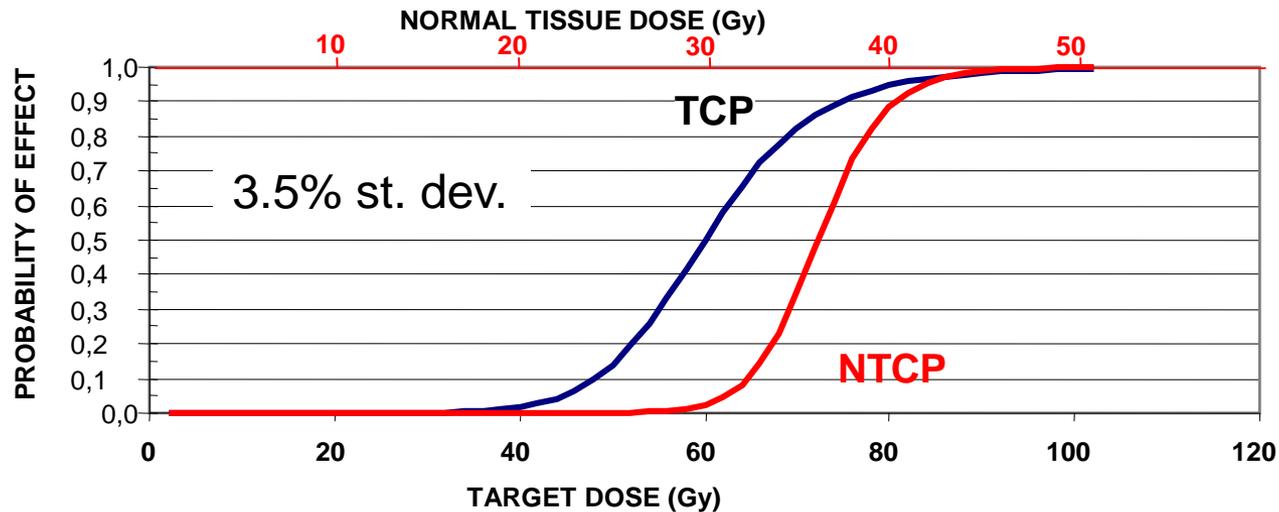


Dose distribution calculations in TPS photon beams

Paweł Kukołowicz
Medical Physics Department, Warsaw, Poland



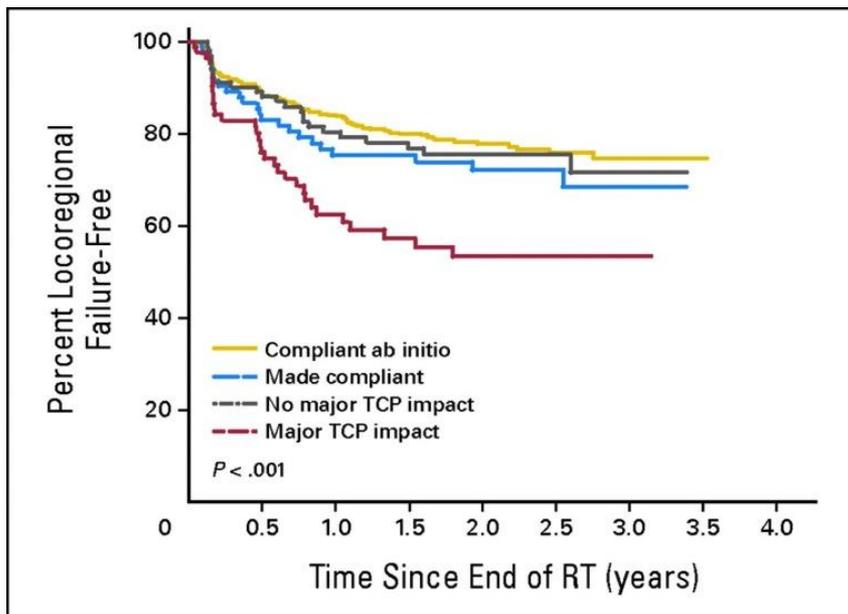
Delivered dose does matter!



In summarising the currently available evidence, general recommendations on accuracy in radiotherapy are still the same as previously reviewed and concluded, ie. for $\pm 3\%$ (sd) on the absorbed dose delivered at the specification point (but expanded to include a tighter requirement on systematic uncertainty of ideally $\leq 1-2\%$); for $\pm 3-5\%$ (sd) on the dose at all other points in the target volume; and for 'a few' mm (sd) on geometric uncertainties.

**Accuracy required and achievable in radiotherapy dosimetry:
Have modern technology and techniques changed our views?
Journal of Physics: conference Series 444 (2013)
David Thwaites**

Clinical trials

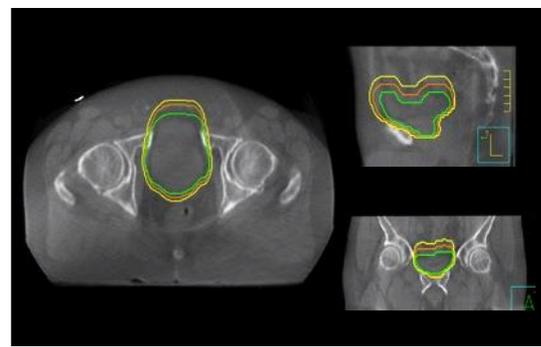
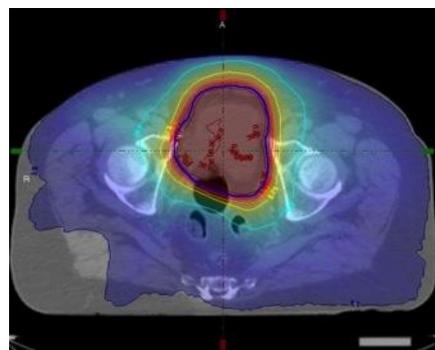
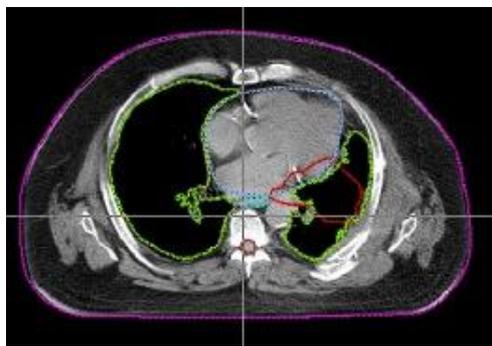
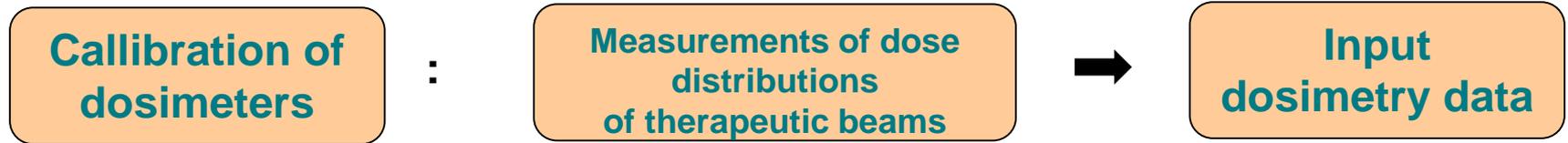


Peters LJ et al. JCO 2010;28:2996-3001

Critical Impact of Radiotherapy Protocol Compliance and Quality in the Treatment of Advanced Head and Neck Cancer: Results From TROG 02.02



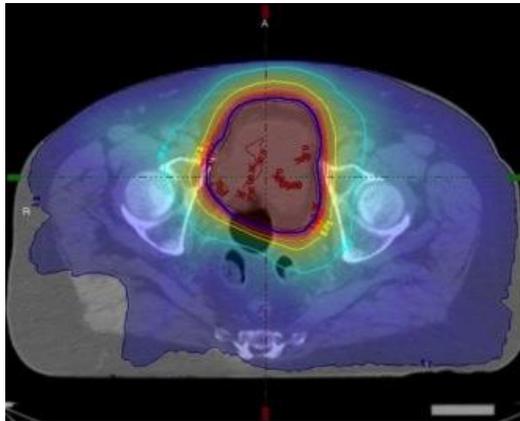
Delivered dose does matter!



Courtesy Liz Miles RTTQA

Treatment planning system

- Accuracy of dose distribution calculation



Treatment planning
Quality control of
Treatment Planning
Systems

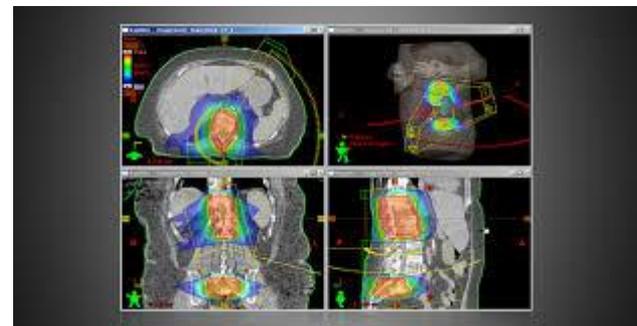


What are characteristics of a good TPS?

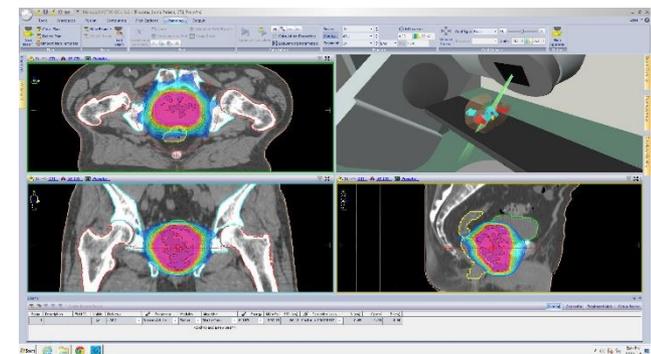
Pinnacle

Varian - Eclipse

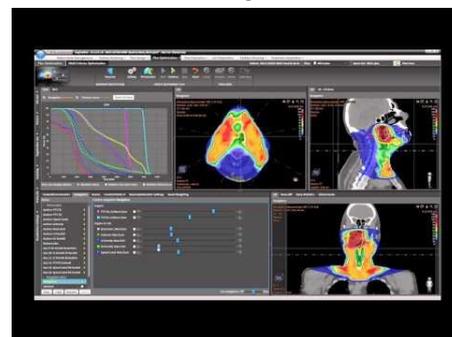
- High accuracy of dose distribution calculations
- Fast calculations
- Should be able to prepare plans for all contemporary techniques
- User friendly
- Robust



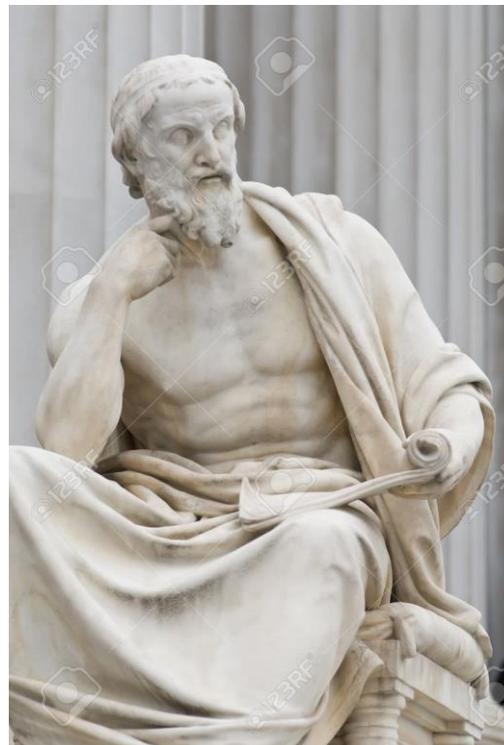
Elekta - Monaco



RaySearch – RayStation



How to build a good model?



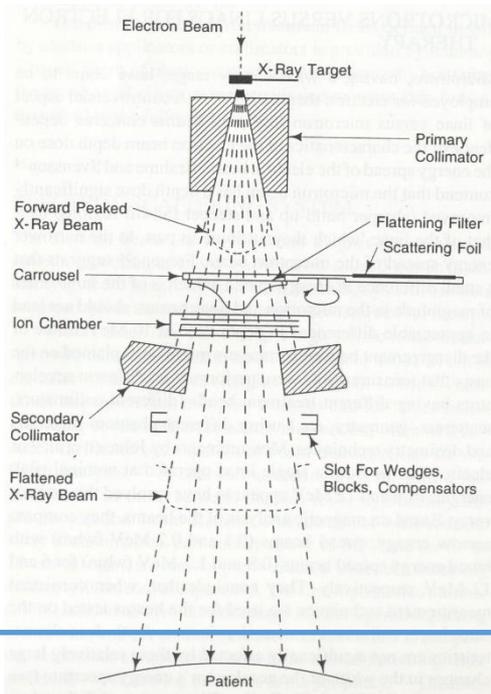
What are characteristics of a good TPS?

- **High accuracy of dose distribution calculations**
- Fast calculations
- User friendly
- Robust

Algorithms implemented in TPS



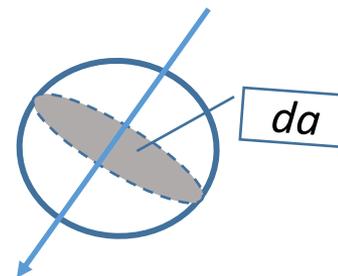
Step 1 - exposure



- What radiation is reaching an absorber
 - fluence and energy fluence
 - spectrum of energy fluence
- We call it: primary radiation

Step 1 - exposure

- Fluence – Φ [$1/m^2$]
 - the number dN of particles (photons) incident on a sphere of cross-sectional area da
- Energy fluence – Ψ [J/m^2]
 - the energy dE incident on a sphere of cross-sectional area da



$$\Phi = \frac{dN}{da}$$

$$\Psi = E \cdot \Phi$$

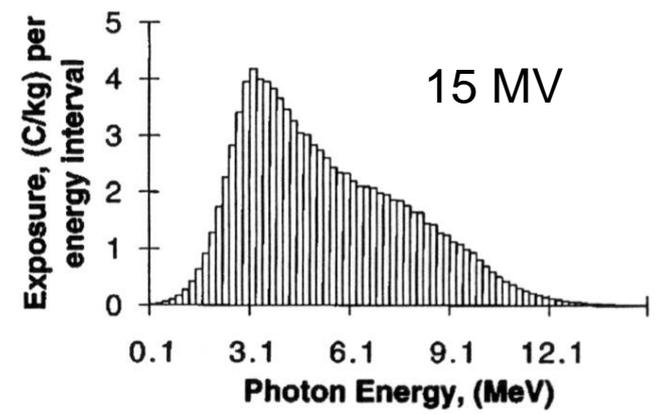
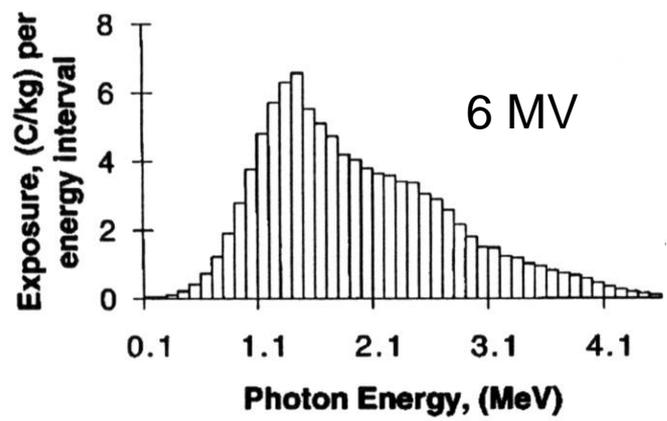


Energy spectrum

- Depends on
 - effective accelerating potential
 - target material
 - flattening filter material and construction
 - there are flattening filter free accelerators
 - head (colimator system) material and construction



Energy spectrum



Energy spectrum calculations

- Reconstruction of spectra by iterative least squares fitting of narrow beam transmission
 - it requires very precise measurements of attenuation factors
- Monte Carlo
 - precise knowledge of the treatment head design
 - now this information is usually available
- Fiting routine
 - a given spectrum is used to calculate PDDs (using a database of Monte Carlo generated Kernels) and compared with the measured ones
 - procedure is repeated until expected compliance is obtained



Energy spectrum calculation

Monte Carlo

L. Grevillot, T. Frisson, D. Maneval, N. Zahra, J.-N. Badel, D. Sarrut, “Simulation of a 6 MV Elekta Precise Linac photon beam using GATE/GEANT4”, *Phys. Med. Biol.*, **56**, (2011).

M. K. Fix, P. J. Keall, K. Dawson, J. V. Sieber, “Monte Carlo source model for photon beam radiotherapy: photon source characteristics”, *Medical Physics*, **31**, (2004).

B. Bednarz, X. G. Xu, “Monte Carlo modeling of a 6 and 18 MV Varian Clinac medical accelerator for in-field and out-of-field dose calculations: development and validation”, *Phys. Med. Biol.*, **54**, (2009).

S. S. Almberg, J. Frengen, A. Kylling, T. Lindmo, “Monte Carlo linear accelerator simulation of megavoltage photon beams: Independent determination of initial beam parameters”, *Medical Physics*, **39**, (2012).

C. J. Karzmark, C. S. Nunan, E. Tanabe, *Medical Electron Accelerators*, McGraw-Hill, USA (1993).

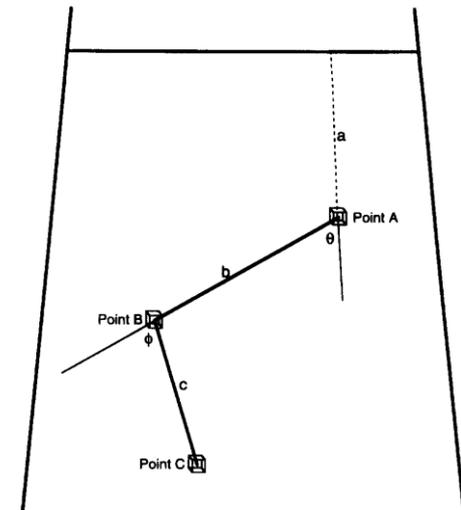
B. Serrano, A. Hachem, E. Franchisseur, J. Hérault, S. Marcié, A. Costa, R. J. Bensadoun, J. Barthe, J. P. Gérard, “Monte Carlo Simulation of a Medical Linear Accelerator for Radiotherapy Use”, *Radiation Protection Dosimetry*, (2006).

O. Chibani, B. Moftah, C.-M. C. Ma, “On Monte Carlo modeling of megavoltage photon beams: A revisited study on the sensitivity of beam parameters”, *Medical Physics*, **38**, (2011).



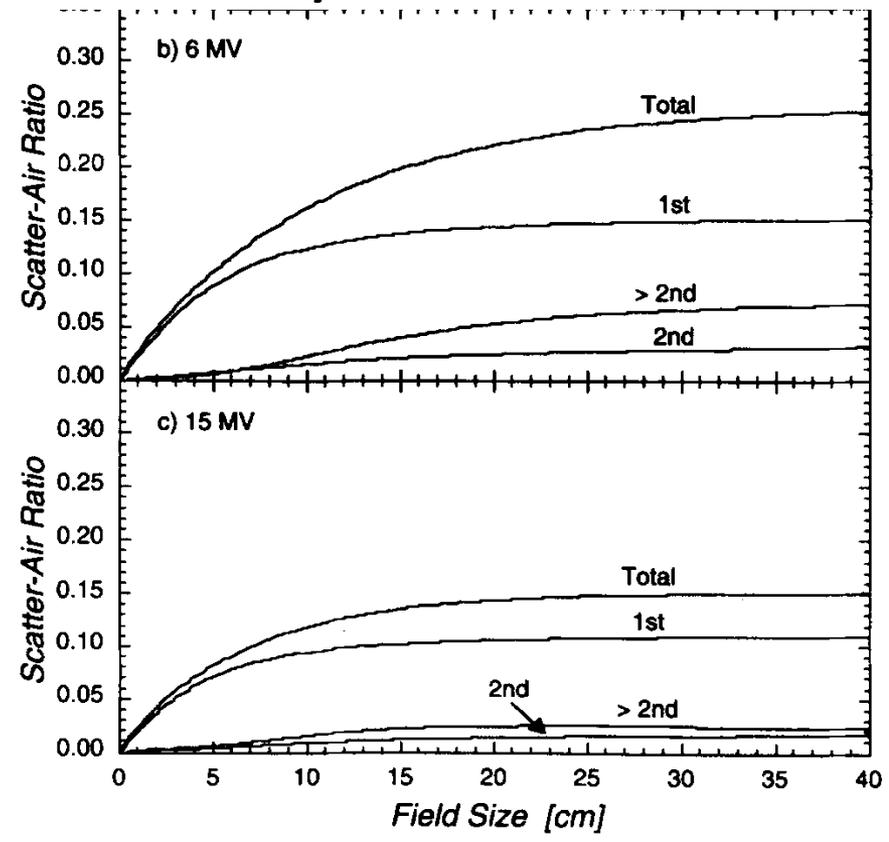
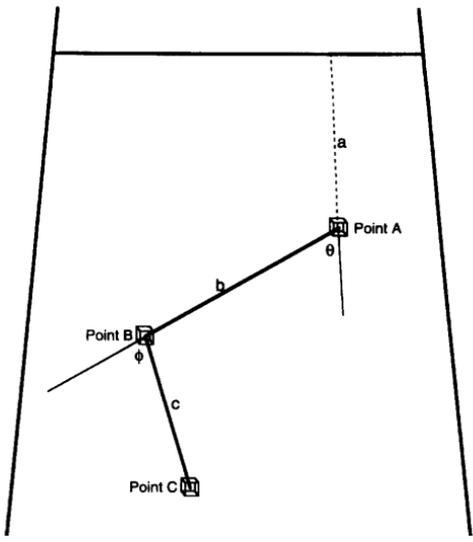
Step 2 – Energy deposition

- Primary and secondary dose
- Primary dose
 - interaction of primary photon
 - energy transferred to charged particle (mostly to electron)
 - electron transferred its energy to medium
- Secondary dose
 - interactions of secondary photons (scattered) and so on



Primary and secondary dose

Precise modeling of primary dose is the most important!

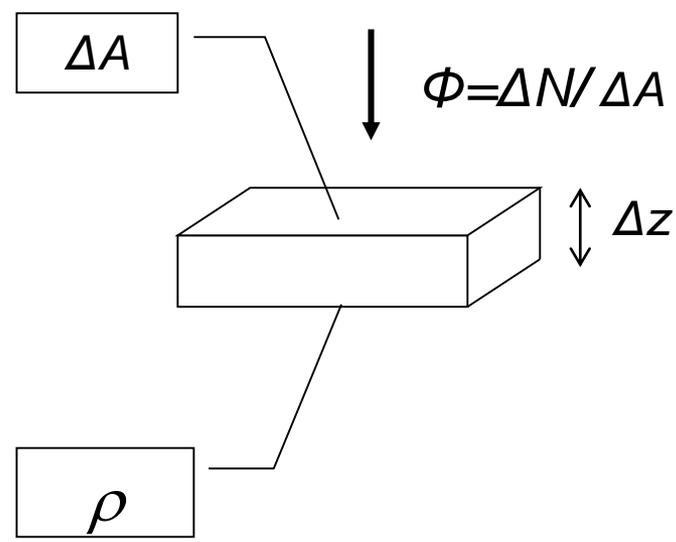


Sontag, Med. Phys. 1995, 22 (6)

Energy transferred from photons to electrons Kerma

$$\left(\frac{\mu}{\rho}\right) \cdot \Phi$$

number of interactions
per unit mass



$$\left(\frac{\mu}{\rho}\right) \cdot \bar{E}_{tr} \cdot \Phi$$

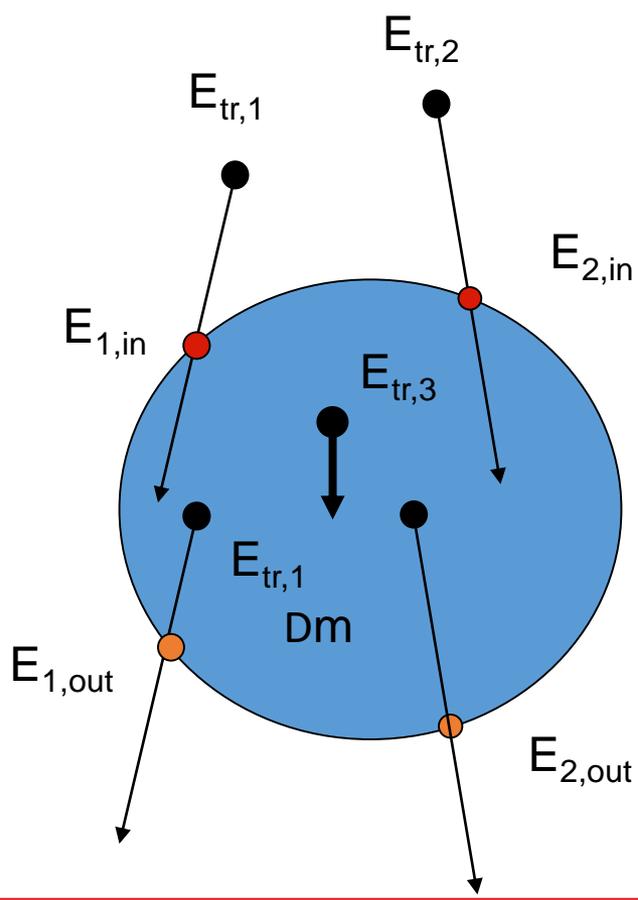
energy transferred
to electrons

Energy transferred to electrons

$$\left(\frac{\mu}{\rho} \right) \cdot \bar{E}_{tr} \cdot \Phi$$

- KERMA
 - Kinetic Energy Released per unit mass

Charged particle equilibrium (CPE)



- Photon interaction
- Electron enters Dm
- Electron leaves Dm

Charged particle equilibrium exists for the volume V if each charged particle of a given type and energy leaving V is replaced by an identical particle of the same energy entering

Kerma Collision versus Absorbed Dose

- If CPD exists

$$\text{Kerma}_{\text{col}} = \text{Kerma} \cdot (1-g)$$

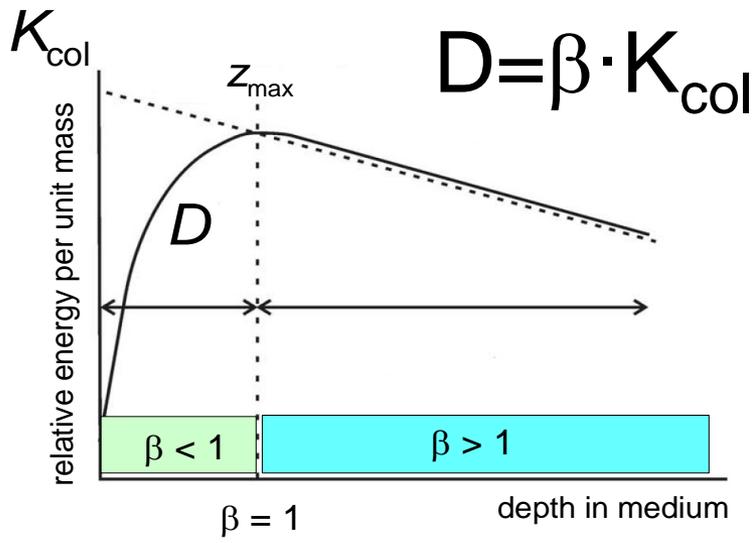
$$\text{Absorbed Dose} = \text{Kerma}_{\text{col}}$$

g – fraction of energy emitted in the form of Bremstrahlung



CPD never exists

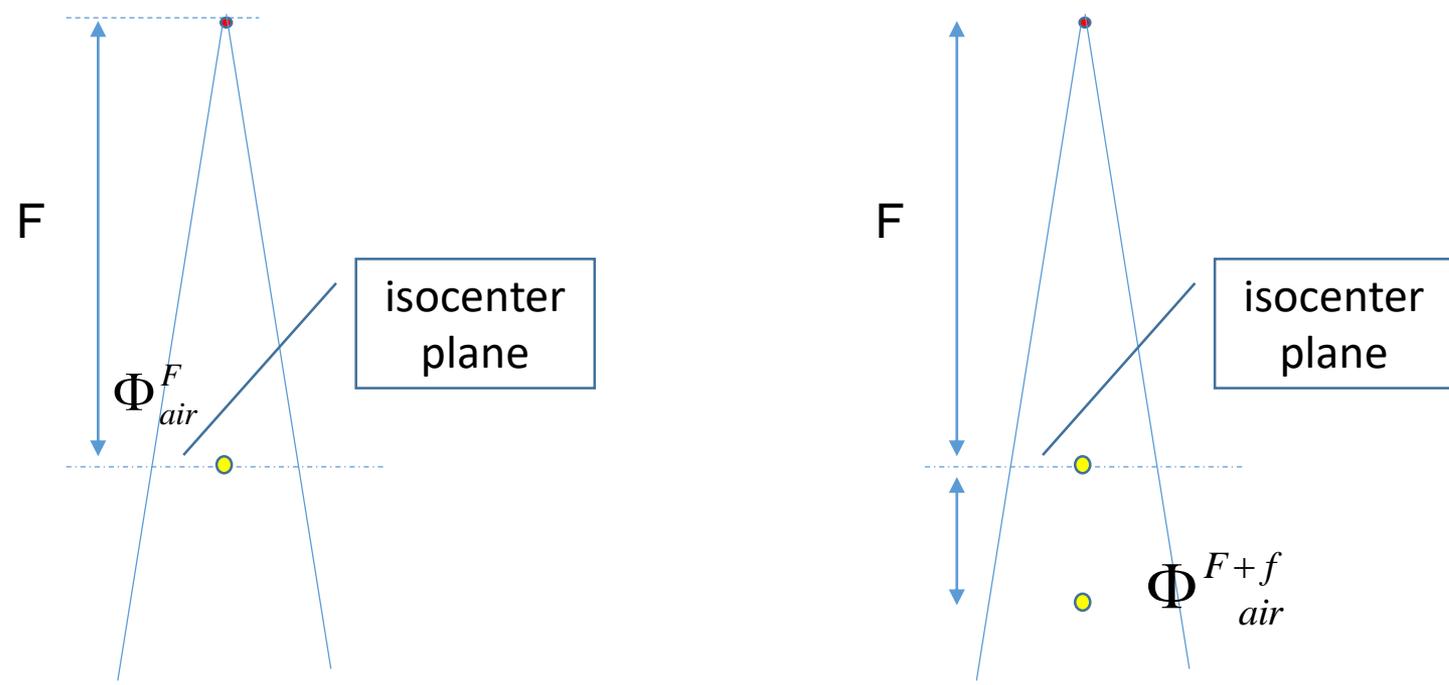
- Transient CPD exists



Absorbed dose is equal to Kerma at a little smaller depth.

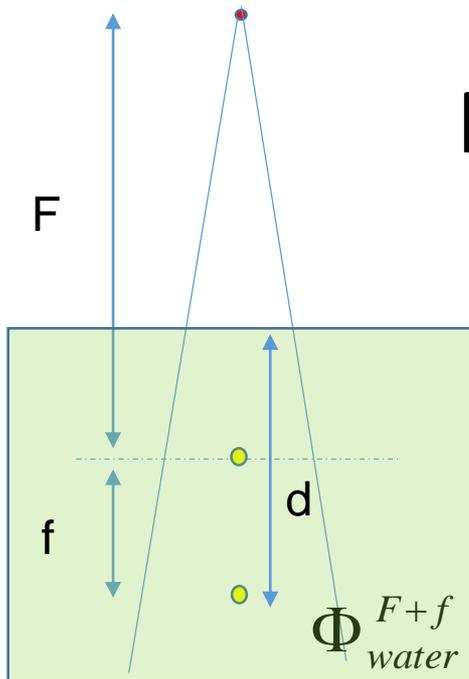
$$D = (1 + f_{TCPE}) \cdot K_{col}$$

Fluence in air – inverse square law



$$\Phi_{air}^{F+f} = \Phi_{air}^F \cdot \frac{F^2}{(F+f)^2}$$

Fluence in water – dose in water



$$\Phi_{water}^{F+f} = \Phi_{air}^F \cdot \frac{F^2}{(F+f)^2} \cdot e^{-\mu \cdot d}$$

Primary dose – dose deposited by electrons

$$D_{water}^{F+f} = \beta \cdot \Phi_{air}^F \cdot \frac{F^2}{(F+f)^2} \cdot e^{-\mu \cdot d} \cdot \left(\frac{\mu}{\rho} \right) \cdot E_{tr} \cdot (1-g)$$

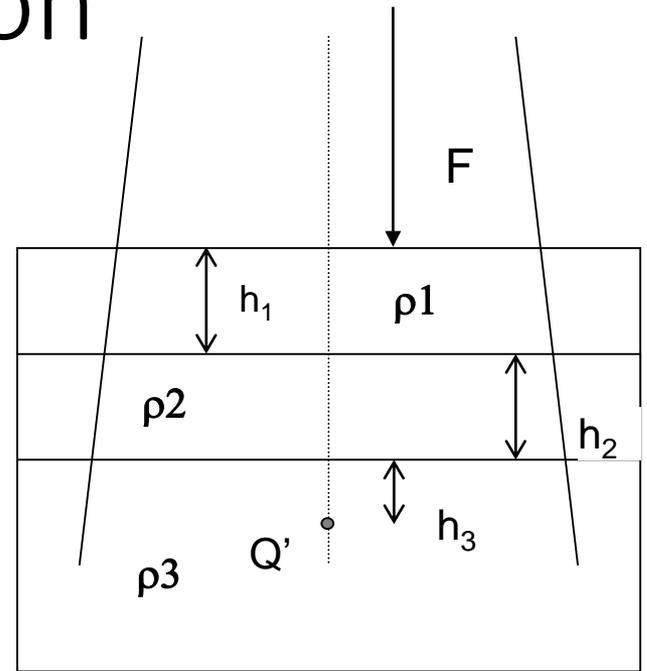
Fluence – real situation

- Radiological depth

$$d_{rad} = h_1 \cdot \rho_1 + h_2 \cdot \rho_2 + h_3 \cdot \rho_3$$

- In general

$$d_{rad} = \sum \rho_k \cdot h_k$$



$$D_{Q'}^{F+\sum h_k} = \beta \cdot \Phi_{air}^F \cdot \frac{F^2}{(F + \sum h_k)^2} \cdot e^{-\sum \mu_k \cdot h_k} \cdot \left(\frac{\mu}{\rho} \right) \cdot E_{tr} \cdot (1 - g)$$

$$D_{Q'}^{F+\sum h_k} = \beta \cdot \Phi_{air}^F \cdot \frac{F^2}{\left(F + \sum h_k\right)^2} \cdot e^{-\sum \mu_k \cdot h_k} \cdot \left(\frac{\mu}{\rho}\right) \cdot E_{tr} \cdot (1 - g)$$

radiological depth

physical distance

Another approach to dose distribution calculation

- Total energy released per unit mass

$$TERMA_{h\nu} = \underbrace{\Phi_{air}^F \cdot \frac{F^2}{(F+f)^2} \cdot e^{-\mu_{h\nu}d} \cdot h\nu}_{\text{primary energy fluence}} \cdot \left(\frac{\mu_{h\nu}}{\rho} \right)$$

primary energy fluence

- What will happen with this released energy?
 - mostly it will be absorbed as primary and secondary dose
 - only a little energy will escape (scattered photons, bremsstrahlung)

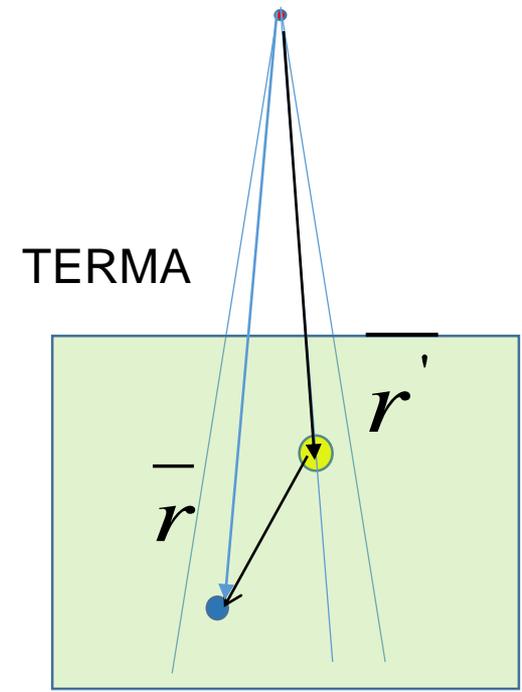
Convolution – monoenergetic case

$$\text{TERMA}_{h\nu} = T_{h\nu}$$

$$D(\bar{r}, h\nu) = \int T_{h\nu}(\bar{r}') \cdot A_{h\nu}(\bar{r} - \bar{r}') d^3 \bar{r}'$$

$$A_{h\nu}(\bar{r} - \bar{r}')$$

Convolution kernel representing the relative energy deposited per unit volume for photons of energy $h\nu$; integral over whole medium



Med.Phys. Papanikolaou 1993,5,1327-1336.

Convolution – polyenergetic (real case)

- Integral over space and energy spectrum

$$D(\bar{r}, h\nu) = \iint \frac{dT_{hv}(\bar{r}')}{dh\nu} A_{hv}(\bar{r} - \bar{r}') d^3\bar{r}' dh\nu.$$

Mohan, Med.Phys, 1985, 12, 592 – 597.



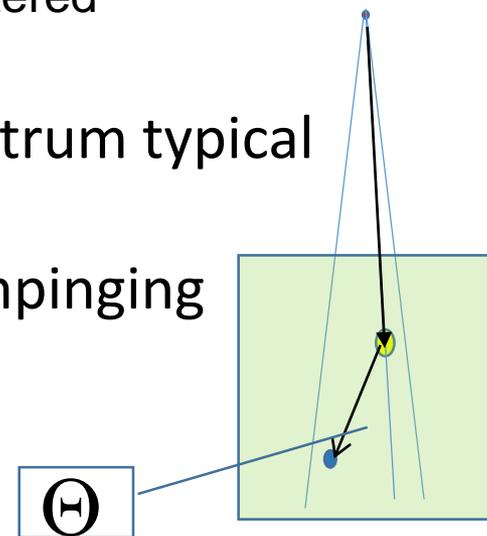
Kernels – Point Spread Function

Anders A. Ahnsjö, Med.Phys. 16 (4), 1989

$$h_w(r, \Theta) = \underbrace{(A_\Theta \cdot \exp(-a_\Theta \cdot r))}_{\text{primary}} + \underbrace{(B_\Theta \cdot \exp(-b_\Theta \cdot r))}_{\text{scattered}} / r^2$$

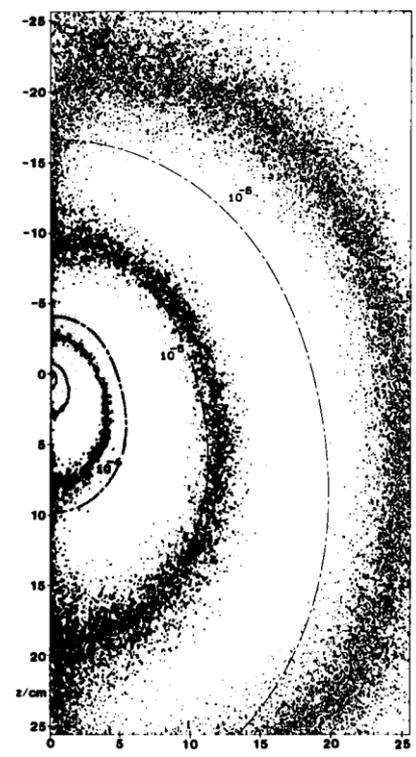
$A_\Theta, a_\Theta, B_\Theta, b_\Theta$

- parameteres generated for beams of spectrum typical for 4Mv, 6MV, 10MV, and 15 MV
- Θ angle with respect to the direction of impinging primary photon
- w – stands for water



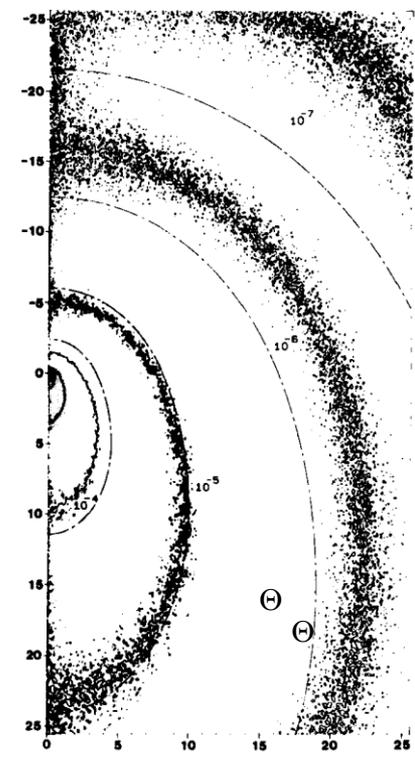
Kernels

0,4 MeV

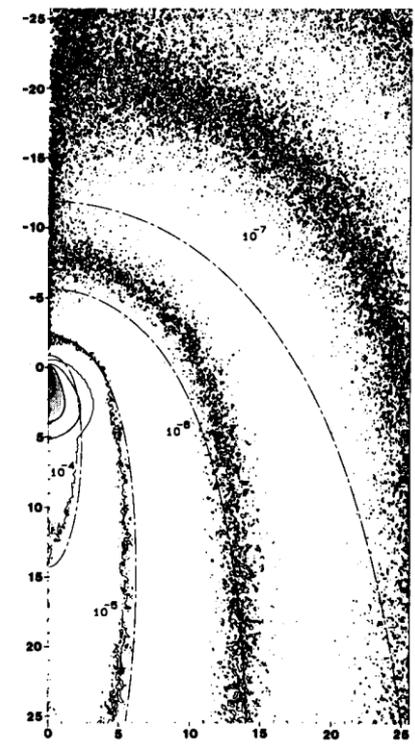


Energy imparted per cm⁻³

1,25 MeV



10 MeV

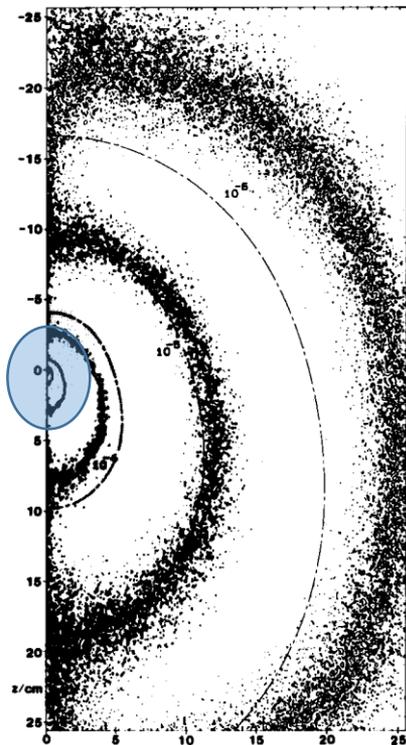


The dash-dotted line first scatter term, calculated using the Klein-Nishina cross sections and neglecting other process than the Compton interaction.

Acta Oncologica, 1987, Ahnesjö

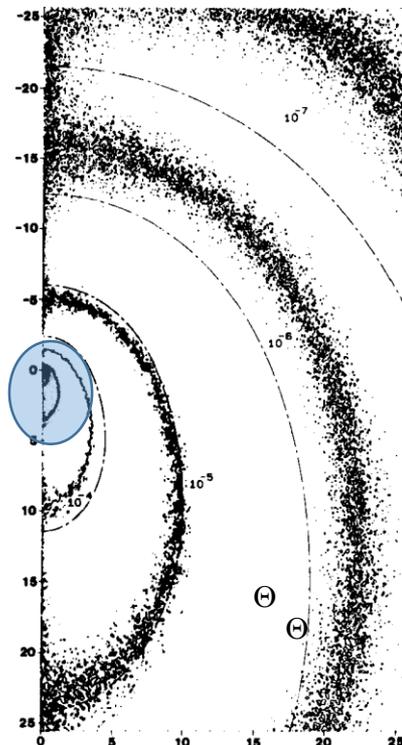
Kernels

0,4 MeV

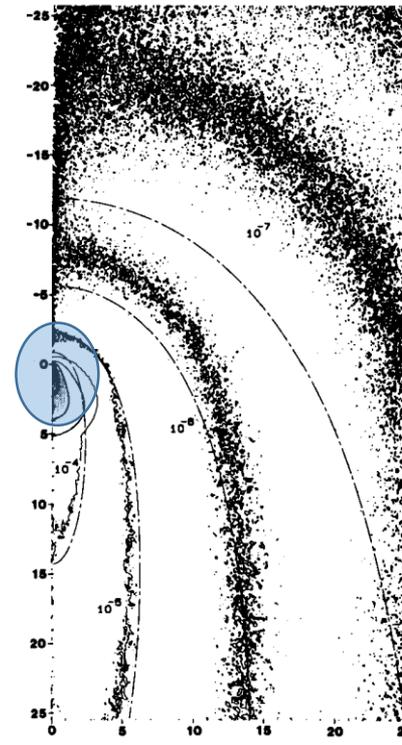


Energy imparted per cm^{-3}

1,25 MeV



10 MeV



The dash-dotted line first scatter term, calculated using the Klein-Nishina cross sections and neglecting other process than the Compton interaction.

Acta Oncologica, 1987, Ahnesjö



Convolution – polyenergetic (real case)

- Integral over space and energy spectrum

$$D(\bar{r}, h\nu) = \iint \frac{dT_{hv}(\bar{r}')}{dh\nu} A_{hv}(\bar{r} - \bar{r}') d^3 \bar{r}' dh\nu$$

$$TERMA_{hv} = \Phi_{air}^F \cdot \frac{F^2}{(F + f)^2} \cdot e^{-\mu_{hv}d} \cdot h\nu \cdot \left(\frac{\mu_{hv}}{\rho} \right)$$

$$h_w(t, \Theta) = (A_{\Theta} \cdot \exp(-a_{\Theta} \cdot t) + B_{\Theta} \cdot \exp(-b_{\Theta} \cdot t)) / t^2$$

$$A_{hv}(\bar{r} - \bar{r}')$$

Mohan, Med.Phys, 1985, 12, 592 – 597.



Approximations

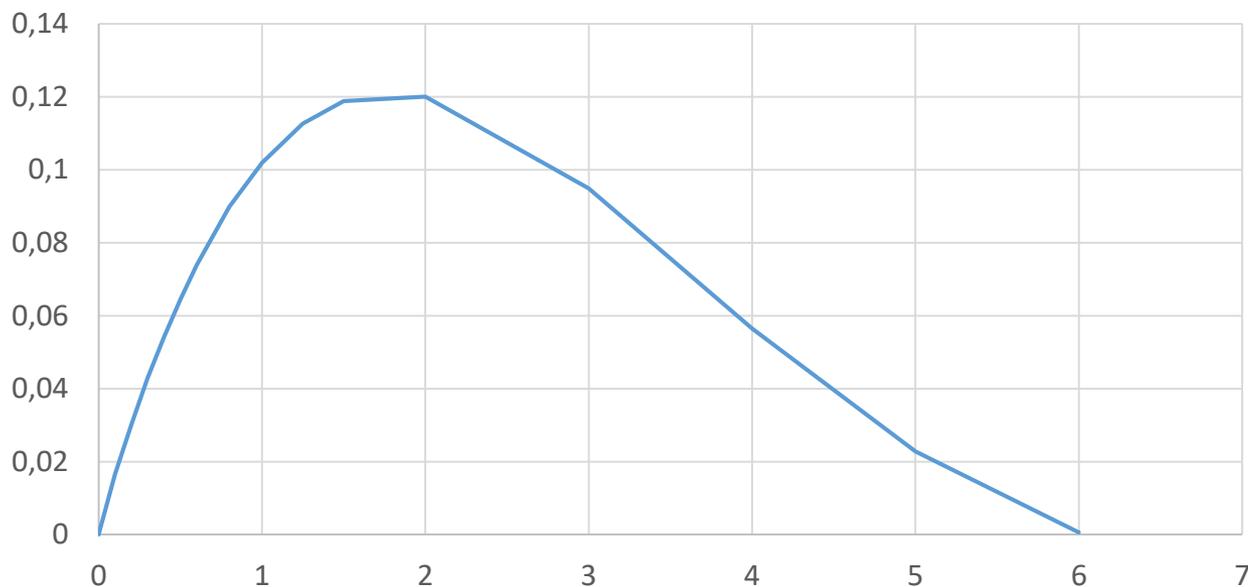
- To allow calculations in a reasonable time several approximations are used
 - treatment planning system dependent
 - the same model different results
 - polyenergetic  monoenergetic (e.g. for mean energy)
 - single energy spectrum is used
 - collapse cone method
 - Kernels generated for water only
 - scaling with density



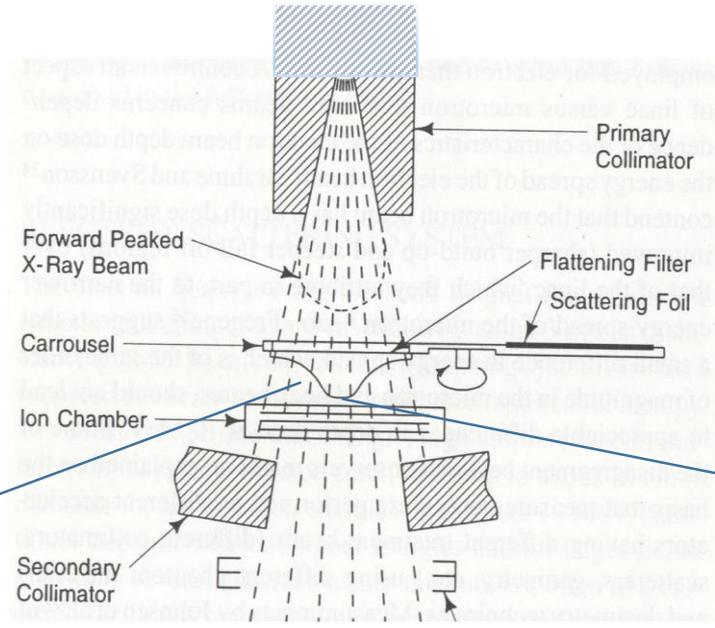
6 MV spectrum

polyenergetic : monoenergetic

Spectrum 6 MV
Mean Energy **1.48 MeV**



Changes of spectrum lateral softening



lower energy

higher energy

single energy spectrum

Collapsed Cone Convolution

speed-up calculations

- 30 x 30 x 30 cm³ water Phantom
- 0.3 cm grid size
- 100 x 100 x 100 calculations point = 1 000 000
- Convolution: contribution from each voxel to each voxel

$$1\ 000\ 000 \times 1\ 000\ 000 = 1\ 000\ 000\ 000\ 000$$



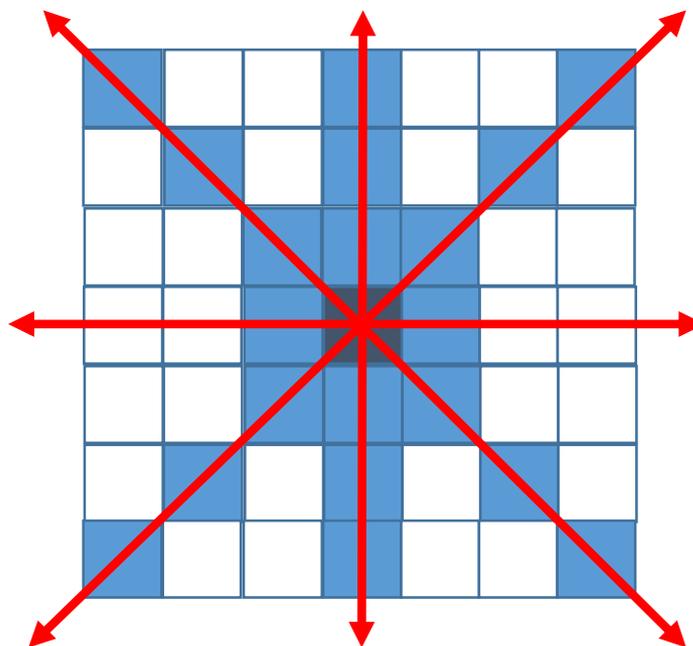
Collapsed Cone Convolution

- CCC approaches assumes that all the energy scattered from one voxel into small cone is absorbed along the line forming the axis of the cone

Collapsed Cone Convolution

2D illustration

Energy desposition
decreases very quickly
with distance



8 cones

Energy is absorber in blue pixels only.



Collapsed Cone Convolution

2D illustration

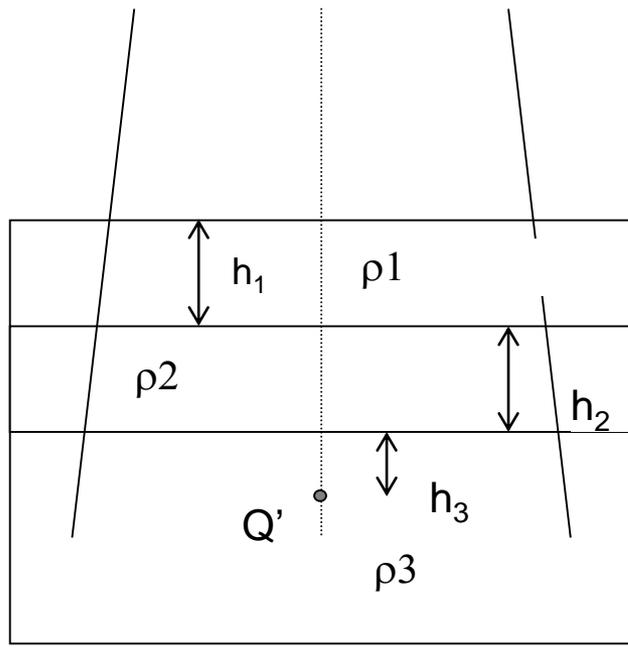
- According to Mackie (Teletherapy: Present and Future, Advanced medical Publishing, 1996)
 - 100 collapsed cones is enough
- Mobius3D – 144 collapsed cones
- Pinnacle – 80 collapsed cones



Approximation

- Scaling depth (distance) with density

$$d_{rad} = \sum_k \rho_k \cdot h_k$$



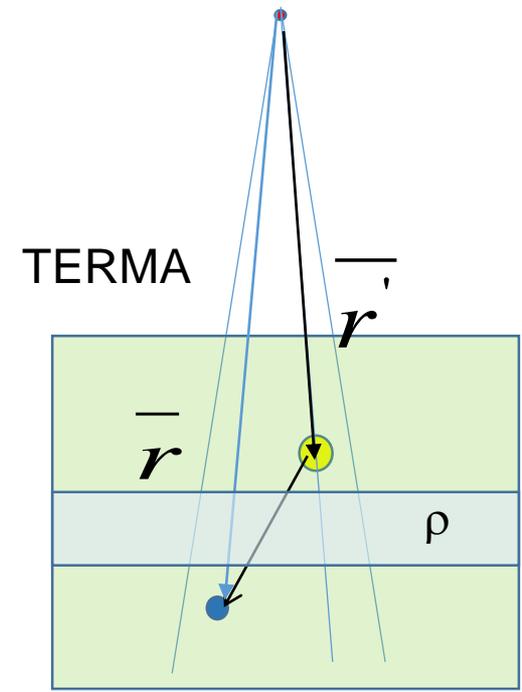
$$D(r, h\nu) = \int T_{h\nu}(\vec{r}') \cdot \underline{A_{h\nu}(\vec{r} - \vec{r}')_{rad}} d^3 \vec{r}'$$

Convolution – monoenergetic case

$$\text{TERMA}_{h\nu} = T_{h\nu}$$

$$D(r, h\nu) = \int T_{h\nu}(\bar{r}') \cdot A_{h\nu}(\bar{r} - \bar{r}') d^3 \bar{r}'$$

$$D(r, h\nu) = \int T_{h\nu}(\bar{r}') \cdot A_{h\nu}(\bar{r} - \bar{r}')_{\text{rad}} d^3 \bar{r}'$$



Summary

- Primary and secondary dose
- Kerma and Collision Kerma versus Dose
- How to describe Kerma by photon fluence

Summary

- It is relatively easy to calculate the dose if
 - Transient CPE exist
 - distance
 - radiological depth
- If there is no CPE situations becomes much more difficult
 - transport of electrons must be considered
 - interface of two dosimetrically different absorbers
 - air-soft tissue, lung-soft tissue, bone-soft tissue



Summary

- TCP exist
- Primary dose is at least 80% of total dose
 - accuracy depends on primary dose calculations
 - scale fluence with inverse square factor
 - depth scaled with density
 - first scatter is much larger than second, third etc.

$$h_w(t, \Theta) = \underbrace{(A_{\Theta} \cdot \exp(-a_{\Theta} \cdot t))}_{\text{primary}} + \underbrace{B_{\Theta} \cdot \exp(-b_{\Theta} \cdot t)}_{\text{scattered}} / t^2$$



Summary

- Total dose

$$D(\bar{r}, h\nu) = \iint \frac{dT_{hv}(\bar{r}')}{dh\nu} A_{hv}(\bar{r} - \bar{r}') d^3 \bar{r}' dh\nu$$

$$h_w(r, \Theta) = (A_{\Theta} \cdot \exp(-a_{\Theta} \cdot r) + B_{\Theta} \cdot \exp(-b_{\Theta} \cdot r)) / r^2$$

primary

scattered



Thank you very much for your attention!



CENTRUM ONKOLOGII – INSTYTUT
IM. MARII SKŁODOWSKIEJ-CURIE