Emerging Technology: Real-Time Monitoring of Treatment Delivery

EPID Exit Dose QA

Arthur Olch, PhD, FAAPM

AAPM Spring Clinical Meeting, March 21, 2017

Or……..

What Dose are the Patients Really Getting ???

Or…….

What Could Go Wrong?

What Could Go Wrong?

- HN treatment, VMAT, PTV extends below shoulders. IGRT doesn't look at shoulders. Small change in shoulder position makes large dose error.
- IGRT causes couch shifts which take immobilization devices considered in the TPS to different locations relative to the isocenter.
- Anatomy changes not appreciated at time of IGRT.
- The linac fails to operate properly after the pretreatment QA is done and passed.

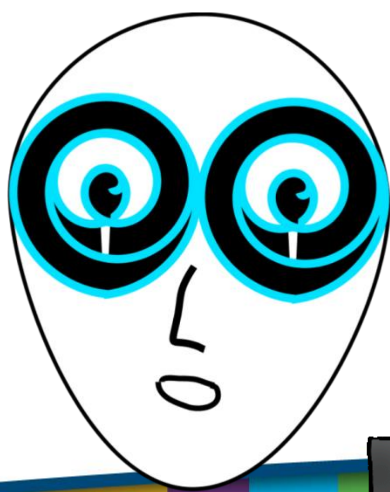
Conflict of Interest

- I am a Sun Nuclear Corporation beta site for PerFRACTION
- **Note: Mention of any commercial product does not constitute an endorsement**

Current State of Patient QA

- Calibrate the linear accelerator
- Routine machine QA
- Commission TPS
- Use very accurate dose calculation algorithms
- Perform Pretreatment patient-specific QA

Daily Treatment



The Ideal

- Gather information for every patient every fraction on the dose they received that day and cumulate it daily
- Compare to planned dose and decide whether to fix anything (like the plan, the patient, patient setup, or the linac)

What will it take, besides having an EPID?

- Need Methods to:
  - Automatically get images out of the EMR into the analysis system
  - Convert pixel values to dose
  - Calculate 2D Gamma for per-beam daily images vs. a reference image
  - use log files with/without cine images to calculate 3D dose
  - Backproject planar dose images to 3D dose
  - Compare daily measured 2D and 3D dose to planned dose

- **No one has the time to perform dose comparisons for every patient every day**

What has already been Done?

Studies go back 15 years !

Radiotherapy and Oncology 88 (2008) 289–309
www.thegreenjournal.com

Systematic review

A literature review of electronic portal imaging for radiotherapy dosimetry

Wouter van Elmpt[a,*,1], Leah McDermott[b,1], Sebastiaan Nijsten[a], Markus Wendling[b], Philippe Lambin[a], Ben Mijnheer[a,b]

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implemented in a radiotherapy department. It provides a safety net for simple to advanced treatments, as well as a full account of the dose delivered. Despite these favourable characteristics and the vast range of publications on the subject, there is still a lack of commercially available solutions for EPID dosimetry. As strategies evolve and commercial products become available, EPID dosimetry has the potential to become an accurate and efficient means of large-scale patient-specific IMRT dose verification for any radiotherapy department.

2D transit dose verification at patient level	Patient/phantom (in vivo)	Essers [22,126], Kirby [156,157], Boellaard [81,158]	Reconstructed exit dose (3D CRT)
	Patient/phantom (in vivo)	Boellaard [159,160]	Reconstructed 2D midplane dose (3D CRT)
	Phantom (pre-treatment)	Wendling [76]	Reconstructed 2D midplane dose (IMRT)
	Patient/phantom (pre-treatment and in-vivo)	McDermott [161,162]	Clinical results for prostate IMRT
	Phantom (pre-treatment)	Talamonti [77]	2D verification (IMRT)
3D dose verification (dose calculated using a CT scan acquired from the planning stage or acquired 'in room')	Patient (planning CT)	Hansen [39] 2007	Back-projected dose based on transmission EPID images and planning CT scan
	Patient (planning CT)	Jarry [163] 1996	Back-projected energy fluence based on EPID images and a Monte Carlo calculation using the planning CT scan
	Patient (planning CT)	McNutt [123,124] 2003	Combined EPID transit dose measurement and planning CT scan in an ''extended phantom'' using the TPS
	Patient (planning CT)	Louwe [166] 2008	Reconstructed 3D dose distribution (breast)
	Patient (in room CT)	McDermott [167] 2002	Reconstructed in vivo dose for rectal cancer patients using cone-beam CT scan
	Patient (in room CT)	Partridge [164]	Back-projected dose based on transmission EPID images and MV cone-beam CT

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Table 4
Overview of the various errors that can be detected with EPID dosimetry

Potential errors	Pre-treatment verification				Treatment verification			
	2D/3D	2D		3D	2D			3D
	No phantom	Behind phantom	Inside phantom	Inside phantom	Before patient	Behind patient	Inside patient	Inside patient
Machine								
Wedge presence and direction	Yes (systematic errors)				Yes (systematic and random errors)			
Presence of segment	Yes (systematic errors)				Yes (systematic and random errors)			
MLC leaf position/speed	Yes (systematic errors)				Yes (systematic and random errors)			
Leaf sequencing	Yes (systematic errors)				Yes (systematic and random errors)			
Collimator angle	Yes (systematic errors)				Yes (systematic and random errors)			
Beam flatness and symmetry	Yes (systematic errors)				Yes (systematic and random errors)			
Linac output during treatment	No				Yes			
Gantry angle	No	Possible	Possible	Possible	No	Possible	Possible	Possible
Plan								
Transmission through leaves	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Steep dose gradients	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
TPS modelling parameters for MLC	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Delivery of wrong patient plan	Yes (if same plan is used for verification and treatment)				Yes	Yes	Yes	Yes
Dose calculation in phantom or patient	No	No	Yes	Yes	No	No	Yes	Yes
Patient								
Table arm obstruction	No	No	No	No	No	Yes	Yes	Yes
Obstructions from immobilisation devices	No	No	No	No	No	Yes	Yes	Yes
Anatomical changes in patient since planning CT	No	No	No	No	No	Yes	Yes	Yes
Anatomical movements during treatment	No	No	No	No	No	Yes	Yes	Yes
Wrong patient during treatment	No	No	No	No	No	Yes	Yes	Yes
Under/over-dose to volumes of interest	No	No	No	No	No	No	Single plane	Yes
Dose distribution in patient during treatment	No	No	No	No	No	No	Single plane	Yes

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A quantification of the effectiveness of EPID dosimetry and software-based plan verification systems in detecting incidents in radiotherapy

Casey Bojechko, Mark Phillps, Alan Kalet, and Eric C. Ford[a)]
Department of Radiation Oncology, University of Washington, 1959 N. E. Pacific Street, Seattle, Washington 98195

- Studied 230 external beam delivery errors
- The majority were related to patient positioning and only 6% of these could be detected by EPID dosimetry when performed prior to treatment.
- 74% could be detected by EPID in vivo dosimetry performed during the first fraction.

Pretreatment EPID QA

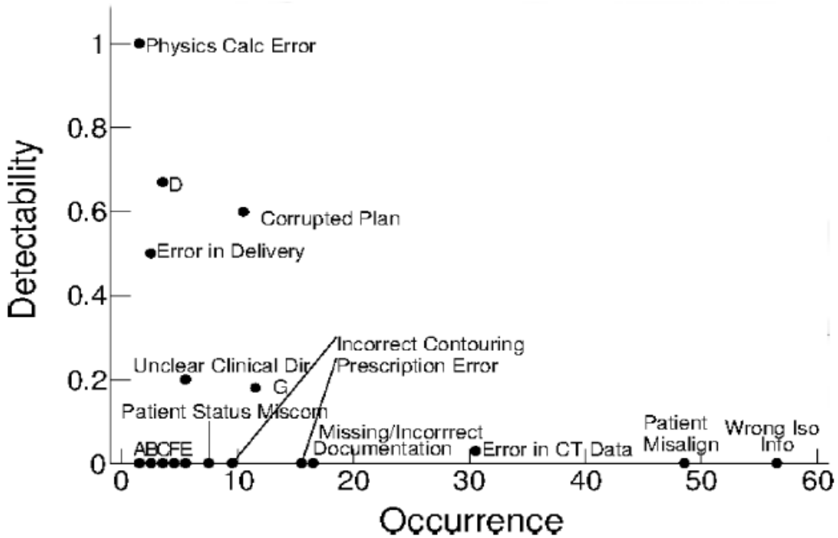

FIG. 1. Pretreatment EPID dosimetry detectability vs occurrence.

In vivo EPID QA

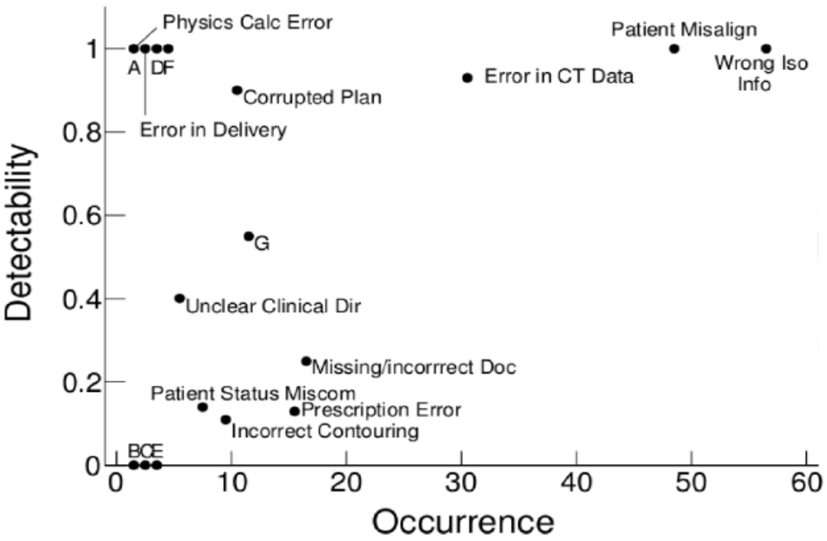

FIG. 2. *In vivo* first fraction EPID dosimetry detectability vs occurrence.

Catching errors with *in vivo* EPID dosimetry

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They detected 17 serious treatment errors out of 4337 treatments using an EPID based per fraction QA approach. ***Nine of these errors would have been missed with pretreatment verification only***

(b) Error type	No. of errors
Patient anatomy	7
Plan transfer	4
Suboptimally tuned TPS parameter	2
Accidental plan modification	2
Failed delivery	1
Dosimetrically undeliverable plan	1
Total	**17**

Fuangrod et al. Radiation Oncology (2016) 11:106
DOI 10.1186/s13014-016-0682-y

Radiation Oncology

RESEARCH Open Access

Investigation of a real-time EPID-based patient dose monitoring safety system using site-specific control limits

Todsaporn Fuangrod[1*], Peter B. Greer[2,4], Henry C. Woodruff[3], John Simpson[2,4], Shashank Bhatia[4], Benjamin Zwan[2,5], Timothy A. vanBeek[6,7,8], Boyd M.C. McCurdy[6,7,8] and Richard H. Middleton[1]

Methods: The system compares measured cumulative transit EPID image frames with predicted cumulative image frames in real-time during treatment using a χ comparison with 4 %, 4 mm criteria. The treatment site-specific thresholds (prostate, HN and rectum IMRT) were determined using initial data collected from 137 patients (274 measured treatment fractions) and a statistical process control methodology. These thresholds were then applied to data from 15 selected patients including 5 prostate, 5 HN, and 5 rectum IMRT treatments for system evaluation and classification of error sources.

Results: Clinical demonstration of real-time transit EPID dosimetry in IMRT was presented. For error simulation, the system could detect gross errors (i.e. wrong patient, wrong plan, wrong gantry angle) immediately after EPID stabilisation; 2 seconds after the start of treatment. The average rate of error detection was 7.0 % (prostate = 5.6 %, HN= 8.7 % and rectum = 6.7 %). The detected errors were classified as either clinical in origin (e.g. patient anatomical changes), or non-clinical in origin (e.g. detection system errors). Classified errors were 3.2 % clinical and 3.9 % non-clinical.

Log File Concerns

- The accuracy of machine information recorded on the log file remains unclear.
- Is the recorded information measured with independent sensors; what is the accuracy and uncertainty of those sensors; can we perform adequate calibration and QA as we do for ion chambers and other QA devices; and are there failure modes for which the sensors fail to detect errors.
- Incident at a TomoTherapy site - the jaw sizes were varying during rotational delivery while the jaw position recorded on the log file recorded the same position as planned. The jaw was driven by a stepping motor and its connection was loose, leaving the jaw freely moving, whereas stepping motor positions recorded on the log file were per the plan.
- It has been speculated that the MLCs in Varian linacs may potentially have the same issue, since they use similar stepping motors for controlling MLCs.
- There are several important aspects of treatment delivery that currently are not recorded in log files, such as beam symmetry and energy.
- Log files can't tell you anything about the patient setup or anatomy changes
- The log file-based QA approach offers many advantages, yet it still requires further investigation of its limitations before it is clinically adopted.

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Log Files !

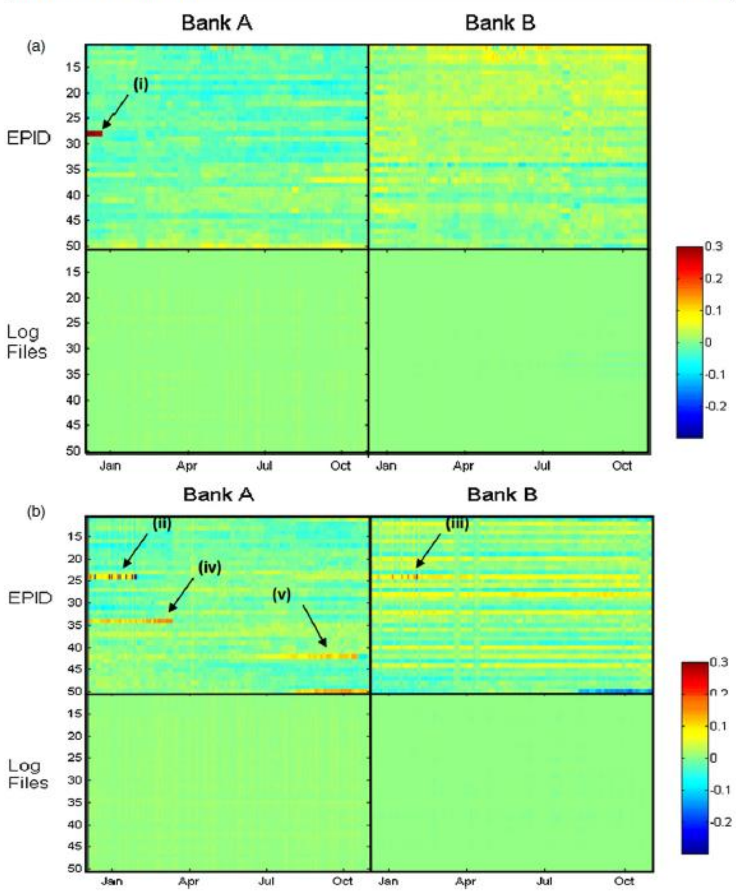

Figure 5. Leaf position errors over time for TB1 (a) and TB2 (b), analysed using both EPIDs and trajectory logs. *X*-axis represents time, *Y*-axis represents the leaf number, ranging from 10 to 50, and *Z*-axis (colour scale) represents the error in position.

Phys. Med. Biol. 59 (2014) N49–N63 doi:10.1088/0031-9155/59/9/N49

Note

Monitoring daily MLC positional errors using trajectory log files and EPID measurements for IMRT and VMAT deliveries

A Agnew[1], C E Agnew[1], M W D Grattan[1], A R Hounsell[1,2] and C K McGarry[1,2]

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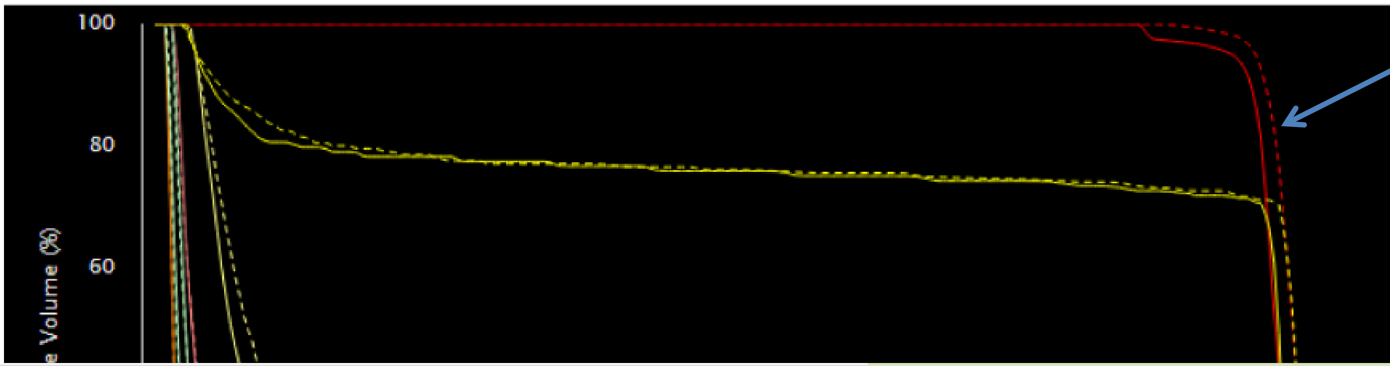
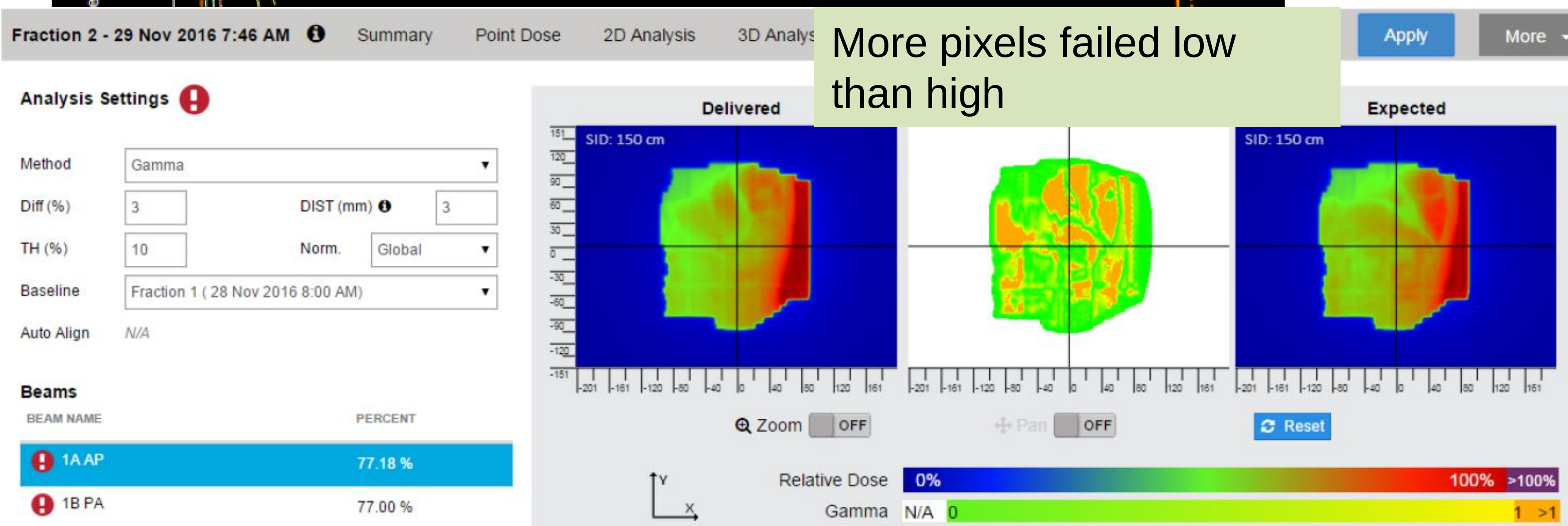
Log File 3D dose vs. EPID Exit images



1% higher delivered dose

More pixels failed low than high



Where are we today?

- Technical advances have been made:
  - Automatic Query Retrieve of images into analysis software
  - Can use integrated or cine EPID images
  - EPID dose can be recalculated in patient planning CT
  - Dose can be calculated on CBCT of the day
  - Log Files with or without EPID images can be used to calculate 3D dose
- Several vendors have commercial products now.
- Some are devices that measure dose at collimator, others use EPID exit dose and/or log files

Commercial Systems

- Sun Nuclear- PerFRACTION 2D and 3D
- DosiSoft – EpiGray
- Math Resolutions - Dosimetry Check
- Mobius Medical – Mobius3D
- Standard Imaging – Adaptivo

- Some use EPID images, some log files, some both

New Paradigm

- Fully automated data capture and analysis makes daily patient treatment QA **feasible**
- Uses imaging hardware we all already have
- Provides a significant enhancement in patient safety and understanding of actual absorbed dose in the patient during the course of treatment

What Can These Systems Do?

1. 2D Gamma Analysis using EPID images per field for fraction N vs. fraction 1 or vs. predicted image from TPS

2. 3D dose, 3D gamma, point dose, and DVH comparison to TPS (in planning CT or CBCT of the day) using Cine images of each field (along with log files)

3. Pretreatment QA using EPID images of each field calculated against the TPS dose or an independent dose calc. Log files can also be used.

Vendors are Dependent on Varian and Elekta

- For Log files – Varian doesn't yet fully support Log files
- For raw cine images- Varian doesn't make available on TrueBeam
- For CBCT registration files – Varian doesn't comply fully with IHE-RO
- Aria and Mosaiq issues
- Elekta issues

Using the EPID as a High Resolution Absolute Dose Detector Array for Pretreatment QA

- Is being offered by several vendors
- Although more efficient and easier than using a separate measurement device, NOT what's novel.

- What's groundbreaking is the ability to detect and measure errors **<u>in daily treatment</u>**.

SNC PerFRACTION

- Performs 2D gamma analysis comparison of the EPID image on the first fraction vs. all subsequent fractions or vs. TPS predicted image (later this year).
- Performs 3D calculation of daily dose in planning CT or CBCT and allows DVH comparisons between daily dose and planned dose. Uses Log Files for dose per CP and cine images for MLC positions.
- Performs pretreatment QA (in air) with DVH analysis in patient CT
- Trends results per patient or per linac

Dedicated Networked PC (Server)

- Embedded MS Win
- Dell Precision T3610
  16GB
- Intel Xeon Processor E5-1607 v2 (Quad Core, 3.0 GHz, 10 MB)
- 3 GB NVIDIA Quadro K4000
- 256GB SSD
- 3TB Enterprise HDD

Software Setup

- Works with Aria and Mosaic
- Setup Server on network
- Web-based interface
- Configure DICOM Listener with connection to RV Database (Aria or Mosaic)
- Configure comparison tests

Workflow

- Export plan, CT, SS, dose grid from TPS to SNC Server
- Get integrated (2D analysis) or cine (3D analysis) EPID images of each treatment field/arc on every fraction
- Can review results in the PerFRACTION software (or just wait for the email failure notifications), create plan and fraction reports

How Sensitive is the System for Finding Errors?

Experimental design

- A series of phantom plans were generated to test various types of errors.
- The first fraction was delivered error-free.
- The subsequent fractions were delivered with induced errors.
- We also verified EPID-linac constancy over the same time frame as for the study images.

Items tested

Test	Induced error (defined at Iso center)	Errors expected in EPID integrated images (EPID at 150 FDD)
Jaw position	1, 2, 3, 4mm	1.5, 3, 4.5, 6 mm
MLC position	1, 2, 3, 4, 5 mm	1.5, 3, 4.5, 6, 7.5 mm
Linac output	0.5, 1, 1.5%	Same as induced
Collimator rotation	1, 2, 3 degrees	1.3, 2.6, 3.9 mm
Couch shift	1,2,3 mm	1.5, 3, 4.5 mm
Static open field	Rails in vs. out	Rails change in position
VMAT arc	Rails in vs. out	Dose distribution changes
Open field arc	Rails in vs. out	Dose distribution changes

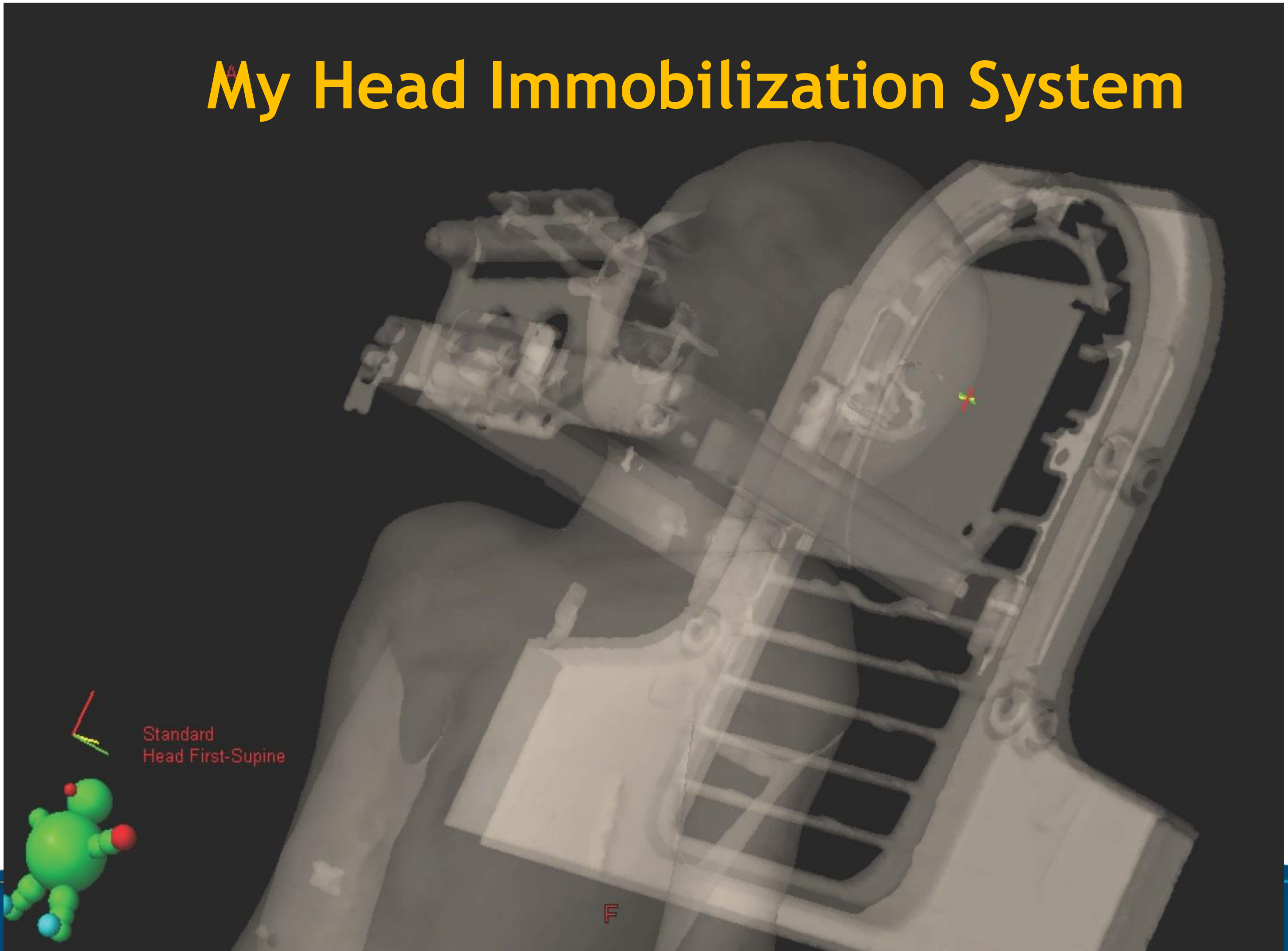
Results

Test	Induced error	PerFRACTION detected error
EPID linac constancy	None	0.20%
Jaw position	1.5 mm	1.3 mm
MLC position	1.5 mm	1.1 mm
Linac output	0.5%, 1.0%, 1.5%	0.5%, 1.2% and 1.6%
Collimator rotation	1 degree	0.7 degree
Couch shift	1.5 mm	1.7 mm
Static open field (Rail effect)	Rails in vs. out	Yes, up to 8% dose change
VMAT arc (Rail effect)	Rails in vs. out	Up to 3% dose change

Conclusions

- We found that PerFRACTION is capable of detecting sub-millimeter and sub-degree changes in field position.
- It can detect output changes to within 0.2%.
- It is fairly sensitive at detecting whether the rails are in or out.

Influence of External Devices and Setup Error



Influence of External Devices

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Upload | Save and Promote | Report | Go to Staging Queue | Comments

Build Number: 1.1.0.163

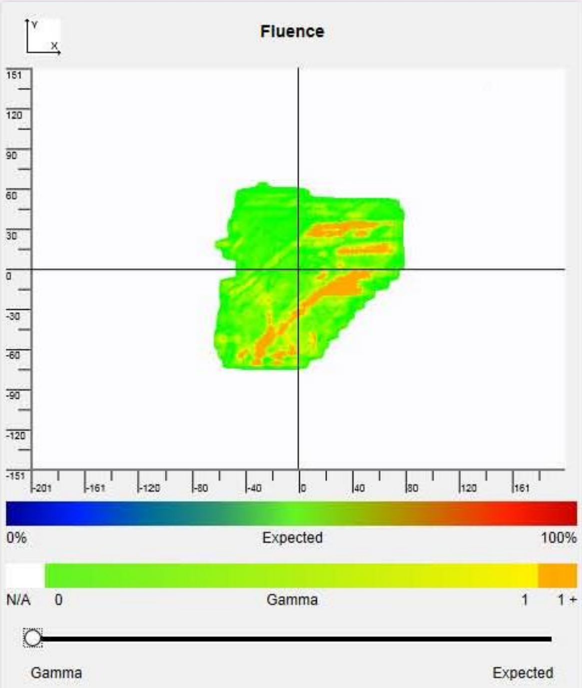
2F LASO2-324	--
2G LPSO-324	! Failed
2H LASO1-353	✔ Passed

Difference Tolerance (%)	2	2
Distance Tolerance (mm)	2	1
Threshold (%)	10	10
EPID Baseline	1	1

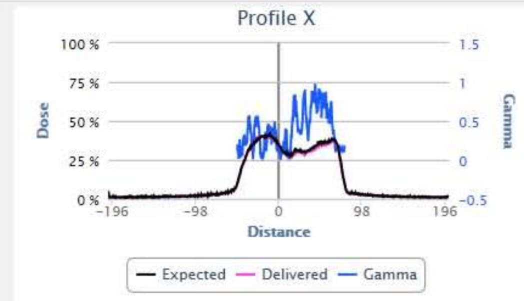
▶ Calculate

This beams exits through head frame structure corresponding to the orange failing pixels

EPID Results



Base Align | Shifted Align | No better match found.

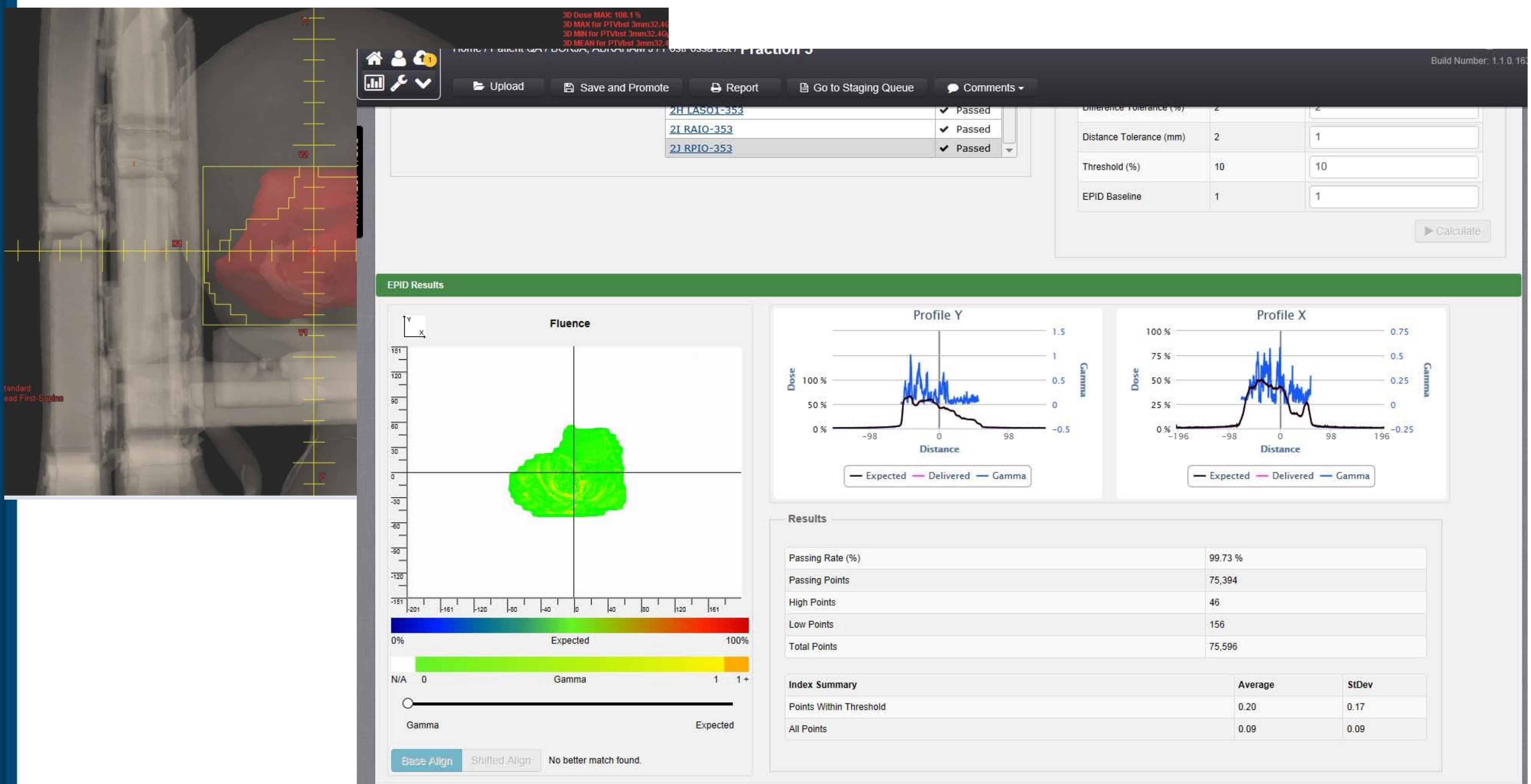


Results

Passing Rate (%)	88.85 %
Passing Points	87,647
High Points	2,715
Low Points	8,284
Total Points	98,646

Index Summary	Average	StDev
Points Within Threshold	0.48	0.42
All Points	0.15	0.21

Beam Without External Device in Path



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Exit Dose Change is Measured

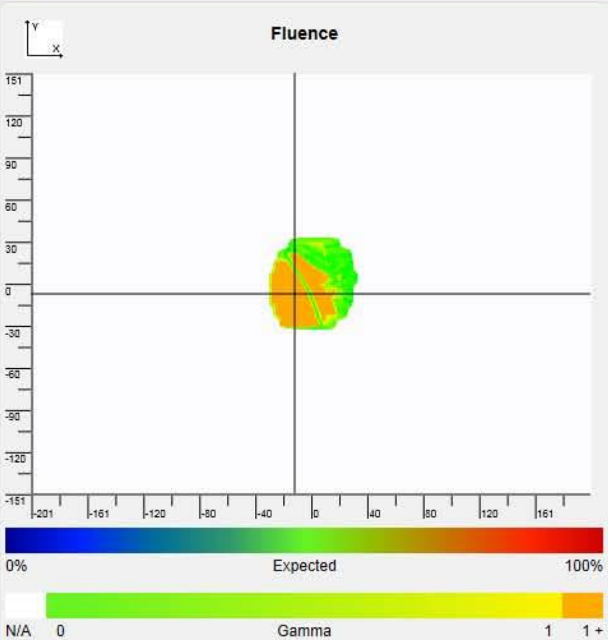
Current Plan:	Sella
Plan Stats:	2 of 30 Fractions
Fraction:	2
Fraction EPID Pass %:	92.59%
Delivered:	8/26/2014 1:11 PM

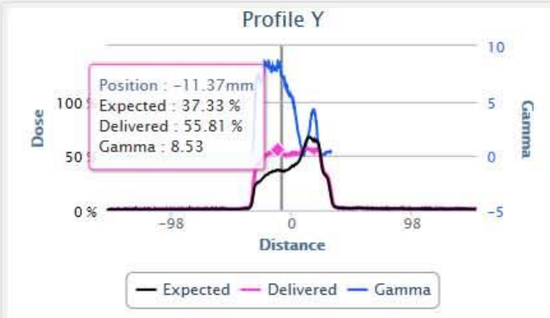
Beam	EPID
1A antsag-90	N/A
1B rpso2-41	✔ Passed
1C rpso-41	! Failed
1D raso-5	✔ Passed
1E raso2-5	✔ Passed
1F lpso-314	✔ Passed
1G lpso-320	✔ Passed

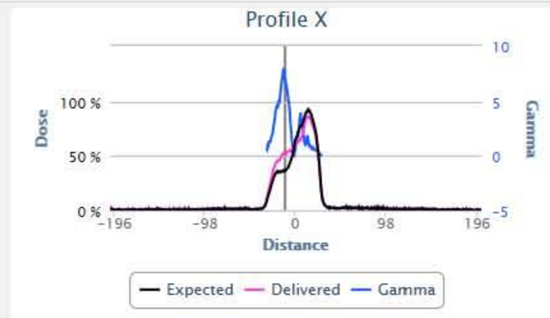
Settings	Dossier Settings	Current Settings
Method	Gamma	Gamma
Normalization	Global	Global
Difference Tolerance (%)	2	2
Distance Tolerance (mm)	1	1
Threshold (%)	10	10
EPID Baseline	1	1

▶ Calculate

EPID Results







Results

Passing Rate (%)	53.38 %
Passing Points	12,161
High Points	6,941
Low Points	3,681
Total Points	22,783
Average	1.83

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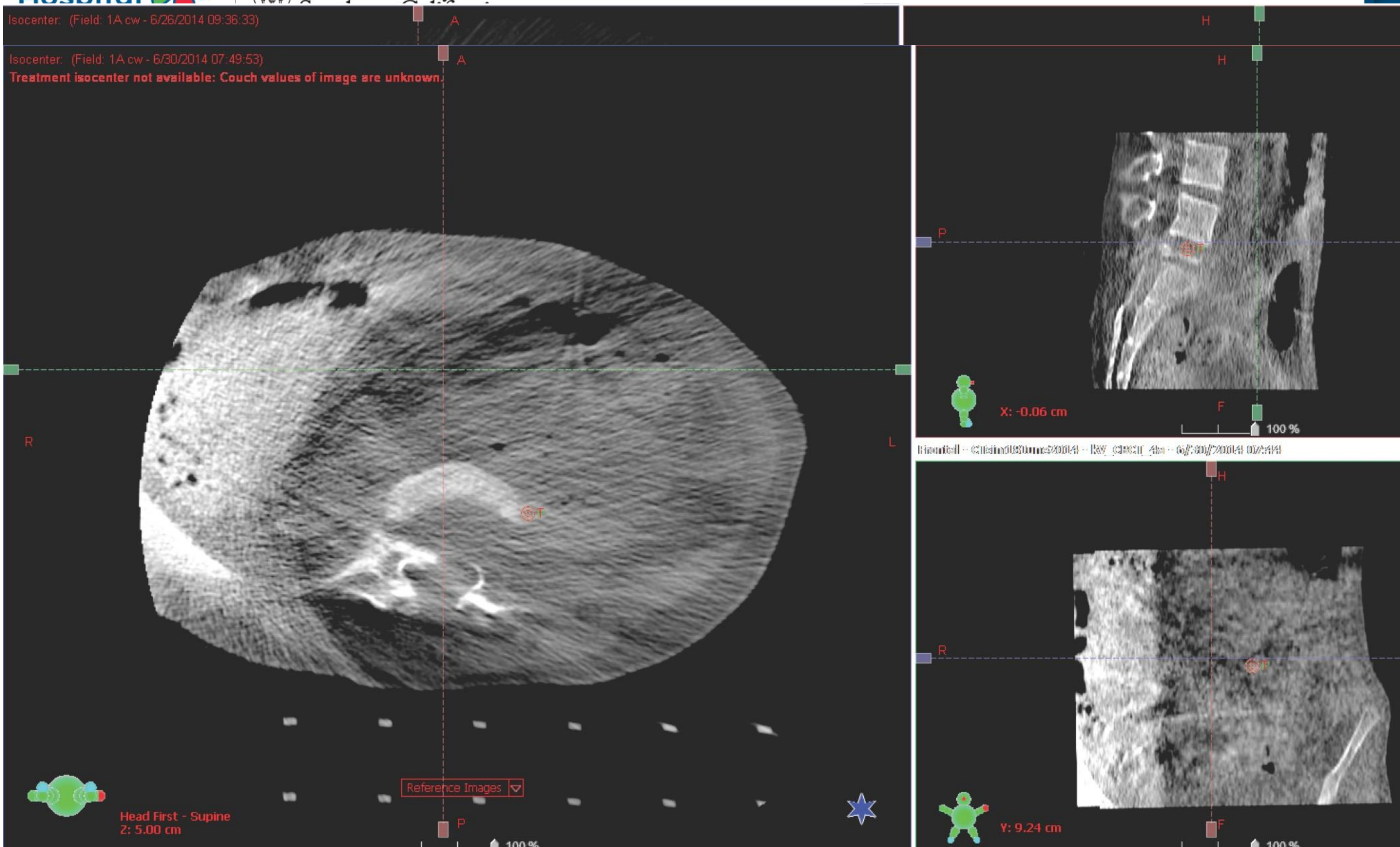
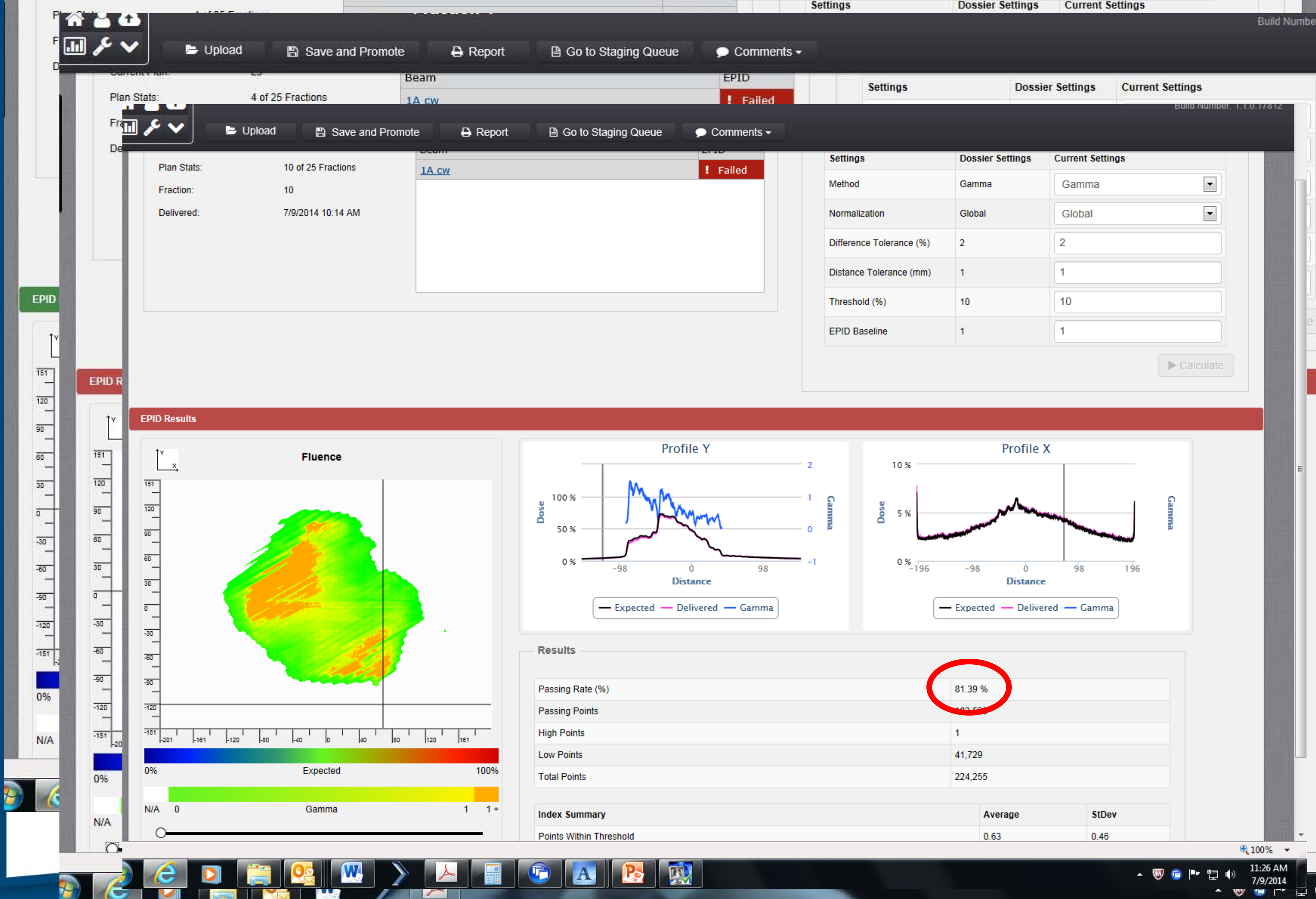
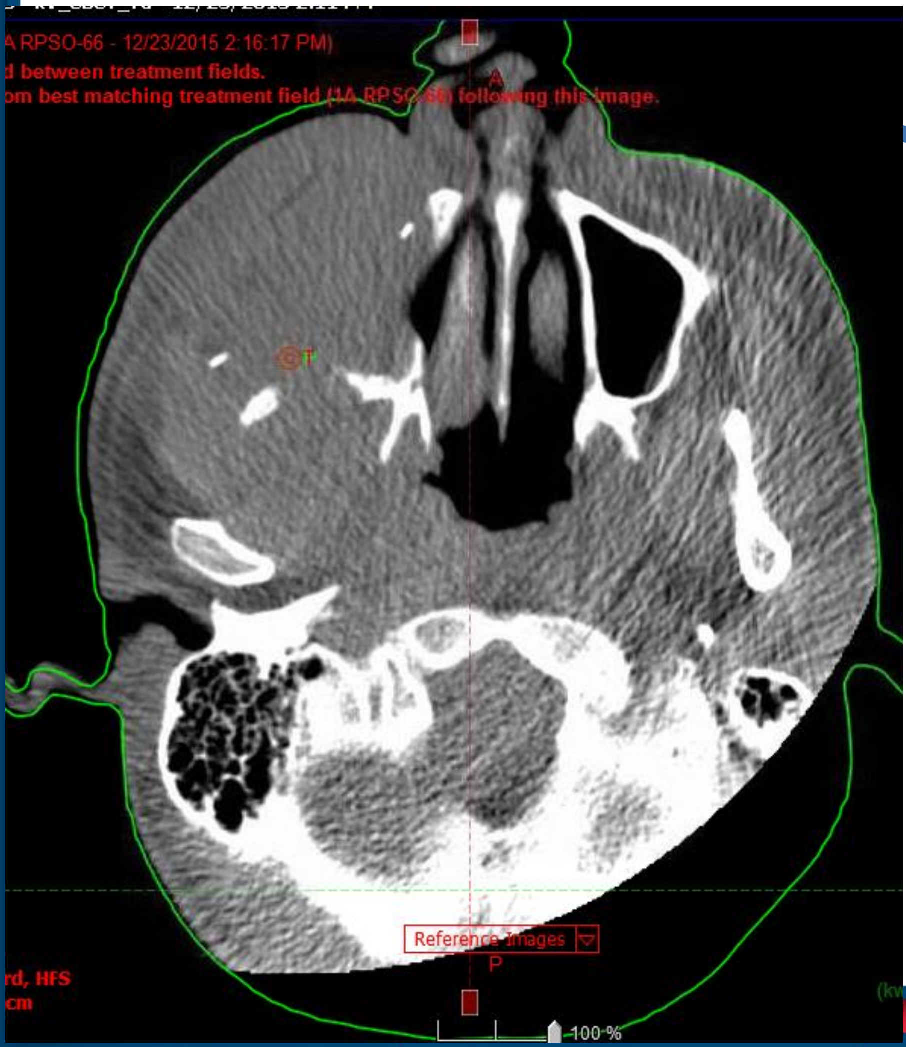


Gamma results for CBCTs



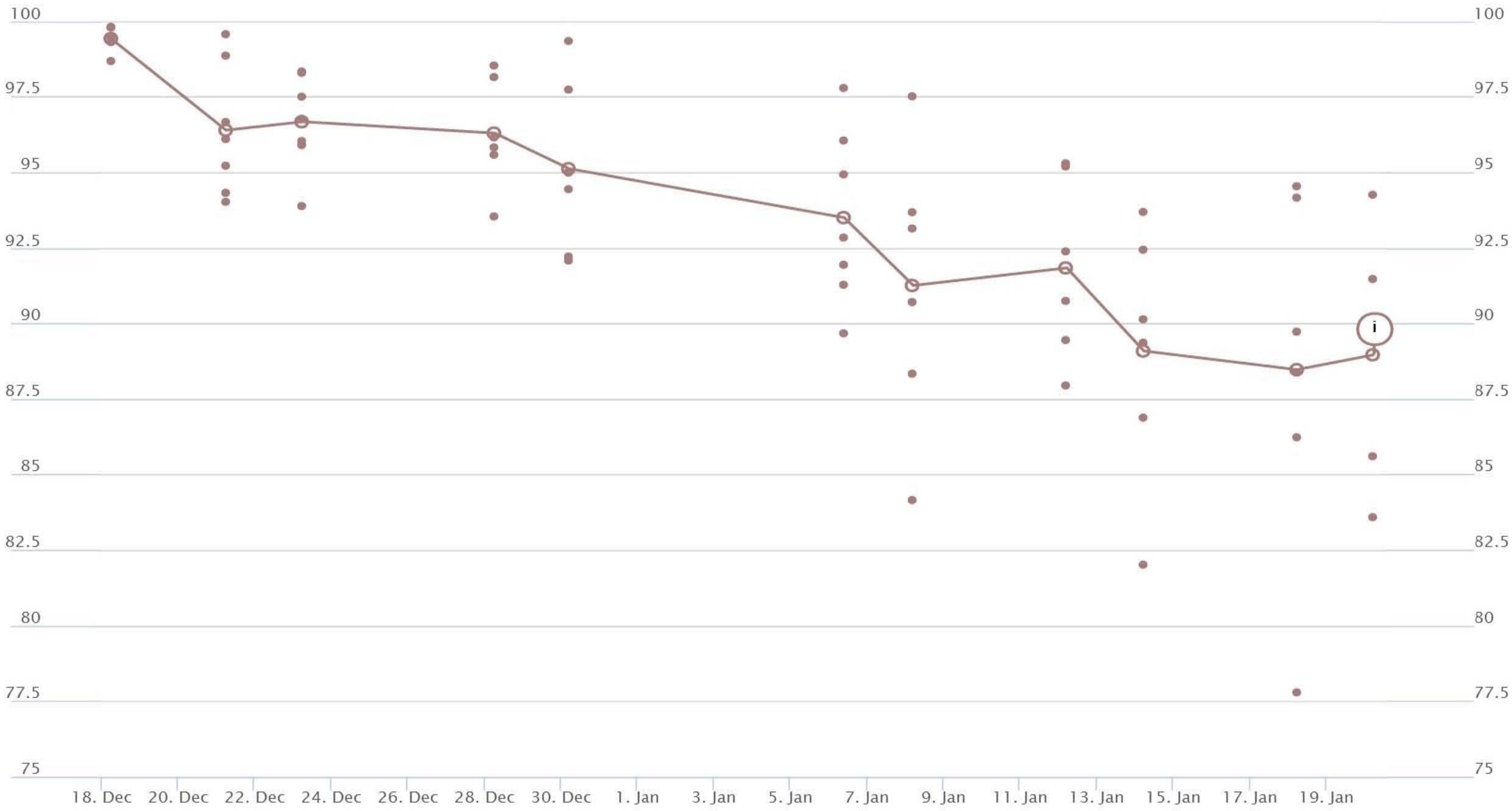
Anatomy Changes Correlate to PerFRACTION Results



Patient Plan Trend Results

(Rt Zygoma) - 2D Planar (Gamma, 3% / 3mm)

Date Range: 17 Dec 2015 to 20 Jan 2016



Automated Daily EPID Exit Dose Analysis Uncovers Treatment Variations

poster at AAPM 2015

- **Methods:** Monitored 20 plans for 18 patients, for a total of 251 fractions. A total of 859 fields were monitored. Nine VMAT, 5 IMRT, and 6 3DCRT plans were monitored. Used 2%G/1mm/10%DT

- **Results:**
- 29% of the fields failed using Gamma analysis with 2%G, 1mm DTA, 10% threshold, 93% pixels passing was considered a pass.
- The average plan passing rate was 92.5%.The average 3DCRT plan passing rate was less than for VMAT or IMRT, 84%, vs. an average of 96.2%.
- When fields failed, an investigation revealed changes in patient anatomy (either weight gain or loss, or changes in bowel gas distribution) or setup variations (residual pitch, roll or translation after IGRT), often also leading to variations of transmission through the couch top or immobilization devices. In many cases, it was not clear as to what caused the field to fail the gamma analysis.
- Increasing the DTA from 1 mm to 2 mm decreased the failure rate by half.

Conclusion

- EPID exit dose systems provide daily automated 2D and 3D dose analysis using EPID integrated or cine images with or without log file usage.
- Pretreatment IMRT QA can be done with the EPID in a time saving manner.
- Therapists deploy EPID, no extra Physics effort.
- Passing rates/trends for each field and plan are provided to uncover delivery/setup errors.
- Tolerance limits to use for analysis not yet established.
- Reasons for failures are multifactorial-MLC/linac delivery problems, **patient setup differences, patient internal anatomy changes**.

Conclusions

- Errors found won’t always be explained
- Errors that are explained can be fixed in a timely way and verified as fixed
- 2D per-beam dose is useful to provide confidence level for passing treatments. 3D dose with DVH analysis gives more clinically meaningful results, both can be used to trigger corrective action by providing information only available with such a system.
- Daily monitoring of patients is feasible in terms of physics time
- **EPID-based daily patient treatment QA will become the standard of care**

The End

Questions?

Vendor Survey of Features

	EPID-Based Pretreatment QA	2D gamma based on fx1	2D gamma based on predicted image from TPS	3D gamma based on cine images	3D gamma based on log files	DVH and pt dose comparison based on cine images	DVH and pt dose comparison on planning CT based on log files	DVH and pt dose comparison on CBCT based on log files	DVH based on recon of EPID exit dose image into planning CT or CBCT
Sun Nuclear- PerFRACTION 2D and 3D	yes	yes	no (later this year)	yes	yes	yes	yes	yes	yes (either)
DosiSoft – EpiBeam	yes	yes	yes	yes	no	yes	no	no	yes (either)
Math Resolutions - Dosimetry Check	yes	no	no	no	no	no	no	no	yes (either)
Mobius Medical – Mobius3D (EPID not used)	no	no	no	no	yes	no	yes	no	no
Standard Imaging – Adaptivo	yes	yes	yes	no	no	no	no	no	no
iViewDose - Elekta	yes	no	no	yes (integrated or cine)	no	no	no	no	yes (just 3D Gamma on planning CT)

References

Author	Journal/Secondary Title	Year	Title
Spreeuw, H.; Rozendaal, R.; Olaciregui-Ruiz, I.; Gonzalez, P.; ...	Medical physics	2016	Online 3D EPID-based dose verification: Proof of concept
Ricketts, K.; Navarro, C.; Lane, K.; Blowfield, C.; Cotten, G....	Int J Radiat Oncol Biol Phys	2016	Clinical Experience and Evaluation of Patient Treatment Verification With a Transit Dosimeter
Neal, Brian; Ahmed, Mahmoud; Kathuria, Kunal; Watkins, T....	Medical Physics	2016	A clinically observed discrepancy between image-based and log-based MLC positions
Miri, N.; Keller, P.; Zwan, B. J.; Greer, P.	Journal of applied clinical medical p...	2016	EPID-based dosimetry to verify IMRT planar dose distribution for the aS1200 EPID and FFF beams
Fuangrod, T.; Greer, P. B.; Woodruff, H. C.; Simpson, J.; B...	Radiat Oncol	2016	Investigation of a real-time EPID-based patient dose monitoring safety system using site-specific contr
Woodruff, H. C.; Fuangrod, T.; Van Uytven, E.; McCurdy, ...	Int J Radiat Oncol Biol Phys	2015	First Experience With Real-Time EPID-Based Delivery Verification During IMRT and VMAT Sessions
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Moran, J. M.; Roberts, D. A.; Nurushev, T. S.; Antonuk, L. ...	Med Phys	2005	An Active Matrix Flat Panel Dosimeter (AMFPD) for in-phantom dosimetric measurements