Small Field Dosimetry Issues: Theory, Calibration and Treatment Planning

Thomas Rockwell Mackie

Director of Medical Devices
Morgridge Institute for Research
and
Professor, Department of Medical Physics
University of Wisconsin
Madison WI

Conflict of Interest Statement:
Part-time consultant to Accuray

Outline

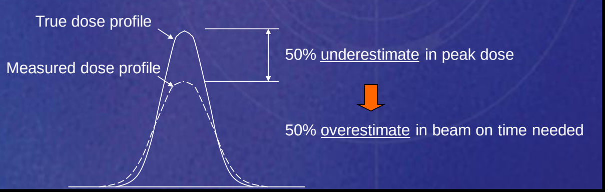
- **Dosimetry Issues Relevant to IMRT, SRS, and SBRT**
  - Charged Particle Equilibrium
  - Temporal Non-Constancy
  - Partial Volume Effects
  - Perturbation Effects for Small Chambers
- **Calibration of Non-Standard Fields**
  - IMRT as a Large Collection of Small Non-Standard Fields
  - IAEA Calibration Initiative for Non-Standard Fields
- **Accurate Planning for Small Fields**
  - Modeling the Beams
  - Different MLCs Types have Different Accuracy Issues
  - Tissue Inhomogeneities are Magnified by Small Fields

The New York Times

Radiation Bills Raise Question of Supervision
By WALT BOGDANICH and REBECCA R. RUIZ
Published: February 25, 2010

Dose in 76 patients exceeded prescription by 50%
Beam measurement error by physicist

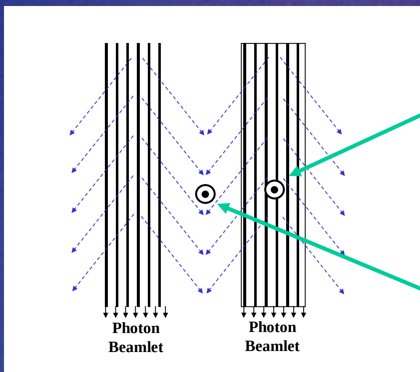
Ion chamber — Detector too large – blurs measured dose profile for small beams



Potential Dosimetry Issues

- Charged particle equilibrium
  - Different spectrum for collection of small fields
  - Non-uniform dose
- Temporal non-constancy
  - A very small effect for ion chambers
  - May not be true for other dosimeters
- Partial volume effect
  - Most important effect especially when measuring output factors for small fields
- Perturbation effects for small chambers
  - Charge multiplication (failure of electronegative gas assumption)
  - Electron emission from electrodes

Non-Uniform Intensity Changes the Energy Spectrum



More High Energy Electrons

More Low Energy Electrons

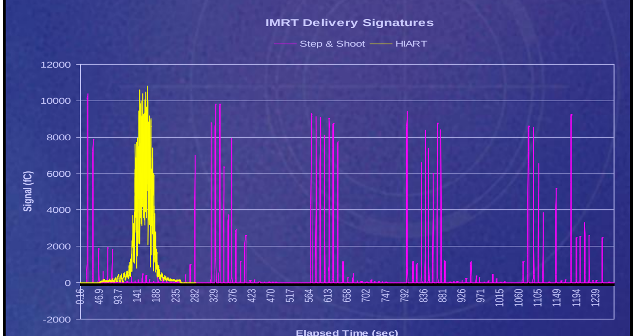
Change in Stopping Power Ratio

Comparison of Spencer-Attix (Δ=10 keV) restricted mass collisional stopping powers ratios (water/air) at 5 cm depth in water for various 6 MV beams with stereotactic and MLC beams.

6 MV beams	Beam quality, TPR(20,10)	Andreo, (1994)	Sánchez-Doblado, (2003)	Column4/Column3
Elekta SL-18 10 x 10 cm²	0.690	1.1187	1.1188	1.000
1.0 cm diameter stereo field			1.1155	0.997
0.3 cm diameter stereo field			1.1153	0.997
Siemens Primus 10 x 10 cm²	0.677	1.1213	1.1221	1.001
2 x 2 cm² irregular on-axis beamlet			1.1203	0.999
2 x 2 cm² irregular 8 cm off-axis			1.1250	1.003

Temporal Delivery of IMRT

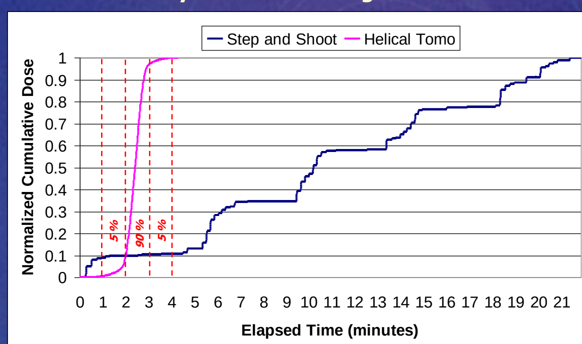
Delivery of Dose to a Single Voxel



From Tim Holmes, St. Agnes Baltimore

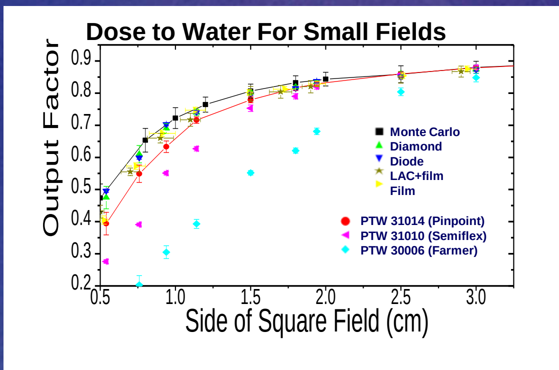
Temporal Delivery of IMRT

Delivery of Dose to a Single Voxel



From Tim Holmes, St. Agnes Baltimore

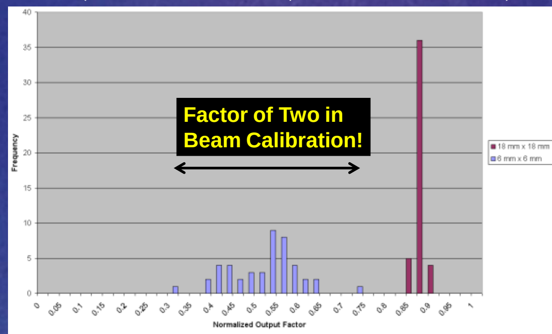
Partial Volume Effect



From Roberto Capote, IAEA

High Uncertainty in Output Factors

Example: Statistics of 45 Output Factors for 6 mm and 18 mm square fields (Novalis, SSD = 1000 mm, depth = 50 mm, various detectors)



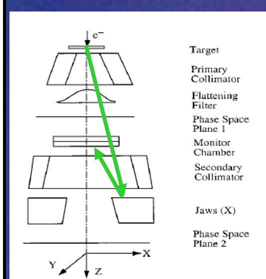
From Wolfgang Ullrich, BrainLab

Reasons for Drop in Output with Small Field Size

- Backscatter into monitor unit from beam defining jaws
- Reduced scatter (phantom and head)
- Electronic disequilibrium
- Obscuration of the source

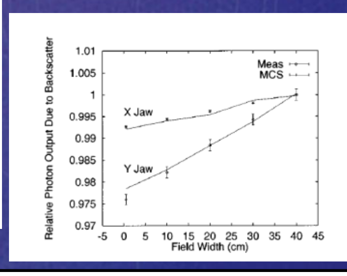
Backscatter into Monitor Chamber

The effect is due to backscattered photons entering the monitor and resulting in feedback to the linac to lower its output

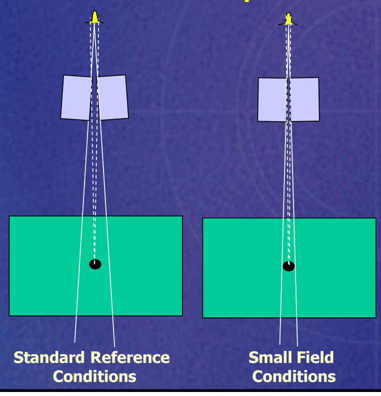


Liu et al., Med. Phys 2000;27:737-744

Varian 2100 – 10 MV. Results with other jaw completely open



Problems with Measuring Conventional Output Factors



- Small field openings obscure the source which is difficult to measure and error prone.
- Amount of phantom scatter changes as well as lateral disequilibrium.
- Partial volume effects can mask machine output factor.

Measured and MC Output Factor (Scp) as Function of Electron-Beam FWHM

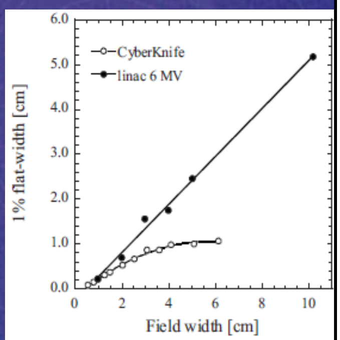
Point source assumption starts breaking down for small fields.

TABLE IV. Measured and MC-simulated $s_{c,p}$, for the four detectors and for the 5, 7.5, and 10 mm collimators, for the various FWHM of the Gaussian spatial distribution of the electron source.

		FWHM 1.4 mm	FWHM 1.8 mm	FWHM 2.2 mm	FWHM 2.6 mm
Coll 5 mm	Measured $s_{c,p}$	Simulated $s_{c,p}$	Simulated $s_{c,p}$	Simulated $s_{c,p}$	Simulated $s_{c,p}$
A16	0.614	0.669	0.643	0.611	0.585
PinPoint	0.613	0.661	0.636	0.607	0.582
Diode	0.710	0.757	0.732	0.704	0.679
Diamond	0.613	0.677	0.639	0.609	0.580
Coll 7.5 mm					
A16	0.801	0.809	0.808	0.799	0.792
PinPoint	0.798	0.805	0.802	0.795	0.789
Diode	0.852	0.757	0.850	0.843	0.842
Diamond	0.815	0.833	0.818	0.813	0.803
Coll 10 mm					
A16	0.859	0.874	0.870	0.860	0.857
PinPoint	0.858	0.867	0.865	0.860	0.857
Diode	0.895	0.909	0.896	0.890	0.886
Diamond	0.871	0.889	0.876	0.872	0.866

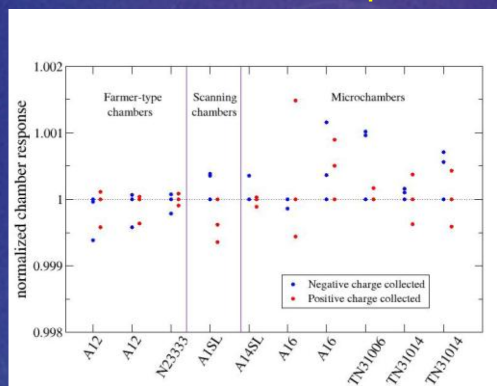
Chamber Selection For Beams without Field Flattening Filters

- Dose flatness insufficient for Farmer-type chamber
- Cavity length should not be greater than 1 cm
- Option: cross calibrate a short chamber with Farmer-type chamber

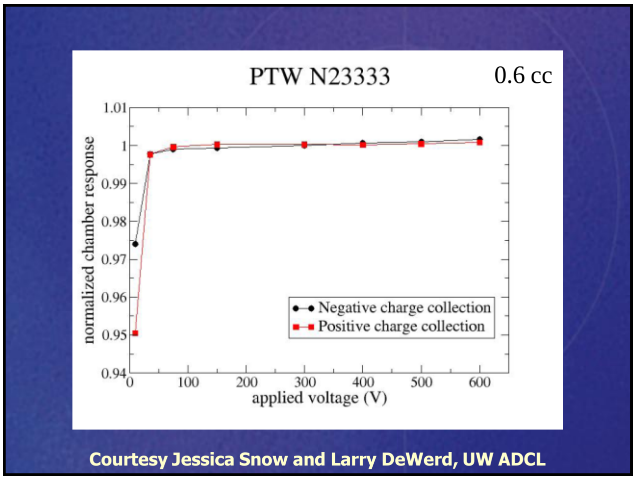


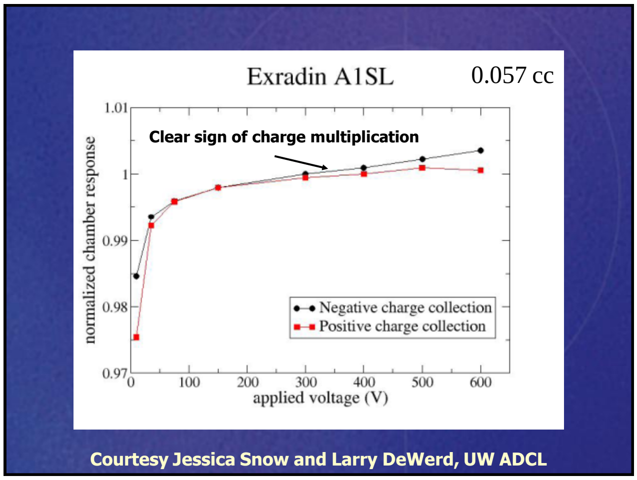
Kawachi et al, Med Phys (2008) 4591

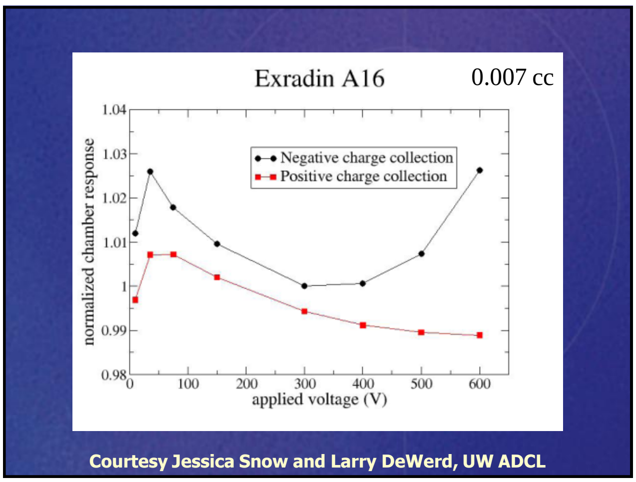
Normalized Chamber Response

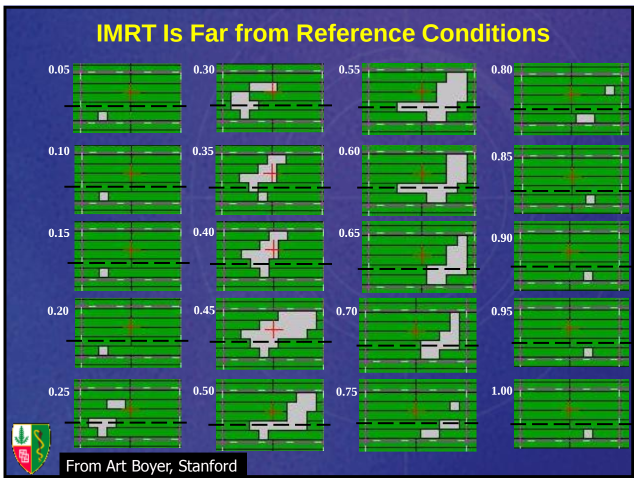


Courtesy Jessica Snow and Larry DeWerd, UW ADCL

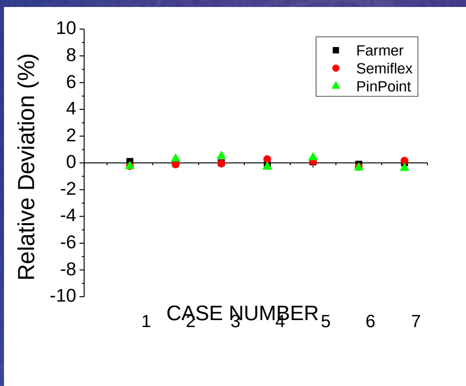

PTW N23333
0.6 cc
normalized chamber response
applied voltage (V)
Negative charge collection
Positive charge collection
Courtesy Jessica Snow and Larry DeWerd, UW ADCL


Exradin A1SL
0.057 cc
Clear sign of charge multiplication
normalized chamber response
applied voltage (V)
Negative charge collection
Positive charge collection
Courtesy Jessica Snow and Larry DeWerd, UW ADCL


Exradin A16
0.007 cc
normalized chamber response
applied voltage (V)
Negative charge collection
Positive charge collection
Courtesy Jessica Snow and Larry DeWerd, UW ADCL

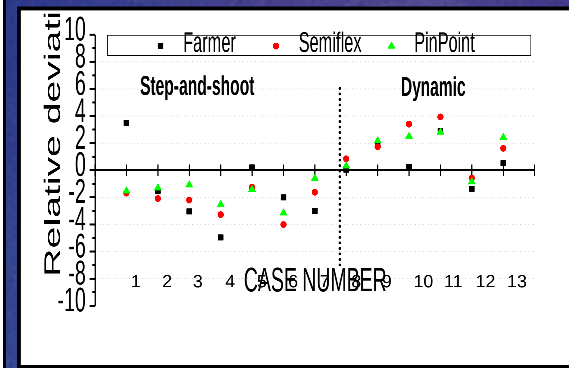

IMRT Is Far from Reference Conditions
From Art Boyer, Stanford

Audit for TRS 398 Reference Dosimetry



From Roberto Capote, IAEA

IMRT Audit



Sánchez-Doblado F, Hartmann G., Pena J., Capote R. *et al*
IJROBP **68** (2007) 301-310

IAEA/AAPM Meeting for the Dosimetry Code of Practice: Small Fields and Novel Beams

Outside Participants

- Jan Seuntjens
- Hugo Palmans
- Karen Rosser
- Saiful Huq
- Wolfgang Ullrich
- Warren Kilby
- Rock Mackie

IAEA

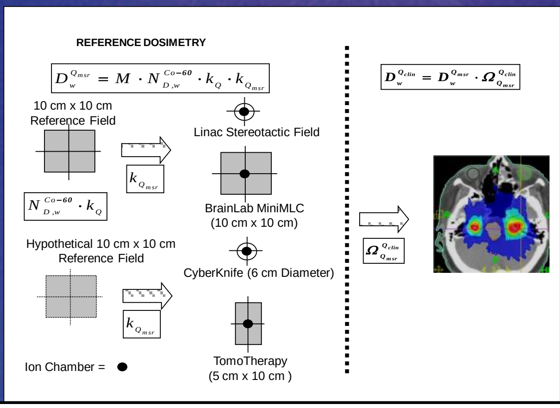
- Pedro Andreo
- Ken R. Shortt
- Stanislav Vatnitskiy
- Roberto Capote
- Joanna Izewska
- Ahmed Meghzifene
- Rodolfo Alfonso

Alfonso et al., A new formalism for reference dosimetry in small and non-standard fields, Med. Phys. 35: 5179 (2008)

Examples of Small and Novel Fields

- GammaKnife - 1.8 cm diameter collimator (1.6 cm on the Perfexon) is the largest collimator – intrinsically composite field – not 100 cm SSD
- Linac SRS beams - extrapolate to small field conditions
- Accuray - 6 cm diameter collimator is the largest collimator – no field flattening filter
- TomoTherapy - 5 cm is the largest slice width – no field flattening filter
- IMRT - made up of numerous small fields

Overview of Static Field Dosimetry

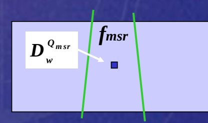


Static Field Calibration

Uses a machine-specific reference field, f_{msr}

$$D_w^{Q_{msr}} = M \cdot N_{D,w}^{Co-60} \cdot k_Q \cdot k_{Q_{msr}}$$

$$k_{Q_{msr}} = \frac{(D/M)_w^{Q_{msr}}}{(D/M)_w^{Q}}$$



Corrects for the differences between the conditions of field size, geometry, and beam quality of the conventional reference field and the machine-specific reference field.

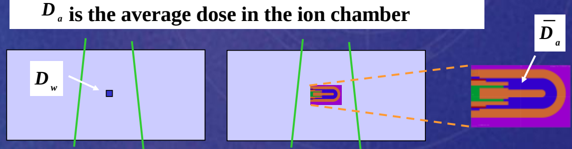
Calculate Using MC

Using method of Sempau et al 2004 *PMB* 49;4427-44

$$k_{Q_{msr}} = \frac{(D_w/\overline{D}_a)^{Q_{msr}}}{(D_w/\overline{D}_a)^{Q}}$$

D_w is the dose at the reference point in water

$\overline{D}_a$ is the average dose in the ion chamber



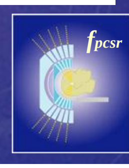
Adapted from Edmond Sterpin

Composite Field Calibration

Uses a plan-class specific reference field, f_{pcsr}

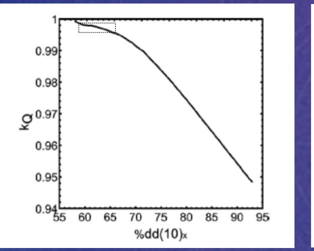
$$D_w^{Q_{pcsr}} = M \cdot N_{D,w}^{Co-60} \cdot k_Q \cdot k_{Q_{pcsr}}$$

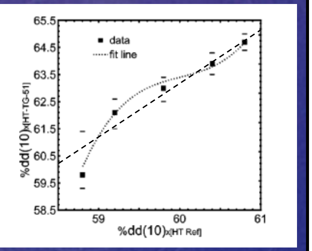
$$k_{Q_{pcsr}} = \frac{(D/M)_w^{Q_{pcsr}}}{(D/M)_w^{Q}}$$



Corrects for the differences between the conditions of field size, geometry, and beam quality of the conventional reference field and the plan-class specific reference field.

"Effective k_Q" for Tomo





1. Determine the %dd(10)x[HT Ref] for a tomotherapy unit for a 5 cm x 10 cm field at 85 cm SSD.
2. Using the graph at the right look up the value of %dd(10)x[HT TG-51].
3. Using the graph on the left and the derived value %dd(10)x[HT TG-51] determine the abscissa and this effective k_Q value is then called $k_Q \cdot k_{Q_{msr}}$ in the IAEA protocol.

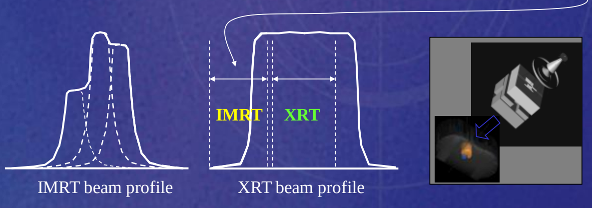
Thomas et al (2005)

Static and Composite Field Calculations for Tomo

Static Field Calibration (Section III.A.1) Jeraj et al 2005	$k_{Q_{msr}}$	Composite Field Calibration (Section III.A.2) Duane et al 2006	$k_{Q_{pcsr}}$
5 cm x 10 cm	0.997	Unmodulated Helical Delivery 5 cm Slice Width	1.000
2 cm x 10 cm	0.993	Unmodulated Helical Delivery 2.5 cm Slice Width	1.000
2 cm x 2 cm	0.990	Unmodulated Helical Delivery 1 cm Slice Width	0.997

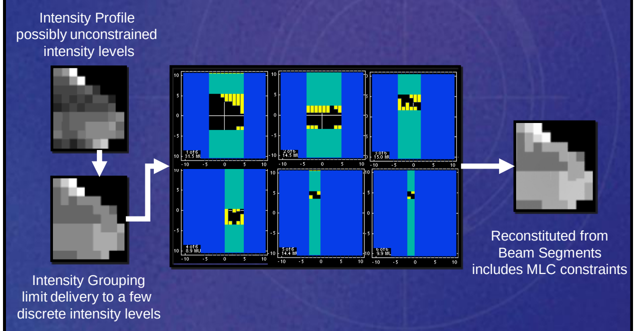
Model-Based Calculation Methods Are Need for IMRT Treatment Planning

- IMRT = Σ small fields
- Dose = function(penumbra+leakage+head scatter)
- Need accurate treatment head model to get this right



From Michael Sharpe, U. of Toronto

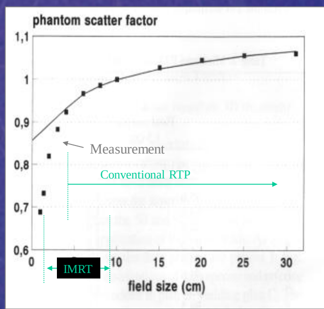
IMRT Is All About Using Small Fields



From Michael Sharpe, U. of Toronto

IMRT Is All About Using Small Fields

- Accuracy of dose model at small field sizes is a consideration
- Convolution-superposition or Monte Carlo desirable

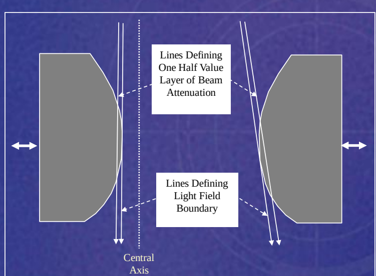


From Michael Sharpe, U. of Toronto

Beam Modeling

- Measured profiles accurately modeled
- Source size
- Output factor (Scp)
- Extrafocal radiation (head scatter)
- Effect of backscatter into monitor unit
- Penumbra model (especially for curved leaf ends)
- Leakage model
- Calculation resolution issues

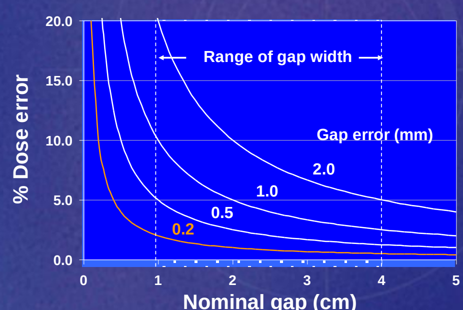
Leaf Penumbra is Important



- **It is important to have an accurate model of the curved leaf ends.**
- **More important for summation of small fields.**

Gap Error is Fundamental fo Conventional MLCs

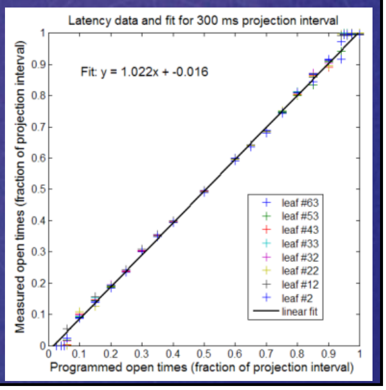
Gap error ⟶ Dose error



From Tom Losasso, Memorial Sloan Kettering

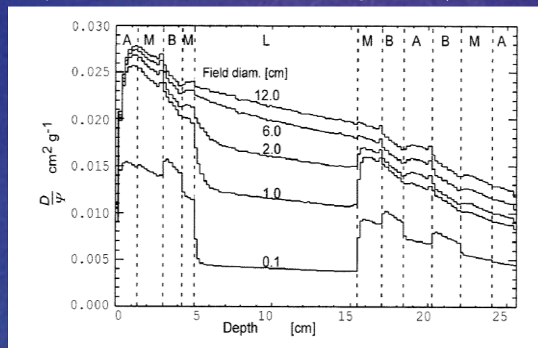
Leaf Latency is Fundamental fo Binary MLCs

- TomoTherapy uses linear fit of measured data to model leaf latency
- Plans with small opening times lead to uncertainty in delivery – also leads to delivery inefficiencies



Dose per Incident Energy Fluence As a Function of Field Diameter

A=Adipose, M=Muscle, B=Bone, L=Lung   4 MV, Parallel Beam



Ahnesjo and Asparadakis, 1999 Phys Med Biol 44:R99-R155

The New York Times

A PINPOINT BEAM STRAYS INVISIBLY, HARMING INSTEAD OF HEALING

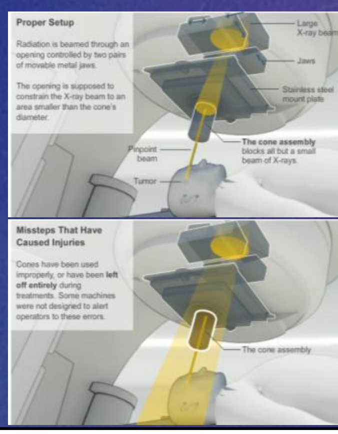
By WALT BOGDANICH and KRISTINA REBELO

Published: December 29, 2010 A fast-growing form of radiation therapy injures patients when its pinpoint beam is allowed to spread too far.

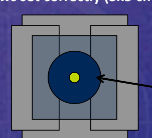
Marci Faber is nearly comatose after a treatment mistake. [treated for trigeminal neuralgia, Evanston, IL]

The New York Times

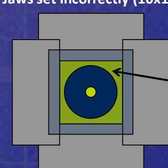
Evanston Accident



Jaws set correctly (5x5 cm)



Jaws set incorrectly (10x10 cm)



The New York Times

Evanston Accident

- Exact cause of jaw setting error not reported. Could be…
  - Planner did not set jaws to 5x5 cm in plan as required
  - Communication error between planning and treatment
- User or system error not picked up by operator at time of planning, QA or treatment
- There was no hardware interlock on machine to recognize insertion of SRS cone, so delivery could be carried out at wrong jaw setting

Conclusions

- **IMRT, SRS and SBRT uses complex field boundaries and/or one or many small circular fields.**
- **Partial volume effects can result in severe error in output factor measurements.**
- **Small chambers exhibit unusual charge collection behavior.**
- **IMRT deliveries are far from the measurement conditions of calibration.**
- **IAEA/AAPM has developed a formalism to account for small and novel beams in more realistic beam conditions.**
- **While worrying about smaller dosimetry errors do not forget about large errors.**