Patient Specific Monte Carlo Simulation for Radiotherapy and Nuclear Medicine

By

Sarath Seneviratne

Research Goals

1. To investigate whether the patient-specific density and radionuclide activity distributions could be used to estimate the absorbed dose distributions in human body during the Nuclear Medicine imaging and internal emitting and external beam radiotherapy applications.

2. To extend the framework for Radiotherapy application

Hybrid-System

- Developed a hybrid-Monte Carlo Simulation to model human body using CT pixel values
  - Apply various object-oriented design patterns during the program development
  - Parameterised, Nested Parameterised and Readout geometries were used in this project
  - SPECT heads for Nuclear Medicine Applications
  - IMRT LINAC for radiotherapy applications
  - Investigated several methods of converting CT numbers into mass density and elemental weight of tissues for dose calculation.
  - Used various optimization techniques and events biasing techniques

What did we achieve?

- Used 41 CT images as the detector and 41 PET images for the source distribution
- Accumulated the energy deposited in each voxels
- Calculated the absorbed dose within organs of interest using image processing techniques
- Nearly 24 hours of computing time was required to simulate 20 million rays on a system
  - 2.1 GHz mobile processor
  - 2 GB RAM.

Based on GEANT4 Tool Kit

GEANT4

- C++, Object oriented class library for particle transport
- Provides three models of EM Physics: Standard, Low Energy & Penelope
- Modelling of time-dependant complex structure using arithmetic & Boolean operators with predefined solid building blocks.
- Accuracy from 250eV to several GeV in Low Energy EM Physics.

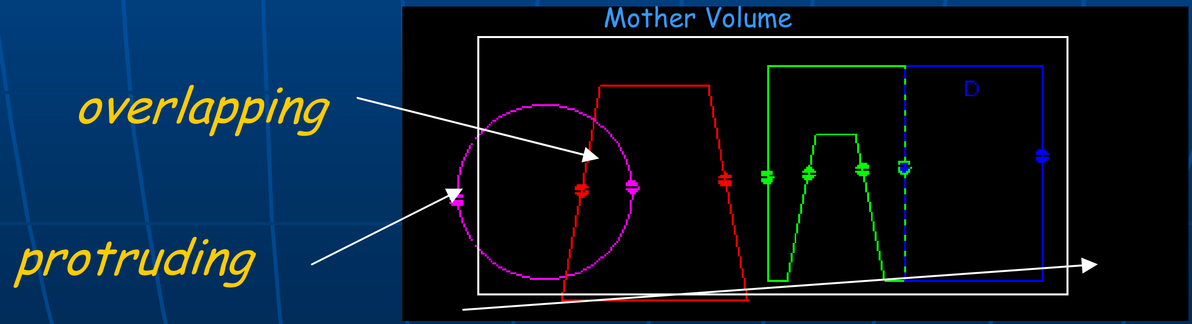
GEANT4

- Transports a particle step-by-step by taking into account all the possible interactions with materials and external electromagnetic fields until the particle:
  - loses its kinetic energy to zero,
  - disappears by an interaction,
  - comes to the end of the simulation volume
- Provides several method to access the transportation process and grab the results:
  - at the beginning and end of transportation,
  - at the end of each stepping in transportation,
  - at the time when the particle is going into the sensitive volume of the detector

Some of the Key features in this application

Overlapped Geometries

- The behaviour of navigation is unpredictable in the overlapped boundaries
- The problem of detecting overlaps between volumes is bounded by the complexity of the solid models description.
  - *Optional checks were used in the object constructions*



EM Physics

- Low energy EM Physics
  - 250 eV *(in principle even below this limit) / 100*ev for electrons and photons
  - Based on Livermore Data Library
- Penelope EM Physics
  - Runs slower than Low energy EM physics,

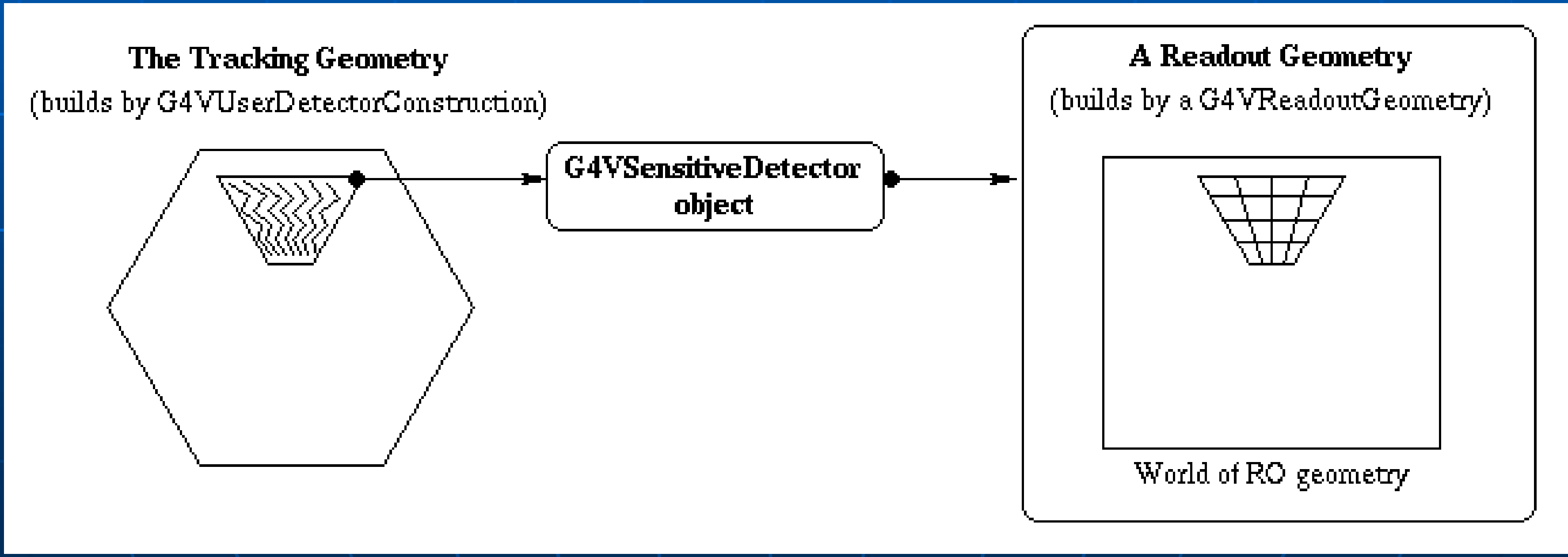
    For example, more accurate for atomic binding effects and Doppler broadening

Sensitive Detector (SD)

- A specific feature to Geant4 is that a user can provide own implementation of the detector and its response
- To create a sensitive detector, derive your own concrete class from the G4VSensitiveDetector abstract base class
- The principal purpose of the sensitive detector is to create hit objects
- Overload the following methods
  - Initialize()
  - ProcessHits() (Invoked for each step if step starts in logical vol.)
  - EndOfEvent()

Readout geometry

- In contrast to the "real "geometry used for tracking, the readout geometry can be considered as a virtual and artificial geometry
  - It is defined in parallel to the real detector geometry



Parameterized Voxels

- Parameterized Volumes are *repeated volumes*
  - *A volume can be different in size, solid type, or material.*
  - Parameterized by the copy number
    - Shape, size, position, rotation, material, sensitivity, visualization, etc.
  - Reduction of memory consumption
  - A volume instance positioned once in its mother volume
  - Used to model SPECT heads in this project

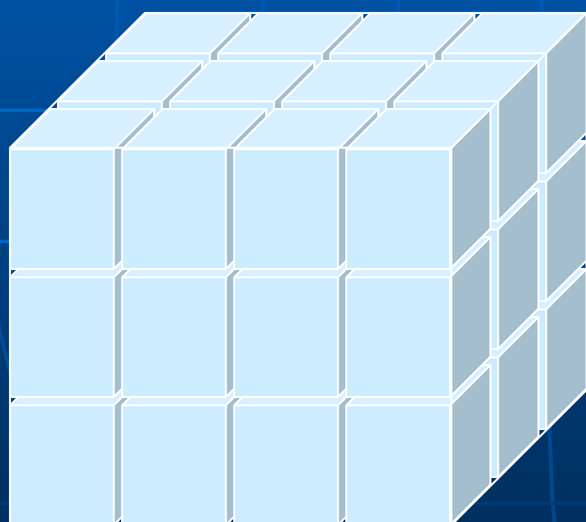
Nested parameterization

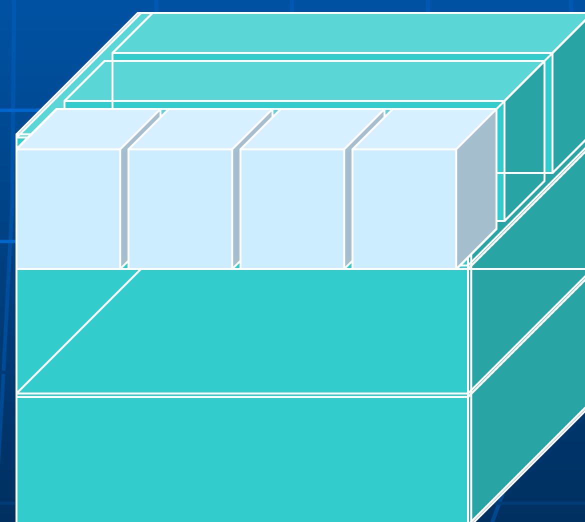
- Based on Makoto Asai (SLAC) presentation

Nested parameterization

- Suppose your geometry has three-dimensional regular reputation of same shape and size of volumes without gap between volumes. And material of such volumes are changing according to the position.
  - E.g. voxels made for CT Scan data (DICOM), Semiconductor, etc.
- Instead of direct three-dimensional parameterized volume,

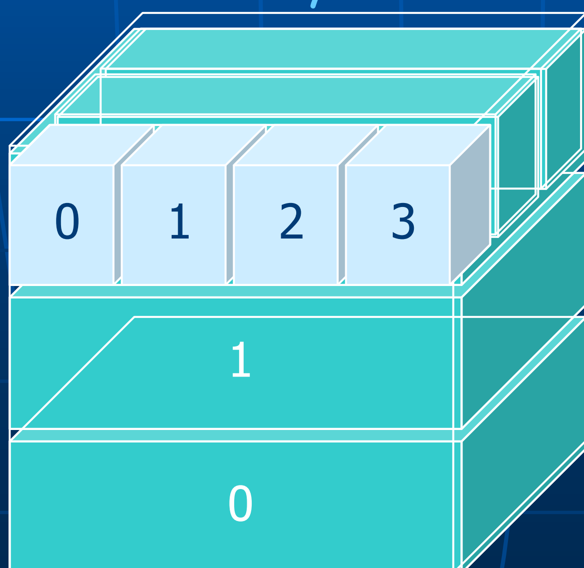
  use replicas for the first and second axes sequentially, and then use one-dimensional parameterization along the third axis.





Nested parameterization

- It requires much less memory for geometry optimization and gives much faster navigation for ultra-large number of voxels compared to ordinary parameterized volume
- Given geometry is defined as two sequential replicas and then one-dimensional parameterization,
  - Material of a voxel must be parameterized not only by the copy number of the voxel, but also by the copy numbers of ancestors.
  - Material is indexed by three indices.



- Can we access to voxels during the simulation without using readout geometry?

Nuclear Medicine

- Absorbed dose calculations are based on MC simulations on MIRD, ORNL phantoms
- It is difficult to account for inhomogeneities inside the human body using phantom models

Radiotherapy

- To destroy malignant cells while minimising damage to surrounding cells
- %5 change in dose can cause the tumour response change by 10 to 20%
- In dose calculation, an accuracy of 2% should be aimed for
- Many treatment planing systems are based on either analytical or kernel based MC codes

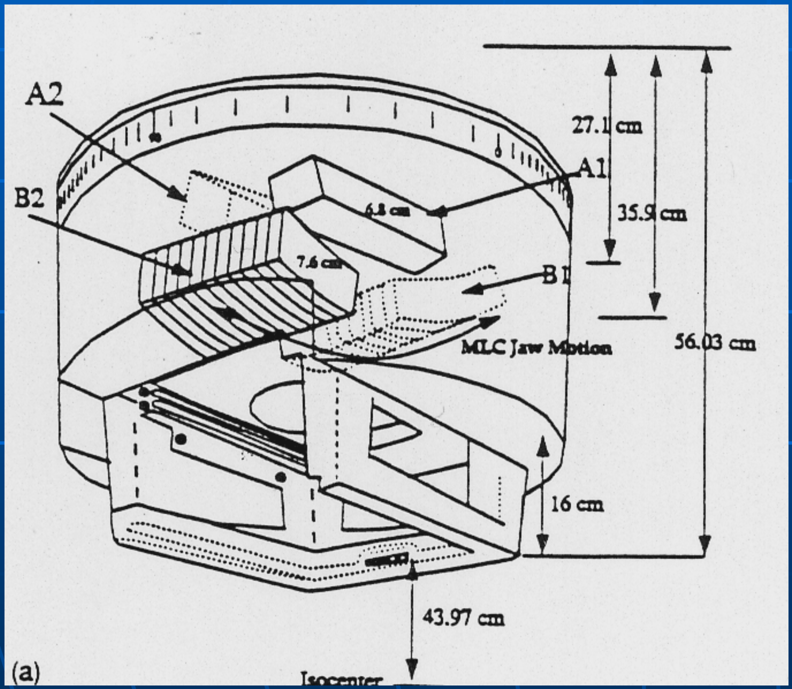
Intensity Modulated Radiation Therapy (IMRT)

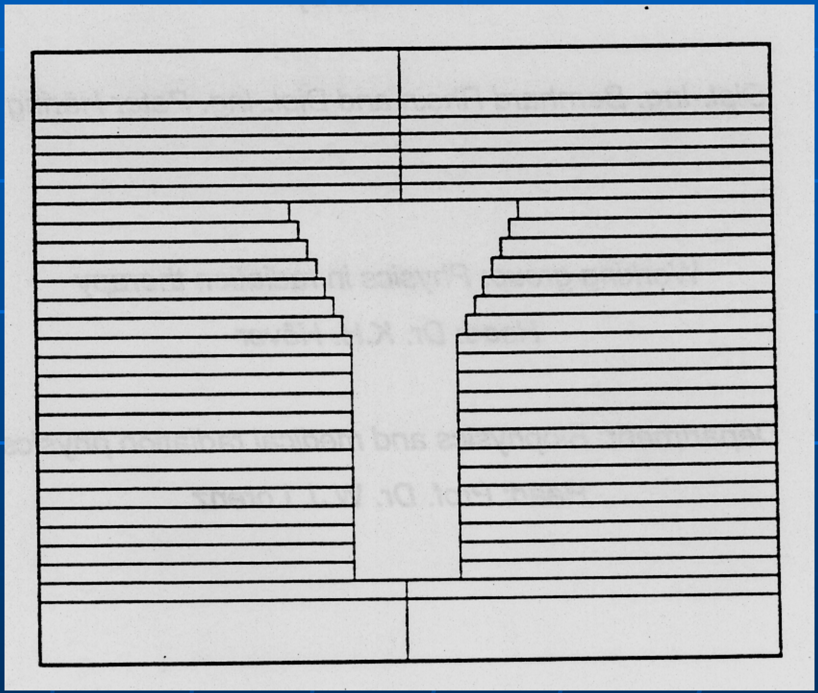
What is IMRT ?

- The purpose of IMRT is to shape isodose lines by varying beam intensity in order to conform to clinical requirement
- Usually involves complicated conformal dosimetry requirement (dose escalation and sensitive organ sparing)
- Inverse Planning
- Field and Intensity shaping using MLC

IMRT - MLC

- Multileaf Collimator





IMRT - MLC Delivery Methods

- Static
  - beam off during leaf/gantry/couch motion
  - slower, simpler
- Dynamic
  - beam on during leaf/gantry/couch motion
  - faster, more versatile, more complicated

Human Phantom using CT

Based on the DICOM application developed by Louis Archambault, Luc Beaulieu and Vincent Hubert-Tremblay.

Human tissues

- Lungs (inhale)
- Lungs (exhale)
- Adipose
- Breast
- Water
- Muscle
- Liver
- Trabecular Bone
- Dense Bone
- Rib Bone

Lung inhale
density = 0.217 g/cm3
H = 0.103
C = 0.105
N = 0.031
O = 0.749
Na = 0.002
P = 0.002
S = 0.003
Cl = 0.002
K = 0.003

Lung exhale
density = 0.508 g/cm3
H = 0.103
C = 0.105
N = 0.031
O = 0.749
Na = 0.002
P = 0.002
S = 0.003
Cl = 0.002
K = 0.003

Muscle
density = 1.061 g/cm3
H = 0.102
C = 0.143
N = 0.034
O = 0.710
Na = 0.001
P = 0.002
S = 0.003
Cl = 0.001
K =0.004

Hounsfield numbers to materials

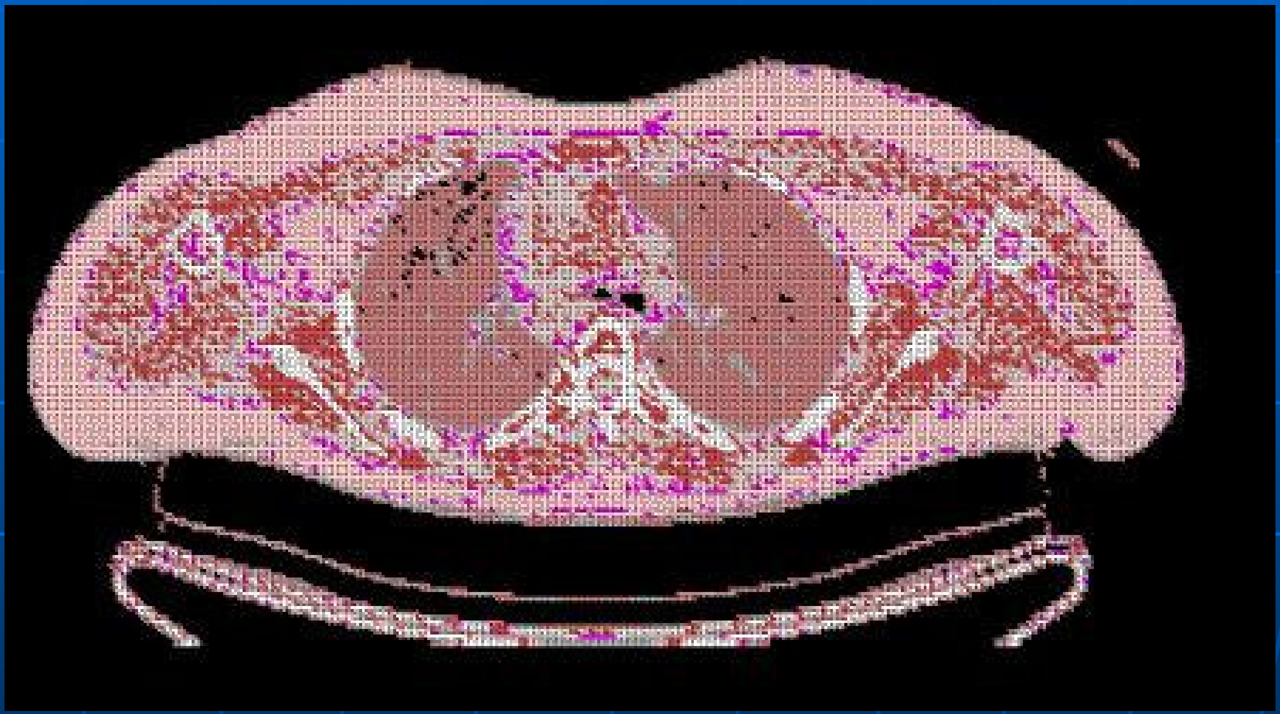
- International Commission on Radiation Units and measurements (ICRU) report 46

- Splits materials in density intervals
  - The voxels of each material will be grouped in density intervals of 0.1 g/cm^3
  - A new material will be created for each group of voxels

CT Number	Density (g/cm^3)
-5000	0.0
-1000	0.0
-400	0.602
-150	0.924
100	1.075
300	1.145
2000	1.856
4927	3.379

Material	Density Range g/cm^3
Air	0. - , 0.207
Lungs (inhale)	0.207 - 0.217
Lungs (exhale)	0.217 - 0.508
Adipose	0.508 - 0.967
Breast	0.967 - 990
Water	1.0
Muscle	1.0 - 1.061
Liver	1.061 - 1.071
Trabecular Bone	1.071 - 1.159
Dense Bone	1.159 - 1.575
Rib Bone	1.579-1.92

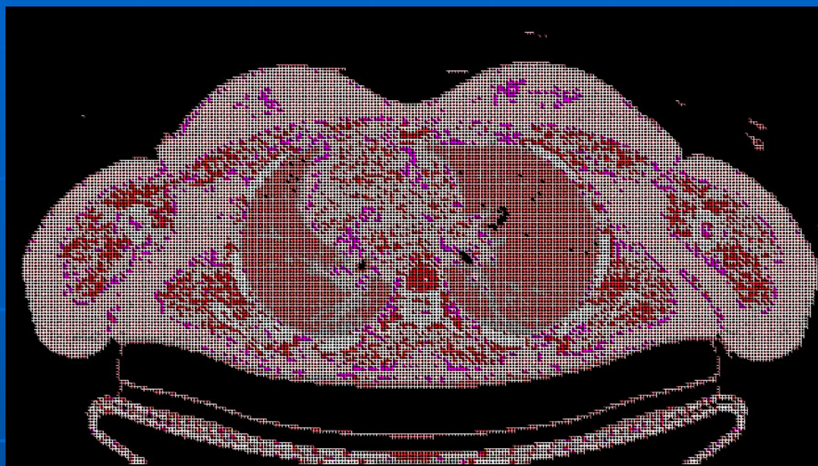
Density Distribution of a CT Slice



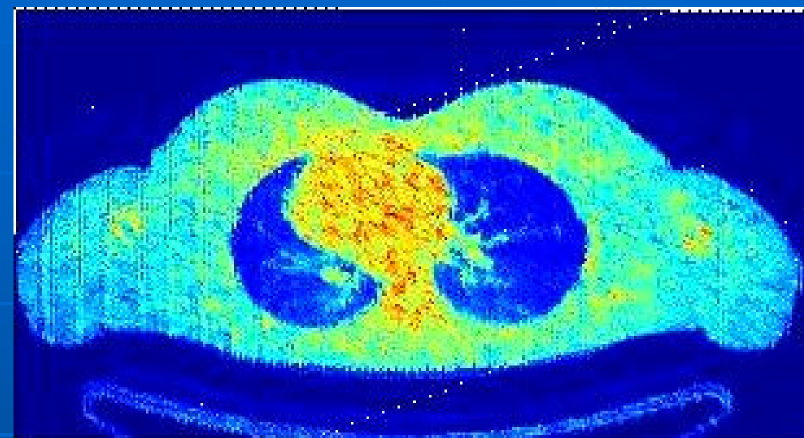
Patient Specific Dose Distribution

Simulation of 41 CT Slices

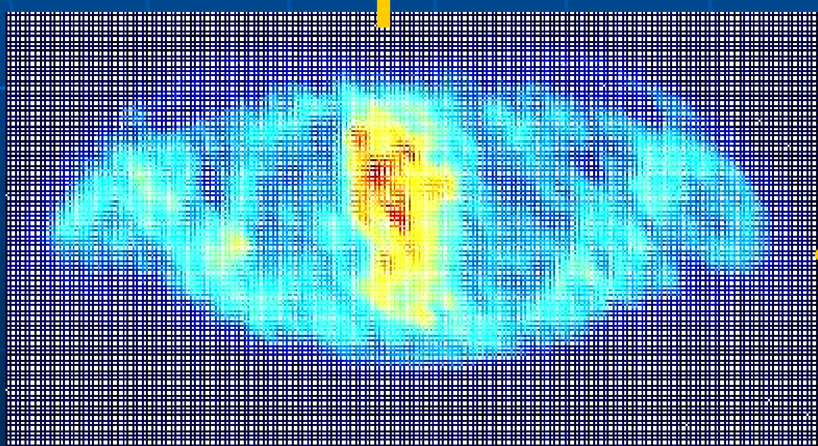
20 MBq 140 keV photon was distributed to the 41 slices



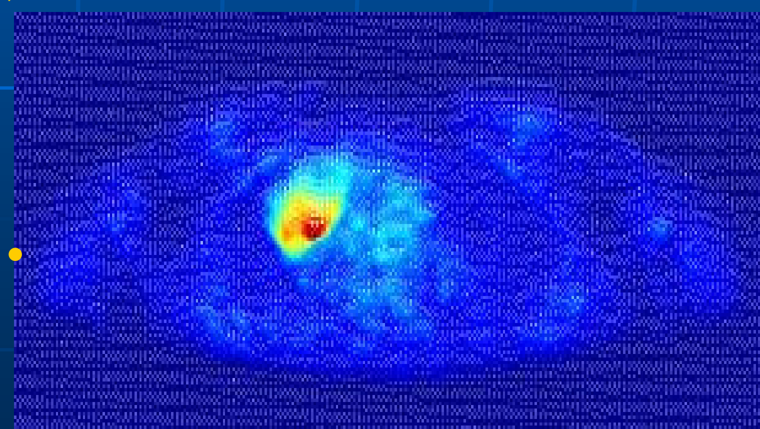
The density distribution in the 11th slice



The absorbed dose distribution in 11th slice



The activity distribution in 1th slice



The activity distribution in 11th slice

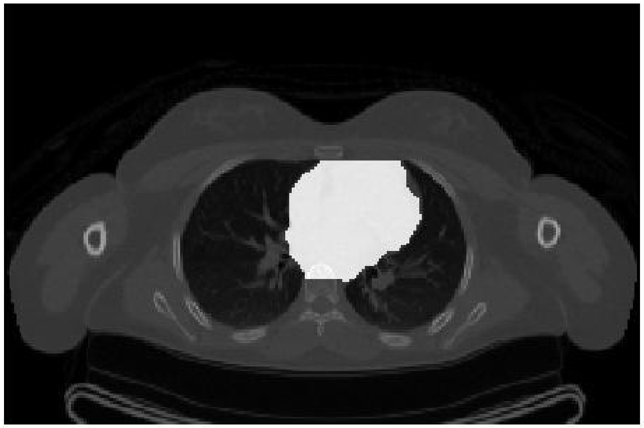
Please note that slices are rotated 180^0 in the simulation

Image Segmentation and Absorbed Dose Calculation

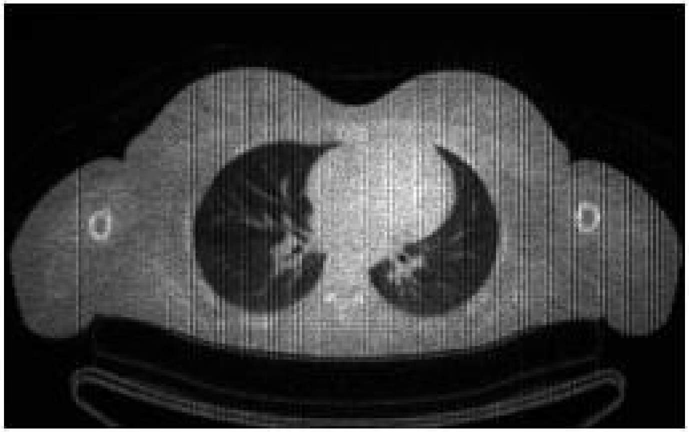
- Organ boundaries were segmented using an image processing algorithm
  - Segment region of interest in CT slices
  - Mapped the corresponding pixels into the voxels in the absorbed dose distribution
  - Calculate the absorbed dose within the segment

Segmentation of Heart Region

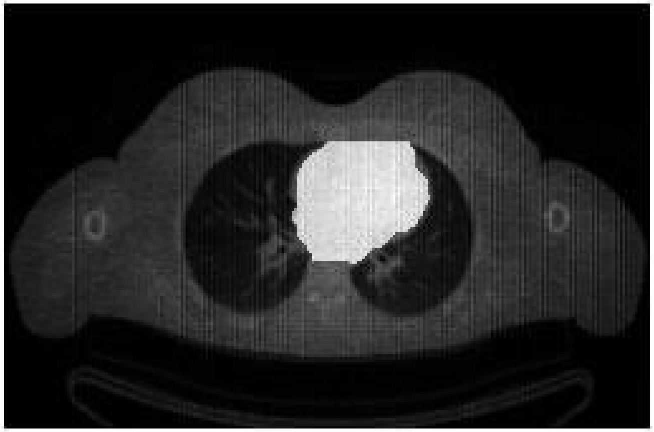
11th CT Slice



Heart region segmented in the 11th CT Slice

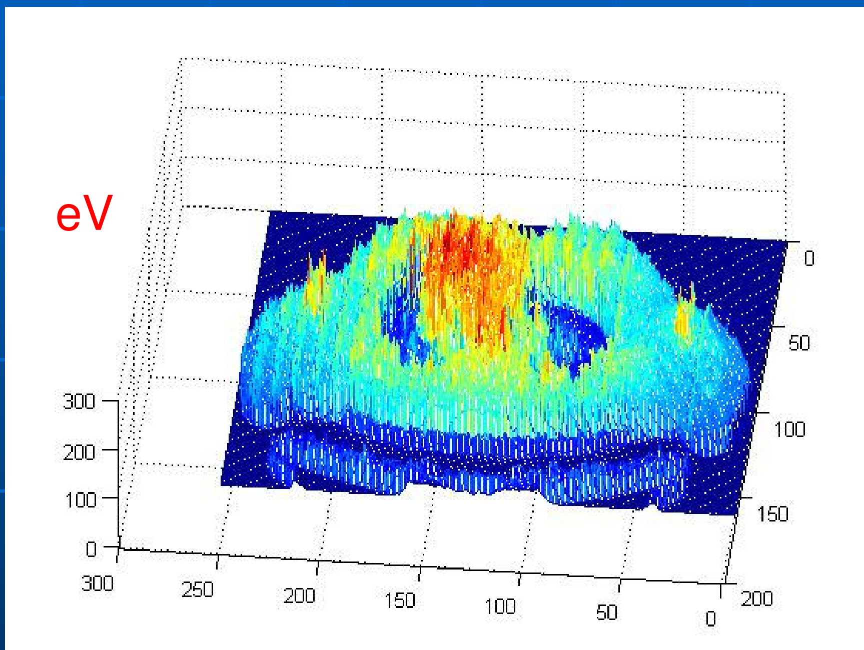


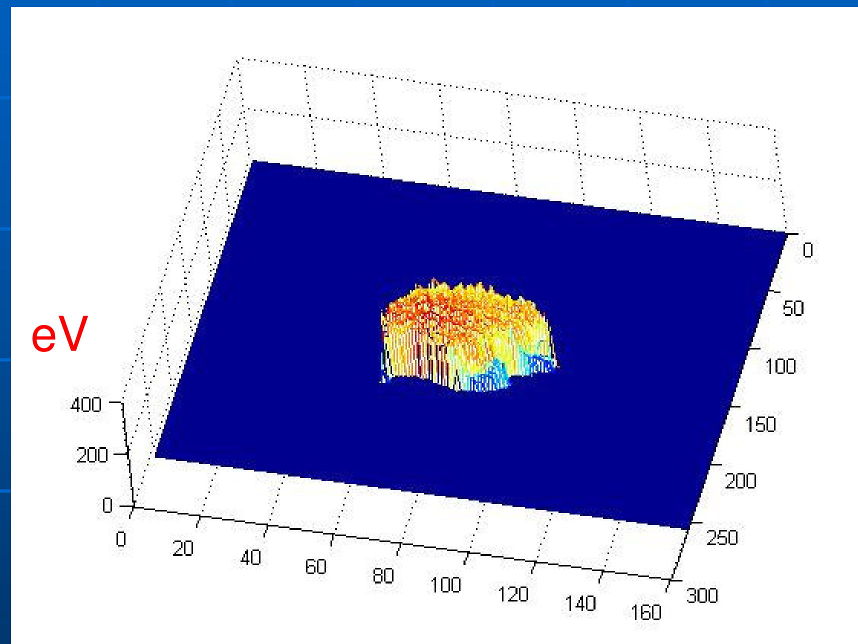
The absorbed dose distribution in 11th slice



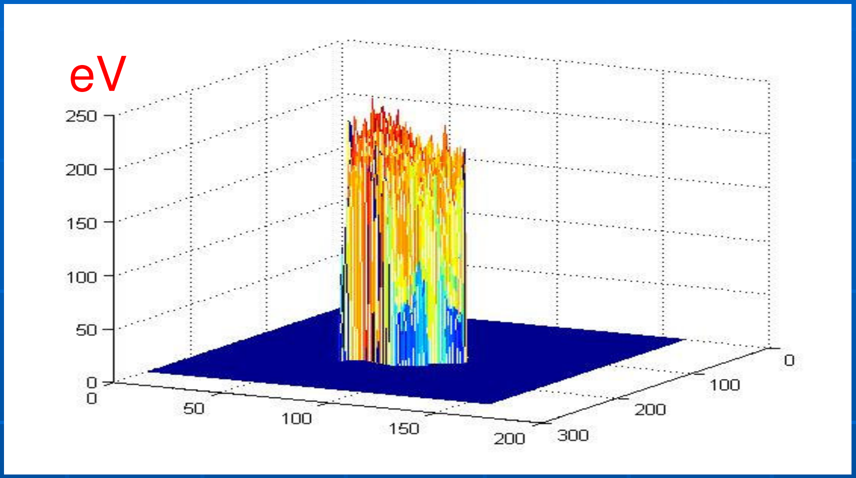
Absorbed dose segmented in Heart region

Segmentation of Heart Region in the absorbed dose distribution





Dose Distribution within the Heart region in the 11th Slice



Pixel Size = 1.95 x 1.95 x 3 mm

No of pixels in the heart region = 1875

Total mass of the heart region = 29.53 g

Absorbed total energy on the Heart area in the 11th slice = 4.73×10^{-14} Joule/sec

(2.95×10^{5} eV)

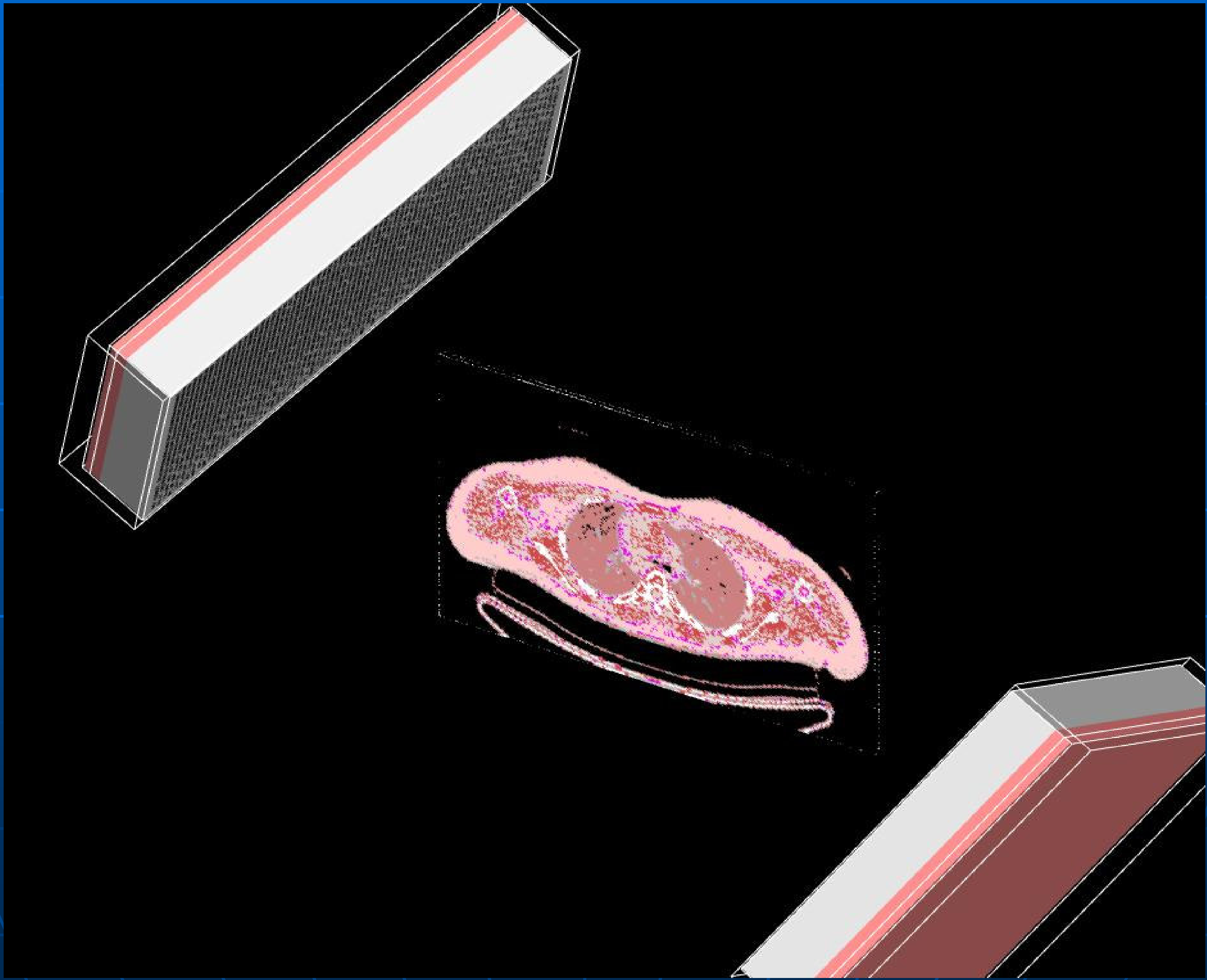
= 1.6×10^{-12} J $kg^{-1} sec^{-1}$

1 Joule = 6.24×10^{18} eV

SPECT System for Nuclear Medicine Application

This system was initially developed to study Probability Matrix for a Maximum Likelihood Expectation Maximization algorithm

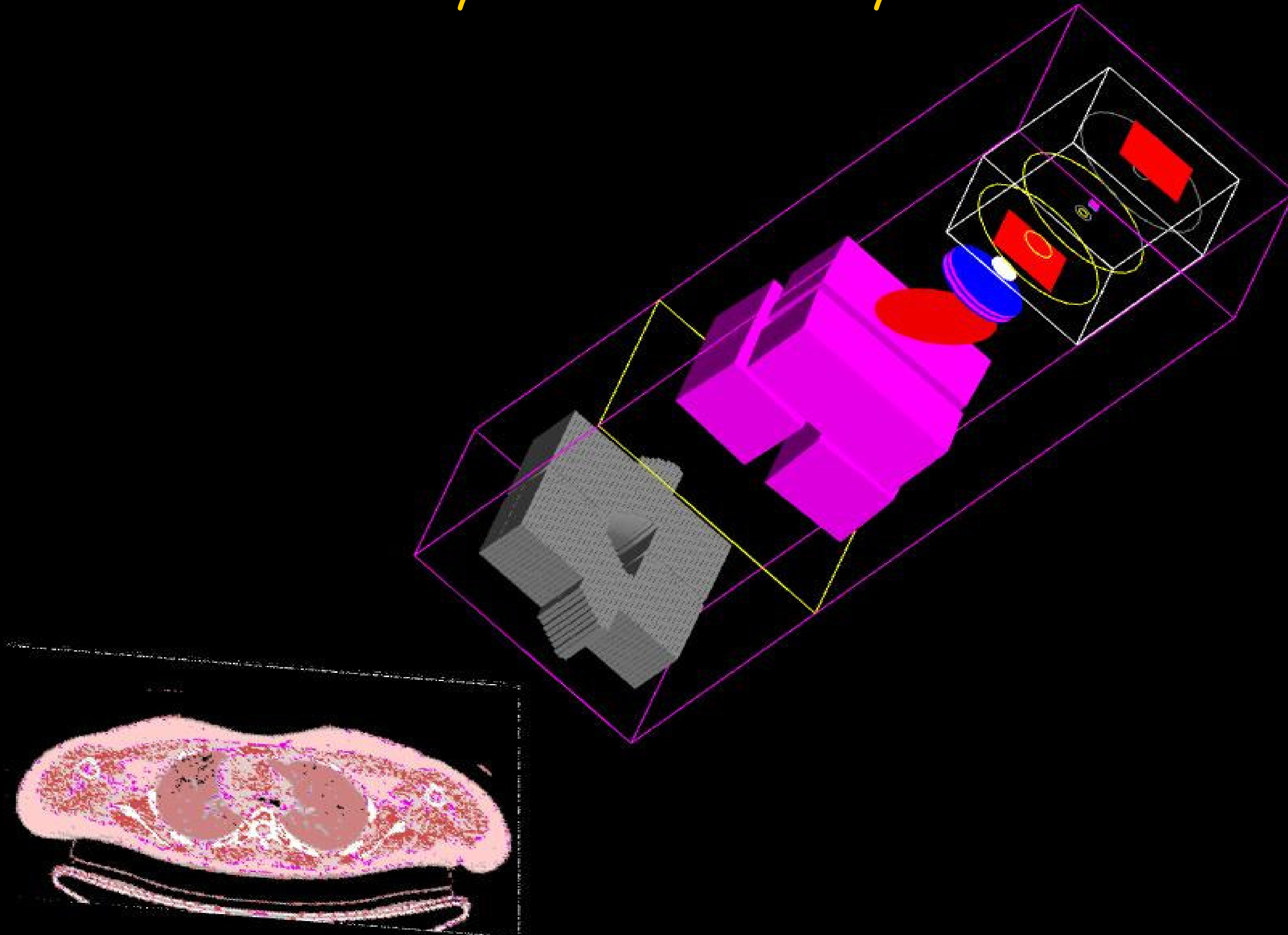
SPECT system in Hybrid-Simulation



IMRT Linac for Radiotherapy Applications

IMRT LINAC module was given as an example in Geant4
(developed by M. Piergentili)

IMRT LINAC in the Hybrid Simulation system



Tools used in this Project

- Geant4 – Latest version
- MATLAB for processing data
- ITK toolkit is used to Co-register images from different modalities
- DCMTK Library for reading DICOM images

Conclusion

- This will provide a Monte Carlo simulation platform for patient specific dose estimation in Nuclear medicine and internal and external beam radiotherapy applications.
- With the advancement of computer technology, we will be able to load an whole body CT data set of an adult in a computer memory (3.0 GHz Quad-core CPU with 12 GB RAM)
- Several voxelization and navigation methods were used
  - Trade off between speed and memory
- Optimised to run either faster or memory efficient depending on the application
- Requires further research on modelling varying activity distributions due to physiological activities of the organs in human body.