Objectives

1. To provide an educational review of the physics and techniques behind convolution algorithms
2. To review the methods used to improve the simulation efficiency i.e. pencil beam and collapsed cone convolutions
3. To briefly review the performance of codes currently used for clinical treatment planning.
4. To discuss the issues associated with experimental verification of dose calculation algorithms.
5. 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

Fluence to dose
Convolution

\[ D(x) = \int T(x') \cdot K(x-x')dx' \]
\[ D(r) = \tilde{T}(r) \otimes K(r) \]

This idea was explored by several papers at the ICCR 1984
Modelling primary photon energy fluence and loss

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

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

$$z_{eq} = \frac{1}{\rho_{\text{water}}} \int_0^z \rho(z') \cdot dz'$$

Modelling dose deposition

- Dose distribution around a single interaction point
  - Point dose kernel
- Separate primary, 1st scatter, 2nd scatter, multiple residual scatter dose kernels

Generation of photon energy deposition kernels using the EGS Monte Carlo code

T D Mackie†, A F Webster†, D W G Rogers† and J I Betzard
Convolve!

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

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

[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
- 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 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
Illustration of Pencil Beam superpositioning (convolution)

Energy fluence ⊗ Dose Deposition Kernel = Absorbed Dose

Construction of Pencil Kernels

**Extraction of pencil beam kernels by the deconvolution method**

Chen-Shou Chui and Radhe Mohan  
*Department of Medical Physics, Memorial Sloan-Kettering Cancer Center, New York, New York 10021*  
(Received 15 June 1987; accepted for publication 14 December 1987)

Experimental determination of the dose kernel in high-energy x-ray beams

Cecilia P. Celberg and Bengt E. Björnholdt  
*Department of Radiation Oncology, Roger Williams Medical Center, Brown University, Providence, Rhode Island 02903*

Timothy G. Zhai  
*Department of Radiation Oncology, Memorial Cancer Center, University of Florida, Gainesville, Florida 32610-0385*  
(Received 26 June 1995; accepted for publication 12 December 1995)

From measurements by differentiating

Use of fast Fourier transforms in calculating dose distributions for irregularly shaped fields for three-dimensional treatment planning

Radhe Mohan and Chen-Shou Chui  
*Department of Medical Physics, Memorial Sloan-Kettering Cancer Center, New York, New York 10021*  
(Received 10 June 1986; accepted for publication 22 October 1986)

A pencil beam model for photon dose calculation

Anders Ahnesjö  
*Department of Radiative Physics, Karolinska Institutet, Stockholm, Sweden and Helen AB, Box 1794, S-751 47 Uppsala, Sweden*

Mikael Sjöö and Pär Trapp  
*Helen AB, Box 1794, S-751 47 Uppsala, Sweden*  
(Received 29 October 1990; accepted for publication 1 July 1991)
Example: Pencil beam model – Nucletron

- 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, 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

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

- Pinnacle
  - Polyenergetic weighted kernels, total energy
  - Off-axis/tilting considered during TERMA
  - Collecting dose or dose point of view
- CMS
  - Two kernels, Primary electron dose and scattered photon dose
  - No Off-axis/tilting
  - Collecting dose or dose point of view
- Nuceltron
  - 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
Further approximation

- Multigrid solution (CMS)
  - 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 (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

Conclusions

- 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

Comparison in homogeneous water phantoms

All systems are expected to work excellent in homogeneous water

Knöös et al, 1994, PMB
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

AAA-PB model in Eclispe

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 %

Cozzi et al, 2008, Z Med Physik
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
  - 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
**Single beam**

Comparison in inhomogeneous phantoms

From Fogliata et al 2007, PMB

Density 0.2 g/cm³

**Two beams**

PB with longitudinal (PB) plus lateral scaling (AAA)

Pencil beam - NC-No Correction, MB-Modified Batho: Both without lateral scaling

AAA- with lateral scaling

Impact of inhomogeneity corrections on dose coverage in the treatment of lung cancer using stereotactic body radiation therapy

Suresh B. Shenoi, Carmen A. Tucson, Sh. Lu, Davina R. Nellesen, Jeffrey C. Oliver, Aurea Dabbs, and Charles R. Gaffney

Med Phys 2007
Multiple beams

PB w/wo lateral scaling and CC vs MC

From Lasse Rye Aarup, Copenhagen

Tangential treatment of breast

Knöös et al, 2006, PMB
**Tangential treatment of breast**

<table>
<thead>
<tr>
<th></th>
<th>6 MV</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Eclipse/ModB</strong></td>
<td></td>
<td><strong>OMP/PB</strong></td>
<td><strong>XiO/Conv</strong></td>
</tr>
<tr>
<td>PTV Mean</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PTV $D_{95}$</td>
<td>91.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PTV $D_5$</td>
<td>108.8</td>
<td></td>
<td></td>
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<tr>
<td>PTV $D_{5-95}$</td>
<td>17.8</td>
<td></td>
<td></td>
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<tr>
<td>Pulm sin $D_5$</td>
<td>92.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulm sin $D_{50}$</td>
<td>3.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Average values for type a** | **Average values for type b**

**Average values for type b**

**Average values for type a**

6 MV

**OMP/PB**

**XiO/Conv**

**Eclipse/AAA**

**Pinnacle/CC**

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5 field 18 MV – lung

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

**Knöös et al., 2006, PMB**
### 5 field 18 MV – lung

<table>
<thead>
<tr>
<th></th>
<th>XiO/Conv Average values for type a</th>
<th>XiO/Conv Average values for type b</th>
<th>Eclipse/AAA Average values for 6 MV</th>
<th>Eclipse/AAA Average values for 18 MV</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTV Mean</td>
<td>100</td>
<td>97.5</td>
<td>100</td>
<td>96.3</td>
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<tr>
<td>PTV D$_{95}$ ~max</td>
<td>92.7</td>
<td>91.3</td>
<td>95.2</td>
<td>91.5</td>
</tr>
<tr>
<td>PTV D$_{5}$ ~min</td>
<td>106.2</td>
<td>102.8</td>
<td>104.4</td>
<td>99.8</td>
</tr>
<tr>
<td>PTV D$<em>{5}$-D$</em>{95}$</td>
<td>13.5</td>
<td>11.6</td>
<td>9.2</td>
<td>8.3</td>
</tr>
<tr>
<td>Pulm Sin D$_{50}$</td>
<td>14.2</td>
<td>19.7</td>
<td>15.7</td>
<td>20.6</td>
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<tr>
<td>Pulm Sin D$_{5}$</td>
<td>103.7</td>
<td>96.3</td>
<td>101.3</td>
<td>91.9</td>
</tr>
<tr>
<td>Pulm Sin D$_{1}$</td>
<td>107.9</td>
<td>100.0</td>
<td>104.3</td>
<td>95.9</td>
</tr>
</tbody>
</table>

#### 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)

AAPM 2008 TU-C-AUD B-3 P Alvarez et al
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 %)

Knöös et al, 2006, PMB
Process of acceptance

1) Generic performance
2) Generic performance in users environment
3) Specific performance in users environment

Vendor/user

User

IEC 62103 – Requirements for the safety of radiotherapy TPS – Responsibility of vendor

- The manufacturer shall provide to the end user a declaration that the end user is authorized to use the TPS and that the TPS is in accordance with the applicable safety requirements.
- The end user and the manufacturer shall cooperate and agree on the system of validation to be implemented in the end user’s site.
- The manufacturer shall provide to the end user a statement that the TPS is in accordance with the applicable safety requirements.

IEC 62103 – Requirements for the safety of radiotherapy TPS – Verification of dose calculation

- The end user shall verify the correctness of the TPS in accordance with the applicable safety requirements.
- The manufacturer shall verify the correctness of the TPS in accordance with the applicable safety requirements.

Verification of dose calculation

Wieslander 2007
MC methods facilitate verification

Consistency of data sets
- Accelerator stability in time
  - Energy, symmetry, output, flatness
- No fluctuation in time
  - Possible to add new verification geometries

Study of beam models
- Labelling in MC codes to keep track of interaction history

Studies of dose components
Separation of dose components in phantoms primary and scatter dose

Virtual linear accelerator
Comparisons in patient geometry

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 dose-effect relations
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  - New plans with old prescriptions and new algorithms?
  - Optimize plans to the same biological effect on PTV and/or OAR?

Discussion is needed between physicists and oncologists to fully understand the effects and potential consequences.

Morgan et al 2008

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!**