Radiotherapy Treatment Planning: Properties of MV beams

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Lecture 2:

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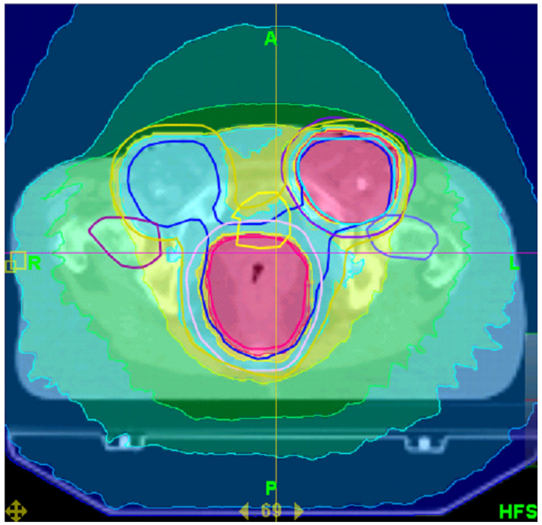
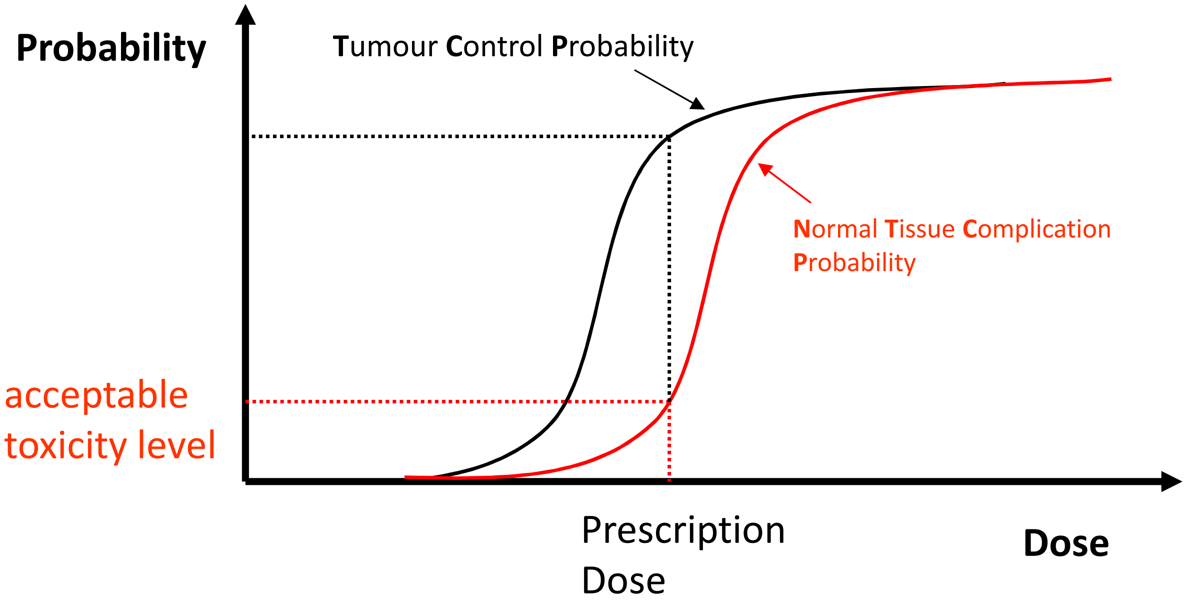


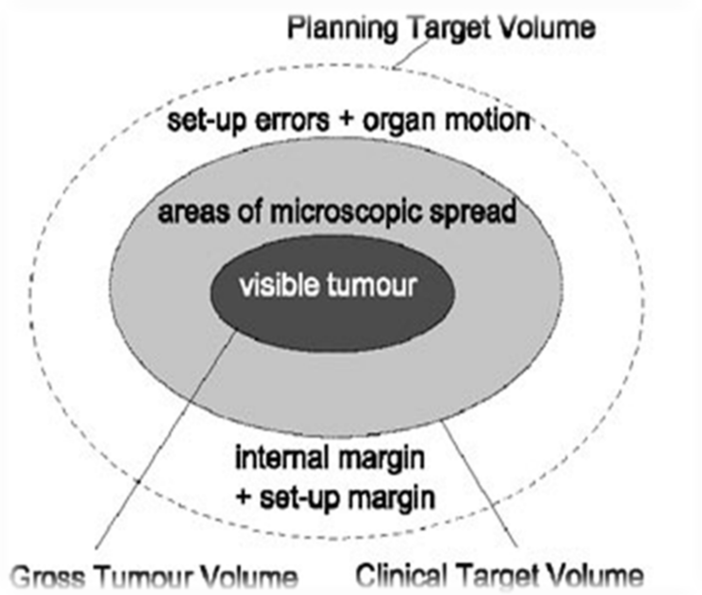
Radiotherapy's Rational & *modus operandi*

Cause – Effect

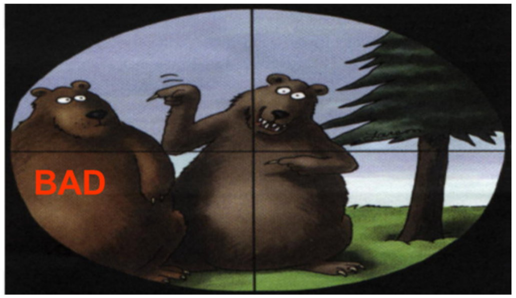


Dose to cancer = tumor control

Dose to normal tissues = side effects



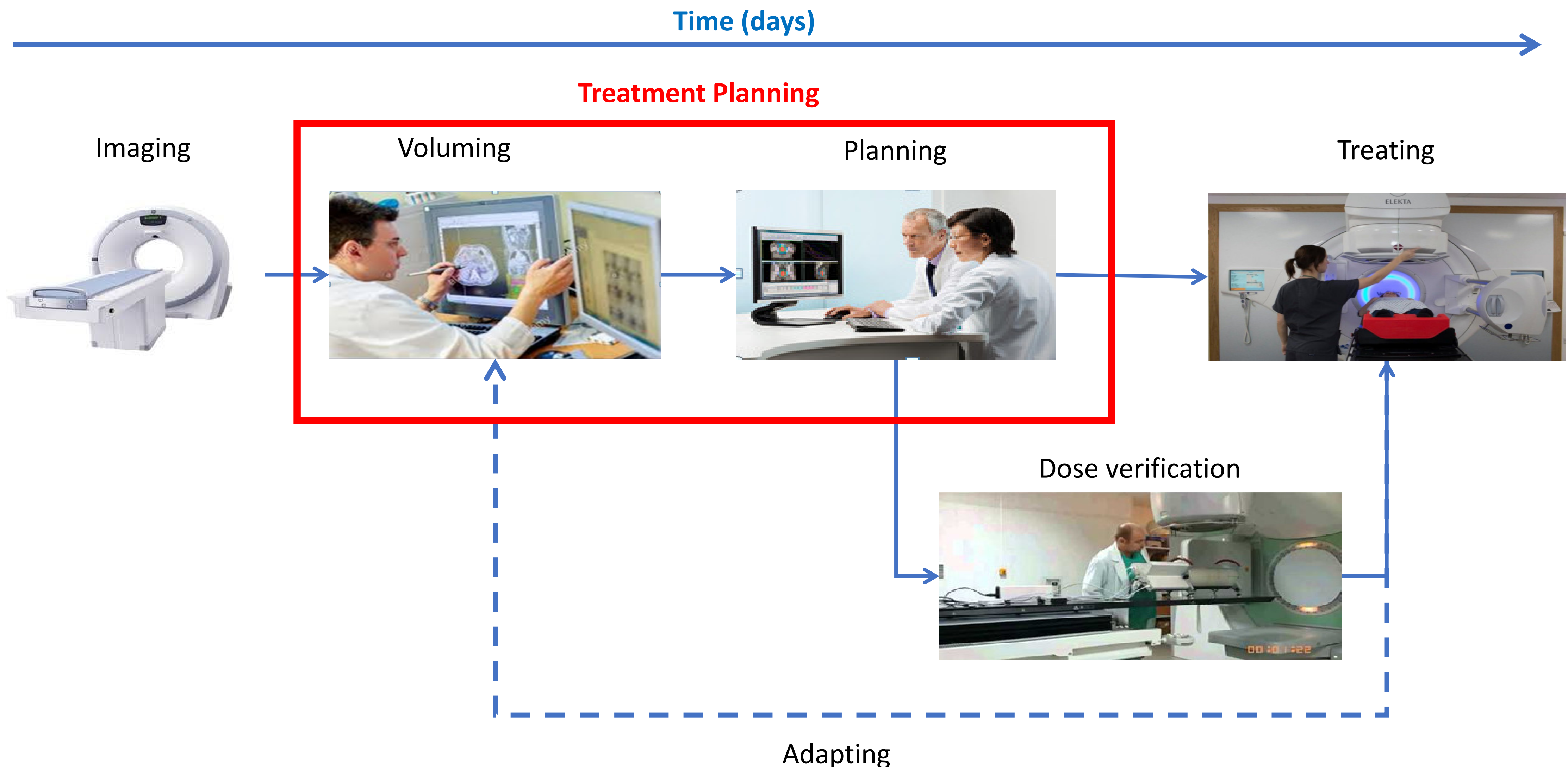
PTV Margin = 2.5Σ + 0.7σ



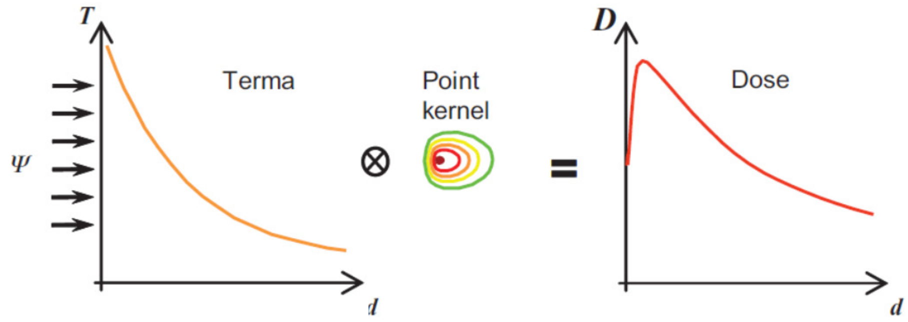
RT mantra

"Treat the bad, spare the good"

2. Radiotherapy Treatment pathway

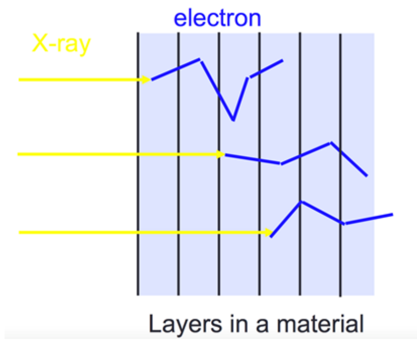


Dose calculation algorithms



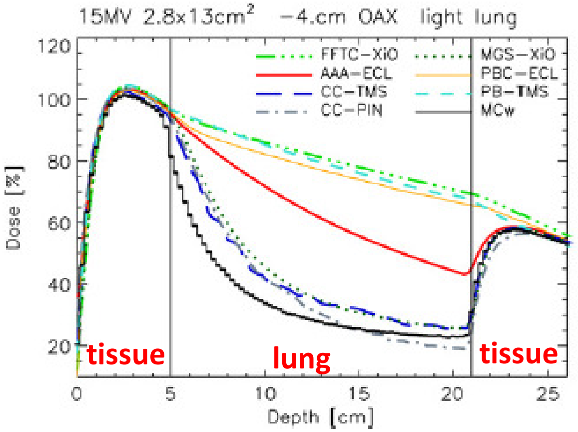
1. Input data (Beam, patient)
2. Dose Calculation equation

$$D(\bar{r}) = \int_E \int \int \int_{\text{volume}} T_E(\bar{s}) h_{\rho_{\text{water}}}(E, \bar{r} - \bar{s}) \, \mathrm{d}^3 s \, \mathrm{d}E$$



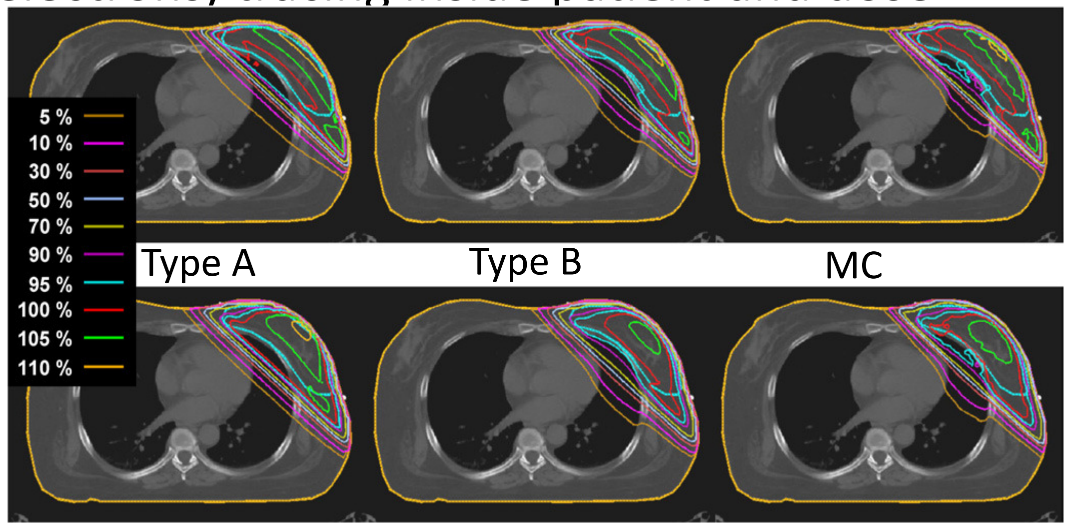
Types of dose calculation algorithms in <u>modern</u> commercial TPS

- **"Type A",** e.g. (FFT) Convolution - homogenous spatially invariant objects.
- **"Type B",** e.g. Superposition – inhomogeneities
- **Monte Carlo** – individual particle (photons **and** electrons) tracing inside patient and dose calculation.

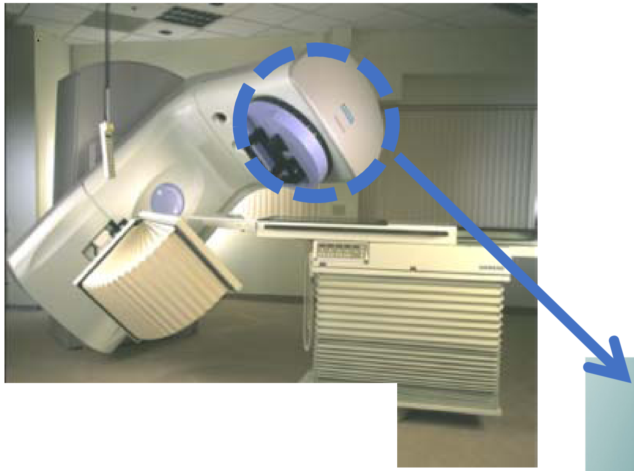


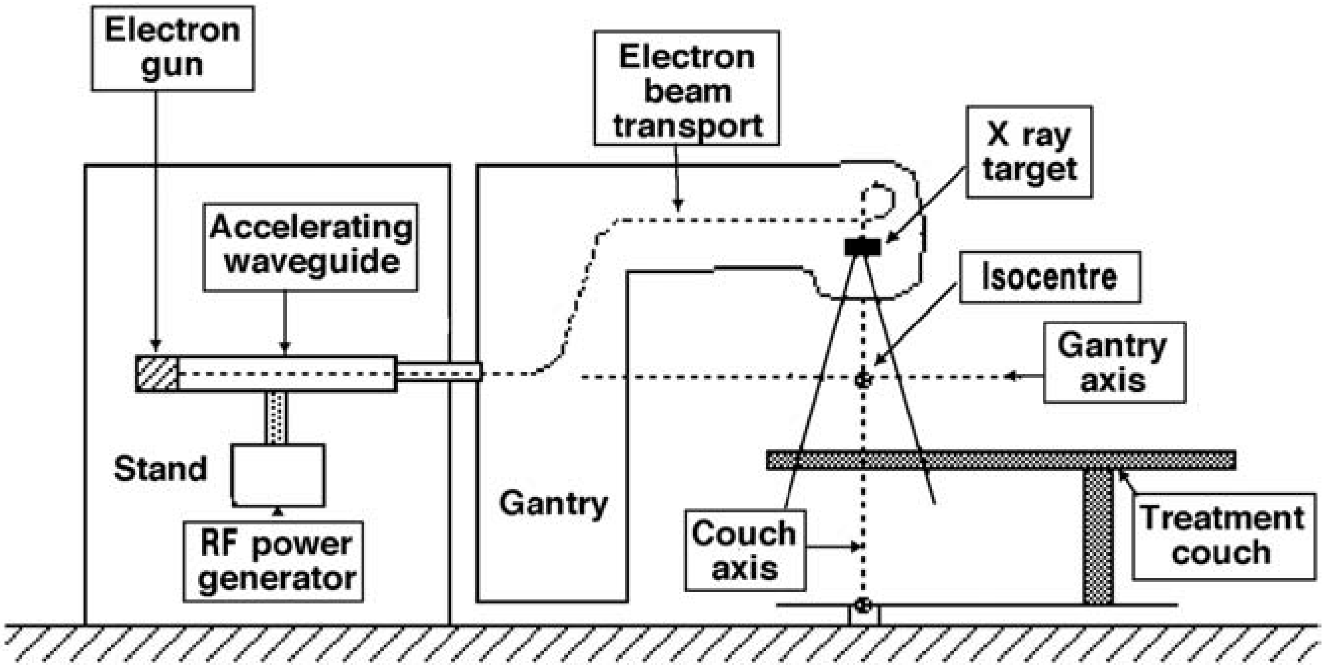
6MV

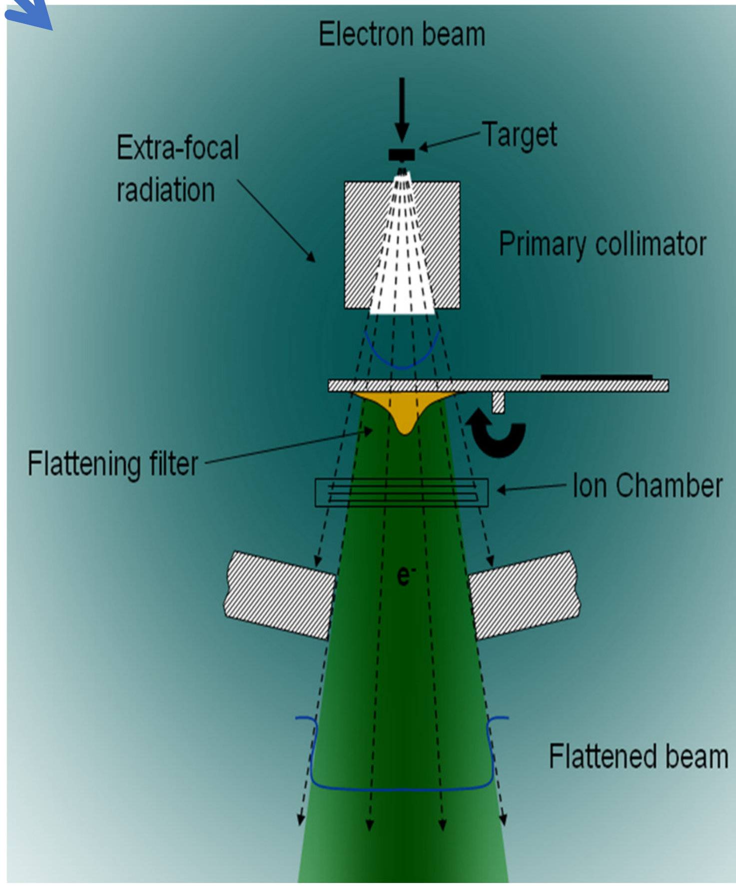
15MV



How a Linac Works - Overview





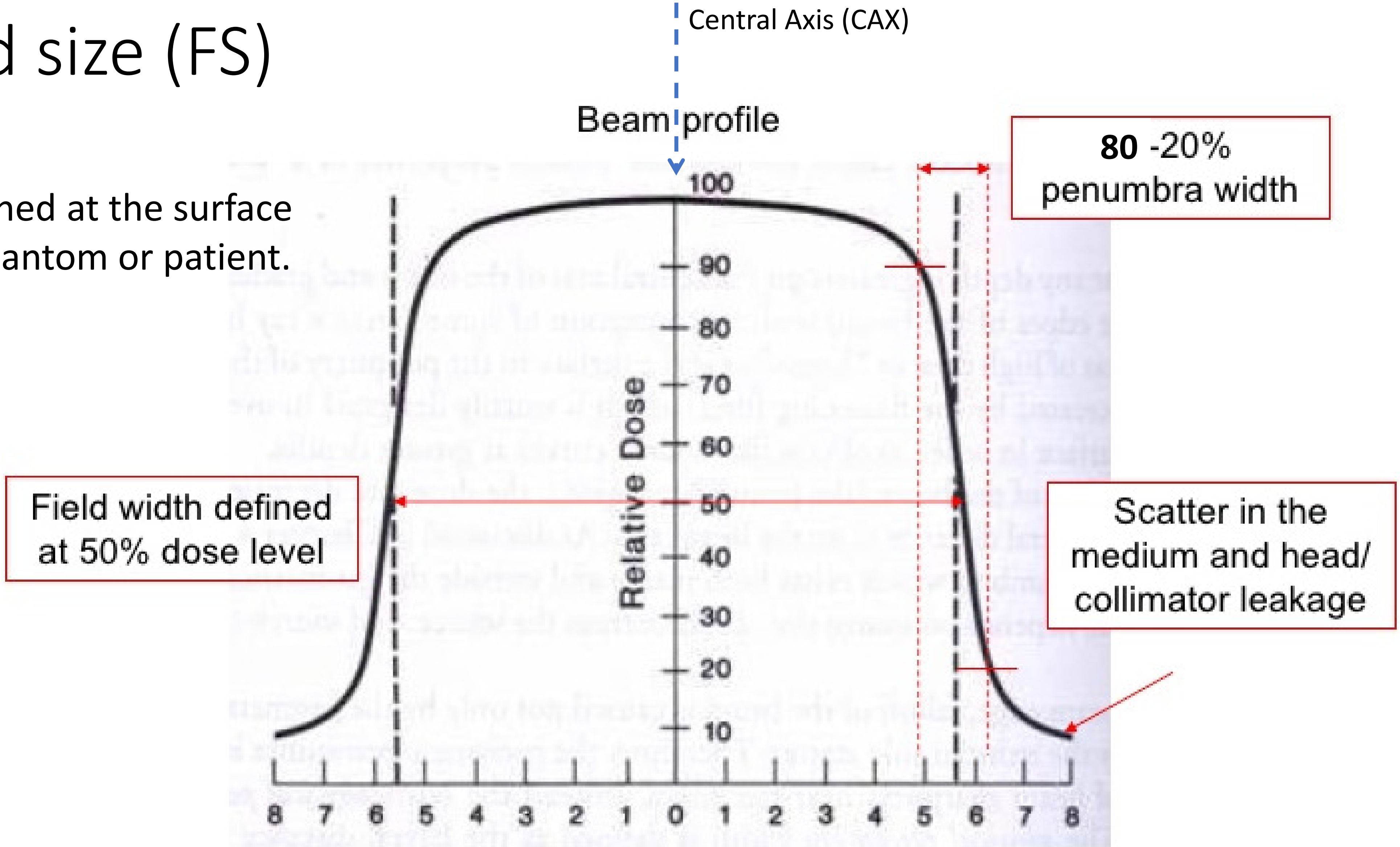


Aim of today is to understand the following…

1. Define field size, PDD and use inverse square law
2. Reproduce MV PDD curves
3. Understand how E, FS and SSD effect %DD in MV beams
4. Charged particle equilibrium and skin sparing affect
5. Calculate equivalent squares
6. Understand TMR and PDD tables
7. Calculate MUs
8. Understand term - Radiological path-length

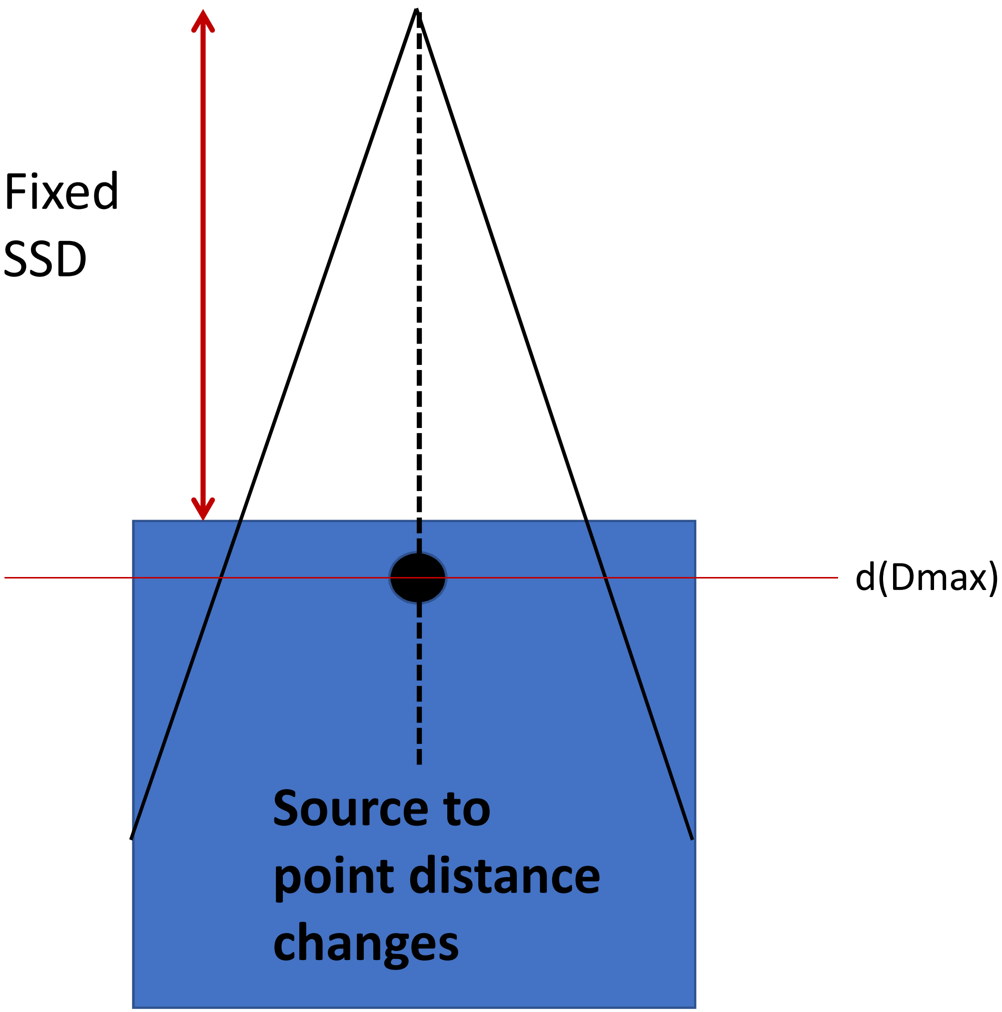
Field size (FS)

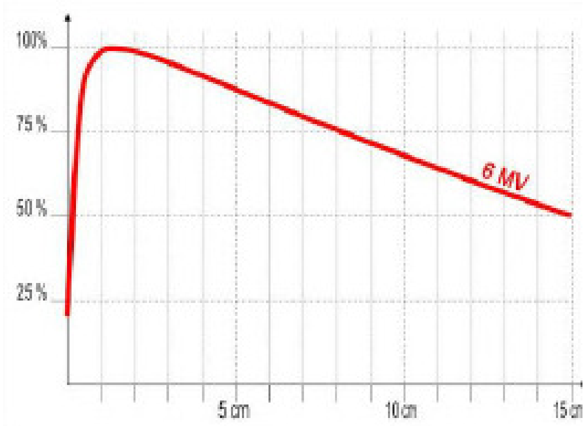
FS is defined at the surface of the phantom or patient.



Percentage Depth Dose (PDD)

= 100* (Dose at point/Dose at depth of max dose)

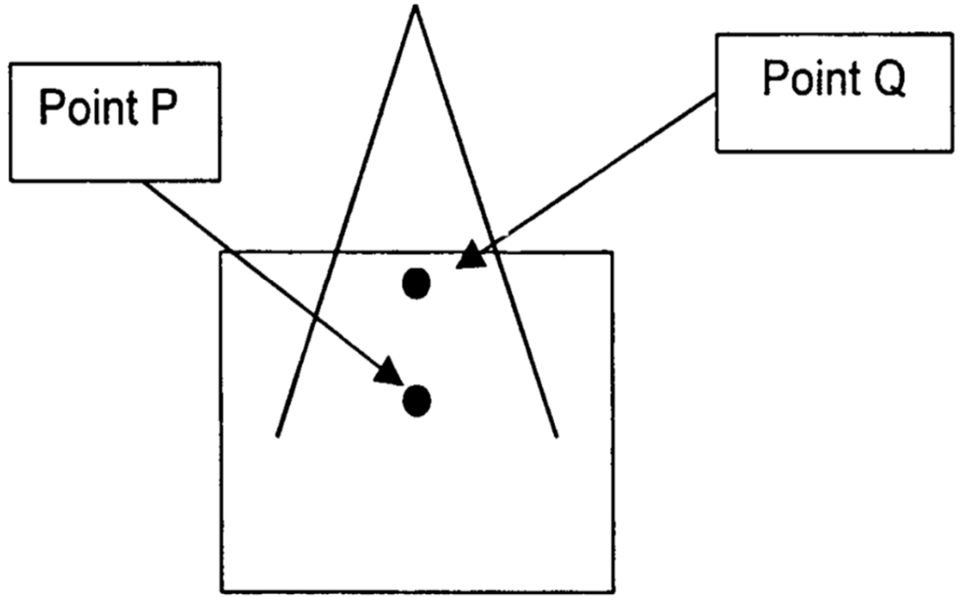




1. Inverse square law
   →Distance = SSD + depth
2. Depth → Attenuation
3. Scatter

How does the dose at point P differ from that at point Q?

- Point P farther away
  - Inverse square
- Point P deeper
  - Attenuation
- Field size at Point P larger
  - More scatter



$$\left(\frac{D_P}{D_Q}\right) = \underbrace{\left(\frac{K_S(r_P)}{K_S(r_Q)}\right)}_{\text{Scatter}} \underbrace{\left(\frac{SSD + d_Q}{SSD + d_P}\right)^2}_{\text{Distance}} \times \underbrace{\left(e^{-\mu(d_P - d_Q)}\right)}_{\text{Attenuation}}$$

Scatter

- Scatter causes dose to increase as dose is scattered into line of the beam.
- Hence dose increases with field size.
- More area for scatter to come from!
- Deeper => even more scatter!

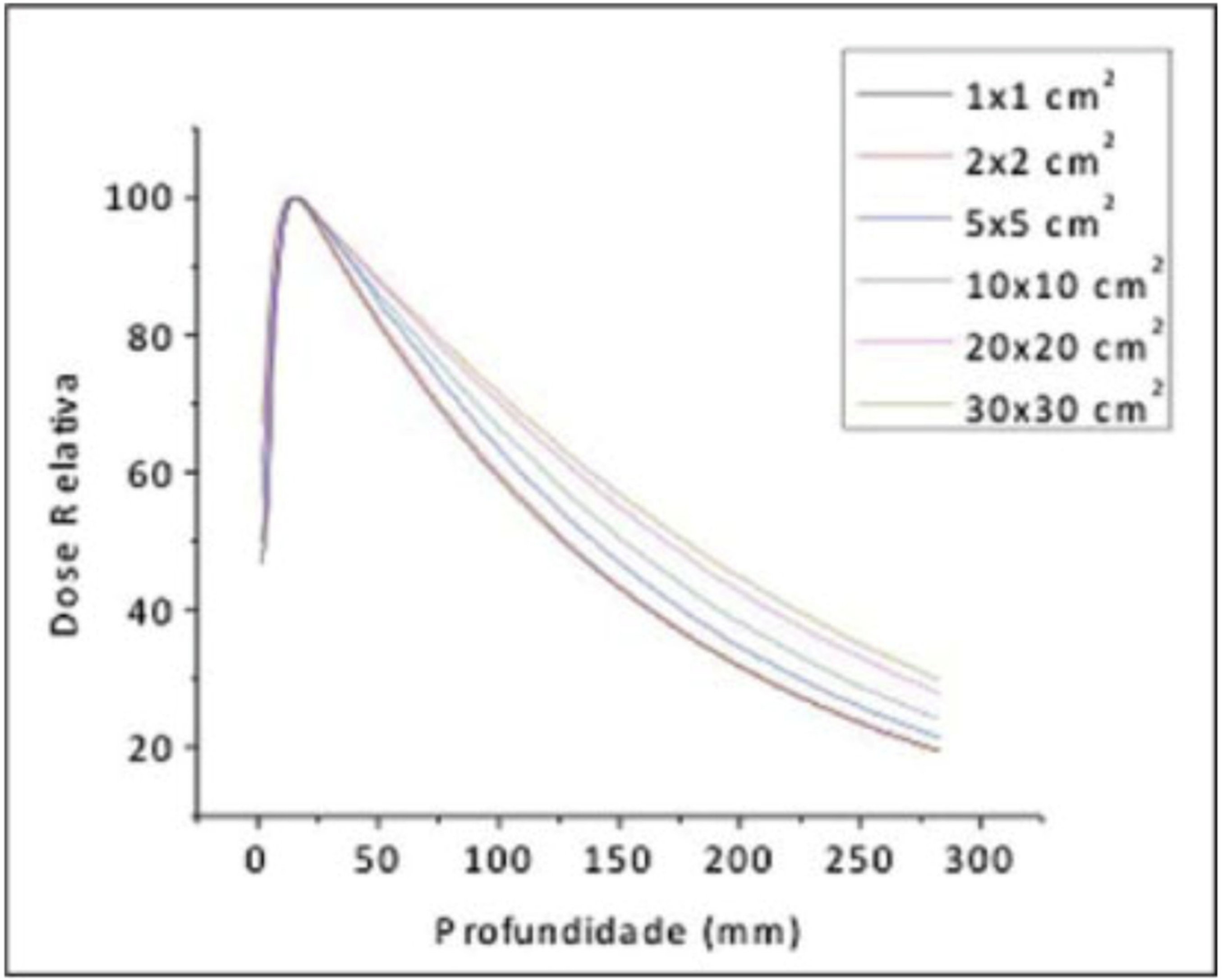


Figure 3. Depth dose rate measured with the ionization chamber.

PDD Vs SSD

Assume Linac acts as a point source.
Then photon flux and therefore dose follows **inverse square law** (beam divergence)

Inverse square law : $\boxed{Intensity \propto {}^{1}/_{(distance)^2}}$

- If SSDistance is **doubled**, then intensity falls **4 times**
- But field size increases and so does the scatter contribution
- Total effect is PDD increase with SSD

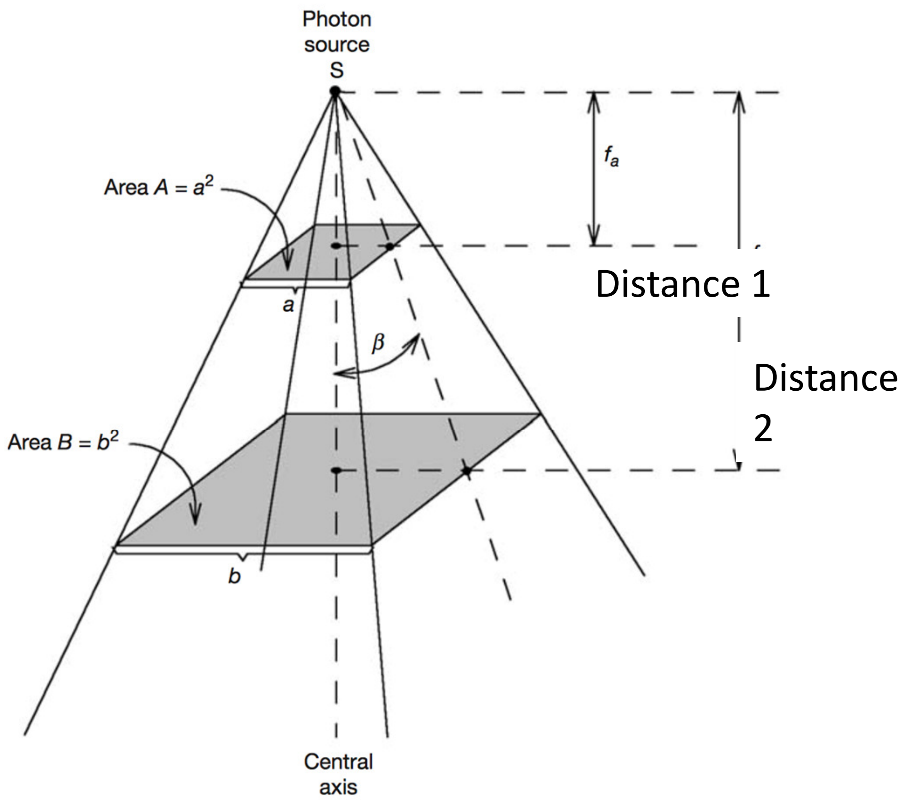
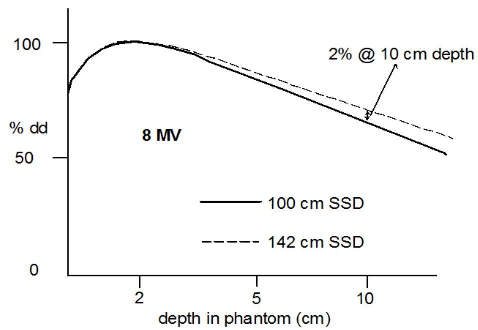
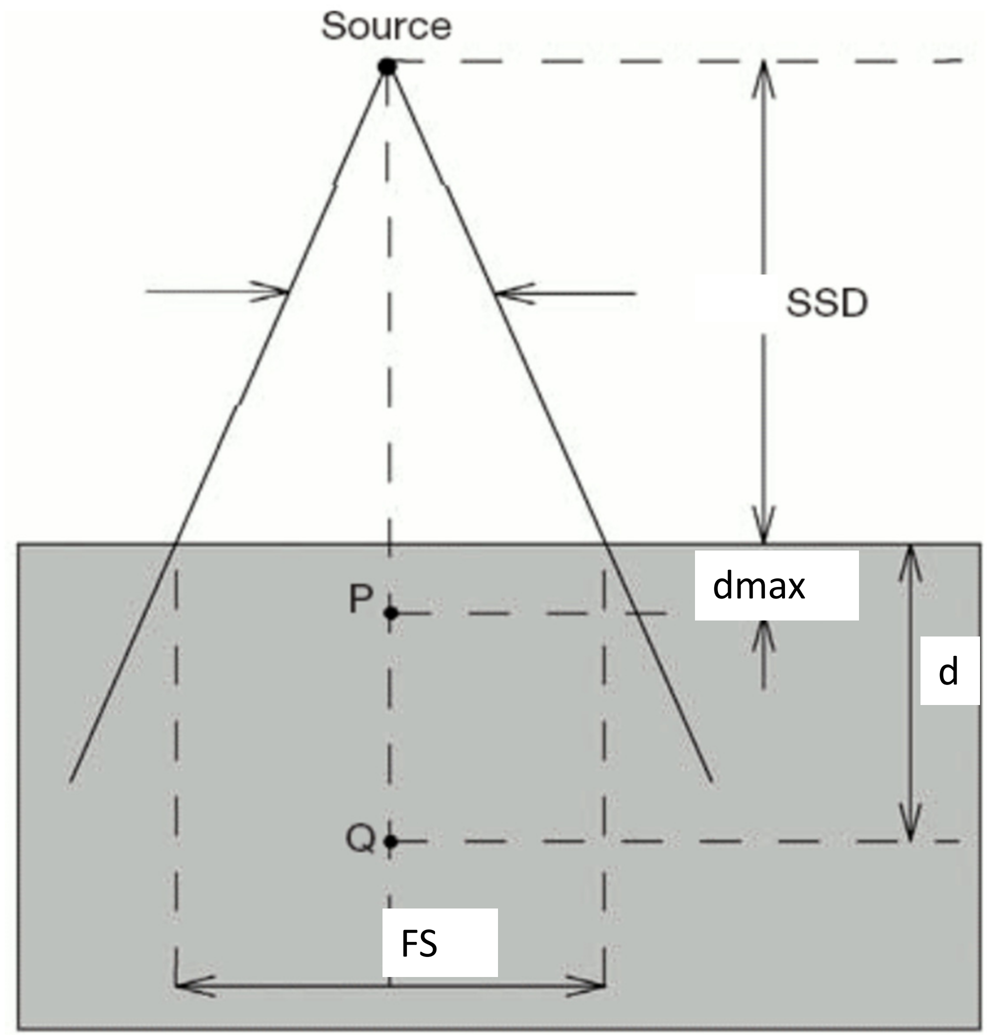


FIG. 6.2. Divergent photon beam originating in a photon point source. At distance f_a from the source S the field size is $A = a^2$, at distance f_b the field size is $B = b^2$.





$$\frac{PDD(SSD_2)}{PDD(SSD_1)} = \left(\frac{SSD_2 + d_{max}}{SSD_1 + d_{max}}\right)^2 \cdot \left(\frac{SDD_1 + d}{SSD_2 + d}\right)^2$$

<u>Example</u>

Dose measured at 10cm deep, 100cm SSD for a 10x10cm field with 6MV beam was 68.4%. What is the PDD if SSD changed to 80cm?

Note: d_{max} for 6MV = 1.5cm

SSD_1 = 100cm
SSD_2 = 80cm
d_{max} = 1.5cm
d = 10cm

$PDD(f_1)$ = 68.4%

$\boxed{PDD(f_2) = 65.9\%}$

PDD Vs Beam energy

d_{max}

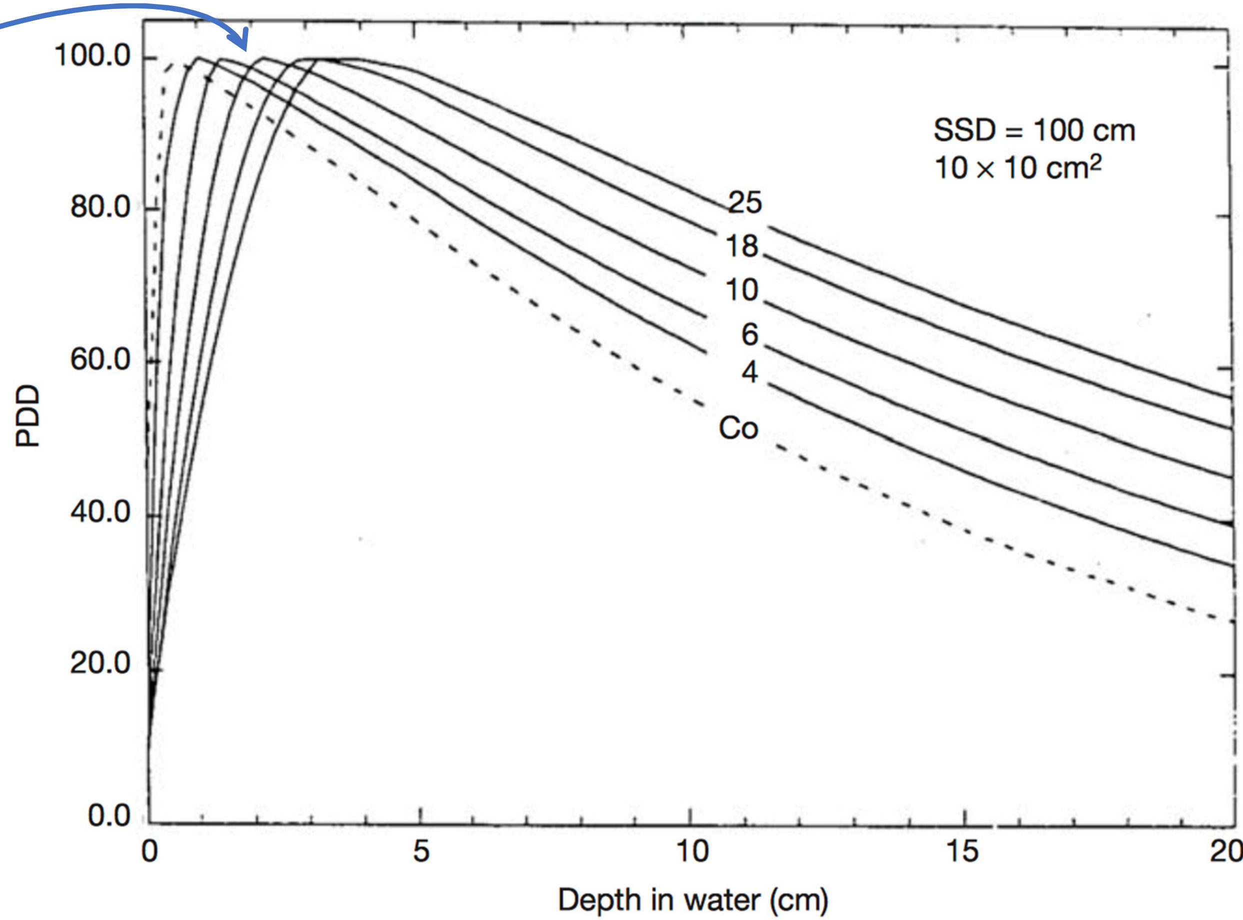


FIG. 6.10. PDD curves in water for a 10 × 10 cm² field at an SSD of 100 cm for various megavoltage photon beams ranging from ^{60}Co γ rays to 25 MV X rays.

Higher-energy beams have greater penetrating power and thus deliver a higher-percentage depth dose

Charged particle equilibrium

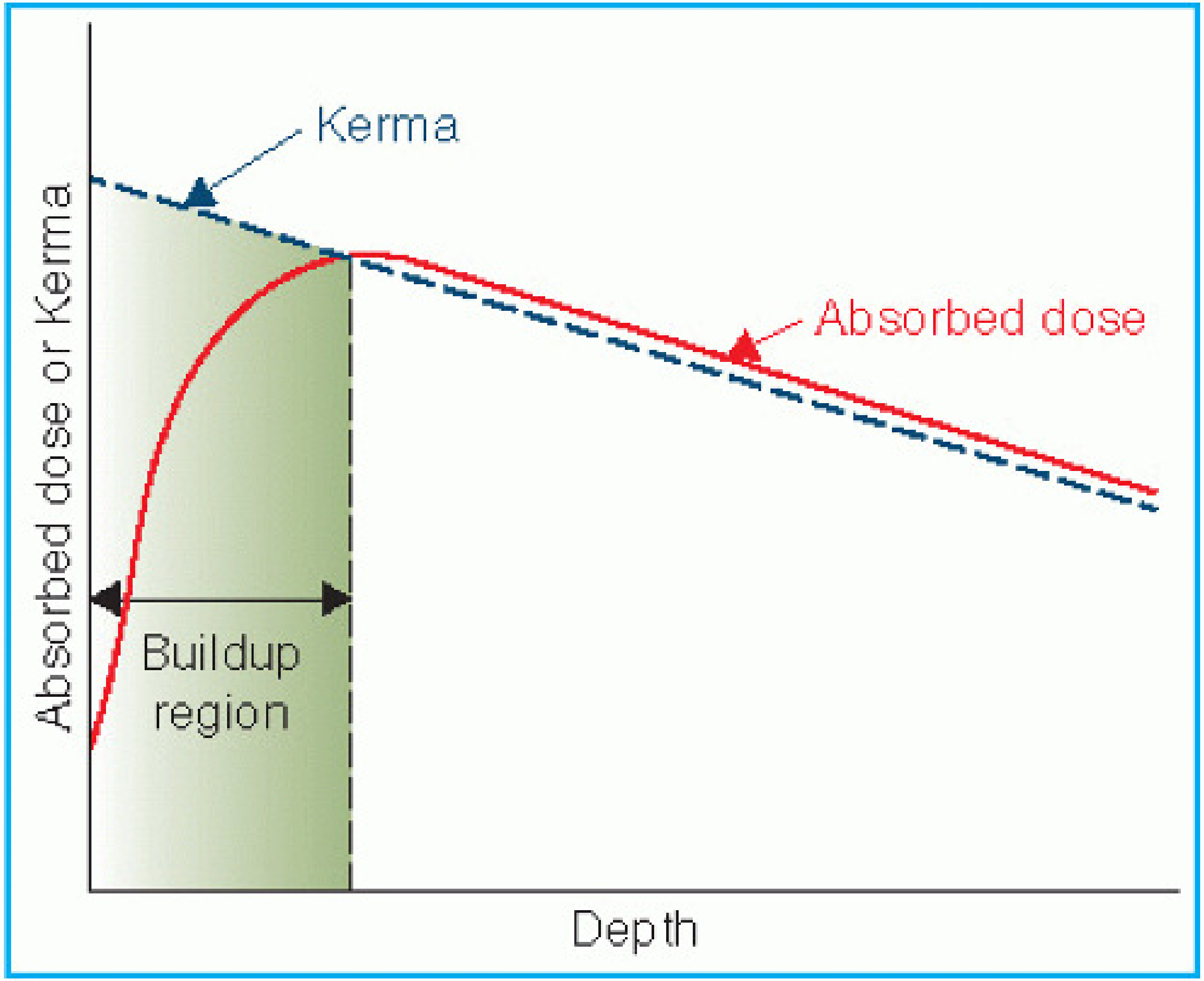
Electrons are the "dose" carrying medium

MeV electrons have a finite range (~ cm)

Point at Dmax for MV X-rays is below skin, e.g. 1.5cm for 6 MV

This results in "skin sparing effect"

What if we want to treat near the surface?



Summary

- Know how field size is defined
- Factors that affect the dose at depth relative to max dose.

1. Inverse square law → distance from source to measurement point
2. Scatter → field size
3. Attenuation → depth in water of measurement point

Next; calculate dose in a patient

Calculating dose in treatment plan.

- 1MU typically required to deliver 1cGy at dmax in water with 10x10cm field with either 100cm SSD or **100cm SAD.**
- Deliver treatments in terms of MUs, but could use time (dose rate).
- Planning system has beam model entered based on measured data
- Calculated MU per beam required to deliver required dose to patient.

Allows us to….

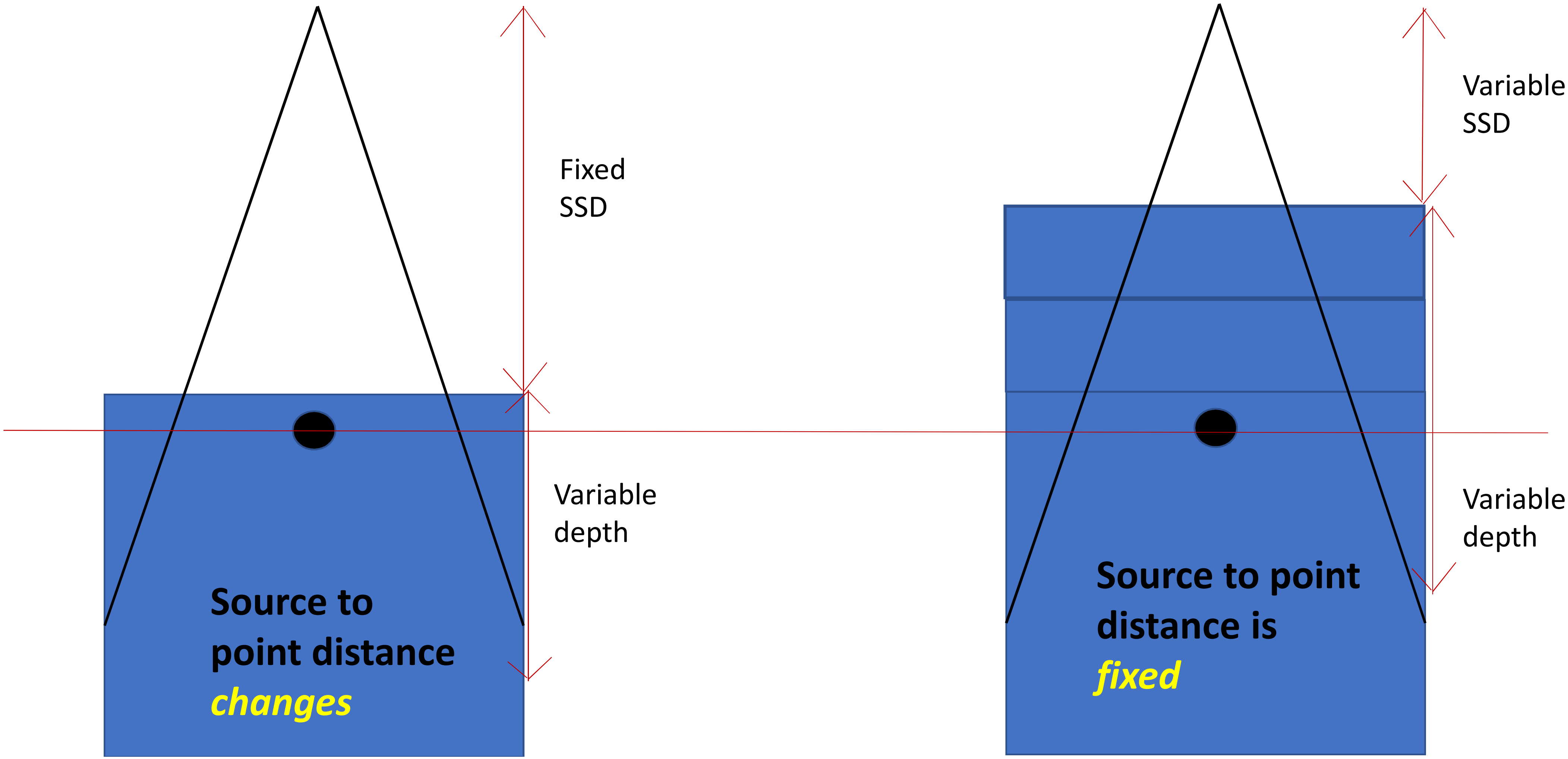
- Apply measured data to clinical dose calculations
- **To calculate the monitor-unit setting on the treatment unit that will deliver an intended dose**

What affects MUs?

- **Beam Energy**.
- **Source Surface Distance**. An increased SSD will mean that increased monitor units will be required to deliver a dose at depth due to the effects of the inverse square law.
- **Percentage Depth Dose (PDD)**. Used for **fixed source-surface distance** calculations only. The PDD describes the dose rate at different depths within a target for an equal source-surface distance. If the target is located at a different depth to the standard field, monitor units will need to be adjusted.
- **Output Factor (OF)**. The output factor is change in dose rate that occurs with different field sizes. Large fields will usually have a higher output factor, leading to increased dose rates for the same number of monitor units.
- **Wedge Factor (WF)**. Takes into account the effect of the wedge on the attenuation of the radiation beam. If a wedge is present, increased monitor units will be required to reach the same dose.
- **Tissue-Maximum Ratio (TMR)**. Used for **fixed source-axial distance calculations** only. The TMR describes the dose rate relative to a dose rate for a similar beam at a different depth within the target. This allows a monitor unit correction to take into account different depths of a target.

PDD
Percentage Depth Dose

TMR
Tissue maximum ratio



What is TMR?

- TMR is defined as the ratio of the dose at a given point in a "phantom" to the dose at the same point at the reference depth of maximum dose.
- TMR has **no inverse square law correction** as distance between source and measurement is **fixed** and only depth changes.
- Unlike PDD, where both depth of measurement and distance from source change.
- It is easier to calculate dose changes.

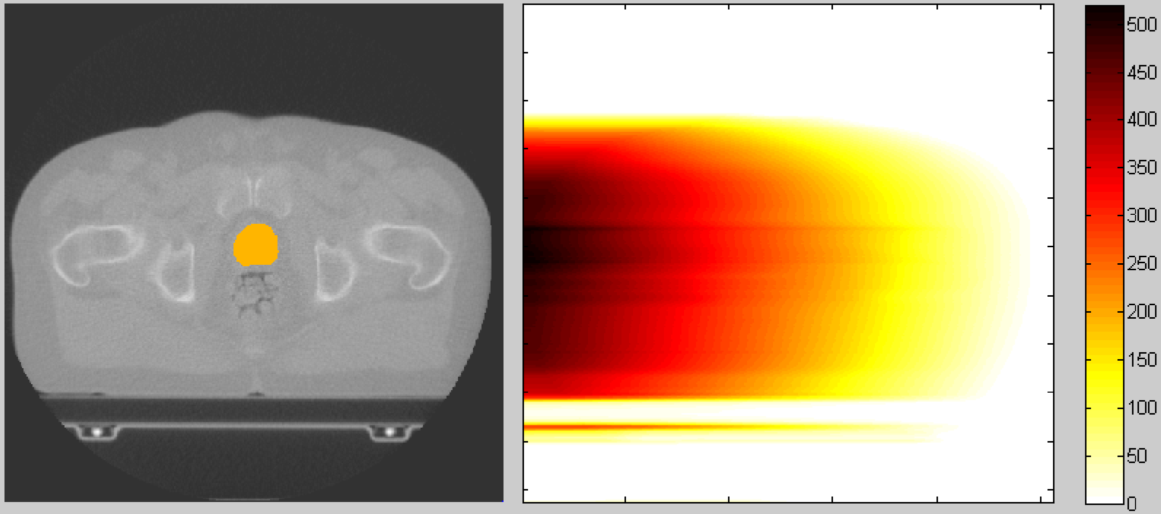
- WHY do we care???

Dose calculation: Water equivalent path length or ‘radiological path length’

The attenuation coefficients for Compton scattering depend on electron density (the number of electrons per unit volume). Electron density is usually quoted relative to water $\rho_{e,w}$

Integrating $\rho_{e,w}$ with respect to distance travelled along the ray from the source of radiation to a point of interest, gives “effective depth” d_{eff}

This can be used to calculate a “correction factor” (*CF*) to correct for the fact that patients are not water



Pt CT image and HUs

HU converted to WEPL, colour relates to increased length of water in that pixel. (mm)

$$CF = \frac{Dose}{Dose\,if\ water} = \frac{TMR(d_{eff}, S)}{TMR(d, S)}$$

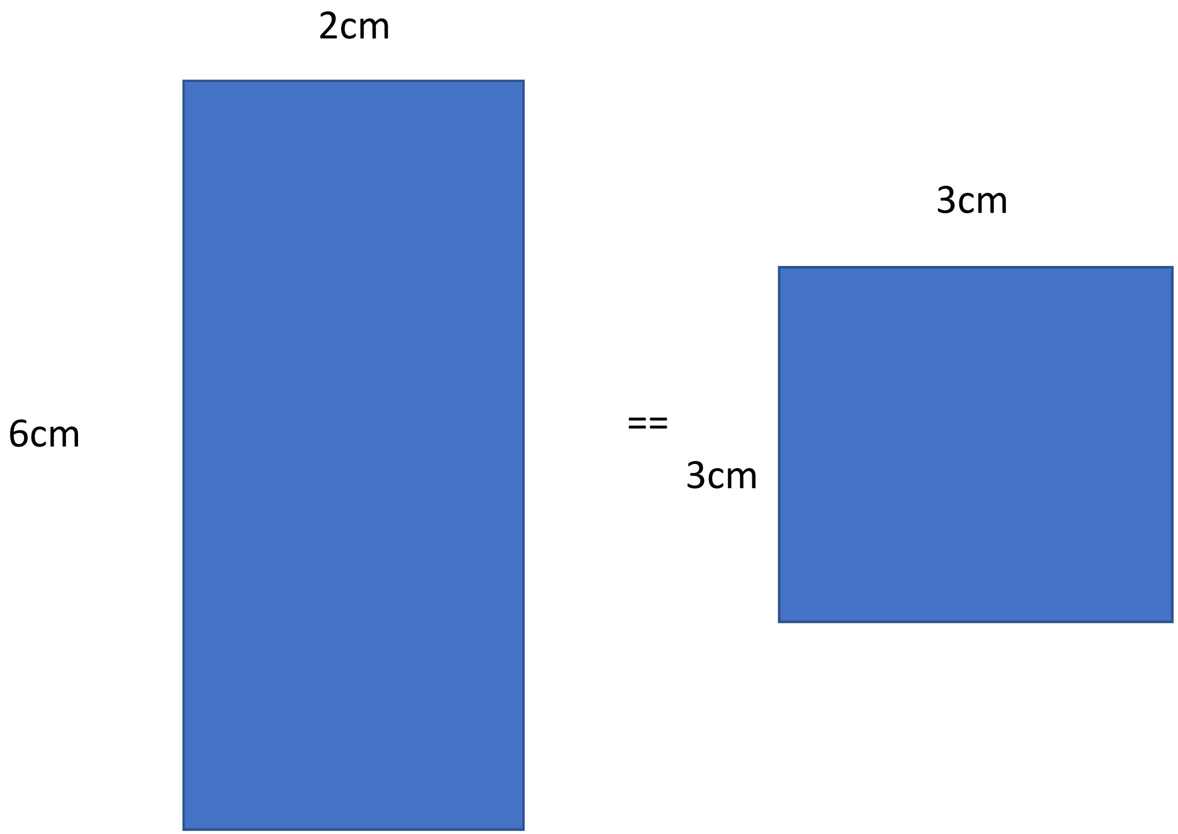
*It does **not** work with PDD, since PDD contains the inverse square as well as the attenuation.*

Equivalent square

$$\frac{ab}{2(a+b)} = \frac{{a_{\mathrm{eq}}}^2}{4a_{\mathrm{eq}}}$$

or

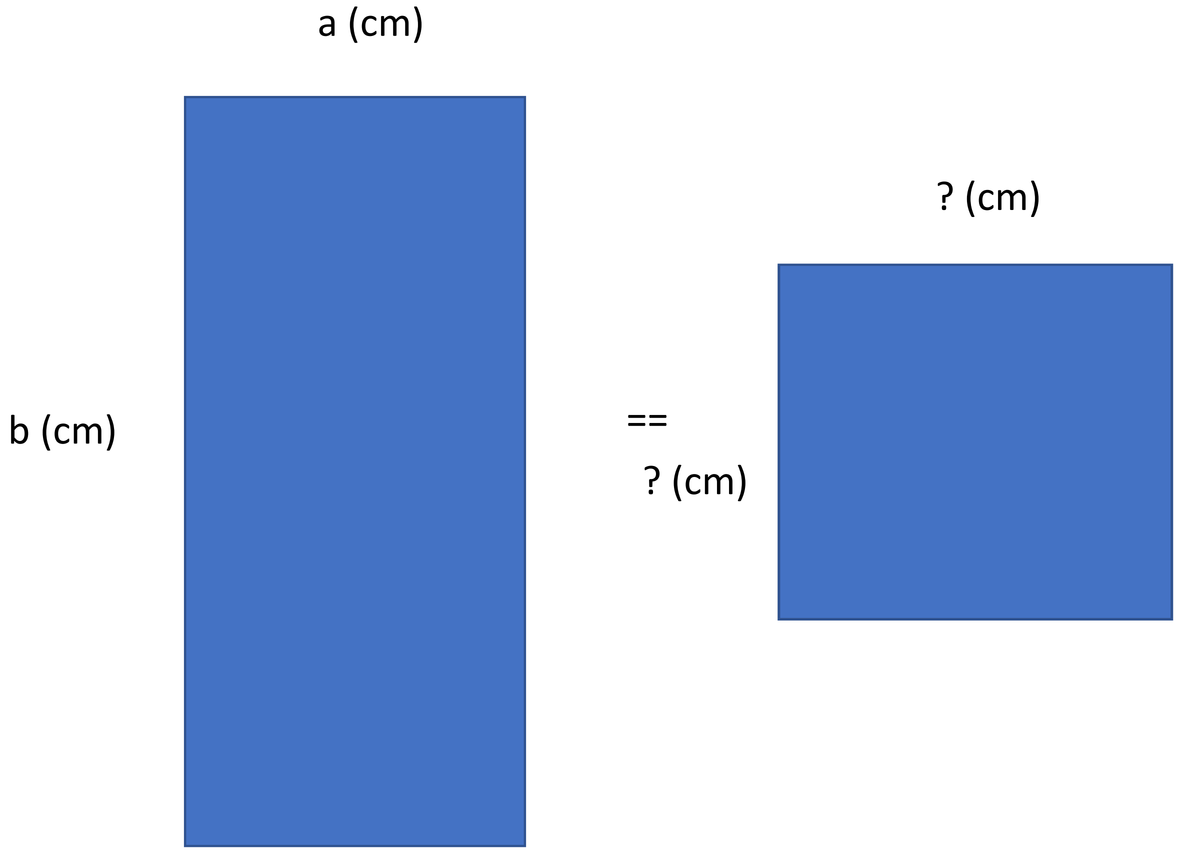
$$a_{\mathrm{eq}} = \frac{2ab}{a+b}$$



Example: The equivalent square to a field with dimensions 2 cm x 6 cm has a side (a_{sq}) 3 cm

Using multi-leaf collimators, a complex field shape is delivered with an area of 76 cm^2 and a perimeter of 51 cm. What is the equivalent square field?

- Area = 76cm
- Perimeter = 51cm



SAD or Isocentric (most common nowadays)

Dose = MU * TMR * Output factor * Wedge factor

$$MU = \frac{\text{prescribed dose (cGy)}}{OF \times TMR \times WF}$$

As Isocentric, distance from source to prescription point is 100cm, and this is the same as the calibration point distance so no need to inverse square law correction.

Typical linac calibration: 1MU = 1cGy (100 SAD, 10x10, dmax)

Example

$$\text{MU per field} = \frac{\text{prescribed dose (cGy)}}{\text{OF} \times \text{TMR} \times \text{WF}}$$

2 opposed fields of equal weight (50%)
60Gy in 30 fractions to midline, 15cm deep, 6MV
10x10 cm fields
No wedges

OF = 1.0; WF = 1.0
TMR = 0.650 (from reference data table)
Total MU = 6000 / (1.0 x 0.65 x 1.0) = 9231
Each field = 4615MU to deliver entire treatment
Each field per fraction = 154 MU

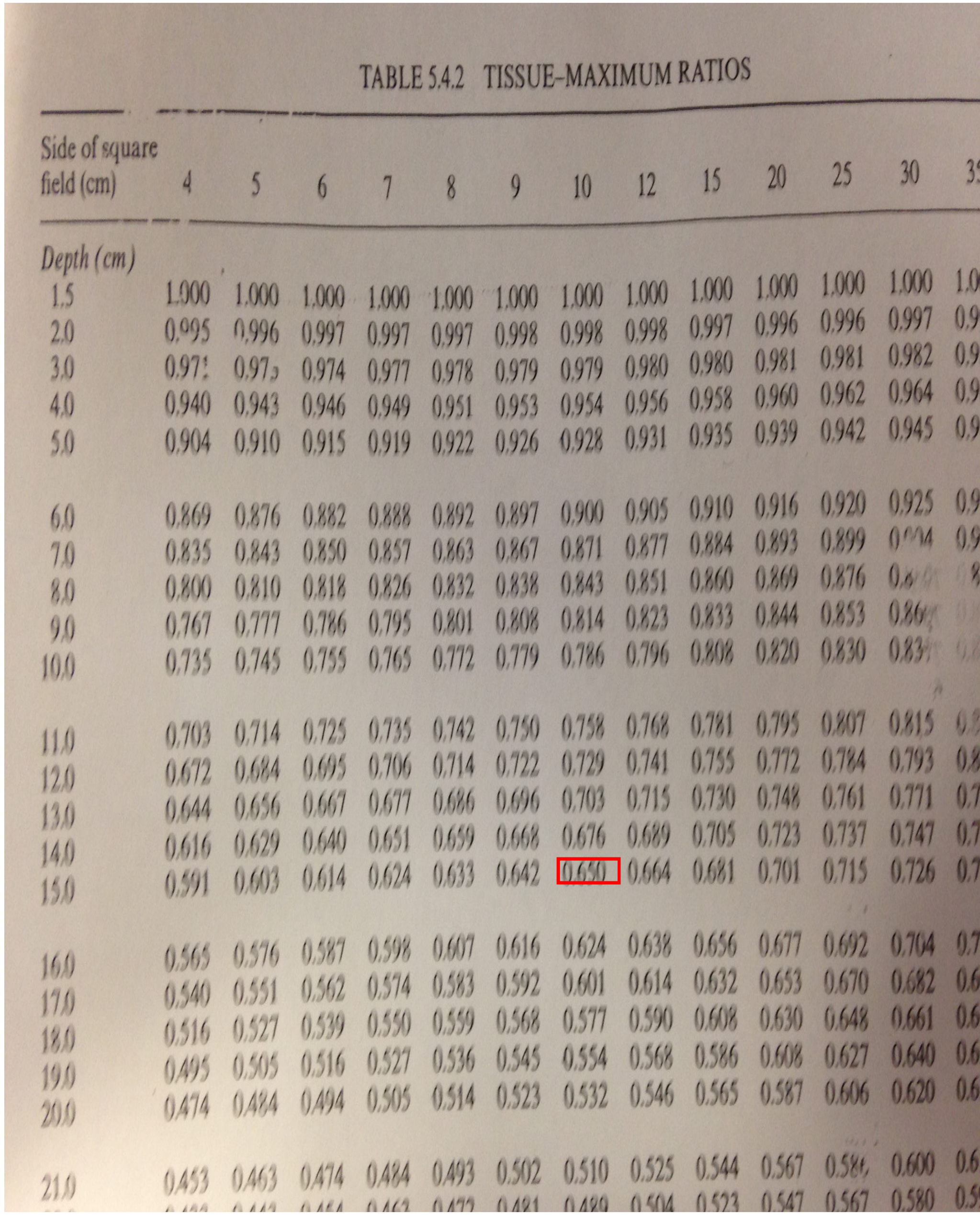


TABLE 5.4.2 TISSUE-MAXIMUM RATIOS

Side of square field (cm)	4	5	6	7	8	9	10	12	15	20	25	30
Depth (cm)												
1.5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2.0	0.995	0.996	0.997	0.997	0.997	0.998	0.998	0.998	0.997	0.996	0.996	0.997
3.0	[illegible]	[illegible]	0.974	0.977	0.978	0.979	0.979	0.980	0.980	0.981	0.981	0.982
4.0	0.940	0.943	0.946	0.949	0.951	0.953	0.954	0.956	0.958	0.960	0.962	0.964
5.0	0.904	0.910	0.915	0.919	0.922	0.926	0.928	0.931	0.935	0.939	0.942	0.945
6.0	0.869	0.876	0.882	0.888	0.892	0.897	0.900	0.905	0.910	0.916	0.920	0.925
7.0	0.835	0.843	0.850	0.857	0.863	0.867	0.871	0.877	0.884	0.893	0.899	[illegible]
8.0	0.800	0.810	0.818	0.826	0.832	0.838	0.843	0.851	0.860	0.869	0.876	[illegible]
9.0	0.767	0.777	0.786	0.795	0.801	0.808	0.814	0.823	0.833	0.844	0.853	[illegible]
10.0	0.735	0.745	0.755	0.765	0.772	0.779	0.786	0.796	0.808	0.820	0.830	[illegible]
11.0	0.703	0.714	0.725	0.735	0.742	0.750	0.758	0.768	0.781	0.795	0.807	0.815
12.0	0.672	0.684	0.695	0.706	0.714	0.722	0.729	0.741	0.755	0.772	0.784	0.793
13.0	0.644	0.656	0.667	0.677	0.686	0.696	0.703	0.715	0.730	0.748	0.761	0.771
14.0	0.616	0.629	0.640	0.651	0.659	0.668	0.676	0.689	0.705	0.723	0.737	0.747
15.0	0.591	0.603	0.614	0.624	0.633	0.642	$\boxed{0.650}$	0.664	0.681	0.701	0.715	0.726
16.0	0.565	0.576	0.587	0.598	0.607	0.616	0.624	0.638	0.656	0.677	0.692	0.704
17.0	0.540	0.551	0.562	0.574	0.583	0.592	0.601	0.614	0.632	0.653	0.670	0.682
18.0	0.516	0.527	0.539	0.550	0.559	0.568	0.577	0.590	0.608	0.630	0.648	0.661
19.0	0.495	0.505	0.516	0.527	0.536	0.545	0.554	0.568	0.586	0.608	0.627	0.640
20.0	0.474	0.484	0.494	0.505	0.514	0.523	0.532	0.546	0.565	0.587	0.606	0.620
21.0	0.453	0.463	0.474	0.484	0.493	0.502	0.510	0.525	0.544	0.567	[illegible]	0.600

Fixed SSD

(direct fields – often used in palliative treatments, e.g. cord compression)

$$MU = \frac{\text{prescribed dose (cGy) X SSD}}{OF \times PDD \times WF}$$

10Gy in 1 fraction prescribed to 5cm deep

6MV

Single field 13.3 x 8 cm

SSD = 100 cm

No wedge

How many MU?

Eq square ≈ 10 cm

OF = 1

PDD = 86.9 (from reference data table)

MU = 1151 MU

6MV PDD table

6 MV X-rays
$D_{10} = 67.5\%$
$d_{80} = 6.7$ cm

TABLES 5.4

TABLE 5.4.1 PERCENTAGE DEPTH DOSES: 100 cm SSD

Side of square field (cm)	4	5	6	7	8	9	10	12	15	20	25	30	35
NPSF	0.979	0.983	0.987	0.990	0.994	0.997	1.000	1.006	1.013	1.023	1.029	1.033	1.037
Depth (cm)													
1.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2.0	98.5	98.6	98.7	98.7	98.8	98.8	98.8	98.8	98.7	98.6	98.6	98.7	98.7
3.0	94.3	94.5	94.7	94.9	95.0	95.1	95.1	95.2	95.2	95.3	95.3	95.4	95.4
4.0	89.6	89.9	90.2	90.5	90.7	90.9	91.0	91.2	91.4	91.5	91.7	91.9	92.0
5.0	84.6	85.2	85.7	86.1	86.4	86.7	$\boxed{86.9}$	87.2	87.5	87.9	88.2	88.5	88.7
6.0	[illegible]	80.6	81.2	81.7	82.1	82.5	82.8	83.2	83.7	84.2	84.6	85.0	85.3
7.0	[illegible]	76.2	76.8	77.5	78.0	78.4	78.8	79.3	79.9	80.7	81.2	81.6	81.9
8.0	[illegible]	71.9	72.7	73.4	74.0	74.5	74.9	75.6	76.3	77.1	77.7	78.2	78.6
9.0	66.9	67.8	68.7	69.4	70.1	70.6	71.1	71.9	72.7	73.7	74.4	75.0	75.4
10.0	63.0	64.0	64.9	65.7	66.4	67.0	67.5	68.4	69.3	70.4	71.1	71.7	72.2
11.0	59.3	60.3	61.3	62.1	62.8	63.5	64.0	65.0	66.0	67.2	68.0	68.6	69.1
12.0	55.8	56.9	57.8	58.7	59.4	60.1	60.7	61.7	62.8	64.1	65.0	65.7	66.2
13.0	52.6	53.7	54.6	55.5	56.3	57.0	57.6	58.6	59.8	61.2	62.1	62.8	63.4
14.0	49.5	50.6	51.6	52.4	53.2	53.9	54.5	55.6	56.8	58.2	59.2	59.9	60.5
15.0	46.7	47.7	48.7	49.5	50.3	51.0	51.7	52.8	54.0	55.5	56.5	57.3	57.9
16.0	43.9	44.9	45.9	46.7	47.5	48.2	48.9	50.0	51.3	52.8	53.9	54.7	55.3
17.0	41.3	42.3	43.3	44.2	45.0	45.7	46.3	47.4	48.7	50.3	51.4	52.3	52.9

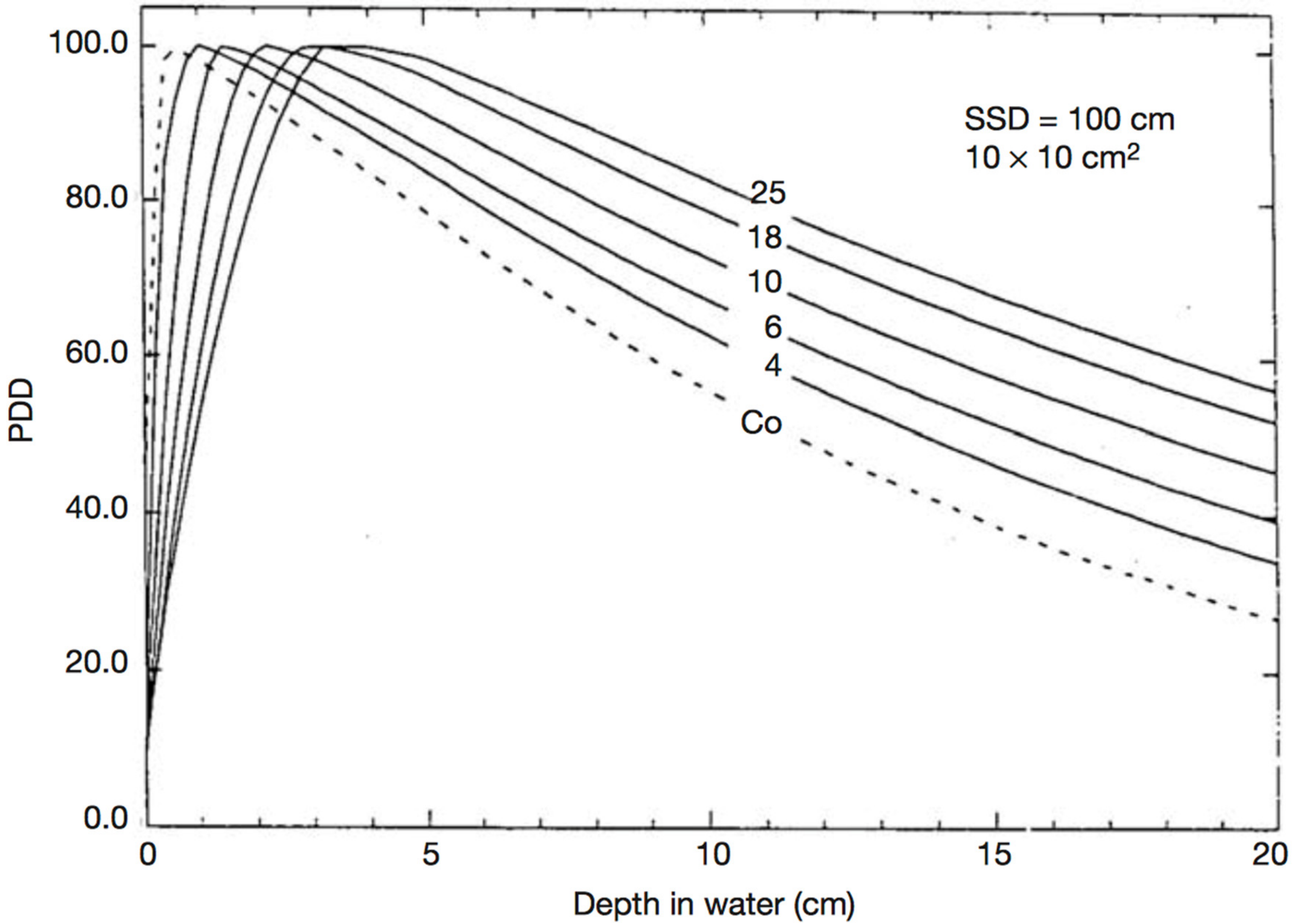
Thank you

(e) Explain why increasing the x-ray energy from 6 MV to 20 MV will result in a higher dose to the midline of the body but a lower dose to the skin.

[4]

(f) Sketch, with labelled axes, the percentage depth dose curves for these two beams. Identify and give reasons for any differences.

[3]



SSD = 100 cm
10 × 10 cm²
25
18
10
6
4
Co
PDD
100.0
80.0
60.0
40.0
20.0
0.0
0
5
10
15
20
Depth in water (cm)