The influence of linear accelerator delivery errors on IMRT

James F. Dempsey, Ph.D.
Department of Radiation Oncology
University of Florida College of Medicine
Gainesville, Florida USA

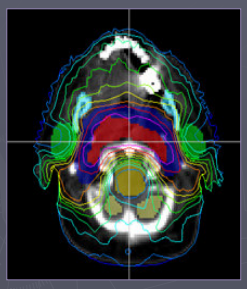
Acknowledgements

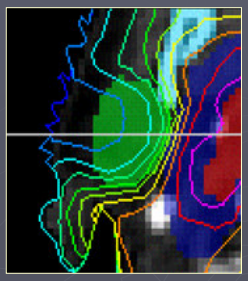
- Thomas J. Losasso — MSKCC
- Jonathan G. Li, Ph.D. — Univ. of Florida
- Chihray Liu, Ph.D. — Univ. of Florida
- Jatinder R. Palta, Ph.D. — Univ. of Florida
- Omar A. Zeidan, Ph.D. — Johns Hopkins
- Tony Stell, M.S. — SUNY Upstate Medical Univ.
- Daniel A. Low, Ph.D. — Washington University

Outline

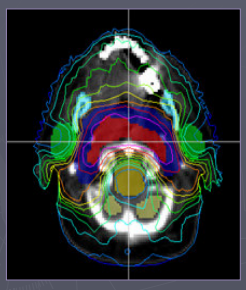
- Delivery Errors!? What Delivery Errors!?
  - Observed Errors
  - Potential Errors
- What is Known About These Delivery Errors?
  - Log Files
  - EPID Measurements
- IMRT QA to prevent delivery potential errors

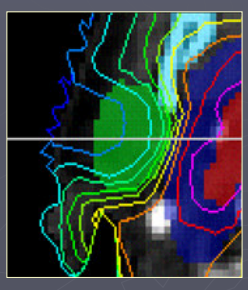
The Motivation for IMRT is Clear!





The Question is: Do We Get What We See in the TPS?





And if not, why? … and then, does it matter?

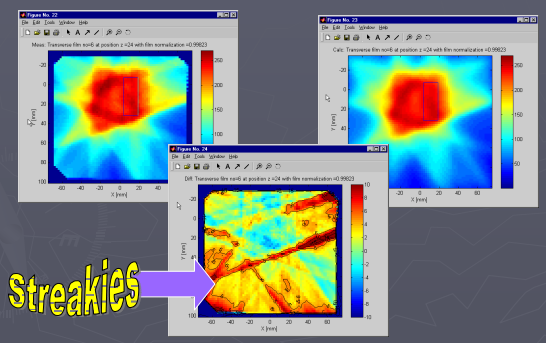
Patient Specific IMRT QA

- We are fairly certain that IMRT is accurate most of the time!
  - Normalization of the plan is typically within 3%
  - Phantom plan agreement in a film plane is reasonable
- But…
- Film agreement is not perfect
- We can not check plans in 3D or w/ Heterogeneities
- Sometimes we have outliers
  - Normalization off by 4% or more
- Something could just fail, and not be detected by current QA methods and not trigger interlocks…
  - Delivery controls and safety designed before IMRT
  - IMRT makes it hard to correlate delivery behavior to accuracy
    - Think about MUs…

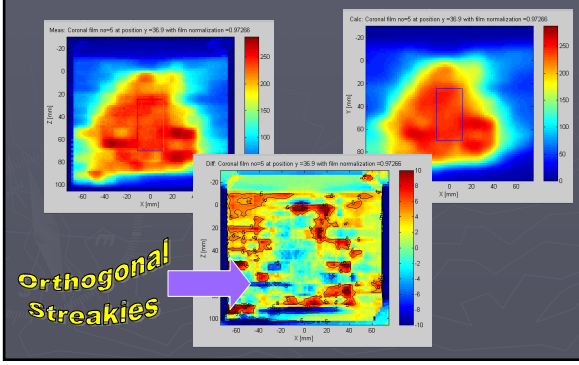
Evidence That Something Could Be Amiss…

- Why would we even suspect that delivery errors exist?!
- Go perform some patient specific IMRT QA
  - i.e. apply the IMRT plan from a patient to some well defined phantom, measure the dose, and compare it with the calculation…
- The answer is typically that
  - The normalization is good to better than 3%
  - The shape of the distribution is not quite right
    - Streakies!
- Let's get a report from the front lines…

Radiographic Film Dosimetry for Patient Specific QA: Axial Planes



Radiographic Film Dosimetry for Patient Specific QA: Coronal Planes



IMRT QA Outliers

See for *e.g.*

Dong *et al.*

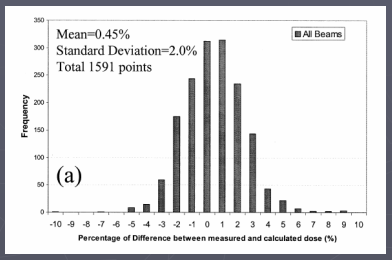
Int. J. Radiation Oncology Biol. Phys., Vol. 56, No. 3, pp. 867–877, 2003

7 Points outside 4σ

In 1600 observations

99.994% C.L.

~Same odds as wining Powerball Multi-state Lotto 4 times



There are lies, damned lies, and then there is statistics… Mark Twain

Surely there is something systematic at work in some cases…

An Important Issue: What is the Definition of Clinical Significance

- Definition of a Cure in Radiotherapy:
  - You Live Long Enough to Die of Something Else…
- Definition of a Clinically Significant Error:
  - Big Enough Not to Be Washed Out By Something Else…
  - A Dosimetric Error That Would Change a Clinical Decision…
  - We have to get back to dose in the patient

Can Errors in IMRT Delivery Matter?

- Yes, if they can change a clinical outcome/decision
- This is not necessarily easy to determine
- Patient Specific IMRT QA
  - Necessary
  - Sufficient?
- We are likely looking for something with low frequency
- We cannot measure dose everywhere in the patient geometry
- Equipment/Algorithm Failure?
- What should IMRT QA consist of?
  - Are outliers an important case to watch for?

Whence Comes the Disagreement?

- It could be delivery error
  - Mechanical Errors?
    - MLC Leaf Positioning
  - Fluence and Timing?
    - Orchestration of MLCs and Fluence

However,

- It could be dosimetry artifacts
  - Some Film Dosimetry Problem?
- It could be algorithmic errors
  - Source Model, Penumbra, MLC Modeling
- More than likely a conspiracy of effects

Study of Delivery Errors in MLC Based IMRT

Monitor Unit Redistribution

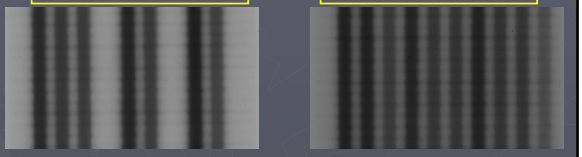
- Delays in the MLC controller communication can cause small errors in MU delivered in individual segments
- Cumulative MUs are correct
- See early reports by
  - Ezzell & Chungbin, J. App. Clin. Med. Phys., 2:138, 2001
  - Xia, Chuang & Verhey, Med. Phys., 29:412, 2002
- To observe shoot simple stripe patterns in SMLC delivery

Static Measurements of Fluence

IMRT Step-and-Shoot
1 MU per strip

Dose Rate: 600 MU/min

Dose Rate: 300 MU/min



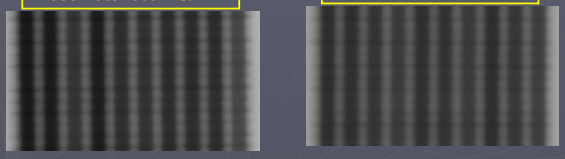
Film measurements of a 10-strip test pattern. The linac (a Varian 2100 C/D) was instructed to deliver 1 MU per strip with the step-and-shoot delivery mode for a total of 10 MU. The delivery sequence is from left to right.

Static Measurements of Fluence

IMRT Step-and-Shoot
2 MU per strip

Dose Rate: 600 MU/min

Dose Rate: 300 MU/min



Film measurements of a 10-strip test pattern. The linac (a Varian 2100 C/D) was instructed to deliver 2 MU per strip with the step-and-shoot delivery mode for a total of 20 MU. The delivery sequence is from left to right.

Why Not Just Ask The Linac?

- "Log File" Analysis
- Use MLC controller logs to look for errors
- See work by
  - Litzenberg *et al.* J. App. Clin. Med. Phys. 3 (2002) 63-72
  - Ezzell & Chungbin, J. App. Clin. Med. Phys., 2 (2001) 138-148
- Validation of "Log Files"?
  - Are they correct?

Linac reported subfield delivery errors

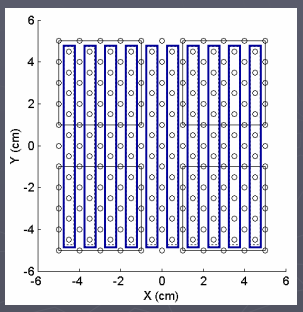
- Two log files are generated by MLC controller for each field delivery
- Each log file records cumulative dose fraction, beam status, and leaf position data for all leaves in the bank.
- Segment MU Log file data has been validated by our group at the University Of Florida
  - Li *et. al.*, Med. Phys. **30**, 799-805 (2003).

Validation of Log Files with Diode Array

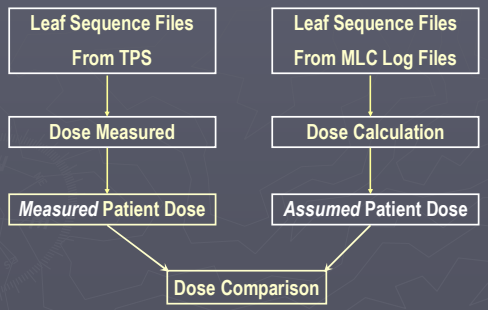
Use Sun Nuclear Map check to measure the "fluence" of simple strip patterns

Very accurate and precise instrument

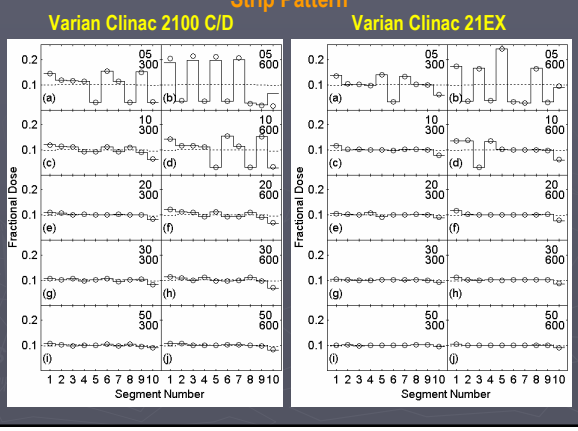
Using the principle of superposition we can check fluence in individual strips



Dosimetric Effect of Delivery Error



Strip Pattern



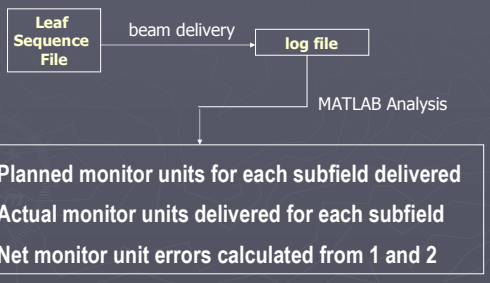
So we can trust them…

- With the validated Log Files we can:
  - perform a large scale study of the accuracy of subfield delivery accuracy
  - determine the frequency and magnitude of the delivery errors
  - study the motion of leaves during delivery
  - study the effect of nominal dose rate
  - study the reproducibility
  - Recalculate the delivered dose using the TPS

Methodology:

- Varian 2100 C/D accelerator
- Millenium 120 MLC
- 91 IMRT patient treatment plans delivered
- Plans delivered at dose rates of
  - 100, 300, & 600 MU/min.
- For details see: Stell *et al.*, Med. Phys. **31**, 1593-1602 (2004).

Data Analysis Procedure:



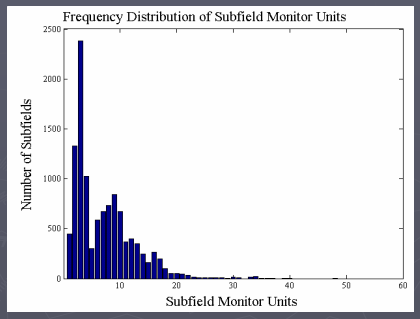
Characteristics of IMRT Plans

- Original plans generated using CORVUS v4.0 for clinical use
- All plans employed 20% fluence modulation
- 10 prostate plans, 65 head and neck plans, and 16 plans from various sites
- Plans use between 5-7 beams
  - may double when split fields are used
- Plans delivered clinically at 300 MU/min.

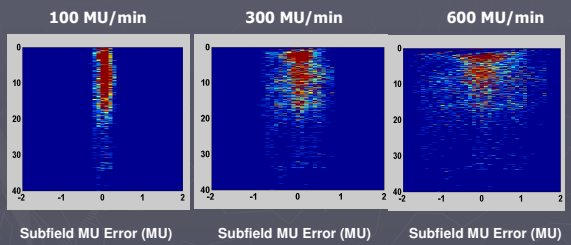
IMRT treatment plans statistics

- 91 clinical IMRT cases
- Represents **635** field deliveries for a single dose rate
- **34,212** subfield deliveries including all three dose rates (**11,404** at each dose rate)

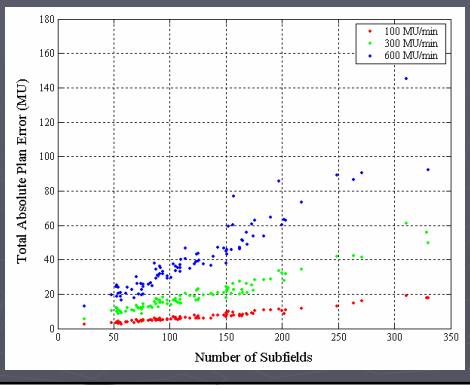
Distribution of Subfield MUs



Individual Subfield Delivery Errors



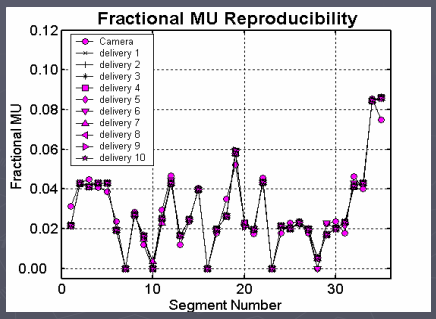
Cumulative Delivery Errors



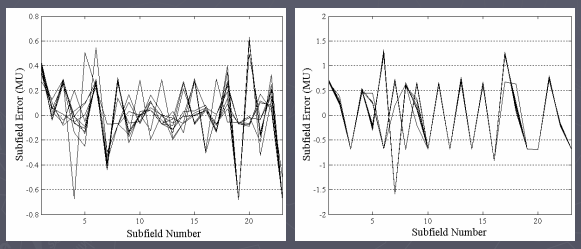
Observations on Segment MUs

- First subfield delivery is associated with a delivery "overshoot" reported by Ezzell *et al.*
- The amount of the overshoot is subtracted from the ensuing field
- The ensuing field also delivered with an overshoot
- Net subfield error is the difference in overshoot between current and previous subfields

600 MU/Min. Reproducibility Same Day

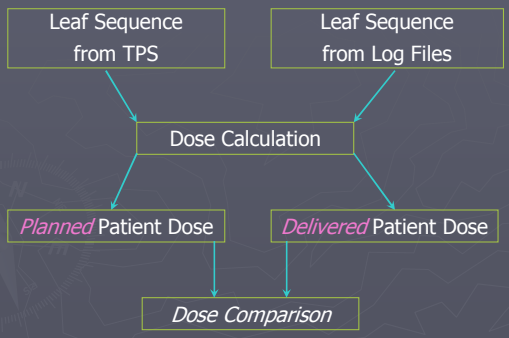


Reproducibility of Subfield Errors 10 Different Days



300 MU/min. **600 MU/min.**

Clinical Significance ?



Data for recalculated plans…

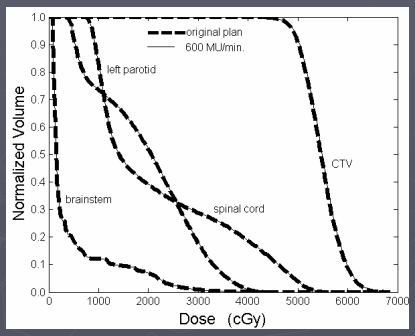
Table I. Relative and absolute plan delivery errors for each of the plans selected for ADAC recalculation.

			relative error (%)		total absolute error (MU)	
Plan	fields	subfields	300 MU/min.	600 MU/min.	300 MU/min.	600 MU/min.
1	14	271	3.78	8.27	41.31	90.5
2	12	264	3.4	7.01	42.07	86.67
3	12	311	3.63	8.63	60.99	145.16

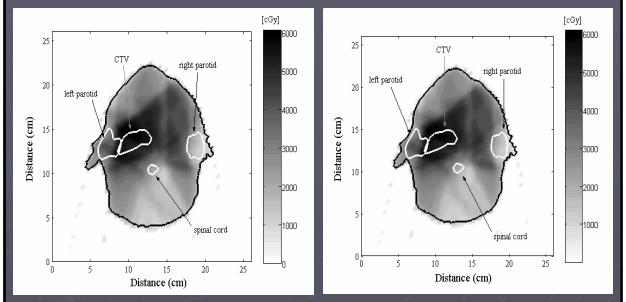
The recalculation process…

- Obtain actual monitor unit distribution from log-file
- Generate Varian shaper (.d60) file that combines monitor unit information with planned leaf positions (one file for each field)
- Combine shaper files and convert into an ADAC format (.Trial file)
- Import .Trial files into ADAC and recalculate dose distribution
- Export RTOG files and compare in Matlab

Original and recalculated DVH for Plan 2

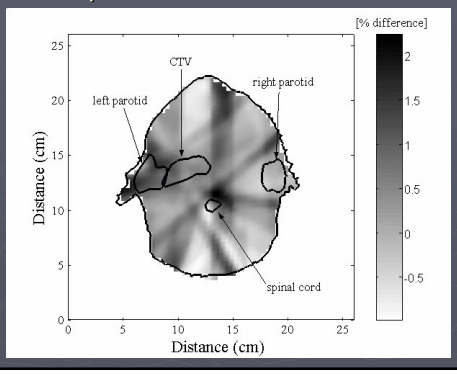


Comparison of absolute dose distributions for Plan 1

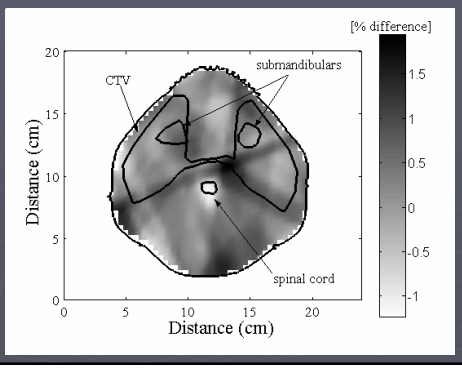


original plan 600 MU/min.

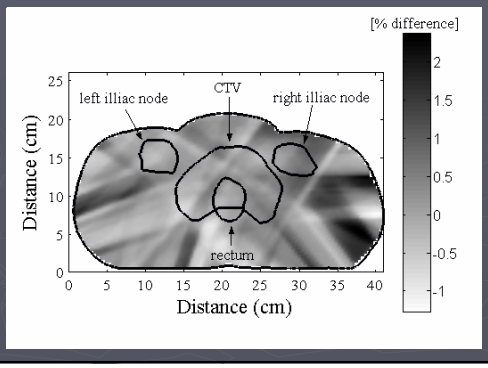
Percent difference from planned dose for Plan 1



Percent difference from planned dose for Plan 2



Percent difference from planned dose for Plan 3



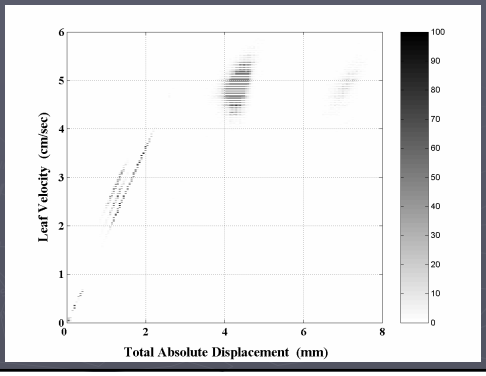
Log File Segment MU Summary

- Magnitude of subfield delivery errors are dose rate dependent and independent of subfield size
- Defined "Worst Case" as largest cumulative MU discrepancy
- No noticeable change to the dose volume histograms due to subfield delivery errors.
- Maximum dose differences are about 3% of the plan dose
- No indication of adverse consequences to the patient for three of the worst case plans studied

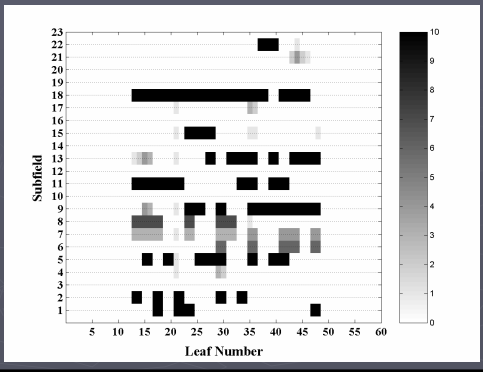
Log File Analysis of Leaf Motions

- Log Files report the positions of all leaves at every sample
- We can calculate average leaf velocities
- Do leaves move as fluence is delivered?
- If leaf motions occur are they reproducible?

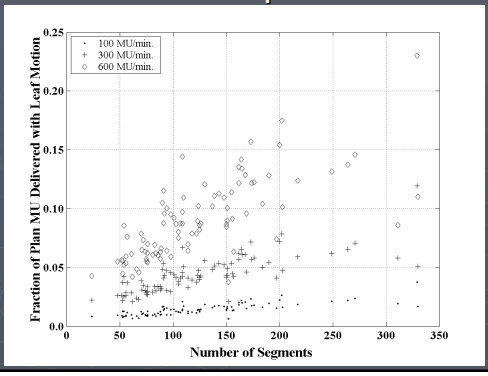
Leaf Velocities in Sample with MUs Delivered



Reproducibility over 10 Days for Leaf Motions



Fraction of MUs Delivered w/ Leaf Motion Reported



Log File Motion MU Summary

- Leaves move faster than previously thought
  - ~5 cm/s
  - We validated this with optical movie & stopwatch
- Log Files report MU delivery with leaf motion
- Leaf motion is fairly reproducible at 600 MU/min.
- These results are not validated!

Dynamic Fluence Imaging

- Use a scintillation based EPID to image the fluence delivered
- Develop a prototype system
- Determine the Requirements of such a system
- Develop a total characterization system to independently measure fluence and shape of any IMRT delivery

Scintillation Camera Based EPIDS

- While EPIDs show great promise for MLC-based IMRT QA
- Most systems have either too few frames per second (FPS) and long integration times
- Start with a CCD Camcorder and Gadolinium Oxysulfide Scintillator (SRI 100)

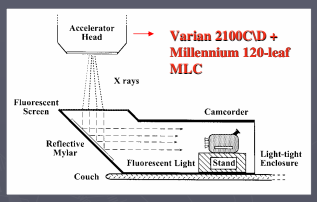
Camera System Characterization

How do we know that the imaging device is capable of measuring the fluence distributions that we seek?

- Signal-to-Noise
- Spatial Resolution
- Fluence Uniformity and Linearity
- Linac Pulse Rate Dependence

We used a 6-MV photon beam delivered from Varian 21000C\D at the nominal dose rate of 600MU/min for all measurements in this work

Imaging System Setup

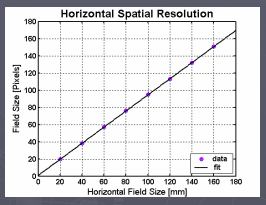


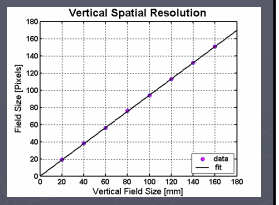
Fluoroscopic Material: $Gd_2O_2S:Tb$ (0.411 g/cm^2) glued to a stainless steel plate (1.24 g/cm^2)

Sony CCD-TRV16 camcorder:
- 30 FPS
- 280 × 320 pixels CCD chip

What can we learn from this simple imaging system?

Spatial Resolution





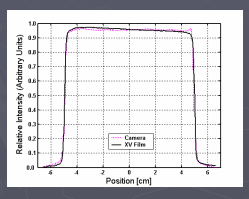
Radial & Transverse profiles of square fields were measured and camera field size determined by the 50% penumbra.

Measure slopes → Spatial resolution of ~ 0.9 mm at field of view focus of 25 × 30 cm^2

Fluence Uniformity and Linearity

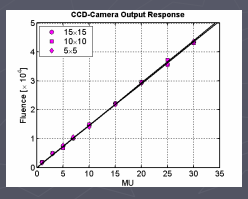
Image intensity information should be directly proportional to incident beam fluence.

Uniformity



Total area under both profiles agrees to within 1%

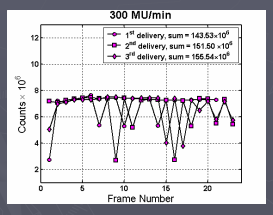
Linearity with Field Size

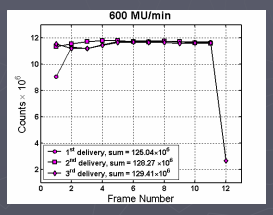


Slope values differences within 2%

Pulse Rate Dependence

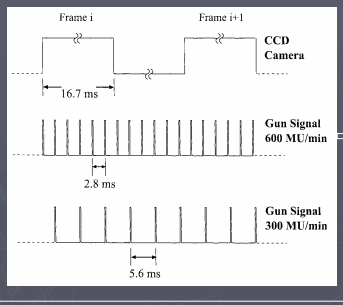
Two square fields of 10 × 10 cm^2 were delivered at two dose rates and at 5 MU/field. The data were digitized and intensity information/frame were extracted.





The frame-to-frame intensity variation is attributed to a combination of an aliasing effect and variation in the output intensity of the linac itself.

Linac/Camera Pulse Sequences



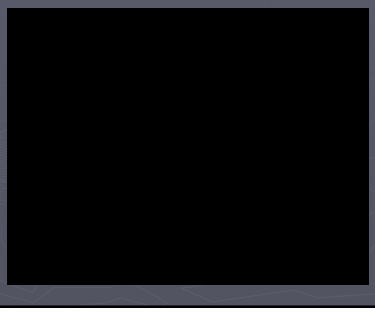
At this dose rate, the gun signal rate matches Klystron signal rate at 360 pps

A schematic of the linac gun signal pulse sequence at two dose rates with respect to the camera frame capture sequence. The diagram depicts the ideal case where the two sequences are not aliased.

The camcorder is not an ideal imaging system. It has several hardware limitations, but it produced very interesting results …

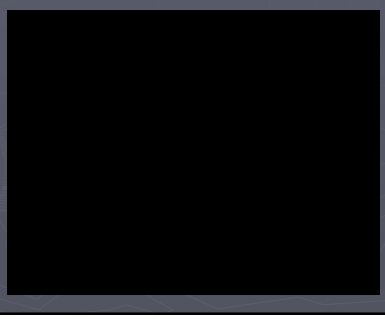
The SMLC Delivery (Raw Movie Data)

Vendor A SMLC IMRT Delivery

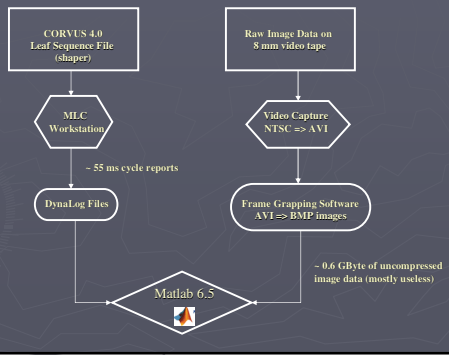


The SMLC Delivery (Raw Movie Data)

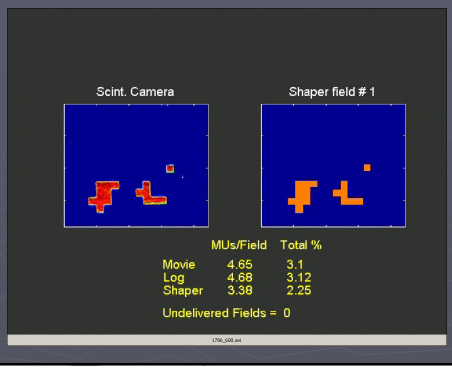
Vendor B SMLC IMRT Delivery



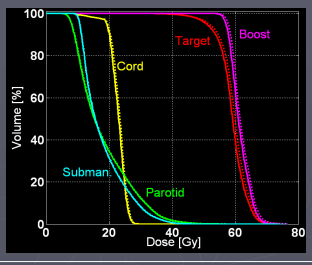
Movie Analysis Procedure



The Movie: again in detail



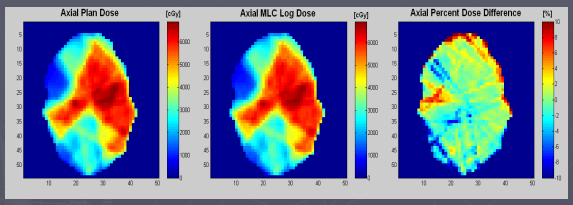
Camera Based Reconstruction



Dose volume histograms of the targets and critical structures for the reconstructed plans based on the leaf sequence files from the treatment planning system (solid lines) and those from the MLC log files (dotted line) . The reconstruction was done in using the Pinnacle treatment planning system with the same patient geometry and dose grid.

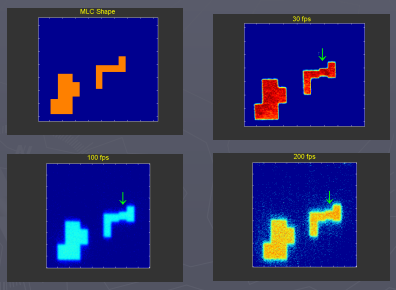
Feedback Treatment Planning Based on the Movie

Imaged MLC delivery errors are accounted for in a recalculated treatment plan



Comparison of the dose distributions in an axial plane between those from the TPS (Plan Dose) and those reconstructed based on the information from the MLC log files at 600 MU/min (MLC log dose) and their percentage dose difference.

Sudden Out-of-Tolerance Leaf Movement



Gd_2O_2S:TB Scintillation plate

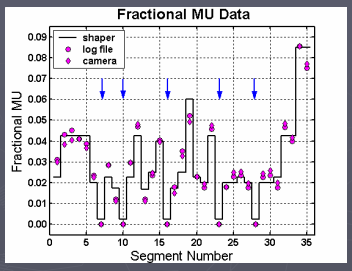
Camera:

30 fps CCD Camera

1000 fps CMOS Camera

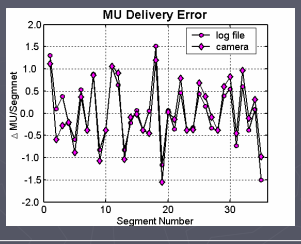
Observation of Leaf Motion During SMLC Delivery

SMLC Delivery



The FMU for a given segment was extracted from the ratio of that segment fluence to the total fluence of all segments.

The Discrepancy Pattern

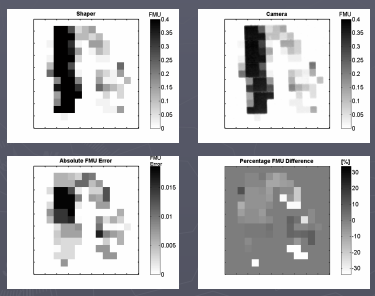


An oscillatory behavior about zero is observed, consistent with a predictor-corrector control algorithm attempting to repair the initial overshoot by repeated over compensation. Results consistent with previous studies*. The segment MUs are redistributed.

* P. Xia *et al.*, Med. Phys. 29, 412-423 (2002)

* G. A. Ezzell *et al.*, J. Appl. Clin. Med. Phys. 2, 412-423 (2002)

Fluence Map Comparison



Very hard to assess MLC delivery errors from fluence maps

We can recalculate fluence maps produced from camera images

What Did We Learn so far?

- The camera system agrees with log file to within 5%. The validated log files can be used as a QA tool for IMRT plan verification.
- Found three types of delivery errors:
  1. FMU delivery errors (FMU redistribution)
  2. Leaf positioning errors: leaf moving while beam is on
  3. Segment dropping (skipping)- only for very small MU segments
- Camera hardware limitations prevent us from pursuing further offline verification of MLC deliveries.
- We need a faster imaging system (hundreds of FPS) with more controls: external strobing, frame rate, shutter speed, …etc

A High Speed Digital Imaging System

Features:

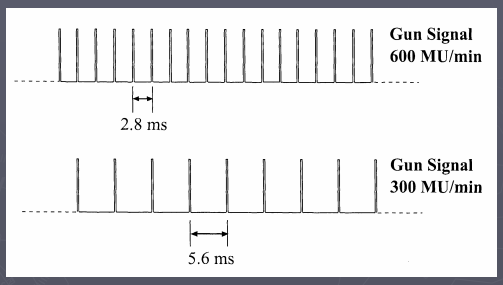
- CMOS camera
- Fire Wire I/O rates of 400 MBits/s
- Up to 512 × 512 pixels
- 10 μs Shutter Speed
- Up to 1000 FPS
- 6 GB onboard memory
- ~$25K

Redlake MotionPro 500

Collect Data at 360 FPS strobed by the sync signal from the Linac

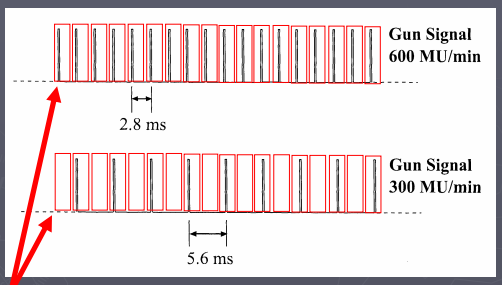
Every single pulse is captured in a frame

Linac/Camera Pulse Sequences



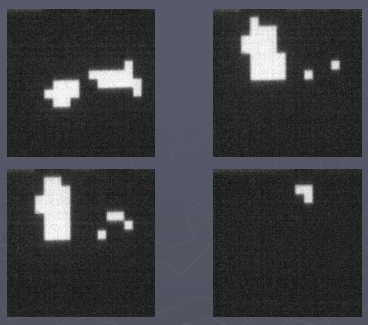
High Speed Camera can trigger on preceding pulse and capture all possible pulses

Linac/Camera Pulse Sequences



High Speed Camera Frames

Very Fast MLC Motions: 72 FPS from 360 FPS Data



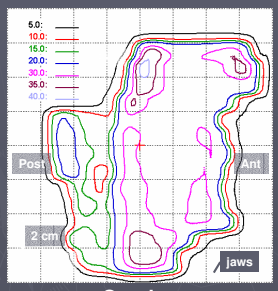
High Speed Camera Analysis

- Log Files predicted that motions occurred often at the end of segment deliveries
- HS Camera shows that the motion typically occurs after fluence is delivered
- HS Camera caught MLC motion at very fast time scales
- HS Camera is the definitive answer in delivery validation

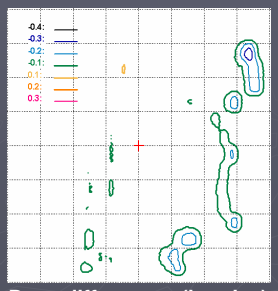
What About DMLC Deliveries

- Similar problems exist in DMLC delivery
- Given pulse structure of the linac, DMLC is also a type of discrete delivery
  - i.e., the leaves don't get far in 5 microseconds and there is a ~3 milisecond wait in between
- Special thanks to Dr. Thomas Losasso for providing some data from MSKCC

Log file → Leaf sequence file → dose distribution



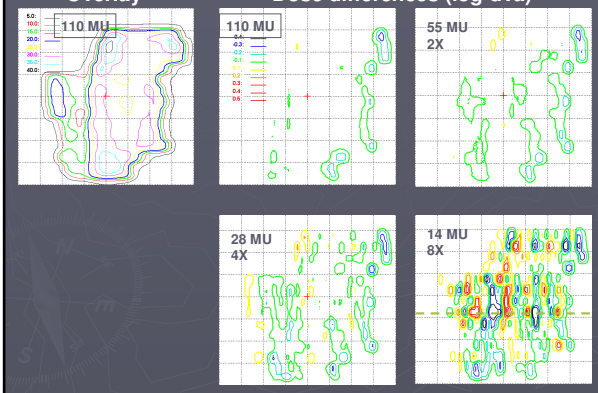
Overlay



Dose differences (log-dva)

Overlay

Dose differences (log-dva)



Timing / communication errors

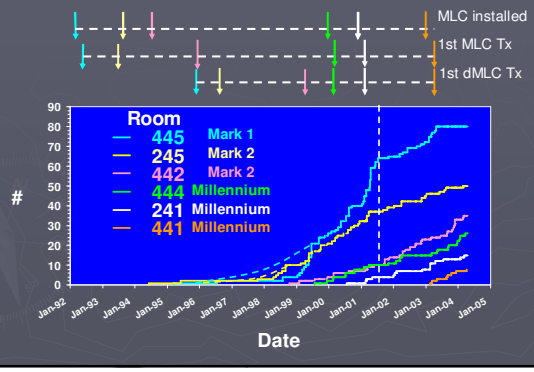
Is there an analogous problem for DMLC?

- **Trailing leaves (B-side) compensate for the leading leaves (A-side)**
- **Dose (MU) error = position error (B) – position error (A)**
  leaf speed (B) leaf speed (A)

Yes, if

- **leaf sequencers actively utilize the beam hold-off to control leaf speed**
- **if leaves can not maintain their rated speed**

Motor replacement history

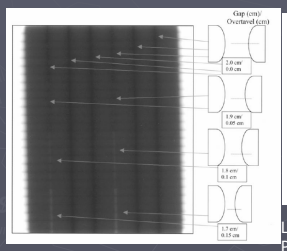


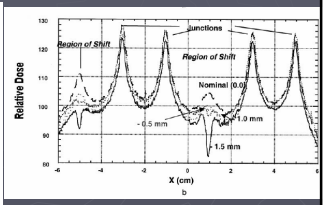
IMRT QA & Delivery Errors

- What consideration should be made for potential Linac delivery errors in periodic IMRT QA?
- Is Patient Specific QA Enough?
- Some Simple Tests That Could Detect Systematic Delivery Errors in MLC-Based IMRT
  - SMLC
  - DMLC

MLC Delivery Device Characterization via Film

- Radiographic meas. of accuracy of leaf travel/ offset And Integral Fluence Maps
- Absolute vs. Relative

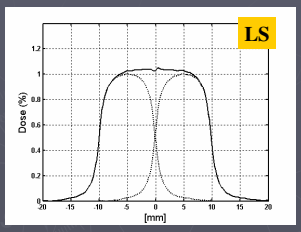


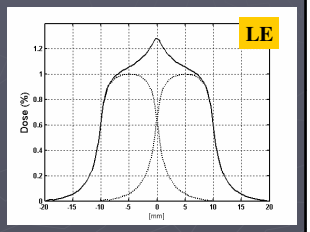


LoSasso T et al. Med. Phys. 2001; 28(11):2209-2219.

Beamlet Superposition: EDR2 measurements

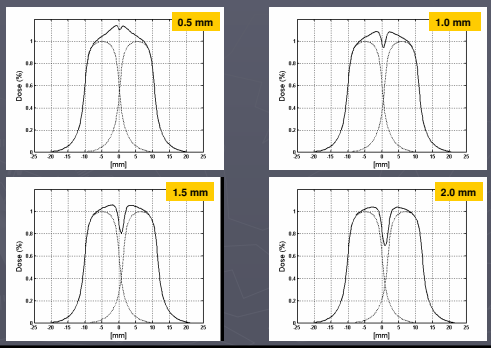
CAX Cross Profiles: 5.0 cm depth, shift = 1.0 cm. Transmission dose is subtracted.





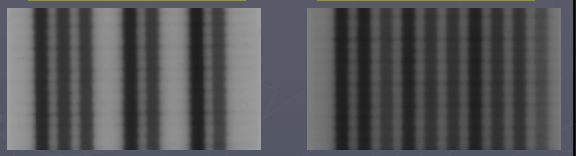
Beamlet Superposition: EDR2, LE

How is the superposition changing with distance between LE profiles?



Proposed MLC QA for SMLC IMRT Delivery Errors

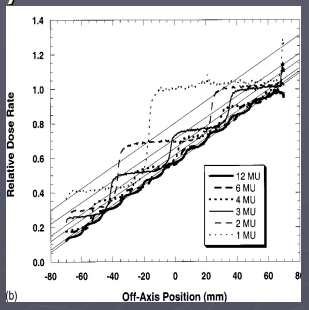
Dose Rate: 600 MU/min **Dose Rate: 300 MU/min**



- Film or diode measurements of a 10-strip test pattern.
- The linac is instructed to deliver X MU/strip, where X is acceptable MU error in a segment
- Action is taken if segments are dropped or significantly low

Proposed MLC QA for DMLC IMRT Delivery Errors

- Film or diode measurements of wedge-like or linearly increasing field.
- The linac is instructed to deliver X MU, where X results in the max leaf velocity employed in IMRT delivery
- Action is taken if profile deviates significantly from are dropped or significantly low



Low *et al.* Med. Phys. **28** (2001) 752-756

Suggested Confidence Limit and Action Level Values for IMRT Planning

Region	Confidence Limit* (P=0.05)	Action Level
δ_1 (high dose, small dose gradient)	3%	5%
δ_1 (high dose, large dose gradient)	10% or 2 mm DTA	15% or 3 mm DTA
δ_1 (low dose, small dose gradient)	4%	7%
$\delta_{90\text{-}50\%}$ (dose fall off)	2 mm DTA	3 mm DTA

* Mean deviation used in the calculation of confidence limit for all regions is expressed As a percentage of the prescribed dose according to the formula, $\delta_1 = 100\% \times (D_{calc} - D_{meas.}/D_{prescribed})$

Segmental Multileaf Collimator (SMLC) Delivery System

	Tolerance Limit	Action Level
MLC*		
Leaf position accuracy	1 mm	2 mm
Leaf position reproducibility	0.2 mm	0.5 mm
Gap width reproducibility	0.2 mm	0.5 mm
Gantry, MLC, and Table Isocenter	0.75 mm radius	1.00 mm radius
Beam Stability		
Low MU Output (<2MU)	2%	3%
Low MU Symmetry (<2MU)	2%	3%

** Measured at all four cardinal gantry angles*

Dynamic Multileaf Collimator (DMLC) Delivery System

	Tolerance Limit	Action Level
MLC*		
Leaf position accuracy	0.5 mm	1 mm
Leaf position reproducibility	0.2 mm	0.5 mm
Gap width reproducibility	0.2 mm	0.5 mm
Leaf speed	±0.1 mm/s	±0.2 mm/s
Gantry, MLC, and Table Isocenter	0.75 mm radius	1.00 mm radius
Beam Stability		
Low MU Output (<2MU)	3%	5%
Low MU Symmetry (<2MU)	2%	3%

Summary

- Delivery Errors exist in MLC based IMRT delivery but appear to frequently be non-catastrophic
- There is a potential for infrequent problems that could be significant
  - Not observed to date
- The orchestration of the motion of leaves and fluence delivery needs further study

Summary

- It is proposed that a periodic method of assessing the magnitude of delivery errors be performed
  - Simple strip test could be done for SMLC
  - Simple linear field could be done for DMLC
- MLC QA for IMRT requires more diligence due to rare, yet important events
  - Outliers
  - Motor Failure

Acknowledgements

- Support of NIH R01 CA100636 Awarded by the National Cancer Institute
- SpectraVision Imaging
- Redlake
- Sun Nuclear

Thanks for Your Attention