The Physics and Technology of CT

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

Michael F McNitt-Gray, PhD, DABR
Professor
Department of Radiology
David Geffen School of Medicine at UCLA
Los Angeles, CA

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)

Background

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

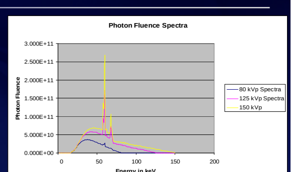
Background

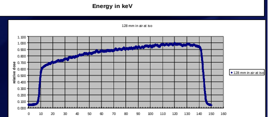
- These form the basis for:
  - CT Dose computer program
  - ImPACT dose calculator
  - k factor approach (Effective dose = k* DLP), which was derived from NRPB simulated data

Current Approaches

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

Modeling the CT scanner

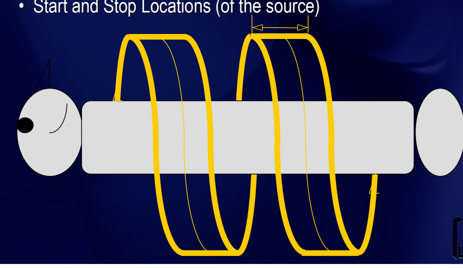




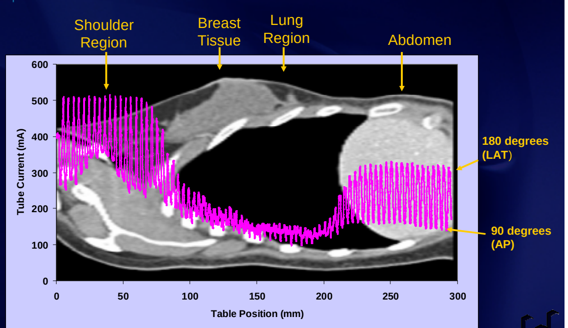
- Spectra
  - Obviously a function of beam energy
- Geometry
  - Focal spot to isocenter
  - Fan angle
- Beam Collimation
  - Nominal or actual
- Filtration
  - Bowtie filter (typically propietary)
  - Other additional filtration (typically proprietary)
- Tube Current Modulation Scheme
  - x-y only,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

Modeling the CT scanner

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

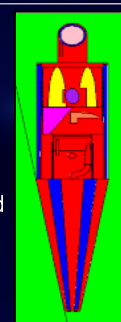


Long Axis Modulation



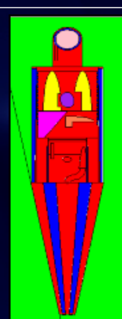
Modeling the Patient

- 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

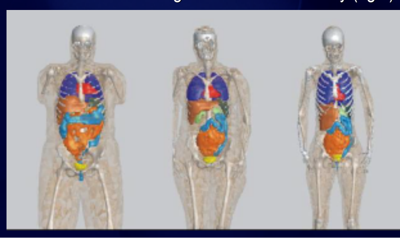


Modeling the Patient

- 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!)



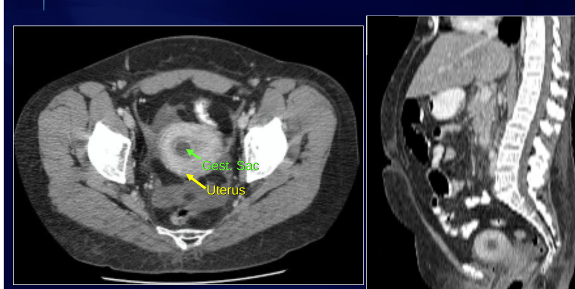
Modeling the Patient

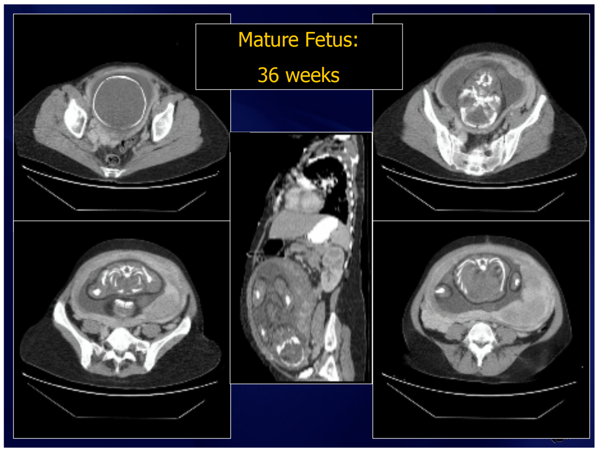
- Xu – pregnant patient
- Bolch – UF Phantoms
- Zubal – Adult male phantoms
- Several others (see http://www.virtualphantoms.org/)

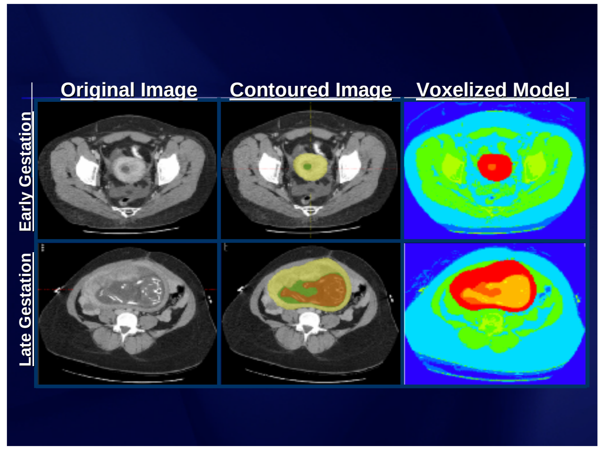
Modeling (Parts of) the Patient

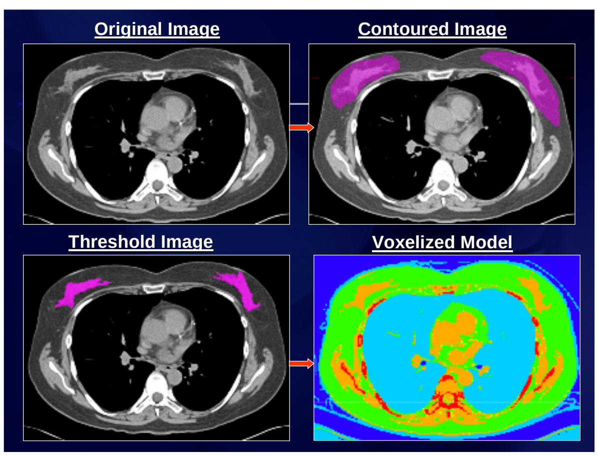
- Embryo/Fetus
- Breast

7 weeks (embryo not visible)









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)

Gestational Age (wks)	Approx. Mother Weight (lbs)	Mother Height	Approx. Perimeter of Mother (cm)	Fetal Dose (mGy/m100As)
5	N/A "obese"	N/A	105	7.3
7	134	N/A	95	8.8
7	137	N/A	86	12.0
12	100	N/A	86	11.4
15	106	5'0"	85	7.6
17	126	5'2"	86	12.2
20	270	N/A	106	5.1
24	120	N/A	111	8.1
24	144	N/A	88	11.5
25	119	N/A	83	12.3
27	244	5'8"	111	10.6
28	163	5'3"	110	9.5
29	220	5'5"	98	9.7
35	136	5'6"	87	10.4
36	N/A	N/A	107	8.9

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

0% 1. Measure CTDI for each scanner
0% 2. Estimate the limitations of CTDI
0% 3. Estimate dose to radiosensitive organs
0% 4. Determine detector efficiencies
0% 5. Determine which MDCT scanner is the most dose-efficient

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

1.
2.
3. Estimate dose to radiosensitive organs
4.
5.

Lee C et al. Organ and effective doses in pediatric patients undergoing helical multislice computed tomography examination. Med Phys. 2007 May;34(5):1858-73.

DeMarco JJ et al. Estimating radiation doses from multidetector CT using Monte Carlo simulations: effects of different size voxelized patient models on magnitudes of organ and effective dose. Phys Med Biol. 2007 May 7;52(9):2583-97.

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

0% 1. Modeling a CT source accurately requires access to proprietary information
0% 2. Modeling a patient accurately involves the use of human volunteers
0% 3. Modeling a patient accurately involves segmenting every organ from image data
0% 4. Simulating an actual scan accurately requires all of the information from the DICOM header
0% 5. Calculating organ dose requires information about patient age, gender, height and weight.

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2.
3.
4.
5.

DeMarco JJ et al. A Monte Carlo based method to estimate radiation dose from multidetector CT (MDCT): cylindrical and anthropomorphic phantoms. Phys Med Biol. 2005 Sep 7;50(17):3989-4004.

Jarry G et al. A Monte Carlo-based method to estimate radiation dose from spiral CT: from phantom testing to patient-specific models. Phys Med Biol. 2003 Aug 21;48(16):2645-63.

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:

$$(D_{absolute})_{E,T} = (NF)_{E,T} * (D_{simulated})_{E,T} * (TotalmAs)$$

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)