National Research Institute of Oncology (Maria Sklodowska-Curie)

ICTP School of Medical Physics for Radiation Therapy:
Dosimetry and Treatment Planning
for Basic and Advanced Applications
ICT Trieste 2025

Models used in treatment planning systems (an introduction to pre-treatment verification of treatment plans)

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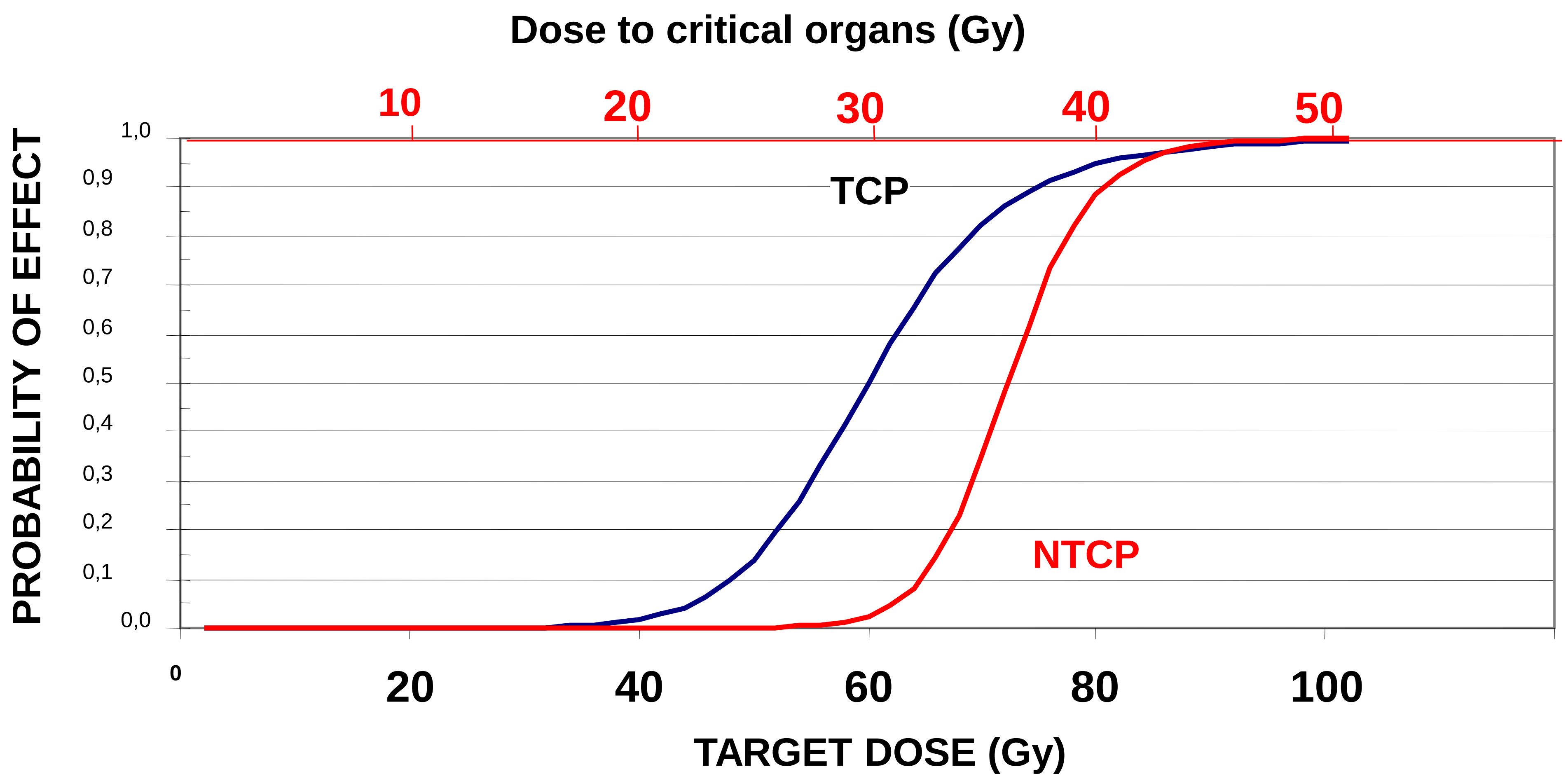
Recommendations on accuracy in radiotherapy



3% (relative sd) on the delivered absorbed dose to the patient
was recommended as the tolerance level on accuracy in dose delivery
Thwaites

7th International Conference on 3D Radiation Dosimetry (IC3DDose)
Journal of Physics: Conference Series **444** (2013) 012006

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Precision of dose calculations matters

Experience of the Imaging and Radiation Oncology Core Houston Quality Assurance Center (IROC)

- results of antropomorphic phantom audit showed that

Photon beam modeling variations predict errors in IMRT dosimetry

Audits Mallory C. Glenn, et all; Green 2022

The audit results published in 2022 indicated that 8–15% phantom irradiations fail to meet quite loose acceptance criteria

- TLD 5 – 7%
- film ≥ 85% pixels passing 5%/3mm to 7%/4 mm gamma criteria

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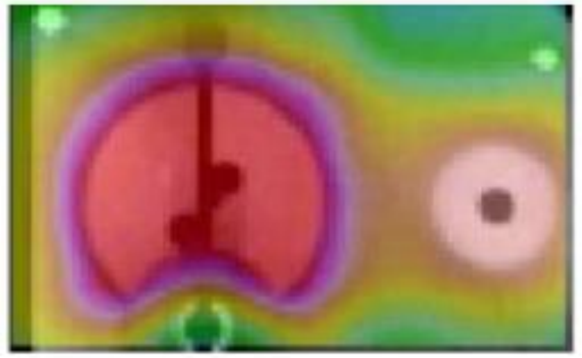
IROC experience

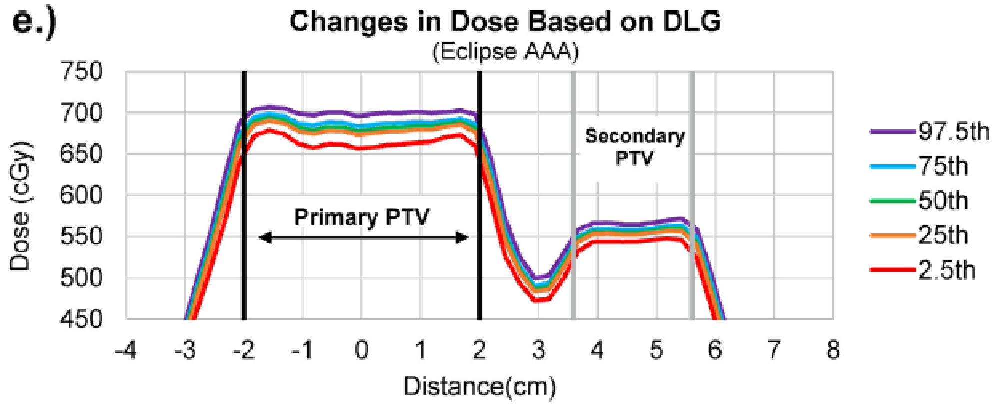
Imaging and **R**adiation **O**ncology **C**ore Houston

IROC Head Phantom

Beam modeling parameters

- were associated with poor or failing audit results
  - 68% of failing cases and 56% of poorly performer irradiations were linked with atypical parameter values
    - MLC transmission factor
    - dosimetric leaf gap





Glenn MC, Brooks F, Peterson CB, Howell RM, Followill DS, Pollard-Larkin JM, Kry SF. Photon beam modeling variations predict errors in IMRT dosimetry audits. Radiother Oncol. 2022 Jan;166:8-14. doi: 10.1016

In contrast

32% of well-performed irradiation were linked with atypical parameter values

Calculation of dose distribution

We have no control over the algorithm used

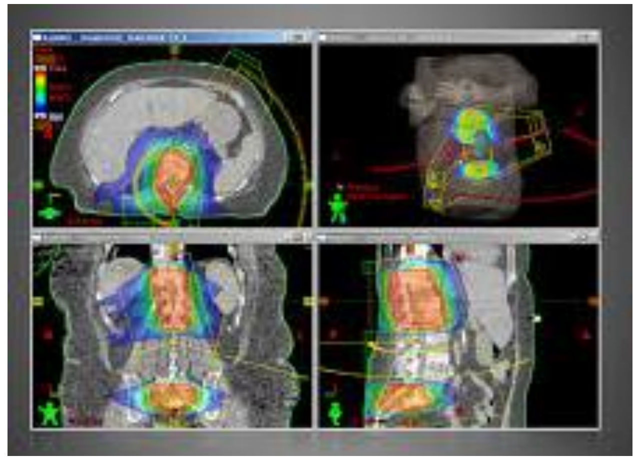
- we are responsible for knowing the results of the verification of the calculations for a given version of treatment planning system (implementation)
  - literature

We have an impact on the quality of the entered data and tuning of some model parameters

- commissioning of radiotherapy treatment planning system
- verification of the calculation of dose distributions

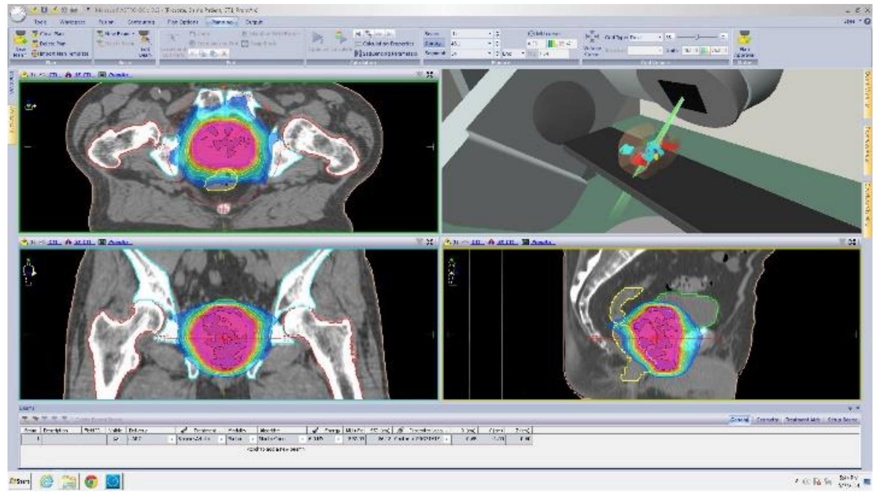
Basic features of a good TPS

Varian - Eclipse



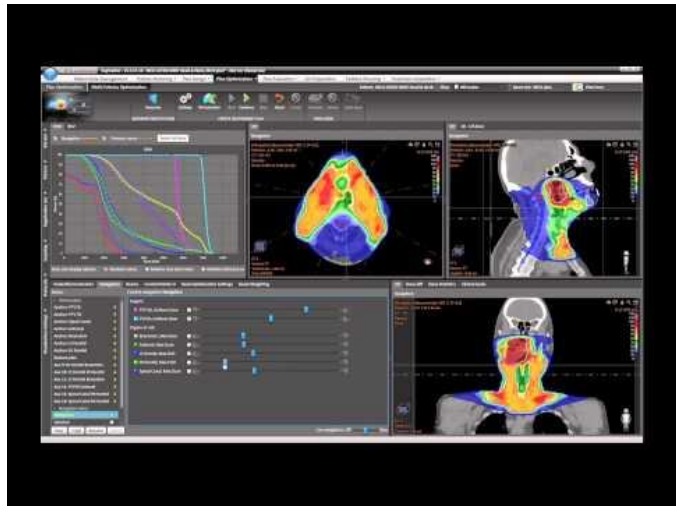
- Accuracy of calculations
- Speed of calculations
- Wide range of applications
- User friendly
- Stable
- ?

Elekta - Monaco



Pinnacle - Philips

RaySearch – RayStation



Theoretical basis of photon beam therapy modeling

Two situations exist

(Transient) Charged Particle Equilibrium

There is no TCPE

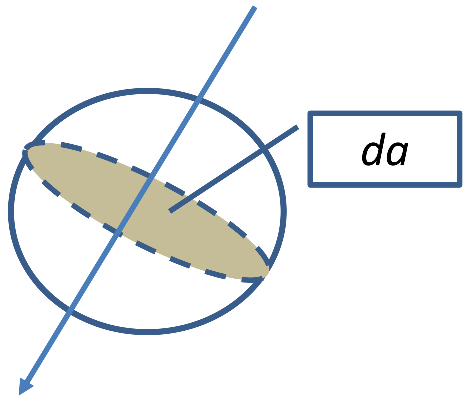
Fluence and Energy Fluence

Fluence – Φ [1/m^2]

number *dN* of particles (photons) incident on a sphere of cross-sectional area *da*

Energy fluence – ψ [J/m^2]

energy *dE* incident on a sphere of cross-sectional area *da*



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

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

Energy deposition

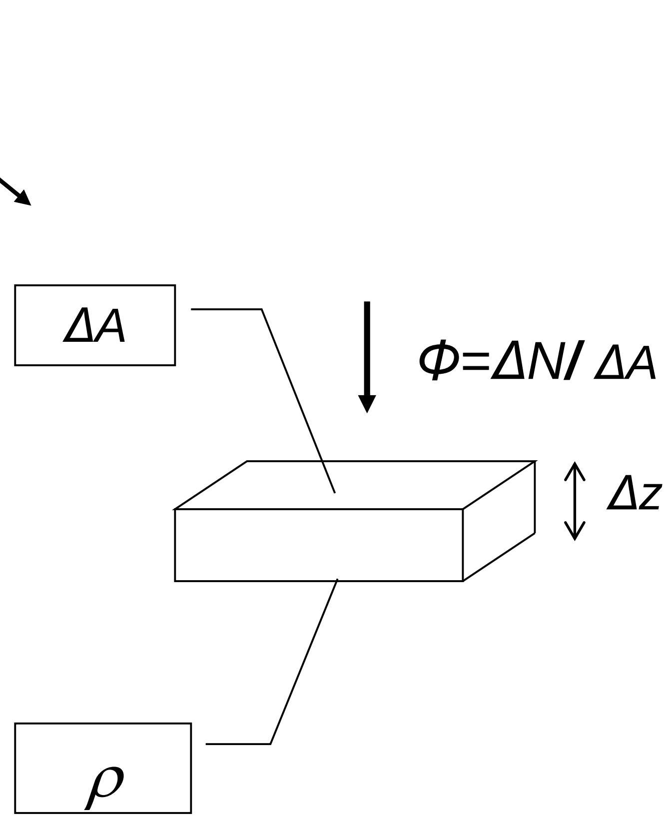
Photons energy is transferred to electrons → Kerma

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

Number of interactions per unit mass

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

Energy transferred to electrons



Kerma and dose

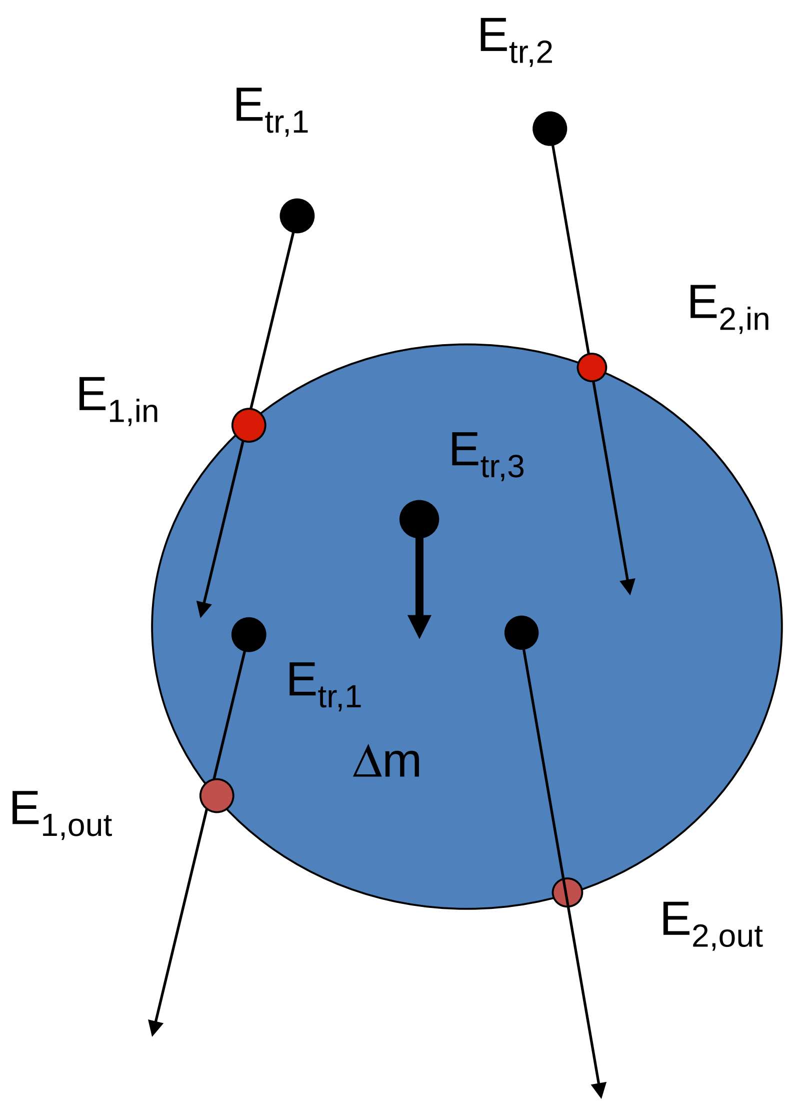
Kinetic Energy **R**eleased per unit **MA**ss

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

$$Kerma_{col} = \left(\frac{\mu}{\rho}\right) \cdot \overline{E}_{tr} \cdot \Phi \cdot (1 - g)$$

$$Dose \approx Kerma_{col}$$

Particle Charged Equilibrium (PCE)



Electron equilibrium exists when:

for every charged particle with momentum **p**

entering the volume V,

there is a particle with momentum **p** leaving the volume V

As a result

almost all energy transferred by photons

to medium is absorber

If TCPE exists than…

Transient Charged Particle Equilibrium

TCPE

TCPE exists if the absorbed dose D is proportional to the collision Kerma Kc.

If energy spectrum of photons is constant the constant of proportionality is the same! It depends on the range of electrons and linear attenuation coefficient.

- in the next graph the curve are in fact little closer to each other!

No TCPE

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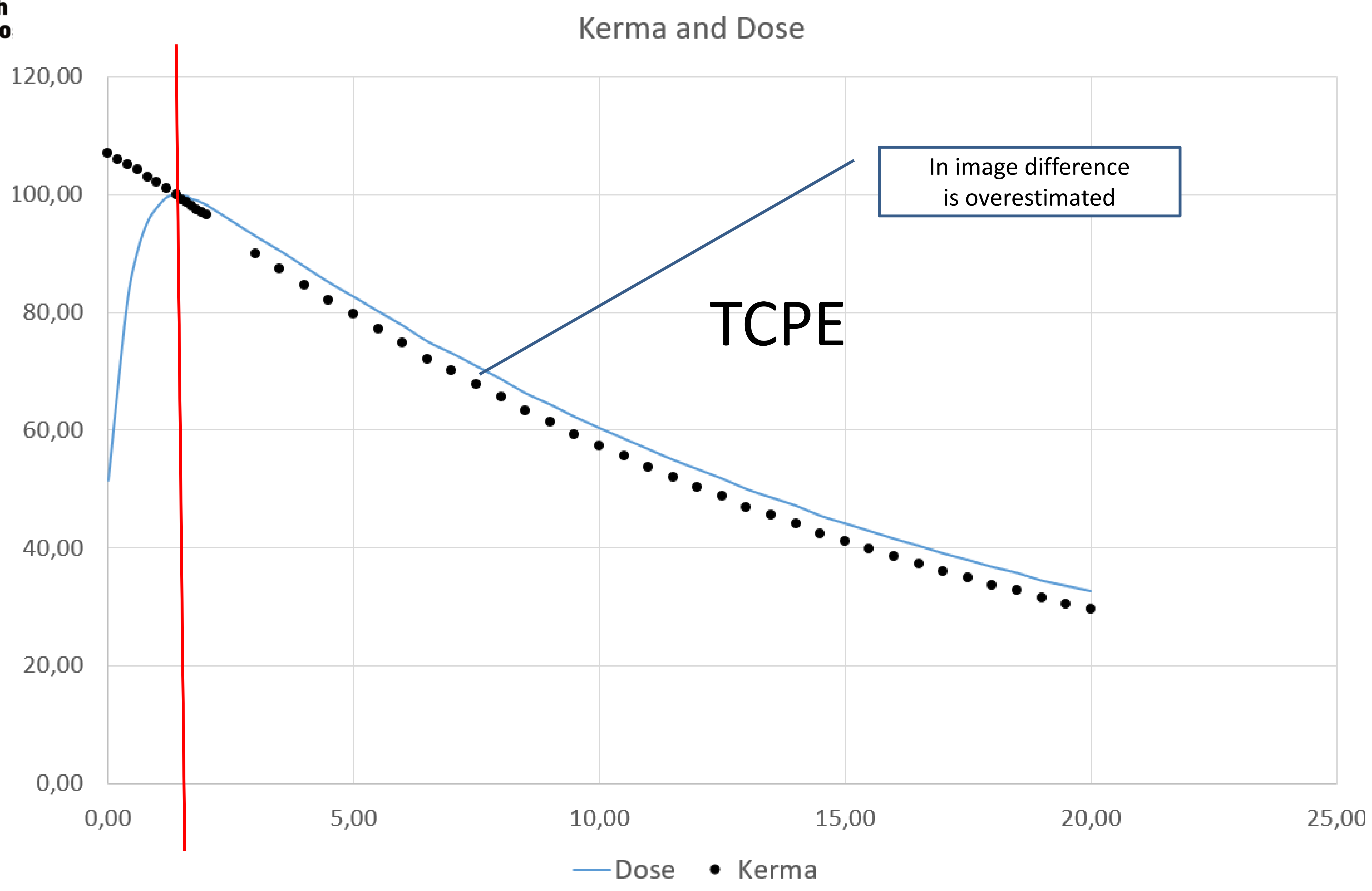


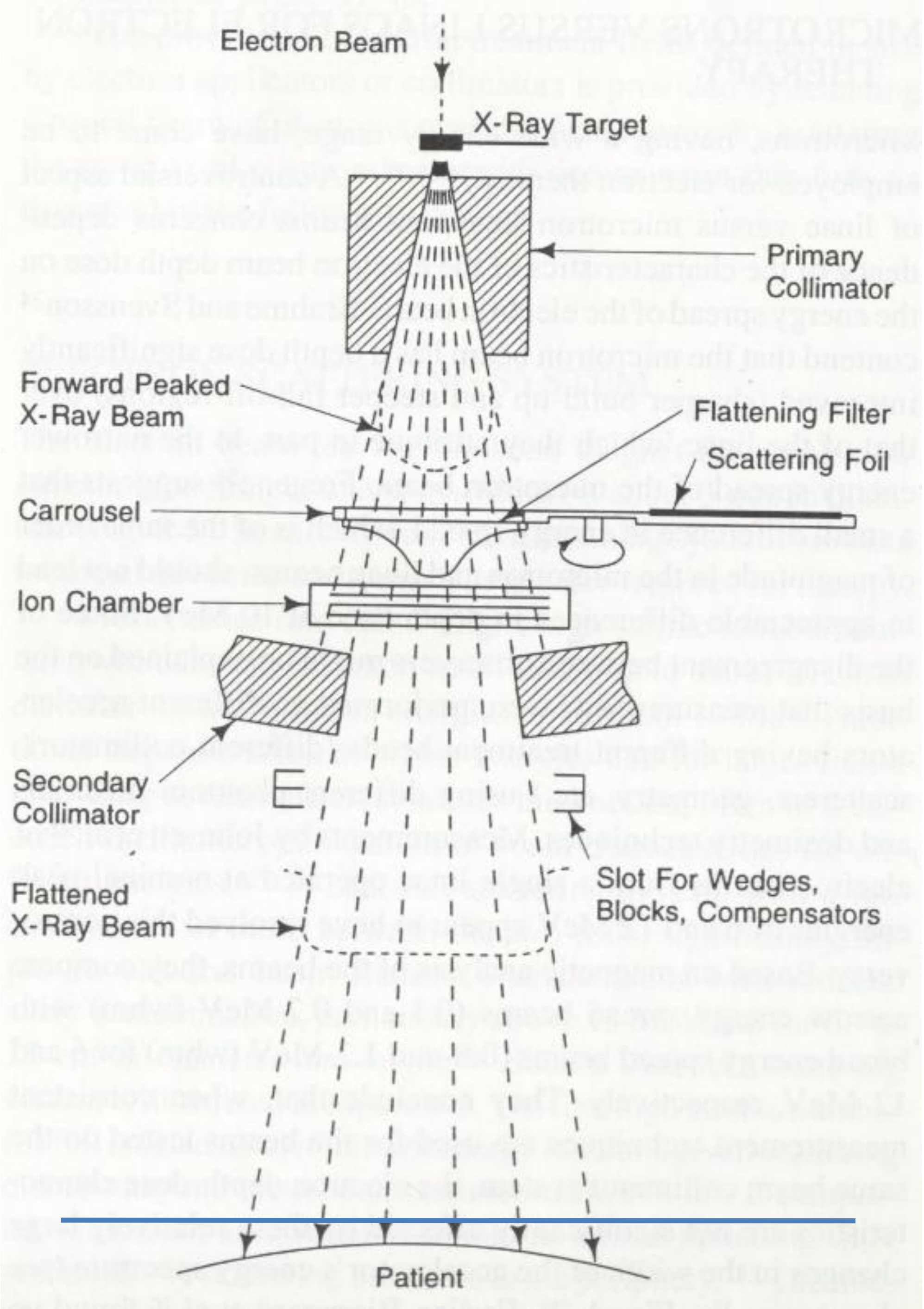
Transient Charged Equlibrium Exist

monoenergetic beam of Energy *hν*

$$Dose_{h\nu} = \left(\frac{\mu}{\rho}\right) \cdot \overline{E}_{tr,h\nu} \cdot \Phi_{h\nu} \cdot \left(1 - g_{h\nu}\right)$$

↑ !

Fluence – Energy fluence



What reaches the absorbent

- Energy fluence spectrum
  - Photons
  - Electron contamination (build-up)

Spatial distribution of energy fluence

Interaction of radiation with absorber (energy deposition)

- Water
- Real situation (inhomogenous)
  - Transit Charged Equlibrium Exists
  - No Transit Charged Equlibrium

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Determination of effective bremsstrahlung spectra

Determination using an iterative technique to minimise the difference between calculated and measured depth dose curves.

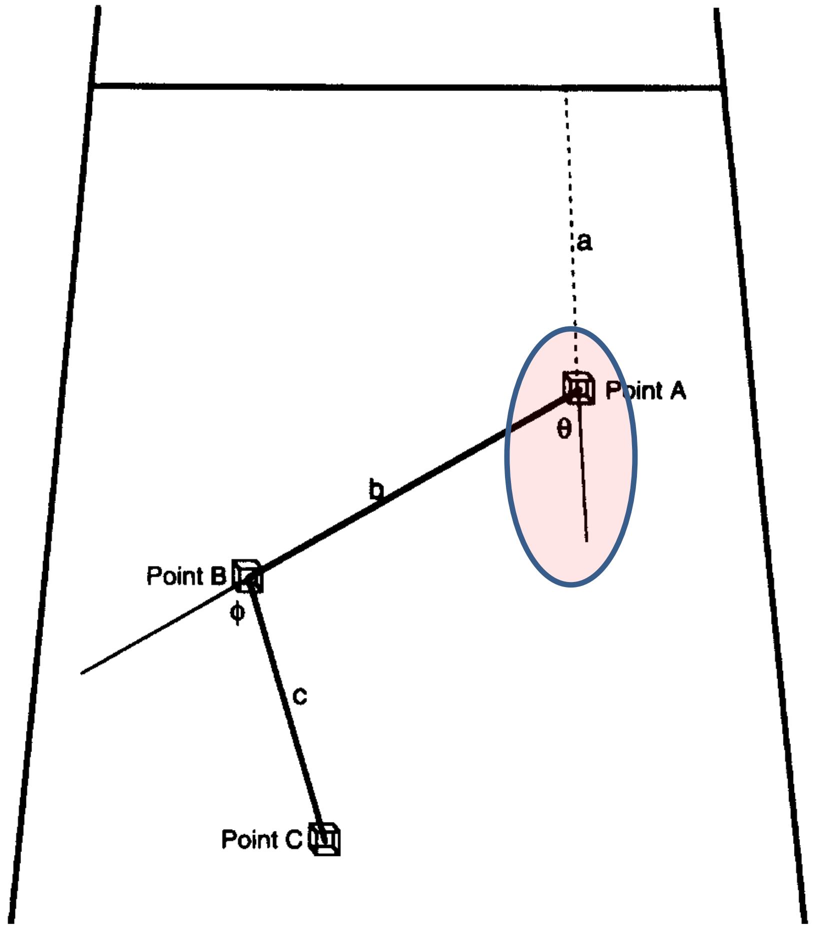
Determination of effective bremsstrahlung spectra and electron contamination for photon dose calculations, Ahnesjo, Andreo, 10.1088/0031-9155/34/10/008

This method is used currently in most of TPS!

Calculation of Depth Dose for monoenergetic beam

Mechanism of dose deposition

- **primary dose**
  - dose deposited by electrons which received energy from the photon (all photons!) in the first interaction which occurred in the absorbent
- **scattered dose**
  - dose deposited by electrons which received energy from scattered photons interaction which occurred in the absorbent



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

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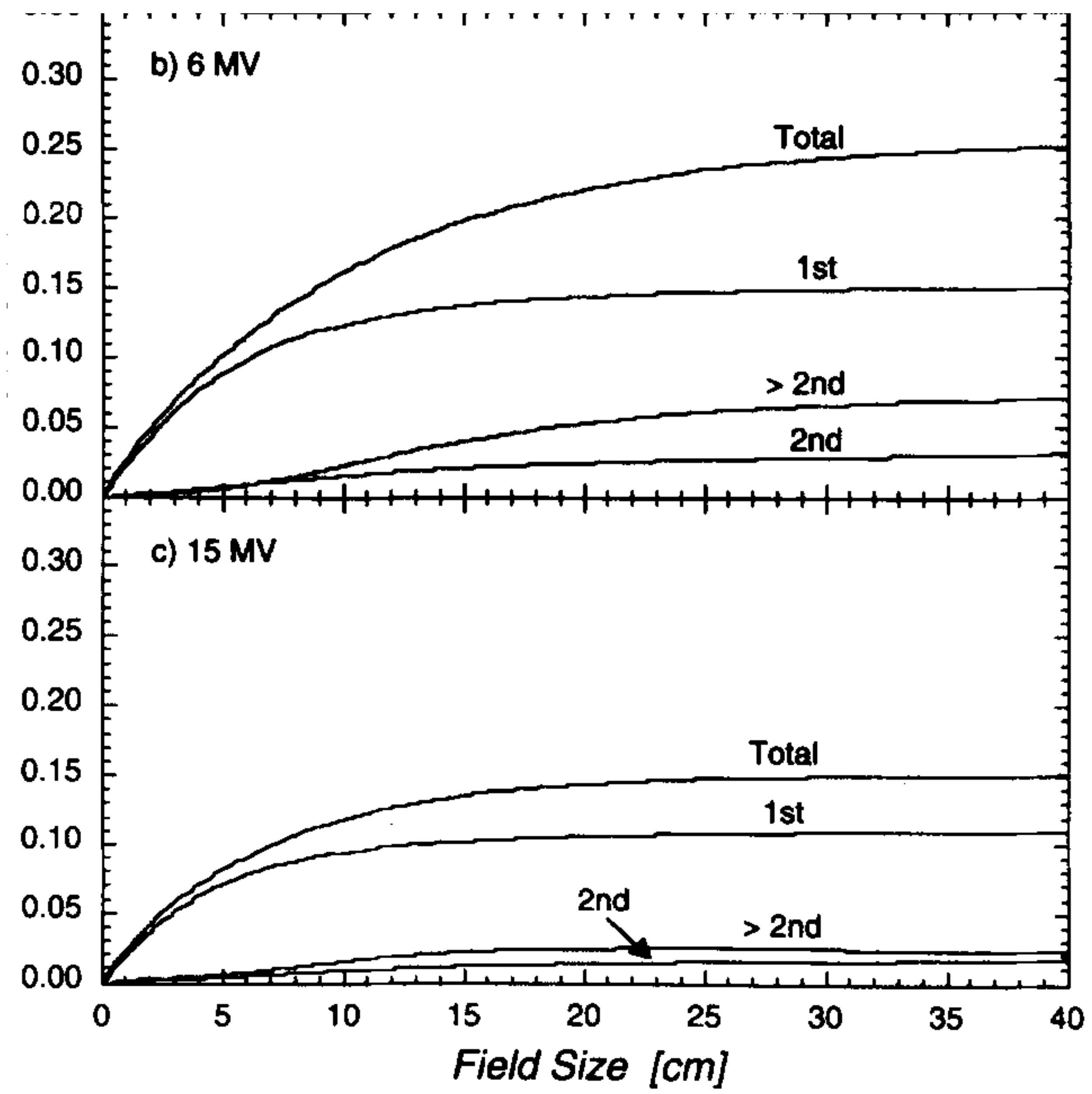
Primary and scattered dose homogeneous absorber

For high energies scattered dose is small in comparison to primary dose!

The larger is energy the smaller is scattered component!

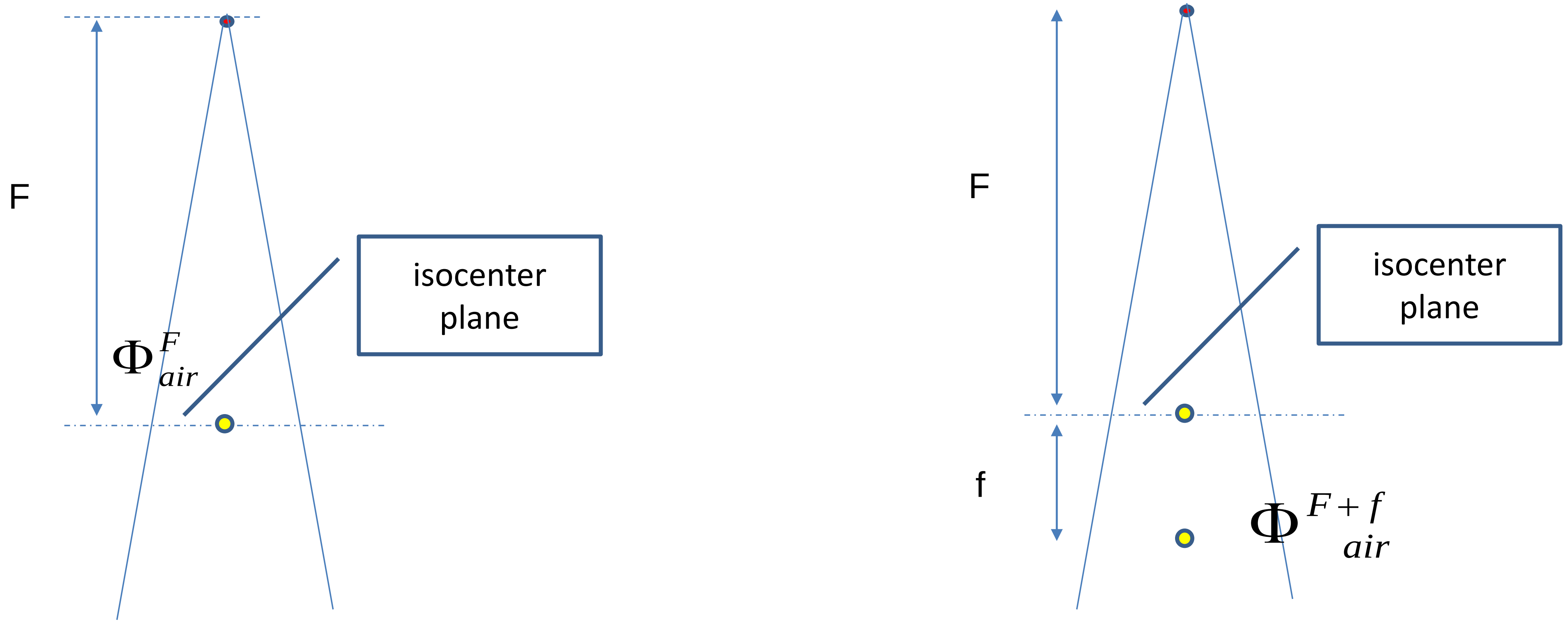


Sontag, Med. Phys. 1995, 22 (6)

Primary dose

Dependence of the fluence in air on a given distance

- inverse square law



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

Transient Charged Equlibrium Exist

monoenergetic beam of Energy *hν*

$$Dose_{h\nu} = \left(\frac{\mu}{\rho}\right) \cdot \overline{E}_{tr,h\nu} \cdot \Phi_{h\nu}^{water} \cdot \left(1 - g_{h\nu}\right)$$

primary dose

Beam attenuation
Compton approximation

Compton is th most important interaction with the matter for megavoltage radiation (6MV – 15MV)

Compton is **not significantly dependent on the atomic number (Z)** of the material

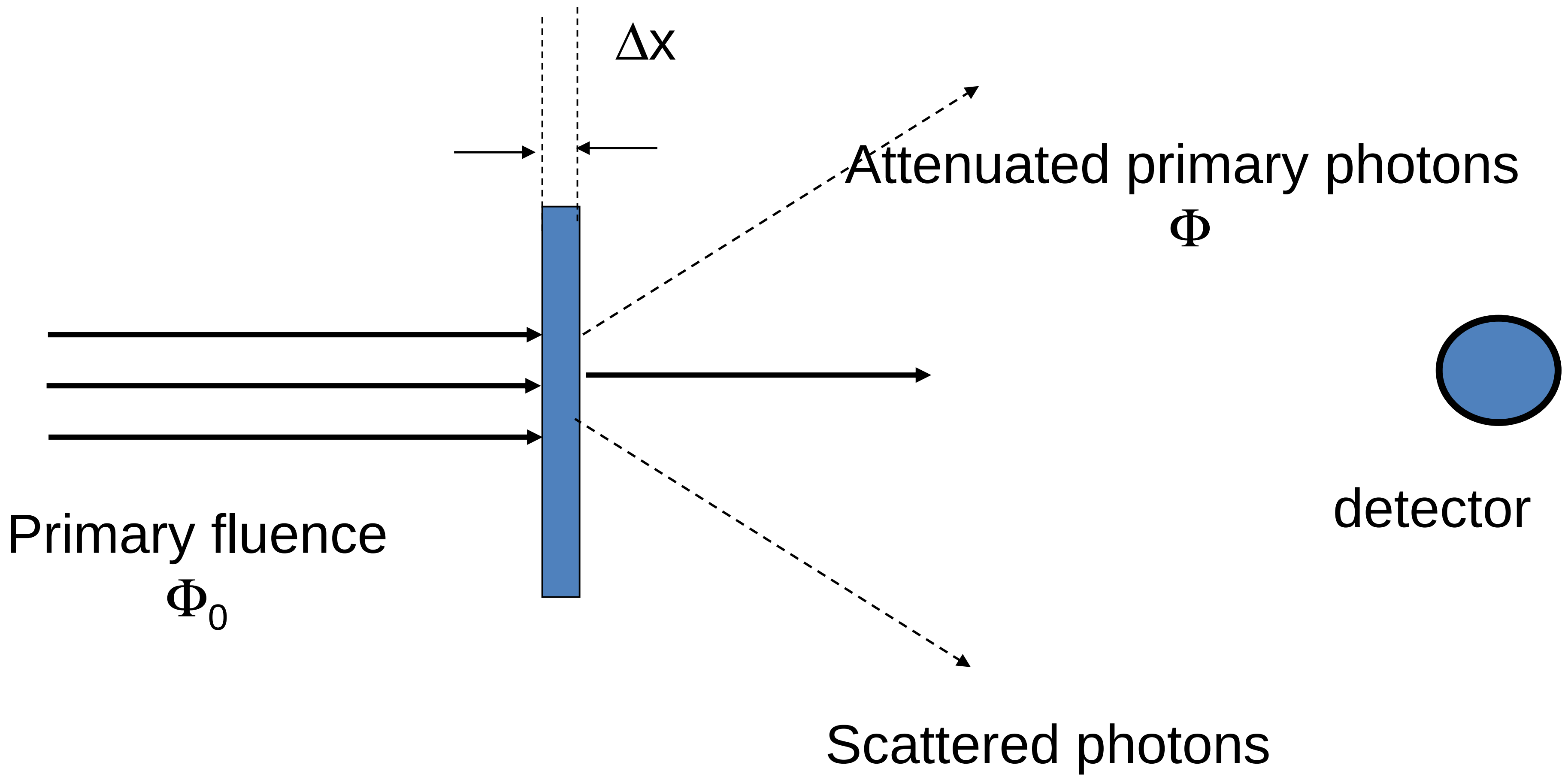
Compton depends on **electron density** of the material

For most elements (tissues), the number of electrons per gram is relatively constant, so

The probability of Compton scattering is proportional to the physical density.

So attenuation of the layer of density ρ is ρ times smaller/larger than water attenuation

Linear attenuation coefficient
for spectrum apparent linear attenuation coefficient



$$\Phi = \Phi_0 \cdot \exp(-\mu \cdot \Delta x)$$

Total energy released per unit mass - TERMA

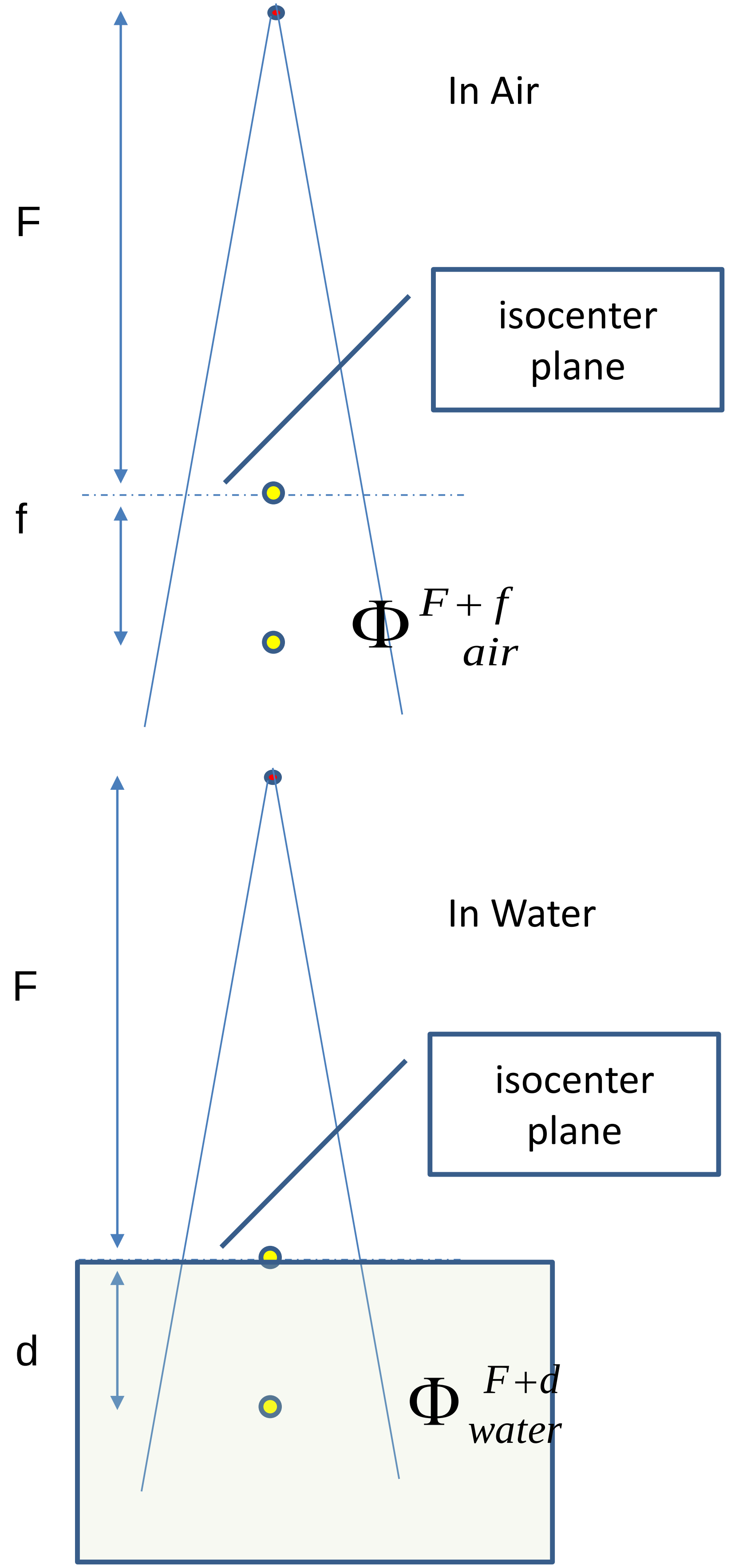
$$TERMA_{h\nu} = \Phi_{air}^{F} \cdot \frac{F^2}{(F+f)^2} \cdot e^{-\mu_{h\nu} d} \cdot h\nu \cdot \left(\frac{\mu_{h\nu}}{\rho}\right) \cdot Etr_{h\nu}$$

primary energy fluence

$$TERMA_{h\nu} = \int_{spectrum} \frac{d\Phi_{air}^{F}}{dh\nu} \cdot \frac{F^2}{(F+d)^2} \cdot e^{-\mu_{h\nu} d} \cdot E_{tr,h\nu} \left(\frac{\mu_{h\nu}}{\rho}\right) dh\nu$$

$$\frac{d\Phi_{air}^{F}}{dh\nu} \cdot \frac{F^2}{(F+d)^2} \cdot e^{-\mu_{h\nu} d}$$

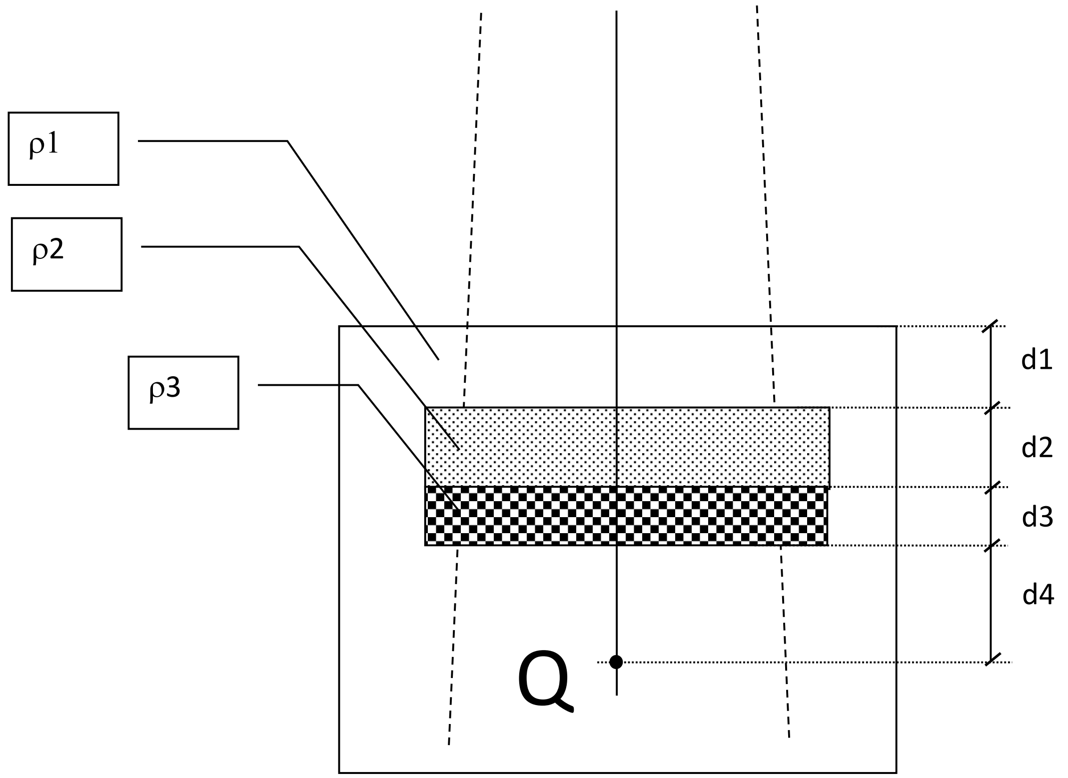
Photon fluence for Energy hv at depth d



Beam attenuation
Compton approximation

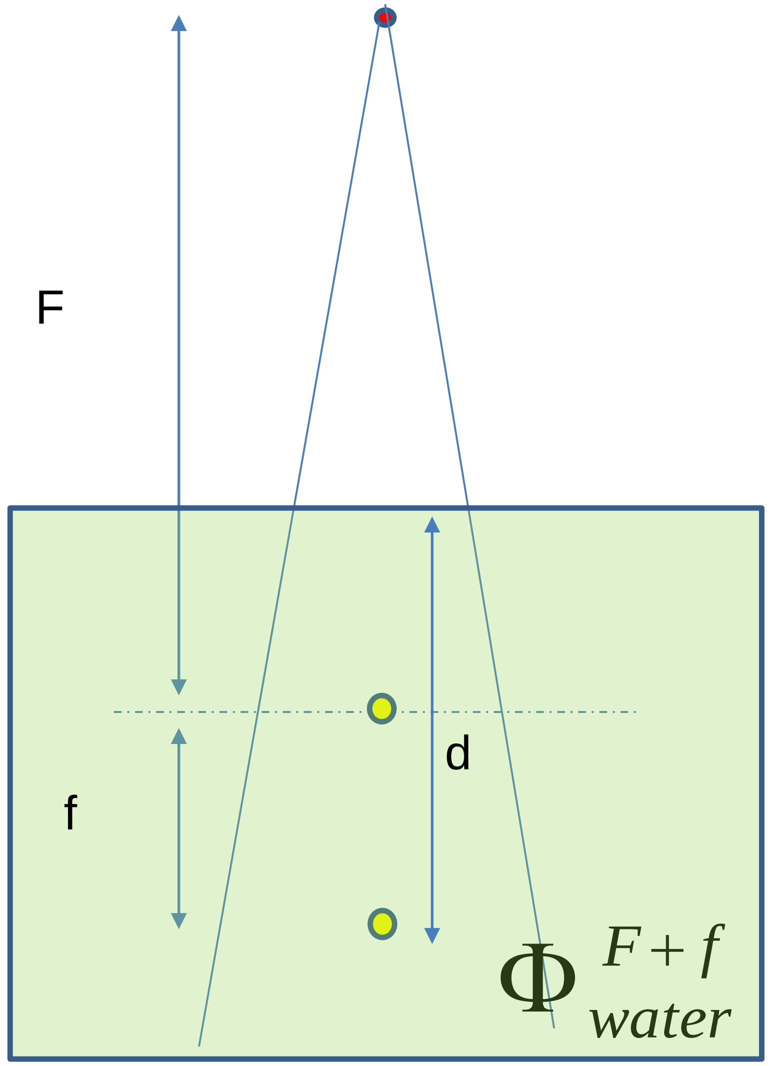
Radiological depth (radiological thickness)

The thickness of water, which attenuates radiation in the same way as a given arrangement of different tissues.



Depth rad. Q= $d1 \cdot \rho1 + d2 \cdot \rho2 + d3 \cdot \rho3 + d4 \cdot \rho1$

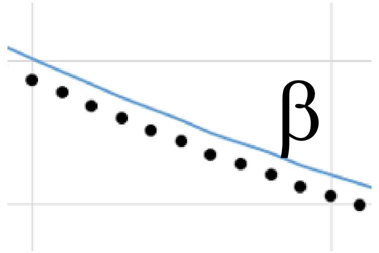
Transient Charged Equilibrium



Fluence in water

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

$$e^{-\mu \cdot (d - d_{max})}$$



Primary dose in water

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

Example

How to calculate the apparent (mean) value

of the linear attenuation coefficient?

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Kernel - Point Spread Function

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

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

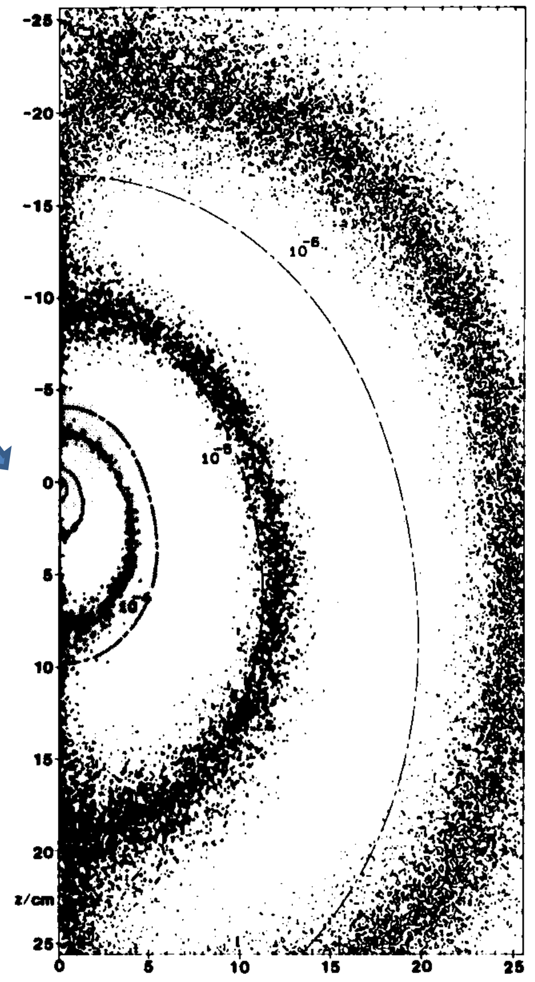
primary

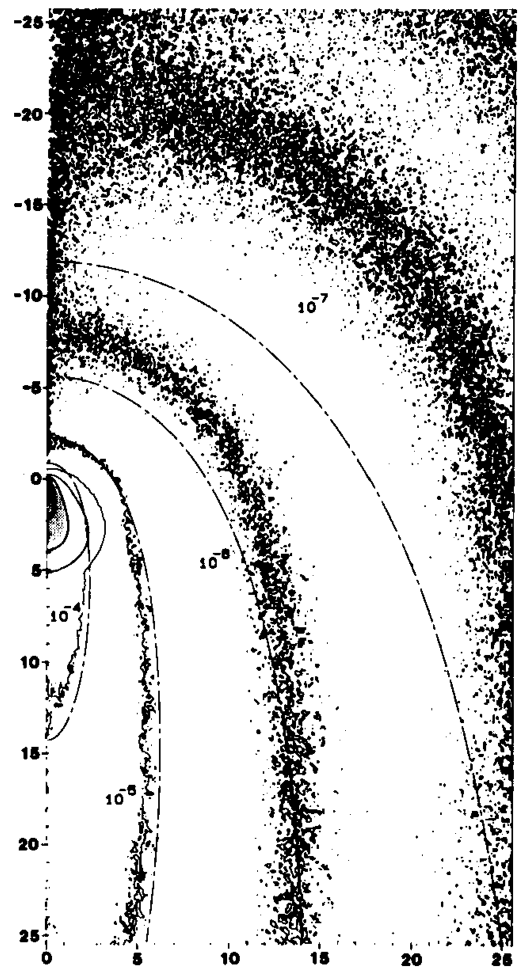
X 0,4 MeV

X 10 MeV

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

interaction





ϴ - azimuthal angle

Parmeters
Table in Ahnesjo paper
for 4, 6, 10 and 15 MeV

Acta Oncologica, 1987, Ahnesjo

Monoenergetic Depth Dose - Kernel

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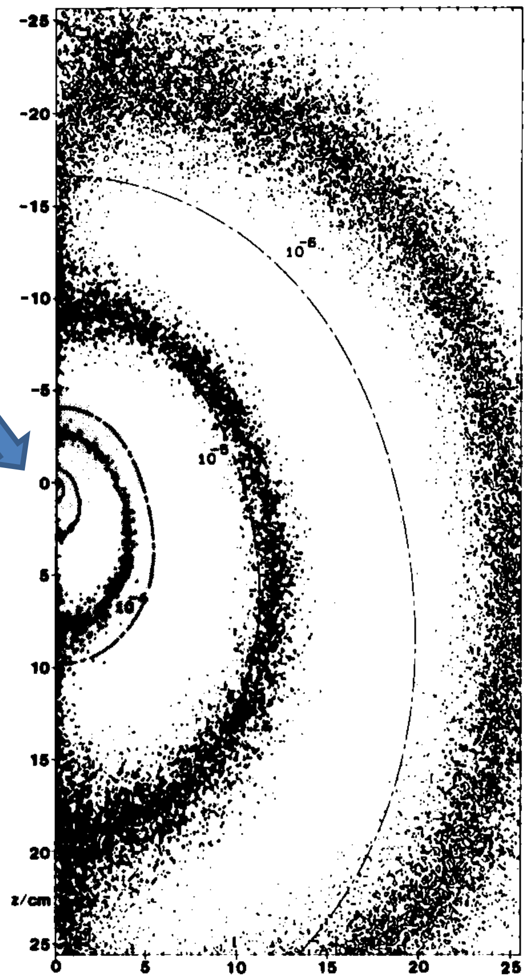
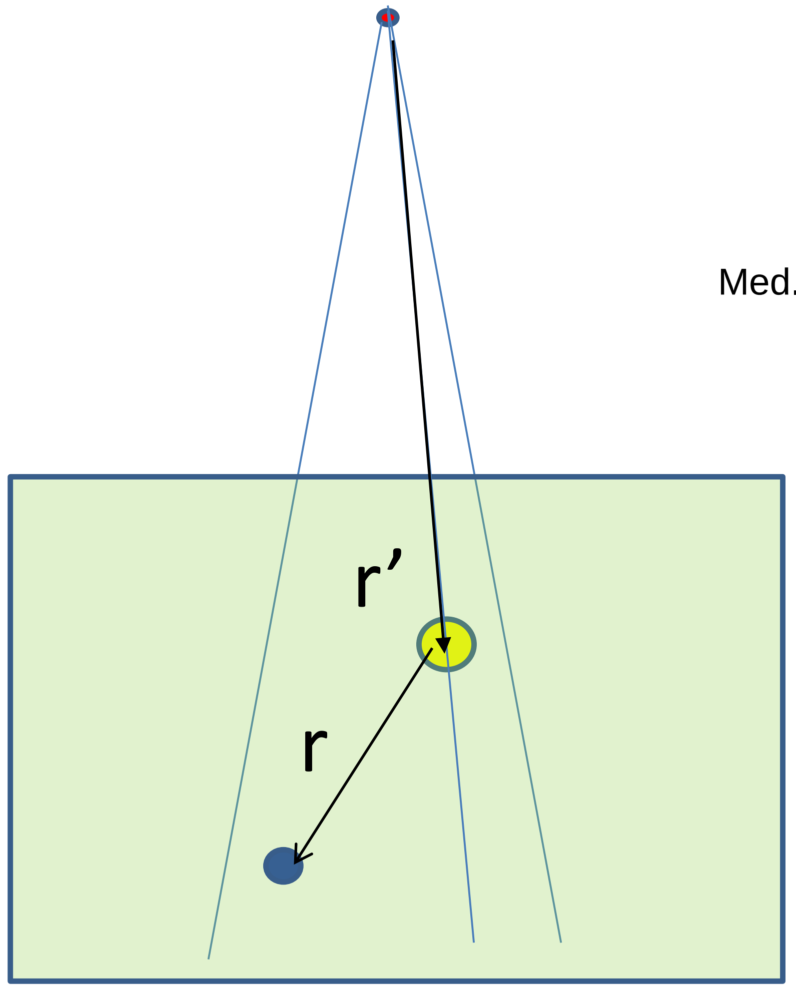
interaction

X 0,4 MeV



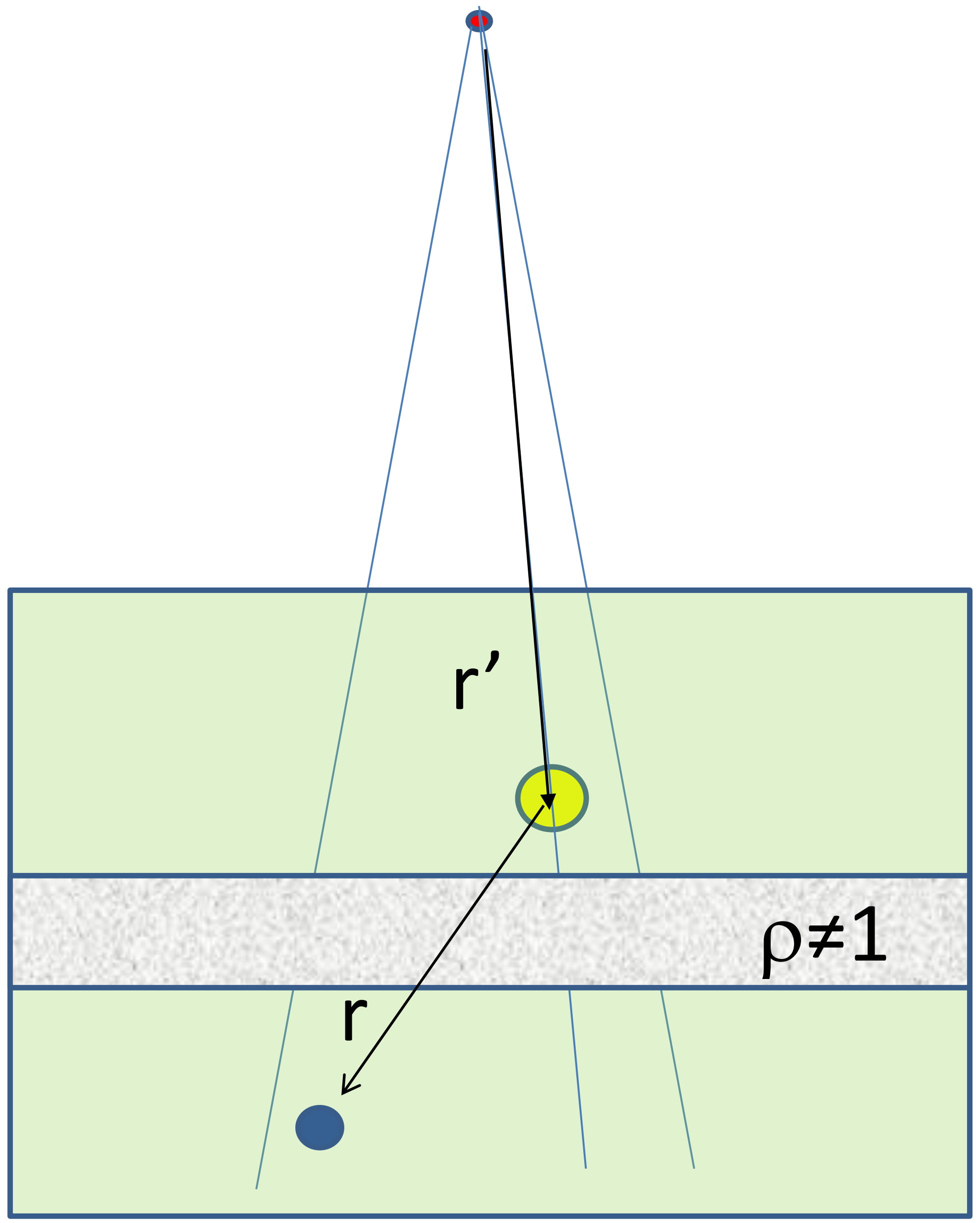


Med.Phys. Papanikolau 1993,5,1327-1336.

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

Kernel

Monoenergetic Depth Dose - Kernel



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

Collapsed Cone Convolution
acceleration of computation- approximation

30 x 30 x 30 cm^3 water phantom
0.3 cm calculation grid

100 x 100 x 100 calculation points 10^6

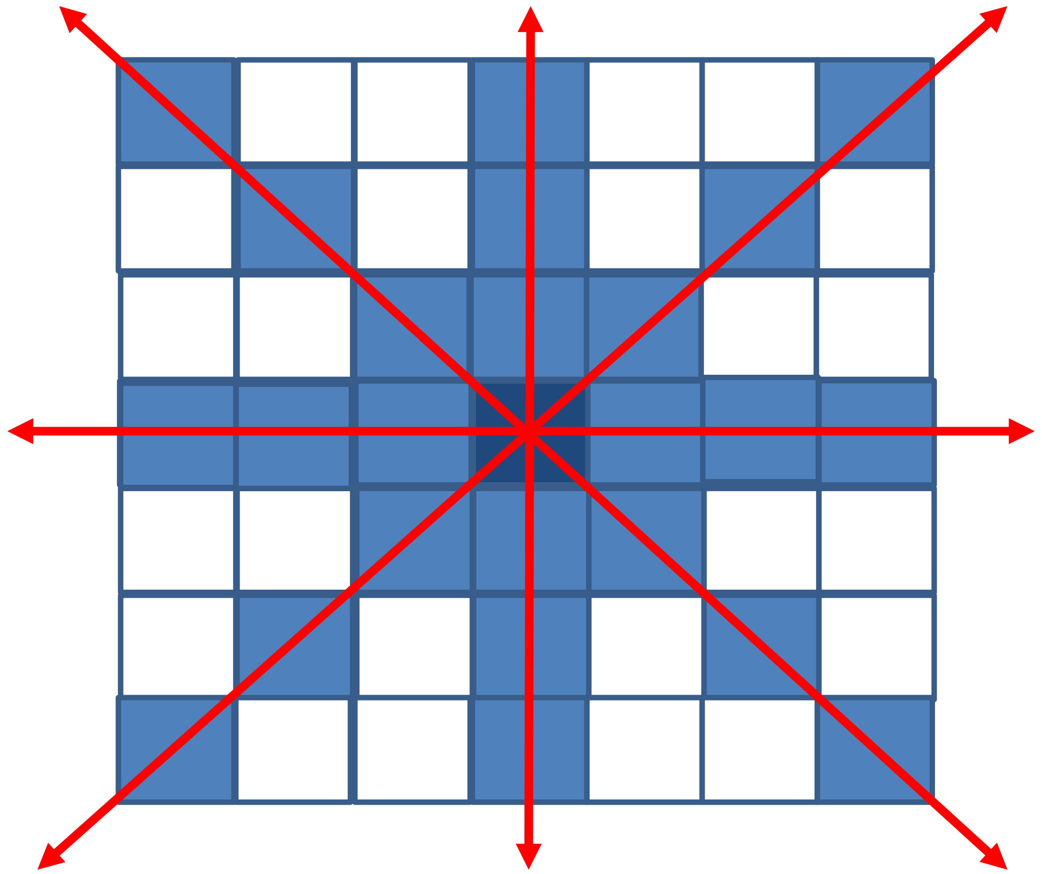
Real full convolution: each point with each point
$10^6 \times 10^6 = 10^{12}$ too long!

Dose deposition decreses very much with distance!

Mackie's opinion – 100 cones is enough!

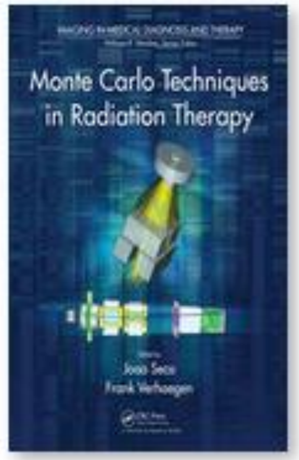
Mobius3D – 144 collapsed cones

Pinnacle – 80 collapsed cones



8 cones
Calculations for blue elements only!

Monte Carlo



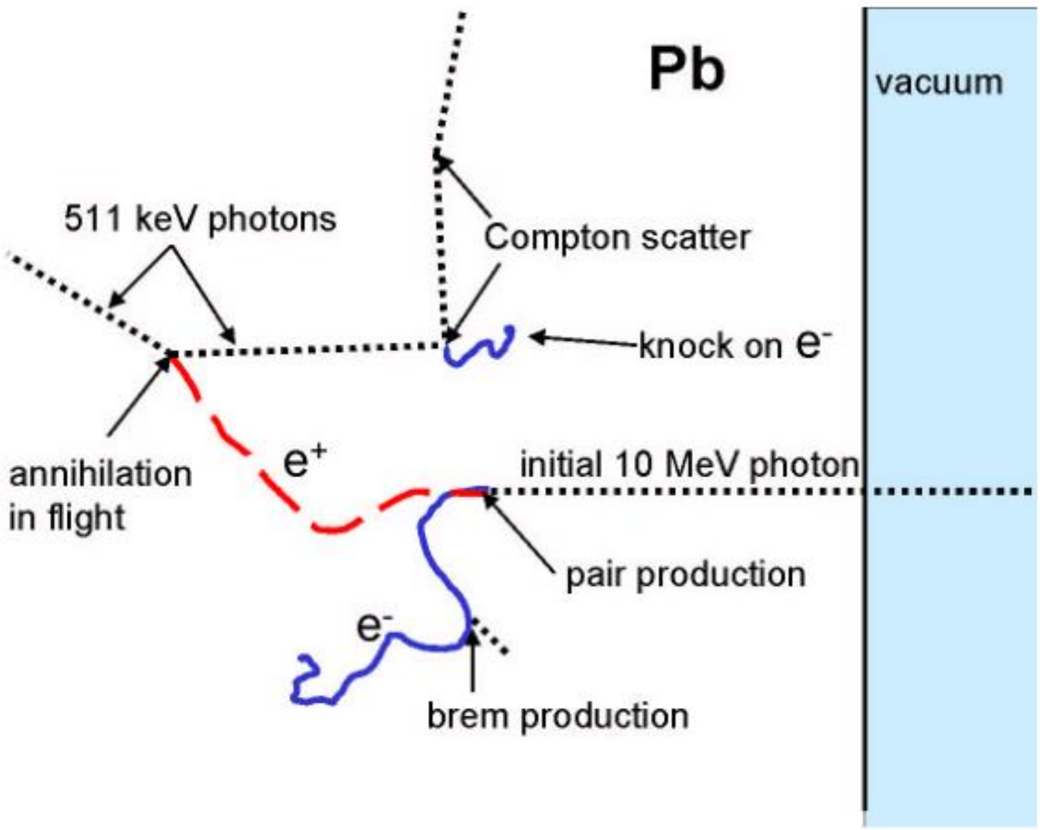
Book

Monte Carlo Techniques in Radiation Therapy

Edited By Joao Seco, Frank Verhaegen

Monte Carlo simulation is the method of radiation transport modeling in which one uses knowledge of the probability distributions governing the individual interactions of electrons and photons in materials to simulate (track) the random trajectories or histories of individual particles

- several Monte Carlo codes are used



Monte Carlo Techniques in Radiotherapy

D.W.O. Rogers

Medical Physics Special Issue, 2002 Vol 58#2, pp 63–70

Eclipse - Acuros

Acuros is the Grid-Based Boltzmann Equation Solvers
for Dose Calculation.

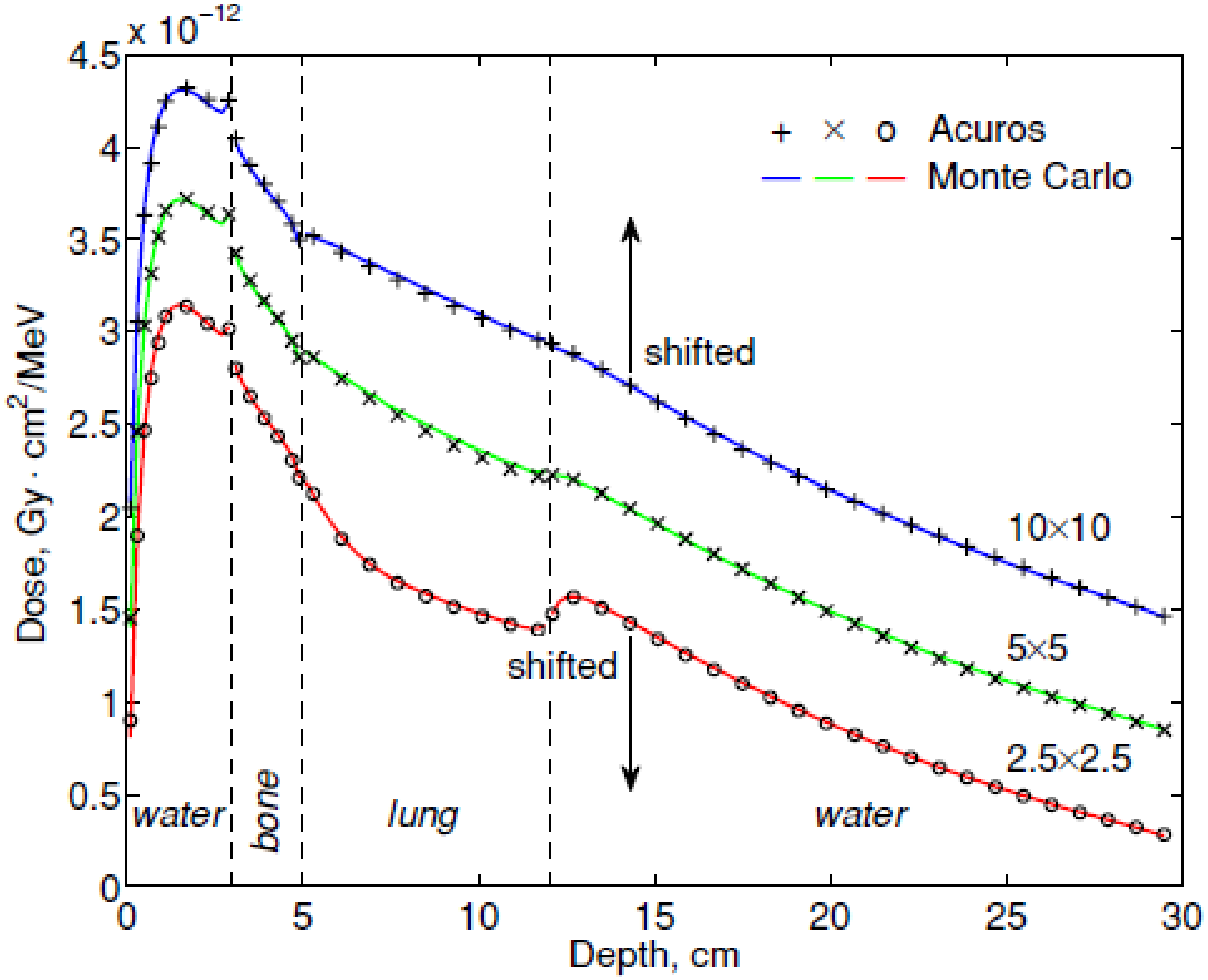
One of the major limitations of most commercially available model-based algorithms for photon dose calculation is the ability to account for the effect of electron transport.

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

This Kernel is valid only for homogeneous absorber.

Acuros – Eclipse
algorithm based on Boltzmann transport equations

6 MV



Validation of a new grid-based Boltzmann equation solver…
Oleg N Vassiliev, doi:10.1088/0031-9155/55/3/002

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Summary

In most current TPS the algorithms are good enough for precise calculation of dose distribution, however final result depends on the data entered and the correct tuning of medel's parameter.

The greatest challenge is modelling the collimating system.
Collimators are not always well modelled in TPS (Hylcon).

Accurate calculation of beam attenuation plays a crucial role.
We have an impact on the quality of the entered data
and tuning of some model parameters.

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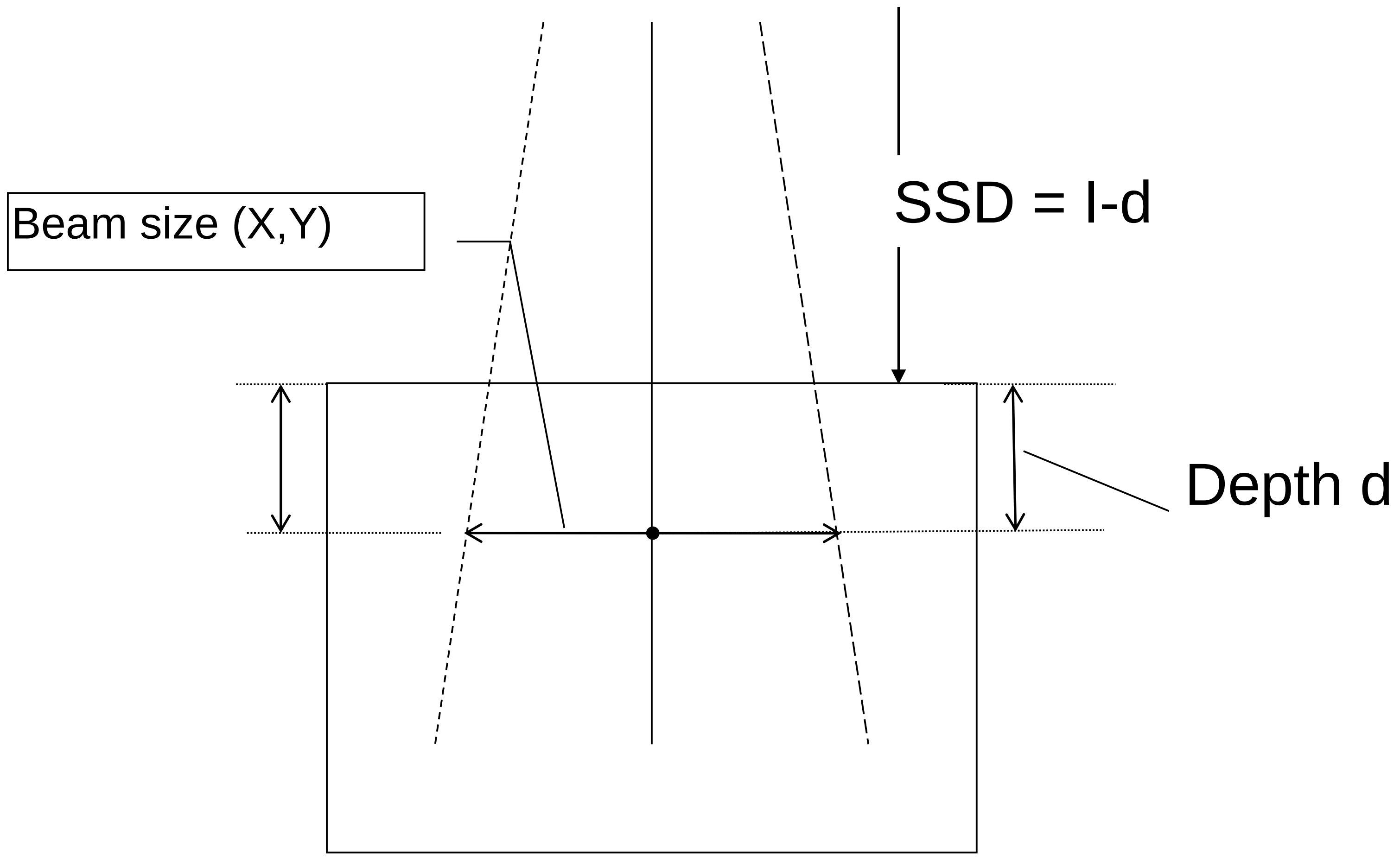
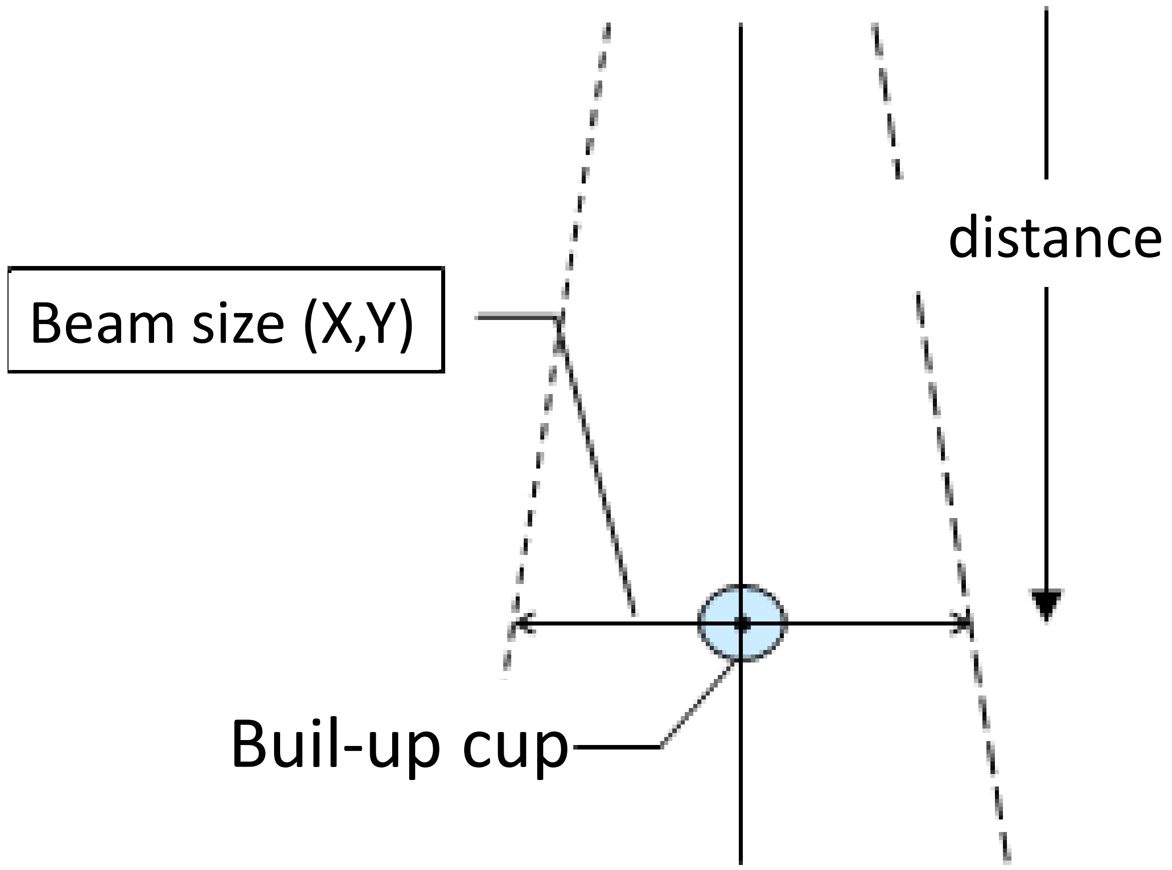
Thank you for your attention!

Appendix

The simplest good model

Tissue Air Ratio - Clarkson (Cunningham) algorithm





$$TAR(X,Y,d) = \frac{MW(X,Y,I-d,d)}{MP(X,Y,I)}$$

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TAR

Does not depend on SSD!

- the only hindrance is a neccesity of manipulation with beam size.

TAR is a very useful tool for converting dosages from one distance to another!

This is a very useful tool for checking MU calculations for 3D.

When there is CPE it gives fairly accurate results!

TAR at d_{max} = Back Scatter Factor (BSF) Peak Scatter Factor

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$$PSF(X_r) = 1 + \frac{t \cdot X_r}{X_r + n}$$

	CO 60	4 MV	6 MV	10 MV	15 MV	24 MV
TPR20/10	0,571	0,626	0,67	0,732	0,765	0,805
% dd (10)	57,9	62,9	66,7	73,1	78,4	85,8
m (cm^{-1})	0,066	0,057	0,049	0,039	0,034	0,027
t	0,106	0,113	0,109	0,106	0,092	0,0875
n	7,3338	4,8832	4,9173	4,1681	3,8347	3,6858

TAR and Depth Dose

$$TAR\left(X\frac{R+d}{I},d \right)=\frac{\left(R+d \right)^{2}}{\left(R+m \right)^{2}}\cdot BSF\left(X\frac{R+m}{I} \right)\cdot DD\left(X,d.R \right)$$

Calculations with TAR depends very little on BSF

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Dose calculations with TAR

for square field A

$$D(A,d,F) = D_{air}(A,F+d)\cdot TAR(A\cdot\frac{F+d}{F},d)$$

$$D_{air}(A,F+d) = \frac{D_{water}(A,d_{ref}=10cm,SSD=90cm)}{TAR(A,d=10cm)}\cdot\frac{100^2}{(F+d)^2}$$

D_{water} – we have from measurements

Primary and Scatter Dose

it is useful for calculations of dose beneath a block

$$D = D_{primary} + D_{scatter}$$

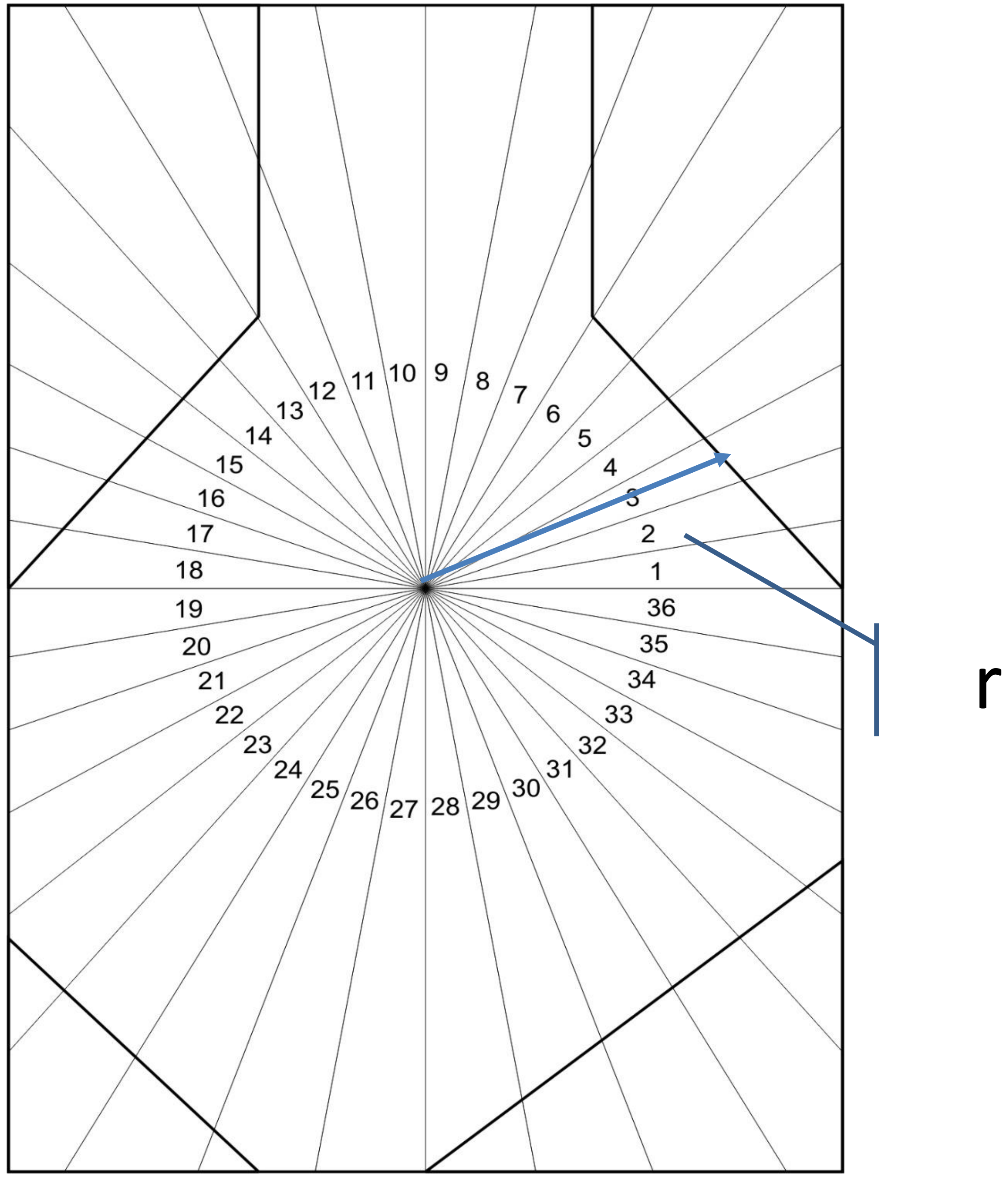
$$TAR_0(d) = \lim_{A \to 0} TAR(A, d)$$

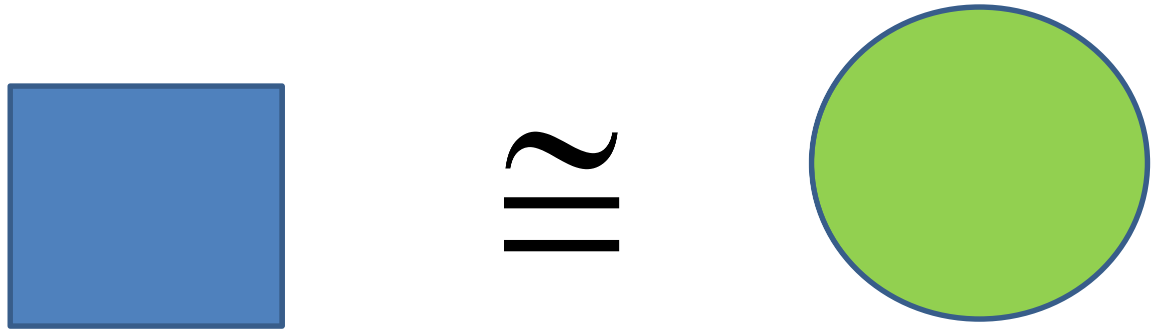
$$SAR = TAR - TAR_0$$

$$D = D_{air} \cdot TAR = D_{air} \cdot TAR_0 + D_{air} \cdot SAR$$

$$D = D_{air} \cdot TAR = D_{air} \cdot \left(TAR_0 + SAR\right)$$

Circular symmetry and TAR





$$TAR\ (A,A) = TAR\ (r) \text{ if } A \cdot A = \pi \cdot r^2$$

$$TAR_{anyshape} = \frac{1}{36}\sum_{1}^{36} TAR(r(10^{o} \cdot i - 5^{0}), d)$$

Thank you for your attention!