The Physics and Technology of CT

Determination of Dose From CT Examinations: Estimating Organ Dose Using Monte Carlo-Based Methods

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Background

- Radiation Dose from CT
- Has always been an area of concern for Medical Physicists
- Increased concern with MDCT
  - Increased utilization
  - Pediatric CT
  - Cardiac CT
  - Screening applications.
- How to accurately estimate radiation dose?
  - Organ dose is a key building block
  - How to estimate organ dose?

Background

- Monte Carlo methods
  - Used in CT for some time
    - NRPB report 250 (1990)
    - GSF (Zankl)

These early reports used:
- Detailed Models of Single Detector, Axial Scanners
- Idealized (Nominal) slice collimation
- Standard Man Phantom
  - MRD V (geometric model)
  - Eva, Adam
Background

- These form the basis for:
  - CT Dose computer program
  - ImPACT dose calculator
  - k factor approach (Effective dose = k * DLP), which was derived from NRPS simulated data

Current Approaches

- Model Scanner in detail
- Model Patient
- Simulate Scan
- Tally Organ Dose

Modeling the CT scanner

- Spectra
  - Obviously a function of beam energy
- Geometry
  - Focal spot to isocenter
  - Fan angle
- Beam Collimation
  - Nominal or actual
- Filtration
  - Bowtie filter (typically proprietary)
  - Other additional filtration (typically proprietary)
- Tube Current Modulation Scheme
  - x-only, z-only, x-y-z, etc.

Source Path - dependent on scan parameters:
- Nominal collimation
- Pitch
- Start and Stop Locations (of the source)
Modeling the Patient

- Geometric
  - e.g. MIRD
  - Standard man
  - Often androgynous
  - Usually single size
- Size and age variations have been created
  - newborn, ages 1, 5, 10, and 15 years
  - adult female, and adult male
  - Including pregnant patient

Modeling the Patient

- All radiosensitive organs identified
  - Location
  - Size
  - Composition and density

Modeling the Patient

- Voxelized Models
  - Based on actual patient scans
  - Identify radiosensitive organs – usually manually
  - Non-geometric
- Different age and gender
- Different sizes
Modeling the Patient

- GSF models (Petoussi-Henss N, Zankl M et al, 2002)
  - Baby, Child, three adult females (shown), two adult males, Visible Human
  - All radiosensitive organs identified manually (ugh!)

Modeling the Patient

- Xu – pregnant patient
- Bolch – UF Phantoms
- Zubal – Adult male phantoms
- Several others (see http://www.virtualphantoms.org/)

Modeling (Parts of) the Patient

- Embryo/Fetus
- Breast

7 weeks (embryo not visible)
Mature Fetus: 36 weeks

Original Image  Contoured Image  Voxelized Model

Early Gestation

Original Image  Contoured Image  Voxelized Model

Late Gestation

Simulating the Scan

- Select Technical Parameters
  - Type of scan (helical, axial)
  - Beam energy
  - Collimation
  - Pitch
  - Tube Current/rotation time
- Select Anatomic Region
  - Head
  - Chest
  - Abdomen/Pelvis
- Translate this to:
  - Start and stop location
  - Source Path
## Results (Angel et al 2006)

<table>
<thead>
<tr>
<th>Gestational Age (wks)</th>
<th>Approx. Mother Weight (lbs)</th>
<th>Mother Height</th>
<th>Approx. Perimeter of Mother (cm)</th>
<th>Fetal Dose (mGy/m100As)</th>
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<td>7</td>
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<td>107</td>
<td>6.9</td>
</tr>
</tbody>
</table>

The Monte Carlo approach to estimating radiation dose from CT is most often used to:

1. Measure CTDI for each scanner
2. Estimate the limitations of CTDI
3. Estimate dose to radiosensitive organs
4. Determine detector efficiencies
5. Determine which MDCT scanner is the most dose-efficient

One limitation to using the Monte Carlo approach to estimating radiation dose is:

1. Modeling a CT source accurately requires access to proprietary information
2. Modeling a patient accurately involves the use of human volunteers
3. Modeling a patient accurately involves segmenting every organ from image data
4. Simulating an actual scan accurately requires all of the information from the DICOM header
5. Calculating organ dose requires information about patient age, gender, height and weight.

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2. 
3. 
4. 
5. 


Monte Carlo for CT Dose - Details

- Monte Carlo Packages
  - MCNP (Los Alamos)
  - EGS
- Model Transport of Photons from a modified (CT) source
- Probabilistic interactions of photons with Tissues
  - Photoelectric
  - Compton Scatter
  - Coherent Scatter
- Tissues need detailed descriptions
  - Density
  - Chemical composition (e.g. from NIST material web site)

Dose Calculations

- Score absorbed dose based upon collision kerma ($K_c$).
- Calculated from MCNP track-length estimate of photon energy fluence.
- Multiply by the material-specific and energy-dependent mass energy-absorption coefficient.
- The mass energy-absorption coefficients were taken from the tables of Hubbel & Seltzer 1995.
- 1 keV energy cutoff for photons

Dose Calculations

- MCNP reports relative dose
  - In our case dose/photon from source
- Have to convert that to absolute dose (mGy).
- Therefore, simulation results must be normalized to absolute dose using measured and simulated air scans

$$ (NF)_{E,T} = \frac{(D_{Air,measured})_{E,T}}{(D_{Air,simulated})_{E,T}} $$

- To calculate Absolute Dose:

$$ (D_{absorb})_{E,T} = (NF)_{E,T} \times (D_{simulated})_{E,T} \times (TotalmA) $$
**Dose Calculations**

- Dose results are reported on a “per 100 mAs” basis.
- We aim for an MCNP relative error < 1%
  - typically requires between $10^6$ and $10^8$ source photons
  - ~2 hours of computing time on a PC for small structures (<5mm)
  - ~15 minutes for large organ structures such as the lung or breast
  - This is also dependent upon the location of the tally structure relative to the scan plane.
  - (can take much longer for full resolution, small structures)

**Validating the CT Scanner Model**

- Benchmark MC Model against physical measurements
  - CTDI Phantoms
    - Head and Body
    - Simulate a tally in a pencil chamber
    - Each kVp and beam collimation combination
    - Measured vs. Simulated
  - Aim for < 5% difference between Simulated and Measured

**Monte Carlo Methods**

- Used to Estimate Organ Doses
- MDCT scanner details
- Scan protocol details
- Different patient models
- Extendable to new geometries/methods
- Used to evaluate effectiveness of dose reduction methods on organ dose (and not just dose to phantoms)