Monte Carlo Simulation of FFF Photon Beam in Radiotherapy

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  - Radiotherapy (3DCRT) using flattening filter
  - IMRT using MLC
  - Flattening filter free (FFF) photon beams
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- Monte Carlo simulations on FFF photon beams
  - Bone dose
  - Skin dose
  - Photon energy spectrum
  - Skin dose with cream

Radiotherapy using Medical Linear Accelerator (Linac)

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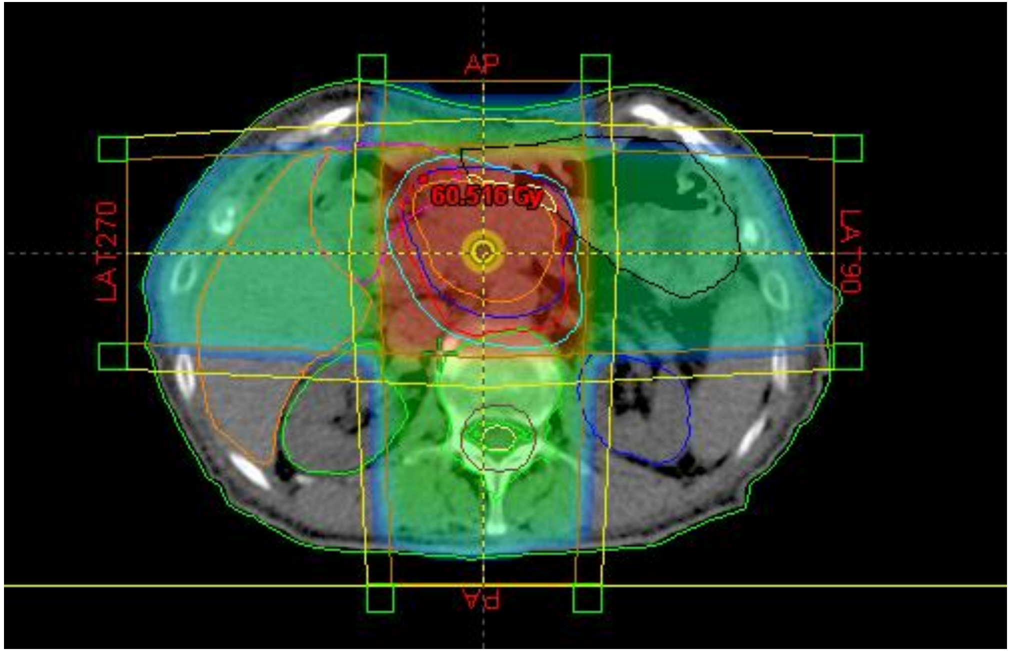
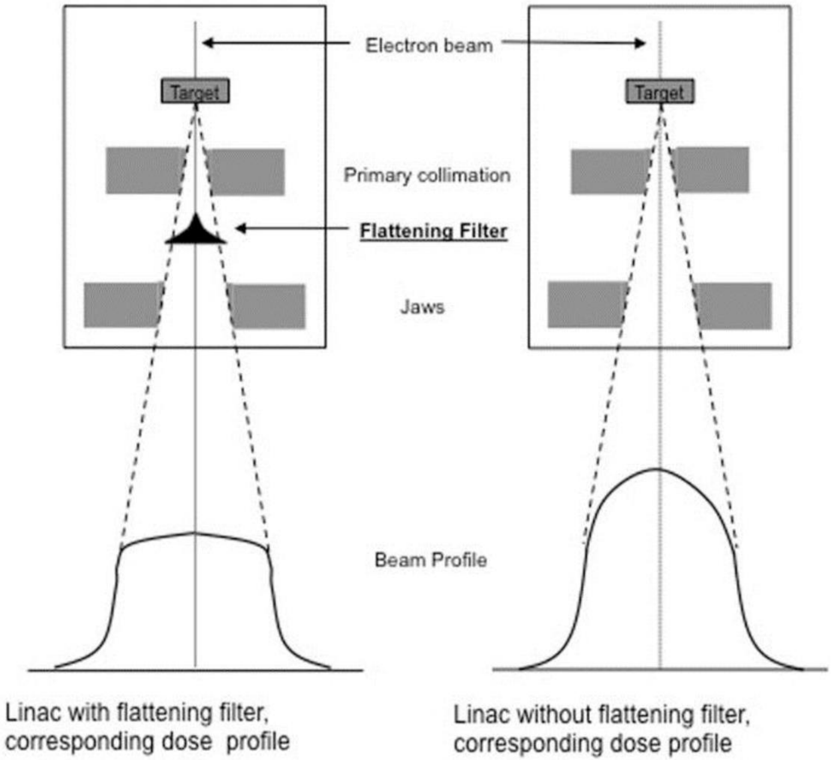
Radiotherapy using 3DCRT



https://www.researchgate.net/profile/Andrei-Fodor/publication/303605048/figure/fig1/AS:366740300156928@1464449109123

Beam Profile with Flattening Filter



https://d3i71xaburhd42.cloudfront.net/3ad871ac39d98da0a3c4d1c7cbb2fa52f73c7708/22-Figure2-1.png

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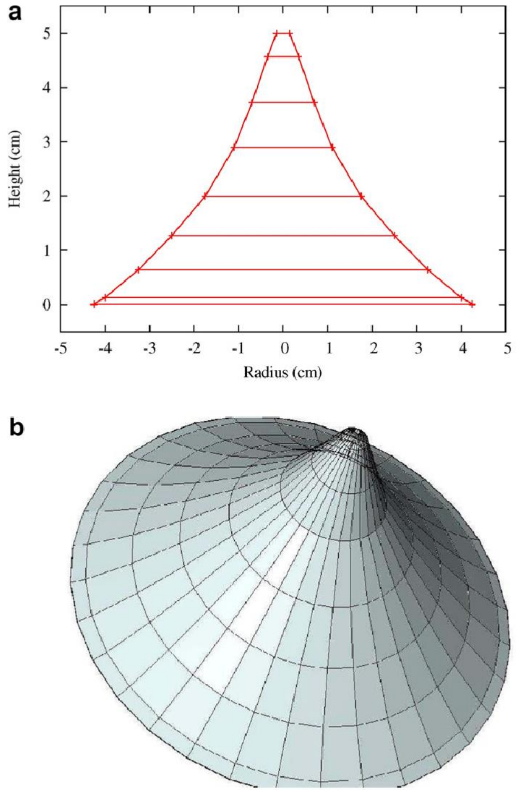
Flattening Filter - Design



Patil *et al Nuclear Instruments and Methods in Physics Research Section B*: Beam Interactions with Materials and Atoms. **269**. 3261-3265. 10.1016/j.nimb.2011.04.013.

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Flattening Filter – 6 MV

Figure 2.1 *A conventional flattening filter for a 6 MV beam (left) and the copper plate used in the flattening filter free mode (right).*

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Linac equipped with Multi-leaf Collimation (MLC)

For photon beams

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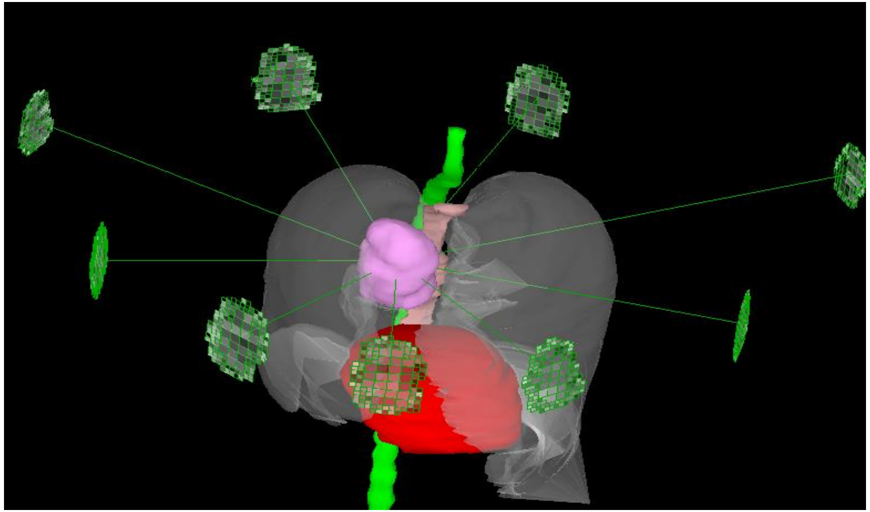
Intensity Modulated Radiotherapy (IMRT)

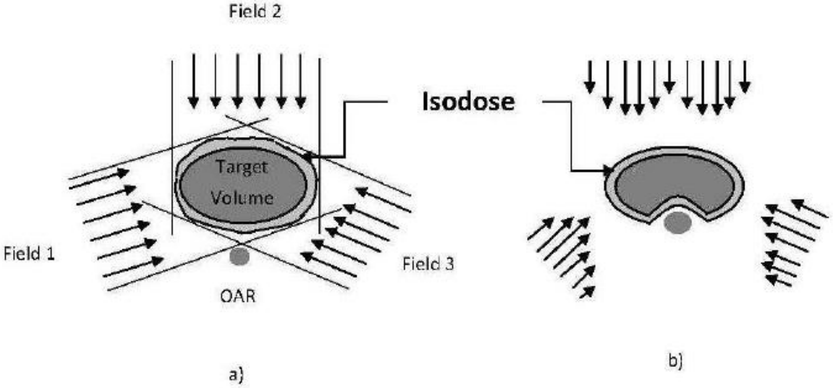
- Conventional beam intensity is either uniform, modified with a wedge or modulated by a compensating filter.

- IMRT is a more recent modality in which incident beams are modulated to improve total dose distribution by many fields.
  - Can be implemented using MLCs.
  - Each beam treats only a portion of the target
  - Can be planned by either standard "forward" or inverse iterative methods
  - Gives more degrees of freedom and potentially more conformal dose distributions than 3DCRT

IMRT – Beam Segments



https://www.researchgate.net/publication/253376946_On_the_Optimization_of_Radiation_Therapy_Planning



Radiotherapy with IMRT

- For IMRT/VMAT delivery, flattening filter is not necessary.
- We can remove the flattening filter from the Linac.

Flattening Filter Free Photon Beams

TABLE 1. Characteristics of commercially available FFF beams. All dosimetric quantities are given for a 10×10 cm^2 field at 100 cm SSD unless otherwise noted and were provided by the manufacturers.

	Varian		*Elekta*		*Siemens*			
Nominal energy (MV)	6 FFF	10 FFF	6 FFF	10 FFF	7 UF	11 UF	14 UF	17 UF
Bremsstrahlung target material	Tungsten		Tungsten		Tungsten			
Approximate mean electron energy on target (MeV)	6.2	10.5	7	10.5	8.9	14.4	16.4	18.3
Filtration	0.8 mm Brass		2mm Stainless steel		1.27 mm Al			
d_{max} (cm)	1.5	2.3	1.7	2.4	1.9	2.7	3.0	3.3
Dose at 10 cm depth (%)	64.2	71.7	67.5	73.0	68.5	74.5	76.5	78.0
Dose 10 cm from central axis (40×40 cm^2 field), at d_{max} (%)	77	60	70[a]	59[a]	68	57	-	-
Maximum dose rate on beam axis at d_{max} (cGy/min)	1400	2400	1400	2200	2000	2000	2000	2000
Dose per pulse on beam axis at d_{max} (cGy/pulse)	0.08	0.13	0.06	0.09/0.14[b]	0.13	0.13	0.13	0.13

[a] Defined at 90 cm SSD, 10 cm depth
[b] Feedback/nonfeedback machine.

Xiao et al *JACMP* 2015;**16**:12.

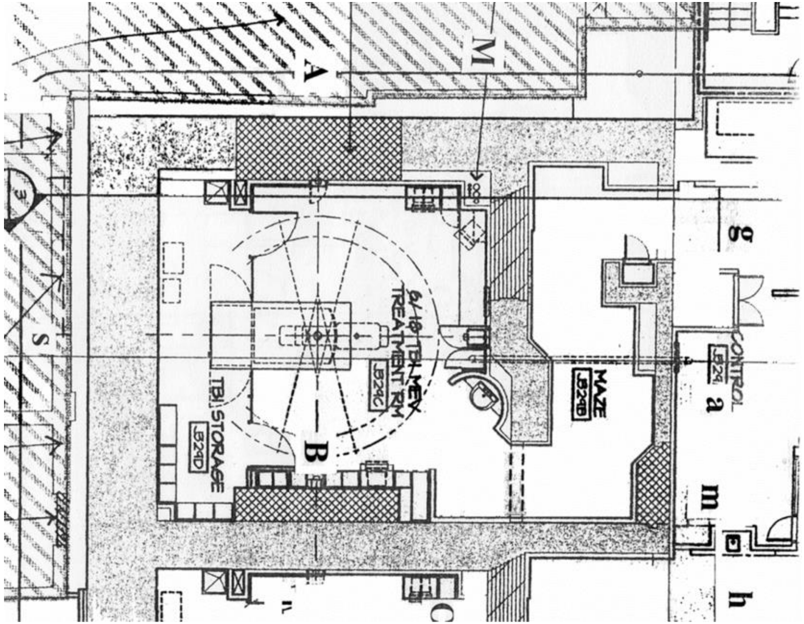
When producing a flat beam, the filter causes a series of negative effects, such as:

- Decreased primary beam intensity, leading to reduced dose rate;
- Differential absorption across the field (changes in beam spectrum) causing problems for dose calculation and beam modelling;
- The need for the introduction of ‘horns’ in the particle fluence to compensate for this angular variation of the spectrum;
- The creation of a significant source of extra-focal scattered radiation;
- Electron contamination in the primary beam;
- Increased leakage radiation from the treatment head, increasing head shielding requirements;
- Amplification of beam steering errors, necessitating the use of active beam monitoring and servo control.

Budgell et al *Phys Med Biol* 2016;**61**:8360

Radiation Protection Consideration – Bunker Design

- Primary shielding
  - Radiation workload
  - Beam energies
  - Dose rates
- Secondary shielding
  - Head leakage and scatter
  - Patient scatter
- Maze
  - Wall and patient scatter
- Occupancy of adjacent areas



Radiation Protection Consideration

- If the only expected change from an FFF beam is an increase in instantaneous dose rate, not an increase in patient dose or throughput, and if the shielding is sufficient for the energy of the machine being installed, then no further increase in primary shielding is likely to be needed for FFF. Due to the reduction in required current per MU, the secondary shielding present is also likely to be sufficient provided there is no large change in the IMRT factor.
- However use of FFF for high dose per fraction treatments may lead to a higher annual dose rate.

Budgell et al *Phys Med Biol* 2016;**61**:8360

Patient Dosimetric Concern of FFF Beam

The presence of the flattening filter removes a large number of low-energy photons and results in beam hardening. For the unflattened photon beam, however, these low-energy photons are part of the beam and contribute to the dose deposition in the photon beam build-up region close to the patient surface. Compared to the flattened photon beam, though unflattened beam has less head scatter and leakage, measurements and Monte Carlo simulations have found that irradiation of the unflattened photon beam results in a higher surface dose than the flattened beam.

Chow and Owrangi *Rep Pract Oncolo Radiother 2016;**21**:63*

Monte Carlo Simulation – based on a Linac with FF

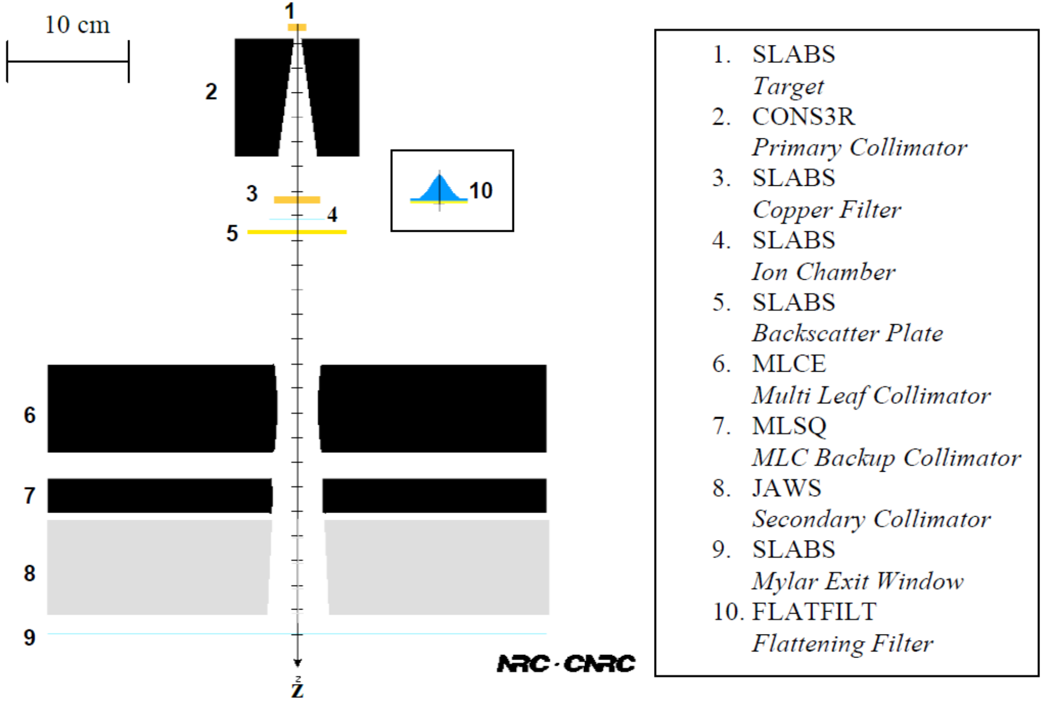


Figure 2.6 Schematic illustration of the accelerator head without flattening filter as it is seen in the xz-plane. The grey-coloured collimators would only appear in the yz-plane and have been added to the figure for completeness. The legend shows the different component modules and what they are used for.

BEAMnrc

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Monte Carlo Simulation – TrueBeam Linac

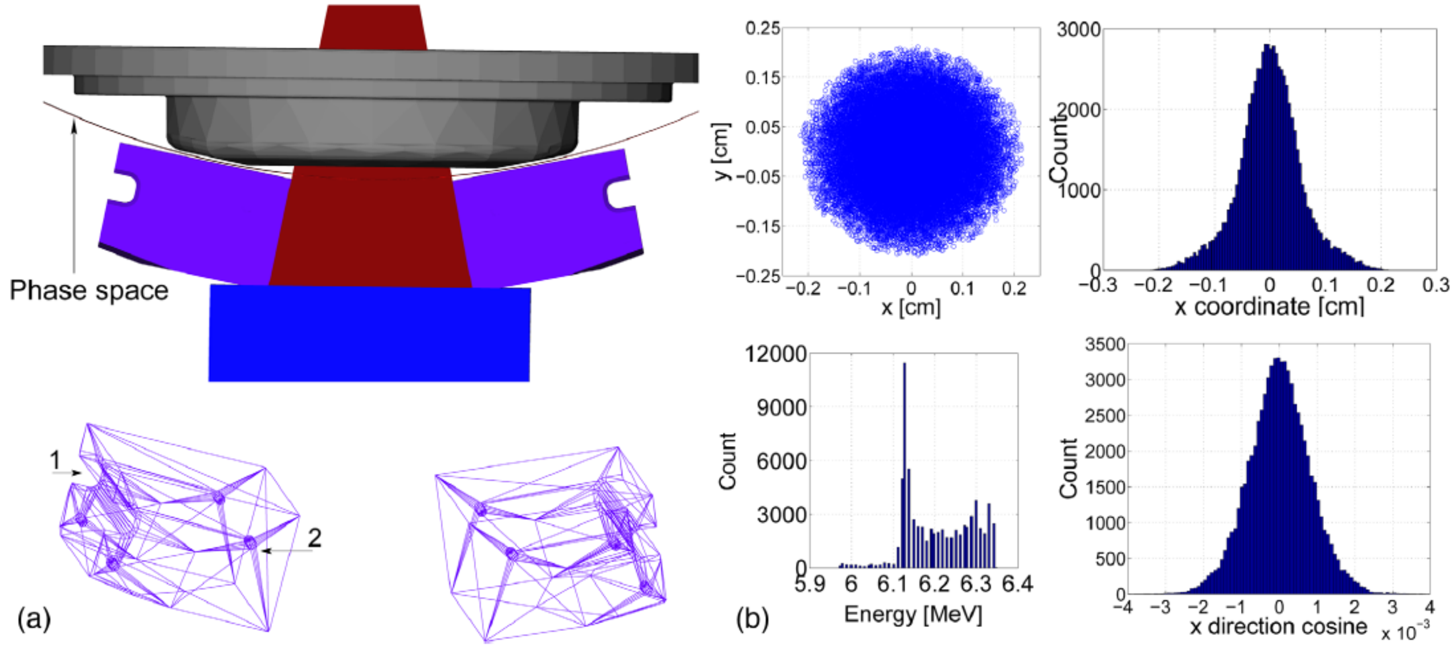

FIG. 1. (a) Part of the TrueBeam treatment head showing the shielding collimator, the cylindrical phase space surface, the upper jaws and the lower jaw block. The middle trapezoid tangent to the jaws is the x-ray field for a 40 × 40 cm^2 open field (at isocenter). The tessellated representation of the movable upper jaws is displayed. Labels one and two point to the bar canal and the mounting holes of the jaws. (b) Phase space of the input Parmela electrons (using 71 712 primary electrons). The plots of the *y* coordinate and *y* direction cosine are not displayed due to their similarity with the *x* correspondent.

Constantin *et al. Med Phys* 2011;**38**:4018.

Geant4

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Some Monte Carlo Results regarding FFF Photon Beams using Phantoms

- Bone heterogeneity and beam angle
- Photon energy spectrum at the surface
- Skin dose enhancement with skin care cream

Phantom Geometry

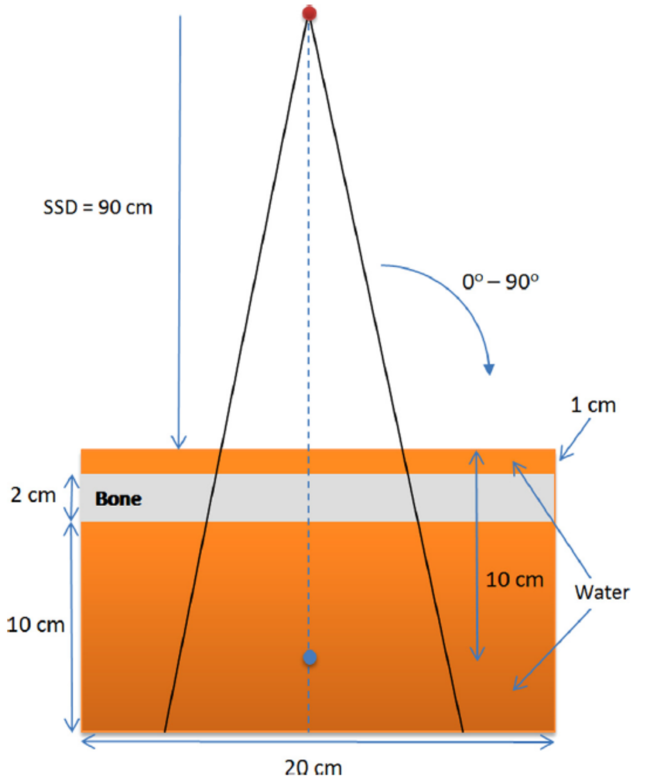

Fig. 1. Schematic diagram (not to scale) showing the calculation geometry of the bone phantom using the unflattened and flattened photon beams. The isocenter is at a depth of 10 cm from the phantom surface. The photon beams were rotated from 0° to 90° clockwise and the thickness of bone was equal to 2 cm. Dose calculations were repeated using the same beam geometry but a phantom with the bone replaced by water for dosimetric comparison.

Beam Angles: 0, 15, 30, 45, 60, 75 and 90 degrees
Photon Beams: 6 MV FFF and 6 MV FF
Phantoms: Heterogeneous (bone and water) and homogeneous (water)

Chow and Owrangi. *Rad Phys Chem* 2014;**101**:46

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Relative Surface Dose vs. Beam Angle

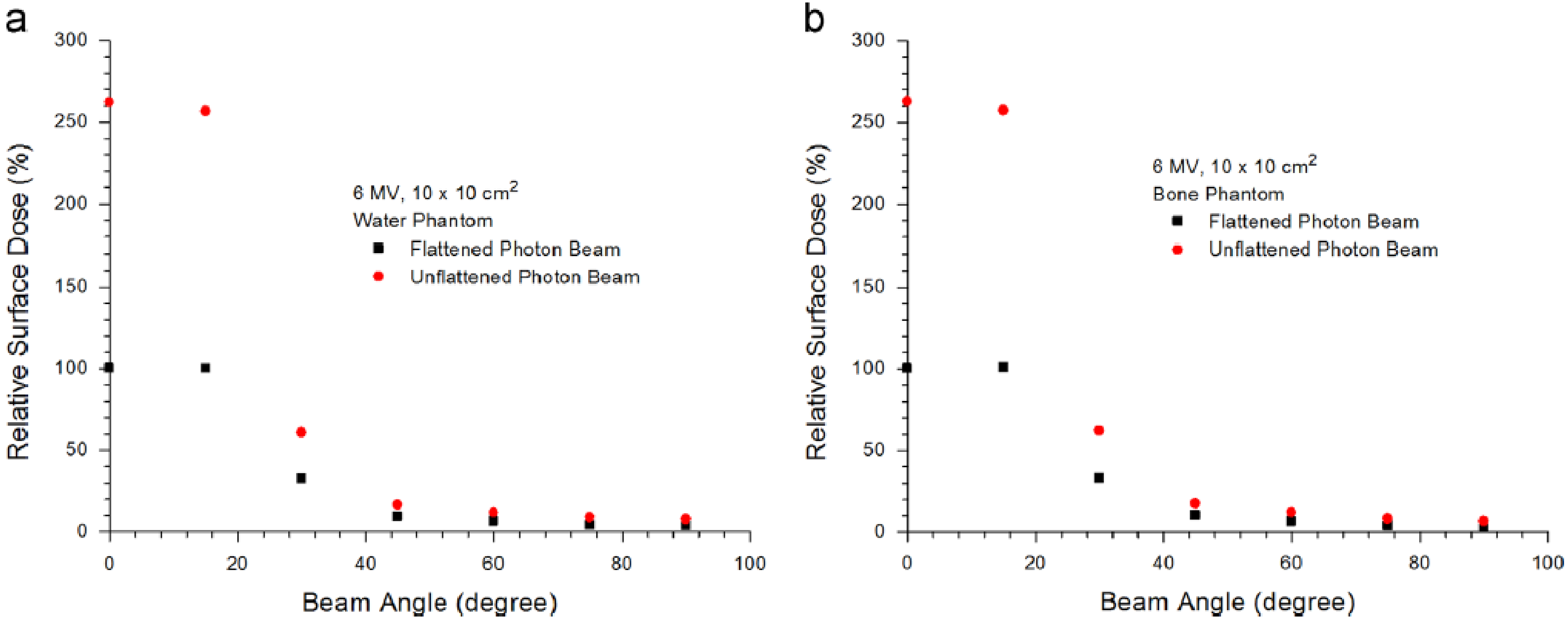

Fig. 6. Relationship between the relative surface dose and beam angle for the unflattened and flattened photon beams in the (a) water and (b) bone phantoms. All doses were normalized to the surface dose of the flattened photon beams with angle equal to 0°.

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Chow and Owrangi. *Rad Phys Chem* 2014;**101**:46

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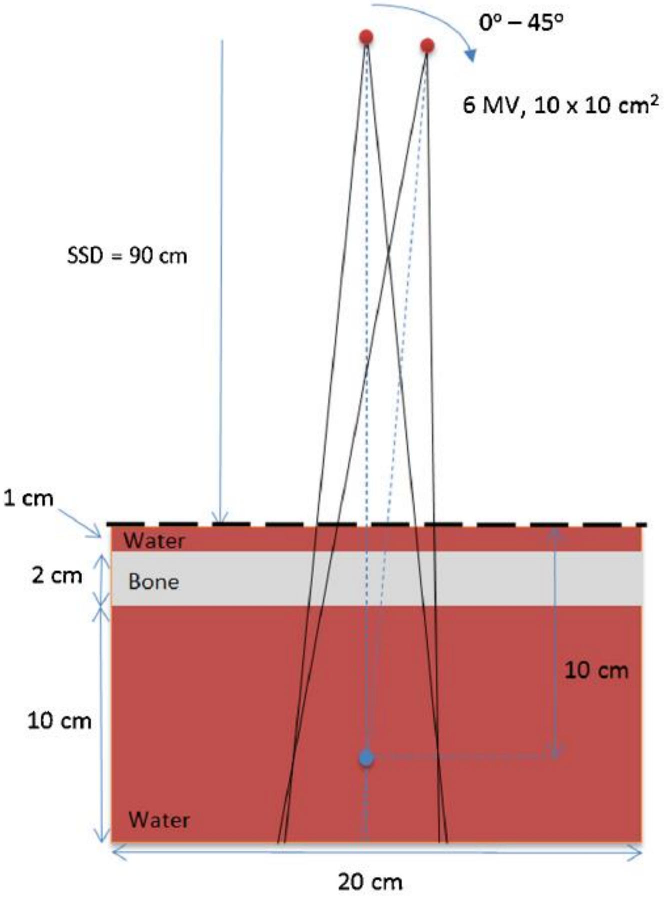
Photon Energy Distribution



Photon energy distribution at the phantom surface

Beam Angle: 0 – 45 degree

Bone and Water phantom

6 MV and 6 MV FFF

Chow and Owrangi. *Rep Pract Oncol Radiother* 2016;**21**:63

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Water Phantom Surface

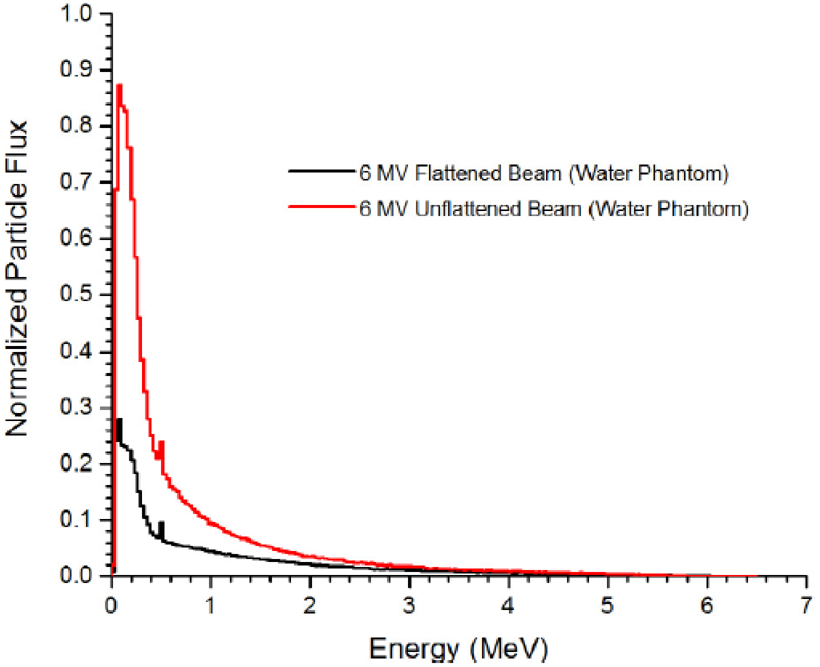

Fig. 2 – Photon energy spectra at the water phantom surface for the 6 MV flattened and unflattened photon beams.

Chow and Owrangi. *Rep Pract Oncol Radiother* 2016;**21**:63

Photon Mean Energy at Surface vs. Beam Angle

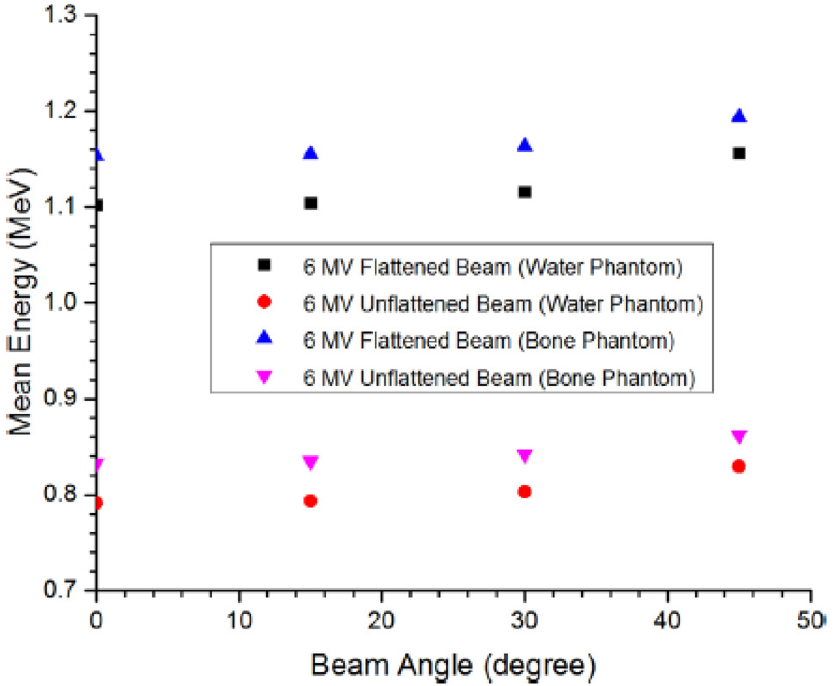

Fig. 8 – The variations of mean photon beam energy in beam angle at the water and bone phantom surface for the 6 MV flattened and unflattened photon beams.

Chow and Owrangi. *Rep Pract Oncol Radiother* 2016;**21**:63

Skin Dose Enhancement with Skin Care Cream

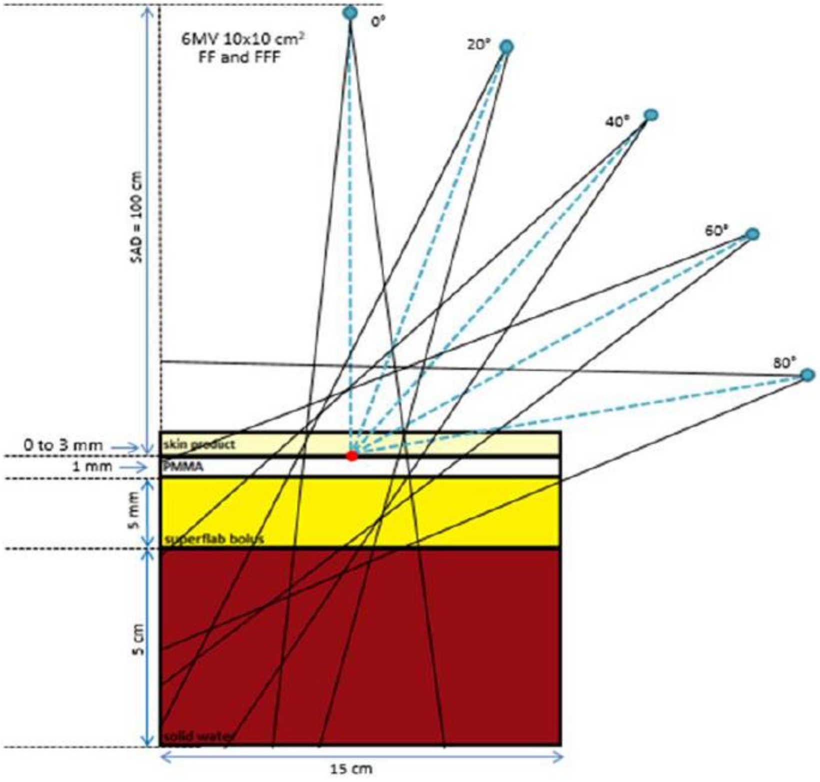

Figure 1. Schematic diagram (not to scale) depicting the beam rotations from 0° to 80° in the experimental setup of Monte Carlo simulations. Skin dose was calculated at the PMMA layer.

The water-based cream contains H, O, C and P, and the density is equal to 0.92 g/cm^3. The silicon-based cream contains C, H, N, O, Si, Ca and Na and the density is equal to 1.14 g/cm^3.

$$DEF = \frac{D_{thickness}}{D_{air}}$$

Sharma and Chow *AIMS Bioeng* 2020;**7**:82

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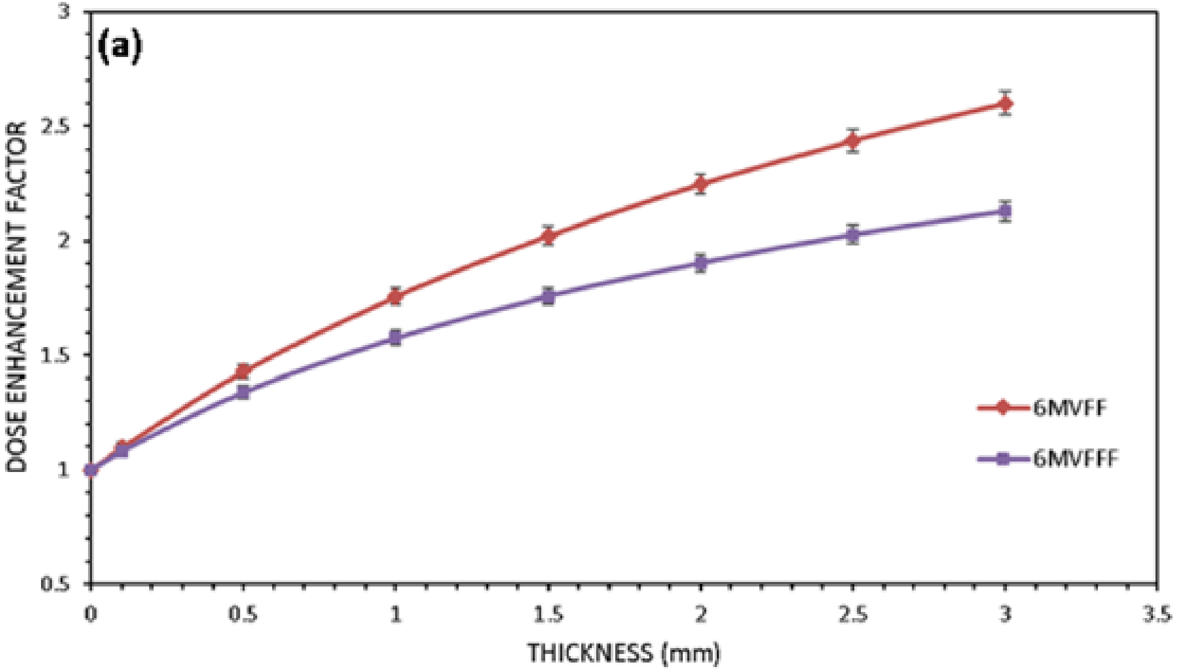
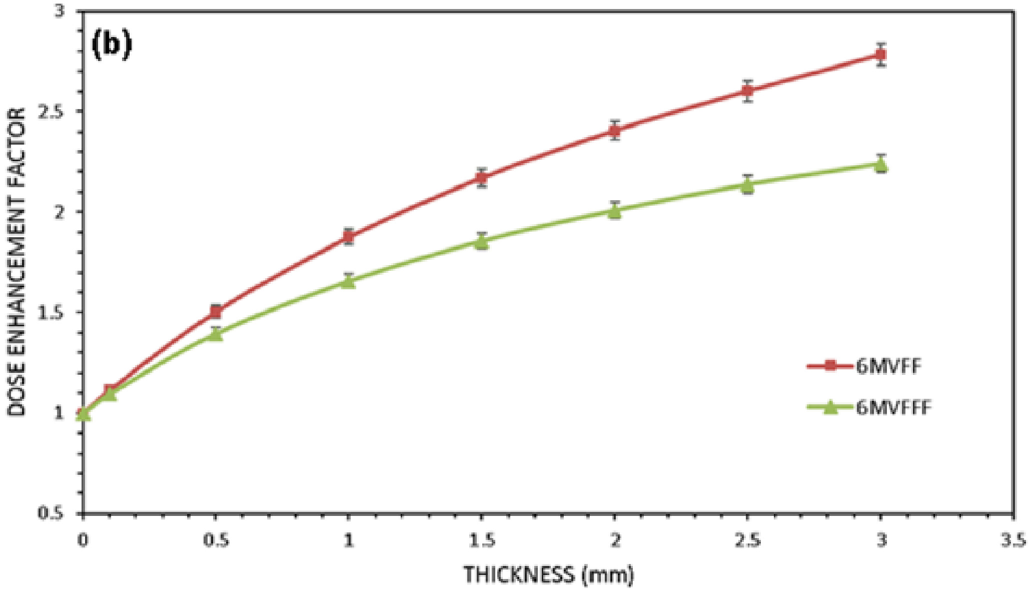
Dose Enhancements vs. Thickness of Cream

Water-based cream



Sharma and Chow *AIMS Bioeng* 2020;**7**:82

Dose Enhancements vs. Thickness of Cream



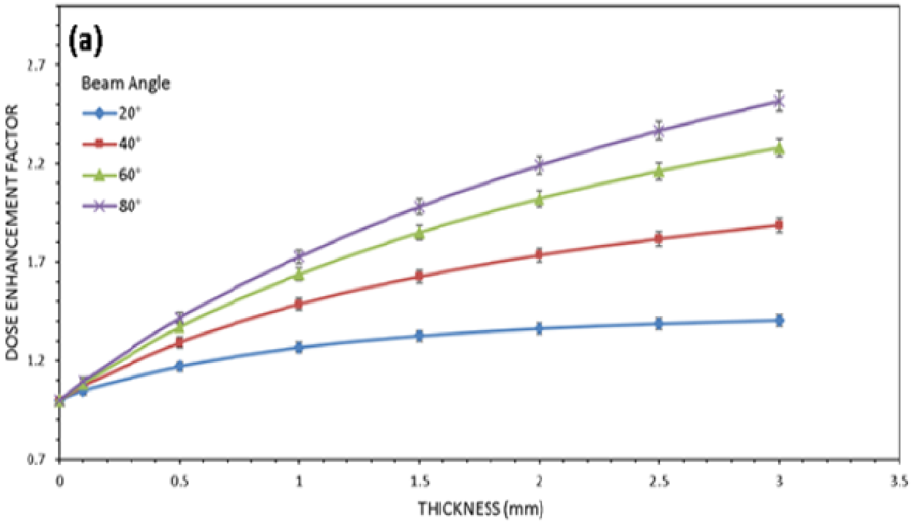
Silicone-based cream

Figure 2. Dose enhancement factor at each thickness for the (a) water-based and (b) silicone-based cream using the 6 MV FF and 6 MV FFF photon beams. The beam angle is equal to zero.

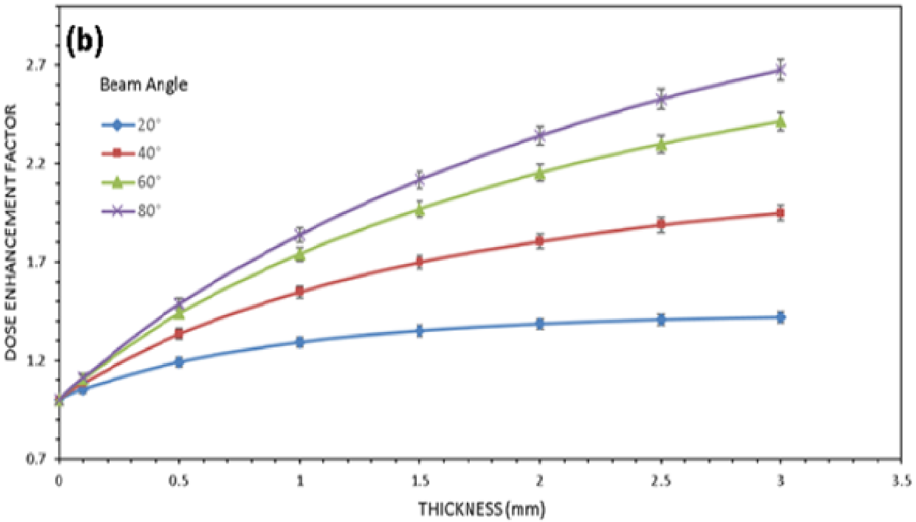
Sharma and Chow *AIMS Bioeng* 2020;**7**:82

Dose Enhancements vs. Beam Angle – Water Based Cream

Water-based cream and 6 MV FF beam



Silicone-based cream and 6 MV FF beam



Sharma and Chow *AIMS Bioeng* 2020;**7**:82

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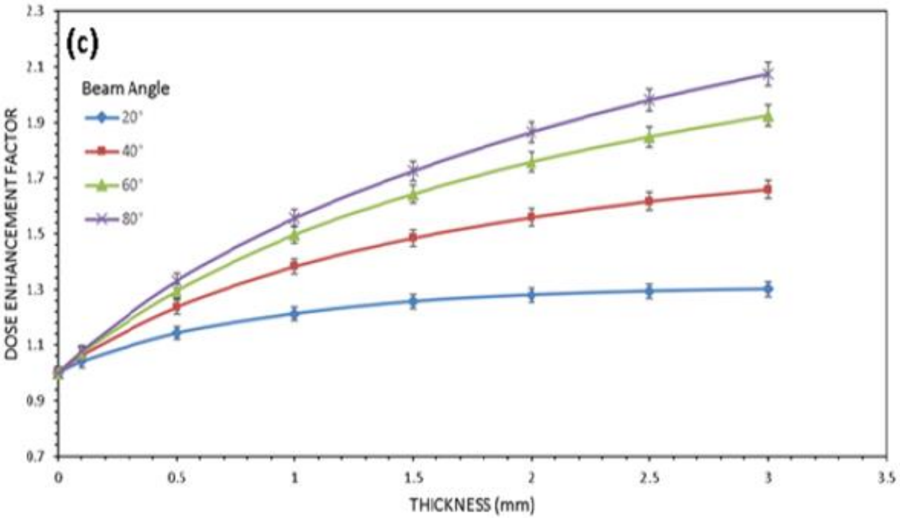
Dose Enhancements vs. Beam Angle – Silicone Based Cream

Water-based cream and 6 MV FFF beam



Silicone-based cream and 6 MV FFF beam

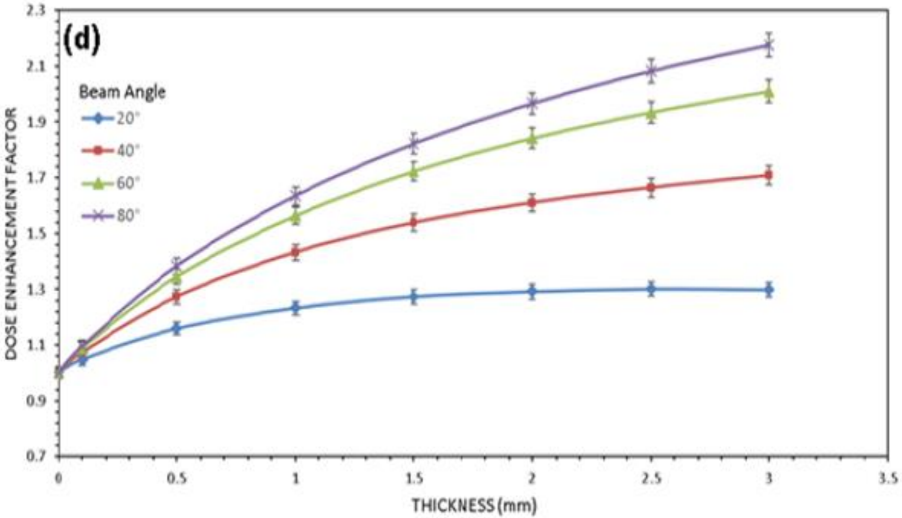


Figure 3. Dose enhancement factor at each thickness for the (a) water-based cream and 6 MV FF beam, (b) silicone-based cream and 6 MV FF beam, (c) water-based cream and 6 MV FFF beam, and (d) silicone-based cream and 6 MV FFF beam. The sample compares various beam angles in the range of 20–80 deg.

Sharma and Chow *AIMS Bioeng* 2020;**7**:82

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Conclusion

- With removal of Flattening Filter, there are concerns in the radiation protection (bunker design) and patient dosimetry for FFF photon beams.
- Presence of Flattening Filter in the MV photon beam affects the surface and bone dose as per phantom study.
- Dose and photon energy spectral variations depend on the beam energy, beam angle, presence of FF and the heterogeneities.
- Dose enhancements are found in FF and FFF beams when water- and silicone-based cream is applied on the phantom surface.

End