Chapter 11-12
Treatment Planning: Single Beams, Combination of Beams

Radiation Dosimetry I

Text: H.E Johns and J.R. Cunningham, The physics of radiology, 4th ed.

http://www.utoledo.edu/med/depts/radther

Patient dose calculation

- The aim of treatment planning is to find the beam arrangement that provides the adequate radiation dose to the tumor while sparing surrounding normal tissues
- Terms used in treatment planning:
  - Reference dose (normalization point, calculation point)
  - Tumor dose
  - Skin (entrance) dose, exit dose

Patient dose calculation

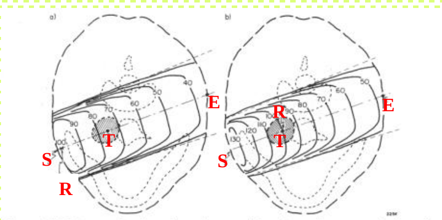
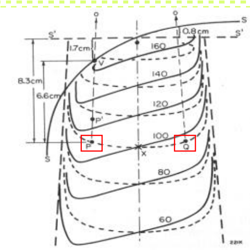


Figure 11-1. Diagrams showing a beam from a cobalt unit treating a tumor in the region of the tonsil. (a) is for a fixed SSD technique and (b) is for an isocentric technique.

- Reference dose: R
- Tumor dose: T
- Skin dose: S; Exit dose: E

Effect of the curved contour surface

Figure 11-2. An isodose chart for a 10 × 10 field from a cobalt unit. The dashed lines are as determined in a water phantom. The solid lines show the distortion of the isodose pattern produced by the curved contour surface.



- Isodose lines are shifted on one side due to "missing" tissue
- Need to correct for curved contour surface

Correction for curved contour surface

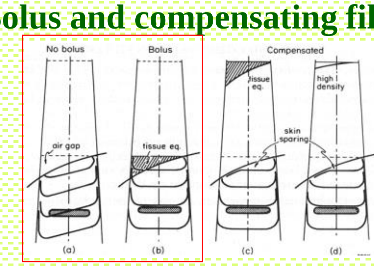
- *Effective attenuation coefficient method*: based on data in Table 11-1 (Co-60) dose to P should be increased and to Q decreased by Δd x 5% (no general account for FS)
  - *The ratio of tissue-air ratios method*: take ratios of TAR's at proper depths; takes into account FS
  - *The effective SSD method*: adjust the dose by the inversed square law ratio
  - These approaches do not account for changes in scatter

TABLE 11-1
Parameters Useful in Correcting Isodose Patterns for Air Gaps

Radiation	SSD (cm)	Attenuation (per cm)	k
x rays up to 1 MV	50	10%	0.8
cobalt 60	80	5%	0.67
x rays from 1 to 5 MV	100	4%	0.7
x rays from 5 to 15 MV	100	3%	0.6
x rays from 15 to 30 MV	100	2%	0.5
x rays above 30 MV		2%	0.4

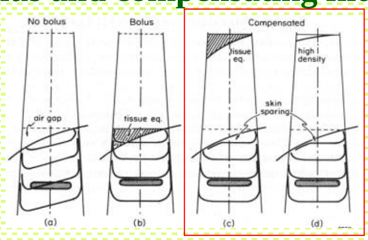
Derived from data for 10 × 10 cm fields. Values for k taken from van der Giessen (V4).

Bolus and compensating filters



- Shape of isodose curves can be preserved with use of tissue-equivalent bolus
- For high energy beams use of bolus prevents skin sparing

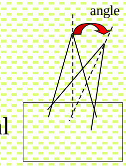
Bolus and compensating filters



- Compensating filter of the same shape can be placed at some distance from the skin
- The filter introduces scatter, and can truly compensate at only one depth

Oblique incidence

- Skin doses increases with increasing angle of incidence
- The depth of maximum buildup decreases
- The dose build-up region is compressed into a more superficial region: skin reactions



Example 1

- Which of the following is false? The skin dose, as a percentage of dose at d_{max} in a 6 MV photon beam will increase when:

A. The SSD is decreased.
B. The field size is decreased.
C. Bolus is used.
D. Fields are treated at oblique incidence

Wedge filters

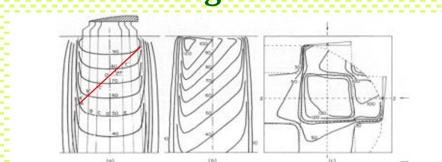


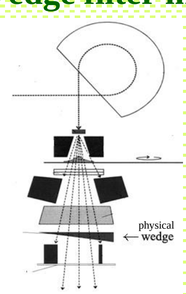
Figure 11-9. (a) Diagram to illustrate the design of a wedge filter to tilt the isodose lines through 45° for an 8 × 8 cm beam from a cobalt unit. (b) Isodose chart for the wedge of a. (c) Dose distribution produced by combining two wedged beams at right angles to produce a region of uniform dose.

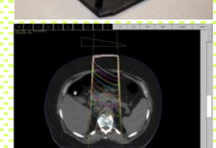
- Specially shaped isodose curves utilize wedges
- Wedge thickness x at each point can be calculated based on the amount of attenuation needed to reduce the dose: $D'/D = e^{-\mu x}$
- Need to account for scatter effectively reducing the angle

Wedge filter implementations

- Hard wedge: set of fixed wedge angles
- Motorized (universal) wedge: physical wedge of the largest wedge angle (steepest gradient) combined with open beam to produce the required isodose tilt
- Dynamic or Virtual wedge: fluence gradient across the beam is produced by progressively moving one of the collimator jaws across the treatment field during the exposure. The amount of MU's can also be varied during the treatment

Wedge filter implementations





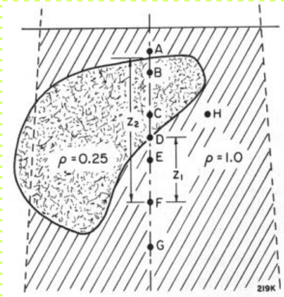
Images from: http://www.posterus.sk; http://titan.radonc.unc.edu/dose/

Example 2

- A field with an effective wedge angle of 30 degrees could be achieved by all of the following except:

  A. Combining open and 60-degree wedged fields for equal doses at the isocenter.
  B. Combining open and 60-degree wedged fields for equal MUs
  C. A Universal wedge, combining wedged and open fields.
  D. A dynamic wedge.
  E. A custom compensator.

Dose corrections for inhomogeneities



- Dose at all points will be altered due to the presence of inhomogeneity
- Two factors:
  - Change in primary fluence due to change in attenuation
  - Change in scatter contribution

Dose corrections for inhomogeneities

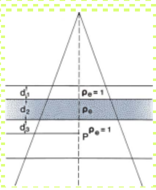
- Use methods similar to correction for curved surfaces
- In TAR correction method introduce dose correction factor for a field size r_d:

$$C = T_a(d', r_d)/T_a(d, r_d)$$

- The equivalent thickness

$$d' = d_1 + \rho_e d_2 + d_3$$

density ρ_e is relative to water



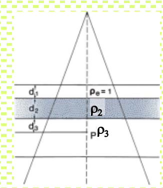
Dose corrections for inhomogeneities

- More accurate correction factor takes into account the proximity of the inhomogeneity (power law method):

$$C = \frac{T_a(d_3, r_d)^{\rho_3 - \rho_2}}{T_a(d_2 + d_3, r_d)^{1-\rho_2}}$$

ρ_3 is the density of the material in which the point lies

ρ_2 is the density of the overlying material



Dose corrections for inhomogeneities

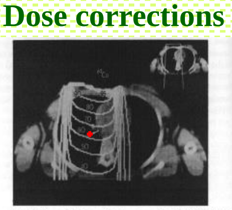


Figure 11-7. A CT image of the chest with isodose curves for a 12 × 10 beam from a cobalt unit superimposed. The placement of the beam is shown in the insert. The isodose curves have been obtained by allowing for the curvature of the patient's anterior surface but neglecting the structures inside of the chest.

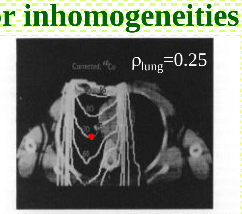


Figure 11-8. The isodose distribution of Figure 11-7 corrected for the tissue inhomogeneities of the chest. Eight CT images were used and dose correction factors were obtained using equations 11-3 and 11-4.

- Effective TAR method: $C = T_a(d', \hat{r})/T_a(d, r)$
- Equivalent circular field size $\hat{r} = r \cdot \hat{\rho}$ is scaled to allow for the way the scattering structures are configured around the point with effective density $\hat{\rho}$

Energy absorption in biological material

In electronic equilibrium condition dose in tissue can be calculated based on the dose measured in a phantom

$$D_{tis} = D_{wat} \cdot (\bar{\mu}_{ab}/\rho)^{tis}_{wat}$$

TABLE 11-2

Values of $(\bar{\mu}_{ab}/\rho)^{tis}_{wat}$ for Muscle, Fat, and Bone and $(\bar{\mu}_{ab}/\rho)^{mus}_{med}$ for Polystyrene, Lucite, and A150 Tissue-Equivalent Plastic Determined Using Equation 7-12 for the Photon Spectra Listed in Table 7-2

Photon Spectrum	$(\bar{\mu}_{ab}/\rho)^{tis}_{wat}$			$(\bar{\mu}_{ab}/\rho)^{mus}_{med}$		
	Muscle	Fat	Bone	Polystyrene	Lucite	A150
1. 60 kV_p	1.040	0.607	4.796	2.617	1.687	1.176
2. 100 kV_p	1.035	0.653	4.409	2.227	1.572	1.085
3. 250 kV_p	0.995	0.973	1.294	1.071	1.051	1.004
4. 270 kV_p	0.997	0.964	1.391	1.089	1.062	1.008
5. 270 kV_p	1.011	0.861	2.486	1.317	1.194	1.038
6. 400 kV_p	0.994	0.988	1.098	1.044	1.034	1.003
7. ^{137}Cs	0.991	1.000	0.957	1.023	1.020	1.001
8. ^{60}Co	0.992	1.001	0.954	1.024	1.049	1.002
9. ^{60}Co	0.992	0.996	0.995	1.029	1.024	1.002
10. 6 MV	0.991	0.998	0.959	1.026	1.021	1.003
11. 8 MV	0.990	0.995	0.962	1.028	1.022	1.005
12. 12 MV	0.990	0.987	0.979	1.039	1.029	1.014
13. 18 MV	0.989	0.980	0.993	1.047	1.033	1.022
14. 26 MV	0.989	0.973	1.004	1.055	1.038	1.029
15. 26 MV	0.990	0.981	0.991	1.047	1.034	1.022
16. 35 MV	0.989	0.965	1.019	1.068	1.044	1.039
17. 45 MV	0.989	0.961	1.027	1.073	1.047	1.044

Energy absorption in biological material

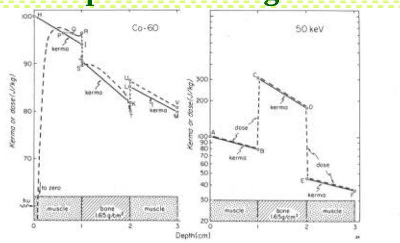


Figure 7-13. Diagram showing kerma and dose in a composite phantom irradiated from the left by cobalt 60 radiation and 50 keV radiation.

- Dose discontinuities at the interfaces with bone and air are the largest for the kV energy range

Dose corrections for inhomogeneities

- The greatest attenuation difference occurs:
  - For the lowest energy
  - For the greatest density difference

Material	Density, g/cm^3
Water	1
Muscle	1.04
Bone	1.65
Fat	0.916
Lung	0.25

Densities of biological materials

Example 3

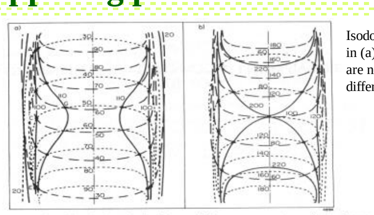
- If heterogeneity corrections are ***not*** done, which of the following is likely to give the greatest discrepancy between calculated and actual dose at a point on the beam axis beyond the heterogeneity?

Medium	Thickness	Photon energy
A. Lung	10 cm	6 MV
B. Lung	10 cm	18 MV
C. Fat	10 cm	6 MV
D. Dense bone	5 cm	6 MV
E. Dense bone	5 cm	18 MV

Combination of beams

- Achieve high dose conformity to the target
- Spare healthy surrounding tissues
- Several general approaches:
  - Opposing pairs of beams and their combination
  - Angled fields and wedge pairs
  - Rotation therapy

Opposing pairs of beams

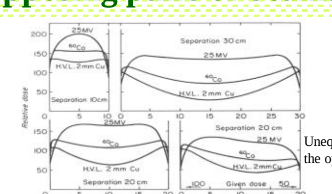


Isodose lines in (a) and (b) are normalized differently

Figure 12-1. Isodose distribution obtained by combining two opposing radiation beams. Both are for 10 × 10 cm beams of cobalt radiation and the entrance surfaces are separated by 20 cm. (a) Fixed source-skin distance with dose values expressed relative to 100 at the maximum of each beam. (b) Isocentric arrangement with dose values expressed relative to 100 midway between the surface from each beam.

- The simplest combination of two fields is achieved by directing them along the same axis from opposite sides

Opposing pairs of beams



Unequal dose to the opposing fields

Figure 12-2. Dose along the axis for 2 opposing 6 × 8 cm fields, for separations of 10, 20, and 30 cm, 25 MV radiation at SSD 100 cm; cobalt 60 at SSD 80 cm; 200 kV radiation, HVL 2.0 mm Cu SSD 50 cm. The 3 symmetrical diagrams were calculated for given doses of 1 Gy to both fields, while the graph in the lower right hand corner results when the given doses are 1 Gy to the left and 0.5 Gy to the right.

- The variation in dose along the axis of opposing pair of beams depends on the field separation and beam energy
- It can be made very small, yielding an almost uniform dosage from one beam entrance to the other

Opposing pairs of beams

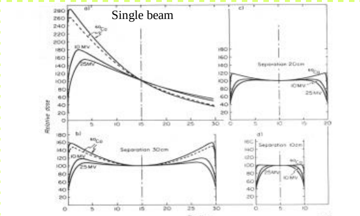


Figure 12-3. Relative dose for 10 × 10 cm beams of cobalt, 10 MV and 25 MV radiation. (a) Single beams with doses normalized at a depth of 15 cm. The dashed line for cobalt is for SAD = 100 cm, the solid line is for SAD = 80 cm. (b) As in a but an opposing beam is added with a separation of 30 cm. (c) and (d) Opposed beams with separations of 20 and

- An arrangement often used for treatment of a tumor situated approximately midway between two parallel surfaces
- High energy beams must be used to avoid the dip in the middle

Opposing pairs of beams

- For small separations (<10 cm) low MV energy beams are well suited: extended region of uniform dose with relatively flat plateau between the maxima
- For larger separations (>15cm) high energy beam are required to avoid hot spots in the regions of both maxima
- Many anatomical sites can adequately be treated with parallel-opposed beams (lung, brain, head and neck lesions)

Opposing pairs of beams

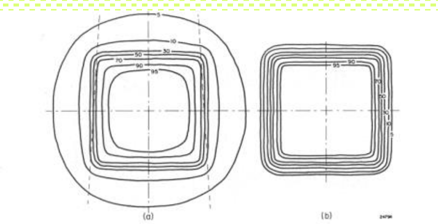


Figure 12-4. Isodose distributions in planes perpendicular to the axis of opposing fields of (a) cobalt-60 and (b) 25 MV radiations. The beams are isocentric, 10 × 10 cm and the separation is 20 cm.

- A uniform "box" coverage is achieved in planes perpendicular to the axis of opposing fields

Opposing pairs of beams

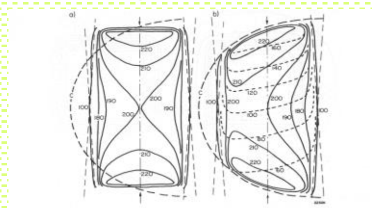


Figure 12-5. Opposed pairs of beams from a cobalt unit. The diagram on the left is similar to Figure 12-1b. The distribution on the right has been corrected for contour shape, the dashed curves being the distribution from the top beam corrected for patient contour as discussed in section 11.02.

- In practice the isodose distribution is altered by curved surfaces and has to be properly adjusted (blocks, etc.)

Combination of opposing pairs

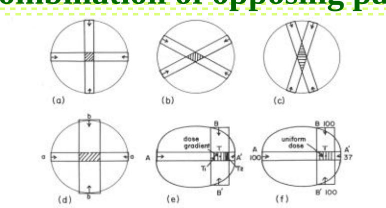
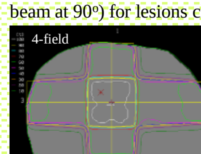


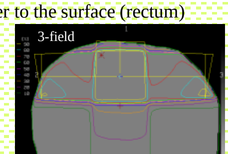
Figure 12-6. Schematic diagram showing possible arrangement of fields. (a) Two opposing pairs at right angles. (b) Two opposing pairs at 120°. (c) Two opposing pairs at 35°. (d) Two opposing pairs of different widths at right angles. (e) Two opposing pairs at right angles treating an off-center tumor. (f) Two opposing pairs at right angles treating an off-center tumor with field A' being given 37% of the amount given the other fields.

- Using setup at different angles, equal or unequal width, and beam intensities, can achieve conformity to the tumor shape/depth

Combination of opposing pairs

- Allows for higher dose in the beam intersection region
- Four-field box (two opposing pairs at 90^{o} angle) used most often for treatment of pelvis with centrally located lesions (prostate, bladder, uterus)
- Three-field box (two wedged opposing beams and 3rd beam at 90^{o}) for lesions closer to the surface (rectum)





Split fields

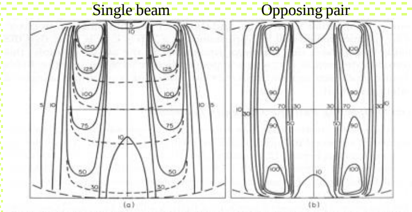


Figure 12-10. Dose distributions for split fields produced by blocking off the central portion of 12 × 10 cm cobalt 60 fields. The block is made of Pb, is 5 cm (approx. 5 HVL) thick, and blocks a region 5 cm wide at the isocenter. The SAD is 80 cm. (a) Single field with isodose curves for unblocked field shown as dashed lines. (b) Opposing pair.

- Can be used to protect sensitive critical structures in the middle of the field

Angled fields and wedge pairs

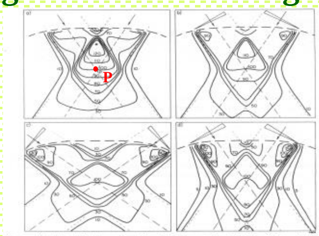
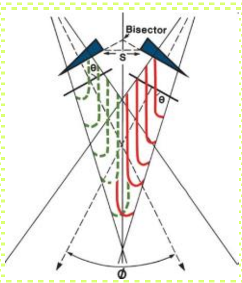


Figure 12-11. Angle fields produced by 6 × 6 beams of cobalt-60 radiation. (a) Beams at 30° from vertical and crossing at point, P, 7 cm below the contour surface. (b) Same as a but with 45° wedge filters added. (c) Same as b but angle increased to 50°. (d) Same as b but with 60° wedges.

- Often used for irradiation of a small tumor through the same skin surface
- Although the fields are directed towards the point P, the high dose region occurs much nearer the surface, therefore the beams should be aimed considerably below P ("past pointing")

Angled fields and wedge pairs



- Parameters of the wedge beams: θ is wedge angle, Φ is hinge angle, and S is separation
- Isodose curves for each wedge field are parallel to the bisector
- An optimum relationship between the wedge angle θ and the hinge angle Φ that provides the most uniform distribution of radiation dose in the plateau:

$$\theta = 90^o - \Phi / 2$$

Three field technique

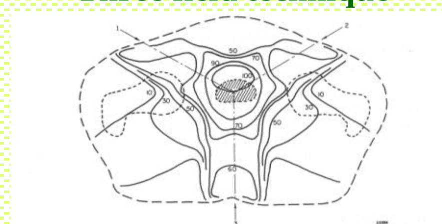
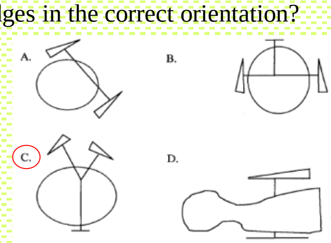


Figure 12-12. Isodose distribution for three 6 × 6 cobalt 60 beams at SAD 80 cm directed toward a bladder tumor. The beams are symmetrically arranged at 120° to each other.

- Provides better dose homogeneity within the tumor
- Homogeneity can be further improved with tissue compensators

Example 4

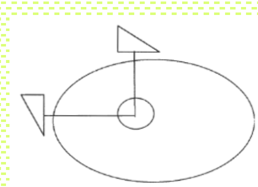
- Which one of the following plans has the wedges in the correct orientation?



Example 5

- The wedge angle that would give the most homogeneous distribution in the "wedged pair" in the diagram below is ___ degrees. (Field axes are at 90°).

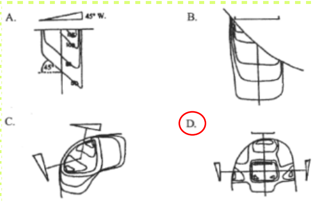
A. 10
B. 20
C. 30
D. 45
E. 60



$$\theta = 90^o - \Phi / 2 = 90^o - 45^o = 45^o$$

Example 6

- Which of the following isodose patterns is consistent with the field configurations and wedges shown?



Example 7

- In a 3-field plan to treat the rectum using open PA and wedged lateral fields, a homogeneous distribution can be obtained in the PTV with either 45° or 60° wedges. With 60° wedges, the relative dose at the isocenter for the PA field would be ___ that in the 45° wedged plan.

A. Greater than
B. Less than
C. The same as

Lateral wedges compensate for depth-dose fall-off of the PA field. The greater is the contribution from PA field, the larger is the wedge angle required

Rotation therapy

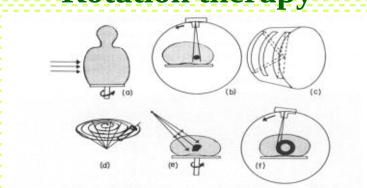


Figure 12-22. Diagrams illustrating the various types of rotation therapy.

- Provides maximum dose uniformity within the tumor and the most of healthy tissue sparing: a) patient in a rotating chair; b) source is moved around a stationary patient; c) source moves in a circular path and simultaneously transverse horizontally to cover the surface of a cylinder; d) x-ray head moves about a spiral with the beam always directed to one point below the surface; e) patient lies on a couch that rotates about a vertical axis; f) beam is offset from the axis of rotation to cover an annular ring about the center of rotation (chest wall irradiation)

Rotation therapy: isodose distributions

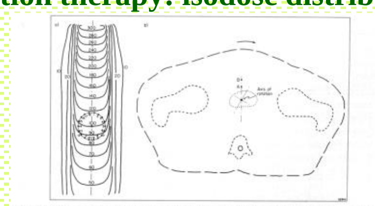


Figure 12-23. Isodose pattern for a cobalt 60 field normalized to 100 at a depth of 15 cm. Source-to-skin distance 65 cm, source-to-axis distance 80 cm, field size at axis 6 × 6 cm. The right side of the diagram shows the contour of the patient, the axis of rotation, and the points A and B at which the dose is to be determined.

- Calculations are generally based on the superposition of single beam isodose charts, with isodes lines normalized to 100% at the axis of rotation
- The total dose at a point in a patient is obtained by adding together the contributions from a series of fixed fields spaced at equal angular intervals

Rotation therapy: effect of energy

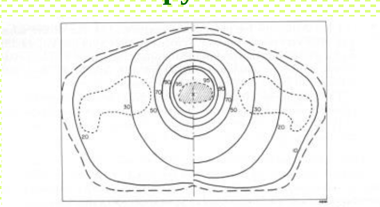


Figure 12-24. Isodose distributions for 360° rotation technique in treatment of cancer of the bladder using 6 × 6 cm field at the tumor. Left-hand side, cobalt 60 with a source-to-axis distance (SAD) of 80 cm. Right-hand side, 10 MV linear accelerator radiation, SAD = 100 cm. These isodose distributions were calculated by the method described in Example 12-6 and by Tsien et al. (T6).

- Penetration depth and skin sparing govern the choice of the beam energy

Rotation therapy: effect of arc length

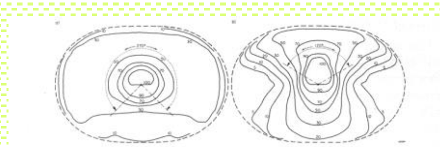
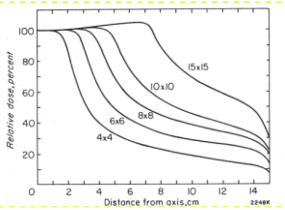


Figure 12-25. Isodose distributions for two angles of arc on an oval phantom. The one on the left is for 270° and the one on the right is for 120°. Both are for cobalt 60 radiation. The high dose region is moved toward the bisector of the arc; the smaller the arc, the greater is this shift.

- As the degree of rotation becomes less than 360°, the isodose curves are deformed in such a way that the side opposite the beam entrance surface become flatter with the decrease in the arc angle
- When the arc angle is 180° or less, the isodose curves tend to be pinched in at the sides and the lower portion again moves further from the axis

Rotation therapy: effect of field size



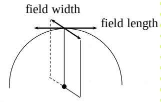


Figure 12-27. Dose profiles for 360° rotation about a 30 cm diameter cylindrical phantom for field sizes from 4 × 4 to 15 × 15 cm.

- The length of the field has a little effect, while the width has a profound effect on the isodose distribution
- Rotational therapy is not recommended if wide fields must be used, due to high dose delivered outside of the target

Comparison of fixed field and rotation therapy

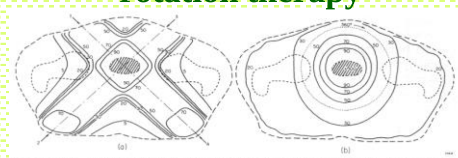


Figure 12-28. Isodose distributions for the treatment of cancer of the bladder using cobalt 60. Left side, distribution for four 6 × 6 cm fields at a source-to-axis distance (SAD) of 80 cm. Right side, rotation therapy using a 6 × 6 cm field at the tumor, also with a source-to-axis distance (SAD) of 80 cm.

- In rotation therapy the skin dose is less than with fixed field therapy (~15 vs. 40%) because rotation therapy is equivalent to using 8 to 12 fields
- The isodose curves for rotation therapy are smoother around the tumor region; with fixed fields "horns" between adjacent fields are present
- However, with fixed fields some areas can be completely spared

Comparison of fixed field and rotation therapy

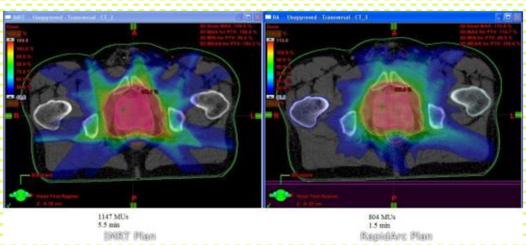


Image from: http://www.varian.com/us/oncology/treatments/treatment_techniques/rapidarc/comparison.html

Summary

- Single beam
  - Isodose distribution with depth is affected by surface contour and tissue inhomogeneities
  - Beam modifiers
- Multiple beams
  - Combination of beams allows for conformal therapy
- Rotation therapy