A Report on Flattening Filter Free Linear Accelerators from the Therapy Emerging Technology Assessment Work Group

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AAPM Annual meeting
2013

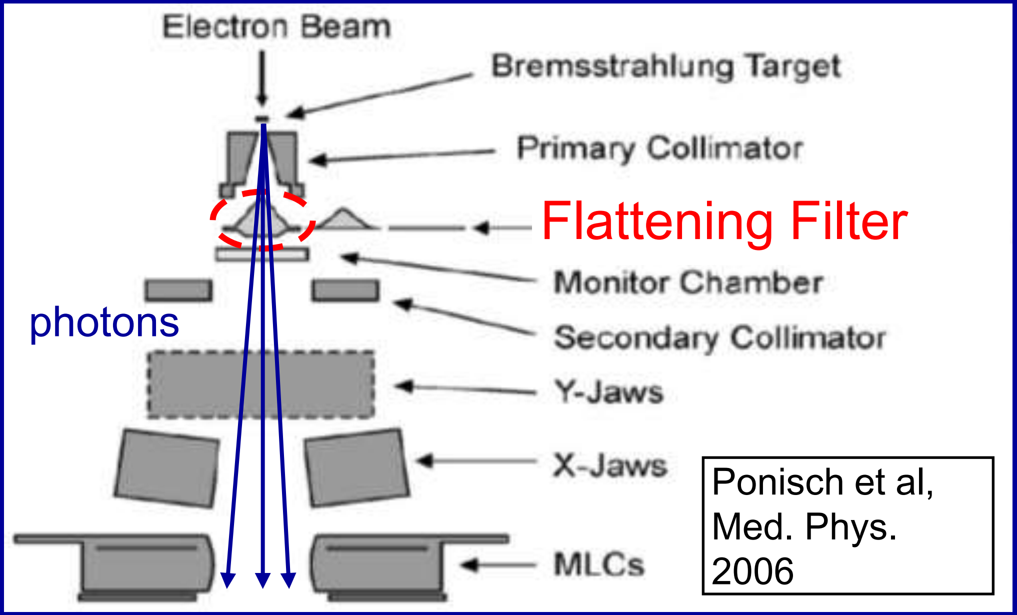
RPC MD Anderson
Radiological Physics Center

THE UNIVERSITY OF TEXAS
MD Anderson Cancer Center
Making Cancer History

Outline

- Introduction
- Technological review
- Physics Issues
  - Acceptance, Commissioning, QA, TPS
- Clinical Issues
  - Applications, Limitations, Safety, Facility planning
- Theoretical issues
- Summary and Recommendations

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)

Initial FFF works

1991: Intracranial SRS study

- Highly elevated dose rate
- Reduced out-of-field dose

More recently:

- Tomotherapy
- Cyberknife
  - Don’t really need a flattening filter

Present day:

- All vendors offer FFF beams

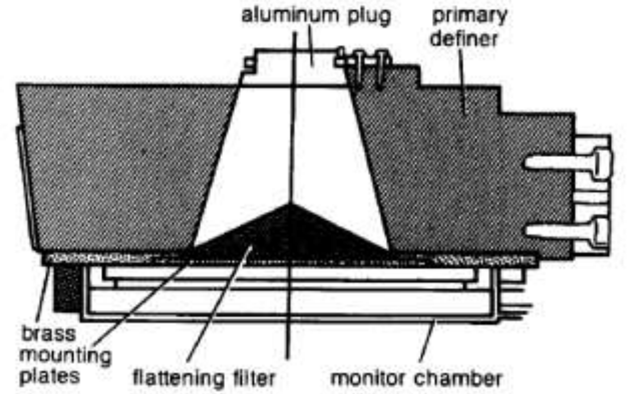


FIG. 1. A cross section through the upper collimator of the Therac-6. The beam is incident on the flattening filter from above.

Radiosurgery with unflattened 6-MV photon beams

P. F. O'Brien and B. A. Gillies
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M. Schwartz
Sunnybrook Health Science Centre, Department of Neurosurgery, 2075 Bayview Avenue, Toronto, Ontario M4N 3M5, Canada

519 Med. Phys. 18 (3), May/Jun 1991

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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 instead of flattening filter
  - 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 recently released - Versa
- 6 MV and 10 MV FFF beams available
- Different electron energy FF vs FFF
  - Energy raised to restore depth dose
  - 2mm Stainless steel filtration
- Higher dose rate (max values)
  - 6 MV: 1400 MU/min
  - 10 MV: 2200 MU/min

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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

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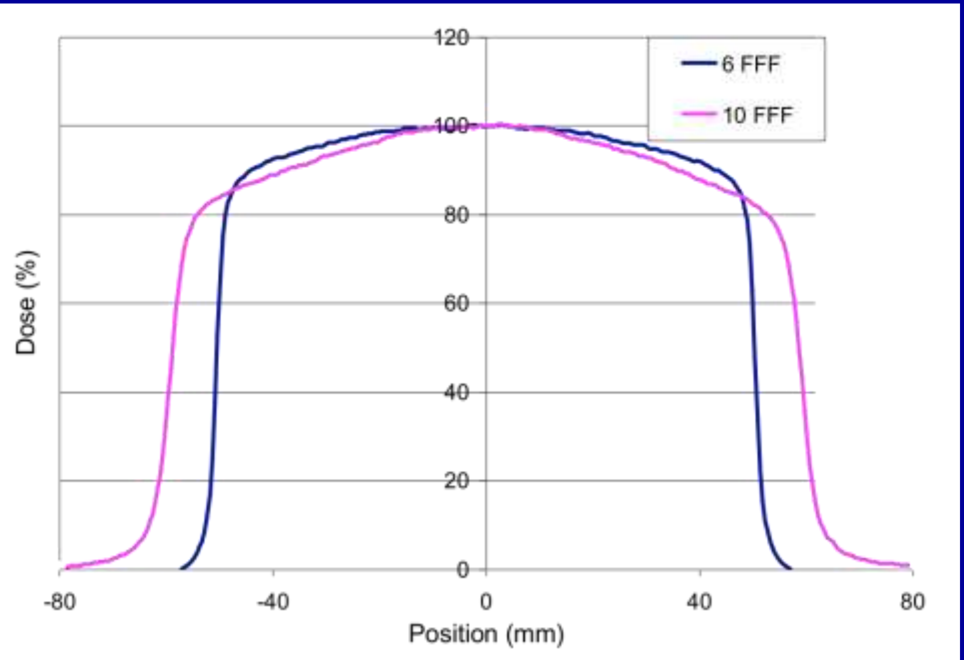
Commissioning

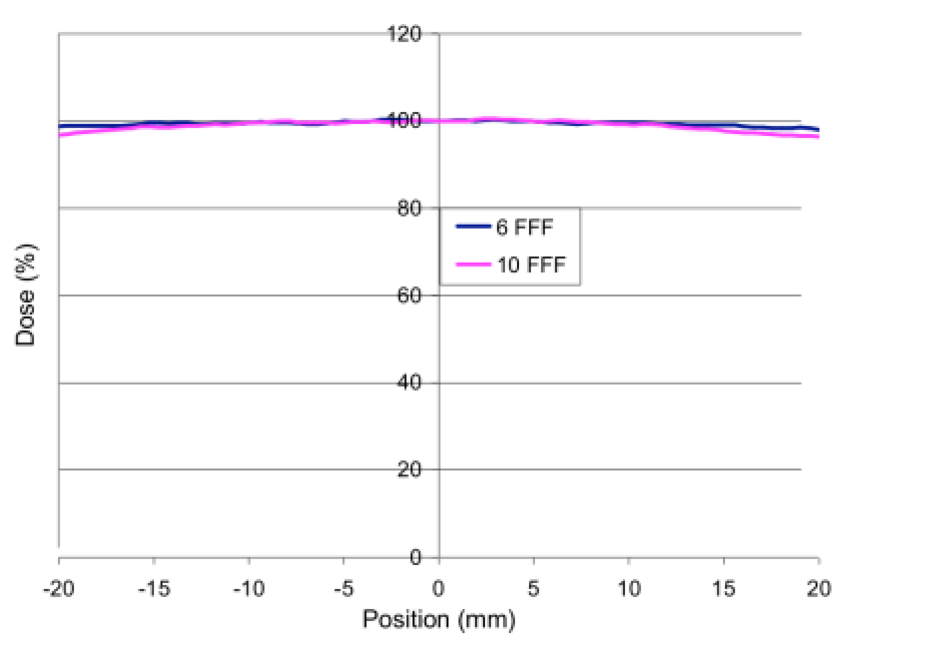
- Calibration
  - Can you just do a standard TG-51?
- Other dosimetric properties

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 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 1.003-1.005 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

- Must verify for all reference dosimetry (including FFF) per WGTG-51 report

- 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
   - Verify the 2-voltage technique for new chambers
     - Perform measurements at a series of V to confirm linear relationship between 1/V and 1/Q
       - True for FF and FFF beams
   - Use the 2-voltage technique
2. For scanning measurements
     - Including PDD(10) for calibration!
   - Once chamber has been verified to be performing normally:
   - Assess recombination (2 voltage technique) to determine the range of recombination for your chamber.
   - Use reasonable clinical judgment

Calibration 3: Pb and k_Q

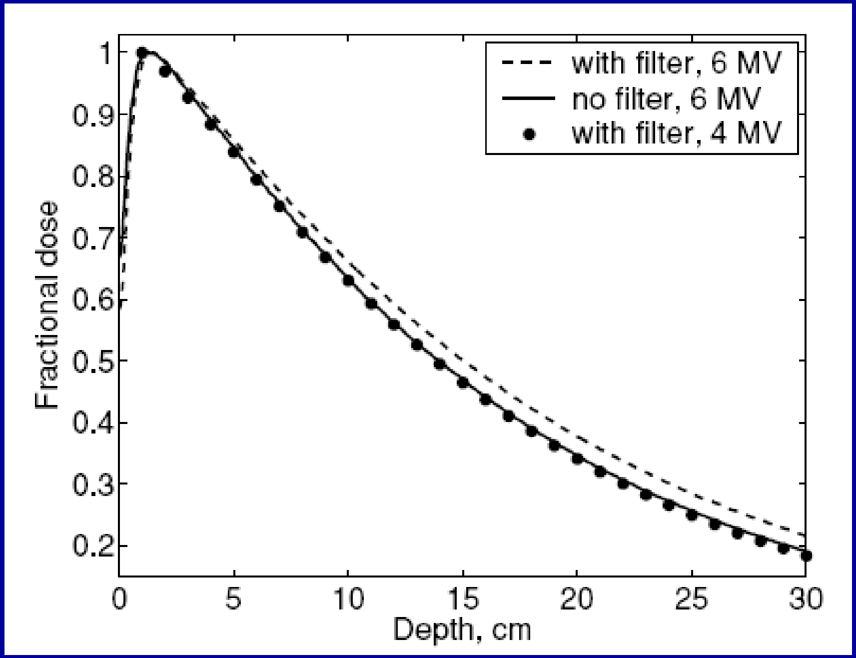
- $PDD(10)_x$ used to calculate k_Q
- Lead foil recommended for E>~10 MV?
  - Is it needed for 10 MV FFF beams? PDD(10)? Unclear.
    - Needs verification
  - Safe choice: use lead
- k_Q
  - Different beam energy (Varian) requires different k_Q
  - Relationship between $PDD(10)_x$ and k_Q still holds
  - 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

Percent Depth Dose

Varian

- FFF beams have a softer spectrum
- Steeper PDD curve
- 

Vassiliev Phys Med Biol 2006;51:1907

Elekta/Siemens

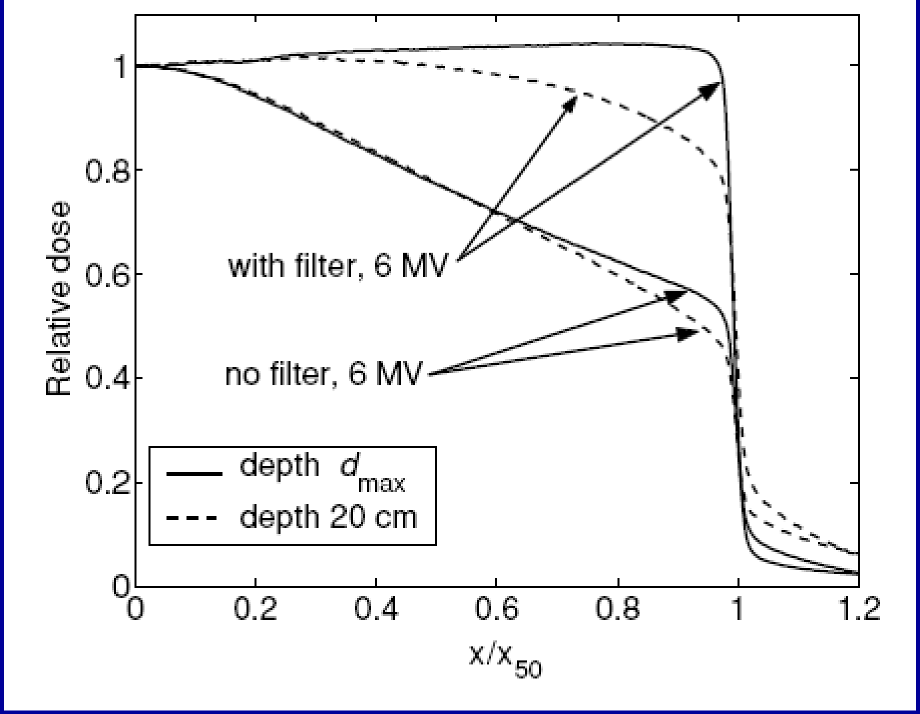
PDD restored

Same PDD

(Doesn't mean all other properties restored)

Profiles

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

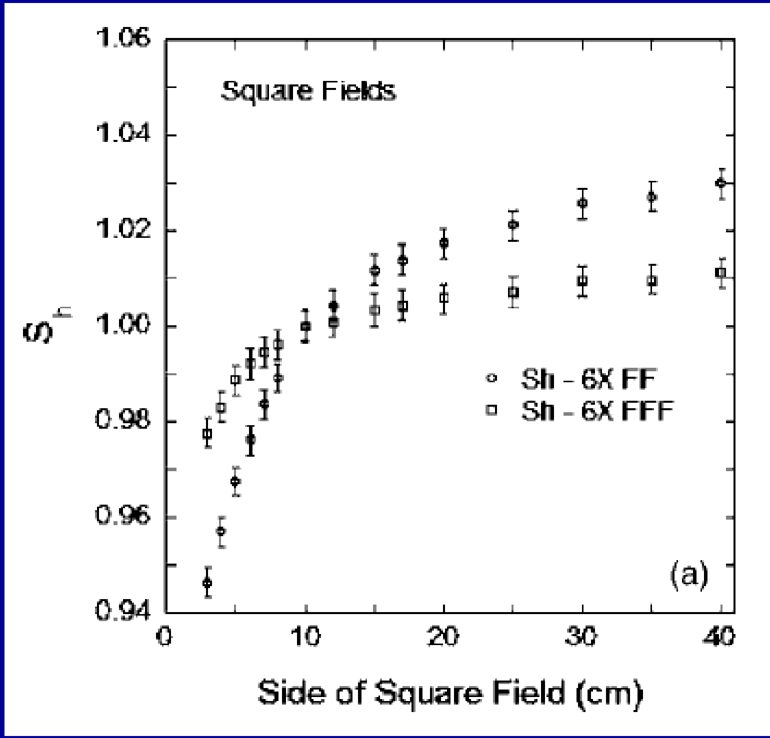


Vassiliev Phys Med Biol 2006;51:1907

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

- Varian:
- Penumbra is sharper

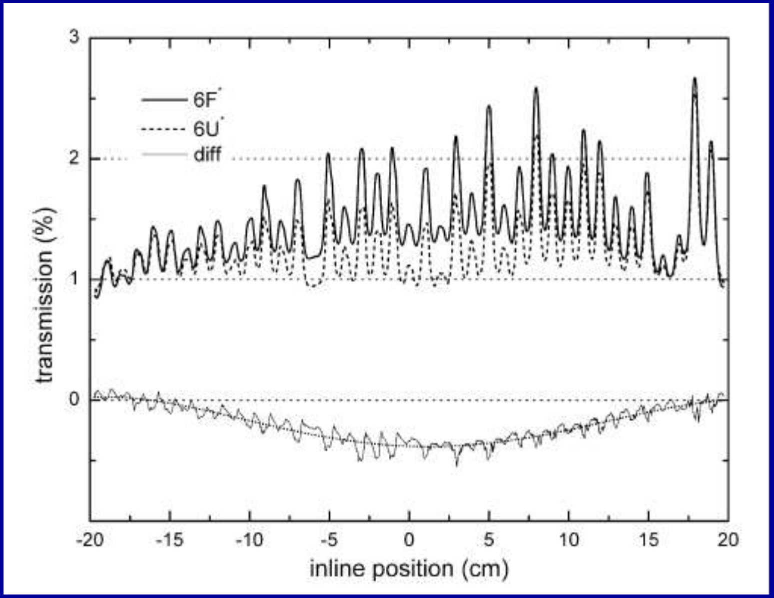
Penumbral widths (mm) in 10 cm depth in water

	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

- Elekta/Siemens
- Penumbra is wider

Poenisch Med Phys 2006;33:1738
Kragl Radiother Oncol 2009;93:141
Huang JACMP 2012;13(4):71

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



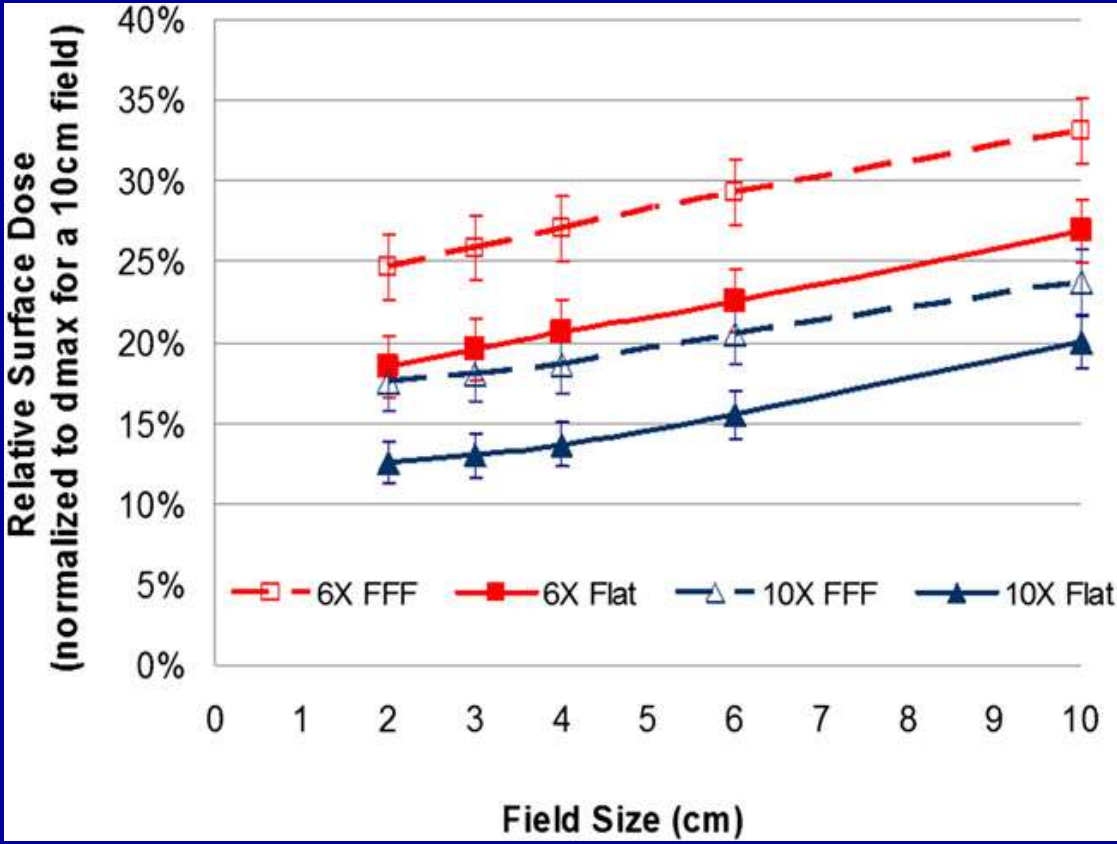
Kragl Radiother Oncol 2009;93:141

Skin Dose

Varian:
Softer spectrum ->
Higher skin dose

Elekta/Siemens:
Restored PDD ->
Less different

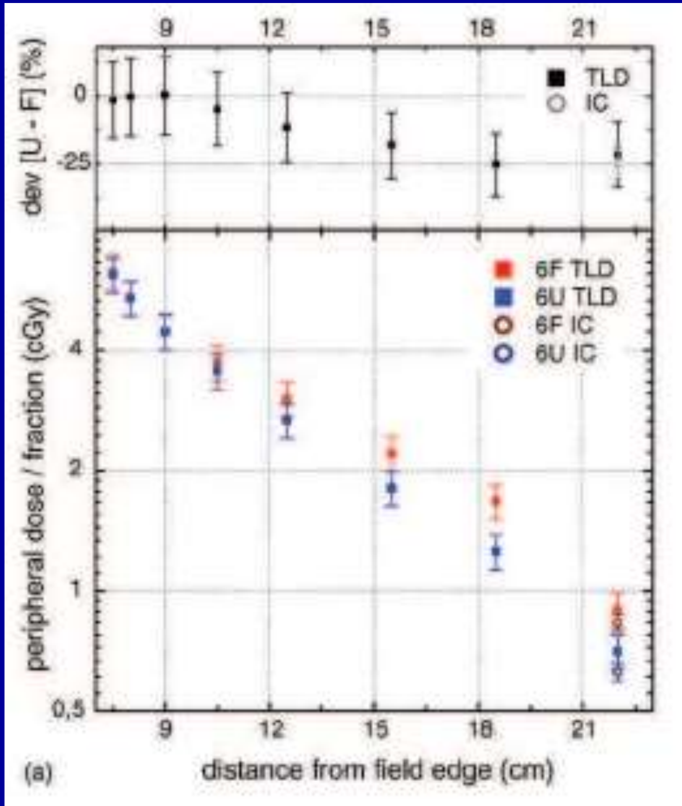
Skin dose more elevated for smaller fields



Wang IJROBP 2012;83:e281

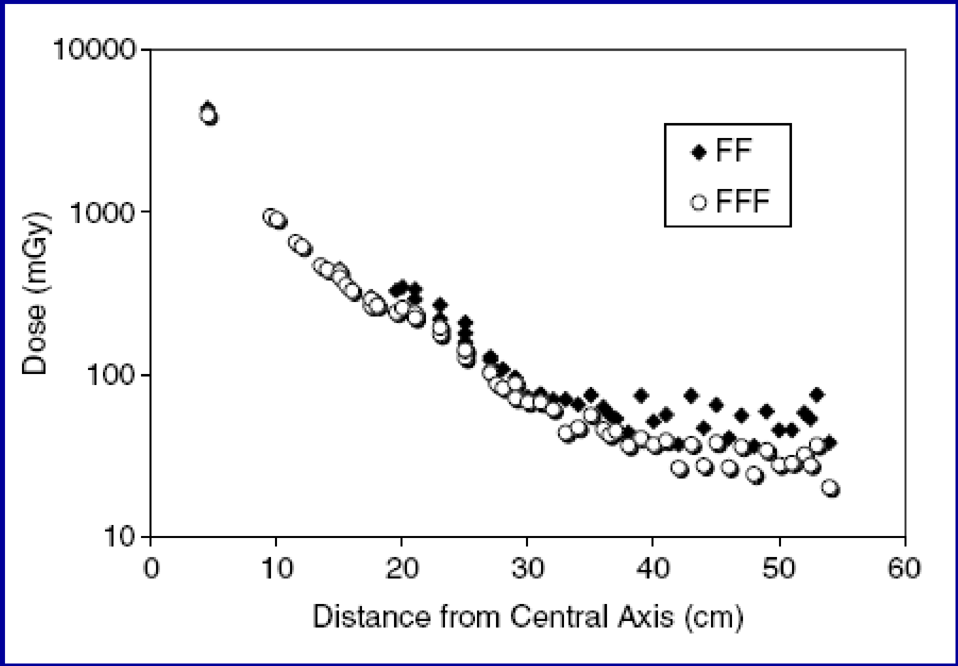
Out of field dose

- 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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Treatment Planning Systems

- 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)

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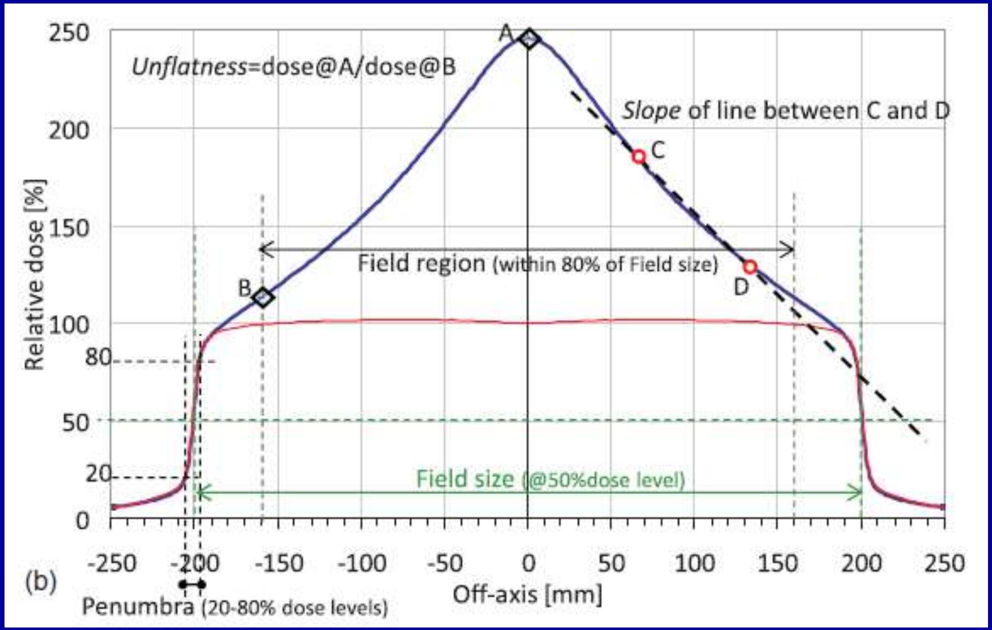
QA

- 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 areas
  - 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 problems via Failure Mode and Effects Analysis
- This is largely procedural, we'll talk more about it under "safety"

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Major applications:

- IMRT
- SRS/SBRT
- Time considerations
- Dosimetry considerations

IMRT

- **Time**
- 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
- Planning time:
  - The same

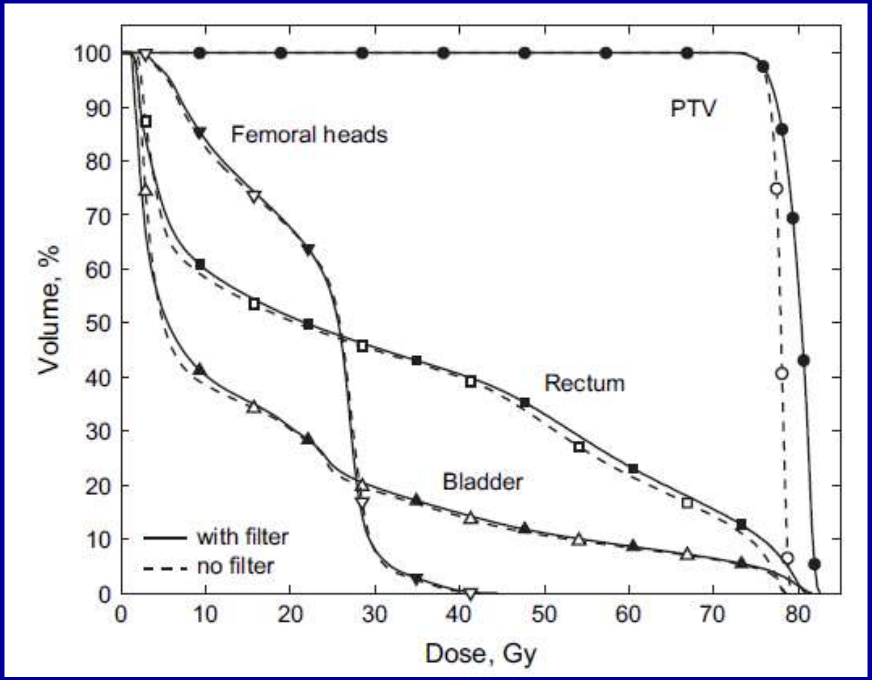
IMRT

- **Dosimetry**

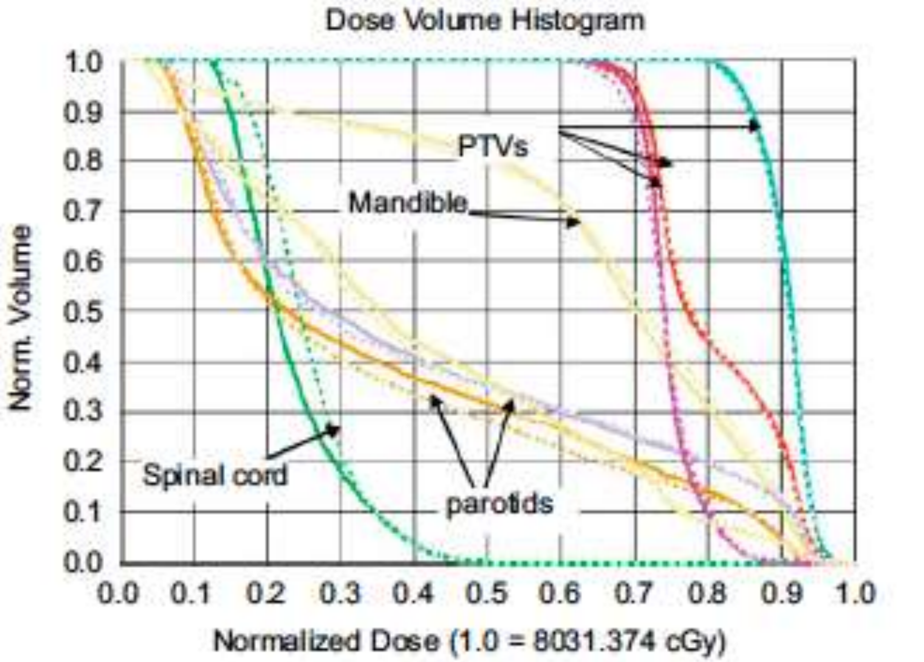
- Prostate, head and neck, brain, lung, esophagus, chest wall…
- IMRT, VMAT…
- Same target coverage
- FFF slightly more conformal
- FFF slightly better OAR sparing
  - Sharper penumbrae
- Differences small

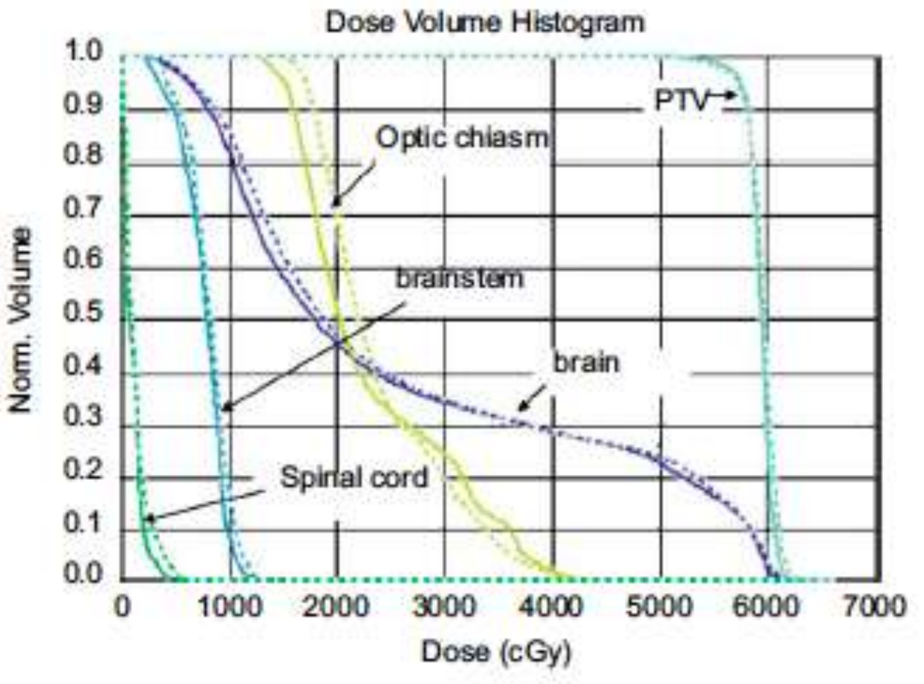
IMRT

- Dosimetry
- **Equivalent treatments**



Vassiliev IJROBP 68:1567;2007
Stathakis Appl Rad Iso 67:1629;2009



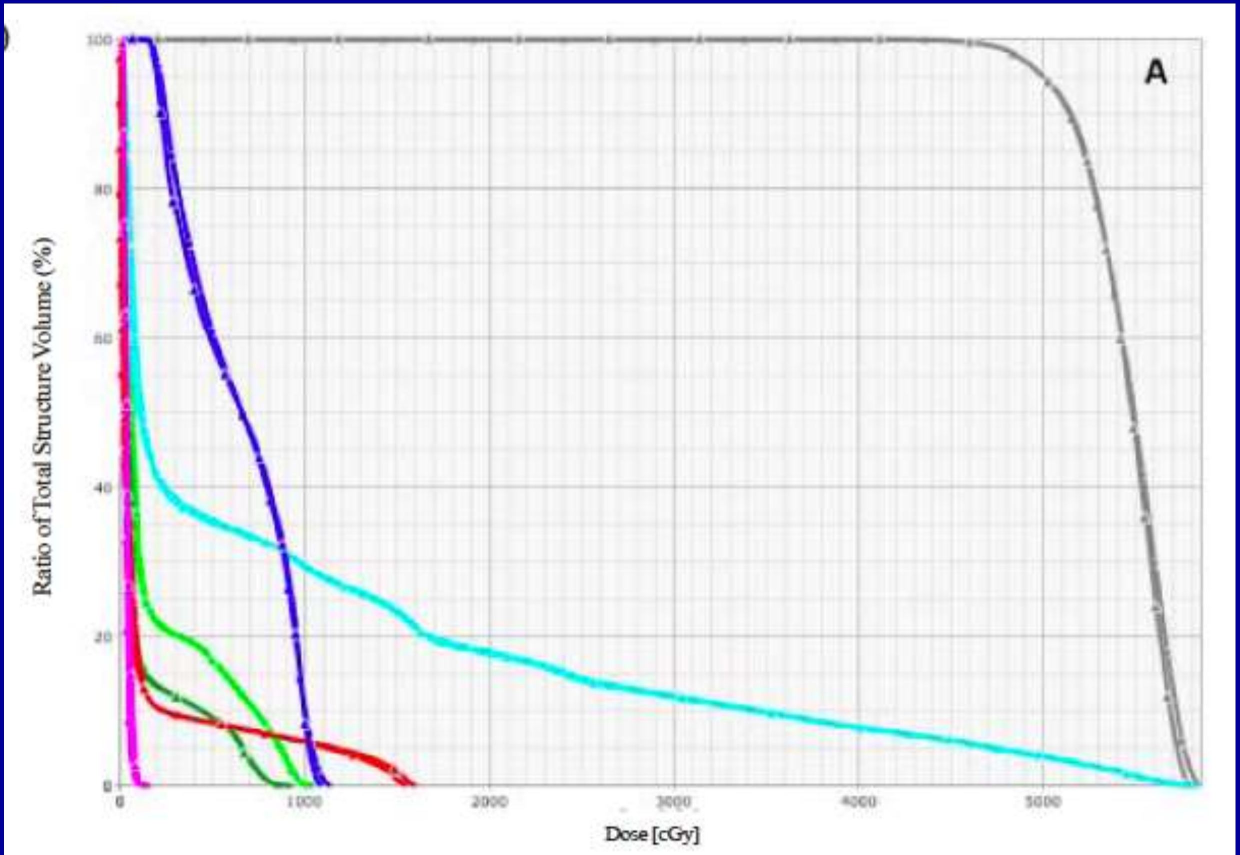


SRS

- **TIME**
- A lot of treatment time is beam-on time
- Notably faster overall treatments
- 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

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Limitations

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

Practical considerations

- Having flattened and FFF beams is OK
  - Clinics have multiple beams
- Each additional beam is more QA!!
- How many beams?
  - Do you need them all?
- Do you need every capability?
  - Wedges don’t make much sense for FFF beams

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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

New risks?

- FFF beams are not largely different
  - Unique dosimetry
  - New workflow

- 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

Safety recommendations

- Consider these and alternate failure modes per clinical practice and devise strategies to address them
  - Go through list in report
  - Skin dose: spread out beams
  - Dose rate concerns: test equipment

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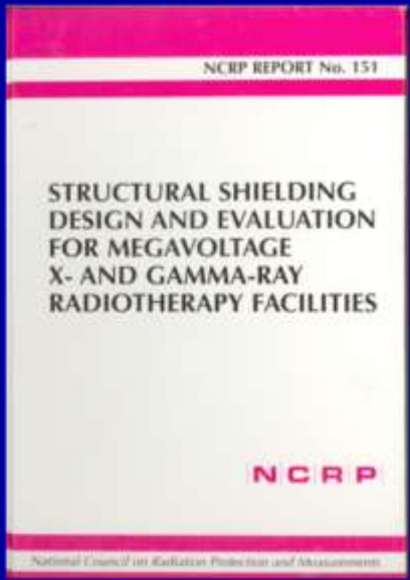
Facility planning

- FFF requires less shielding Kry et al., PMB 54:1265;2009
  - Unless drastically different workload
- Linacs offer both modalities, must shield for both
  - Conservatively means FF shielding



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Radiation Biology

- Higher dose rate means differences in biology
- DNA repair kinetics
  - LQ model
    - DNA damage from a given particle, proportional to dose (linear term) – dose rate independent
    - DNA damage from different sub-lethal events from different particles (quadratic term) * of interest *
  - DNA may repair between these sub-lethal events
    - Lower dose rate = more time for repair
    - Higher dose rates = less opportunity for repair
  - Repair kinnetics modeled as exponential decrease of damage with half-time τ

Radiation Biology

- The importance of the repair depends on:

  treatment time/repair half-time (T/τ)

  – radiation is less effective at larger T/τ
- Sub-lethal repair kinetics are uncertain
  – τ ~0.4 hr to 5-6 hrs, depending on the study/system

- Implication: better tumor control with faster delivery
  – FFF treatments are more effective at killing cells
- Also, more normal tissue toxicity
- Unclear if discernible difference in clinical practice
- Treatment time doesn't change much except for SRS

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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 (worst for Varian)
  - Not as good for 3D and emergent cases
  - Additional QA if increase number of beams

Recommendations

- Commissioning and QA:
  - Follow standard acceptance test, commissioning, and periodic QA programs
    - Profile shape replaces flatness
  - Test all devices for dose-rate characteristics
    - commissioning, scanning, IMRT QA
  - Pay attention during calibration
    - Confirm Pion
    - Address partial volume effect
      - Center chamber
    - Calculate k_Q in traditional manner

Recommendations

- Treatment planning
  - Confirm your TPS can handle FFF beams
  - Do comparative planning FF vs FFF
  - Use beam arrangements to spread out skin dose
- Safety
  - Construct a FMEA table to mitigate new risks

End