TPS: algorithms

ICTP SCHOOL ON MEDICAL PHYSICS
Radiation Therapy:
Dosimetry and Treatment Planning
for Basic and Advanced Applications
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Paweł Kukołowicz
Medical Physics Department, Warsaw, Poland

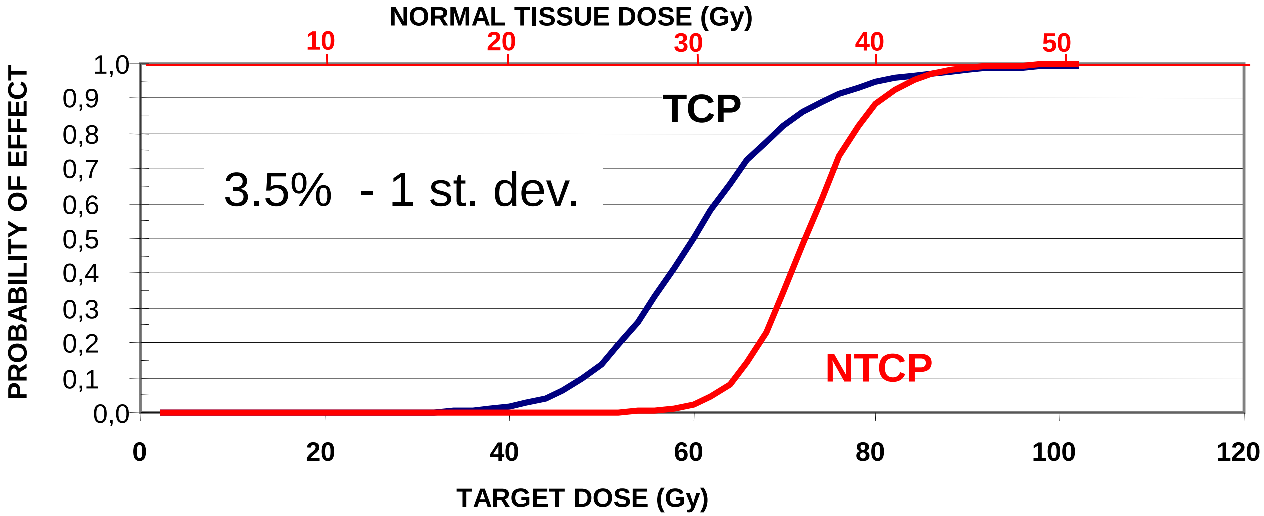
CENTRUM ONKOLOGII – INSTYTUT
IM. MARII SKŁODOWSKIEJ-CURIE

Paweł Kukołowicz

- Head of Medical Physics Department at Cancer-Center Institute of Oncology in Warsaw, Poland
- Medical physicist from 1980
- Dosimetry, treatment planning, education
- p.kukolowicz@zfm.coi.pl

- I our department we have accredited Secondary Standard Laboratory (calibration with Co60)

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 +/- 3% (sd) on the absorbed dose delivered at the specification point (but expanded to include a tighter requirement on systematic uncertainty of ideally ≤ 1-2%); for +/- 3-5% (sd) on the dose at all other points in the target volume; and for 'a few' mm (sd) on geometric uncertainties.

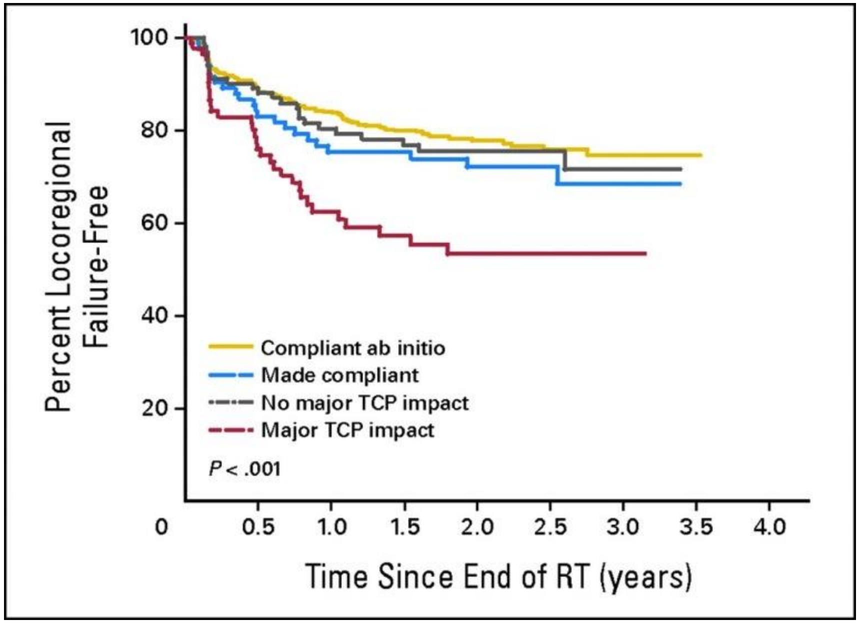
Accuracy required and achievable in radiotherapy dosimetry: Have modern technology and techniques changed our views? Journal of Physics: conference Series 444 (2013) David Thwaites

How many patients will receive dose smaller of 7%?

- 7% = 2 standard deviations
- MEAN ± 2 SD covers 95% of samples
  - 2.5% will receive dose larger of at least 7%
  - 2.5% will receive dose smaller of at least 7%

  - Consequences
    - TCP decreases of about 7% - 14%
    - (based on normalizeddose gradient concept)

Clinical trials

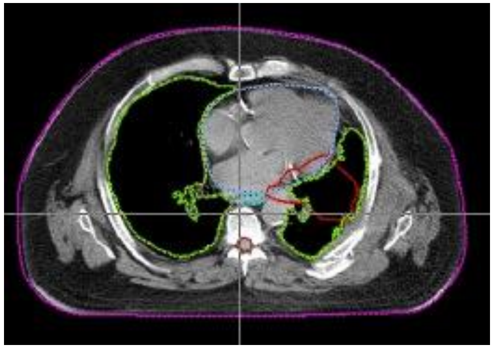


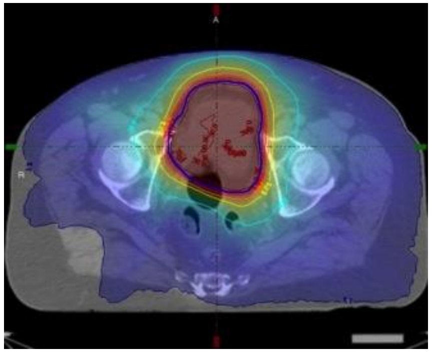
Peters L J et al. JCO 2010;28:2996-3001

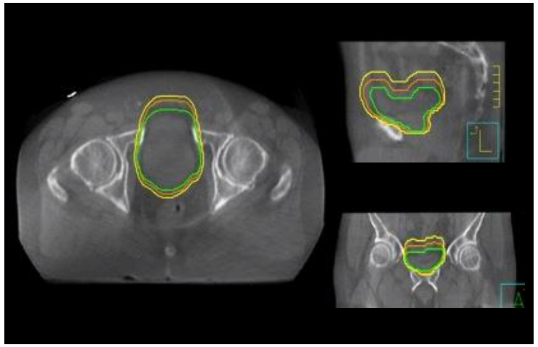
Critical Impact of Radiotherapy Protocol Compliance and Quality in the Treatment of Advanced Head and Neck Cancer: Results From TROG 02.02

Delivered dose does matter!

Callibration of dosimeters : **Measurements of dose distributions of therapeutic beams** ➡ **Input dosimetry data**





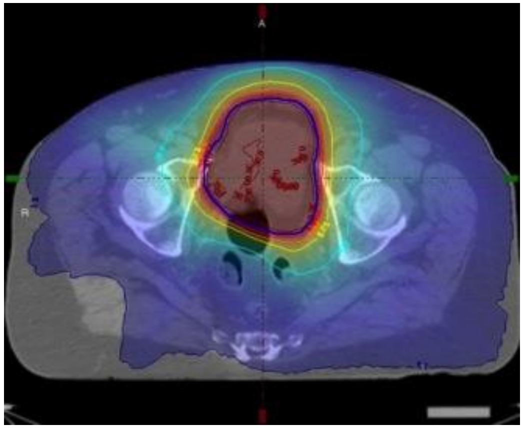


Pre-treatment imaging Tumour & OAR Outlining ➡ **Treatment planning Quality control of Treatment Planning Systems** ➡ **Treatment delivery**

Courtesy Liz Miles RTTQA

Treatment planning system

- Accuracy of dose distribution calculation



Quality control of Treatment Planning Systems

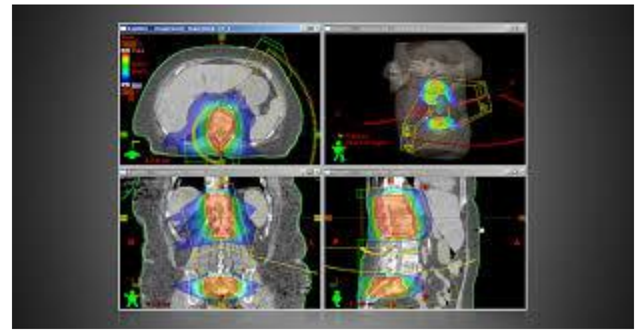
All our clinical decisions are made based on the treatment plan prepared with a TPS!!!

What are characteristics of a good TPS?

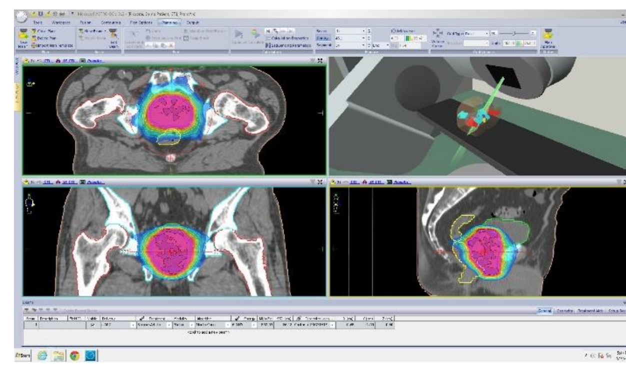
Pinnacle

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

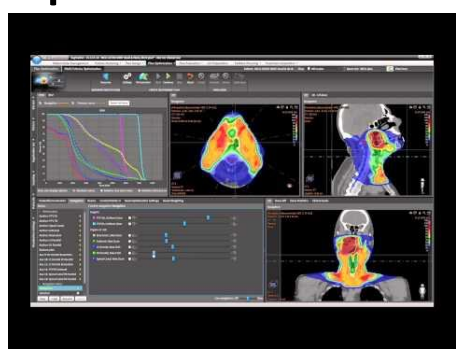
Varian - Eclipse



Elekta - Monaco



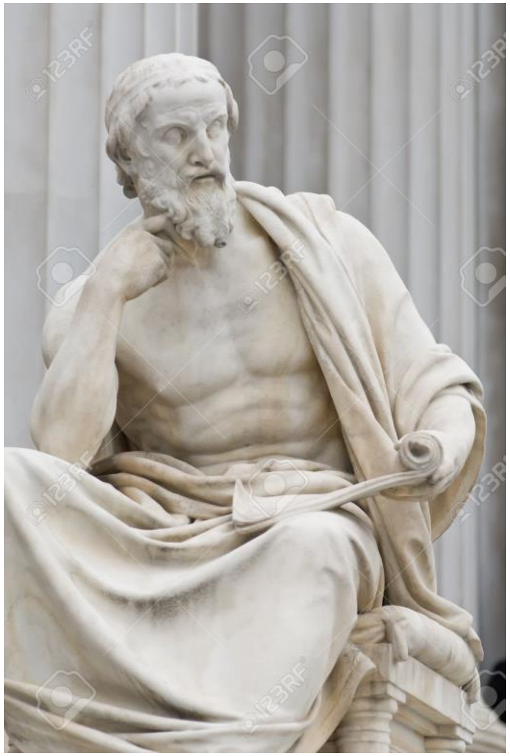
RaySearch – RayStation



Initial remarks

- In general
  - what you see is what you get
    - You must use the TPS you have!
- Everything you may do is
  - get to know deeply the system
    - to read carefully manual,
    - to read papers on quality control issues,
    - to have contact with other, more experienced users,
    - to learn about the system limitations!!!

How to build a good model?



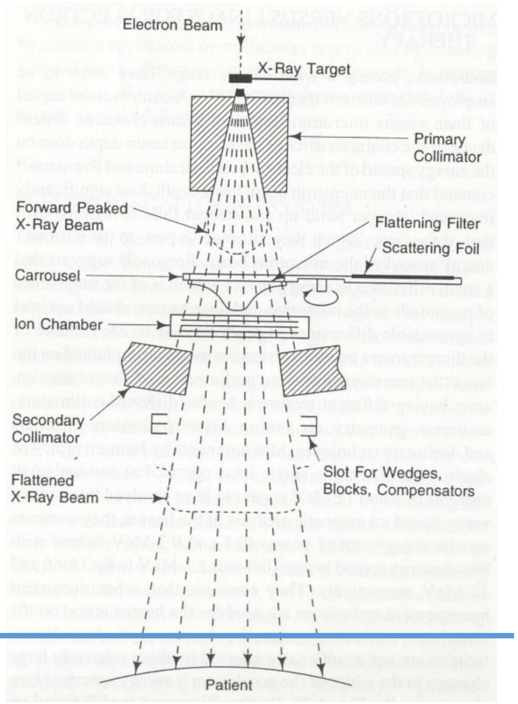
What are characteristics of a good TPS?

WWW.COI.PL

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

Algorithms implemented in TPS

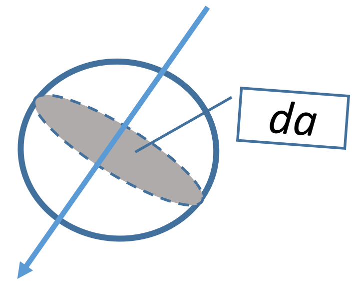
Step 1 - exposure



- What radiation reaches the absorber
  - fluence and energy fluence
    - spectrum of energy fluence
- We call it: primary radiation

Step 1 - exposure

- Fluence – Φ [1/m²]
  - the number *dN* of particles (photons) incident on <u>a sphere</u> of a cross-sectional area of *da*
- Energy fluence – ψ [J/m²]
  - the energy *dE* incident on <u>a sphere</u> of cross-sectional area of *da*



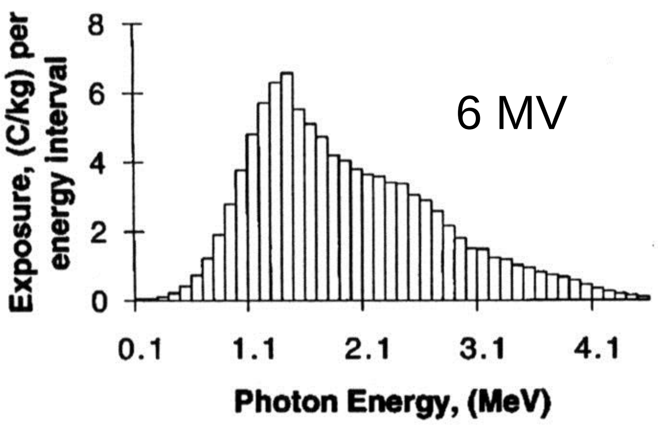
$$\Phi = \frac{dN}{da}$$

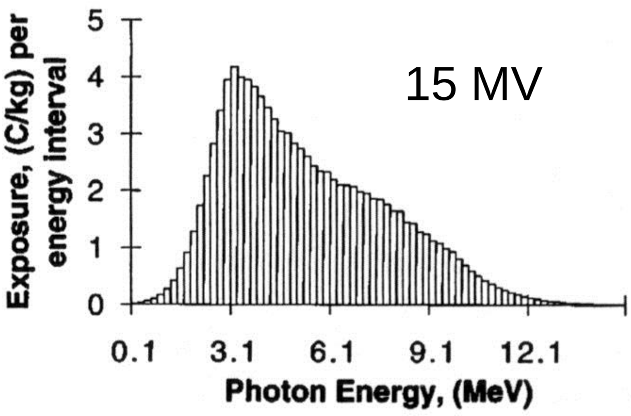
$$\Psi = E \cdot \Phi$$

Energy spectrum

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

Energy spectrum

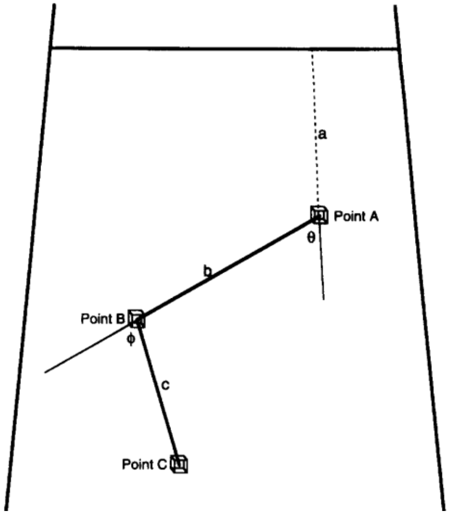




Energy spectrum calculations

- 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

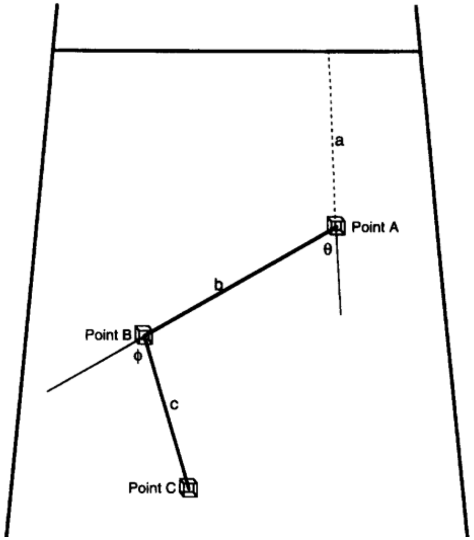
Step 2 – Energy deposition

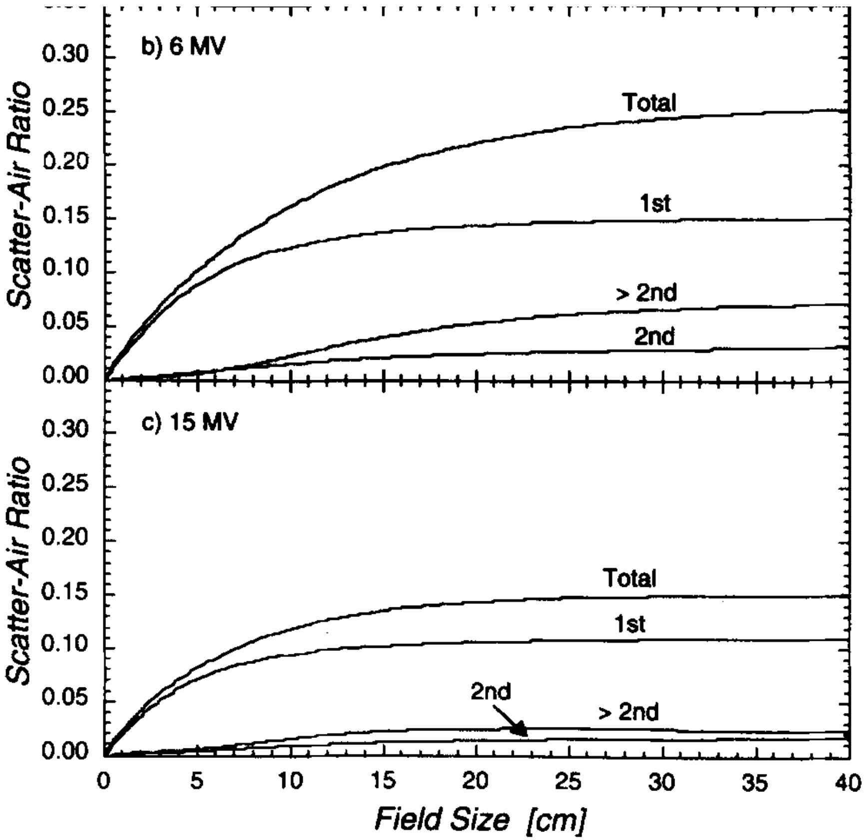


- Primary and secondary dose
- Primary dose
  - interaction of primary photon
    - energy transfered to charged particle (mostly to electron)
      - electron transfered its energy to medium
- Secondary dose
  - interactions of secondary photons (scattered) and so on

Primary and secondary dose

Precise modeling of primary dose is the most important!





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

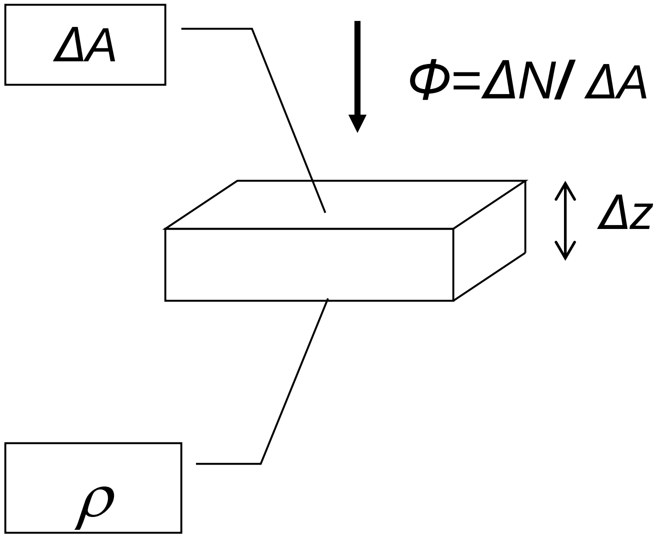
Energy transfered from photons to electrons Kerma

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

number of interactions per unit mass

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

energy transferred to electrons

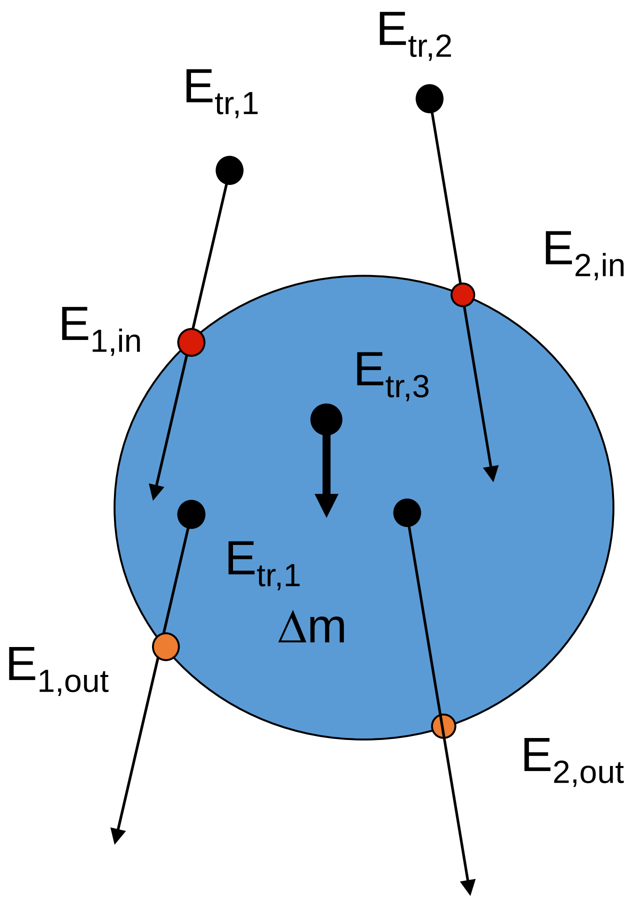


Energy transferred to electrons

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

- KERMA
    - Kinetic Energy Released per unit mass

Charged particle equilibrium (CPE)



- Photon interaction
- Electron enters Δm
- Electron leavs Δm

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

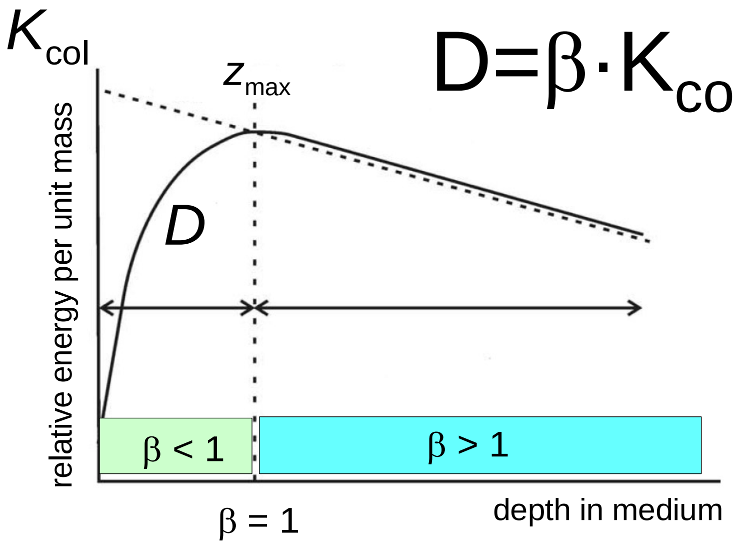
$$Kerma_{col} = Kerma \cdot (1-g)$$

$$Absorbed\ Dose = Kerma_{col}$$

g – fraction of energy emmited in the form of Bremstrahlung

CPD never exists

- Transient CPD exists

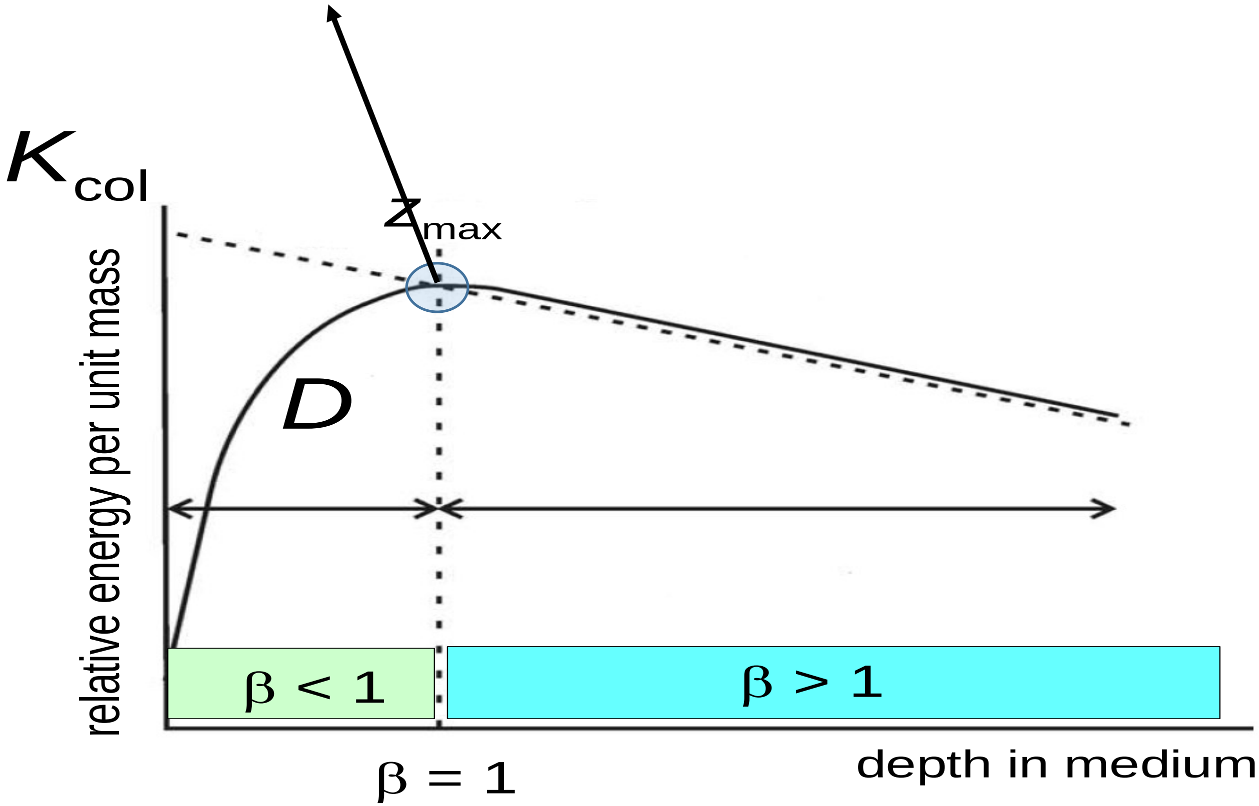


$$D=\beta\cdot K_{col}$$

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

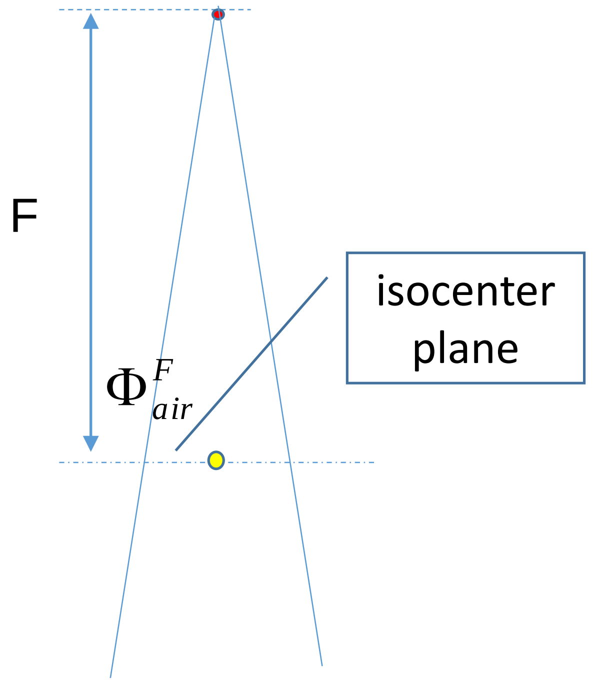
$$D=(1+f_{TCPE})\cdot K_{col}$$

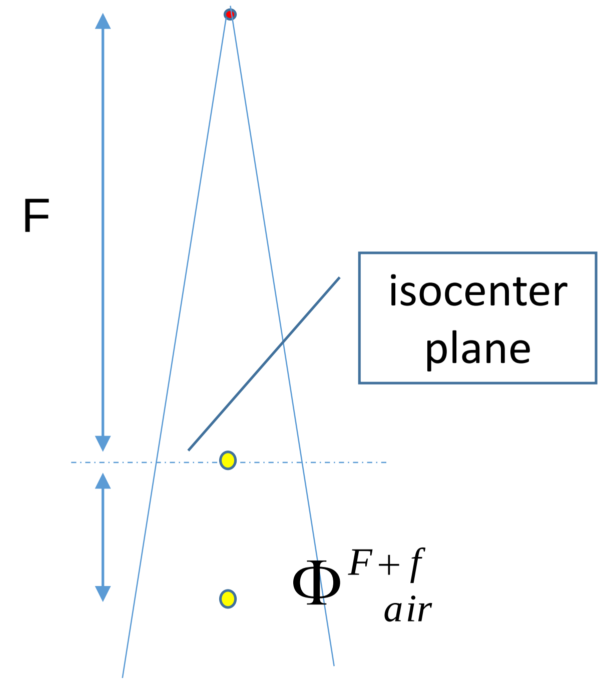
Is the CPE at dmax?



How does the fluence dependence on the distance?

Fluence in air – inverse square low





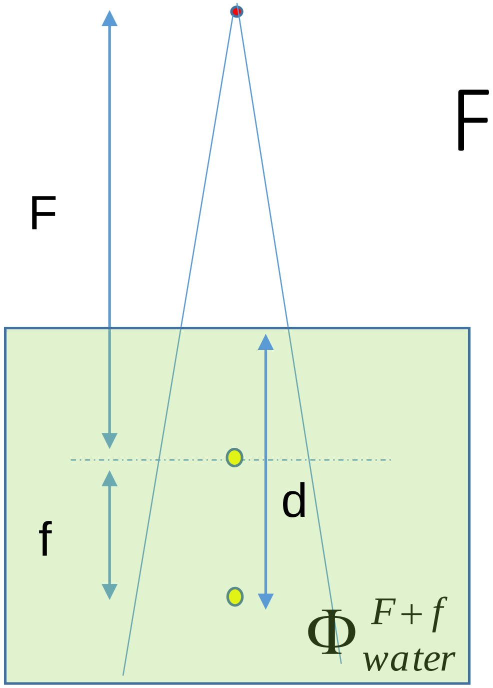
$$\Phi_{air}^{F+f} = \Phi_{air}^{F} \cdot \frac{F^2}{(F+f)^2}$$

Uncertainty – errors in distance

- Error in distance of 1 cm approximately leads to:
  - 1% error
  - 2% error
  - 3% error

Uncertainty – errors in distance

- Distance to isocenter = 100 cm
  - $\Delta = 99^2/100^2 \approx 0.98$
  - 2%
  - Precise calibration of telemeter does matter!



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

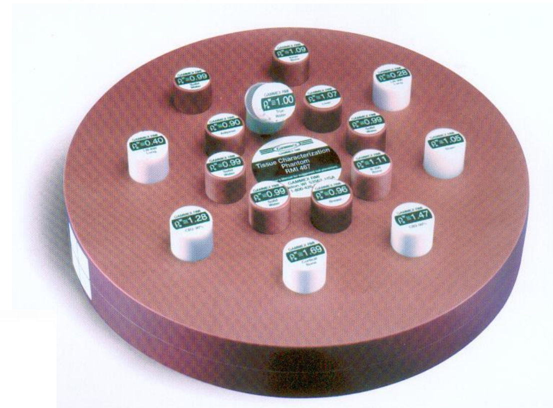
$$D_{water}^{F+f} = \beta \cdot \Phi_{air}^{F} \cdot \frac{F^2}{(F+f)^2} \cdot e^{-\mu \cdot d} \cdot \left(\frac{\mu}{\rho}\right) \cdot E_{tr} \cdot (1-g)$$

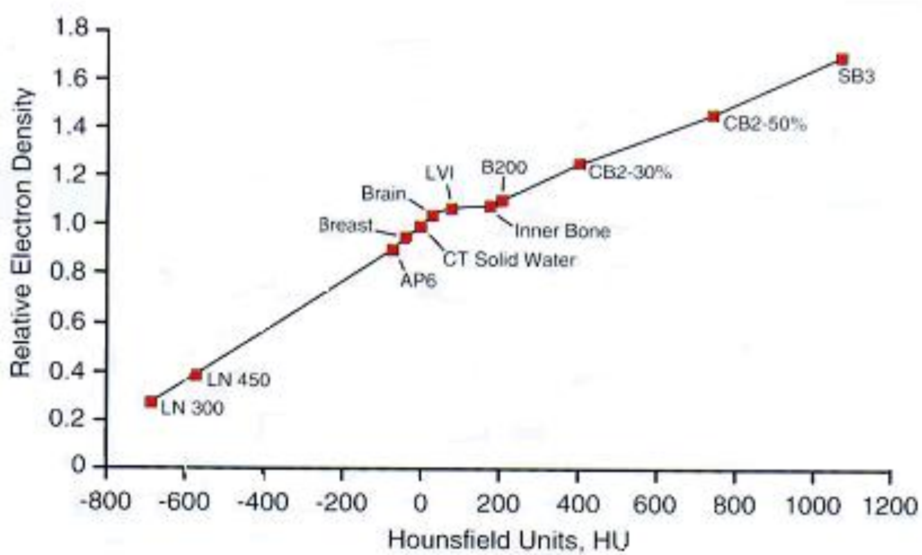
Uncertainty – errors in depth

- Error in depth of 1 cm approximately leads to:
  - 1% error
  - 3% error
  - 5% error

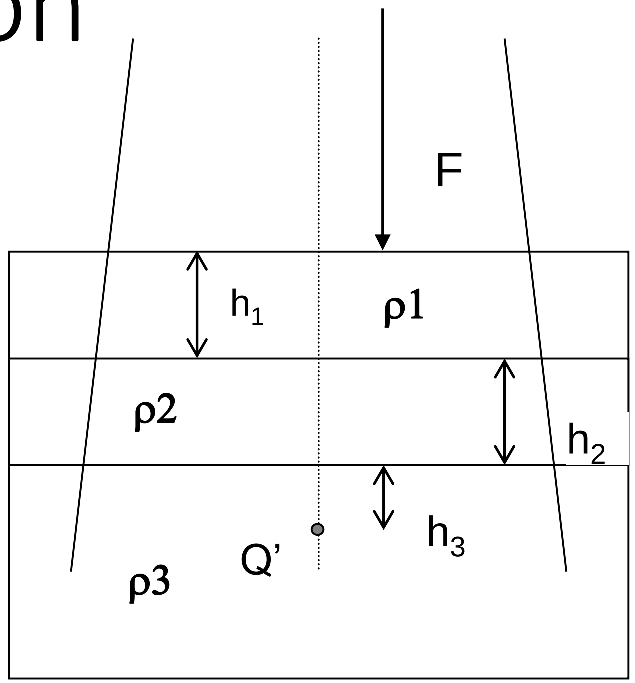
Difference of 1 cm of soft tissue

- μ ≈ 0.05 1/cm
- Δ ≈ exp(-0.05) ≈ 0,95
- 5%





Fluence – real situation



- Radiological depth

$$d_{rad} = \frac{h1 \cdot \rho 1 + h2 \cdot \rho 2 + h3 \cdot \rho 3}{\rho_{water}}$$

- In general

$$d_{rad} = \sum \rho_k / \rho_{water} \cdot h_k$$

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

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

radiological depth

physical distance

Another aproach 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

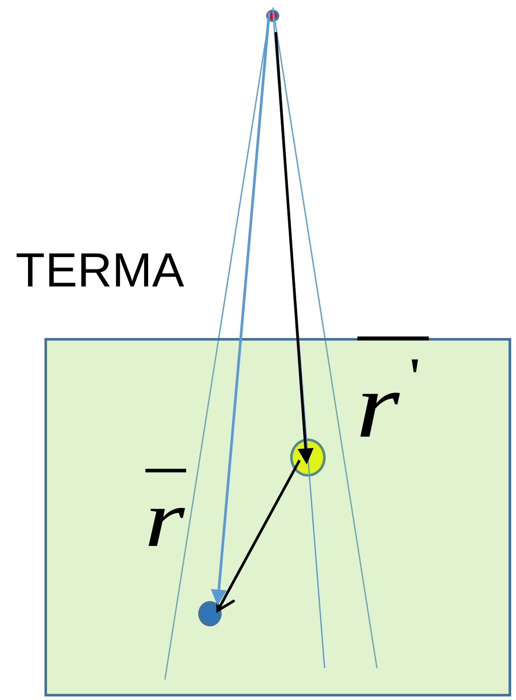
- What will happen with this released energy?
  - mostly it will be absorbed as primary and secondary dose
    - only a little energy will escape (scattered photons, bremstrahlug)

Convolution – monoenergetic case
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 hv; integral over whole medium



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

Convolution – polyenergetic (real case)

- Integral over space and energy spectrum

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

Mohan, Med.Phys, 1985, 12, 592 – 597.

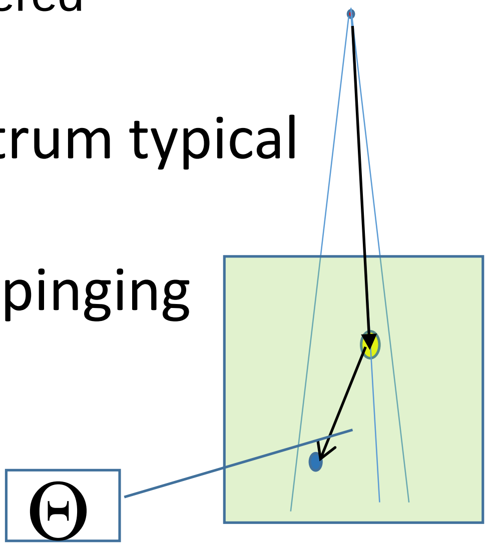
Kernels – Point Spread Function

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

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

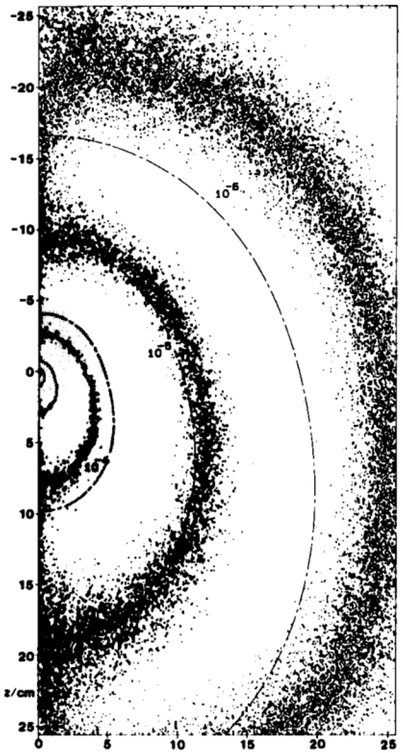
$$A_\Theta, a_\Theta, B_\Theta, b_\Theta$$

- 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

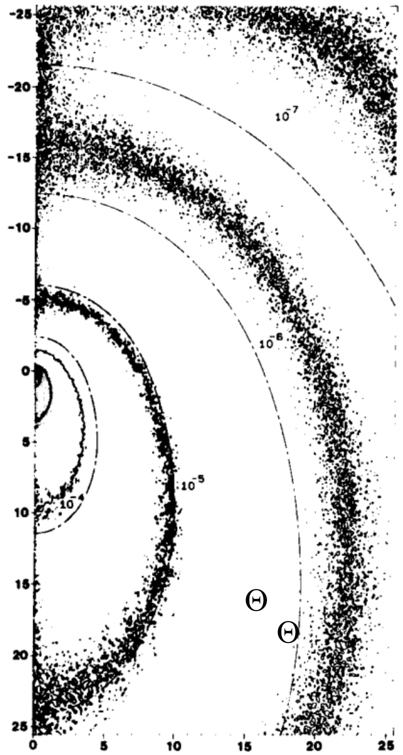


Kernels

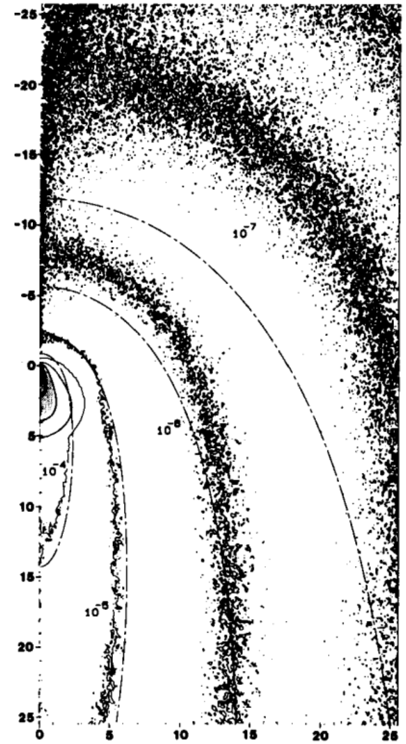
0,4 MeV



1,25 MeV



10 MeV



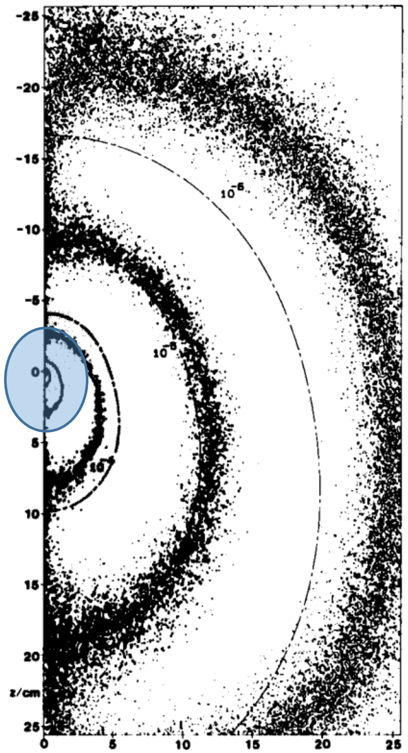
Energy imparted per cm^{-3}

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

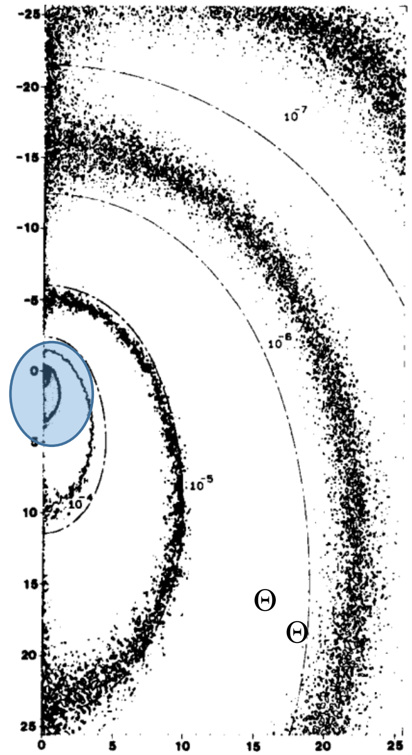
Acta Oncologica, 1987, Ahnesjo

Kernels

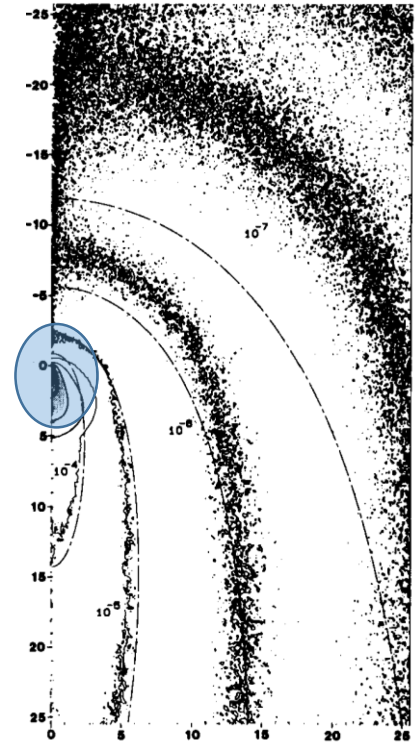
0,4 MeV



1,25 MeV



10 MeV



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Convolution – polyenergetic (real case)

- Integral over space and energy spectrum

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

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

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

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

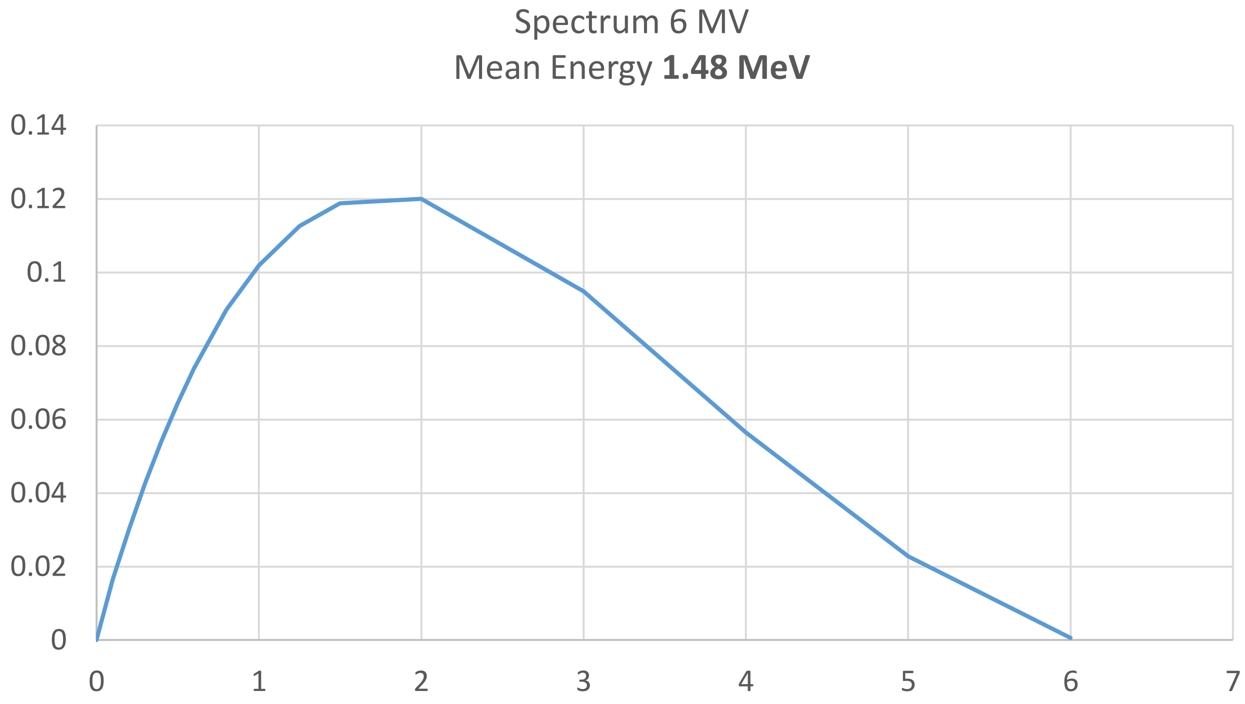
Mohan, Med.Phys, 1985, 12, 592 – 597.

Approximations

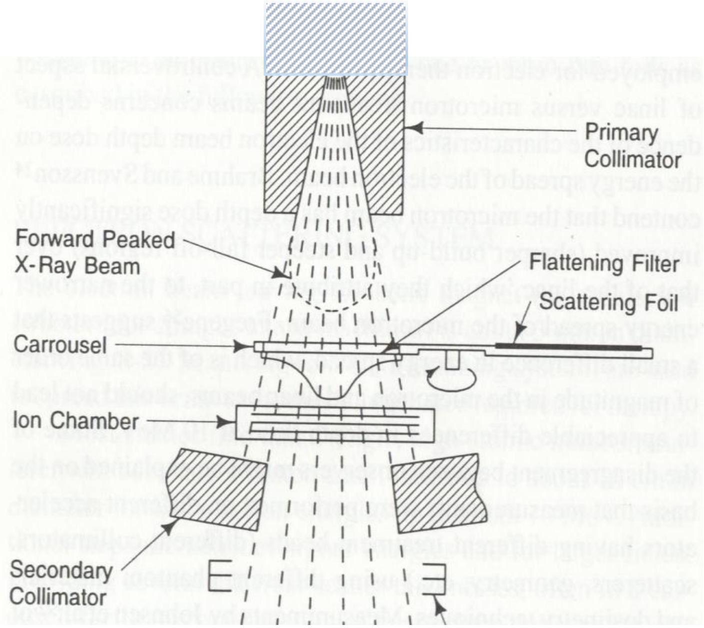
- To allow calculations in a resonable time several approximations are used
  - treatment planning system dependent
    - the same model different results
  - polyenergetic → monoenergetic (e.g. for mean energy)
  - single energy spectrum is used
  - collapse cone method
  - Kernels generated for water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

6 MV spectrum

polyenergetic : monoenergetic



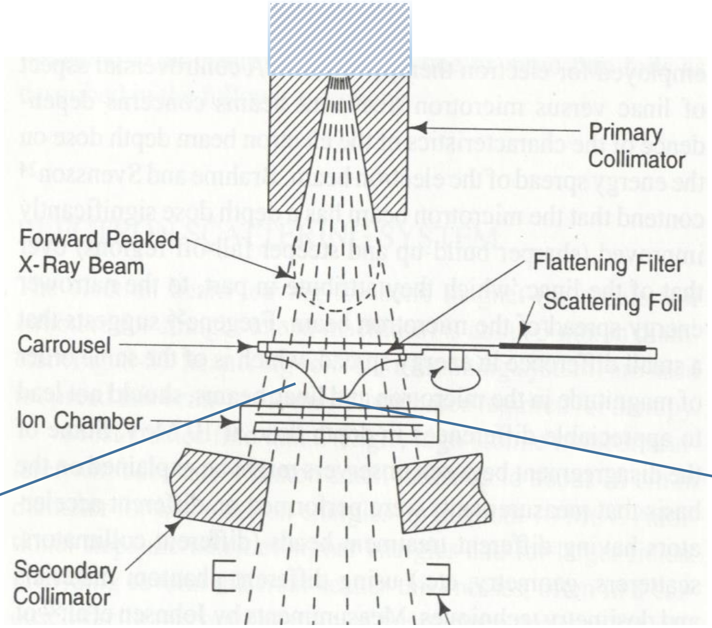
Changes of spectrum
lateral softenning



single energy spectrum

Changes of spectrum
lateral softenning

lower energy



higher energy

single energy spectrum

Collapsed Cone Convolution
speed-up calculations

- 30 x 30 x 30 cm^3 water Phantom
- 0.3 cm grid size
- 100 x 100 x 100 calulations point = 1 000 000

- Convolution: contribution from each voxel to each voxel

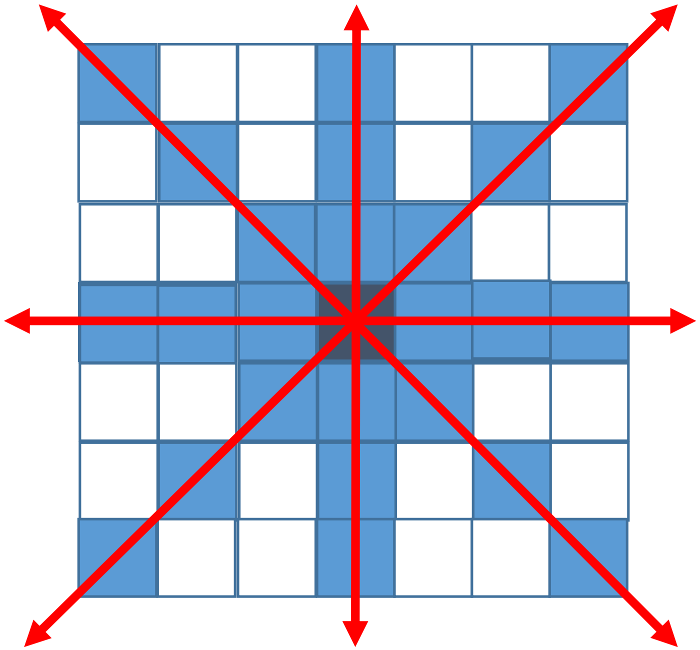
1 000 000 x 1000 000 = 1 000 000 000 000

Collapsed Cone Convolution

- CCC aproaches 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



8 cones

Energy desposition decreases very quickly with distance

Energy is absorber in blue pixels only.

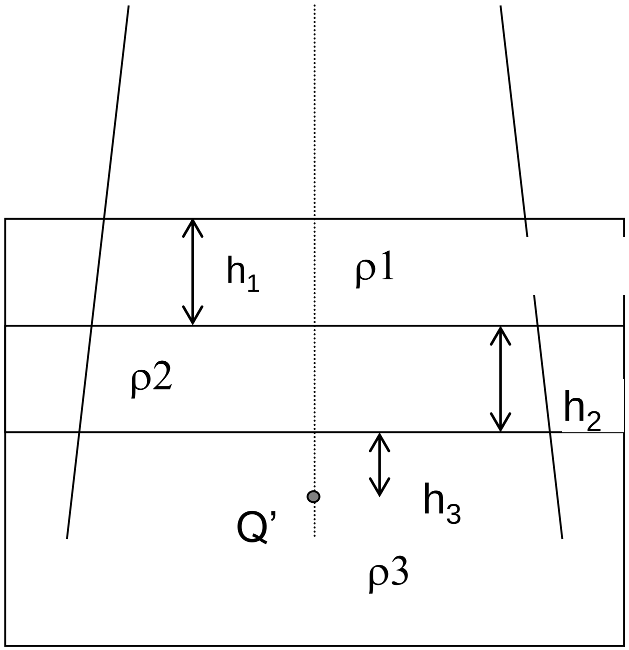
Collapsed Cone Convolution
2D illustration

- 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

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



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

Two spaces -worlds

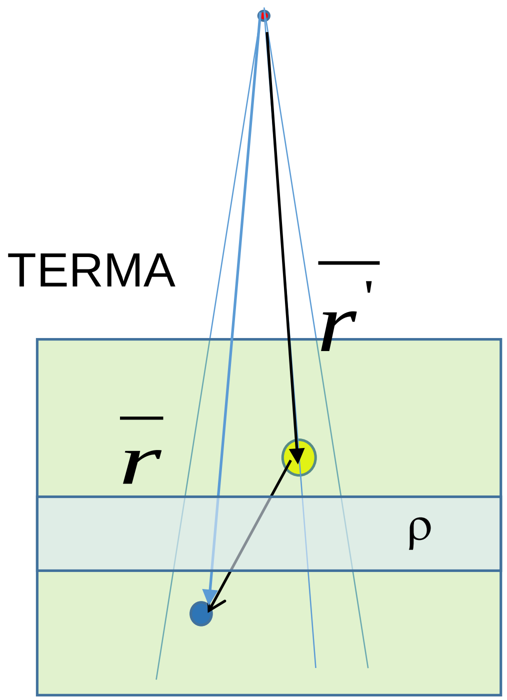
- World 1
  - Air – fluence is scaled with distance according to square factor
    - Precise
- World 2
  - Medium – Terma and Kernel are scaled with radiological distance (density is taken into account)
    - approximation

Convolution – monoenergetic case

$TERMA_{h\nu} = T_{h\nu}$

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

Square factor and scaling with density



Summary

- Be especially careful with
  - Measurements of
    - small beams
    - OF
  - Extrapolations
    - range of data entered into the system
    - range of CT made for your patient

  - Distributions in the vinicity
    of two much different matrials (Air – soft tissue)

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Summary

- Primary and secondary dose

- Kerma and Kolision Kerma versus Dose

- How to described 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 becoms 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.

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

Thank you very much for your attention!

Life is complicated but very fascinating!