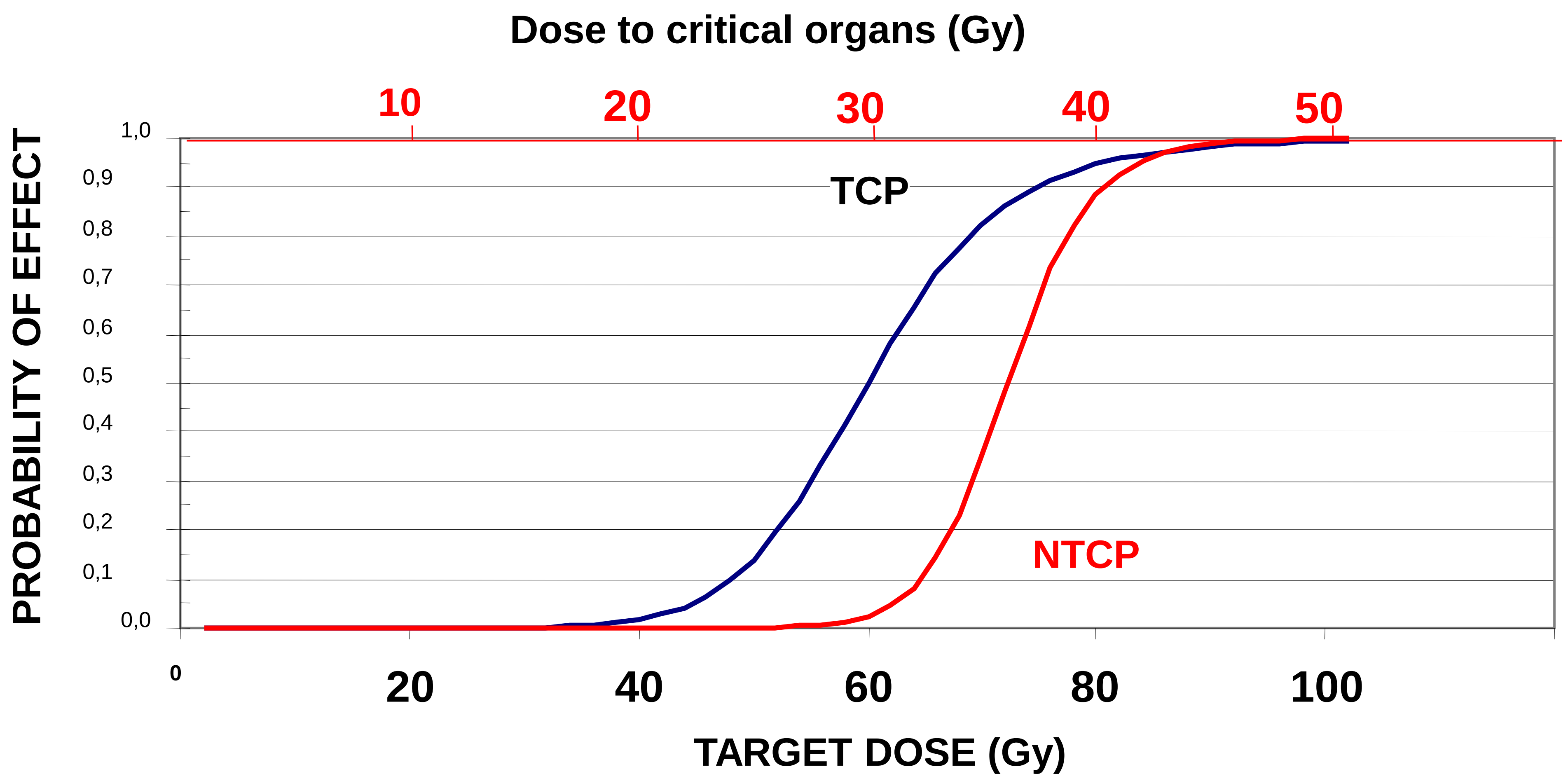
Maria Sklodowska-Curie
National Research Institute of Oncology

TPS algorithms
part I - basics

Paweł Kukołowicz

Department of Medical Physics,
The Maria Sklodowska-Curie National Research Institute of Oncology
5 W.K. Roentgena st., 02-781 Warsaw, Poland

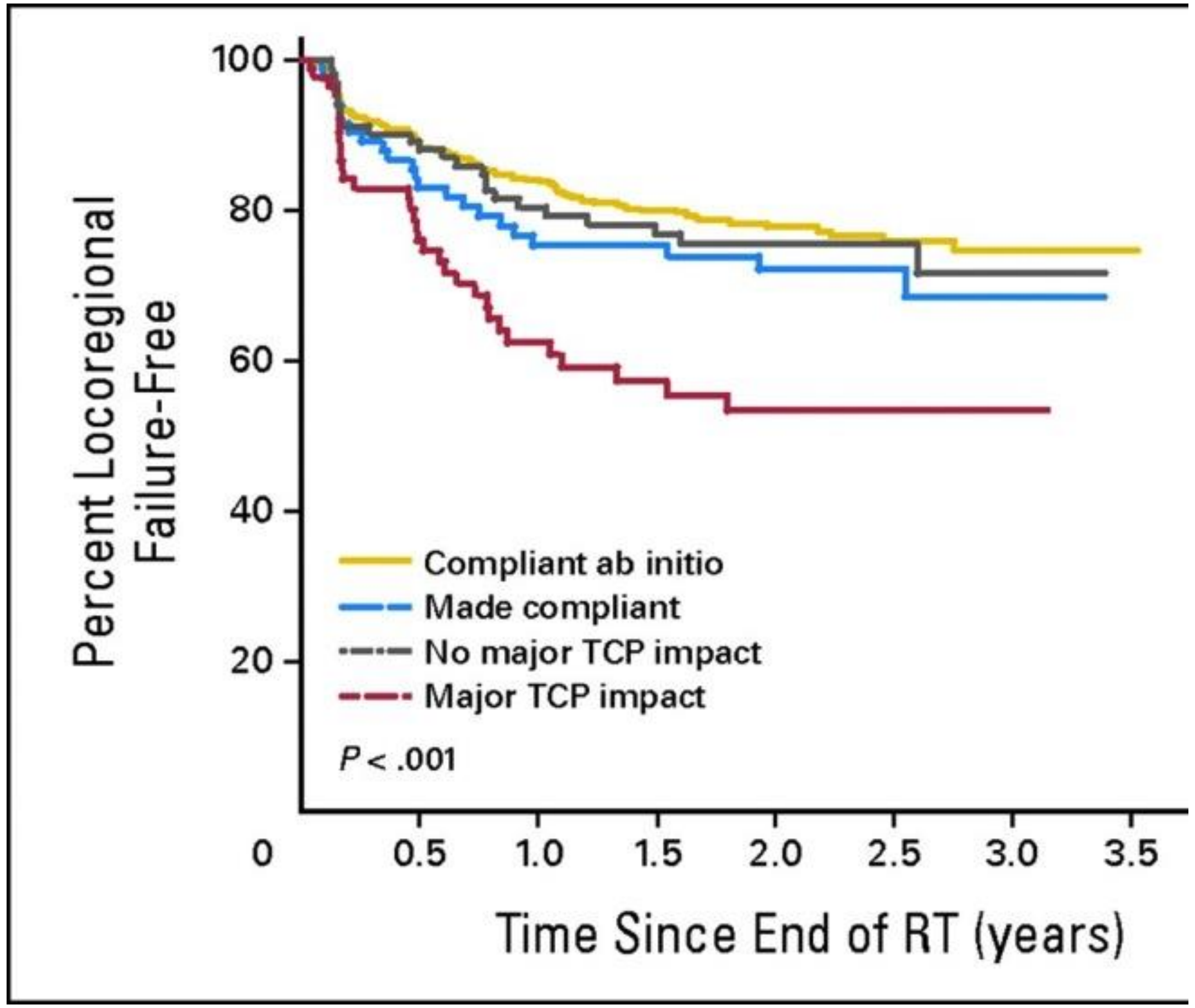
Recommendations on accuracy in radiotherapy



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

Precision of dose delivery matters



At TMC review, 25.4% of the patients had noncompliant plans but none in which QARC- recommended changes had been made. At secondary review, 47% of noncompliant plans (12% overall) had deficiencies with a predicted major adverse impact on tumor control. Major deficiencies were unrelated to tumor subsite or to T or N stage (if N), but were highly correlated with number of patients enrolled at the treatment center (five patients, 29.8%; 20 patients, 5.4%; P .001). In patients who received at least 60 Gy, those with major deficiencies in theirtreatment plans (n 87) had a markedly inferior outcome compared with those whose treatment was initially protocol compliant (n 502): 2 years overall survival, 50% v 70%; hazard ratio (HR), 1.99; P .001; and 2 years freedom from locoregional failure, 54% v 78%;HR, 2.37; P .001, respectively.

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

Major sources of uncertainty in dose delivery

Maria Sklodowska-Curie National Research Institute of Oncology

1. Absolute and relative dosimetry

2. Calculation of dose distribution using a treatment planning system

   1. Preparation of TPS

   2. Algorithm of dose calculation

3. Implementation of irradiation

   1. Accuracy of patient positioning

   2. Changes of patient anatomy

Estimates of Uncertainty (in terms of one standard deviation) in absolute dose for megavoltage photons.

Source of Uncertainties	Uncertainty at Present (%)	Uncertainty in Future (%)
Dose at the calibration point in water	2.5	1.0
Additional uncertainty for other points	0.6	0.3
Beam Monitor stability	1.0	0.5
Beam flatness	1.5	0.5
Patient data	1.5	1.0
Patient set up and organ motion	2.5	2.0
Overall (excluding dose calculation)	4.3	2.5
Dose calculation algorithm (multiple levels)	1.0 / 2.0 / 3.0 / 5.0	1.0 / 2.0 / 3.0
TOTAL	4.4 / 4.7 / 5.2 / 6.6	2.7 / 3.2 / 3.9

AAPM REPORT NO. 85

Calculation of dose distribution

We have no control over the algorithm used

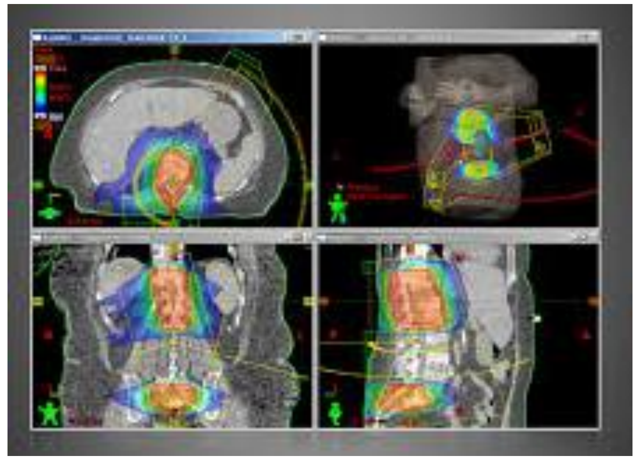
- we are responsible for knowing the results of the verification of the calculations for a given treatment planning system (implementation)
  - literature

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

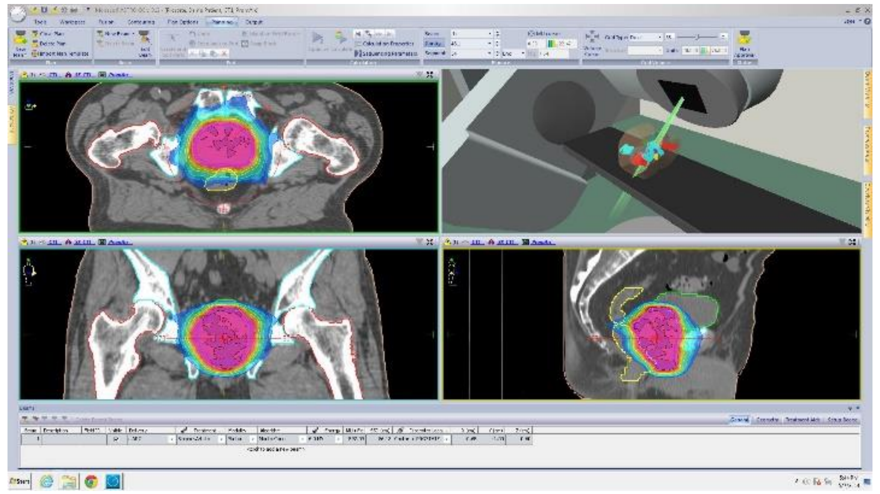
Wide range of applications

User friendly

Stable

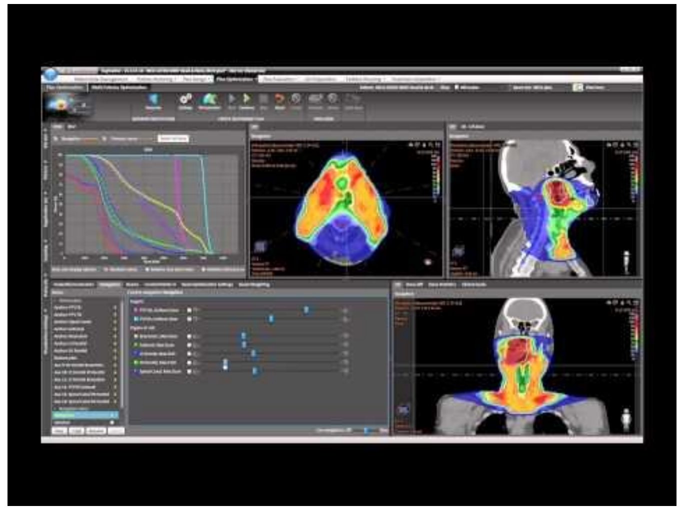
?

Elekta - Monaco



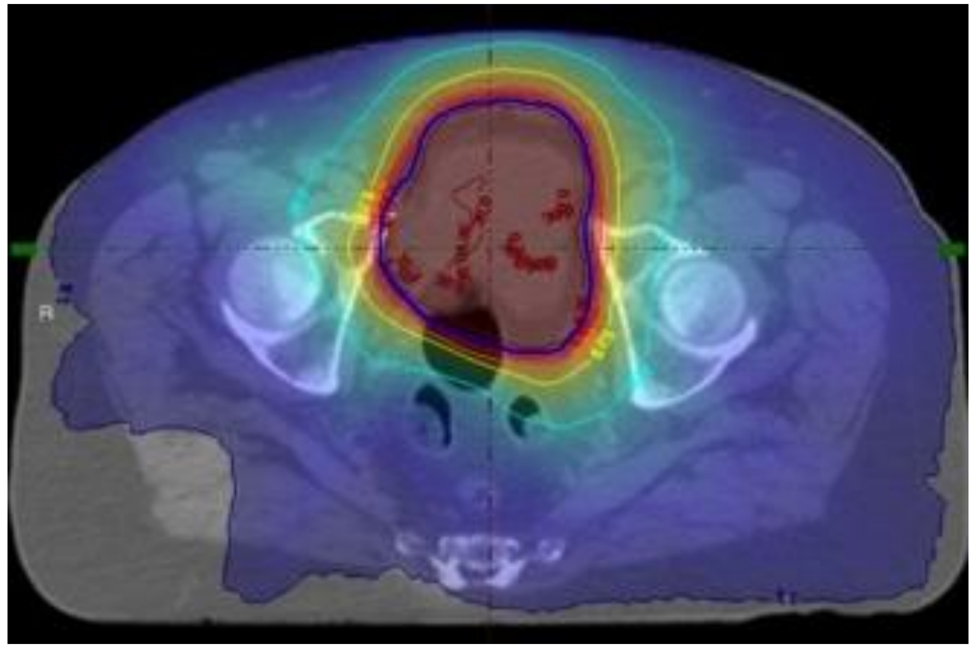
Pinnacle - Philips

RaySearch – RayStation



Maria Sklodowska-Curie
National Research
Institute of Oncology

Theoretical basis of photon beam therapy modeling
(Transient) Charged Particle Equilibrium



Transient Charged Equlibrium Exist

monoenergetic beam of Energy *hν*

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

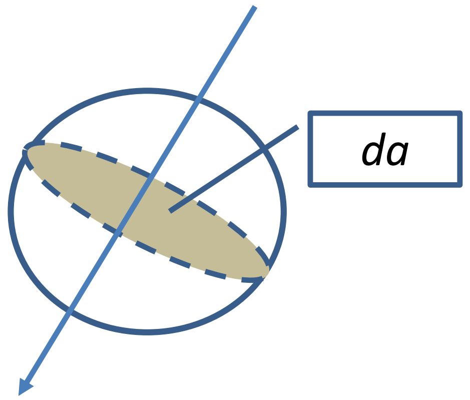
Fluence and Energy Fluence

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*

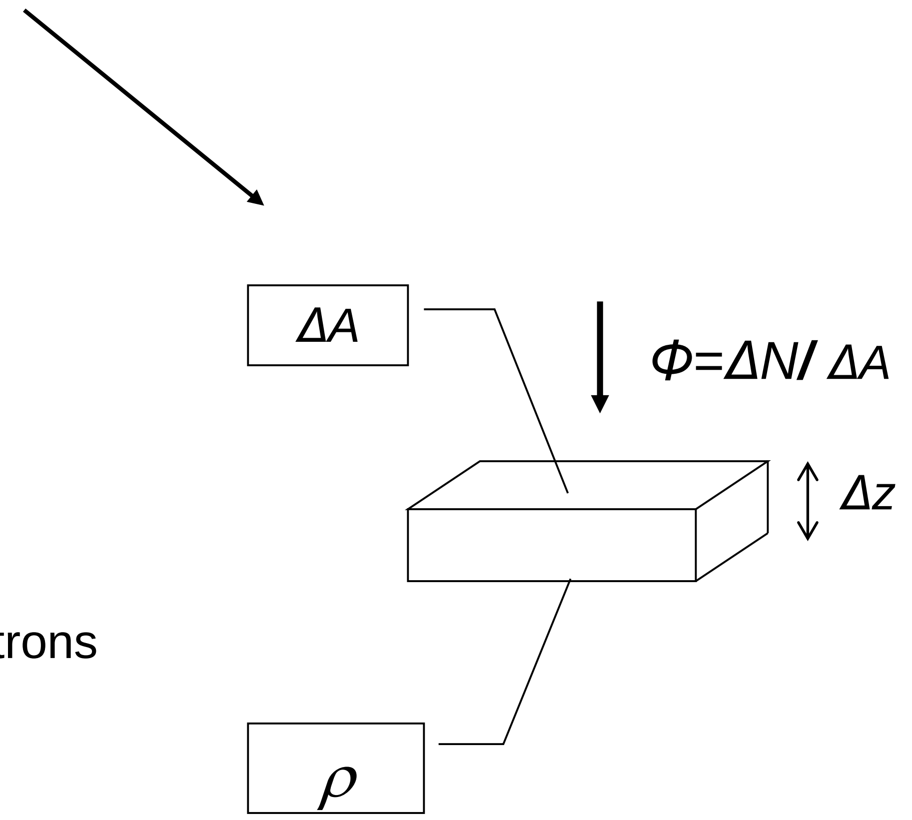


$$\Phi = \frac{dN}{da}$$

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

Energy deposition

Photons energy is transferred to electrons → Kerma



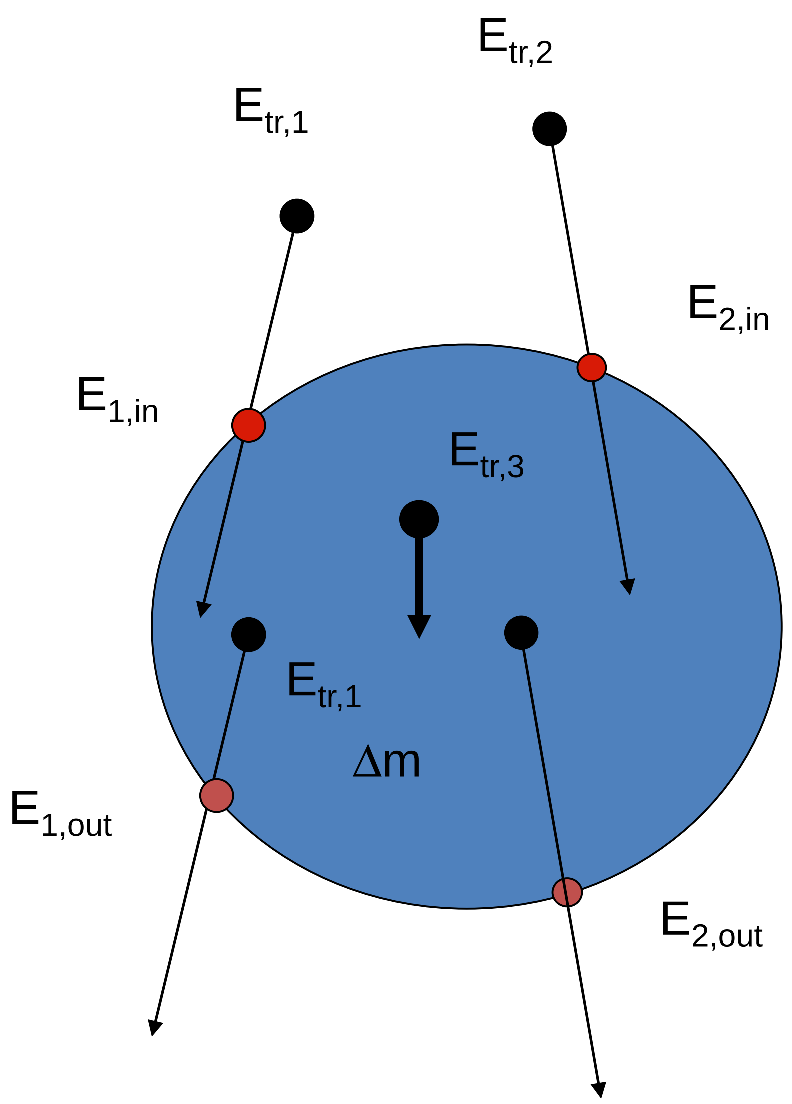
$$\left(\frac{\mu}{\rho}\right)\cdot\Phi$$

Number of interactions per unit mass

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

Energy transferred to electrons

Charged equilibrium



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 V is absorbed

Kerma

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

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

Bremsstrahlung – energy lost on radiation

Maria Sklodowska-Curie
National Research Institute of Oncology

$\text{Dose} = \text{Kerma} \cdot (1\text{-}g) = \text{Kerma}_{colision} = K_c$

g is the part of electron energy
lost for bremsstrahlung

And everything in dose deposition
becomes simple!

Energy of electron (MeV	Range of electrons (g/cm^2)	fraction on radiation (g)
0.1	0.0143	0.0006
1.0	0.4359	0.0036
2.0	0.9720	0.0071
4.0	2.019	0.0317
10.0	4.917	0.0404

Transient Charged Particle Equilibrium
TCPE

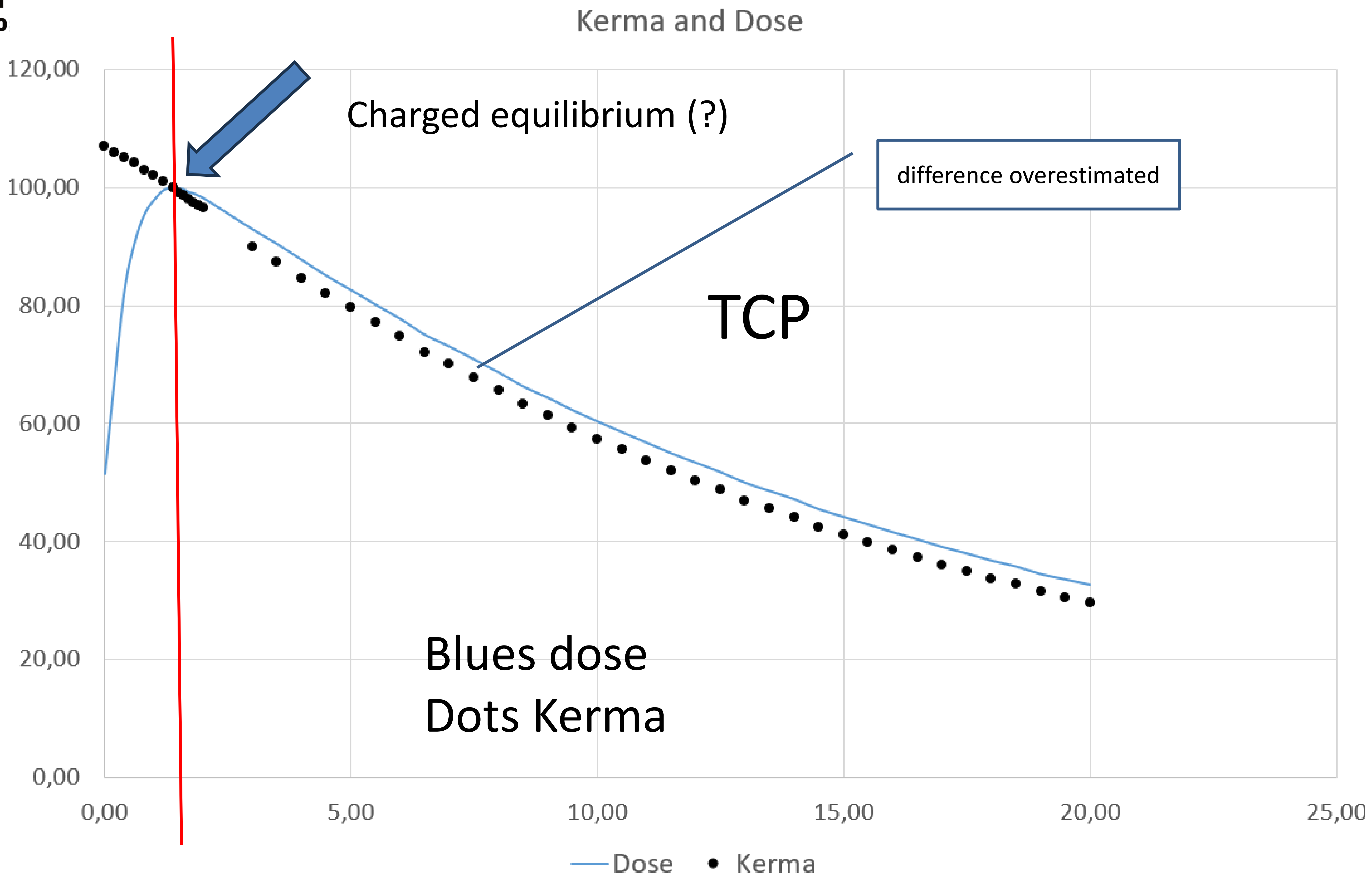
TCPE exists if the absorbed dose D is proportional to the collision Kerma Kc.

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.

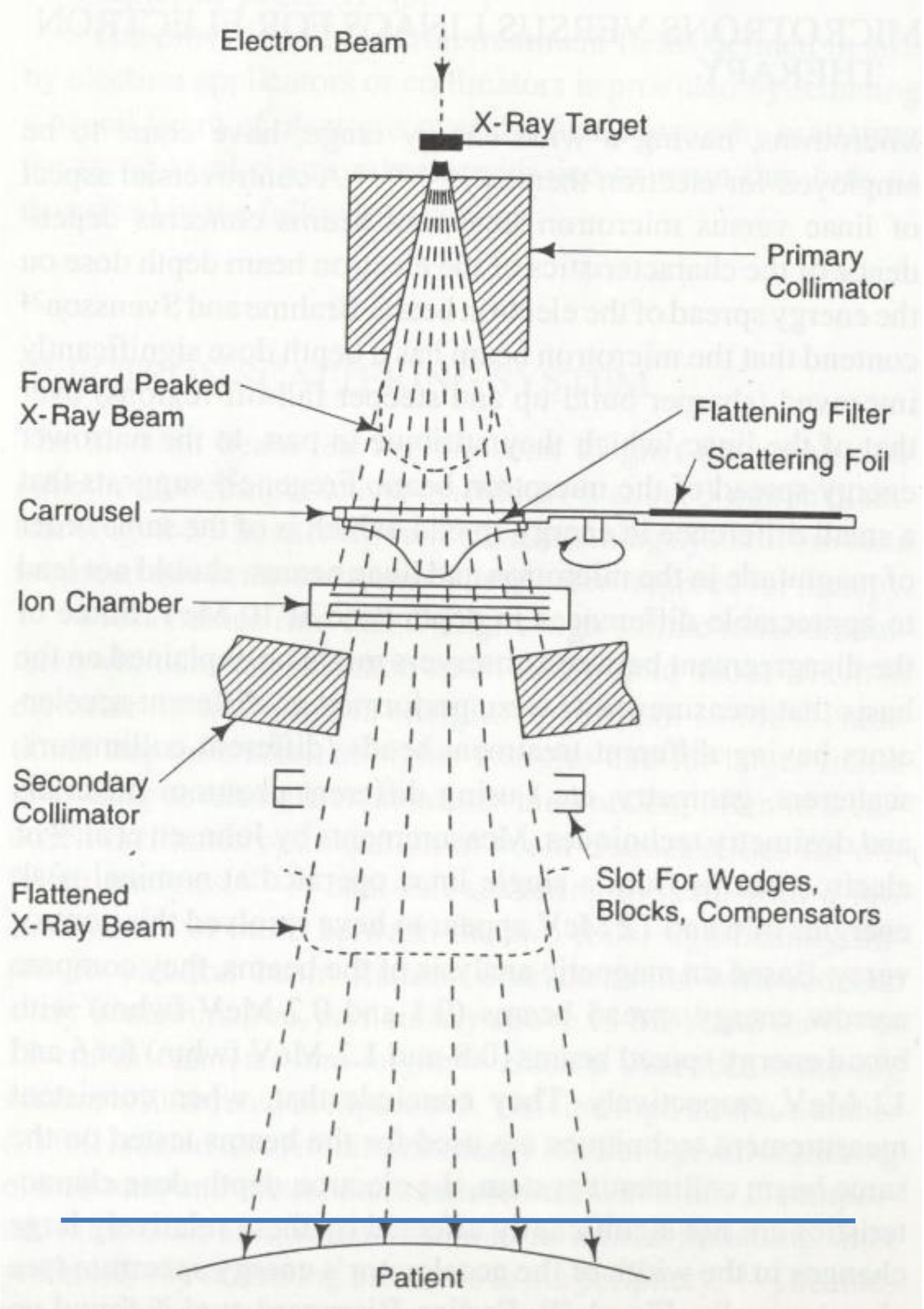
- in the next slide the constant of proportionality is overestimated!

No TCP

Maria Sklodowska-Curie
National Research Institute of Oncolo



Fluence – Energy fluence



What reaches the absorbent

- Energy fluence spectrum (SFE)
  - Photons
  - Electron contamination

Spatial distribution of energy fluence

Interaction of radiation with absorber (energy deposition)

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

Maria Sklodowska-Curie National Research Institute of Oncology

Determination of effective bremsstrahlung spectra - methods

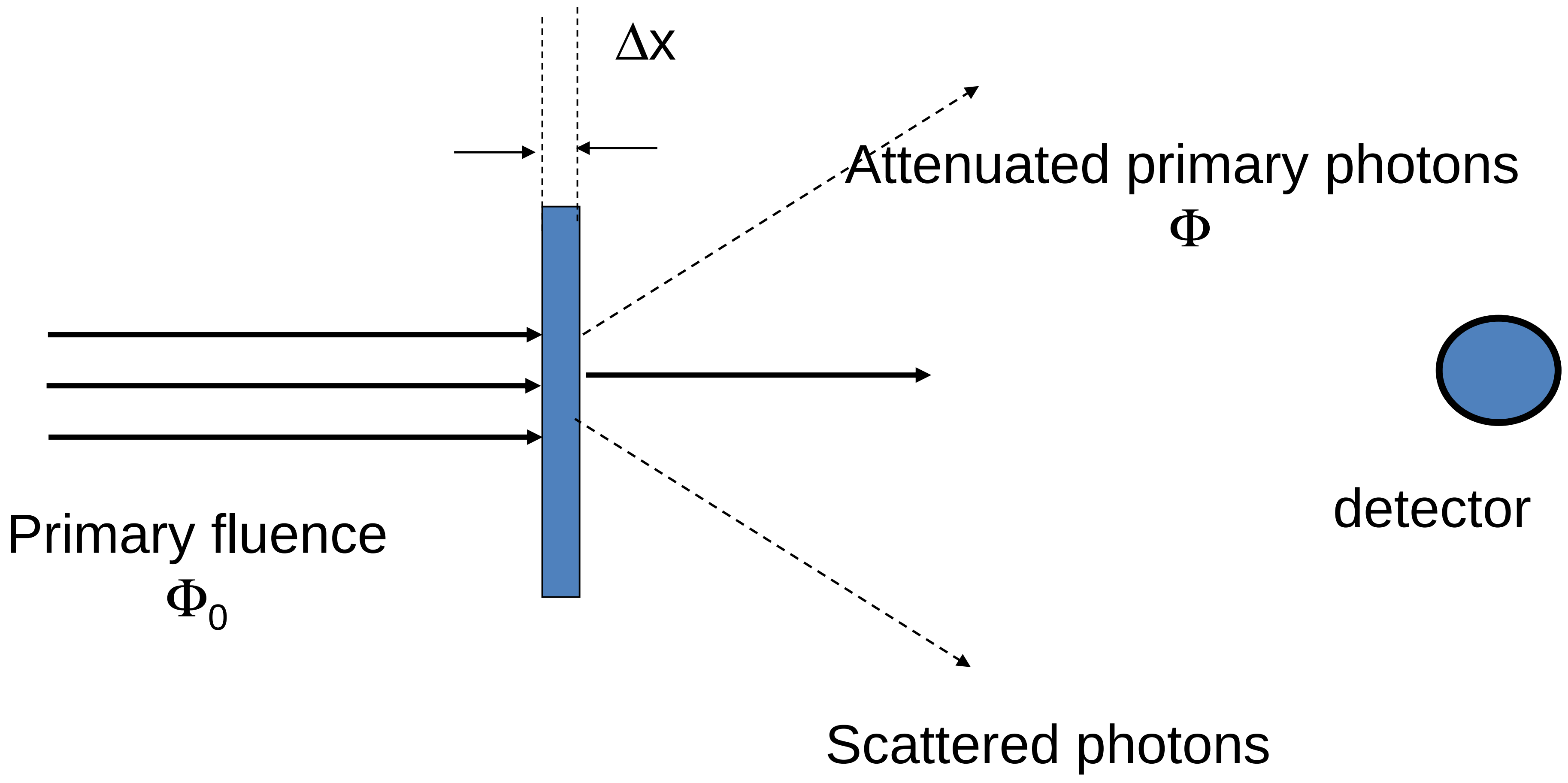
Reconstruction of spectra from measured transmission data (very cumbersome and difficult)

Reconstruction of 4-MV bremsstrahlung spectra from measured transmission data, Huang et al., doi.org/10.1118/1.595356

Unfolding linac photon spectra and incident electron energies from experimental transmission data, with direct independent validation, McEwen, Rogers, doi.org/10.1118/1.4754301

Linear attenuation coefficient

Maria Sklodowska-Curie
National Research
Institute of Oncology



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

Transmission measurements

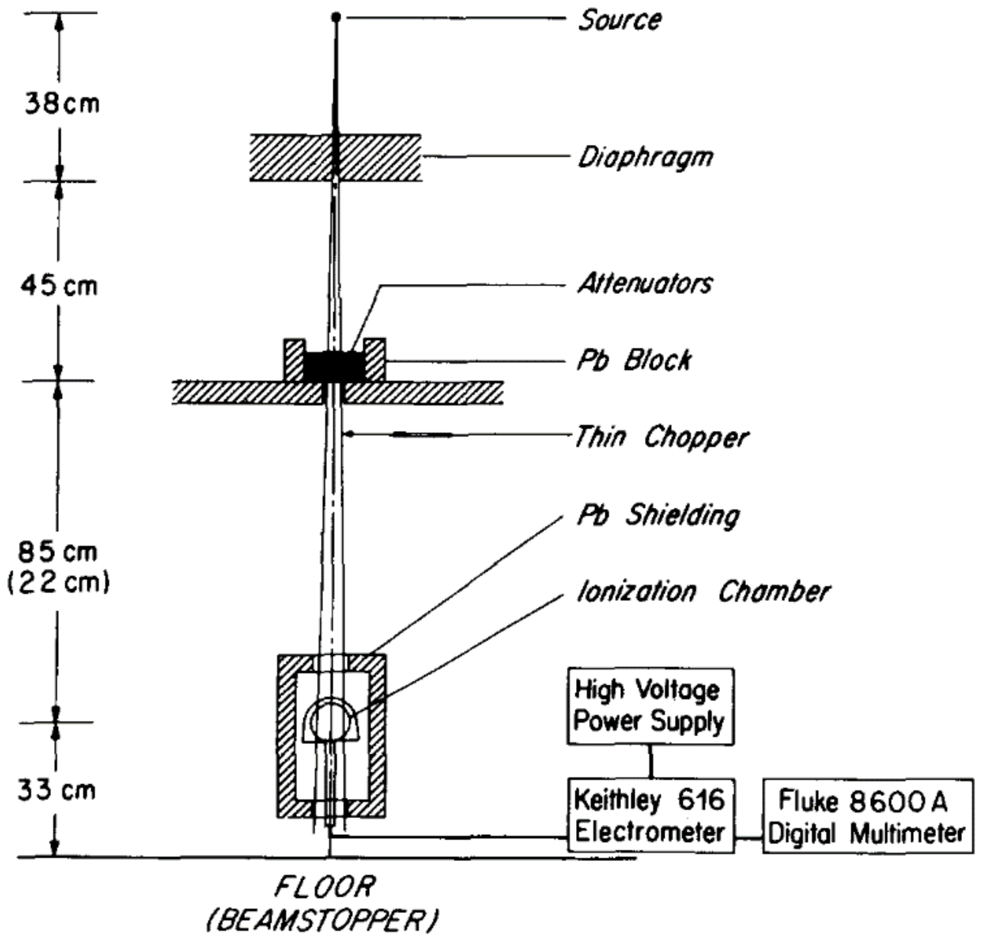
J (many) measurements of transmission T

allows to reconstruct a photon spectrum

measurements should be very precise

uncertainty < 0,01% for large T

uncertainty < 0,01% for small T

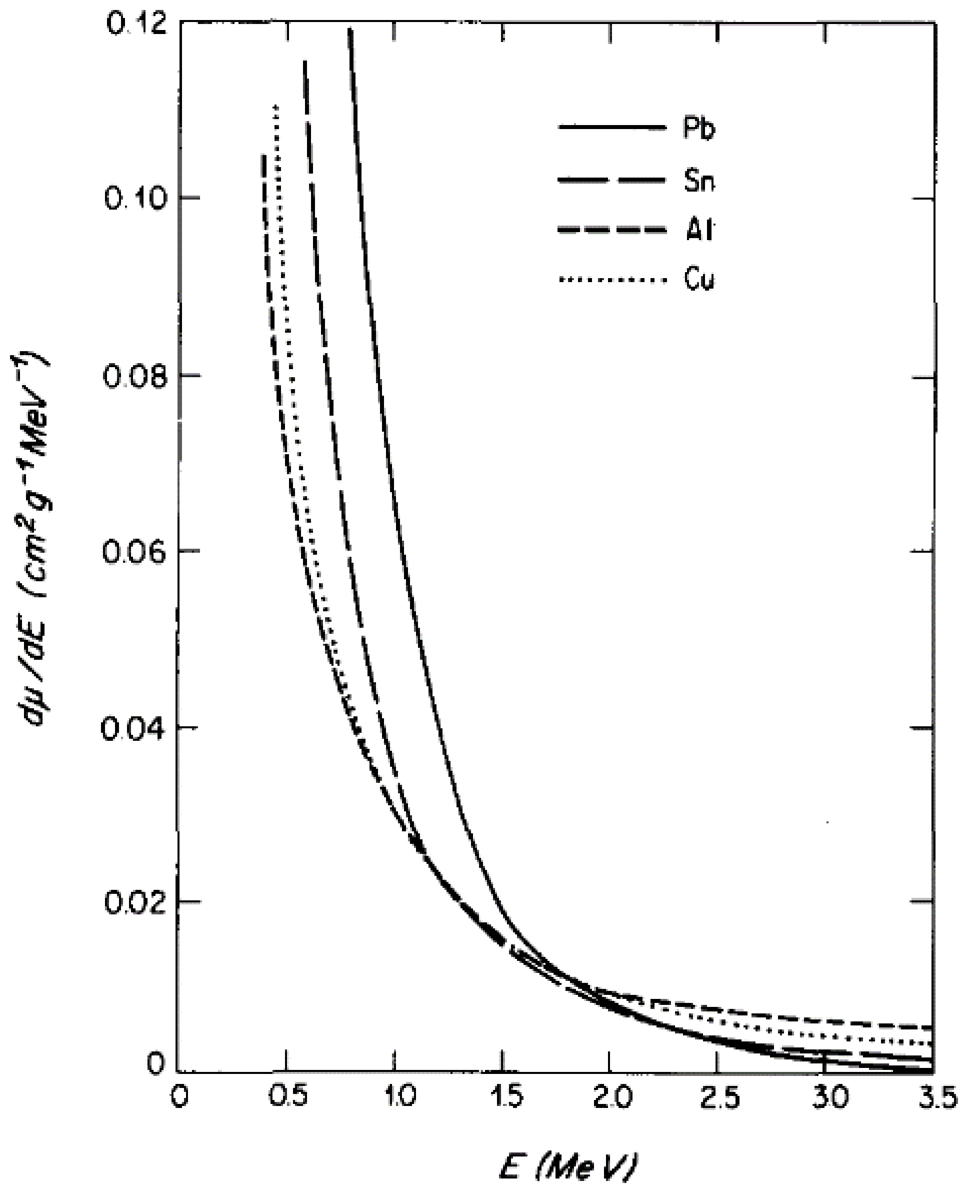


experimental set-up

Huang et. al., Med. Ph. ,1983, 10(6)

What attenuating materials?

Maria Sklodowska-Curie
National Research Institute of Oncology



ambiguity of μ when the photon energy exceeds 3 MeV. Low Z materials, such as Cu and Al, have a small change in μ over the energy range of interest (0.1–4 MeV) and will exhibit poor sensitivity to the spectral changes when used alone. However, the large value of the ratio of μ in Pb for 0.1 MeV to μ in Al for 4 MeV suggests that an optimum combination of Pb and Al may enhance the sensitivity for the spectral analysis.

Pb for E < 1,8 MeV
Al for E > 1,8 MeV

Huang et. al., Med. Ph. ,1983, 10(6)

Spectrum reconstruction

Maria Sklodowska-Curie National Research Institute of Oncology

$$T(x) = \frac{S(x)}{S(0)} = \int_0^{E_{max}} \Phi(hv) \cdot \exp(-\mu(hv) \cdot x) d(hv)$$

Simpson's numerical method of integral calculation

$$T_{x_i} = (\Delta hv / 3) \sum_{j=1}^{J} \alpha_j \exp(-\mu_j x_i) \cdot \Phi(hv_j)$$

α_j =
- 1 dla j = 1 i J
- 4 dla j = 2, 4, ..., J-1
- 2 dla j = 3, 5, ..., J-2

- for attenuator of thickness x_i,
- energy range was devided into J compartments of $\Delta h\nu$
  - the middle of the compartment is $h\nu_j$

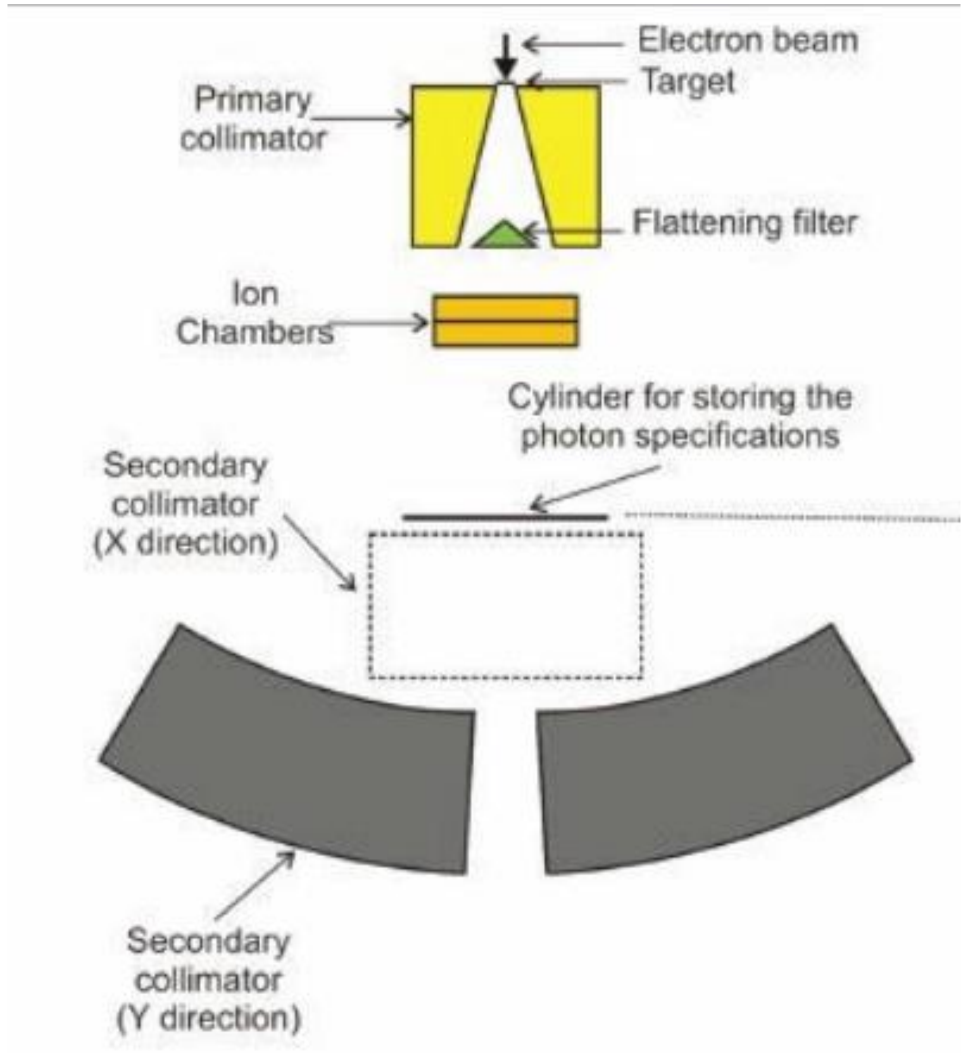
Determination of effective bremsstrahlung spectra - methods

Maria Sklodowska-Curie National Research Institute of Oncology

Monte Carlo methods**;** they require a precise knowledge of the treatment head design.

Mohan, et al. Energy and angular distribution of photons from medical linear accelerators., 10.1118/1.595680

Rogers, et al. BEAM: A Monte Carlo code to simulate radiotherapy treatment units, doi.org/10.1118/1.597552



Cross sectional view of 6 MV Elekta linear accelerator head

Sadoughi
J Med Signals Sens. 2014 Jan-Mar; 4(1): 10–17

Determination of effective bremsstrahlung spectra

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

- set of dose distribution for pencil beams for monenergetic beams

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

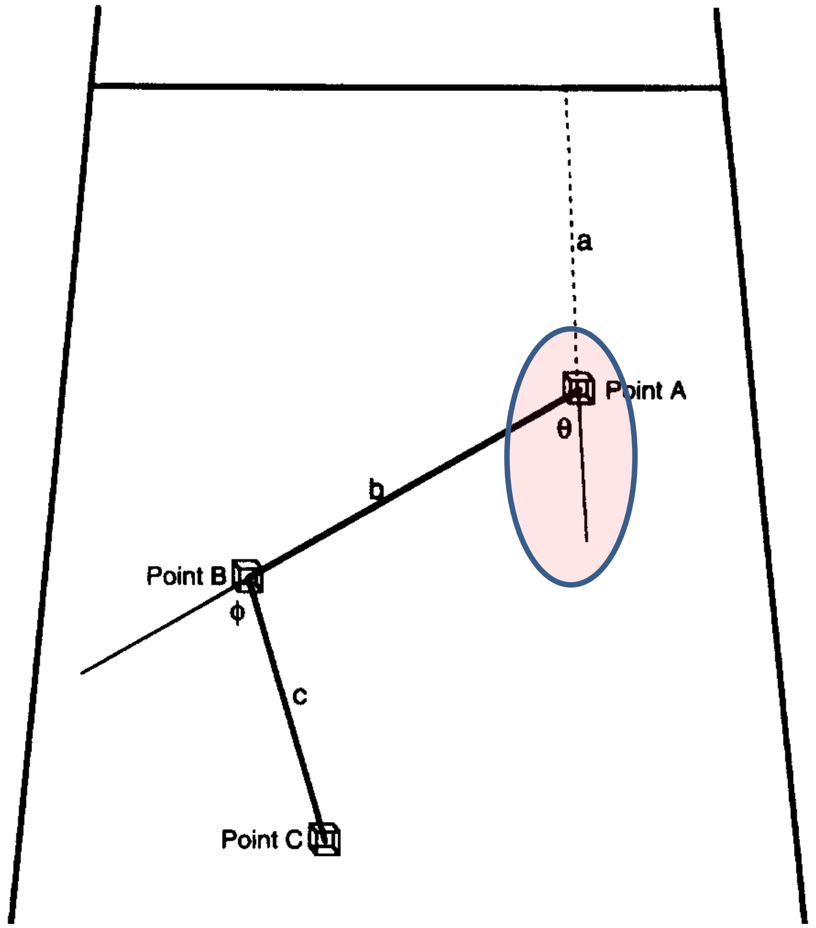
This method is used currently in most of TPS!

Calculation of Depth Dose for monoenergetic beam

Maria Sklodowska-Curie National Research Institute of Oncology

Mechanism of dose deposition

- **primary dose**
  - dose deposited by electrons which received energy from the photon 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)

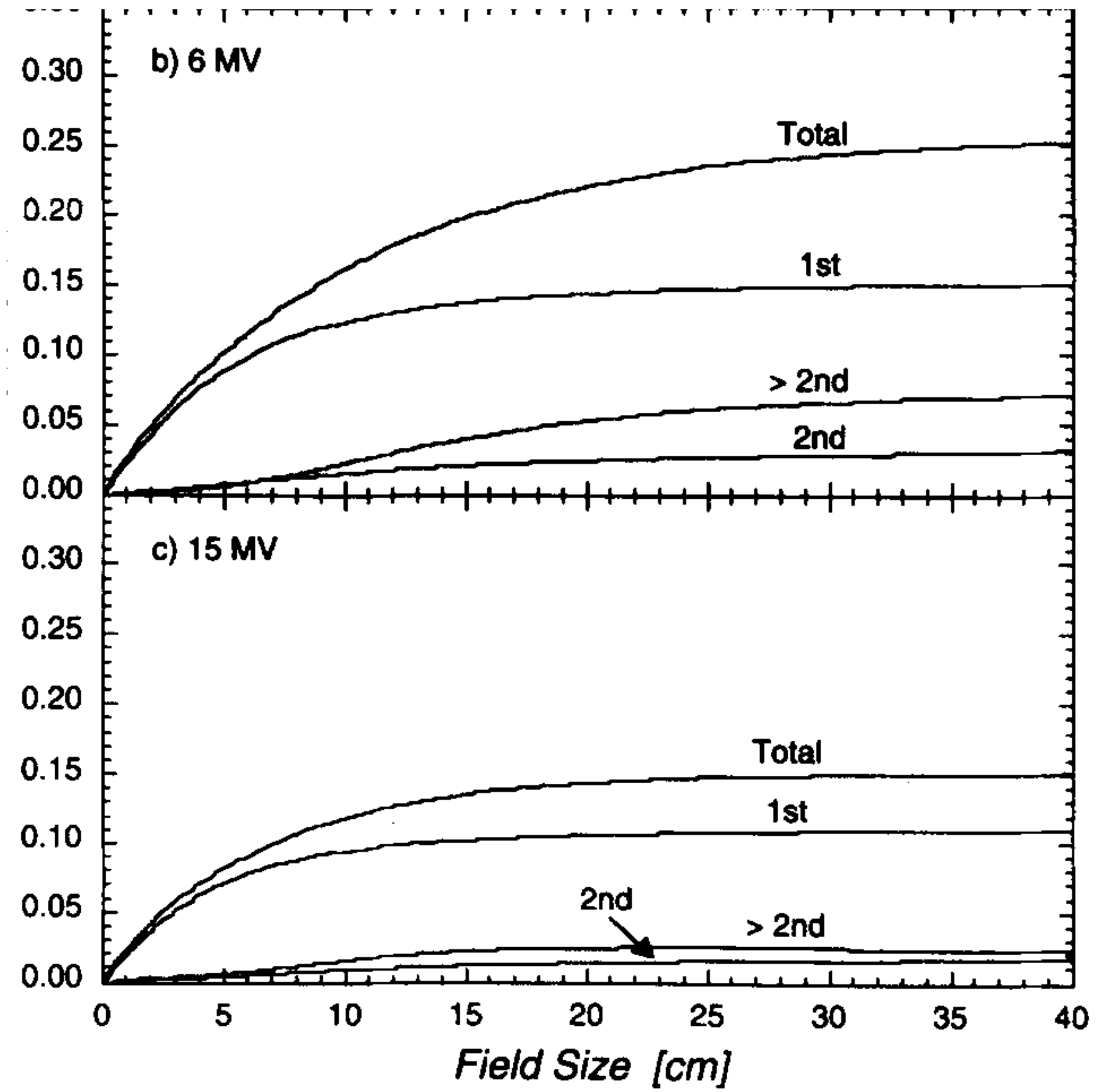
Primary and scattered dose

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)

Transient Charged Equlibrium Exist

monoenergetic beam of Energy *hν*

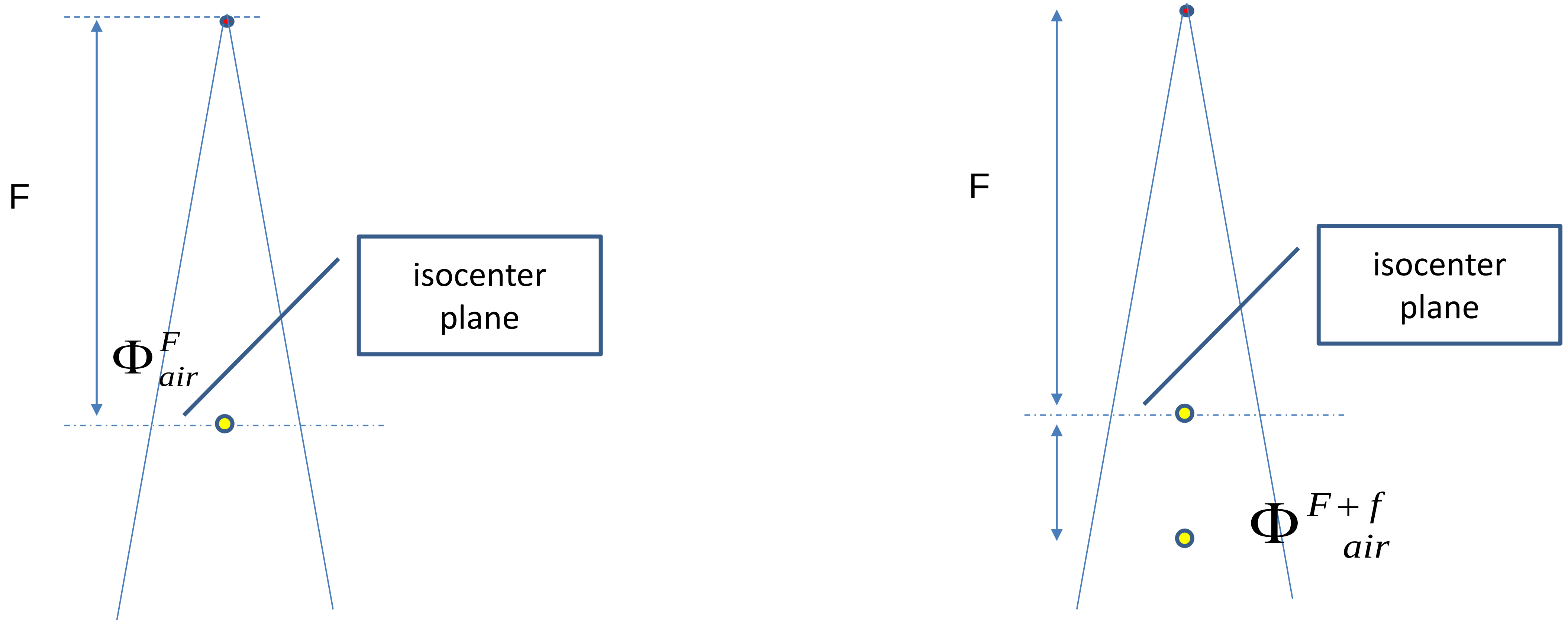
$$Dose_{h\nu} = \left(\frac{\mu}{\rho}\right) \cdot \overline{E}_{tr,h\nu} \cdot \Phi_{h\nu} \cdot \left(1 - g_{h\nu}\right)$$

primary dose

Primary dose

Dependence of the fluence in air on a given distance

- inverse square law



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

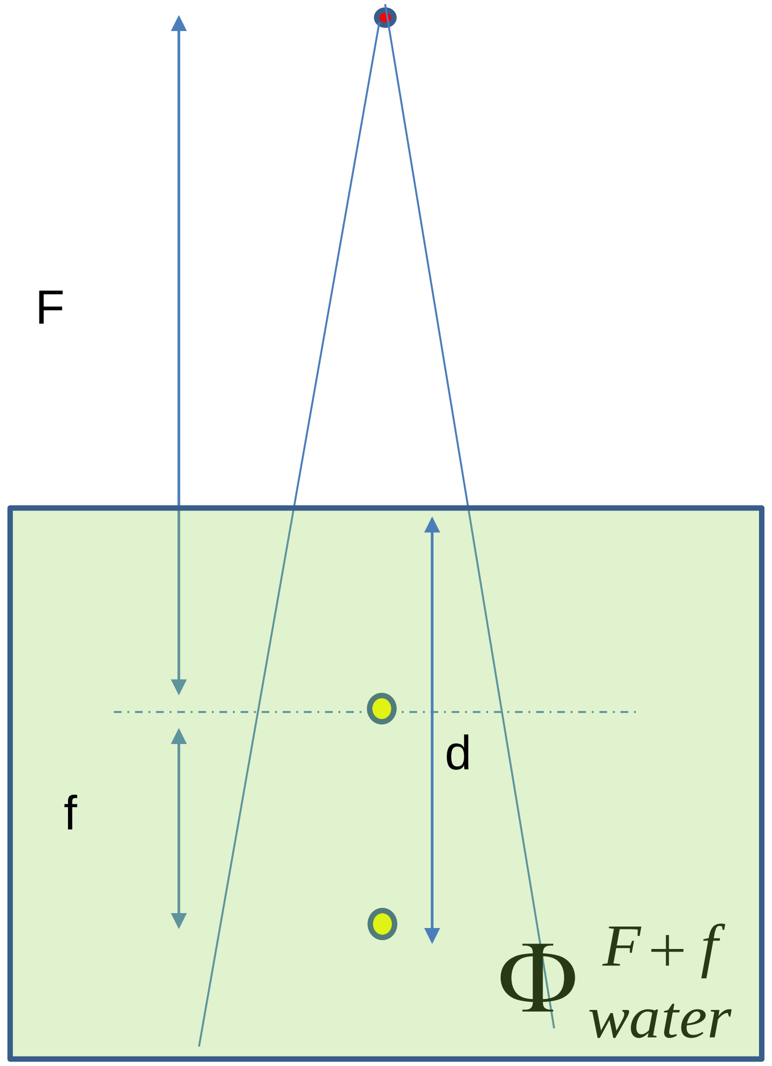
Another notation

Total energy released per unit mass - TERMA

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

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

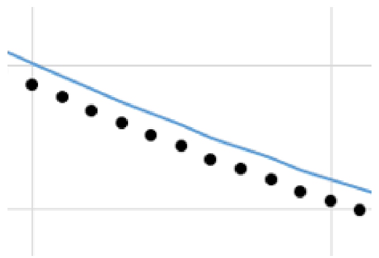
Transient Charged Equilibrium



Fluence in water

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

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



Primary dose in water

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

Maria Sklodowska-Curie
National Research
Institute of Oncology

Kernel - Point Spread Function

Anders A. Ahnsjö, 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 scattered

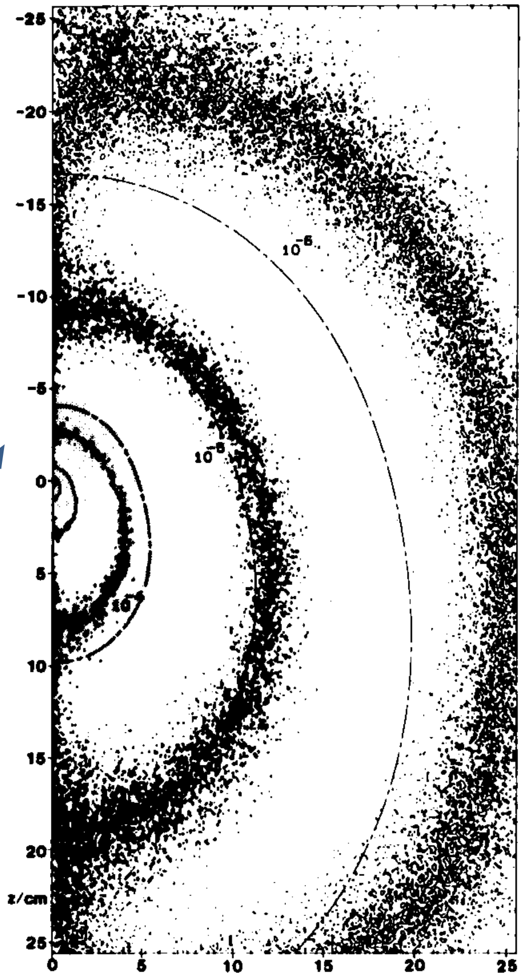
$A_\Theta, a_\Theta, B_\Theta, b_\Theta$

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

ϴ - azimuthal angle

interaction

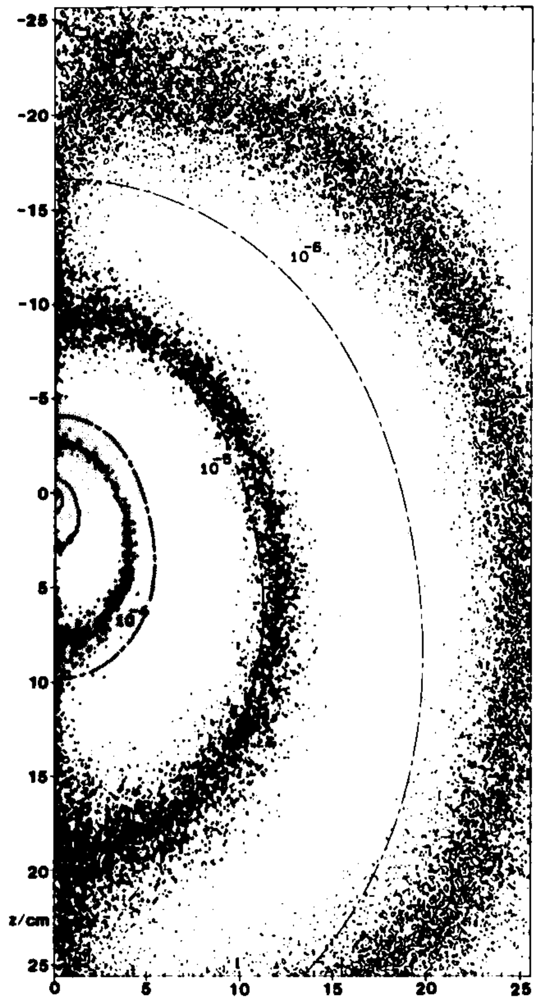
X 0,4 MeV



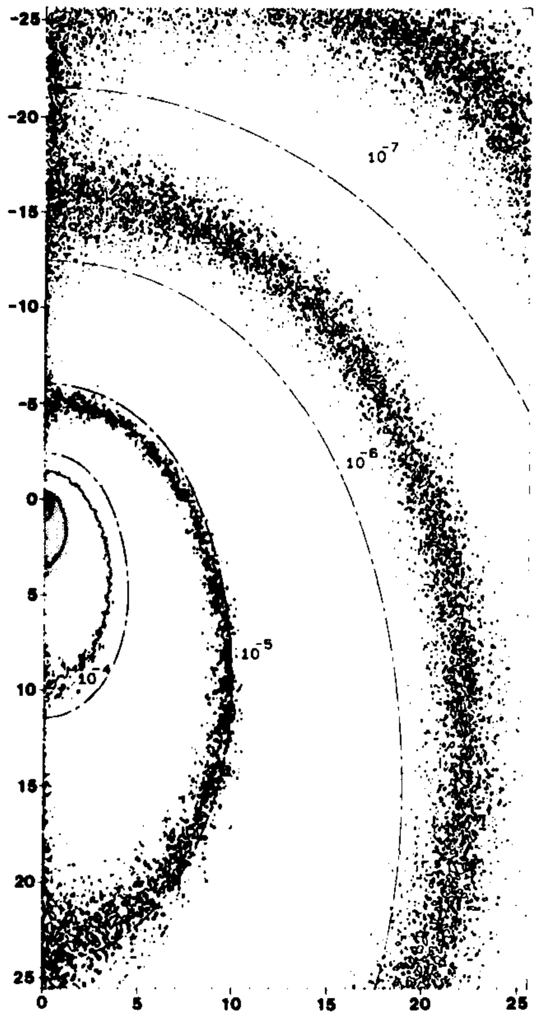
Kernels

Monte Carlo

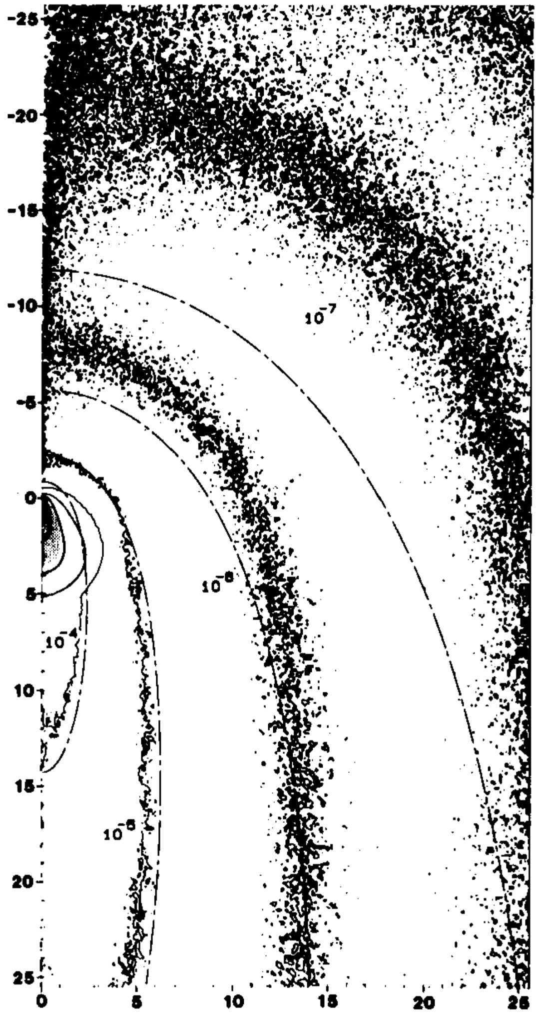
0,4 MeV



1,25 Mev



10 MeV

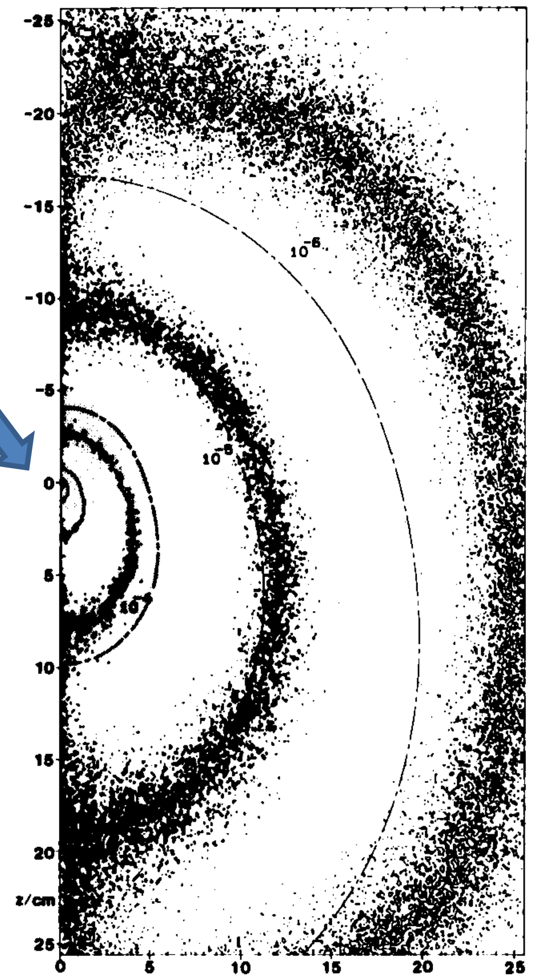


Acta Oncologica, 1987, Ahnesjo

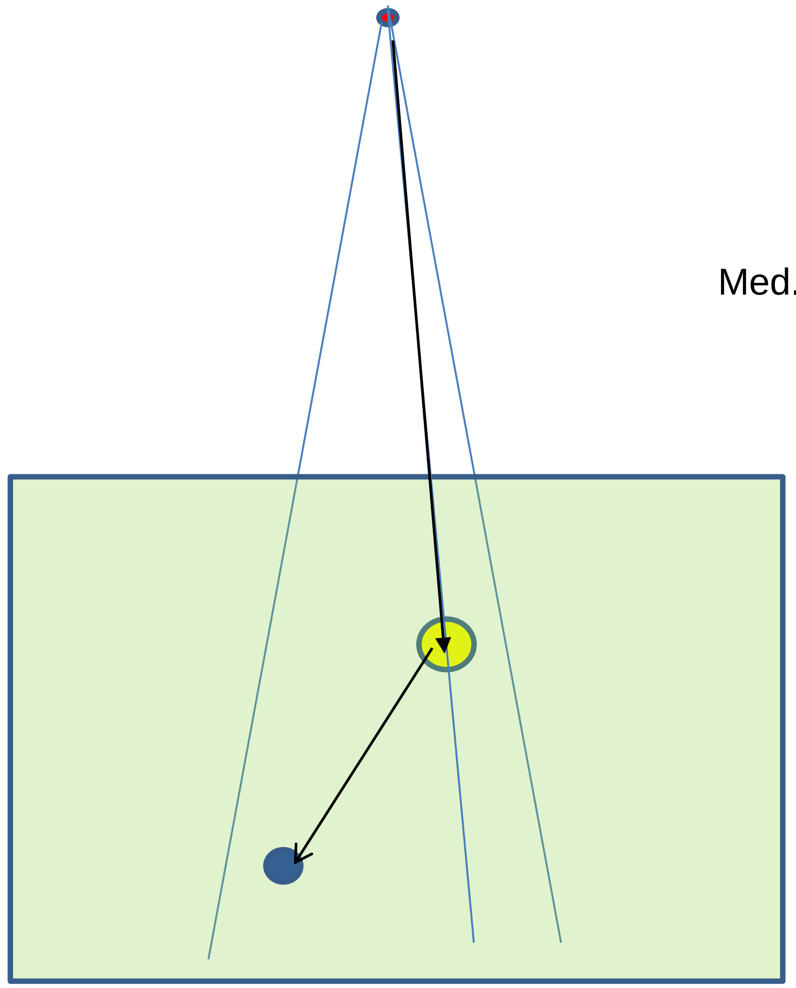
Monoenergetic Depth Dose - Kernel

interaction

X 0,4 MeV



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

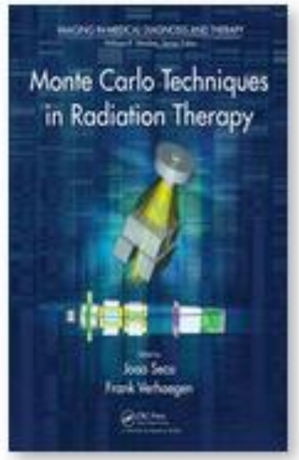


$$D(\bar{r}, h\nu) = \int T_{h\nu}\left(\bar{r}'\right) \cdot A_{h\nu}\left(\bar{r} - \bar{r}'\right) d^3\bar{r}'$$

Kernel

Maria Sklodowska-Curie
National Research
Institute of Oncology

Monte Carlo



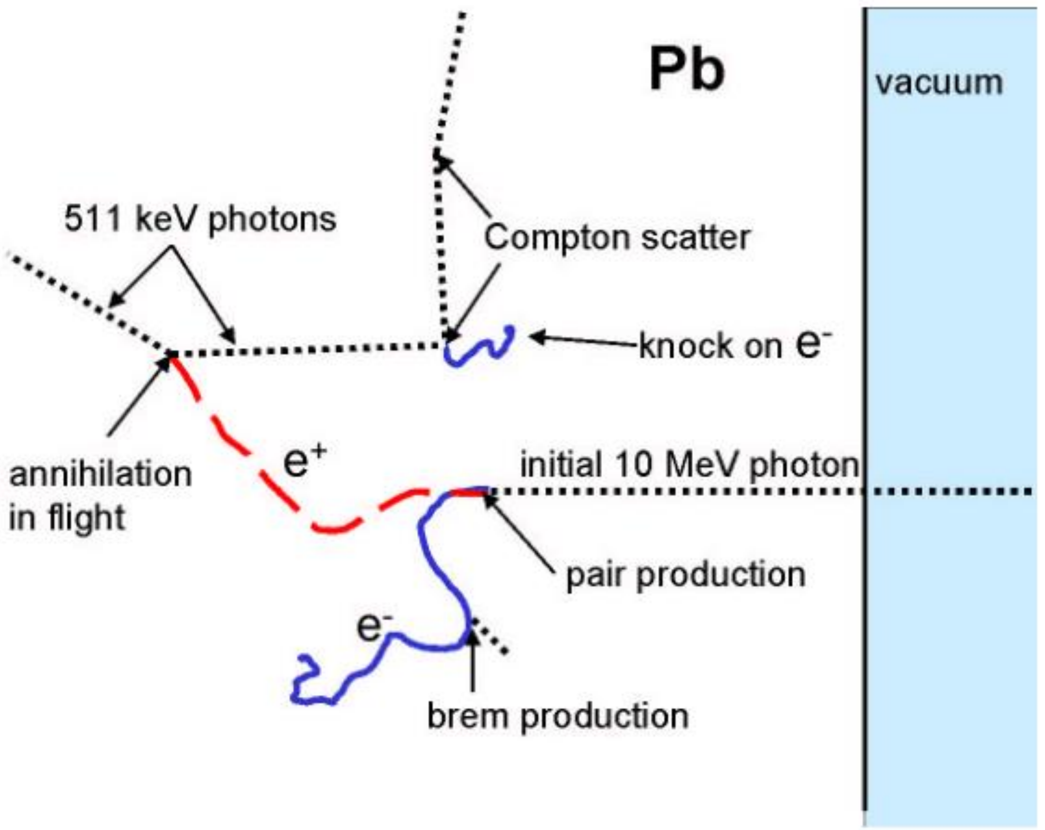
Book

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 <u>probability distributions</u> 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

Monte Carlo example

Spectrum from monoenergetic DD

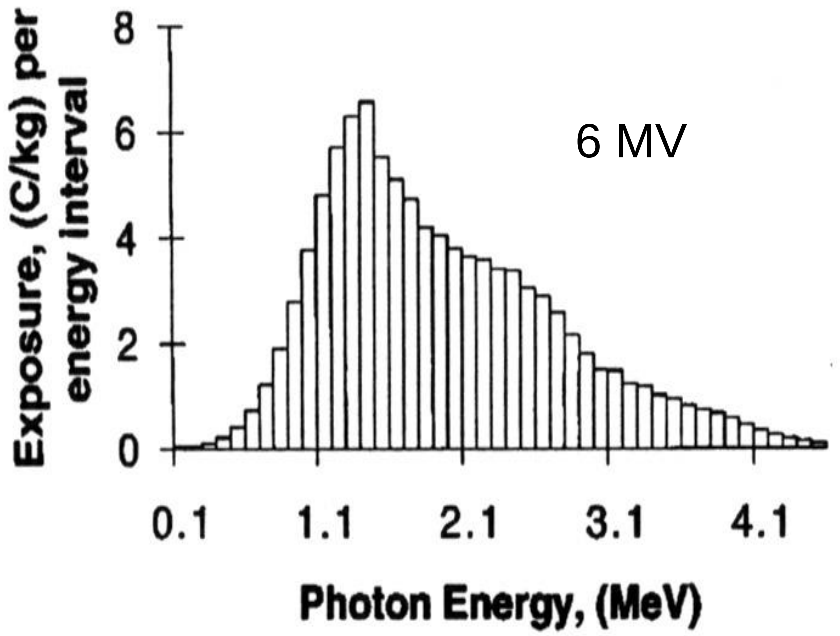
$$DD(z, X_{sq}, \{\Psi\}) = \int DD_{hv}(z) \cdot \Psi(hv) dhv$$

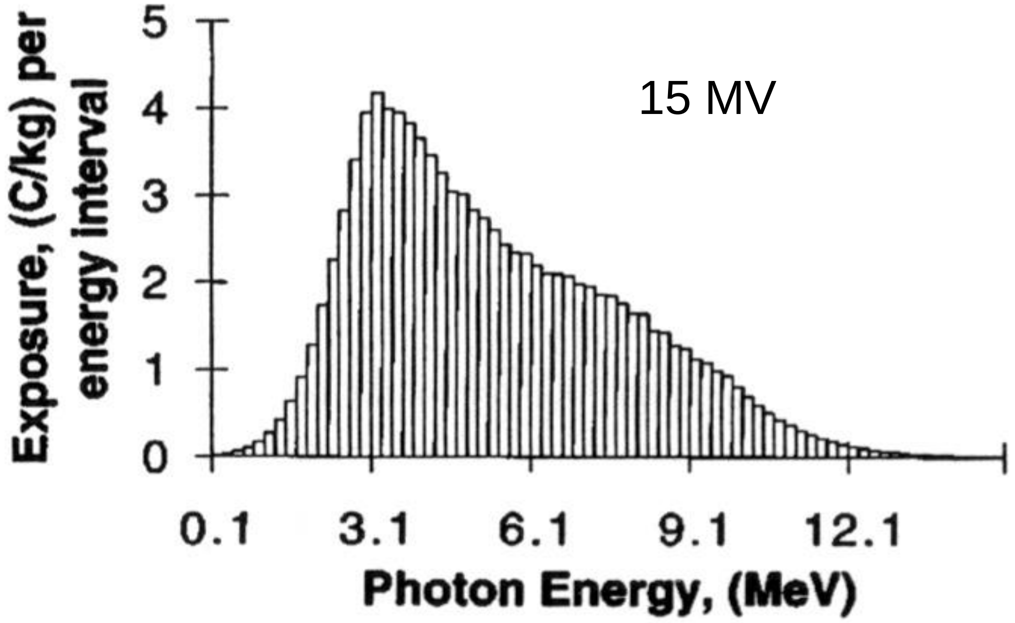
- The aim is to minimize the differences between calculated and measured dose ditributions
  - Ψ(hv) is search
  - depth doses may be measured for several beam sizes and for a range of depths (depth > 5 cm)

Generation of Energy Fluence

Electron hits the target and Bremstrahlung radiation (photons) is produced

Typical energy spectrum for linear accelerators





For dose distribution calculations energy spectrum should be known!

Questions to be addressed concerning spectrum

Maria Sklodowska-Curie National Research Institute of Oncology

1. Does spectrum depend on beam size?

- dependence is negligible (dosimetry)

2. Does spectrum depends on wedges

- Yes, for physical wedges; a significant problem for Electa (60^{o} motorized wedge)

3. Dose spectrum depends on position in beam?

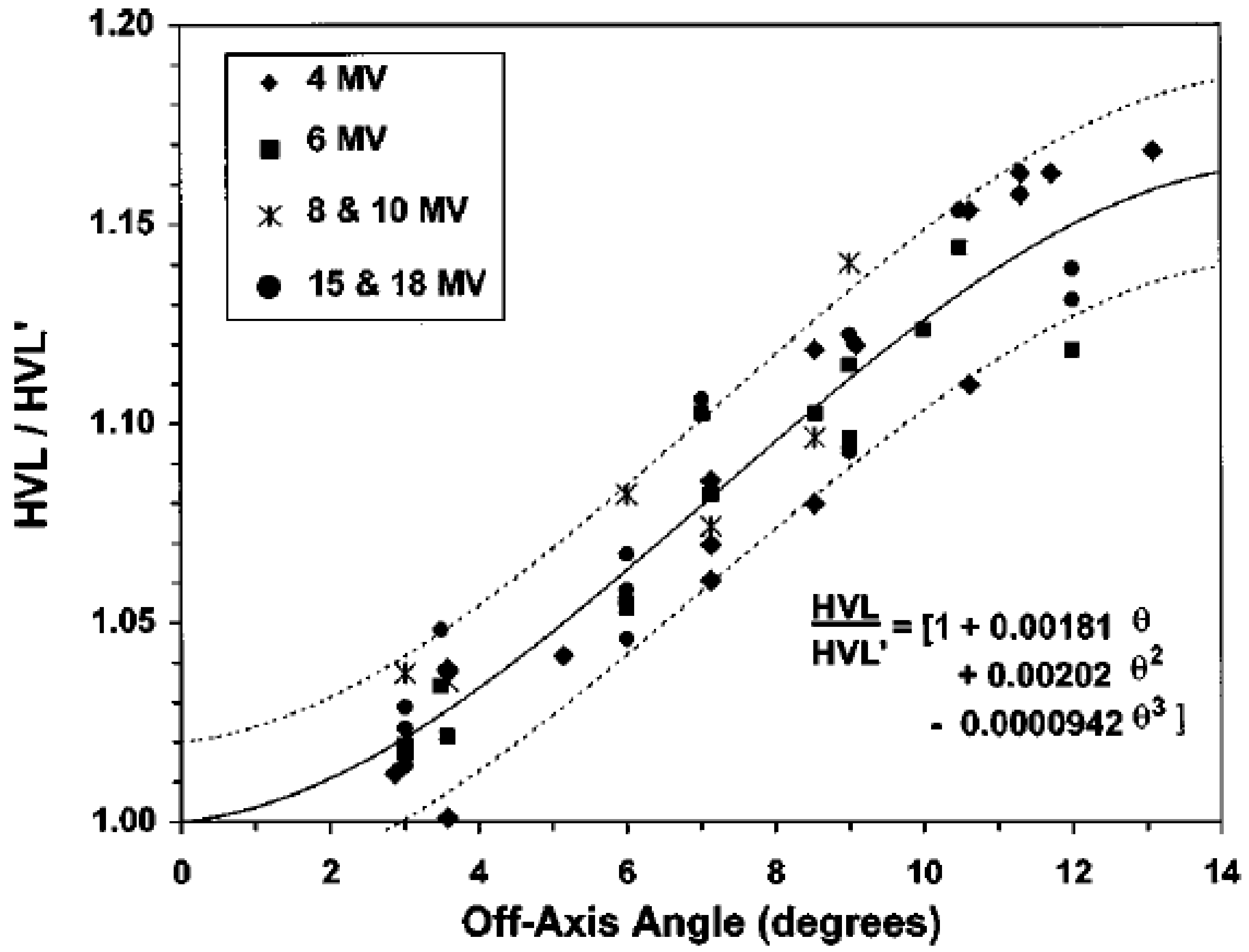
- YES, for very precise calculations it should be taken into account in the model

Do flatening filter and flatening filter free accelarators have different spectrum,

- YES

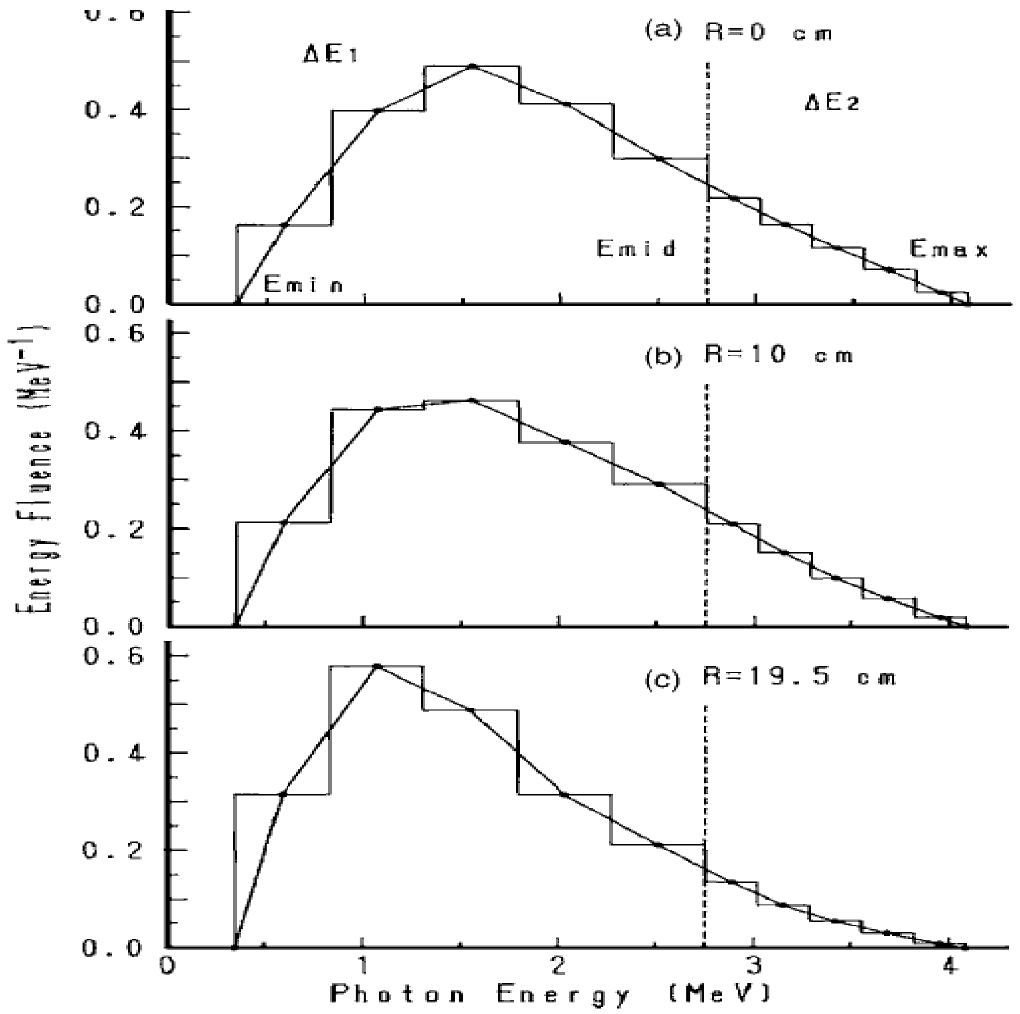
Dependence of the photon energy on the distance from the central axis

HVL - Half Value Layer

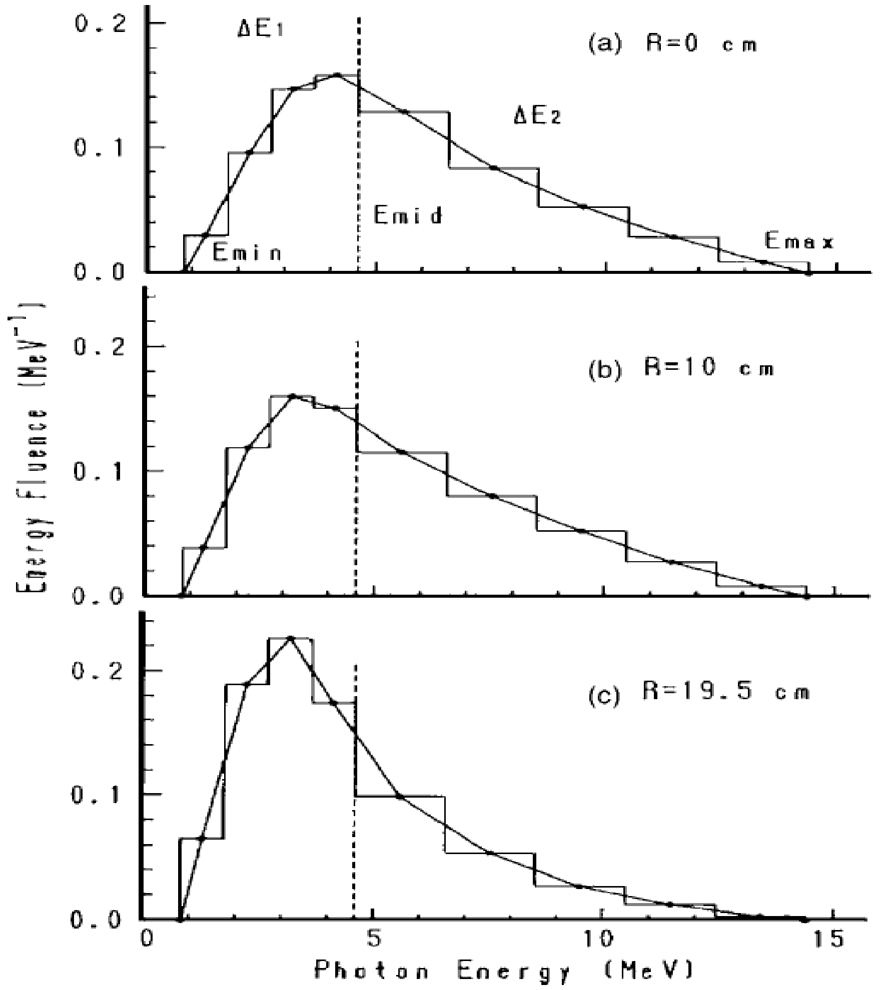


Dependence of the photon Energy on the distance from the central axis

4 MV



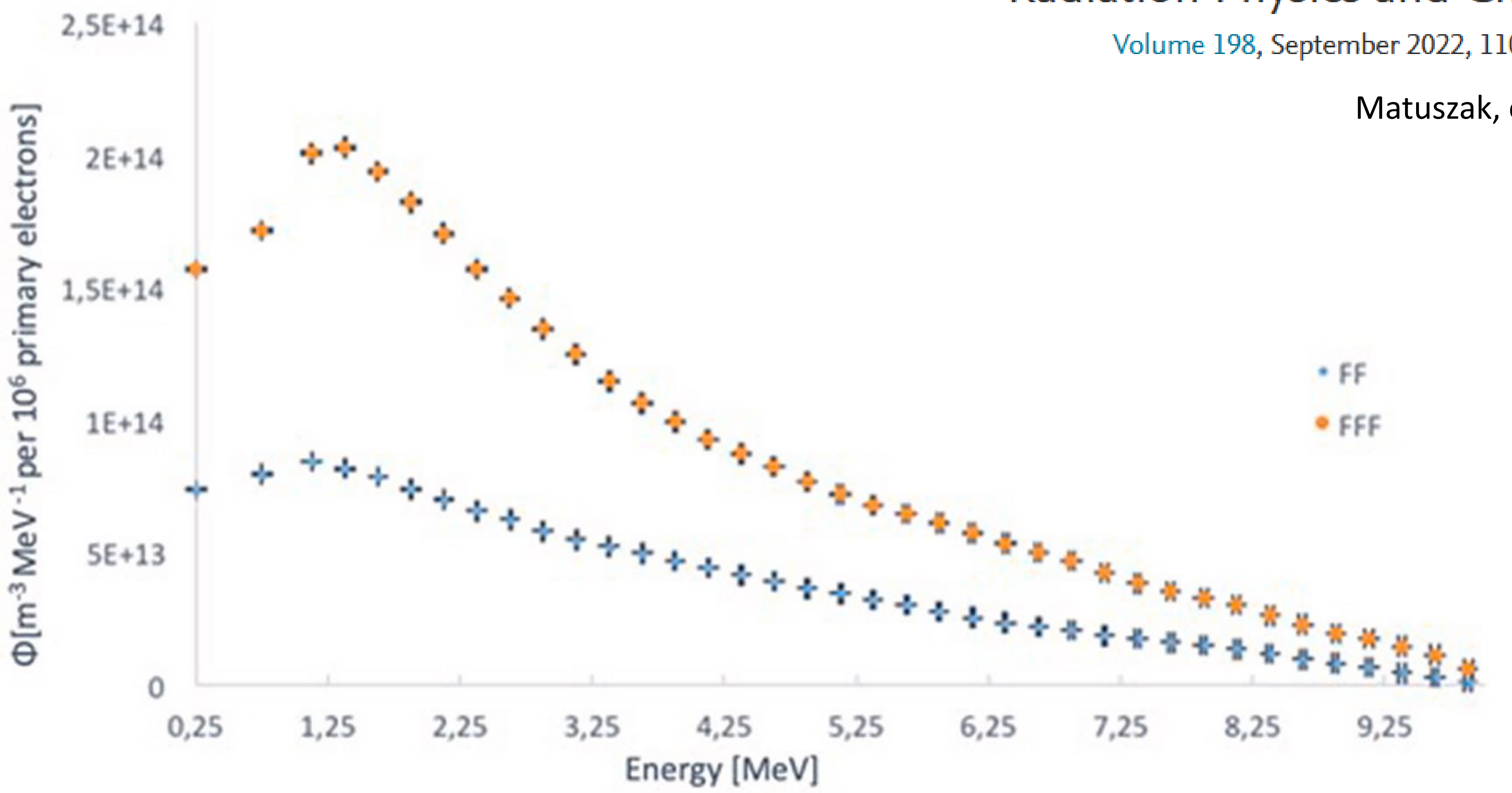
15 MV



FF beams

Iwasaki, Medical Physics Volume 33, Issue 11Nov 2006

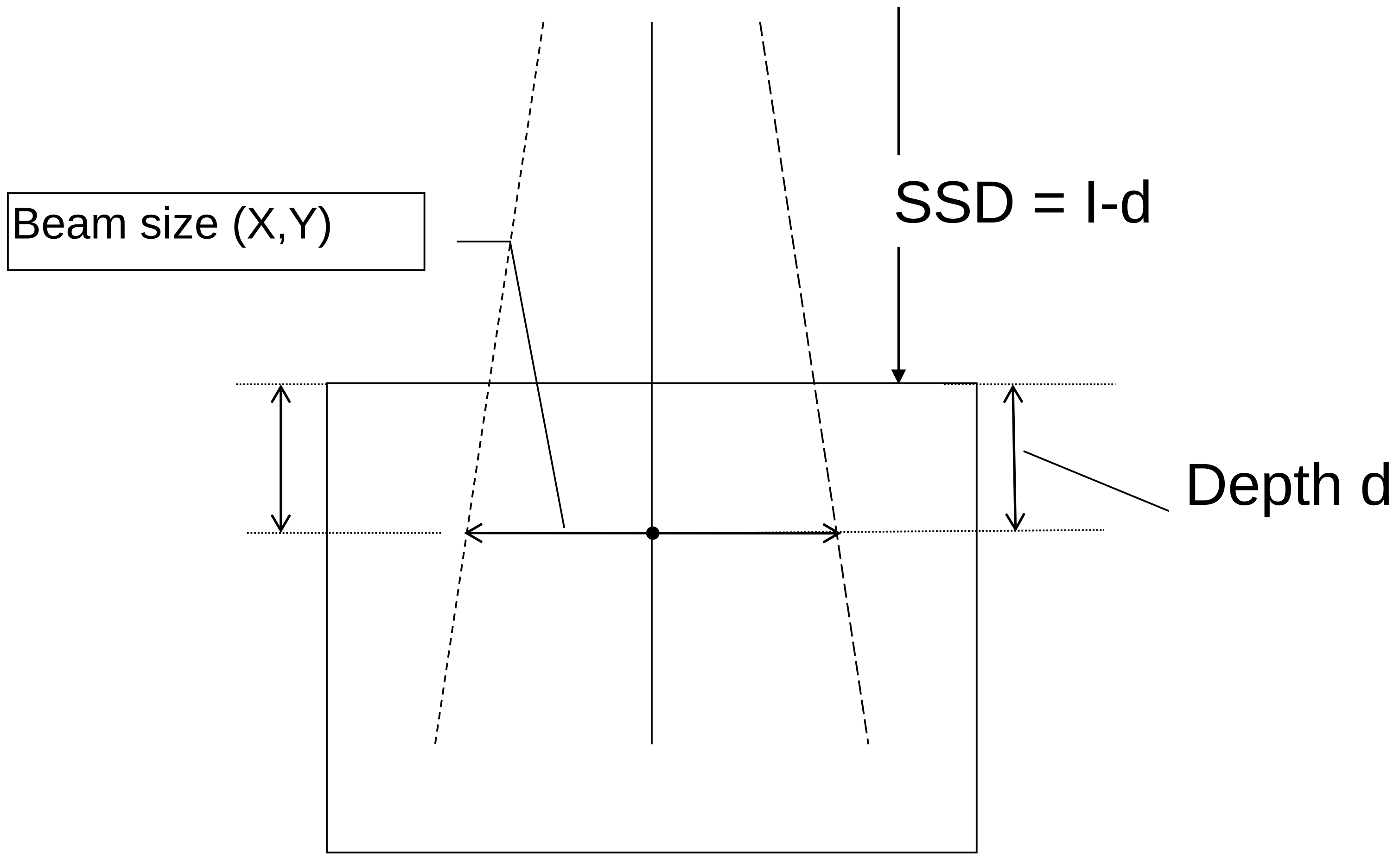
10 MV FF and FFF spectrum
depth 14.5 cm; SSD 85.5 cm, field size 5 × 5 cm^2

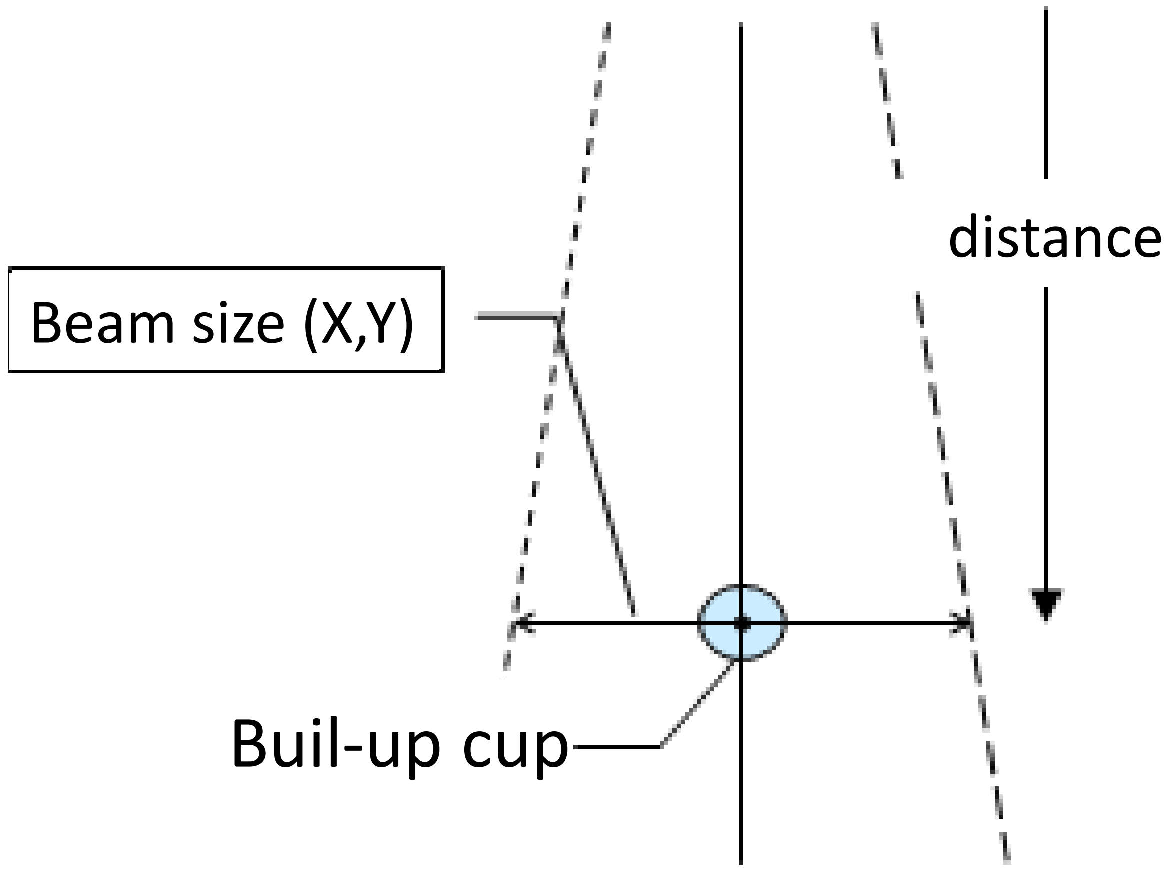


Radiation Physics and Chemistry
Volume 198, September 2022, 110211
Matuszak, et al.

The simplest good model

Tissue Air Ratio - Clarkson (Cunningham) algorithm





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

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

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

	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

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

Calculations with TAR depends very little on BSF

Dose calculations with TAR

for square field A

$$D(A,d,F)_{water} = D_{air}(A,F+d)\cdot TAR\left(A\cdot\frac{F+d}{I},d\right)$$

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

D_{water} – we have from measurements

Primary and Scatter Dose

Maria Sklodowska-Curie National Research Institute of Oncology

it is useful for calculations of dose beneath a block

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

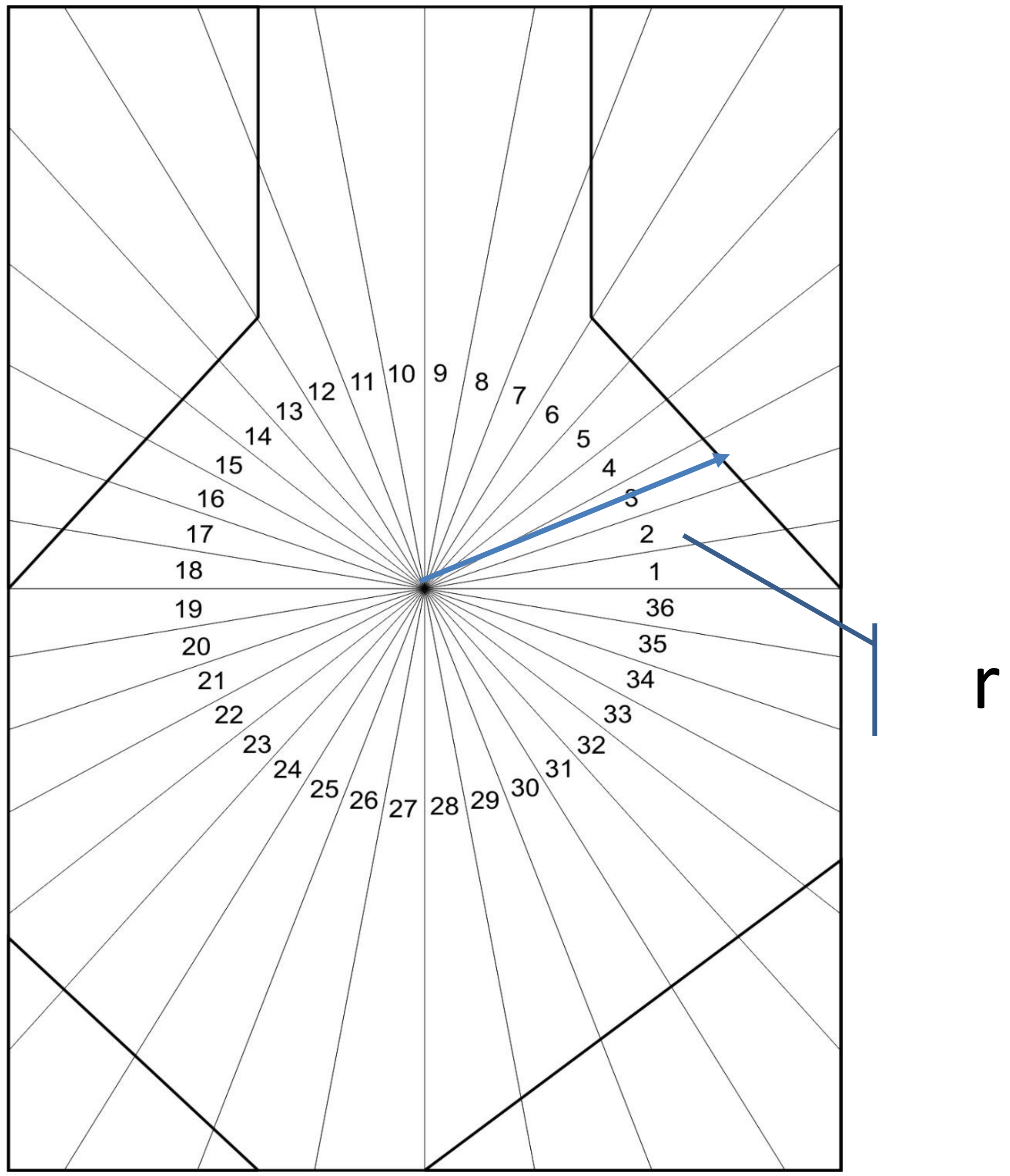
$$TAR_0(d) = \lim_{A \to 0} TAR(A, d)$$

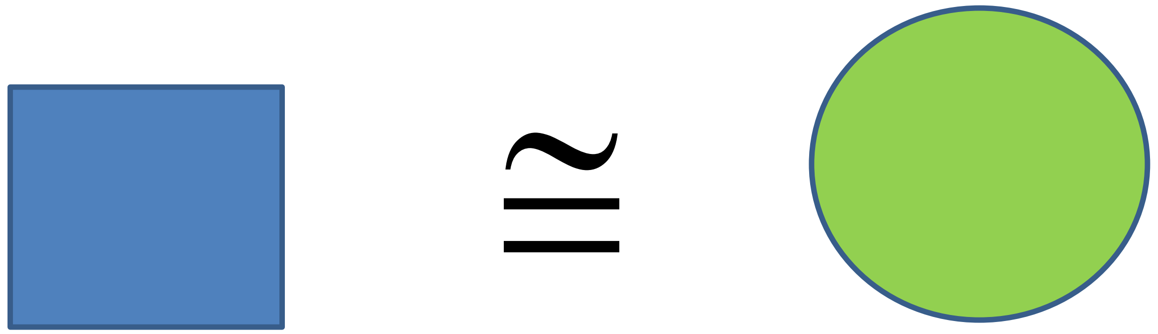
$$SAR = TAR - TAR_0$$

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

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

Circular symmetry and TAR





TAR (A,A) = TAR (r) 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!