Flattening Filter Free c-arm Accelerators

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A Report on Flattening Filter Free c-arm Linear Accelerators: Therapy Emerging Technology Assessment Work Group

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TETAWG Report

- Technological review
- Acceptance testing, commissioning, QA
- Facility planning and radiation safety
- Radiobiology
- Clinical applications

Current talk

- Technological review
  - Concept and implementation
- Acceptance testing and commissioning
- Safety and QA
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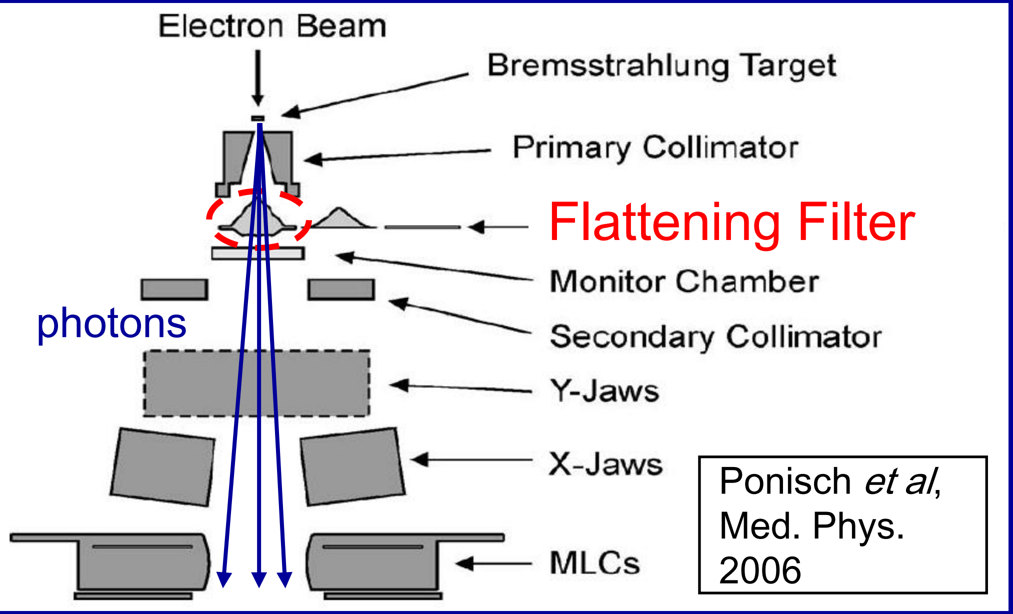
Why flattening filter free / Why flattening filter?



In the filter:

- Photons are absorbed ⇒ reduced efficiency
- Photons are scattered ⇒ increased contamination radiation
- Neutrons are produced ⇒ increased contamination radiation

Flat profile

- Only flat at one depth
- Patients and tumors aren't flat

Can it be removed ?

- In SRS, small field may be sufficiently flat regardless of FF
- In IMRT, optimal fluence maps are not "flat" (MLC)

Implementation – Varian

- 6 MV and 10 MV FFF beams available
    - High Intensity Mode
- Same beam (same electron energy FF vs FFF)
  - Delivered through different carrousel port
    - 2mm brass
  - W instead of Cu target for 10 MV beam
  - Softer photon spectra
- Higher dose rate (max values)
  - 6 MV: 1400 MU/min
  - 10 MV: 2400 MU/min
- TrueBeam offers 5 photon beams

Implementation – Siemens

- Implemented FFF modality, but no longer in radiotherapy market.
- 7 UF, 11 UF, 14 UF, 17 UF
- Different electron energy FF vs FFF
  - Energy raised to restore depth dose
  - 7 UF PDD ~ 6 FF PDD
- All beams operate up to 2000 MU/min
- Linac only equipped with subset of beams
  - 1 FF beam, 1-2 FFF beams

Implementation – Elekta

- FFF modality planned, but still under development
- 6 MV (1000 MU/min) and 10 MV (2000 MU/min)
- Energy would be tuned for each mode such that FF and FFF beam quality would be comparable
  - PDD restored
  - Output factors/skin dose/etc. likely different

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Acceptance Testing

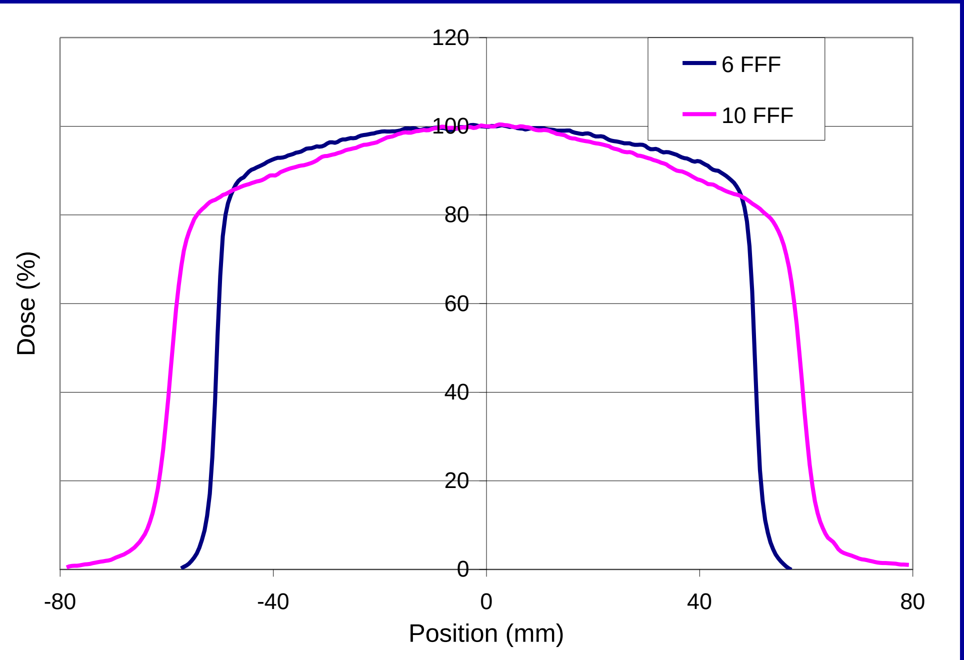
- Similar to conventional FF beams
  - AAPM TG-45 and TG-142
- Measure beam profile shape instead of flatness
  - Definition depends on manufacturer specifications and agreement
- Caution about dose rate effects (recombination)
  - Scanning ion chamber

Commissioning

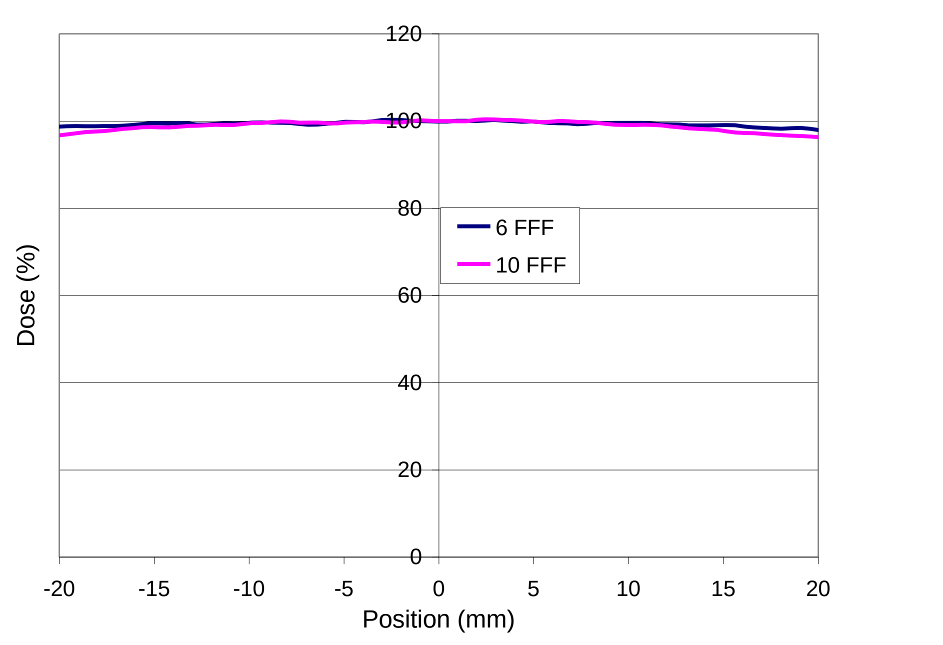
- Calibration
  - Can you just do a standard TG-51?
- Other dosimetric properties

Calibration 1: Size of ion chamber

- Is a farmer chamber appropriate for calibration?
  - Non-flat beam -> Volume averaging concerns



~0.2% error from volume averaging (6 and 10) over 2 cm



Size of ion chamber recommendations

- Some small effect
- Options
  - Use a Farmer chamber and ignore the 0.2% error
  - Use a Farmer chamber and correct for partial volume averaging
  - Use a smaller chamber (check with AAPM TG-51 working group on appropriate chambers)
- Pay attention to centering the chamber

Calibration 2: Recombination

- Recombination is a function of dose per pulse
  - NOT nominal dose rate – dose rate changed by pulse dropping

	6 MV		10 MV	
	FF	FFF	FF	FFF
Varian	0.03	0.08	0.03	0.13
Elekta	0.03	0.06	0.06	0.15

Dose per RF pulse (at d_{max}), cGy/pulse

- TG-51: accounted for with P_{ion} – 2 voltage technique.
- An approximation of recombination
  - Valid for FFF beams? (calibration)
  - Variation with depth and off-axis position? (scanning)

Calibration 2: Recombination

- P_{ion} is larger for FFF beams
- 2 Voltage technique works for evaluated chambers (within 0.2%)

Pion ~ 1.003 for FF beams at 10 cm

	6 MV FFF		10 MV FFF	
Chamber	**10 cm**	**d_{max}**	**10 cm**	**d_{max}**
Exradin A-12	**1.006**	**1.009**	**1.010**	**1.014**
PTW TN30013	**1.005**	**1.008**	**1.011**	**1.013**
NEL 2571	**1.008**	**1.013**	**1.015**	**1.018**

Kry et al, JACMP 13(6):318;2012

- Variation with depth/off axis position
  - Up to 1% variation (chamber specific)
  - Also variations for FF beams – but on a smaller scale (<0.3%)

Recombination recommendations

1. For calibration
   - Use the 2-voltage technique
     - With caution for untested chambers
   - Not necessarily sufficient
     - Assumes linear relationship between 1/V and 1/Q
     - Perform measurements at a series of V to confirm
       - True for FF and FFF beams
2. For scanning measurements
     - Including PDD(10) for calibration!
   - Assess recombination (2 voltage technique) to determine the range of recombination for your chamber.
   - Use reasonable clinical judgment

Calibration 3: Pb and k_Q

- PDD(10)$_x$ used to calculate k_Q
- Lead foil recommended for E>~10 MV?
  - Is it needed for 10 MV FFF beams? Unclear. PDD(10)?
    - Needs verification
  - Shortcut method for high energy beams (eq. 15 in TG-51) – which calculates PDD(10)$_x$ from measurement of PDD(10) instead of PDD(10)$_{Pb}$ not validated for FFF
    - Don’t use without verification
  - Safe choice: use lead
- k_Q
  - Different beam energy (Varian) requires different k_Q
  - Relationship between PDD(10)$_x$ and k_Q still holds
  - Determine k_Q in the traditional manner

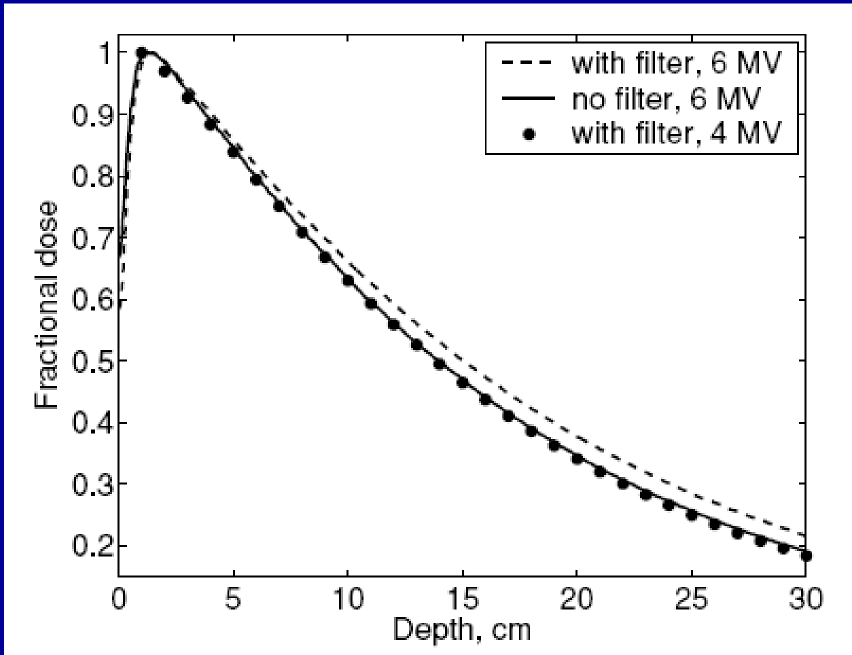
Commissioning

- Calibration is the most interesting part!
- Remainder is similar to commissioning of flat beam
  - Collect same data
- Values will be different, TPS beam model will be different
  - Most differences don’t really matter

PDDs

- PDD steeper (maybe)

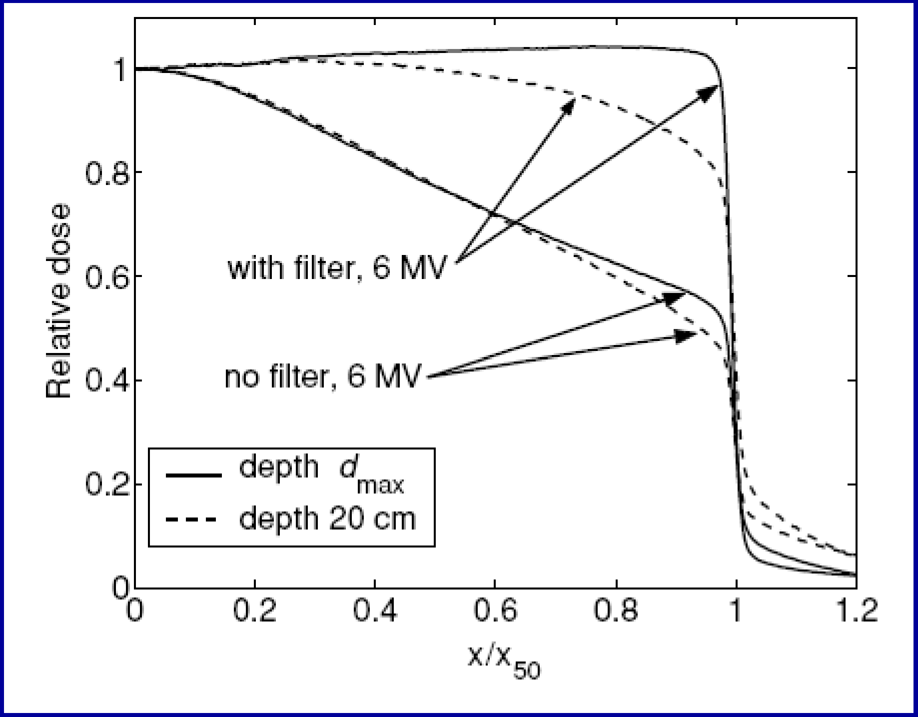
Varian



Vassiliev Phys Med Biol 2006;51:1907

Profiles

- FFF beams are forward peaked
- Profiles are minimally depth dependent (spectra consistent)



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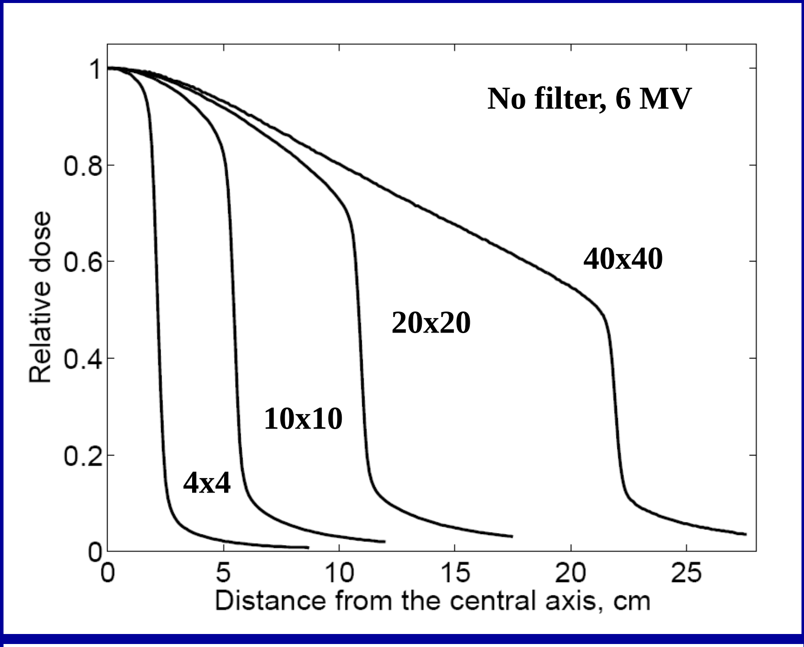
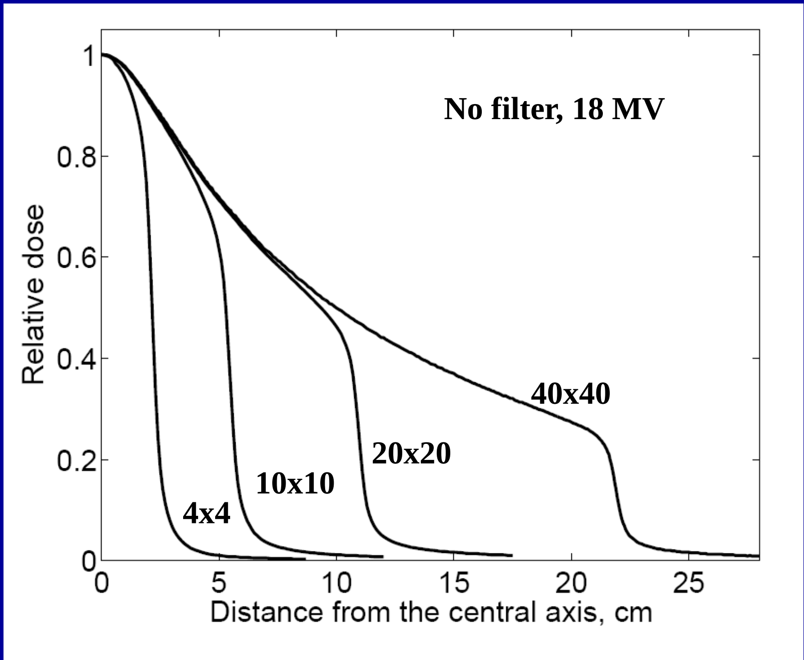
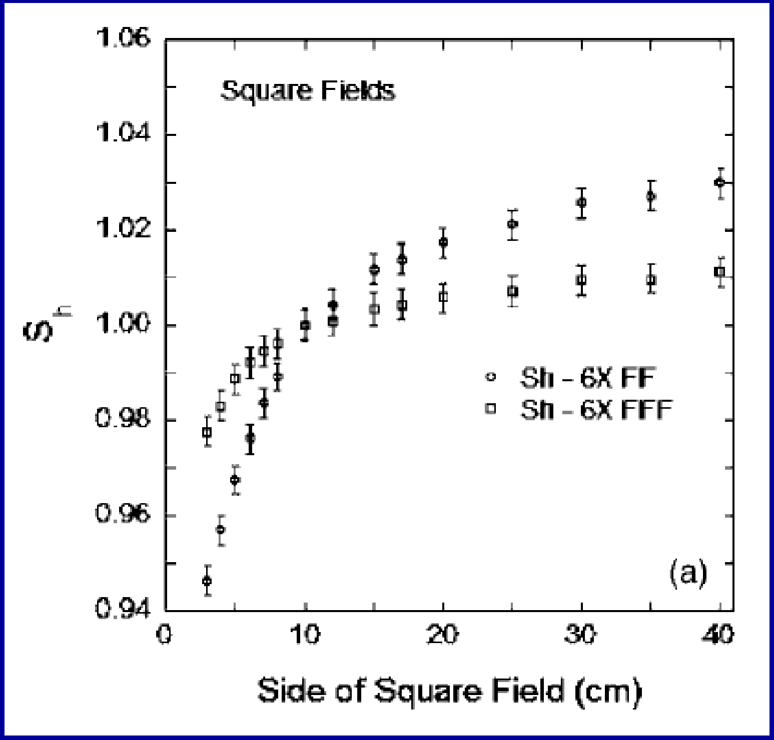




Output factors

- FFF beams have reduced field-size dependence
  - Less head scatter

S_h



Zhu Med Phys 2006;33:3723

$S_{c,p}$

Field size (cm^2)	6 MV FF	6 MV FFF
2 × 2	0.865	0.909
3 × 3	0.908	0.938
4 × 4	0.928	0.953
6 × 6	0.958	0.973
10 × 10	1	1
15 × 15	1.033	1.022
20 × 20	1.054	1.037
30 × 30	1.082	1.056

Vassiliev Phys Med Biol 2006;51:1907

Penumbra and MLC transmission

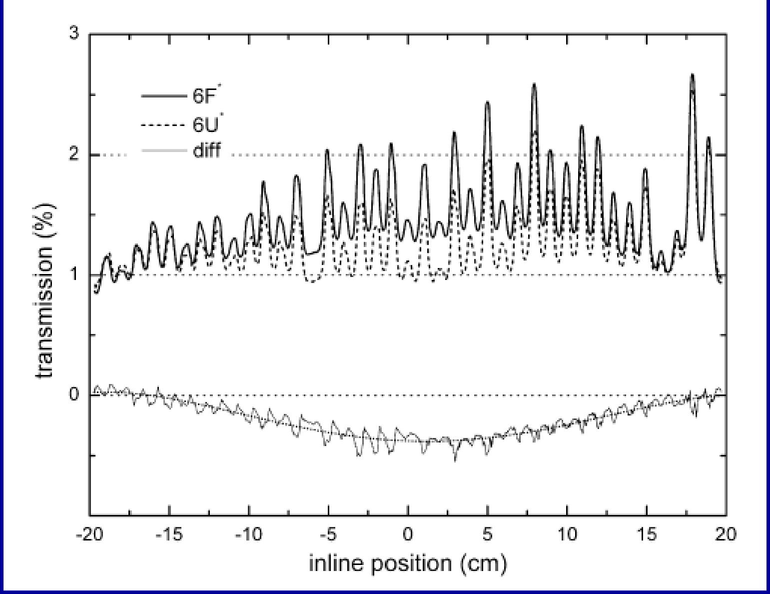
- Penumbra is made sharper
  - In MLC direction
  - less extra-focal radiation

Penumbral widths (mm) in 10 cm depth in water

	Field size (cm^2)	6F	6U
Inline	5 × 5	3.3	3.1
	10 × 10	3.9	4.1
	15 × 15	4.4	4.5
	20 × 20	4.9	5.2
Crossline	5 × 5	5.4	4.7
	10 × 10	6.2	5.4
	15 × 15	6.9	6.1
	20 × 20	7.3	7.0

Poenisch Med Phys 2006;33:1738
Kragl Radiother Oncol 2009;93:141

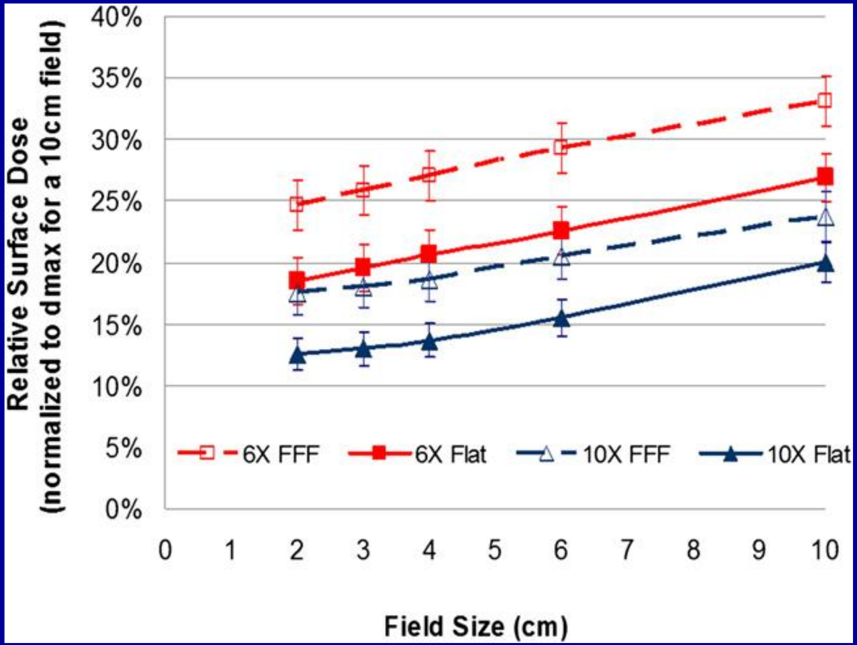
- Less and more uniform MLC transmission
  - Softer and spatially uniform spectrum



Kragl Radiother Oncol 2009;93:141

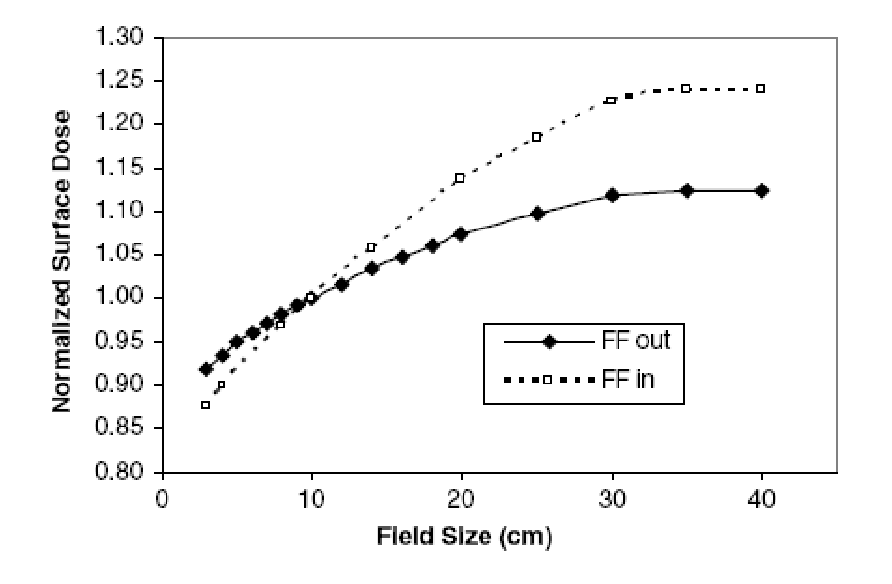
Skin Dose

- Softer spectrum
  - Higher skin dose



Wang IJROBP 2012;83:e281

- Less low-E contamination from head scatter
  - Increases more slowly with increasing field size

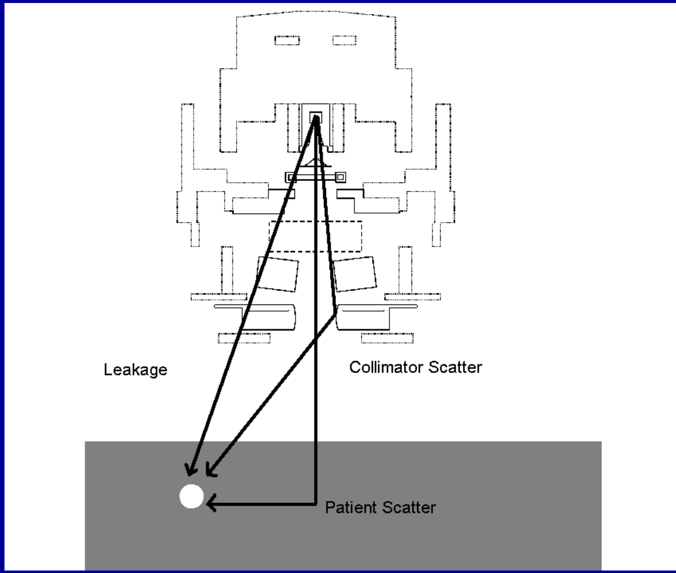


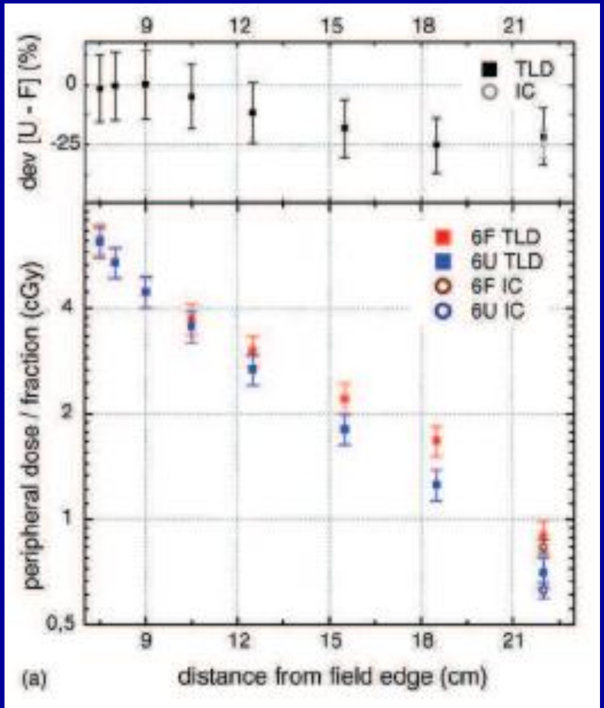
Cashmore Phys Med Biol 2008;53:1933

- Caution – lots of literature assesses "skin dose" at 3-5 mm
  - ICRP/ICRU recommendation is either at 0.07 mm or 1mm.

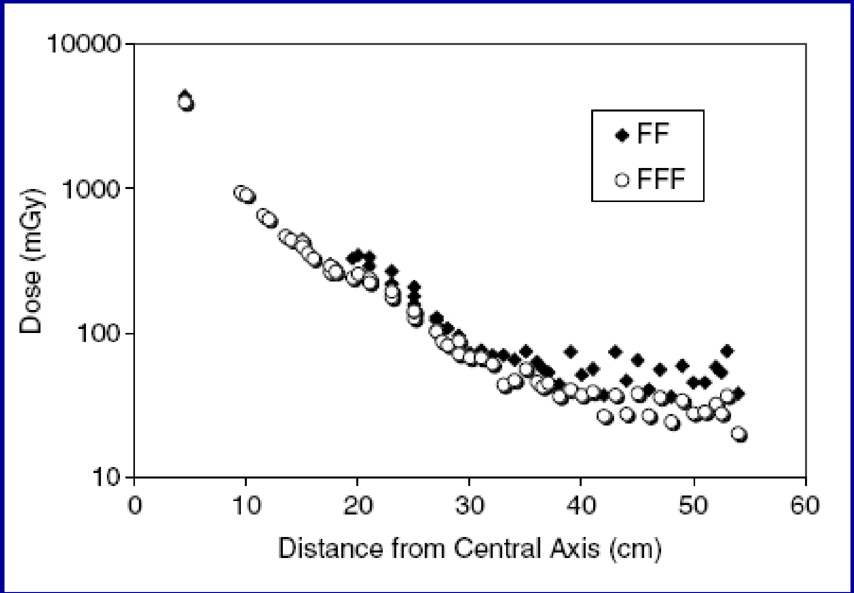
Out of field dose

- Composed of
  - Patient scatter
  - Head leakage
  - Collimator scatter
- Generally lower with FFF





SRS
Kragl et al, Z Med Phys 2011;21:91



IMRT **Kry et al. Phys Med Biol 2011;55:2155**

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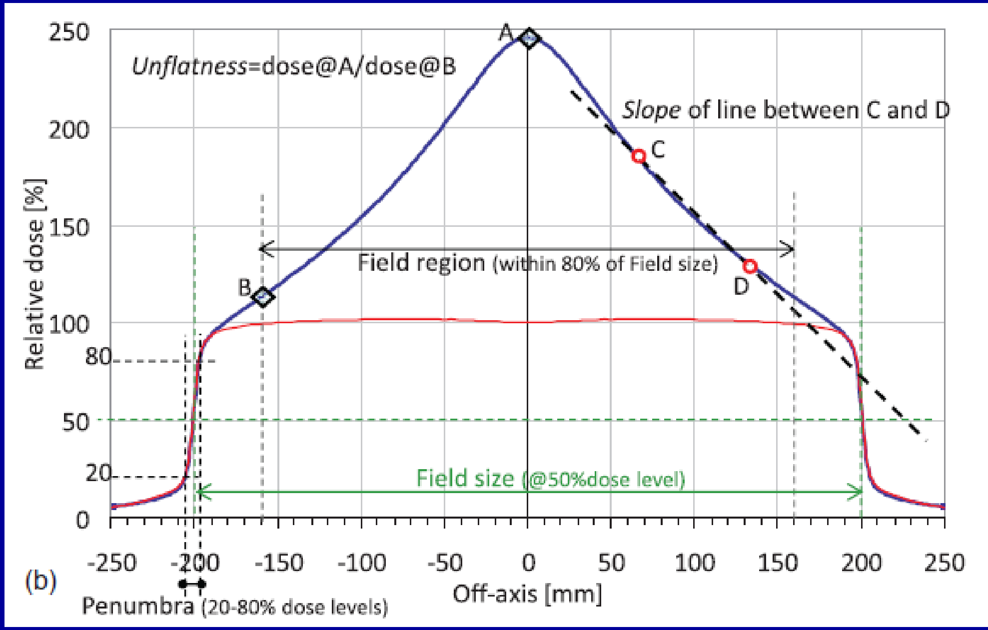
Safety

- Machine performance
  - Per manufacturers, MLC and dose/dose rate controller systems are sufficient to allow IMRT, VMAT, gating, etc. in FFF mode
  - Studies all seem to support this

QA

- Largely follow TG-142
- Profile shape is glaring new FFF feature
  - Already moved to "profile shape" rather than flatness
  - Assess point by point
  - Assess with slopes of the profile
- Does it match baseline? (TPS)



Fogliata Med Phys 39:6455;2012

New QA?

- FFF beams are not largely different but there are unique features.
- Is additional QA needed?
- Are procedural changes needed?

- Assess risk of failure modes via Failure Mode and Effects Analysis
- Based on FMEA scores, consider and design additional safety/QA procedures.
- Example is provided, but is only a suggestion. Individuals should assess risks based on their clinical practice/procedures.

FMEA for FFF beam

Failure Mode and Effects Analysis

Failure Mode	O	S	D	Risk Probability Number (product)
Inaccurate calibration, e.g., error in P_{ion}	2	5	6	60
Failure to account for excessive skin dose	5	6	4	120
Dose problems from low MU segments	3	4	4	48
Inaccuracy of QA devices	4	5	4	80
Wrong beam type selection due to confusing user interface in planning	3	4	4	48
Wrong beam type selection due to confusing user interface in delivery	2	6	3	36
Use of wedges or other devices for which FFF wasn't commissioned	2	6	4	48
Failure to catch problem during treatment due to fast delivery	3	5	5	75
Calibration error due to chamber placement off-axis	2	5	6	60

QA and safety recommendations

- Perform TG-142 on the FFF beams
- Consider alternate failure modes per clinical practice and devise strategies to address them
  - Go through list in report

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Treatment Planning Systems

- TPSs are model based
- Most major commercial TPSs can model FFF beams
  - At least current versions
- Planning systems do an excellent job matching measured data
  - Easier to model beam because of uniform spectrum -> better agreement (Kragl 2012)
- FFF beams can be used for:
  - Most clinical applications

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IMRT

Treatment time

- nasopharynx & prostate plans (Fu, PMB 49;1535:2004)
- Various dose rates, leaf speeds, # fields…

  10-30% faster delivery with FFF
- Good
  - Less patient motion, more patient comfort
- Perspective
  - Not a big time saving
    - Most treatment time is not beam-on time
  - VMAT reduces treatment time more than FFF modality

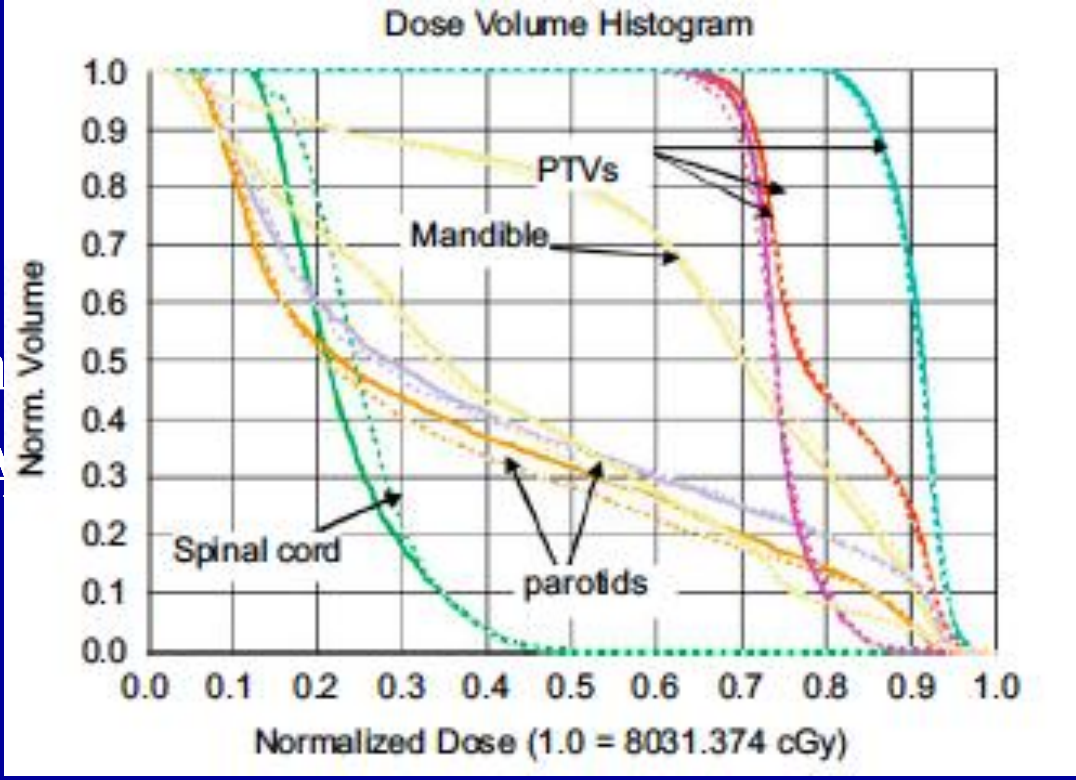
IMRT

Dosimetry

- Prostate, head and neck, brain, lung, esophagus, chest wall…
- IMRT, VMAT…
- Same target coverage
- FFF slightly more con
- FFF slightly better OA
- Differences small

Equivalent treatments

Equivalent planning time



SRS

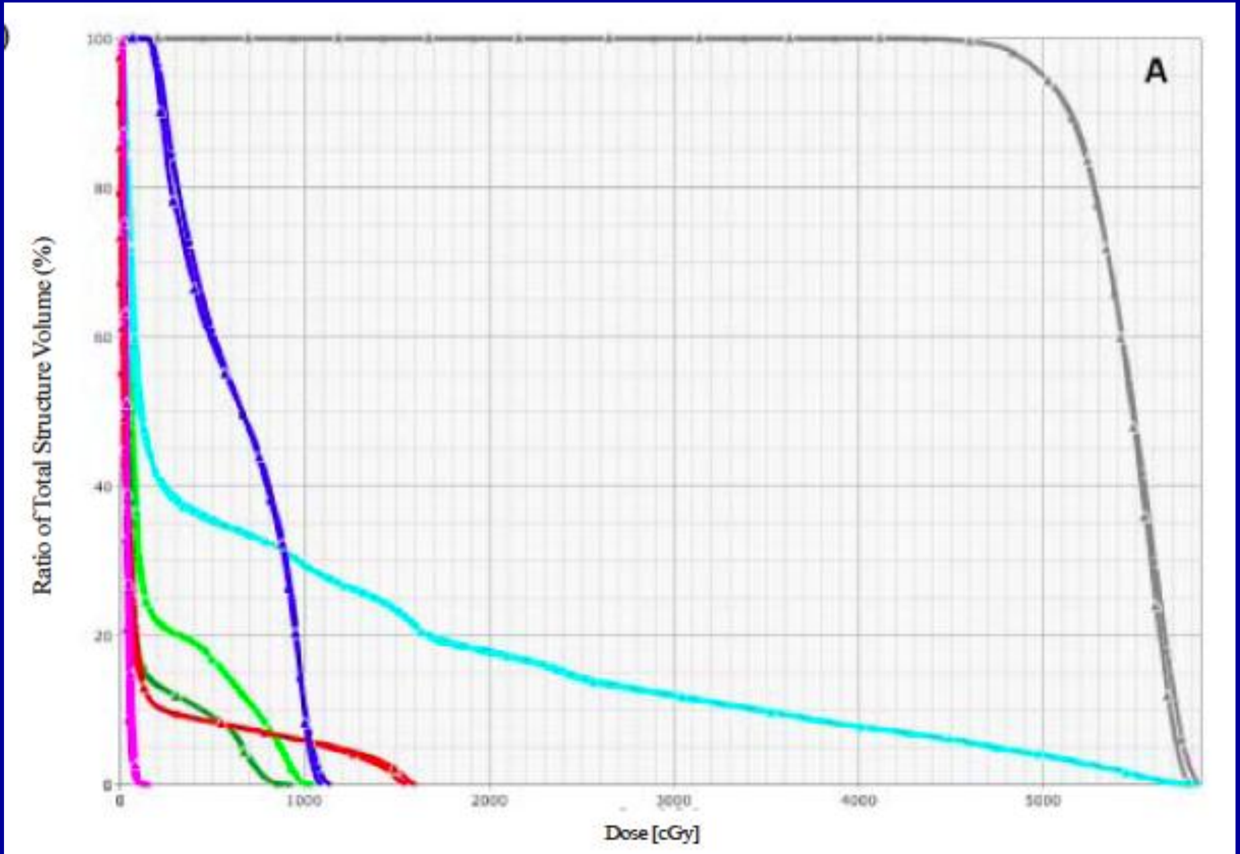
TIME

- A lot of treatment time is beam-on time
- SBRT lung treatment time (Vassiliev JACMP 10;2009)
  - 25 s/field reduced to 11 s/field
  - Facilitates breath hold/gating
- CNS radiosurgery (12-30 Gy in 1-5 fx) (Pendergast J Radiosurgery SBRT 1:117;2011)
  - Average time patient was in room 10:42
  - Facilitates using standard time slots for SRS

SRS

DOSIMETRY

- All doses very similar (Target and OARs)
  - Equivalent treatments



Vassiliev JACMP 10;2009

3D treatments

- Forward planned options, e.g., breast
  - Can do IMRT or FiF with FFF
  - May require change in clinical workflow/practice
- Emergent cases
  - Vendors could include internal flat-beam optimization
  - No good solution currently
  - Most clinics need a flat beam as well

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Summary

- Applications:
  - Any IMRT or SRS/SBRT
- Advantages
  - Faster delivery
  - OAR sparing, less out-of-field dose, better modeling by TPS
- Disadvantages
  - Higher skin dose
  - Not as good for 3D and emergent cases
  - Additional QA if increase number of beams