The dawn of PET Monte Carlo: a personal experience

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*IEEE Transactions on Medical Imaging*
*IEEE Transactions on Radiation and Plasma Medical Sciences*
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“Homemade” Neutron Transport Monte Carlo code

HEP Experiment: Electroproduction of $\pi^+$ ($e+p \rightarrow e+n+\pi^+$) at threshold
(NINA 5 GeV electron accelerator at Daresbury Laboratory, UK)
Fig. 3. Schematic diagram of the neutron counter

A. Del Guerra, “A compilation of n-p and n-C cross sections and their use in a Monte Carlo program to calculate the neutron detection efficiency in plastic scintillator in the energy range 1–300 MeV”, Nuclear Instruments and Methods, Volume 135(2), 1976, 337-352-
Fig. 3. Total efficiency of the bare counter for several threshold values. The solid curves are the Monte Carlo predictions.

A bite of History

First Monte Carlo\(^{(1)}\) applications using computers were done at Los Alamos (1943), by Metropolis, Ulam and Von Neumann with the ENIAC\(^{(2)}\) for neutron diffusion problems → MCNP (Neutron Scattering and Absorption in U and Pu)

The problem of first interaction:

\[1 - \exp(-\mu x) = R \quad \text{[with } 0<R<1\text{]} ; \quad \exp(-\mu x) = 1-R ; \quad -\mu x = \ln (1-R)\]

\[-\mu x = \ln (R) ; \quad x = -1/\mu x \quad (\ln R)\]

Pseudo-random generator → R

The analog computer: the FERMIAC

\(^{(1)}\) Stan Ulam suggested the name after “Monte Carlo Casino”: he was a poker player.

\(^{(2)}\) Electronic Numerical Integrator And Computer

\(^{(3)}\) Invented by Fermi and built by Percy King in 1947. Used at LANL till 1949
DECISION POINTS IN MONTE CARLO

Fig. 2. A schematic of some of the decisions that are made to generate the “history” of an individual neutron in a Monte Carlo calculation. The nonuniform random-number distributions $g$ used in those decisions are determined from a variety of data.

The FERMIAC

How does it works? (1)

“The Fermiac mainly consists of three parts:

1. The *lucite platform*, that serves as a neutron direction selector

2. The *rear drum*, that measures the elapsed time based on the velocity of the particular neutron in question

3. The *front drum*, that measures the distance traveled by the neutron between subsequent collisions based on neutron velocity and the properties of the material being traversed”

(1) From: F.Coccetti, 2016

Stan Ulam with the FERMIAC in his hand, the analog computer invented by Fermi for neutron transport study (from: F. Coccetti, 2016)
The Encounter with Walter Ralph Nelson

From left to right: Walter Ralph Nelson, Alan Nahum, Alberto Del Guerra in front of Nelson’s house at Palo Alto
• The Ettore Majorana Center, ERICE (TP), Italy
  Director of the Center: Antonino Zichichi
• The International School of Radiation Damage and Protection
  Director of the School: Alessandro Rindi (LBL, USA)

First Course in 1976
• Advances in Radiation Dosimetry and Medicine
  Director of the Course: Ralph Thomas (LBL, USA)

Second Course in 1978
• Computer Techniques in Radiation Transport and Dosimetry
  Directors of the Course: W.R. Nelson and T. Jenkins (STANFORD, USA)
  Monte Carlo programs discussed: (n-γ transport) ANISN, DOT, MORSE; (e-γ) EGS, ETRAN (with the First Medical Applications); (Hadronic cascade) AEGIS, CASIM, FLUKA, HETC
Why did I fall in love with EGS?

General flow-diagram of The EGS4 code system
Our first application of EGS4: 90° Compton Scattering Tomography \(^{(1,2)}\)

The principle of this technique is to irradiate a biological target with a narrow monoenergetic X- or γ-ray beam (100-2000 keV) and to detect the fluence of photons scattered into a well defined solid angle in order to obtain information on the mass density of the target.

Since the dominant process is Compton scattering, the fluence is proportional to the electron density, hence to the mass density. Original application was in densitometry as an alternative technique to trasmission densitometry.

**The COSCAT experiment**
Application to pulmonary studies at the CNR Institute of Physiology (Pisa, Italy): line source, 90° scattering, gamma camera.

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Fig. 1. Schematic drawing of the COSCAT apparatus: a $^{203}$Hg line source collimated to a narrow planar beam irradiates a section of the human thorax; a large-field gamma camera detects the 90° Compton-scattered photons.


Fig. 8. Comparison of the Monte Carlo results with the experimental data taken with a sawdust phantom (density 0.3 g/cm$^3$) as described in the inset. The solid circles are the experimental raw data, and the superimposed histogram is the Monte Carlo simulation. The open circles are the experimental data after the attenuation correction has been applied and the solid line $a$) is a linear fit to these points. The solid line $b$) is the effect of applying a further geometric correction for the beam divergence. The total-to-single scattering ratio, as obtained by Monte Carlo calculation, is also superimposed as a histogram (right-hand scale).
The HIgh Spatial resolution Positron Emission Tomograph (HISPET)

A Hexagonal Positron Emission Tomography camera based on MWPC \(^{(1)}\)

Expected figures of merit:
1- High Spatial Resolution: few mm (FWHM)
2- Long axial coverage: 45 cm
3- Low cost: gas chamber w/ lead-glass tube converter, instead of scintillator/PM

\(^{(1)}\) A. Del Guerra et al., “Medical Positron Imaging with a Dense Drift Space Multiwire Proportional Chamber”, IEEE TMI, 1(1) 1982, 4-11

Fig. 7. Proposed Positron Camera made of six modules arranged to form a hexagonal prism. Each module has a 45 × 45 cm\(^2\) active area and has two 2-cm thick lead glass tube converters.
The nightmare of the simulation

Fig. 1. A hexagonal-type multiplanar positron camera: a) perspective view, b) plan view, c) cross view.
I. POSITRON MODE

1.) The position energy is sampled from a CDF table.

2.) The position is followed in the phantom until its
   a) comes to rest (i.e., <10 keV) and produces
   b) two 511 keV annihilation photons, by annihilates

3.) In the above "positron transport" model, all
   a) wave function (gamma and annihilation) and
   b) no particles are followed outside the phantom
   c) once annihilation has
   d) obtained, the "two-gamma" mode takes over.

4.) The state function for each of the produced
   a) wave is saved for two subsequent calls to
   b) starting position in the "two-gamma" mode.

II. TWO-GAMMA MODE

1.) In the "two-gamma" mode, the photons are followed
   a) at the decay and/or interact on either the
   b) photon (positron) or and/or the detector.
   c) They are detected when they fall below a cutoff

2.) All charged particles that are produced in the
   a) phantom are immediately processed, but those that
   b) are produced in the detector are transported until
   c) they fall below: E < 40 MeV for the particular
   d) isotopes and beams.

3.) A possible candidate interaction is one that occurs
   a) in one of the four conversions with a charged particle
   b) that has enough energy to get into a hole, this is
   c) decided in either of two ways:
   d) a) the E.L. is greater than a fixed cutoff,
   e) b) the E.L. is compared against a probability
   f) table by sampling methods (CDF=0.8), the
   g) user code UCCRR was used in order to determine
   h) the detection probability table for two hole
   i) 511 keV (i.e., 0.511/0200 cm (511/1)) and
   j) having four converters.

4.) In either case, when more than one such event
   a) occurs in any of the何况es, the one closest
   b) to the "wire plane" is chosen (i.e., corresponding
e) to the signal that arrived earliest in time.

5.) Subsequently, the point of interaction is translated
   a) to the middle of the converted to account for
   b) parallel error (offset) and the spatial
   c) resolution of the detector is used in sampled
   d) included (I.C.V.E. =

6.) An acceptable event is one in which coincidence
   a) interactions occur between the two gamma in
   b) directly opposite helical sectors.

7.) Histograms are created for
   a) position E.L. distribution
   b) position range (beam flight)
   c) two-gamma mode (both at rest and in flight)
   d) point spread function (nominal and expanded)
   e) line spread function (normal and expanded)
   f) the point and line spread functions are recorded
   g) on order to account for phase space (collission)
   h) a versatile plot showing the transport of the two
   i) gamma is provided on request (EPST = 0).

RUNNING STATUS: USE \UCPET\UCPET.CDF DATA
The simulation of the converter

Fig. 1. Schematic drawing of a MWPC equipped with a lead glass tube converter plane for PET imaging.

Fig. 2. Calculated efficiency of a 1 cm thick converter as a function of the photon energy (solid lines); ○ - experimental data.

A. Del Guerra et al., "3-D PET with MWPCs: preliminary tests with the HISPET prototype", Nuclear Instruments and Methods A269, 1988, 425-429.
Left: Simulation results for a point-like source in the center of the complete HISPET tomograph: 4 mm (FWHM)

Right: Experimental results for the two planes only prototype: 8 mm FWHM (consistent with the simulation of the 2 plane prototype)
SMALL ANIMAL PET: YAPPET

The first research prototype (University of Ferrara, 1998)

The first commercial prototype (ISE, Pisa- University of Pisa, 2003)
Small scintillator matrix coincidence experiment vs simulation
(25 match-like 3x3x20mm³ YAP crystals coupled to R2486-06 Hamamatsu PSPMT)

Pulse Height

The so-called first interaction method

Optimize the spatial resolution, by only using Compton interaction events and rejecting the photopeak events.

Make the pseudo-selection on the basis of the pulse-height.

Digital radiography with solid state detectors (Si/Ge/HgI₂/CdTe)

Fig. 2. Sample plots of photon (circles) and electron (solid) tracks as obtained with the SHOWGRAF package [5]. In the simulation a monochromatic pencil beam of 5000 photons impinges onto a 300 μm thick silicon crystal with infinite lateral dimensions: (a), (b) and (c) side view for an incident energy of 20, 60 and 100 keV, respectively. X- and Y-scale are the same.

Simulation of the imaging capability of a two-density phantom mimicking a breast calcification: (a) schematic drawing of the phantom and the two-slab detector; (b) 2D image of the phantom: cross view(top), grey-level representation as obtained from the simulation, pixel dimension 200x200 \(\mu m^2\) (bottom); (c) profile cut through the calcification.
PET–based hadrontherapy treatment verification (PTRAN code)

Energy deposition (Ep=140.5 MeV) - Planar view

Energy deposition (Ep=140.5 MeV) - Lego plot

Fig. 3. Energy loss distribution in the zx plane (at y = 0), as obtained with a proton beam of 140.5 MeV in water: (a) isocontour plot for a 2 mm wide beam; (b) lego plot for a 12 mm wide beam.

Fig. 6. (a) Distribution of $^{15}$O nuclei as produced by 140.5 MeV protons in water along the zx plane at $y = 0$ for a 12 mm wide beam; (b) corresponding distribution of $^{13}$N.
Rationale:
The p interactions within the human body produce $\beta^+$ emitters radioactive atoms. The activity distribution is somehow related to the dose distribution. In particular the activity fall-off can give an indication of the Bragg-peak.

Positron Emitter nuclei production cross section vs proton energy for: (Left) $^{15}\text{O}$, (Center) $^{13}\text{N}$, (Right) $^{11}\text{C}$

Fig. 5. Relative comparison between experimental data by Oelfke et al. (1996) and simulated activity curve. The calculated energy deposition vs \( z \) is also plotted. (a) After 23 min of irradiation with 62 MeV protons in Lucite; scan acquisition started 40 min after the end of irradiation. (b) After 26 min of irradiation with 110 MeV protons in Lucite; scan acquisition started 24 min after the end of irradiation.
PET–based hadrontherapy treatment verification (state of the art)

Main contribution:

$^{11}$C ($T_{1/2} \approx 20.3$ min)

$^{10}$C ($T_{1/2} \approx 19.3$ s)

$^{15}$O ($T_{1/2} \approx 2.0$ min)

$^{13}$N ($T_{1/2} \approx 10.0$ min)

J Pawelke et al., Proceeding: Ion Beams in Biology and Medicine (IBIBAM), 26.-29.09.2007, Heidelberg, Germany

Courtesy of J. Bauer, HIT
The *Inside* Project
(see talk by Elisa Fiorina – Tuesday 9.30 - Aula Magna)

**DOSE PROFILER**
Prompt secondary particles imaging

**BI-MODAL IMAGING SYSTEM**
for particle range monitoring and verification

**IN-BEAM PET**
induced $\beta^+$ activity imaging
BRAIN PET: the TRIMAGE project

The MR system will be based on a very compact 1.5 T cryogen free superconducting magnet, with an integrated PET system:

- Reduction in cost for installation and maintenance.
- Reduction in claustrophobia effects.
- Better physiological measures since the patient's arm will be accessible.
- High sensitivity of the PET detector
The PET System Monte Carlo Performance

- High Spatial resolution 2 mm (DOI)
  (a factor 2 better than a clinical PET/MR)

- High Efficiency (6.8% at CFOV)
  (at least a factor 3 better than a clinical PET/MR)

- Axial FOV = 150mm
  (almost a factor 2 shorter than clinical PET/MR)

- Transaxial FOV = 110 mm radius
  (ok for the head)
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... and many more
Monte Carlo is not a magic black box

The black box of Monte Carlo calculations

Be sceptical of the results of anybody else’s Monte Carlo computer code.
Be especially sceptical of your own code.
No matter how you word your disclaimer, you will still “carry the can” filled with your own bugs (BLIF)
THANK YOU
VERY
MUCH
FOR YOUR
ATTENTION