

NORTH AMERICAN MEDICAL PHYSICS APPLICATIONS OF THE GEANT4 SIMULATION TOOLKIT*

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Geant4 is a toolkit for the simulation of the passage of particles through matter. While Geant4 was originally developed for High Energy Physics, applications now include Nuclear, Space and Medical Physics. Medical applications include characterizing machines and sources, calculating dose and the development of imaging technology. This paper surveys Geant4 medical applications in North America, explains why users choose Geant4 and discusses the challenges of bringing Geant4 to this community.

1. Why Geant4 is Used in Medical Physics

The Geant4 Simulation Toolkit^{1,2} began in 1994 as a research project for a new general-purpose simulation code for High Energy Physics (HEP). One of the first large object-oriented software applications in physics, Geant4 has become the standard simulation package for most HEP experiments including three of the four experiments at the Large Hadron Collider. Geant4 was chosen for these applications because of its ability to handle very complex constructive geometry and to handle all particles. In the US, the BaBar collaboration, which was the first major HEP user of Geant4, has by now simulated over 5×10^9 events.

1.1. *The Place of Monte Carlo in Medical Physics*

Within Medical Physics, Monte Carlo has been used for many years to characterize machines and sources, to calculate dose and to develop imaging technologies. In treatment planning, where the workflow involves imaging, then planning, then simulation of the plan, with the latter steps often iterated several times, time constraints generally lead to use of parameterized models rather than Monte Carlo, but a hybrid approach may use parameterized models for the first few iterations and Monte Carlo for subsequent iterations. Monte Carlo is superior to parameterized models in cases of material inhomogeneity, such as at

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the tissue/air interfaces of the lung, in the complicated tissue/bone interfaces in the head and neck, or near implants made of high atomic weight materials.

Retrospective studies are computationally similar to treatment planning but are done after the fact, to look at whether the dose calculated by parameterized models is correct. Some studies involve actual patient data, other studies use simulated patients (hardware or software models called "phantoms").

Medical imaging technology is in a period of rapid advance, moving towards higher resolution, higher speed, lower dose and better ability to differentiate tissue types. Monte Carlo is used to evaluate new designs.

1.2. *Why Some Medical Physicists Choose Geant4*

Geant4 is still quite new to Medical Physics. Other codes, such as EGSnrc, XVMC, MCNP, PENELOPE and FLUKA have a longer history in this field. However use of Geant4 is increasing rapidly. Frank Verhaegen of McGill University, titled an article for MedicalPhysicsWeb³ "GEANT4: a new giant in medical physics."

Why do medical physicists choose Geant4 given the availability of other well established codes? A first reason is that Geant4 can handle all types of particles, as opposed to the "Gold Standard" in Medical Physics, EGSnrc, which handles only electron and gamma. With the growth of proton and ion therapy, due to the appealingly sharp dose depth cutoff of the Bragg Peak, there is significant interest in "all-particle" codes.

A second reason users turn to Geant4 is its ability to handle complex geometry. Geant4 offers the most flexible geometry description of any Monte Carlo. Medical Physics applications include complex parts of proton intensity modulated radiotherapy machines (IMRT), multileaf collimators (MLCs) and brachytherapy sources.

Another unique aspect of Geant4 is that it can model sources and geometries in motion, such as the rotating parts of an IMRT beam line, dynamic MLCs, a brachytherapy source moving through a catheter, moving parts of imaging systems and even the motion of patient organs from respiration, etc.

Geant4 has the ability to handle fields, both electric and magnetic. This can be helpful in simulation of the treatment head or in novel, real-time imaging treatment modalities where the treatment is performed in a magnetic field.

Another appealing quality of Geant4 is its use of modern programming techniques (object-oriented, C++). All other codes currently in use are in FORTRAN. Finally, Geant4 is open and free - Geant4 source code is

distributed to the user who is welcome not only to add user code but to modify the source code and even to repackage, redistribute or sell that source code.

2. Some Medical Physics Applications of Geant4 in North America

We will now discuss some of the recent Geant4 medical applications in North America. Space does not allow a complete list of such efforts, but an assortment of projects are described to give a sense of the breadth and depth of activities.

2.1. *Characterizing Machines and Sources*

Geant4 has been used for design and quality assurance for beam therapies, brachytherapy and even for a novel form of therapy, "electronic brachytherapy." Therapeutic beams may be x-rays (from bremsstrahlung of electrons on a high Z target, typically 4 to 25MeV), electrons (for skin or small depth treatments, special cases of whole body irradiation, and for inter-operative radiotherapy, 4 to 25 MeV) and protons or ions (from a cyclotron, typically around 160 MeV).

Work by Paganetti, Jiang, Lee and Kooy⁴ at Harvard/Massachusetts General Hospital used Geant4 to simulate the treatment head for a proton linac including complexities such as the motion of intensity modulator wheels and the varying fields of steering magnets. At MD Anderson Cancer Center, Peterson, Polf, Frank, Bues and Smith⁵ used Geant4 to study variations in scanned beam proton therapy doses due to random magnetic beam steering errors.

On the other end of the proton therapy suite, a collaboration of University of Texas, M. D. Anderson and Université Laval, including Archambault, Polf, Beaulieu and Beddar⁶, chose Geant4 to study the scintillation detectors used for dose measurement. Flanz and Paganetti⁷ used Geant4 to study overall radiation protection issues for proton therapy suites.

Brachytherapy (from the Greek for "short", referring to short distance therapy) typically involves gamma and beta emitters placed outside the body close to the skin (for superficial tumors), temporarily inserted into the body through catheters or permanently implanted ("seeds"). Geant4's flexible geometry has made it popular for modeling such applicators and seeds and calculating the resulting dose. Examples of such studies include modeling of an Iridium 192 source by Poon, Reniers, Devic, Vuong and Verhaegen⁸ of McGill University, an Iodine 125 source by Carrier⁹ of Université Laval and the "Active Mammosite" device by Winston, Black and Cudjoe¹⁰ at Hampton University.

A novel treatment system, "electronic brachytherapy," mixes qualities of beam therapy with qualities of brachytherapy. A device is temporarily inserted through a catheter, but the device is not a radioactive seed but a miniature x-ray

tube. A group at McGill University, including Liu, Poon, Bazalova, Reniers, Evans, Seuntjens and Verhaegen, in collaboration with Rusch¹¹ from the equipment manufacturer Xoft Inc, used Geant4 to model this "Axxent x-ray tube", choosing Geant4 for its ability to handle complex geometry.

2.2. Treatment Planning and Retrospective Studies

Jiang, Seco and Paganetti¹² at Harvard/Massachusetts General Hospital have used Geant4 to study dose from proton therapy to the head and neck region to see where the dose calculated by Monte Carlo differs from that calculated by analytical methods. Also at Harvard, Paganetti, Jiang and Trofimov¹³ used Geant4's ability to handle moving geometries to study dose to the lung in breathing patients. Treatment plans that incorporate this dimension of movement in time are referred to as "4D plans." While many Monte Carlo codes can handle a single motion (such as the beam angle changing during treatment), Geant4 puts no limit on how many parts of the geometry may be in motion (beam position, multileaf collimator motion, respiration, etc.). In the absence of this 4D ability, time-slicing can allow one to build up a moving geometry's dose calculation by summing dose from several static setups, but such an approach can require an unwieldy number of slices if there are multiple simultaneous motions, and interplay effects must be handled carefully to avoid time-binning artifacts.

Yet another study from Harvard/Massachusetts General, in collaboration with University of Florida and Rensselaer Polytechnic, by Zacharatou Jarlskog, Lee, Jiang, Bolch, Xu and Paganetti¹⁴, used Geant4's all-particle capabilities to study the risk associated with neutron radiation in proton therapy. The issue here is that while the primary proton beam's shape can be well controlled, the interaction of these protons in the patient's body results in secondary neutron radiation generated within the body and heading in many directions. In studying the risk from this secondary dose, the team created five separate patient models, ranging from a 9 month to 14 year old, and including both genders, to account for significant differences among these patient groups.

In prostate brachytherapy, treatment planning involves decisions about where in the prostate to place on order of 100 small radioactive seeds. Standard calculation techniques look at each seed individually and then sum the resulting dose. A retrospective study by Carrier, D'Amours, Verhaegen, Reniers, Martin, Vigneault and Beaulieu¹⁵, of CHUM, used imaging to determine the actual location of seeds after implant and then used Geant4 to calculate the effects of

"interseed attenuation," the effect each seed has in blocking some dose from surrounding seeds.

2.3. *Imaging*

Many developers of imaging technology use Geant4 by way of GATE, the Geant4 Application for Emission Tomography, which wraps around Geant4 to simplify use and add imaging features. Within the North American community, a group at UCLA's Crump Institute for Molecular Imaging, including Taschereau, Chatziioannou, Vu and Douraghy use GATE in small animal studies. To facilitate their work they developed a very high resolution voxelized mouse phantom. They use this phantom, for example, to study dose from 18-flourine compounds¹⁶. Another study at the Crump Institute by Douraghy, Rannou, Alexandrakis, Silverman and Chatziioannou¹⁷ uses GATE to study dual modality optical PET (OPET), which combines optical tomography with positron emission tomography. And a Crump Institute group including Vu, Yu, Silverman, Farrell, Shah, Tseng and Chatziioannou¹⁸ uses GATE to study specialized beta detectors for use with microfluidic chips.

Other developers studying imaging use Geant4 directly rather than through GATE. At Emory University, Sechopoulos, Suryanarayanan, Vedantham, D'Orsi and Karellas¹⁹ used Geant4 for the first comprehensive study of radiation dose to different organs from x-ray scatter during mammography and breast CT.

2.4. *Validation Studies*

Before any particular Monte Carlo can be used for treatment planning, validation studies must be published in appropriate journals. A variety of studies have been undertaken by Geant4 developers and medical physicists to validate Geant4 against measured data and other Monte Carlo codes. Faddegon of UCSF, in collaboration with Asai, Perl and Tinslay of SLAC, have calculated such benchmarks as large field electron dose distributions²⁰, variation reduction techniques (bremsstrahlung splitting)²¹ and thick target bremsstrahlung²².

3. Challenges for Geant4 in Medical Physics Applications

3.1. *Technical Challenges*

Because the Geant4 toolkit was originally developed for a different field, HEP, changes were needed to make it more usable for medical applications. The original applications of Geant4 involved highly specialized detector

development. Geant4 was therefore set up with the assumption that users would write their own "hit" classes (user code called when a particle enters a given detector volume which then models an electronics readout, scores dose, charge, etc.). Writing such classes was a burden for those medical physics users who just wanted to score standard quantities. Accordingly, Geant4 now provides ready-to-use scoring capabilities - the user just specifies what quantity to score along what geometry (plane, spherical surface, etc.). The object-oriented design of Geant4 made it fairly easy to add these capabilities to the toolkit.

A second challenge for Geant4 was to improve physics results at energy scales appropriate for Medical Physics. To the original developers of Geant4, the energies typical for radiation treatment were considered "low energy" and of low priority. With a very significant part of the Geant4 user community now coming from Medical Physics and Space Physics, new focus has been applied to improving performance at these lower energies (refinements to scattering, etc.). The modular design of Geant4 has proven useful here.

A third technical challenge involved the geometries to be modeled. While Geant4 boasts the worlds most flexible geometry for the hierarchical, constructive solid geometry typical of HEP spectrometers, HEP beamlines, medical linacs and brachytherapy sources, the medical physics world adds the requirement to model a different kind of geometry - patient geometry, read in from scan data as very large three dimensional arrays of densities. Such geometries are not complex in the same way as HEP detectors, but can involve very large numbers of voxels (3 million is common). To accommodate this geometry required changes to particle navigation, memory management and visualization. Geant4's software design has made such changes feasible.

3.2. Funding Challenges

Geant4 core development has been primarily funded by the HEP community. To bring more resources to bear on the technical challenges for medical physics applications, there is a corresponding challenge for funding. Some funding for Geant4 has recently emerged from the Space Physics community (ESA, JAXA and NASA), however dedicated medical funding for core Geant4 development has been limited (coming from Japan and Italy). Given Geant4's demonstrated usefulness in Medical Physics, it is hoped that funding will come from the North American medical community. An interesting parallel is that the current "Gold Standard" Monte Carlo for medical physics, EGSnrc, though currently maintained by Canada's National Resource Council, primarily for the medical

physics community, has its own roots in another HEP project begun at SLAC in the 1970s, the EGS Monte Carlo.

3.3. Sociological Challenges

Bringing Geant4 from HEP to Medical Physics has involved communication challenges. Some issues simply involve terminology (what HEP calls an "event", medical physics calls a "history"). Each field has its own set of acronyms, and terms like "low energy" have orders of magnitude different meaning between the two fields. A greater issue is that the two communities don't attend the same conferences and don't subscribe to the same journals.

HEP experiments often involve large collaborations (thousands of people). Such collaborations may assign several people to spend nearly full time learning about Geant4, digging into its details, discussing with Geant4 developers and optimizing performance. Medical Physics studies are typically by single individuals or very small collaborations. One cannot expect them to devote such manpower to understanding Geant4. Technical improvements, such as ready-to-use scoring classes, are a help, as are applications like GATE that wrap Geant4 for specialized uses, but a greater issue is that someone needs to provide easy-to-access guidance on how to tailor Geant4 for medical applications (such as what parameters are appropriate for what use cases).

The Geant4 North American Medical Users Organization (G4NAMU)²³ was launched in 2005 to address such guidance issues. Work is now under way to form international working groups, combining medical physics users with Geant4 developers to further address these issues. An initial group will focus on recommendations for Geant4 physics Lists (the code that specifies which physics processes to model and what parameters to use). Another group will explore strategies for assembling various reusable components into easier-to-use medical applications.

4. Conclusion

Medical applications of Geant4 in North America and throughout the world have been increasing rapidly due to the overall growth of Monte Carlo use in Medical Physics and the unique qualities of Geant4 as an all-particle code able to handle complex geometry, motion and fields with the flexibility of modern programming and an open and free source code. Work has included characterizing beams and brachytherapy sources, treatment planning, retrospective studies, imaging and validation. Challenges from the technical to the sociological have been addressed.

That software originally designed for HEP has found so many applications in Medical Physics should not come as a surprise - the histories of both fields go back to the same particle physics roots. Indeed, the first medical linac in the western hemisphere grew from the very institution, Stanford University, that also gave birth to the world's longest HEP accelerator. The first treatment from that medical linac was performed exactly fifty years ago this year. The transfer of technology between HEP and Medical Physics continues today.

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