WE-B-AUD C CE-Therapy
July 30, 2008

Dose calculation algorithms in 3DCRT and IMRT

Tom Knöös, Lund, Sweden

Brendan McClean, Dublin, Ireland

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Celebrating the present
Preparing for the future
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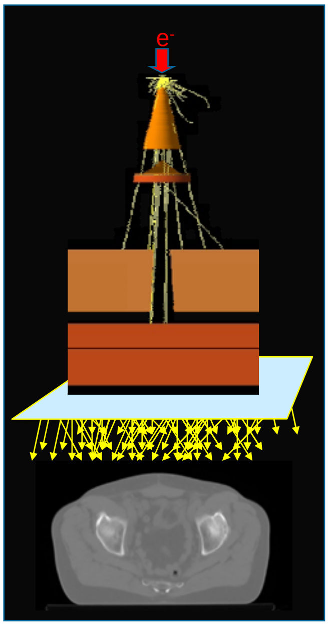
Objectives

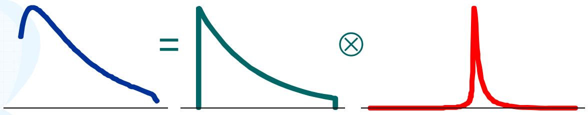
1. To provide an educational review of the physics and techniques behind convolution algorithms
2. To review the methods used to improve the simulation efficiency i.e. pencil beam and collapsed cone convolutions
3. To briefly review the performance of codes currently used for clinical treatment planning.
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



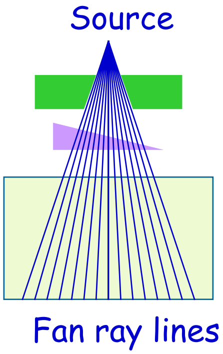
[1D convolution]

$$D(x) = \int T(x') \cdot K(x-x')dx'$$
$$D(\mathbf{r}) = T(\mathbf{r}) \otimes K(\mathbf{r})$$

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

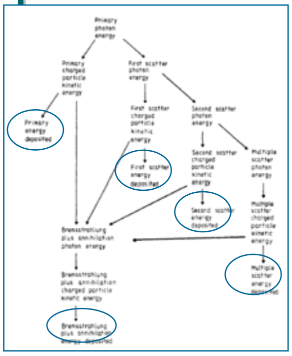


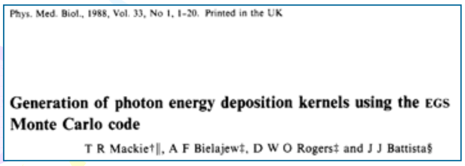
$$T(E,z) = \frac{\mu_E}{\rho} \cdot \Phi(E,z) \cdot E = \frac{\mu_E}{\rho} \Phi_0(E,0) \cdot e^{-\mu_E \cdot z_{eq}} \cdot E$$

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

Modelling dose deposition

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

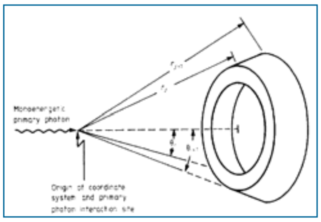




Phys. Med. Biol., 1988, Vol. 33, No 1, 1-20. Printed in the UK

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

T R Mackie†‖, A F Bielajew‡, D W O Rogers‡ and J J Battista§



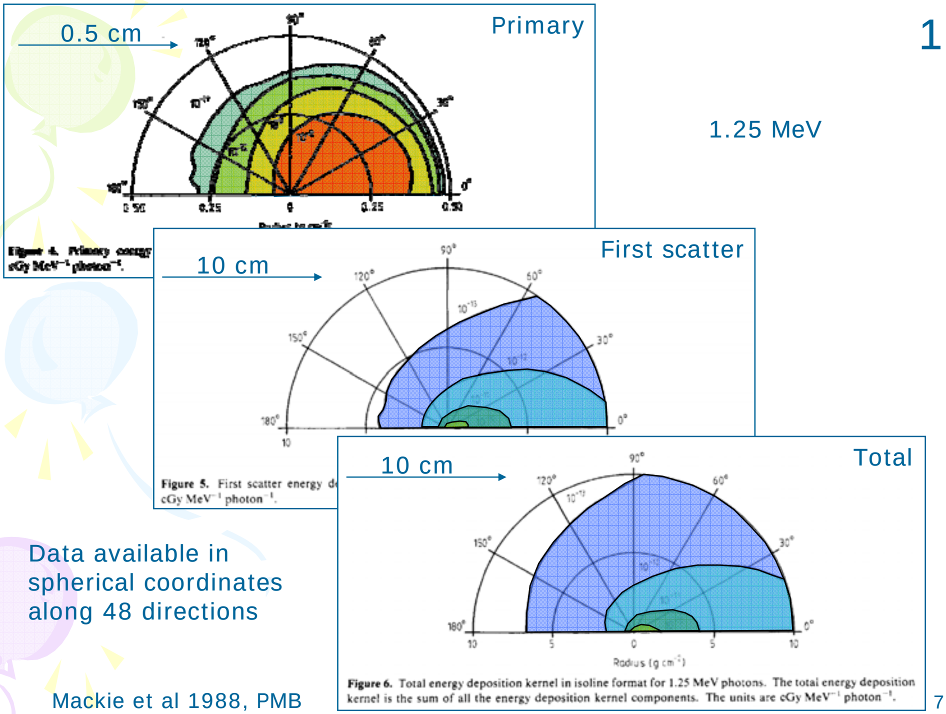


Figure 4. Primary energy … cGy MeV⁻¹ photon⁻¹.

Figure 5. First scatter energy d… cGy MeV⁻¹ photon⁻¹.

Figure 6. Total energy deposition kernel in isoline format for 1.25 MeV photons. The total energy deposition kernel is the sum of all the energy deposition kernel components. The units are cGy MeV⁻¹ photon⁻¹.

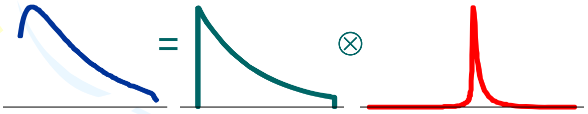
1.25 MeV

Data available in
spherical coordinates
along 48 directions

Mackie et al 1988, PMB

Convolve!

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



[1D convolution]

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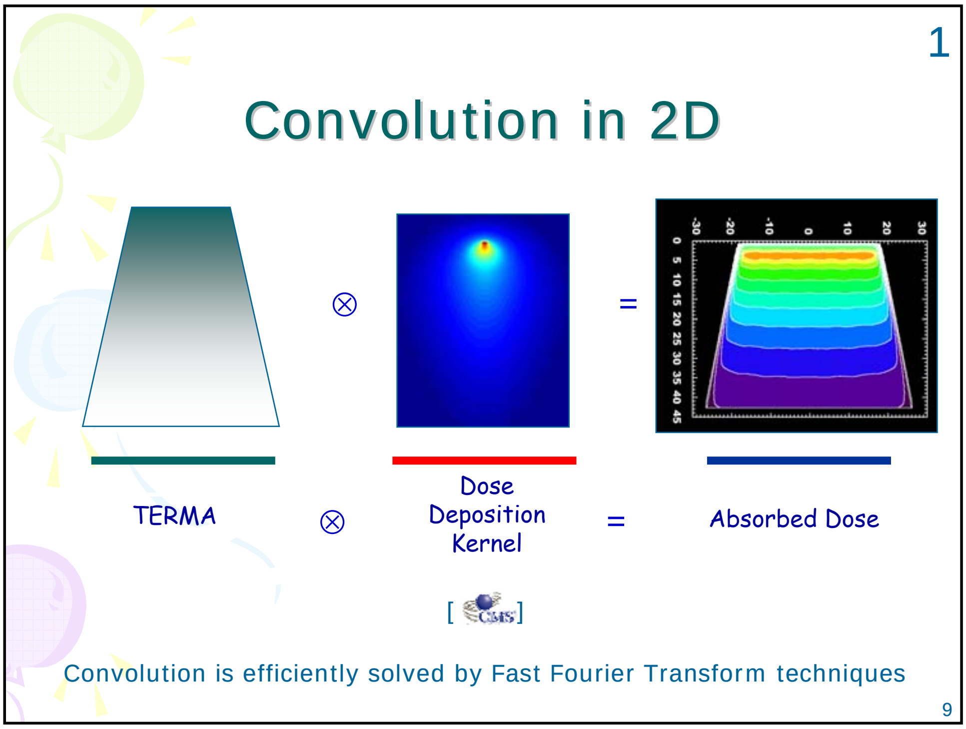

Convolution in 2D

TERMA ⊗ Dose Deposition Kernel = Absorbed Dose

Convolution is efficiently solved by Fast Fourier Transform techniques

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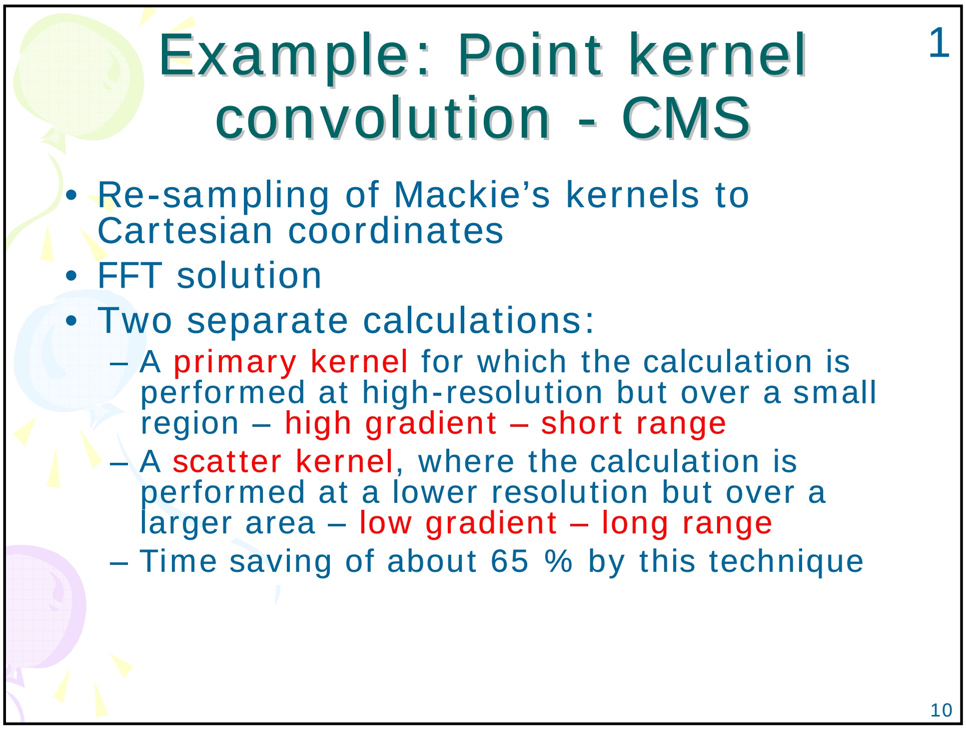


Example: Point kernel convolution - CMS

- 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

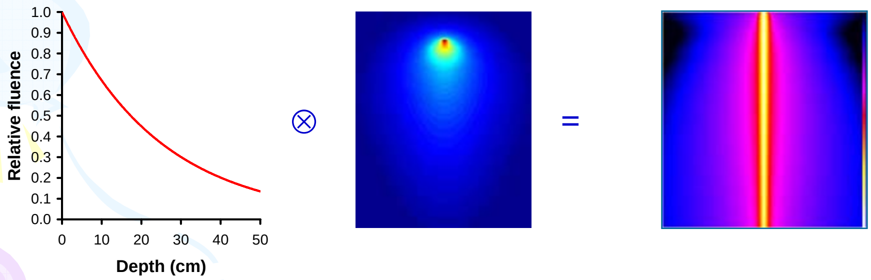
Limitations of convolution

- 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

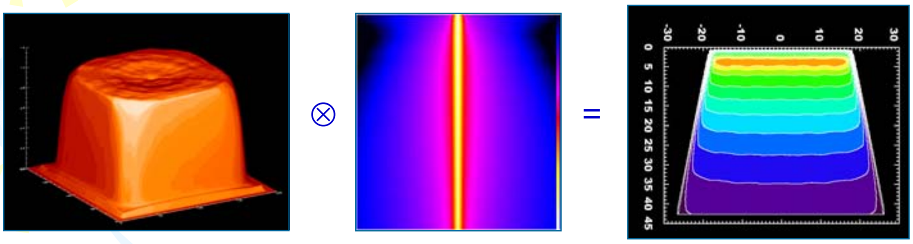
1st approximation Pencil Beam

- 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)

De-convolved from measurements ←

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

Crister P. Ceberg and Bengt E. Bjärngard
Department of Radiation Oncology, Roger Williams Medical Center, Brown University, Providence, Rhode Island 02908-4735

Timothy C. Zhu
Department of Radiation Oncology, Shands Cancer Center, University of Florida, Gainesville, Florida 032610-0385

(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[a)]

Radhe Mohan and Chen-Shou Chui
Department of Medical Physics, Memorial Sloan–Kettering Cancer Center, New York, New York 10021

(Received 30 June 1986; accepted for publication 22 October 1986)

Calculated by Monte Carlo methods ← ↓

A pencil beam model for photon dose calculation

Anders Ahnesjö
Department of Radiation Physics, Karolinska Institute, Stockholm, Sweden and Helax AB, Box 1704, S-751 47 Uppsala, Sweden

Mikael Saxner and Avo Trepp
Helax AB, Box 1704, S-751 47 Uppsala, Sweden

(Received 29 October 1990; accepted for publication 1 July 1991)

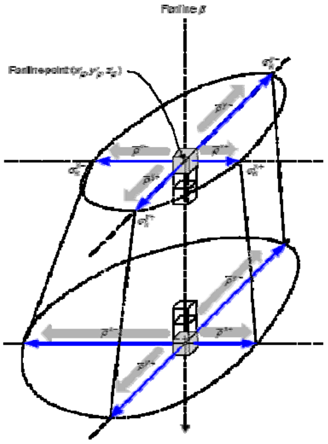
Example: Pencil beam model – Nucletron

- 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)

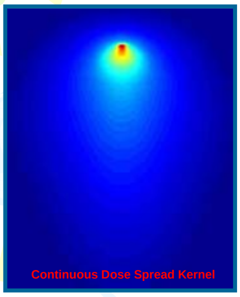
Example: Pencil beams model - Eclipse

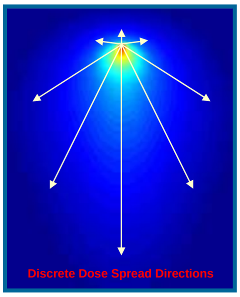
- Uses pencil beams extracted from measurements (SPB) or from Monte Carlo calculation (AAA)
- Heterogeneities handled via effective path length – longitudinal
- AAA adds a scaling of the spread of the pencil based on density – lateral
- AAA also have an extensive beam modelling

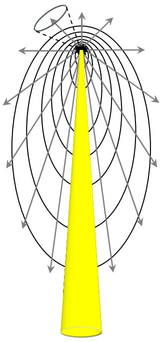


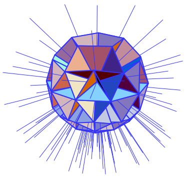
Analytical Anisotropic Algorithm

2nd approximation Collapsed cone convolution

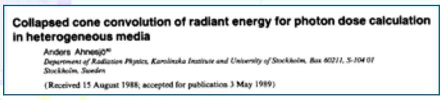

Continuous Dose Spread Kernel


Discrete Dose Spread Directions


Quantization in cones


Collapsed Cones

Kernels are discretised


Collapsed cone convolution of radiant energy for photon dose calculation in heterogeneous media

Anders Ahnesjö[a]

Department of Radiation Physics, Karolinska Institute and University of Stockholm, Box 60211, S-104 01 Stockholm, Sweden

(Received 15 August 1988; accepted for publication 3 May 1989)

Collapsing removes the inverse square law – only exponential attenuation is left

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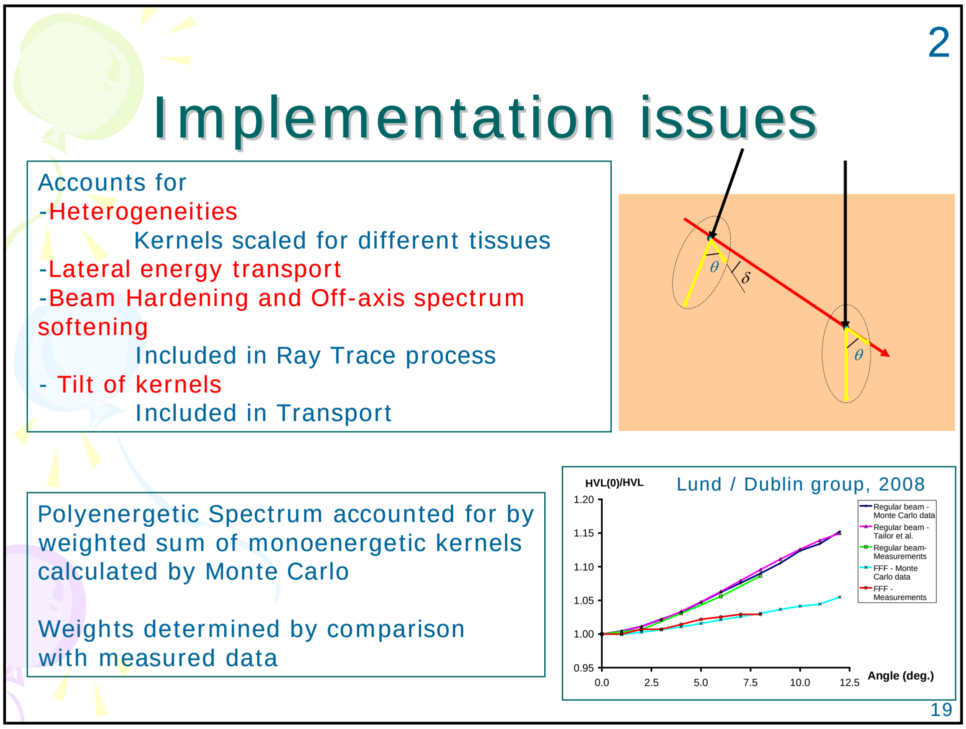
Number of collapsed cones or directions

- 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



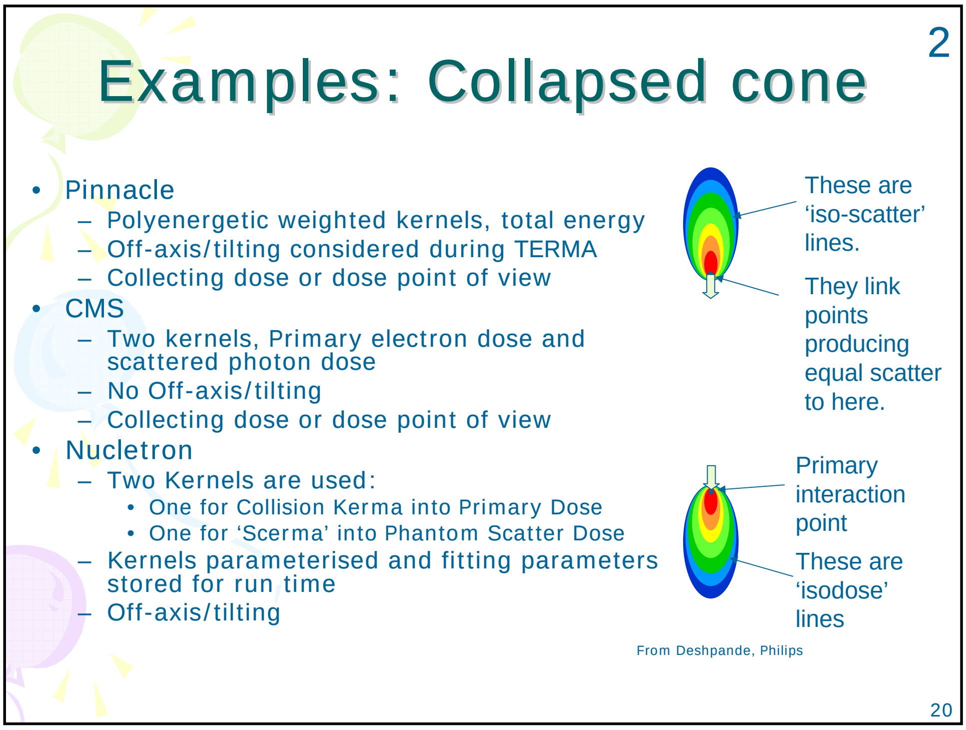
Implementation issues

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

Lund / Dublin group, 2008



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
- Nucletron
  - 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

These are 'iso-scatter' lines.

They link points producing equal scatter to here.

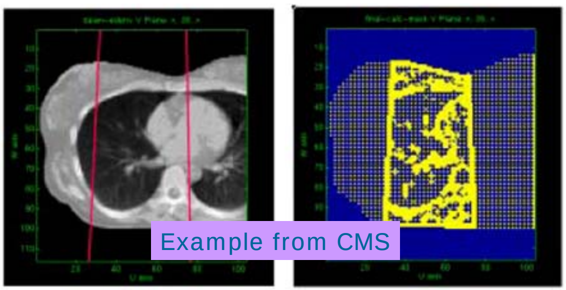
Primary interaction point

These are 'isodose' lines

From Deshpande, Philips

Further approximation

- Multigrid solution (CMS)
  - 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

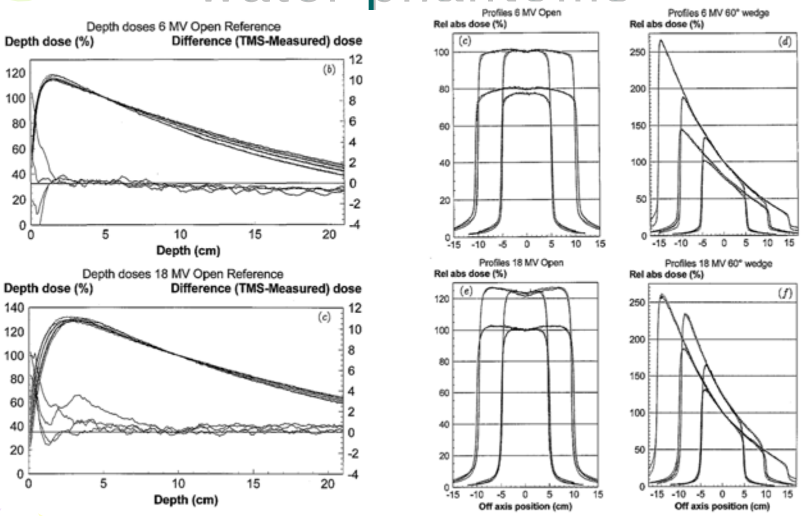
Conclusions

- 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

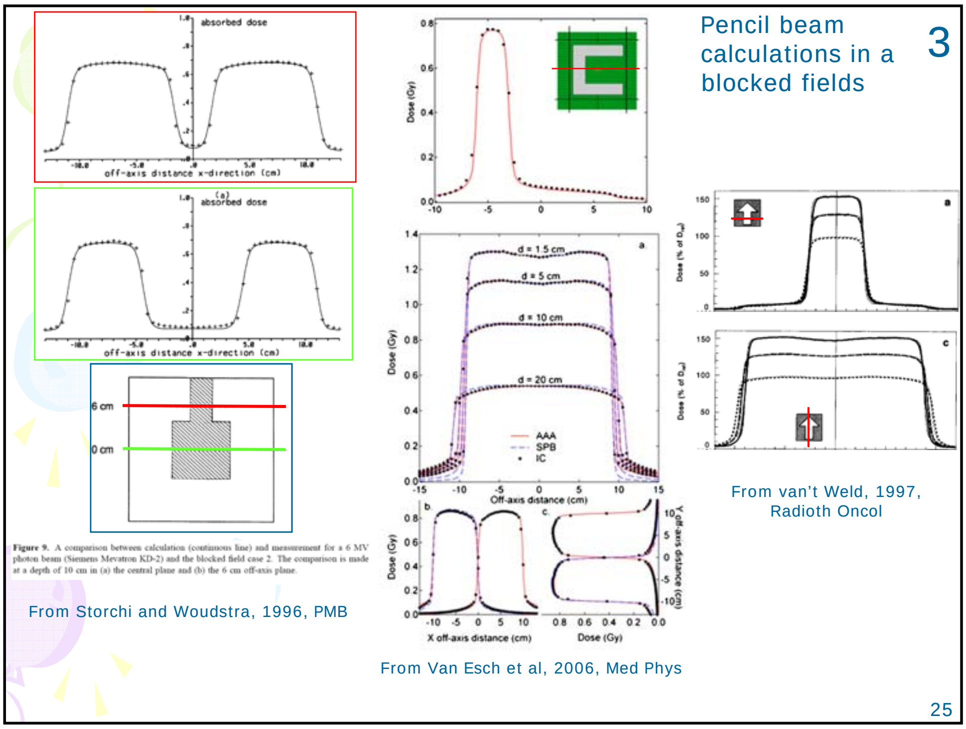
3

Comparison in homogeneous water phantoms



All systems are expected to work excellent in homogenous water

Knöös et al, 1994, PMB



Pencil beam calculations in a blocked fields

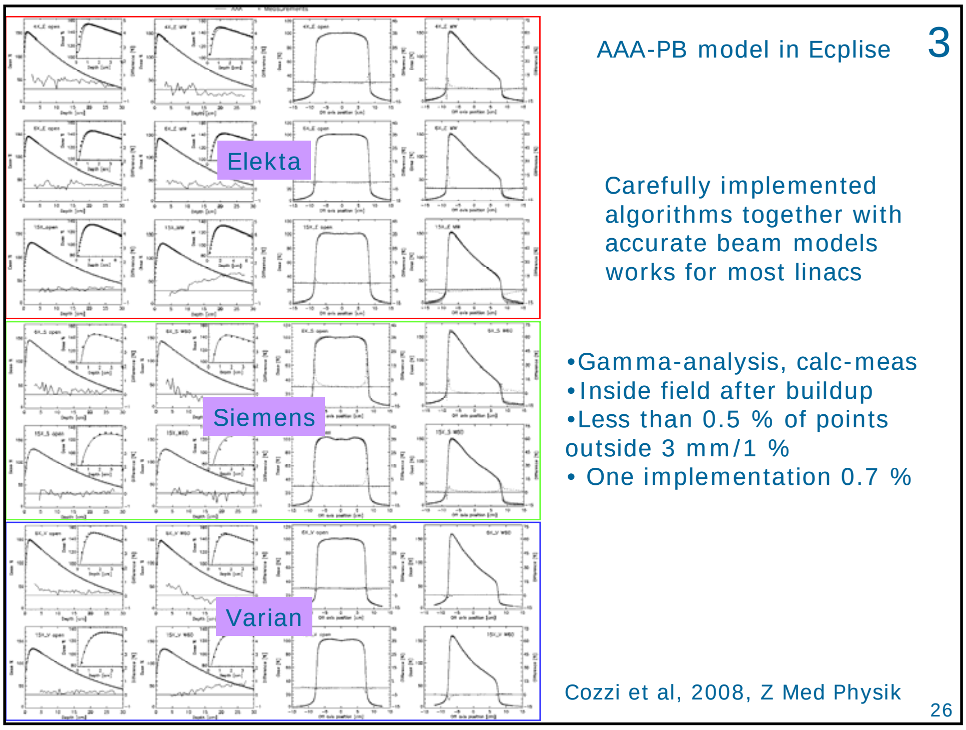
3

Figure 9. A comparison between calculation (continuous line) and measurement for a 6 MV photon beam (Siemens Mevatron KD-2) and the blocked field case 2. The comparison is made at a depth of 10 cm in (a) the central plane and (b) the 6 cm off-axis plane.

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 Ecplise

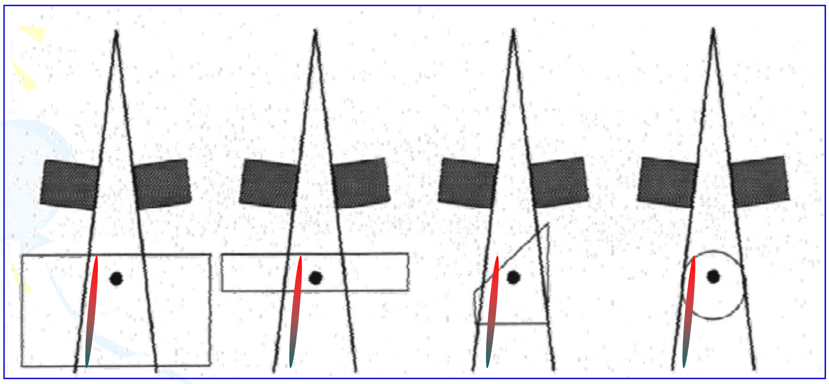
3

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

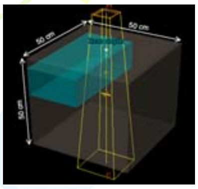
Convolution methods in homogeneous water

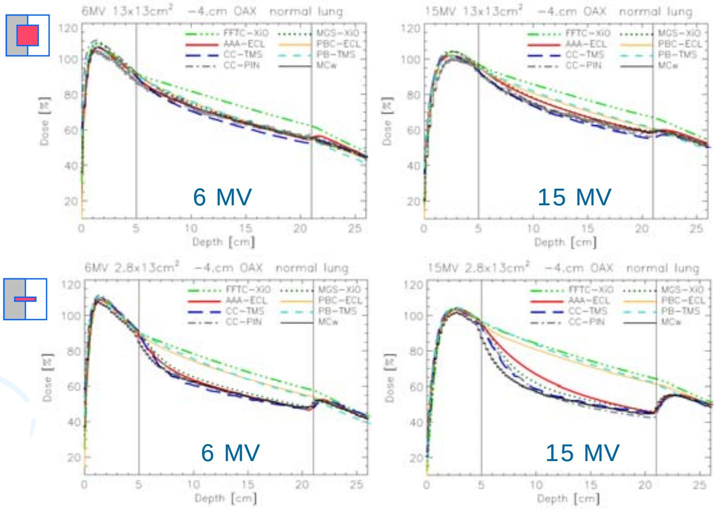
- Differences in beam modelling
  - Head scatter
  - Electron contamination
  - Wedges/Blocks
  - MLC
- May lead to slightly different accuracy
- Basically all models perform well in water
  - Point, pencil or collapsed cone implementations

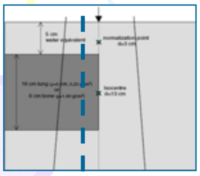
Single beam

3

Comparison in inhomogeneous phantoms







From Fogliata et al 2007, PMB

Density 0.2 g/cm^3

Two beams

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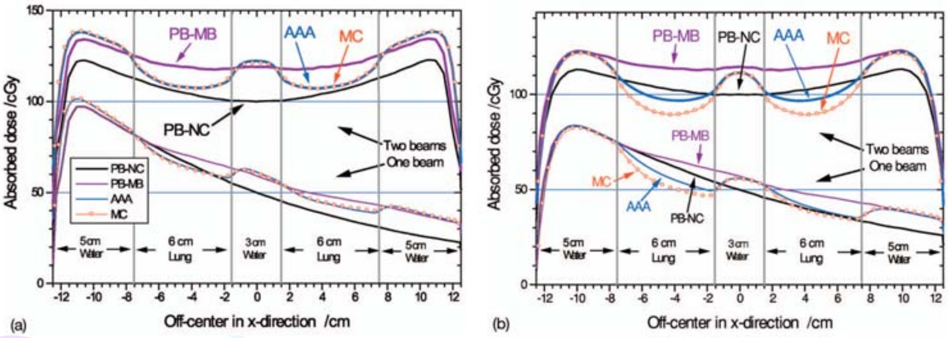
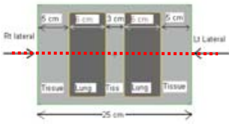
PB with longitudinal (PB) plus lateral scaling (AAA)

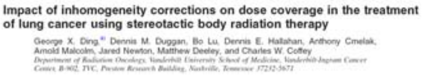
Pencil beam - NC-No Correction, MB-Modified Batho: Both without lateral scaling
AAA- with lateral scaling



6 MV

10 MV

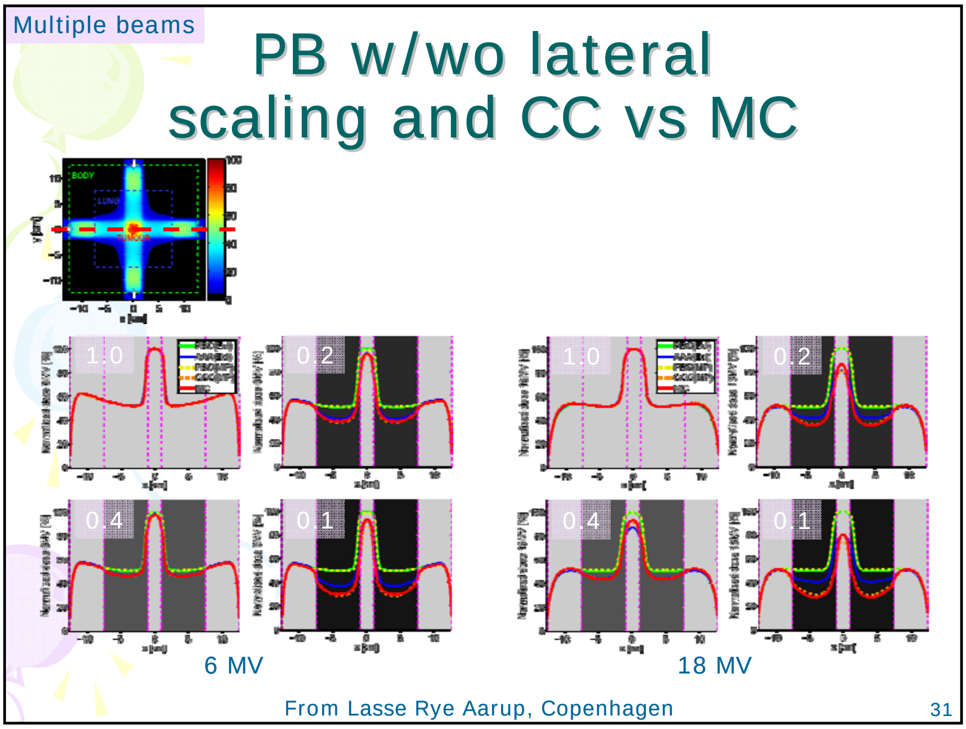




Impact of inhomogeneity corrections on dose coverage in the treatment of lung cancer using stereotactic body radiation therapy

George X. Ding,[a] Dennis M. Duggan, Bo Lu, Dennis E. Hallahan, Anthony Cmelak, Arnold Malcolm, Jared Newton, Matthew Deeley, and Charles W. Coffey
Department of Radiation Oncology, Vanderbilt University School of Medicine, Vanderbilt-Ingram Cancer Center, B-902, TVC, Preston Research Building, Nashville, Tennessee 37232-5671

Med Phys 2007



Multiple beams

PB w/wo lateral scaling and CC vs MC

6 MV

18 MV

From Lasse Rye Aarup, Copenhagen

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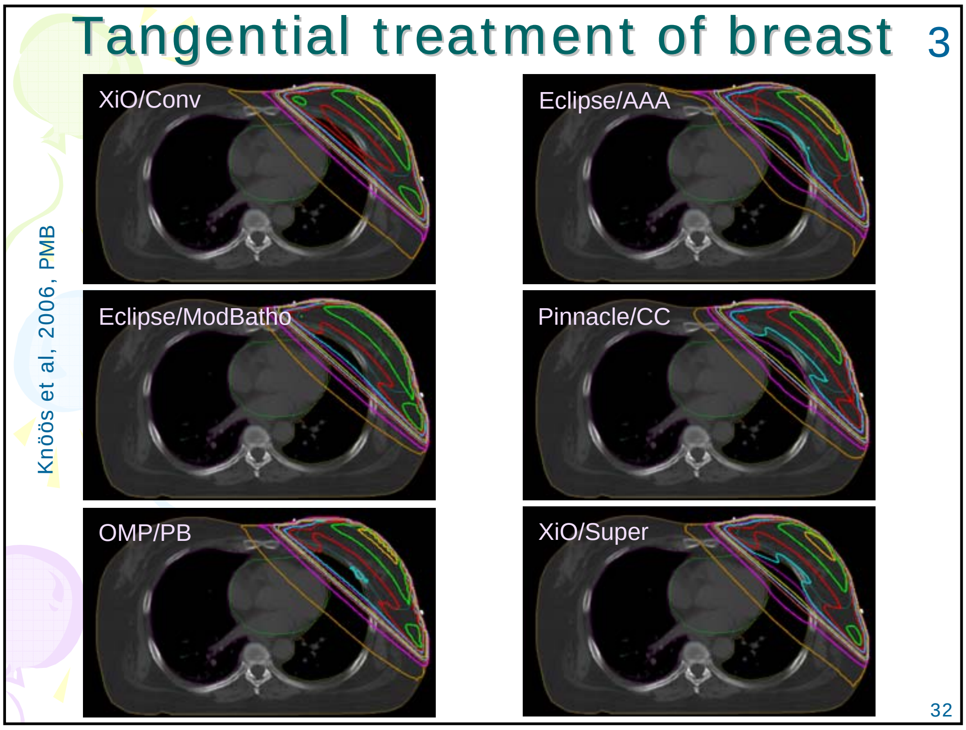
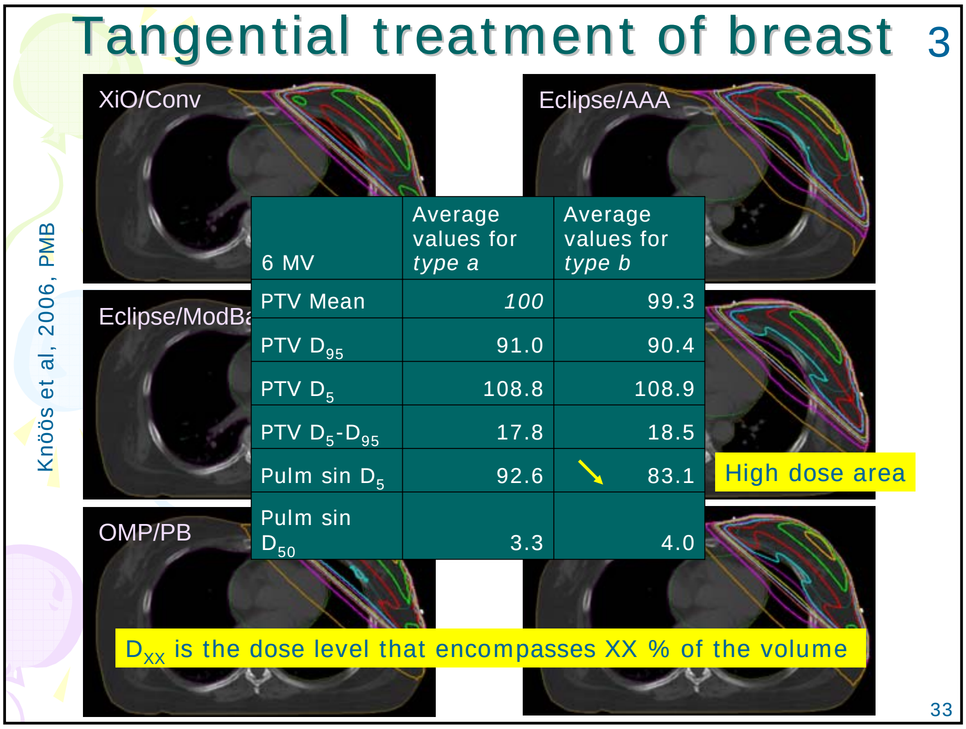


Tangential treatment of breast 3

Knöös et al, 2006, PMB

32



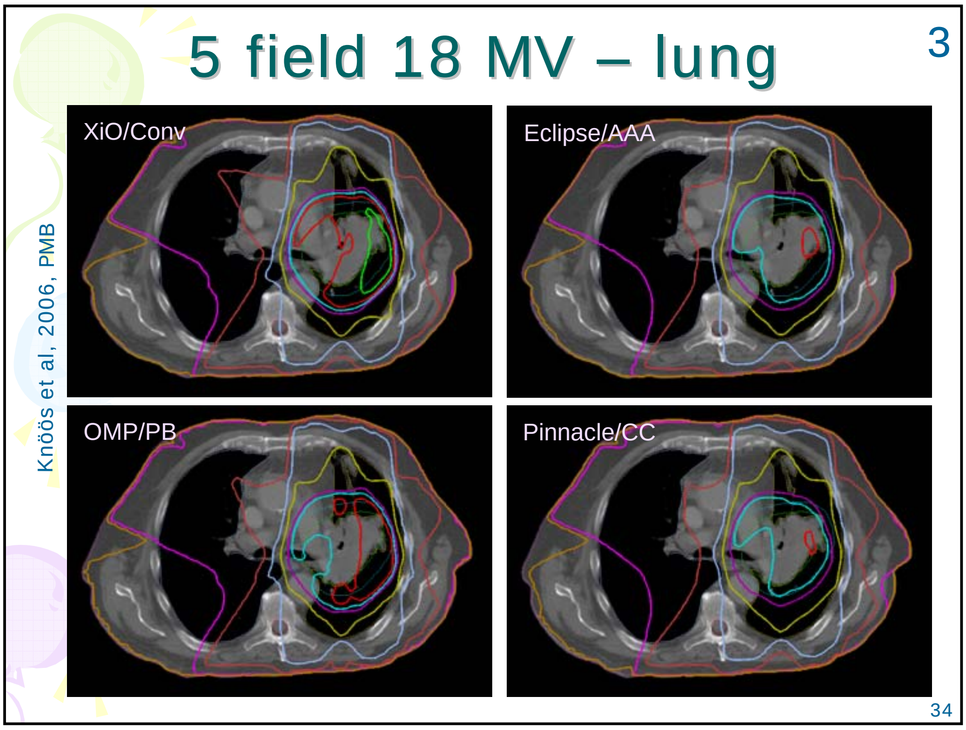
Tangential treatment of breast

6 MV	Average values for *type a*	Average values for *type b*
PTV Mean	*100*	99.3
PTV D_{95}	91.0	90.4
PTV D_5	108.8	108.9
PTV D_5-D_{95}	17.8	18.5
Pulm sin D_5	92.6	↘ 83.1
Pulm sin D_{50}	3.3	4.0

High dose area

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

Knöös et al, 2006, PMB

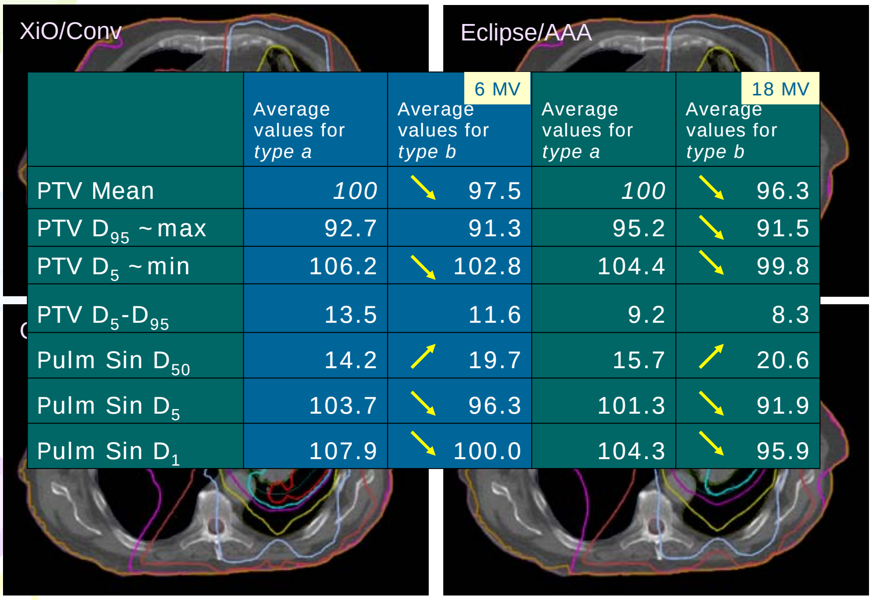


5 field 18 MV – lung

Knöös et al, 2006, PMB

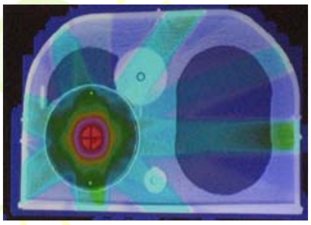
5 field 18 MV – lung

3



	6 MV Average values for *type a*		18 MV Average values for *type a*	
	Average values for *type a*	Average values for *type b*	Average values for *type a*	Average values for *type b*
PTV Mean	*100*	↘ 97.5	*100*	↘ 96.3
PTV D_{95} ~max	92.7	91.3	95.2	↘ 91.5
PTV D_5 ~min	106.2	↘ 102.8	104.4	↘ 99.8
PTV D_5-D_{95}	13.5	11.6	9.2	8.3
Pulm Sin D_{50}	14.2	↗ 19.7	15.7	↗ 20.6
Pulm Sin D_5	103.7	↘ 96.3	101.3	↘ 91.9
Pulm Sin D_1	107.9	↘ 100.0	104.3	↘ 95.9

Knöös et al, 2006, PMB



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

How to verify dose calculation algorithms?

AAPM REPORT NO. 46

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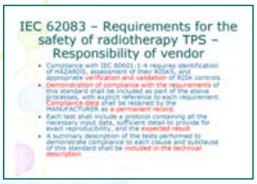
Gerald Kutcher
George Starkschall
Robin …
Jake Van Dyke

Med Phys 1998

Process of acceptance

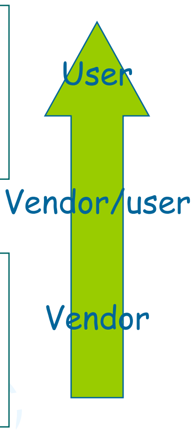


IEC 62083 – Requirements for the safety of radiotherapy TPS – Responsibility of vendor

- Compliance with IEC 60601-1-4 requires identification of HAZARDS, assessment of their RISKS, and appropriate verification and validation of RISK controls.
- Demonstration of compliance with the requirements of this standard shall be included as part of the above processes, with explicit reference to each requirement. Compliance data shall be retained by the MANUFACTURER as a permanent record.
- Each test shall include a protocol containing all the necessary input data, sufficient detail to provide for exact reproducibility, and the expected result
- A summary description of the tests performed to demonstrate compliance to each clause and subclause of this standard shall be included in the technical description

IEC 62083 – Requirements for the safety of radiotherapy TPS

- The MANUFACTURER shall provide an installation test document as part of the technical description that includes, as a minimum, performance of the ABSORBED DOSE distribution calculation algorithm tests given in 11.2.
- The tests shall also demonstrate correct functioning of the RTPS hardware components and their ability to achieve predetermined results when performing TREATMENT PLANNING functions.

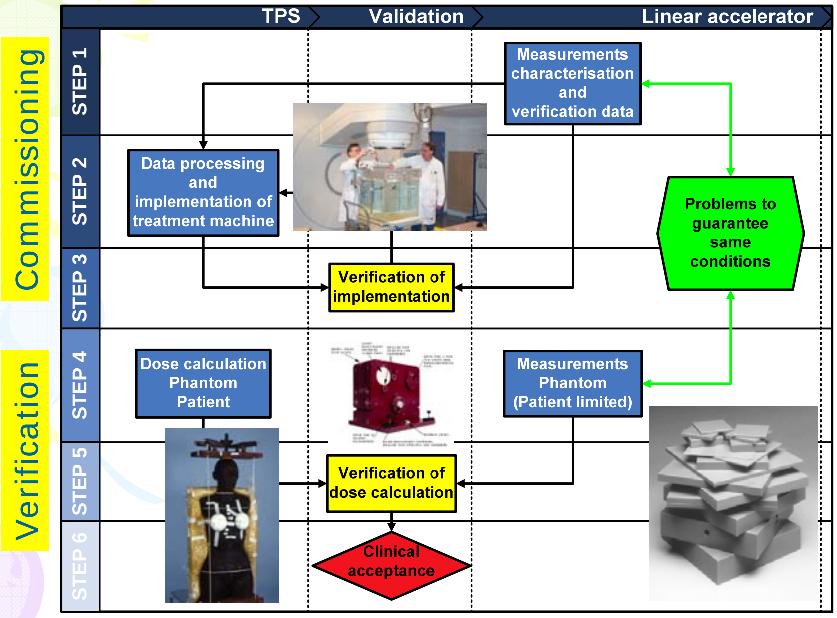


3) Specific performance in users environment

2) Generic performance in users environment

1) Generic performance

ESTRO booklet no 7, 2004

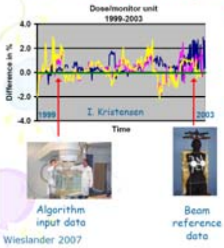


Verification of dose calculation

Wieslander 2007

MC methods facilitate verification

Consistency of data sets

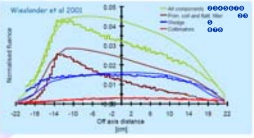


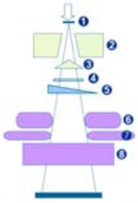
- Accelerator stability in time
  - Energi, symmetry, output, flatness
- No fluctuation in time
  - Possible to add new verification geometries

Wieslander 2007

Study of beam models

Labelling in MC codes to keep track of interaction history

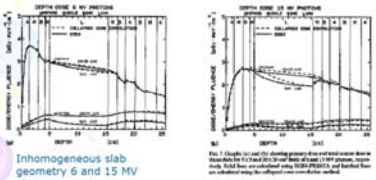




Wieslander 2007

Studies of dose components

Separation of dose components in phantoms primary and scatter dose



Inhomogeneous slab geometry 6 and 15 MV photons

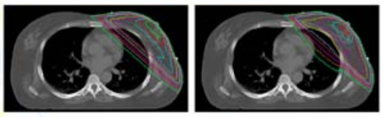
A. Ahnesjö, Med. Phys., 1989

EGS4

Wieslander 2007

Virtual linear accelerator

Comparisons in patient geometry



TPS calculated dose distribution based on the virtual accelerator

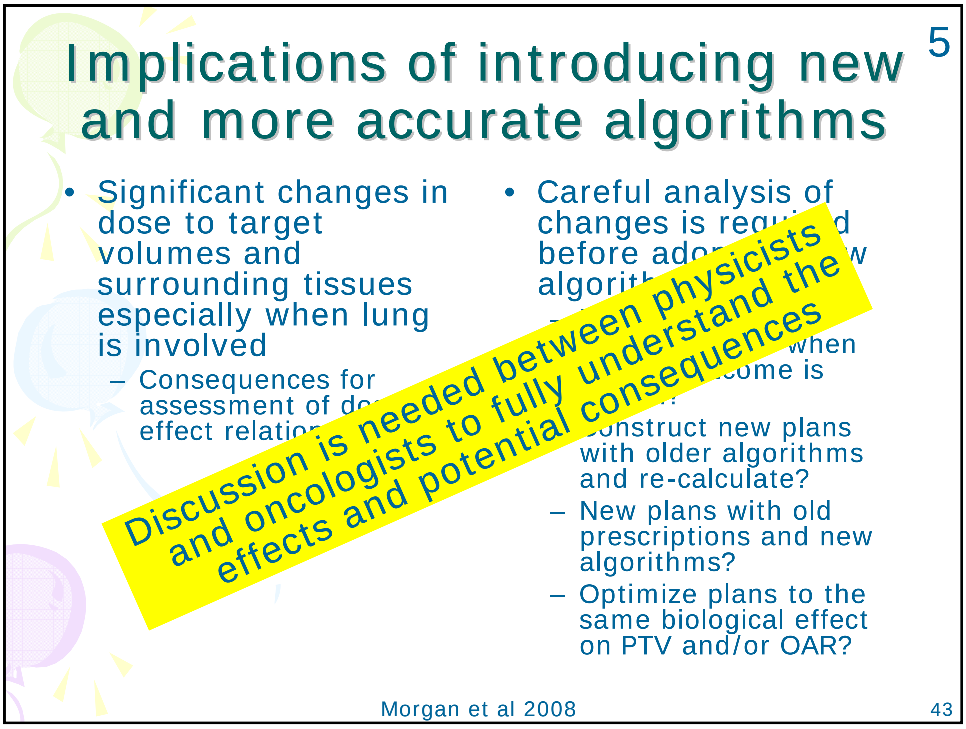
MC calculated dose distribution based the virtual accelerator

Wieslander 2007

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?

Morgan et al 2008



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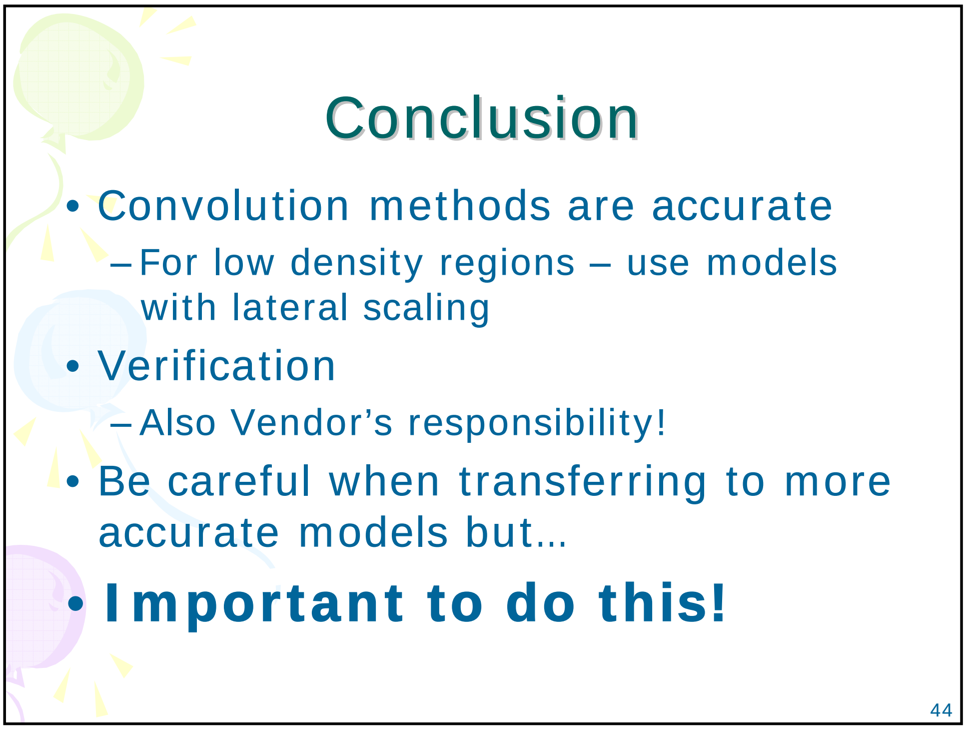
Discussion is needed between physicists and oncologists to fully understand the effects and potential consequences

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!**