Objectives

1. To provide an educational review of the physics and techniques behind model based algorithms e.g. convolution/superpositioning models.

2. To review the methods used to improve the simulation efficiency i.e. pencil beam and collapsed cone convolutions.

3. To briefly review the vendor codes currently used for clinical treatment planning.

4. To briefly review the potential clinical implications of accurate calculated dose distributions.
The Problem

- Modelling the linac
  - Energy fluence
    - Source models
    - Monte Carlo
- Modelling of dose in patients
  - Interpolation and correction of measured data
  - Fluence to dose modelling
  - Monte Carlo

Remember

- Photons are indirect ionizing radiation
- Produces electrons through interaction
  - Pair production, Compton and photo
- Electrons deposit energy by ionization

Thus keeping track of electrons is highly important for accurate dose calculations
Photon Fluence via TERMA to Absorbed Dose using Convolution

\[ D(x) = \int T(x') \cdot K(x - x') \, dx' \]

\[ D(r) = T(r) \otimes K(r) \]

This idea was explored by several papers at the ICCR 1984

What is TERMA?

- Ray-tracing Total Energy Released in Mass (TERMA)
- Similar to determining effective or radiological depth

\[ T(E, z) = \frac{\mu_E}{\rho} \cdot \Phi(E, z) \cdot E = \frac{\mu_E}{\rho_0} \Phi_0(E, 0) \cdot e^{-\mu_E z_{eq}} \cdot E \]

\[ z_{eq} = \frac{1}{\rho_{water}} \int_0 \rho(z') \cdot dz' \]
Dose deposition kernel - $K$

- Primary: 0.5 cm
- First scatter: 10 cm
- Total: 10 cm

5 MeV
15 MV

- 1.25 MeV
- 10.0 MeV

The fraction of energy deposited within radial bins as function of radius

Mackie et al 1988, PMB

AAPM 2009
Convolve!

- Apply the dose kernel to each TERMA point
- Integrate over the whole volume i.e. a convolution

\[
D(x) = \int T(x') \cdot K(x-x')dx'
\]

[1D convolution]

Convolution in 2D

Convolution is efficiently solved by Fast Fourier Transform techniques.
Example: Point kernel convolution - CMS

- Re-sampling of Mackie’s kernels to Cartesian coordinates
- Fast Fourier Transform (FFT) solution
- Two separate calculations:
  - A primary kernel for which the calculation is performed at high-resolution but over a small region – high gradient – short range
  - A scatter kernel, where the calculation is performed at a lower resolution but over a larger area – low gradient – long range
  - Time saving of about 65 % by this technique

Limitations of convolution

- Kernels are not invariant in space
  - Energy distribution varies with position in beam
    - Beam softening laterally
    - Beam hardening longitudinally
- Kernels vary with density
- Divergence leading to tilted kernels
- Pre-calculated kernels won’t make it!!!
- FFT not suitable – analytical methods must be used – time consuming
- Approximate methods required
1st approximation

Pencil Beam

- Reduce the dimensionality of the problem by pre-convolving in the depth dimension

=> Pencil beams (PB)

- Superposition of pencil beams in 2D => Faster

- Creation by: De-convolution or differentiation from measurements or by Monte Carlo methods

Illustration of Pencil Beam superpositioning (convolution)

Energy fluence \times Deposition Kernel = Absorbed Dose
Example: Pencil beam model – Nucletron OMP

- Pencil beams based on MC calculated point kernels, integrated and fitted to a limited number of depth doses
- Separates “primary” and “scatter” dose
- Heterogeneities handled via effective path length – only longitudinal scaling
- Extensive beam modelling

Nucletron (former MDS Nordion and Helax-TMS)

Example: Pencil beams model - Eclipse

- Uses pencil beams extracted from measurements (SPB) or from Monte Carlo calculation (AAA)
- Heterogeneities handled via effective path length – longitudinal
- AAA adds a scaling of the spread of the pencil based on density – lateral
- AAA also have an extensive beam modelling

Analytical Anisotropic Algorithm
**2nd approximation**
Collapsed cone convolution

- Kernels are discretised
- Collapsing removes the inverse square law – only exponential attenuation is left

**Number of collapsed cones or directions**

- Sufficient density of cones to distribute energy to all voxels
  - Not possible but at least while the energy is significant
  - ~100 (Mackie et al, 1996 Summer school)
  - Voxels will be missed at large distances – very low energy contribution
- 128 CC are used in CMS (48 for the fast version)
- 106 CC are standard in OMP
Implementation issues

Accounts for
- Heterogeneities
  Kernels scaled for different tissues
- Lateral energy transport
- Beam Hardening and Off-axis spectrum softening
  Included in Ray Trace process
- Tilt of kernels
  Included in Transport

Polyenergetic Spectrum accounted for by weighted sum of monoenergetic kernels calculated by Monte Carlo

Weights determined by comparison with measured data

Examples: Collapsed cone

- Philips - Pinnacle
  - Polyenergetic weighted kernels, total energy
  - Off-axis/tilting considered during TERMA
  - Collecting dose or dose point of view

- CMS - XiO
  - Two kernels, Primary electron dose and scattered photon dose
  - No Off-axis/tilting
  - Collecting dose or dose point of view

- Nucletron – Oncentra MasterPlan
  - Two Kernels are used:
    - One for Collision Kerma into Primary Dose
    - One for ‘Scerma’ into Phantom Scatter Dose
  - Kernels parameterised and fitting parameters stored for run time
  - Off-axis/tilting
  - Recursive dose collect/deposit model along parallel lines

These are ‘iso-scatter’ lines.

They link points producing equal scatter to here.

Primary interaction point

These are ‘isodose’ lines

From Deshpande, Philips
Further approximation

- **Multigrid solution (CMS - XiO)**
  - Only calculate dose using superposition at points where it is necessary, and at all other points use interpolation to get a reasonable estimate of dose

- **Adaptive CCC (Philips - Pinnacle)**
  - Only performs convolution at every 4th point in the TERMA array
  - Gradient search performed on TERMA array
  - Dose in between is interpolated if gradient low (i.e. TERMA doesn’t change much)
  - Convolution performed at every point if TERMA gradient high

Example from CMS

Summary of Models/Algorithms

- **Inhomogeneities** are handled by scaling the kernels rectilinearly with electron density according to the theorem by O’Connor 1957

- **Type a** – Models primarily based on EPL scaling for inhomogeneity corrections.
  - Eclipse/SPB, OMP/PB, PPLAN, XiO/Convolution
  - LONGITUDINAL scaling

- **Type b** – Models that in an approximate way consider changes in lateral electron transport
  - Pinnacle/CC, Eclipse/AAA, OMP/CC, XiO/Superpositioning.
  - LONGITUDINAL and LATERAL scaling
Performance of Convolution Models

Carefully implemented algorithms together with accurate beam models works for most linacs:

- Gamma-analysis, calc-meas
- Inside field after buildup
- Less than 0.5 % of points outside 3 mm/1 %
- One implementation 0.7 %

AAA-PB model in Ecplise

Cozzi et al, 2008, Z Med Physik
Pencil beam calculations in a blocked fields

From Storchi and Woudstra, 1996, PMB

From Van Esch et al, 2006, Med Phys

From van’t Weld, 1997, Radioth Oncol

A problem using pencil beams
Irregular geometries

The same dose to ● in all geometries since the PB is pre-integrated to a certain depth/length

See also Hurkmans et al, 1986, RO
Convolution methods in homogeneous water

- Differences in beam modelling (not part of this SAM)
  - Head scatter
  - Electron contamination
  - Wedges/Blocks
  - MLC
- May lead to slightly different accuracy
- Basically all models perform well in water
  - Point, pencil or collapsed cone implementations

Comparison in inhomogeneous phantoms

From Fogliata et al 2007, PMB
Common implementation vs MC

Small solid lesion in low density lung tissue e.g. stereotactic treatment

Eclipse/ModBatho
OMP/PB
XiO/Conv
Eclipse/AAA
Pinnacle/CC
XiO/Super

Tangential treatment of breast

Knöös et al. 2006, PMB
### Tangential treatment of breast

<table>
<thead>
<tr>
<th></th>
<th>6 MV</th>
<th>Average values for type a</th>
<th>Average values for type b</th>
</tr>
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<tbody>
<tr>
<td>PTV Mean</td>
<td>100</td>
<td>99.3</td>
<td></td>
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<tr>
<td>PTV D_{95}</td>
<td>91.0</td>
<td>90.4</td>
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<tr>
<td>PTV D_{5}</td>
<td>108.8</td>
<td>108.9</td>
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<tr>
<td>PTV D_{5}-D_{95}</td>
<td>17.8</td>
<td>18.5</td>
<td></td>
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<tr>
<td>Pulm sin D_{5}</td>
<td>92.6</td>
<td>83.1</td>
<td></td>
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<tr>
<td>Pulm sin D_{95}</td>
<td>3.3</td>
<td>4.0</td>
<td></td>
</tr>
</tbody>
</table>

D_{XX} is the dose level that encompasses XX % of the volume.

### 5 field 18 MV – lung
5 field 18 MV – lung

Results from RPC thorax phantom

- 15 cases planned with type a
  - 84% ± 16% of the pixels met the criteria (5%/5mm)

- 30 cases planned with type b
  - 99% ±4% of the pixels met the criteria (5%/5mm)
Conclusions – Dose changes

- **Prostate**
  - non-significant

- **H&N**
  - none (depending on accuracy of scatter integration) and air cavities (air or low dense water)

- **Breast**
  - slightly lower dose to breast and especially in lung in proximity to the target however larger irradiated lung volume

- **Lung - PTV**
  - 2-4 % lower average dose
  - Wider penumbra

- **Lung (treated side)**
  - 10 % lower dose to the highest irradiated parts of the lung
  - 5 % higher dose (15 => 20 %) to the lung \( D_{50} \)

- **Lung (healthy side)**
  - Average dose identical (9.8-10.7 %)

Implications of introducing new and more accurate algorithms

- **Significant changes in dose to target volumes and surrounding tissues especially when lung is involved**
  - Consequences for assessment of dose-effect relationships

- **Careful analysis of changes is required before adopting new algorithms**
  - Retrospectively re-calculate plans when clinical outcome is known?
  - Construct new plans with older algorithms and re-calculate?
  - New plans with old prescriptions and new algorithms?
  - Optimize plans to the same biological effect on PTV and/or OAR?
Implications of introducing new and more accurate algorithms

- Significant changes in dose to target volumes and surrounding tissues especially when lung is involved
  - Consequences for assessment of effects
  - Careful analysis of changes is required before adopting new algorithms

Discussions are needed between physicists and oncologists to fully understand the effects and potential consequences

- Construct new plans with older algorithms and re-calculate?
- New plans with old prescriptions and new algorithms?
- Optimize plans to the same biological effect on PTV and/or OAR?

Conclusion

- Convolution methods are accurate
  - For low density regions – use models with lateral scaling
- Verification
  - Also Vendor’s responsibility!
- Be careful when transferring to more accurate models but…

**Important to do this!**