# Evaluation of Monte Carlo Simulations Performance for Pediatric Brachytherapy Dosimetry


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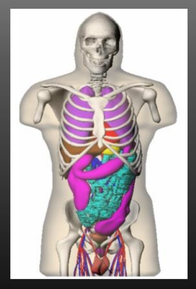
## Overview

Dosimetry of Brachytherapy applications was examined in the present study. Brachytherapy sources and clinical treatment plans were simulated. Our goal was to use simulations to evaluate clinical treatment protocols, and optimize them.

- The GATE Monte Carlo simulation toolkit was used
- Two Brachytherapy sources were simulated:
- TG-43 protocol was applied to validate our simulations.
- A clinical treatment plan was created in Nucletron's Oncentra and then simulated, in order to validate our code.
- XCAT anthropomorphic models used in order to simulate pediatric applications.
- Tools were developed to make our system easy to use in medical practice.



## Introduction

Cancer is a relative rare disease in children, but represents the second leading cause of childhood death. Pediatric tumors are generally encountered using multi-modal treatment. Brachytherapy is a rare approach but already applied in several situations such as soft-tissue sarcomas. Brachytherapy presents several advantages in modern medicine and is favorably compared with other more aggressive techniques in specific pediatric applications. Brachytherapy can result to low toxicity on healthy tissue and decrease the possibilities for late malignancies.

The limitation of such technique is the need for specific methodology adapted to patient's characteristics. Monte Carlo (MC) simulations can accurately determine dosimetric parameters in realistic cases.

GATE is a MC simulation toolkit based on the precise modeling of the physical processes of the Geant4 code. It is dedicated to Nuclear Imaging and Radiotherapy applications with large flexibility in using voxelized phantoms and complex geometries with movement incorporation. GATE is extensively validated, although realistic simulations are highly demanding in computational resources.

Detailed digital human phantoms can provide the ground truth for dosimetric parameters in brachytherapy applications.

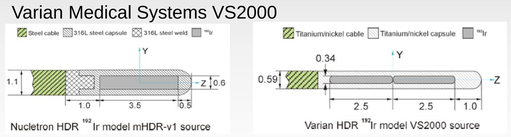
## Objectives

The purpose of the present study is to validate GATE toolkit on brachytherapy realistic applications and to evaluate brachytherapy plans on pediatric applications for accurate dosimetry on sensitive and critical organs of interest. Moreover, our work aims on creating a database of simulated brachytherapy sources that can be used for different situations as also a database of different simulated treatment plans, for fast counseling.

## Materials / Methods (I)

Two brachytherapy sources (Fig.1) were modeled and validated. Their spectrum characteristics are shown in Table 1:

- Nucletron microSelectron mHDR-v1 (classic)
- Varian Medical Systems VS2000




Nucletron HDR $^{192}$Ir model mHDR-v1 source — Varian HDR $^{192}$Ir model VS2000 source

***Fig.1*** *Materials and dimensions (mm) of Nucletron mHDR-v1 and Varian Medical Systems VS2000 sources.*

## Materials / Methods (II)

***Table.1*** *Mean Energy and Mean Number of Emitted Photons of γ-Rays as Result of γ-Decay and Characteristic X-Rays, by both b- and EC Decay Processes of $^{192}$Ir.*

| | |
|---|---|
| **Mean energy $E_{mean}$** | **0.3547 MeV** |
| **Effective energy $E_{eff}$** | 0.3977 MeV |
| **Effective mass energy absorption coefficient $(\mu_{en}/\rho)_{a,eff}$** | 2.914 x $10^{-2}$ $cm^2$ $g^{-1}$ |
| **Air kerma-rate constant $\Gamma_\delta$** | 0.1091 μGy $h^{-1}$ $MBq^{-1}$ $m^2$ |
| **Mean number of photons emitted per decay** | 2.3 (2.299) |

In the present study, the recommendations of the American Association of Physicists in Medicine (AAPM) and the European Society for Radiotherapy and Oncology (ESTRO) were used. The protocols are based on measured (or measurable) quantities and decouple a number of interrelated quantities. They also point calculations of two-dimensional dose distributions around interstitial sources.

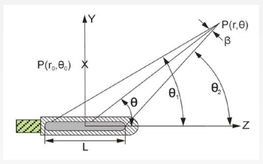



***Fig.2*** *Schematic diagram of the TG-43 geometrical parameters.*

TG-43 protocol utilizes a number of quantities such as the anisotropy function, F(r,θ); dose rate constant, Λ; geometry factor, G(r,θ); radial dose function, g(r); and air kerma strength, $S_k$ (Fig.2).

Technical Features

- The simulations were carried out in the GateLab GRID using 500 CPUs in parallel.
- The "Standard Model" of the Geant4 physics was selected
- $10^{10}$ primaries were used, in order to achieve uncertainties lower than 3%.

## Results (I)

### Validation of Nucletron mHDR-v1 simulation model

***Table 2.*** *Simulated radial dose values compared with theoretical ones from TG-43. Radial Dose Constant (Λ) is depicted in pink.*

| r (cm) | Absolute Dose Rate (cm-2) | g(r) (MC) | g(r) ref. | Δg (%) |
|---|---|---|---|---|
| **0.1** | 67.600 | 0.947 | 0.979 | 3.24% |
| **0.3** | 11.823 | 0.990 | 0.993 | 0.32% |
| **0.5** | 4.559 | 0.998 | 0.997 | 0.07% |
| **1.0** | **Λ=1.176 (ΔΛ=6.02%)** | 1.000 | 1.000 | 0.00% |
| **2** | 0.297 | 1.002 | 1.003 | 0.05% |
| **4** | 0.074 | 0.997 | 0.997 | 0.02% |
| **6** | 0.032 | 0.976 | 0.973 | 0.30% |
| **10** | 0.010 | 0.874 | 0.871 | 0.35% |
| **14** | 0.004 | 0.689 | 0.682 | 1.06% |

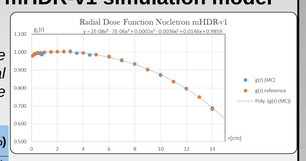



***Fig.3*** *Radial Dose Function.*

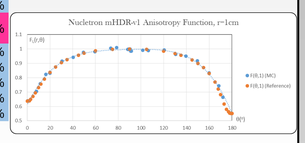



***Fig.4*** *Anisotropy Function.*

## Results (II)

### Validation of Nucletron mHDR-v1 simulation model

***Table 3.*** *Simulated radial dose values compared with theoretical ones from TG-43. Radial Dose Constant (Λ) is depicted in pink.*

| r (cm) | Absolute Dose Rate (cm-2) | g(r) (MC) | g(r) reference | Δg (%) |
|---|---|---|---|---|
| **0.1** | 50.178 | 0.941 | 0.975 | 3.48% |
| **0.3** | 10.240 | 0.988 | 0.990 | 0.25% |
| **0.5** | 4.129 | 0.996 | 0.995 | 0.08% |
| **1.0** | **Λ=1.097 (ΔΛ=0.00%)** | 1.000 | 1.000 | 0.00% |
| **2** | 0.279 | 1.003 | 1.005 | 0.17% |
| **4** | 0.070 | 1.002 | 1.002 | 0.01% |
| **6** | 0.030 | 0.979 | 0.981 | 0.19% |
| **10** | 0.010 | 0.880 | 0.881 | 0.06% |
| **14** | 0.004 | 0.689 | 0.693 | 0.52% |

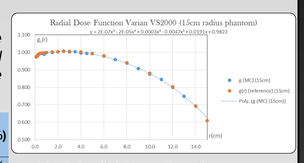



***Fig.5*** *Radial Dose Function.*

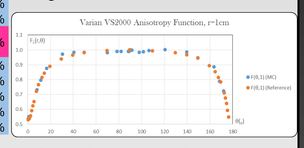



***Fig.6*** *Anisotropy Function.*

### Validation of treatment plan evaluation for gynecological cancer

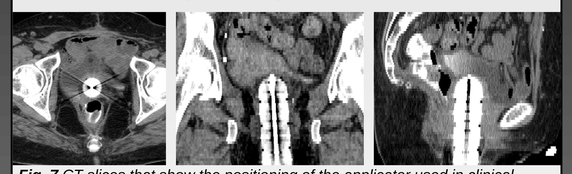


***Fig. 7*** *CT slices that show the positioning of the applicator used in clinical practice. (Transverse- Coronal- Sagittal view)*

Using CT seen on Figure 7, and the coordinates of the 9 sources used in this situation, we modeled it using GATE and XCAT phantom. Nucletron's Oncentra extracts data that show the relative dose in several positions, as presented on Table 4.

***Table 4.*** *Comparison between reference dose points by Oncentra and those simulated in GATE. As seen, the relative difference validates our model.*

| | Surface of the applicator | | | At 5mm | | |
|---|---|---|---|---|---|---|
| **Pos** | **Relative Dose (%)** | **MC Rel Dose (%)** | **Relative Difference** | **Relative Dose (%)** | **MC Rel Dose (%)** | **Relative Difference** |
| **1** | 137.69 | 130.77 | 5.03% | 89.64 | 90.36 | 0.81% |
| **2** | 154.20 | 149.37 | 3.13% | 99.12 | 98.83 | 0.29% |
| **3** | 157.72 | 153.61 | 2.61% | 103.72 | 104.92 | 1.16% |
| **4** | 154.71 | 152.28 | 1.57% | 104.97 | 105.15 | 0.17% |
| **5** | 152.66 | 151.77 | 0.58% | 105.06 | 102.32 | 2.61% |
| **6** | 154.70 | 153.54 | 0.75% | 104.97 | 104.86 | 0.11% |
| **7** | 157.72 | 150.33 | 4.68% | 103.71 | 103.13 | 0.56% |
| **8** | 154.19 | 151.03 | 2.05% | 99.12 | 98.52 | 0.61% |
| **9** | 137.67 | 137.05 | 0.45% | 89.66 | 91.91 | 2.51% |
| | | **Average** | **2.32%** | **100.00** | **100.00** | **0.98%** |

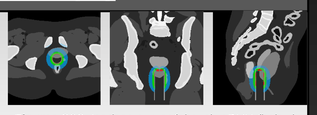
### Application of our GATE MC model for pediatric gynecological cancer

For the application of our model some tools had to be created so that the clinicians can be able to use it. Tools that extract the dose in organs of interest, as seen on Table 5, isodose curves as seen on Figure 8 and cDVHs as seen on Figure 9.

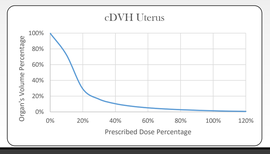
## Results (III)

***Table 5.*** *Dose in organs of interest.*

| Organ | Prescribed Dose Percentage (%) |
|---|---|
| Vagina | 100.00% |
| Urethra | 66.86% |
| Bladder | 30.35% |
| Uterus | 21.65% |
| Rectum | 16.04% |
| Ovaries, Fallopian tubes | 6.79% |
| Ureters | 4.78% |
| Small Intestine | 0.79% |
| Large Intestine | 0.59% |
| Kidneys | 0.23% |
| Spinal Cord | 0.13% |
| Liver | 0.10% |
| Heart | 0.03% |
| Lungs | 0.02% |



***Figures 8&9.*** *Isodose curves(above), cDVH (below).*




## Discussion

The MC simulations resulted in accurate dosimetry in terms of dose rate constant (Λ), radial dose $g_L(r)$ and anisotropy function F(r,θ) for both sources. The simulations were executed using ~$10^{10}$ number of primaries resulting in statistical uncertainties lower than 2%. The differences between the theoretical values and the simulated ones ranged from 0.01% up to 3.3%. The simulated DVH using an adult female XCAT model was also compared to a clinical one resulting in differences smaller than 5%. Finally, a realistic pediatric brachytherapy simulation was performed to evaluate the absorbed dose per organ and to calculate DVH with respect to heterogeneities of the human anatomy.

GATE is a reliable tool for brachytherapy simulations both for source modeling and for dosimetry in anthropomorphic voxelized models. Our project aims to evaluate a variety of pediatric brachytherapy schemes using a population of pediatric phantoms for several pathological cases.

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