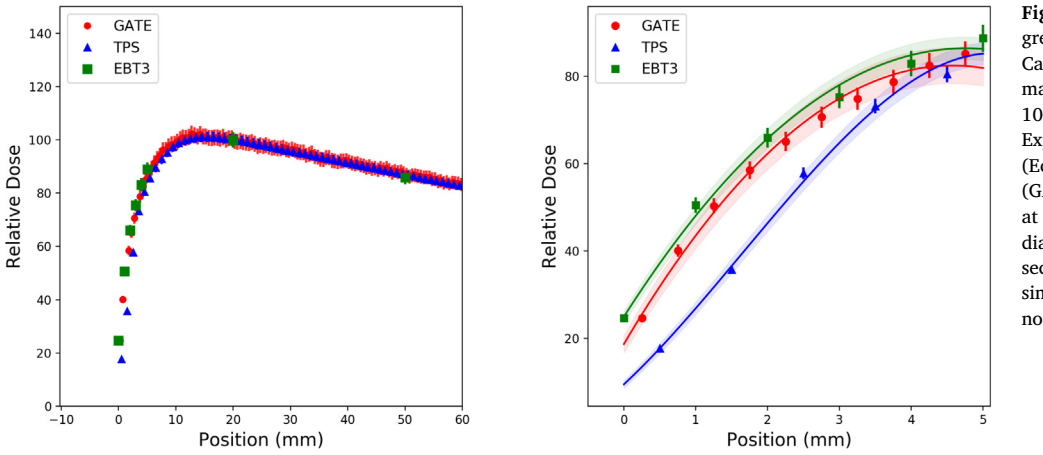


Fig. 3. Left: Experimental (EBT3 films – green), TPS (Eclipse AAA – blue) and Monte Carlo (GATE – red) dose distributions, normalized at 20 mm in depth, for a $10 \times 10\,cm^2$ irradiation field; Right: Experimental (EBT3 films - green), TPS (Eclipse AAA – blue) and Monte Carlo (GATE – red) dose distributions, normalized at 20 mm in depth, for a $10 \times 10\,cm^2$ irradiation field. Dose values are fitted with a second order (experimental data and GATE simulation) and third order (TPS) polynomial functions in the range [0,5] mm.

using a $1 \times 1 \times 1\,mm^3$ resolution. For the GATE simulation, 60×10^9 electrons were simulated to reach a mean statistical uncertainty of about 3% per voxel with a $5 \times 5 \times 0.5\,mm^3$ resolution. Fig. 3 (left) shows the percentage depth dose distributions normalized by the dose value at 20 mm in depth. A deep dose value was chosen for the normalization in order to compare how the various dose distributions evolve at the surface of the phantom for a given dose delivered deeper.

Doses values were not available at the same positions due to the difference between the EBT3 film thickness (28 μm active layer) and the resolution of the TPS (1 mm) and GATE (0.5 mm) dose maps. To facilitate the comparison, the dose distributions were fitted using second order (experimental data and GATE simulation) and third order (TPS) polynomial functions. The obtained functions are shown on Fig. 3 (right), with a mean discrepancy of 7% for GATE and 25% for the TPS (respectively 24% and 62% for the maximal discrepancy) compared to the experimental data in the range [0–5] mm.

3.3. Surface dose: IMRT plans

A more advanced analysis of the surface dose distribution was performed using a static IMRT irradiation plan on a $20 \times 20 \times 20\,cm^3$ PMMA phantom. EBT3 film measurements were done at 1, 2, 3, 4, 5, 20 mm. The TPS dose map was produced with a $1 \times 1 \times 1\,mm^3$ resolution. 420×10^9 incident electrons were simulated in the GATE toolkit to reach a mean statistical uncertainty of about 4% per voxel with a $5 \times 5 \times 1\,mm^3$ resolution. The dose maps (EBT3, TPS, GATE) were resampled to the same resolution ($5 \times 5 \times 1\,mm^3$) and normalized by the mean dose value at 20 mm in depth (Fig. 4).

To quantify the evolution of the two-dimensional spatial dose distribution at the surface of the phantom, 2D-gamma indexes (4%/3 mm) were computed for the TPS and Monte Carlo dose maps with respect to the experimental measurements (Fig. 5). The gamma scores obtained for the different depths are presented in Table 1. The results confirm the conclusion of Section 3.2. While TPS and GATE dose calculations were both in good agreement with the data at 5 mm in depth, only GATE calculations were still compatible with EBT3 films measurements closer to the surface.

3.4. Example of clinical application

After the validation on PMMA phantoms, the GATE Monte Carlo toolkit was tested on a clinical VMAT breast cancer treatment. The clinical case corresponded to a leaf breast tumor with internal mammary lymph nodes. The PTV was defined with a 5 mm skin retraction and a 50 Gy irradiation dose. Two different plans were created by the Eclipse AAA TPS using a 1 mm spatial resolution for dose calculations (Fig. 6 (left)): VMAT optimization without bolus (Plan 1), VMAT optimization with a 5 mm bolus (Plan 2). The dose coverage values of the PTV were really closed for the two VMAT optimizations (Table 2).

Following the different steps presented in Fig. 1, the GATE toolkit was used to compute the mean percentage depth dose distributions in the breast volume with a 1 mm spatial resolution for three different irradiation configurations: a VMAT simulation performed according to Plan 1 (optimization and irradiation without bolus) and two VMAT simulations performed according to Plan 2 (optimization with a bolus) with and without using a 5 mm bolus during the irradiation. For this test, a numerical phantom was produced from the DICOM-RT Image of the patient by using only water material to avoid possible biases induced by the difference of material compositions between the TPS and the Monte Carlo simulation. For the irradiation with a 5 mm bolus, the bolus geometry was extracted from the DICOM-RT Structure file and added to the numerical phantom. Fig. 6 (right) shows that the two surface dose calculations without bolus corresponding to VMAT Plan 1 and 2 are quite similar, with a maximum deviation of 15% in the first 5 mm. These results, whose main purpose is to illustrate possible applications of the Monte Carlo toolkit, seems to confirm that for this clinical case a 5 mm skin retraction is sufficient to avoid possible optimization difficulties of PTV covering that could lead to high dose spots

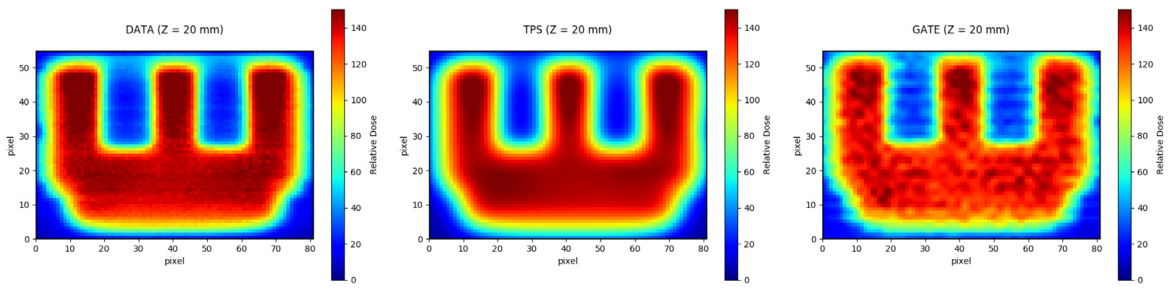


Fig. 4. Experimental (EBT3 films – left), TPS (Eclipse AAA – center) and Monte Carlo (GATE – right) 2D dose maps at 20 mm for a static IMRT plan irradiation. Mean dose values are used for normalization.

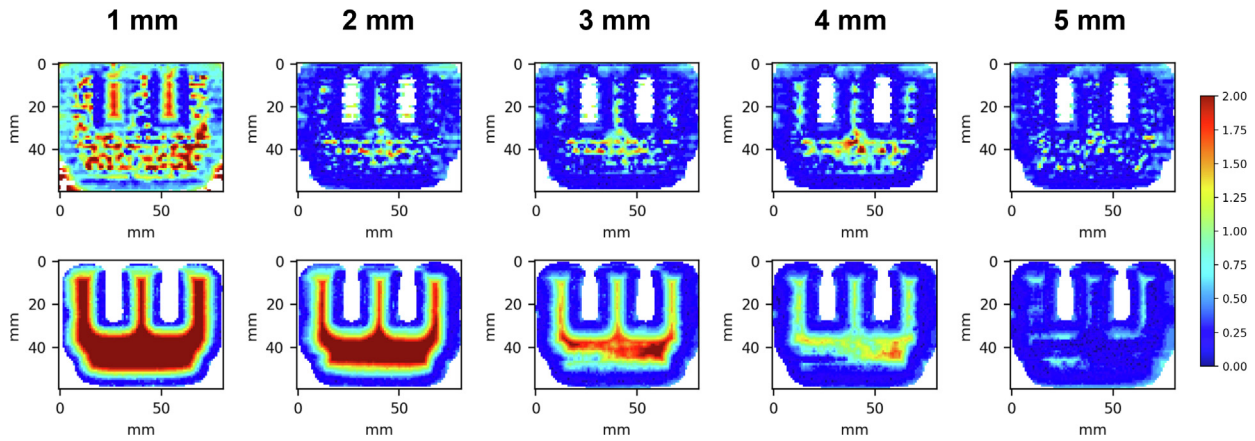


Fig. 5. 2D-gamma index distributions (4%/3 mm) for GATE (top) and TPS (bottom) calculations with respect to experimental (EBT3) dose maps for a static IMRT plan irradiation for various depths.

Table 1
Gamma scores (4%/3 mm) for GATE and TPS calculations with respect to experimental (EBT3) dose maps for an IMRT plan irradiation at various depths.

	Depth				
	1 mm	2 mm	3 mm	4 mm	5 mm
GATE	68%	96%	96%	94%	99%
TPS	44%	60%	76%	89%	100%

Table 2
PTV coverage of two VMAT plans with and without a 5 mm bolus. DX% is the % of the planned dose (50 Gy) delivered to X% of the PTV volume. VY% is the % of the PTV volume that received at least Y% of the planned dose (50 Gy).

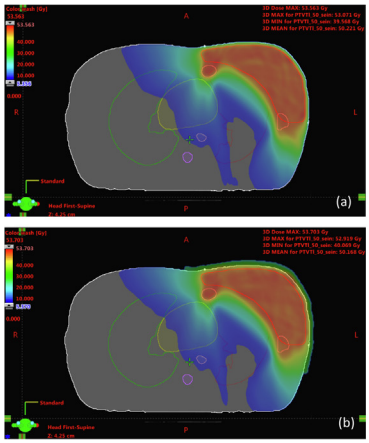
	Without bolus	With bolus
D98%	94.3%	94.4%
D2%	104.2%	104.2%
V95%	97.1%	97.2%

in the build-up region.

4. Discussion

The detailed comparison of 3D surface dose distributions highlights the interest of using in a complementary way the dosimetric data from the TPS and the Monte Carlo simulation for breast cancer treatments in radiotherapy. However, despite the general good agreement between experimental data and Monte Carlo dose calculations, Figs. 3 and 5 show a larger discrepancy in the first millimeter. This should be explained by the difficulty to measure and compute a precise dose at the air-tissue interface. The uncertainty may be reduced in the simulation by using a finer resolution for the surface region to limit the size of the voxel containing heterogeneous materials (air-tissue) that bias dose calculations. But this can only be done at the expense of a longer computation time to maintain a small statistical error. It should also be noted that this first voxel problem exists at the TPS level. It is indeed very difficult with the Eclipse software to match the real surface of the patient with the limit of the geometrical box used for the dose calculation. Some publications even recommend defining a volume of 1–2 cm (air) around the patient to overcome calculation errors introduced by this problem [32]. The potential interest of such solutions may be easily tested within the GATE Monte Carlo toolkit.

Besides the precision of dose calculations, the other important parameter for using the toolkit is the computing time. For the different validation steps presented in this paper, full simulations (started from the electron beam) have been done on a computing grid. These kind of simulations were obviously time consuming due to the small efficiency of X-ray production and the propagation of many secondary particles in the various accelerator head components. The mean computing time was about 15 h for 10^9 electrons. The multi-thread mode is not available in the current version of GATE. However, the final toolkit for patient dose calculation will benefit from the large acceleration factor provided by the use of phase spaces. These phase spaces can be either provided directly by the manufacturer for the most recent accelerators or created by the user itself within the GATE software. Based on the simulations performed on a clinical VMAT plan (Section 3.4), the use of phase spaces will give a mean acceleration factor of about 175. It



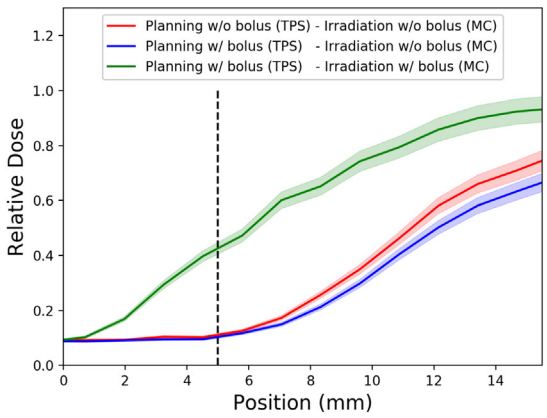


Fig. 6. Left: TPS dose maps for VMAT planning without (a) and with a 5 mm bolus (b); Right: Monte Carlo calculations of percentage depth dose distributions (breast) for different planning (TPS) and irradiation (MC) configurations: planning and irradiation without bolus (red), planning with a 5 mm bolus and irradiation without bolus (blue), planning and irradiation with a 5 mm bolus (green). The dashed line represents the position of the first voxel of the phantom.

corresponds to a mean computing time of about 10 h on one CPU to get the surface dose distributions presented in Fig. 6. The acquisition of a 6 cores commercial computer by the clinical center will make it possible to consider the recalculation of a VMAT treatment with 3 different protocols (margins, bolus) in about 5 h (for an affordable price). This computation time is compatible with the main objective of the toolkit, which is not to be used systematically for each patient but only in complex cases for which surface dose distribution can be problematic. It may also be possible to use the toolkit in parallel with the clinical routine to create superficial dose databases that can be used for patient follow-up.

The techniques used for breast cancer radiotherapy can vary a lot between institutions, with each center currently using protocols mainly based on empirical principles. The comparison of these techniques/protocols with regard to the surface dose is made difficult by both the complexity of the measurements and the lack of precision of the TPS. The Monte Carlo toolkit developed in this work can assist the medical physicists in this task by adding to the general dosimetric data (provided by the TPS) detailed information on the superficial dose distribution. The presented results highlight both the lack of precision of the TPS and the advantage of using Monte Carlo simulation to improve the calculations in the first 5 mm of tissues. The user-friendly aspect of this toolkit, that only needs DICOM-RT files (image, plan, structure and dose) as input parameters, makes this kind of analysis easily accessible to medical physicists in a clinical context. The toolkit will be available in open-access to allow its regular improvement by the users. An interesting option would be for example to add the possibility to parameterize a patient movement or a change in breast morphology to evaluate the impact of these treatment uncertainties on the surface dose distribution.

5. Conclusion

An open-source Monte Carlo toolkit has been developed for surface dose calculation in VMAT breast cancer radiotherapy. This toolkit, based on GATE/Geant4 codes, aims at supplemented the treatment planing systems by providing a precise calculation of the superficial dose distribution. The user-friendly aspect of the software, that only needs DICOM-RT files (image, plan, structure and dose) as input parameters, makes this kind of analysis easily accessible to medical physicists in a clinical context. In its actual version, the tool has been validated against experimental data with a Varian NovalisTx accelerator and compared to the Eclipse AAA TPS. An on-going project plans to add other accelerator models (Varian Novalis True Beam, Elekta Versa HD, Accuray Thomotherapy) and other TPS (Accuray Precision, Elekta Monaco, Philips Pinnacle).

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