The Future Is Now - EPID In Vivo Dosimetry

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Symposium 2020

UC San Diego
RETHINKING MEDICAL PHYSICS

Disclosures

- Receive grant funding from Varian Medical Systems

Outline

- Errors detected by pre-treatment vs in-vivo measurements
  - For ideal detection scenarios and real life practice
- Methods to analyze in-vivo EPID data
  - Forward projection image predictions
  - Back-projection dose estimates
- Current clinical implementation and experience gained from in-vivo use to date
- How automation aids implementation. Commercial software available
- Requirements for widespread implementations
  - Complementary QA checks needed
- Future clinical uses
  - Real-time error detection
  - Uses in adaptive planning

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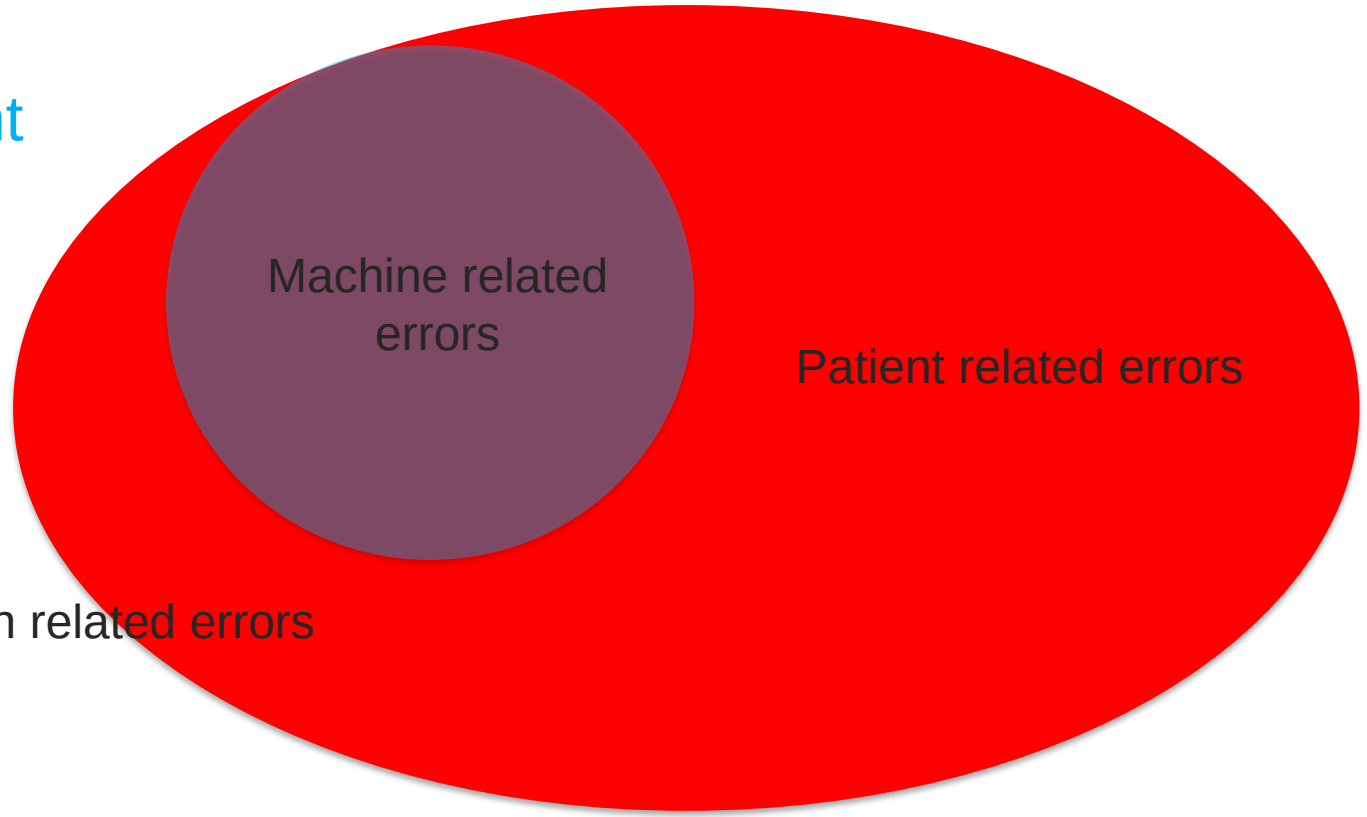
Error Detection with the EPID

Pretreatment

In-vivo



Pretreatment

Potential Error	Error Type	References
Machine-related	Transfer error	Mans et al. (2010), Mijnheer et al. (2015)
Plan-related	Dose calculation error	Mans et al. (2010), Fidanzio et al. (2015), Mijnheer et al. (2015)
	Immobilization system not included in the treatment plan	Fidanzio et al. (2015)
	Bolus material not taken into account	Mijnheer et al. (2015)
Patient-related: anatomy changes	Changes in atelectasis and pleural effusion	Piermattei et al. (2009), Mans et al. (2010), Persoon et al. (2012), Wendling et al. (2012), Persoon et al. (2013), Fidanzio et al. (2015), Mijnheer et al. (2015)
	Variation in patient contour when the patient becomes more relaxed during treatment	Mans et al. (2010), Fidanzio et al. (2015), Peca et al. (2015)
	Gas pockets in the planning CT scan resulting in an underdose in the PTV during treatment	Camilleri et al. (2014), Cilla et al. (2014), Fidanzio et al. (2015)
	Weight loss resulting in an overdose in the PTV during treatment	Mans et al. (2010), Camilleri et al. (2014), Cilla et al. (2014, 2016)
	Incomplete bladder filling resulting in an overdose in the PTV during treatment	Ricketts et al. (2016)

Potential Error	Error Type	References
Patient-related: delivery errors	Bar of the treatment couch in the entrance beam during treatment	Piermattei et al. (2009), Fidanzio et al. (2015)
	Imperfect immobilization allowing the patient to move during treatment	Hanson et al. (2014), Cilla et al. (2016)
	Wrong patient setup during treatment	Fidanzio et al. (2015), Mijnheer et al. (2015)

Clinical 3D dosimetry in Advanced Radiotherapy. Mijnheer

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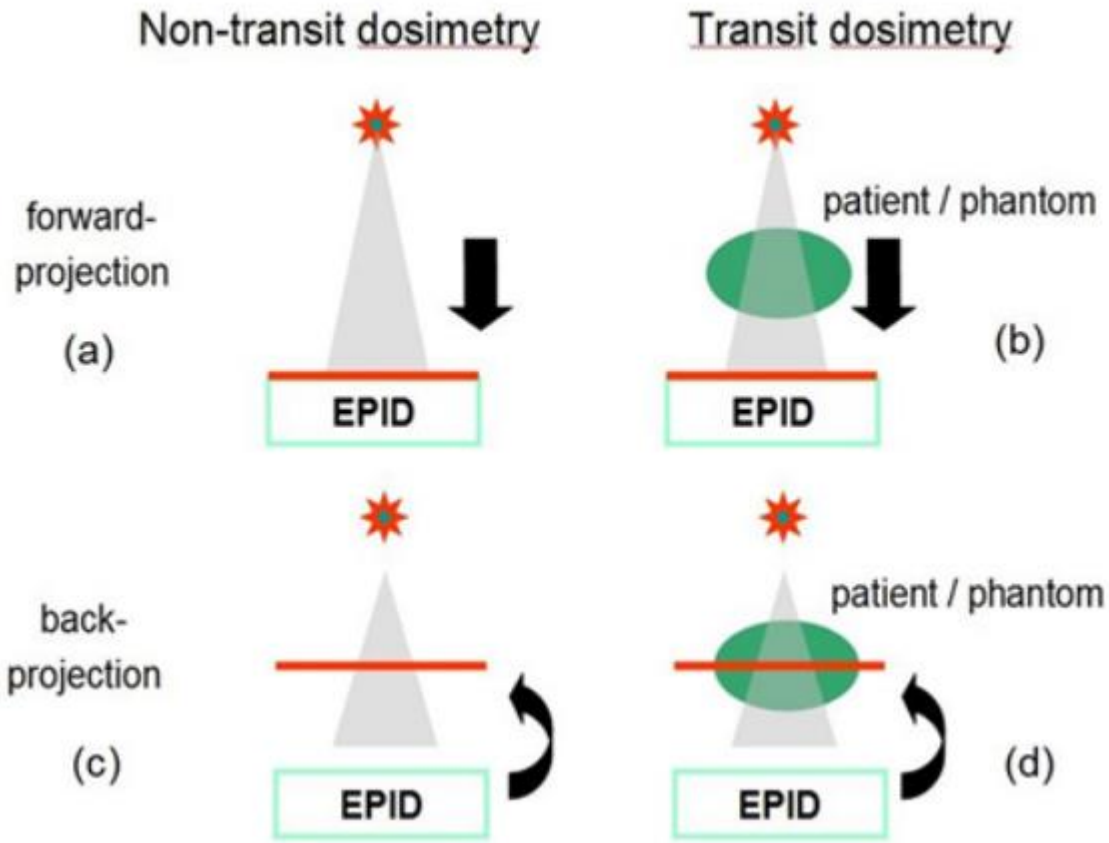
Measurement Approaches

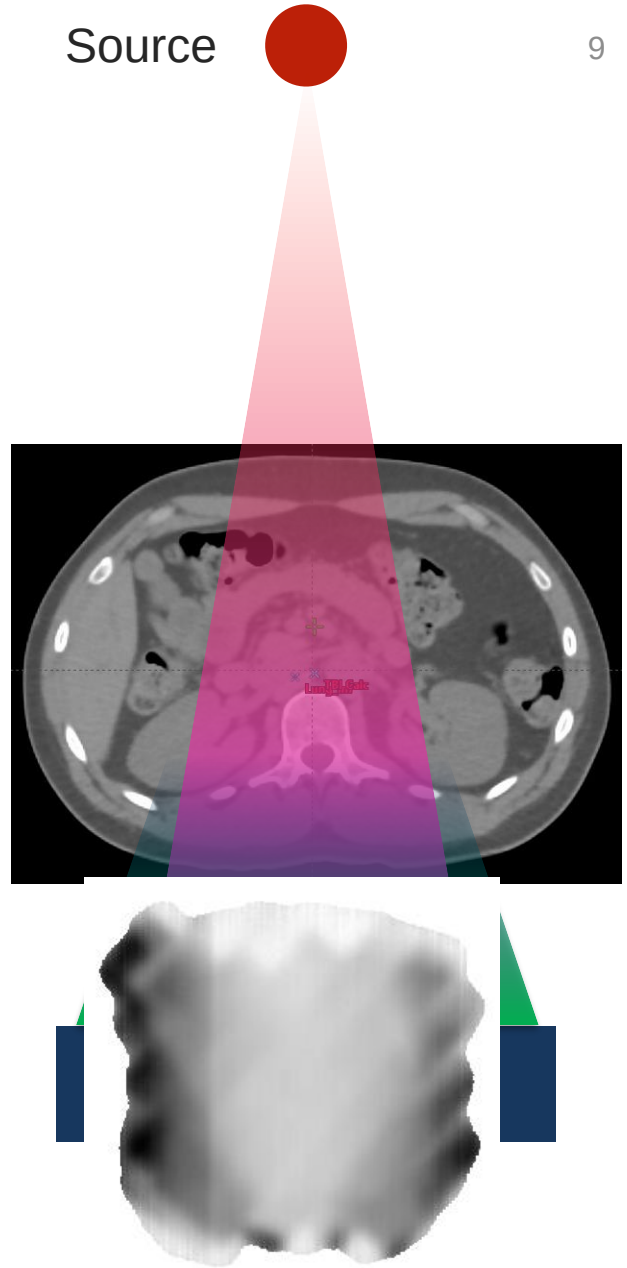
- Non transit dosimetry
  - Make a prediction of EPID image no patient/phantom in the way.
  - From EPID image make a prediction of the fluence at isocenter.
- Transit Dosimetry
  - Make a prediction of the image.
  - From the image make a prediction of the dose.



B Mijnheer J. Phys.: Conf. Ser. 2017

Transit Dosimetry (forward projection)

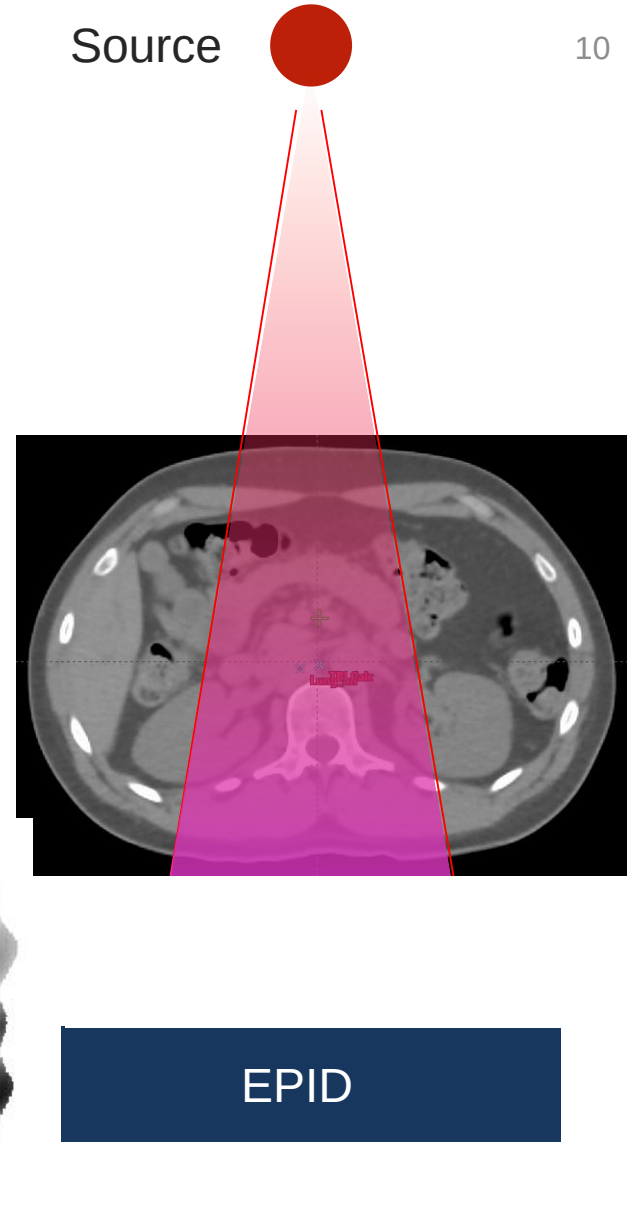
- Determination of greyscale image at the level of the EPID
  - Primary Fluence
  - Scattered Fluence
  - Response of the EPID



Chytyk et al Med Phys 2013

Back Projection (3D)

- Reconstruct dose in patient
  - From EPID image estimate primary fluence and scattered fluence at EPID level
  - Separate primary fluence
  - Back-project primary fluence to incident fluence
  - Use incident fluence to estimate dose



Wendling et al Med Phys 2006

Back Projection (3D)

- EPID image is measured with patients anatomy during treatment.
- However dose is calculated on anatomy acquired during planning.
- Able to detect changes in planned dose.
- Does not calculate delivered dose!
- Need CBCT.

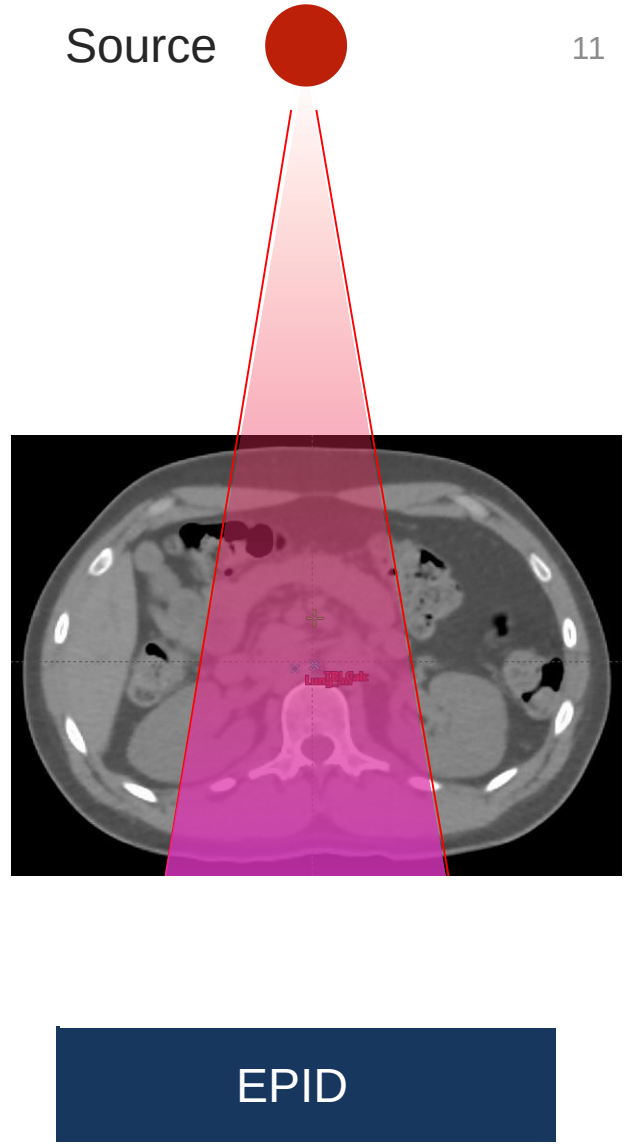
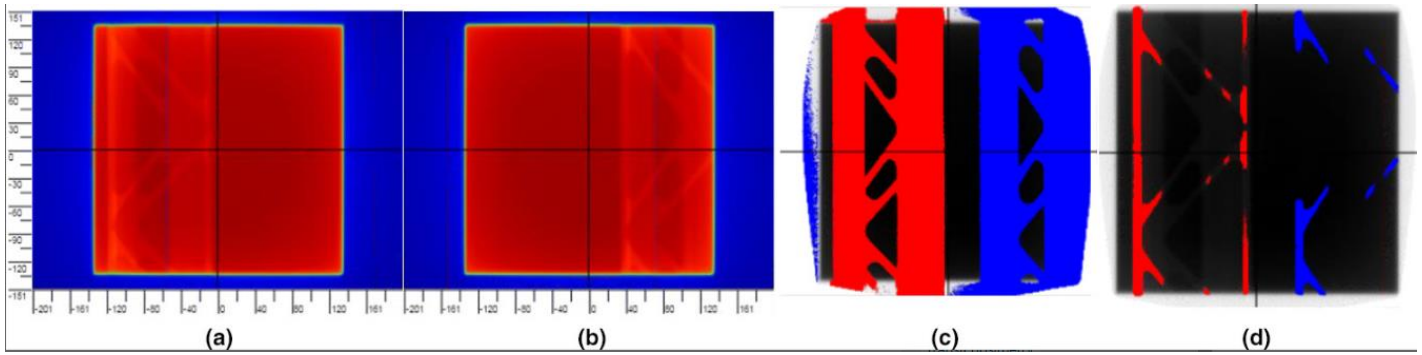
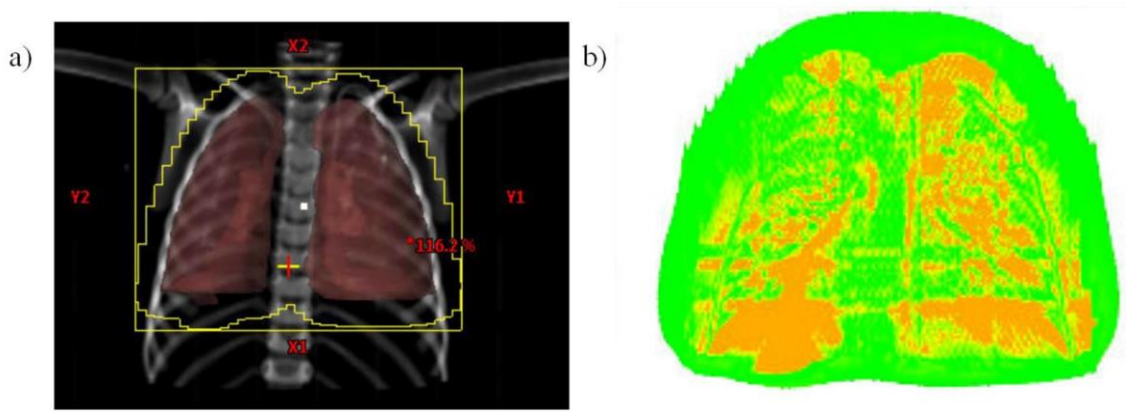


Image Difference

- Compare EPID images day 1 to EPID image day n
- Relative differences



Zhuang, Olch. J Appl Clin Med Phys 2018

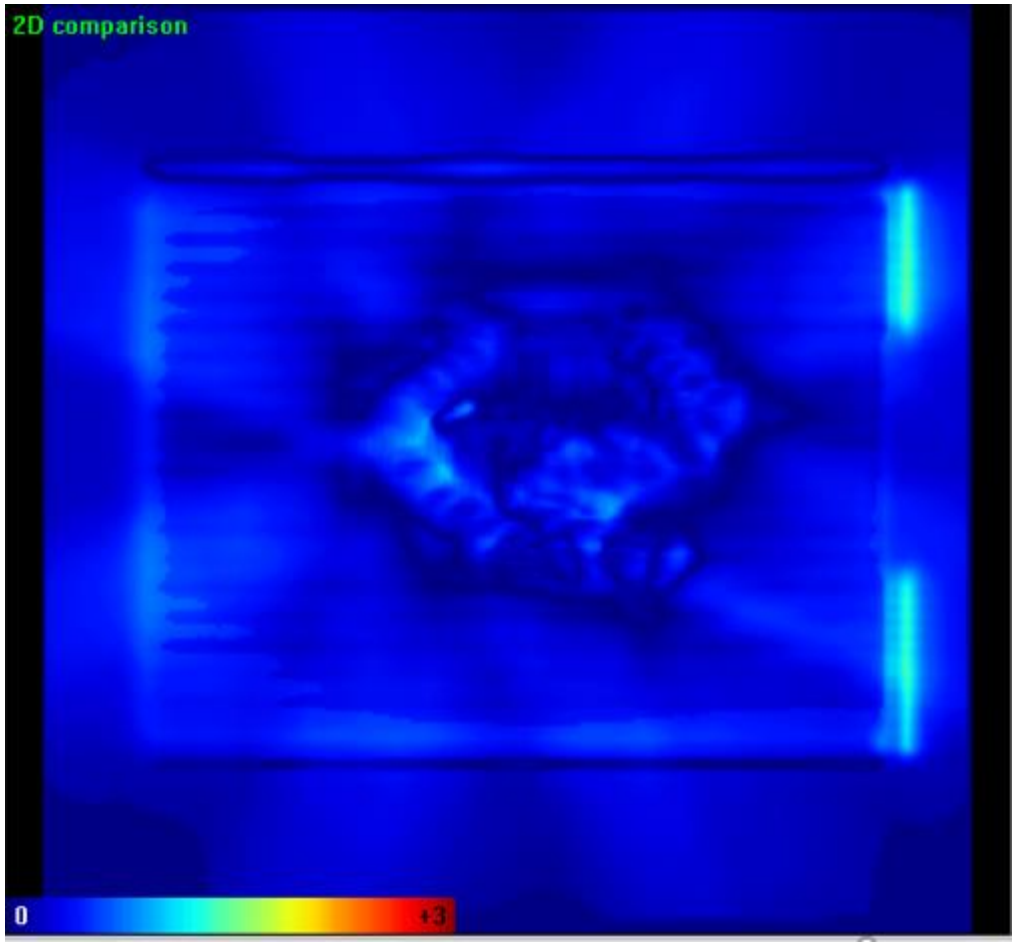


Olch et al Adv. In Rac Onc 2019

Comparisons

- Image level
  - 0D point comparison
  - 2D image comparison
- Patient level
  - 0D point comparison (isocenter)
  - 2D plane comparison
  - 3D volumetric comparison
- Typically Gamma Comparison

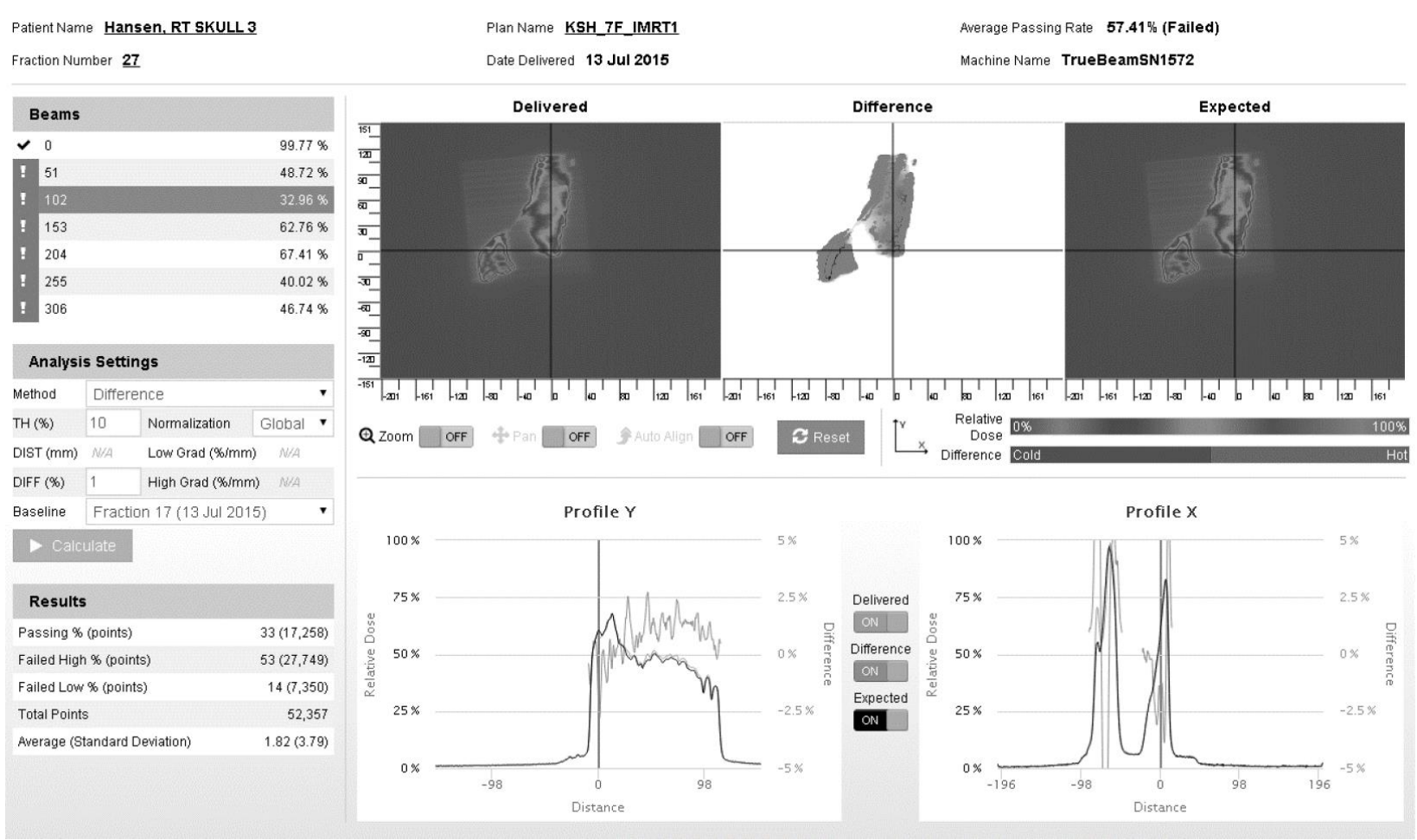
Planar Gamma Evaluation



Pros and Cons

Method	Pros	Cons
Point Dose	• Simple quick algorithms • Simple to commission	• Sensitivity to errors reduced • Less information available
3D Dose	• 3D dose map • Able to reconstruct DVHs	• More complex to commission

Analysis



Hsieh et al. Prac Rad Onc, 2017,

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In the Clinic

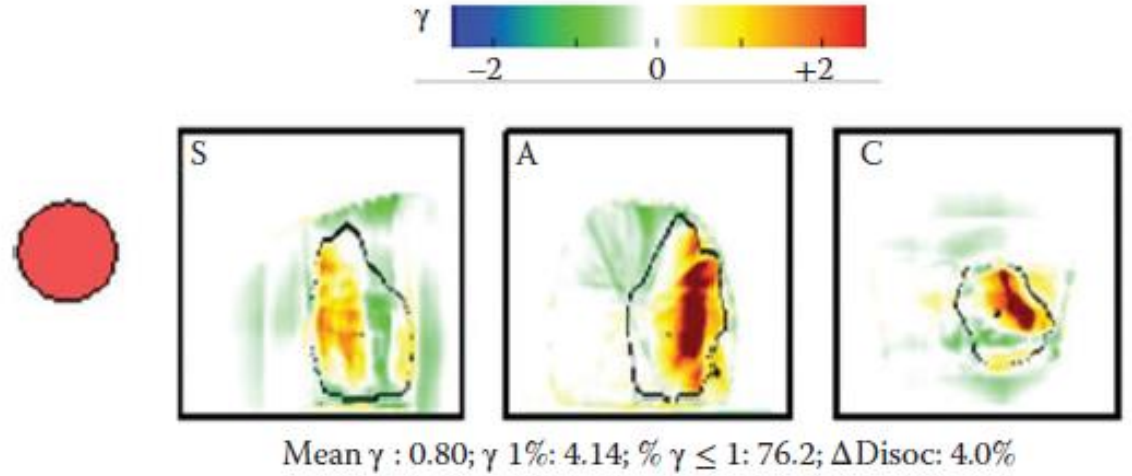
- **NKI has been using in-vivo system clinically for a long time.**
  - Have replaced pre-treatment with in vivo measurements.
  - Detected 17 major errors 2005-2009 (over 4000 patients)
  - 9 of these errors would have been missed with Pre-treatment only

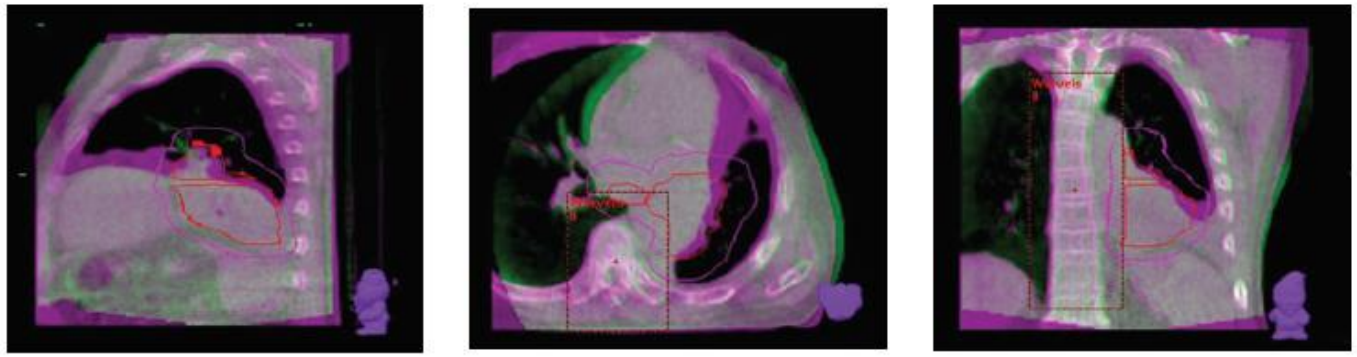
TYPE OF ERROR	NUMBER OF ERRORS
PATIENT ANATOMY	7
ACCIDENTAL PLAN MOD	2
PLAN TRANSFER	4
SUBOPTIMALLY TUNED TPS	2
FAILED DELIVERY	2
DOSIMETRICALLY UNDELIVERABLE PLAN	1
TOTAL	17

Mans et al. Med Phys. 37(6) 2010

Lung

- Alert raised by EPID measurement
- Comparison of CBCT (green) and planning CT (purple)
- Reduction of Atelectasis
- Replanning scan was made

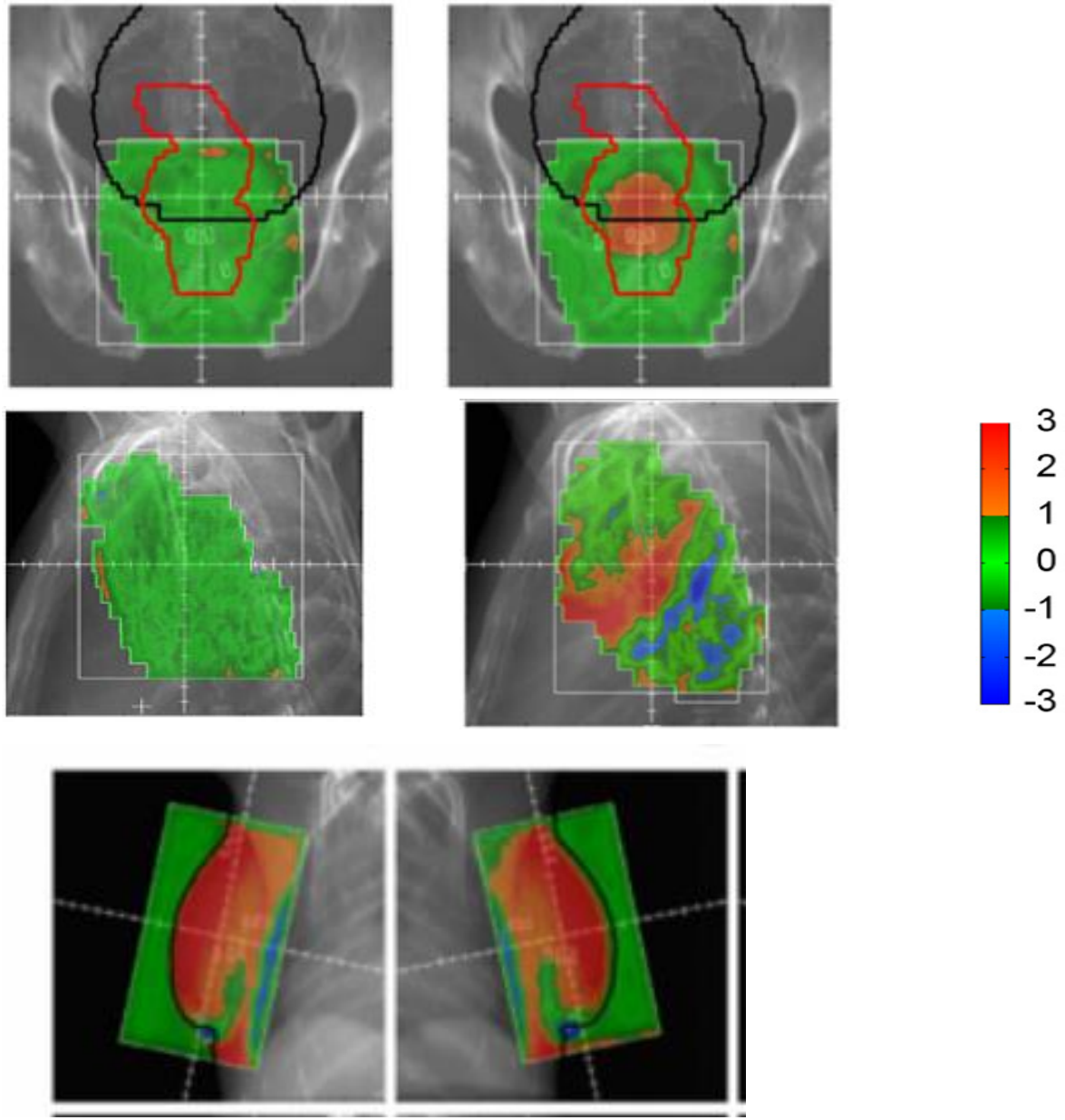




Clinical 3D dosimetry in Advanced Radiotherapy. Mijnheer

Prostate, Lung, Breast

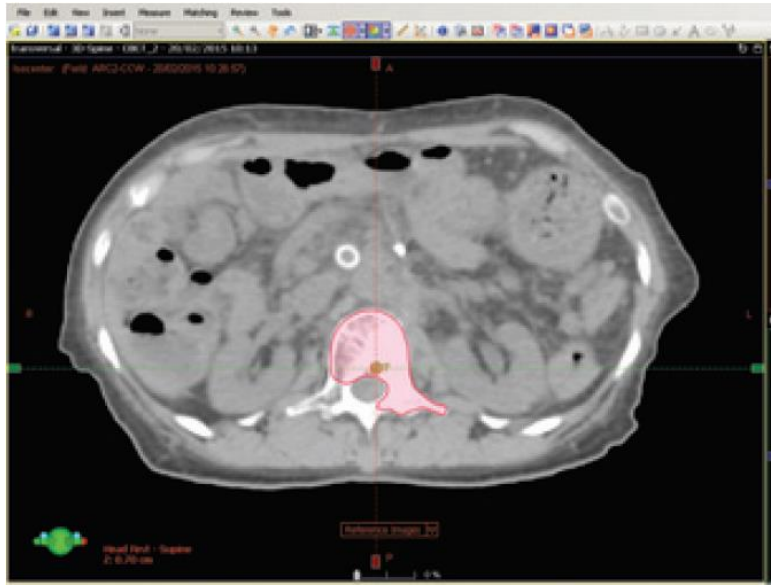
- Gas bubbles
- Change in atelectasis
- Setup for breast patient

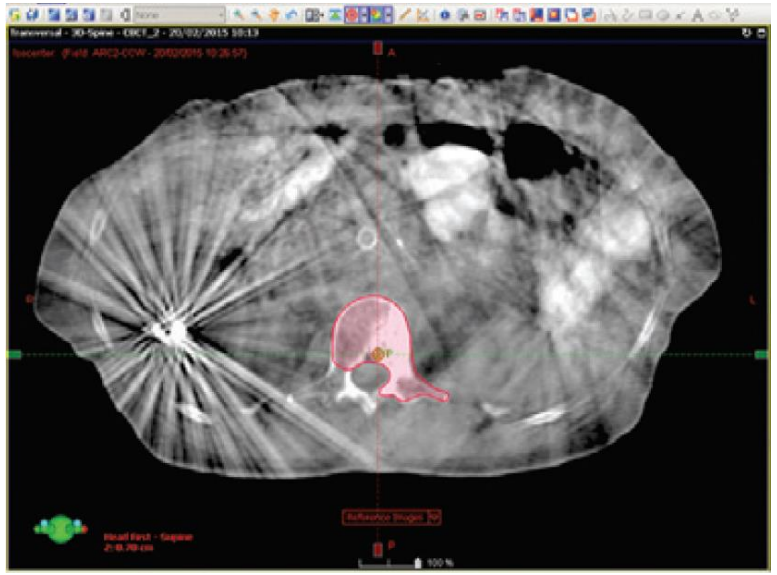


Persoon et al Phys Med and Bio. 2012

Spine

- 25% decrease in 3D gamma pass rate
- Stent moved into treatment field between fractions



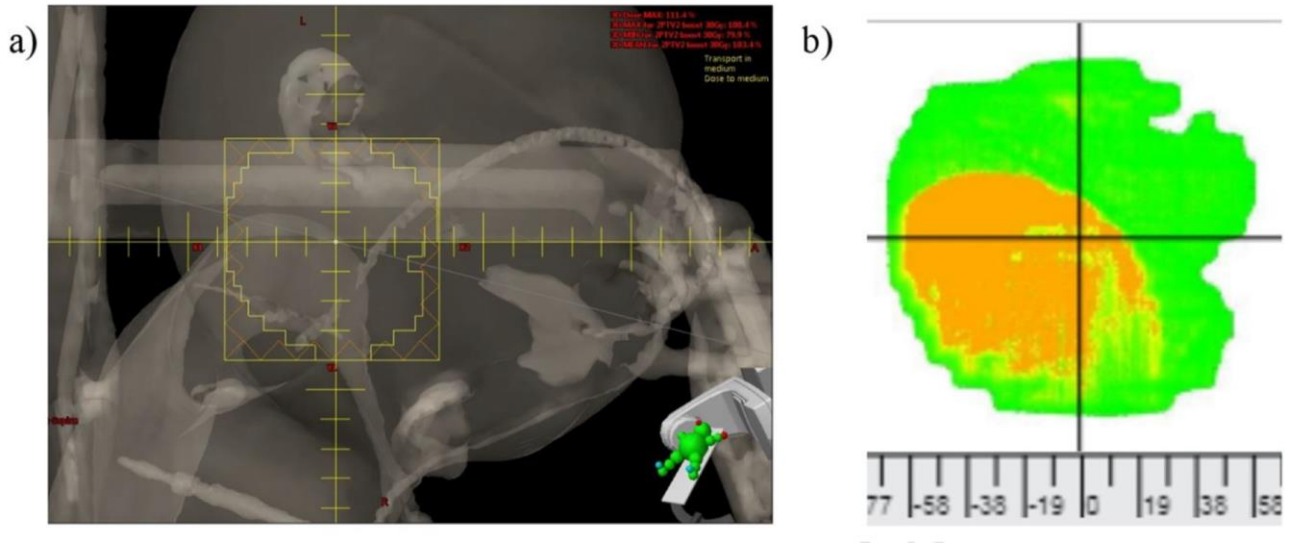


Van Uytven et al. Med Phys 2015

Clinical 3D dosimetry in Advanced Radiotherapy. Mijnheer

Shoulder

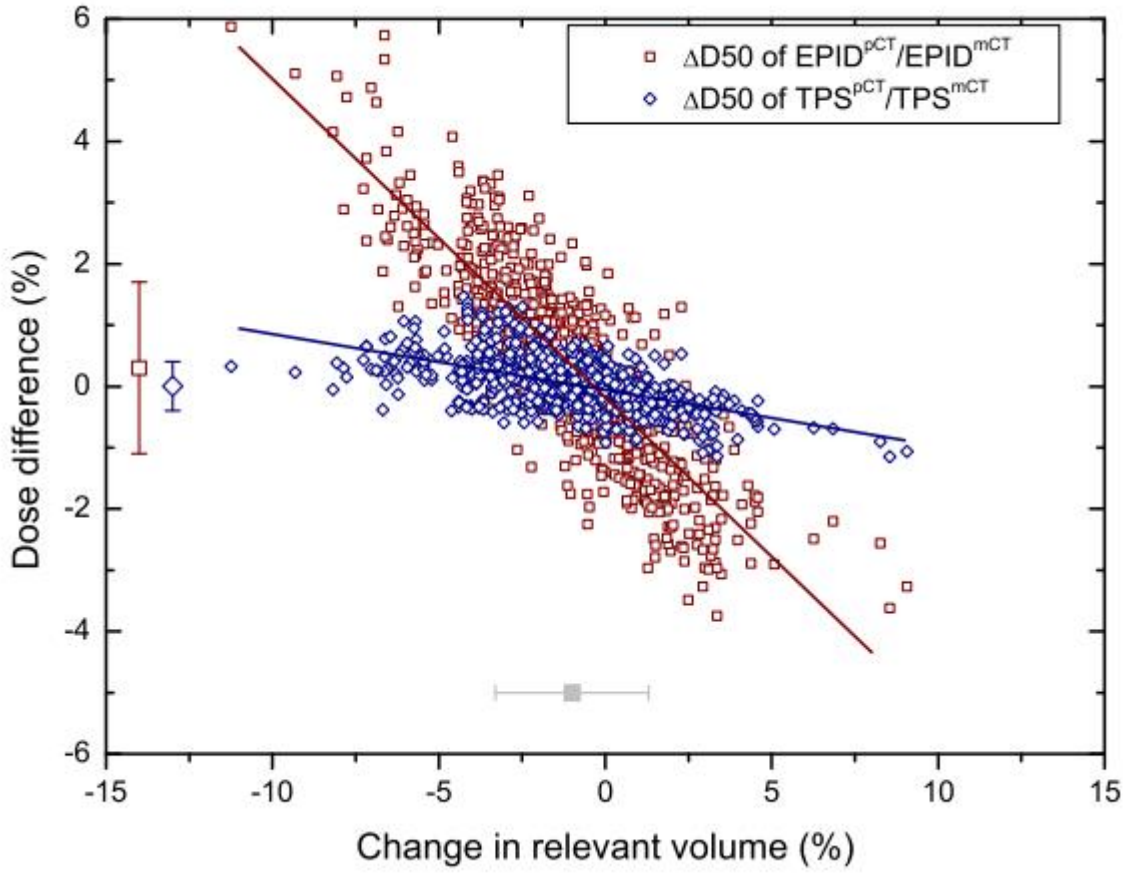
- Image comparison with first fraction shows change in shoulder position



Olch et al. Adv. In Rac Onc 2019

Clinical Impact of Errors

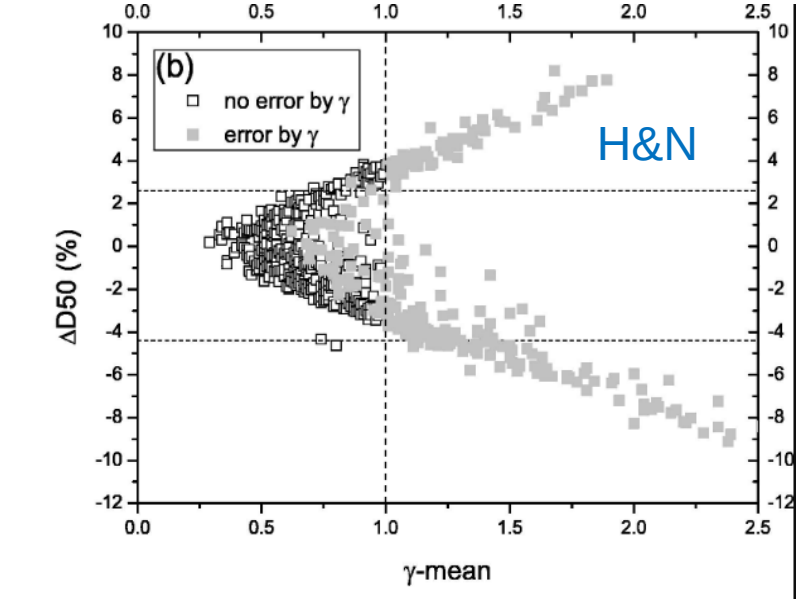
- Head and Neck treatments
- Planning CT deformed to CBCT
- Change in EPID dose and TPS dose for ΔD50
- EPID has enhanced sensitivity

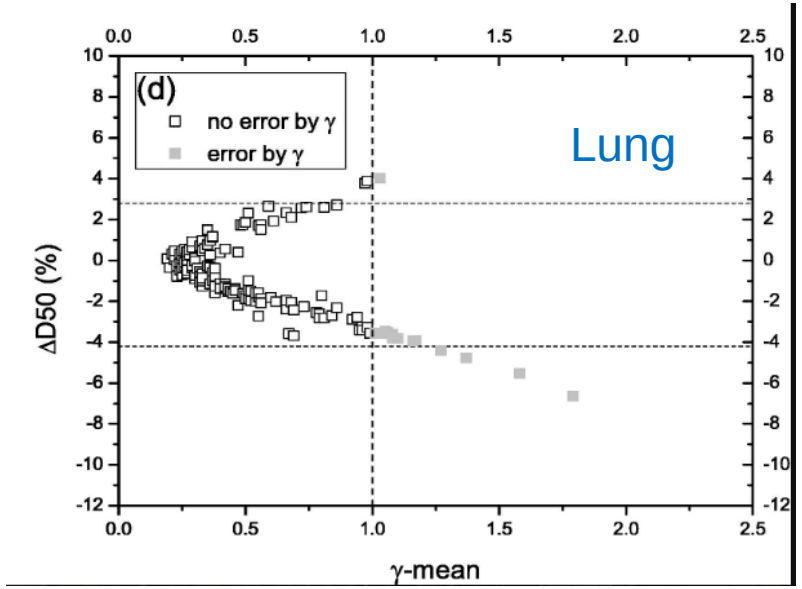


Rozendaal et al Radio and Onc 2015

Clinical Impact of Errors

- Tolerance levels on mean gamma and gamma 1%.
- Compare gamma mean and ΔD50 for H&N and Lung
- Good correlation for lung less specific for H&N.



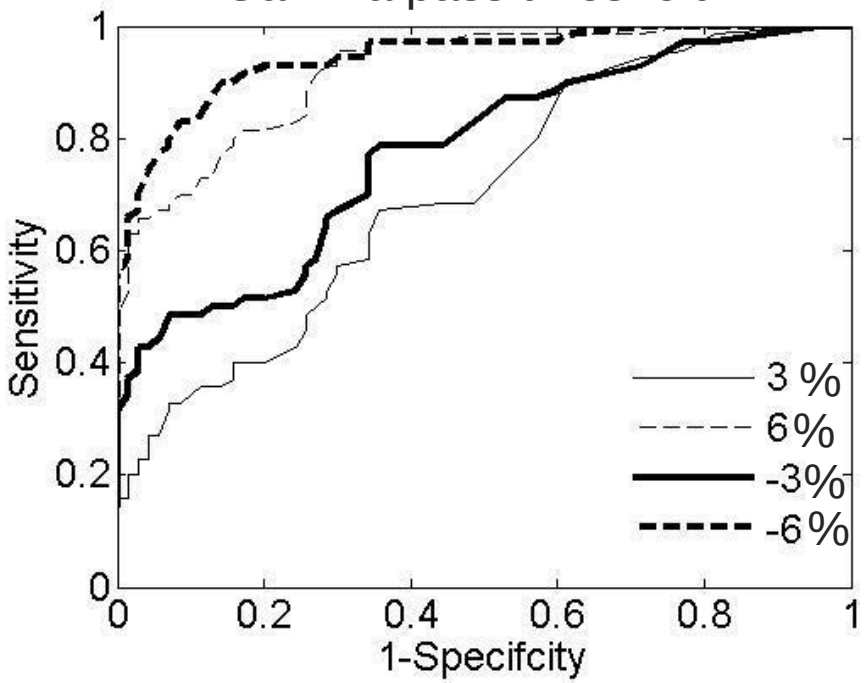


Rozendaal et al Radio and Onc 2014

Setting Tolerance Levels

- Model EPIDs sensitivity to different errors
  - Deliver plan, introduce errors in TPS
  - Measures changes in gamma pass rate(3%/3mm)
  - Construct ROC
  - Investigate changes in PTV dose metrics

ROC curves varying Gamma pass threshold



Bojechko & Ford Med Phys 2015.

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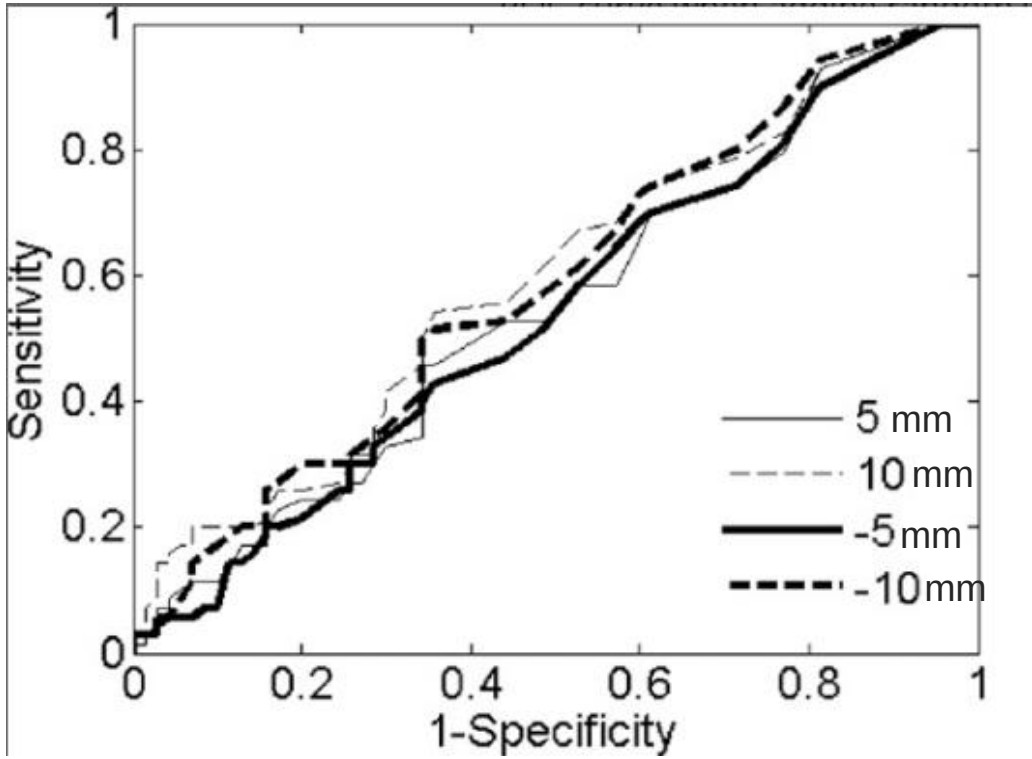
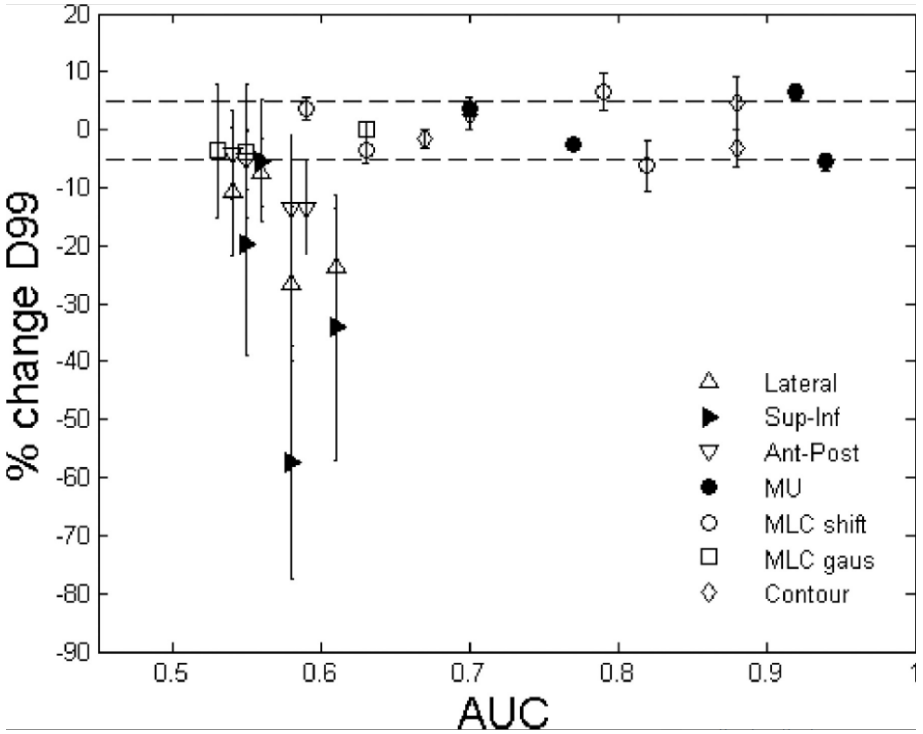


Bojechko & Ford Med Phys 2015.

Clinical Impact of Errors

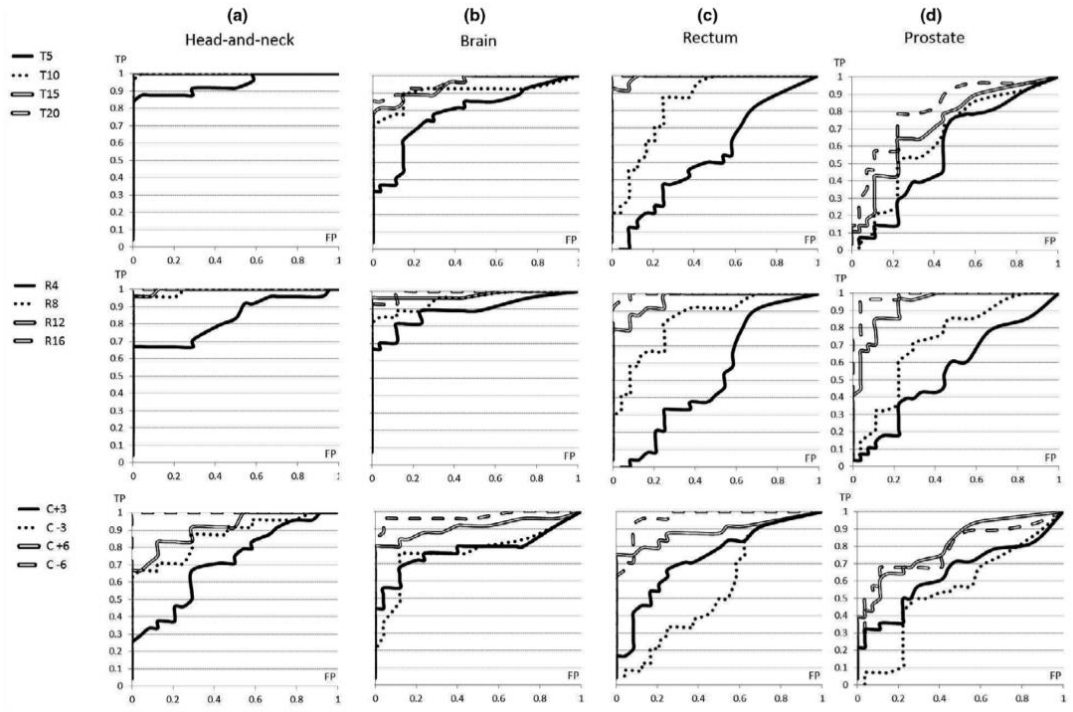
- ROC analysis, compare AUC vs change in D99.
- Different errors introduced
  - MU scaling
  - MLC shifts
  - Patient contour changes
  - Patient shifts



Bojechko, Ford Med Phys 2015

Clinical Impact of Errors

- Simulated errors in synthetic CT.
- Use various indicators
  - ΔDiso, γ-mean, γ-max, γ-passrate, ΔPTV_{D2} , ΔPTV_{D50} , ΔPTV_{D98}
- Use different in vivo alert criteria per treatment site
- Excellent detection of transitions, rotation, contour changes for expect for prostate sites



I Olaciregui-Ruiz et al Med Phys 2019

Challenges to Setting Thresholds

- Different dose calculations (0D,2D,3D)
- Different algorithms
- Different DVH parameters (D50, D2,D95)
- Difference treatment sites
- Gamma metrics

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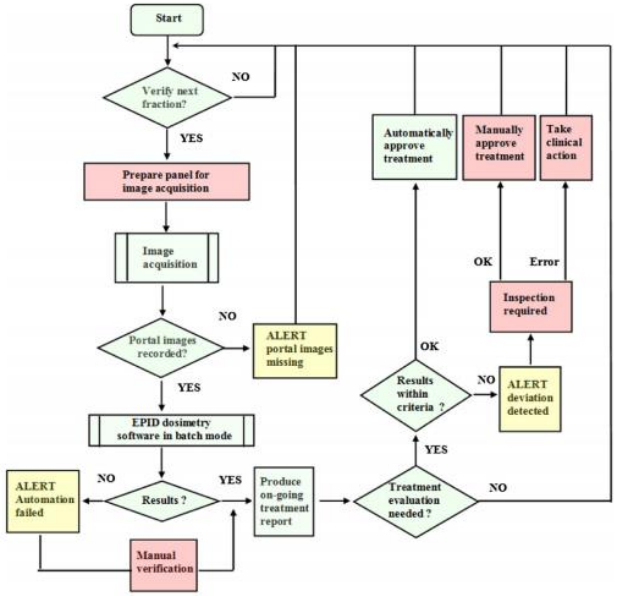
Automation

- Automation is necessary for implementation, due to the increased workload of additional analysis
- Need to Automate
  - Export (images, other data)
  - Analysis
  - Alerts

Automation: NKI

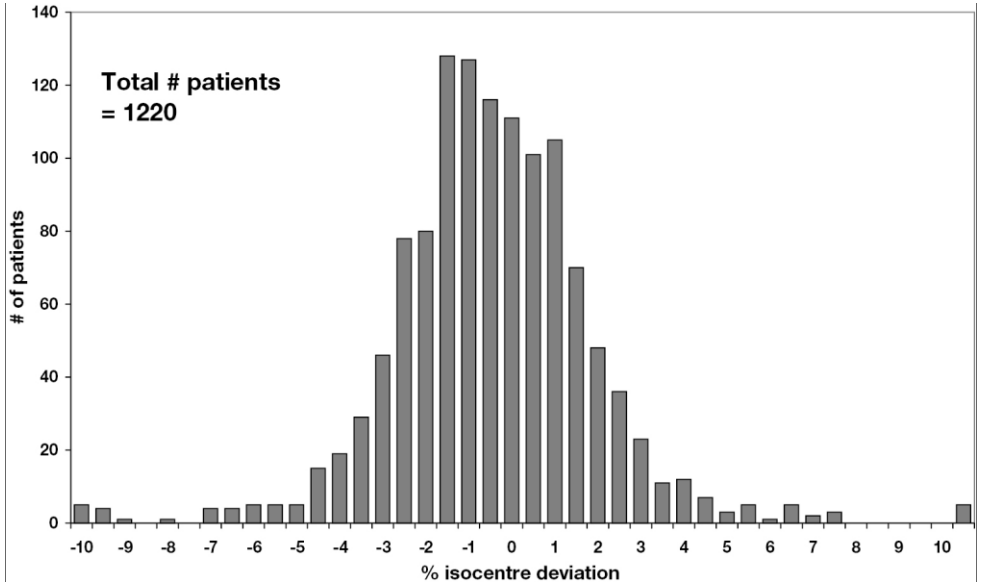
- Call verification software after portal images have been recorded
  - Results are available a few minutes after fraction is delivered Alerts raised if a threshold is exceeded.
  - Significantly reduces workload, less error prone.
  - Alerts grouped into 3 Categories
    - Limitations of calculation model
    - Patient anatomy changes
    - Other (delivery or planning errors, output deviations…)
- Inspection of alerts 0.25 FTE.



Olaciregui-Ruiz et al. Phys. Med. Biol. 2013.

Automation: Royal Marsden

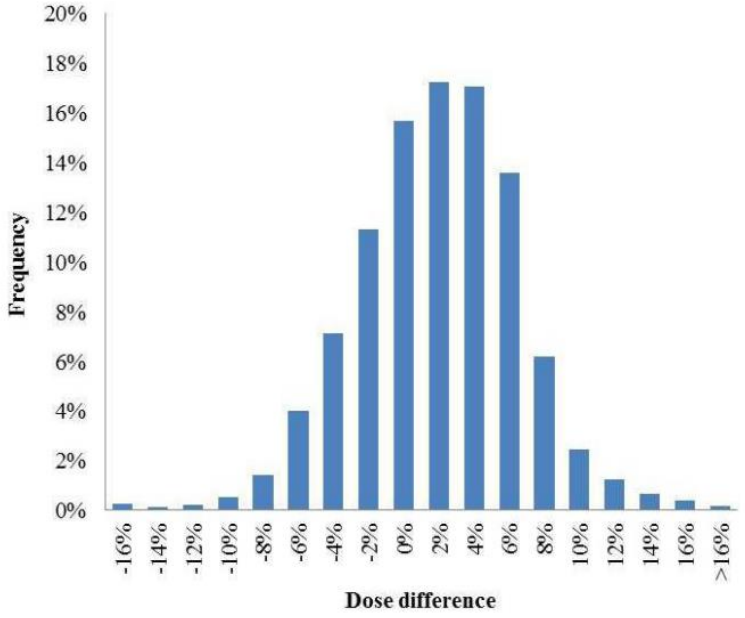
- Based on NKI system
- Compared to TLD measurements less time consuming on unit and analysis. Able to account for deviations based on 2D info
- Replaced nearly all pre-treatment verification
- Flagged when tolerance level is exceeded.



Hanson et al. Phys. Med. Biol. 2014.

Automation: Institut Curie

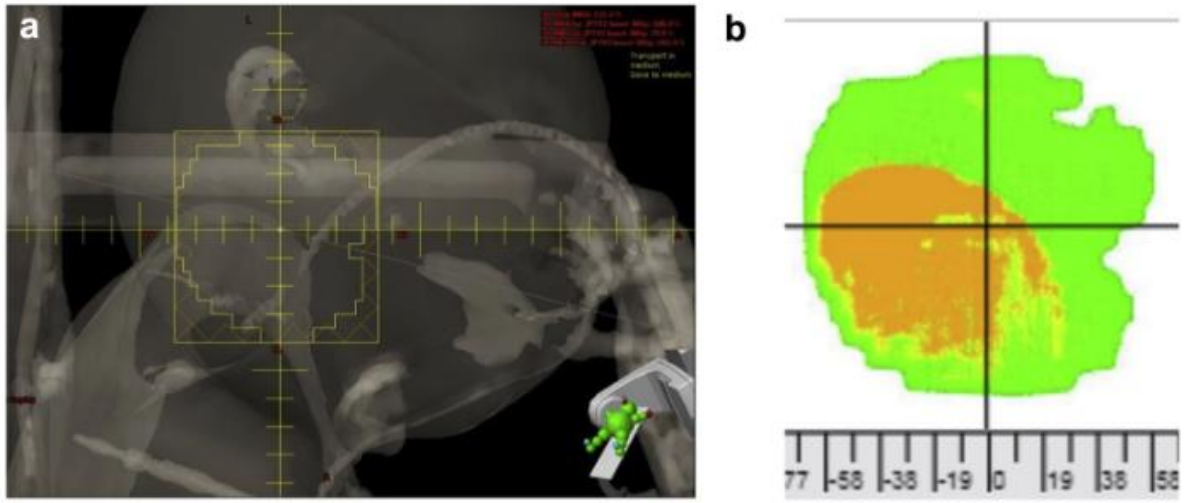
- EPIGray
  - Dose to point
- IVD one the first 3 fractions of treatment
- Difference between TPS and dose estimate 1.9% +/- 5.2%
- Automating day to day comparisons



Celi et al. J Appl Clin Med Phys 2016

Automation: Children's Hospital Los Angeles

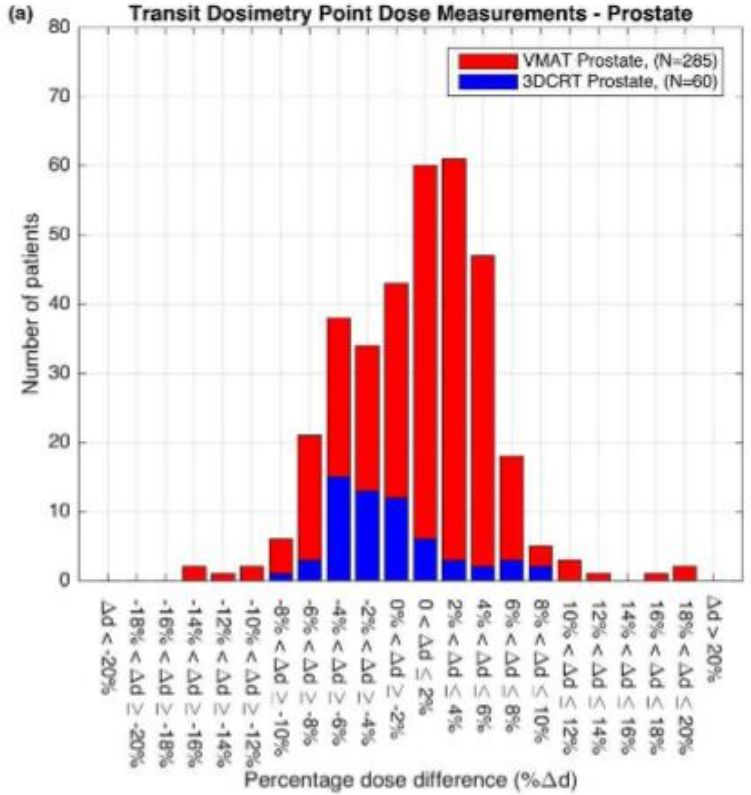
- PerFRACTION
- EPID images compared to baseline images
  - Perform gamma analysis for image, fraction, course of treatment
  - Failures due to body position change, internal anatomy change, external device position, unknown source
- Near total automation



Olch et al Advances In Rac Onc 2019

Automation: Edinburgh Cancer Centre

- Dosimetry Check
- Alert triggered when dose difference between TPS and DC at plan ref point exceeds 10%
  - Majority of alerts for breast patients



Nailon et al Rad Onc Phys 2019

Commercial Software

- EPIgray
  - Celi et al. J Appl Clin Med Phys 2016
- Dosimetry Check
  - Gimeno et al. Phys Med 2015,
  - Nailon et al Rad Onc Phys 2019
- PerFraction
  - Hsieh et al. Prac Rad Onc, 2017,
  - Zhuang, Olch. J Appl Clin Med Phys 2018,
  - Olch et al. Adv. In Rac Onc 2019
- SOFTDISO
  - Cilla et al 2016, Piermattei et al 2018
- EPIDos
- IViewDose
- Adaptivo

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Clinical Implementation

- Selection of system
- Commissioning
- Setting tolerance levels
  - Alert criteria differs from one institution to another
- Follow up actions
  - Policies and procedures for when an alert is raised

Error Types that Still Escape Detection

- Prescription Errors
  - Error in plans fractionation, location or total dose
- Incorrect Contouring
  - Portion of contour missing or incorrect volume used for planning
- Errors in field planning parameters/Suboptimal plan creation
  - Error in field parameters made during planning stage
- Error detected after fraction is delivered
  - Not suitable for SBRT, SRS treatments

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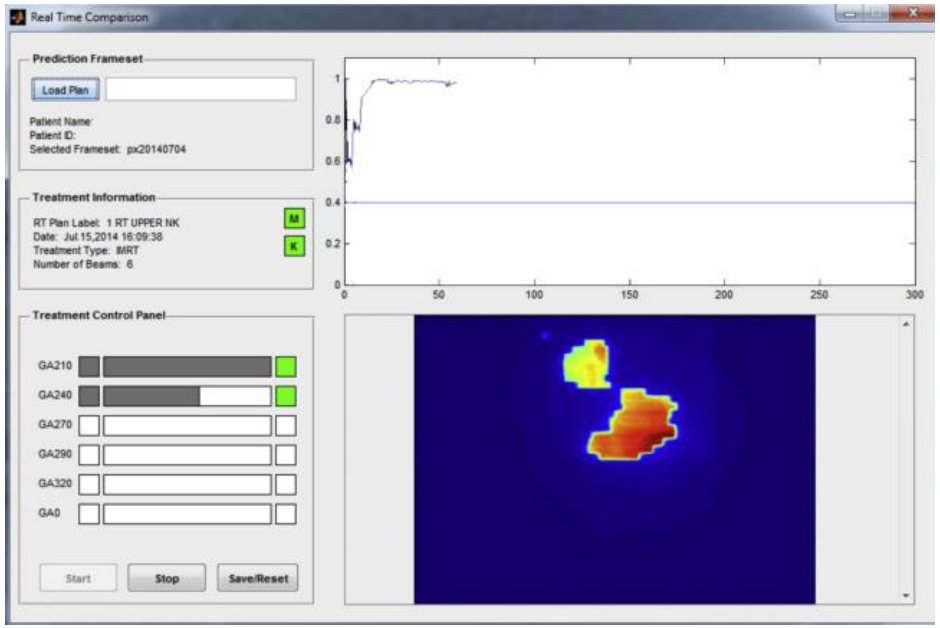
Real-Time Dosimetry

- Post treatment assessment of some treatments is not clinically useful.
- Diodes/MOSFETS are used to monitor treatments in real time, stop treatment if measured values deviate significantly from planned.

Real-Time Dosimetry

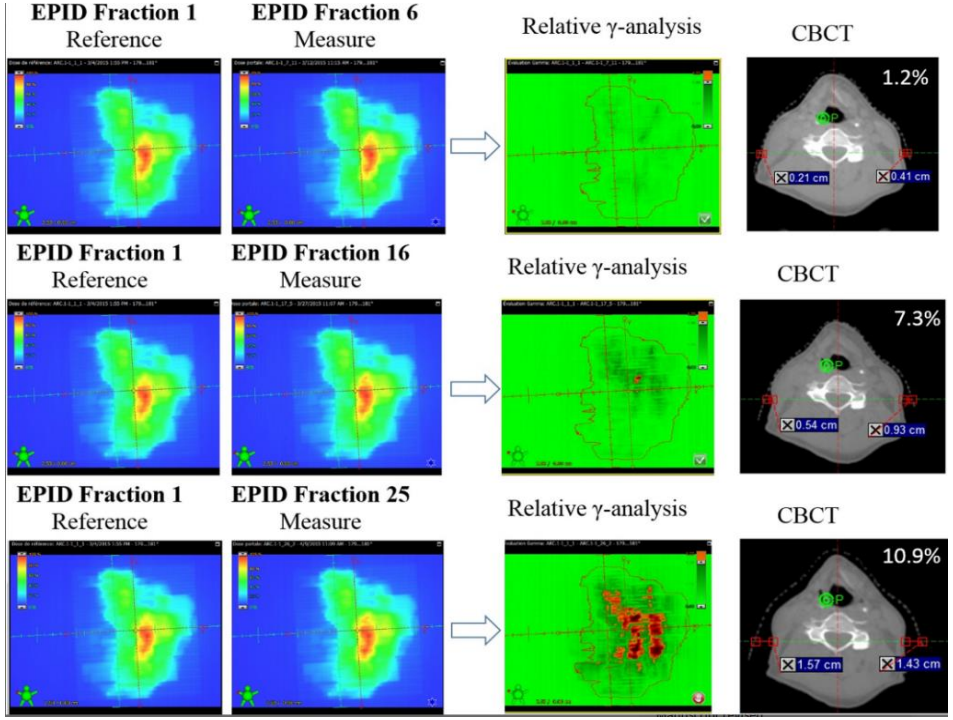
- EPID real-time prediction of images.
- WatchDog Project
  - Reference data set of EPID images is compared to acquired EPID images at a frame rate of 0.1s.
  - Comparison was performed to cumulative frame to gauge overall delivery quality.



Woodruff et al. Rad Onc Biol Phys 2015

Adaptive Planning

- Analysis of lung and head and neck patients have observed progressive anatomical changes
  - In-vivo dosimetry can provide quantitative metrics
- EPID based verification of OAR doses
- Real time adaptation



O Piron et al Med Phys 2018

Concluding Remarks

Additional Resources

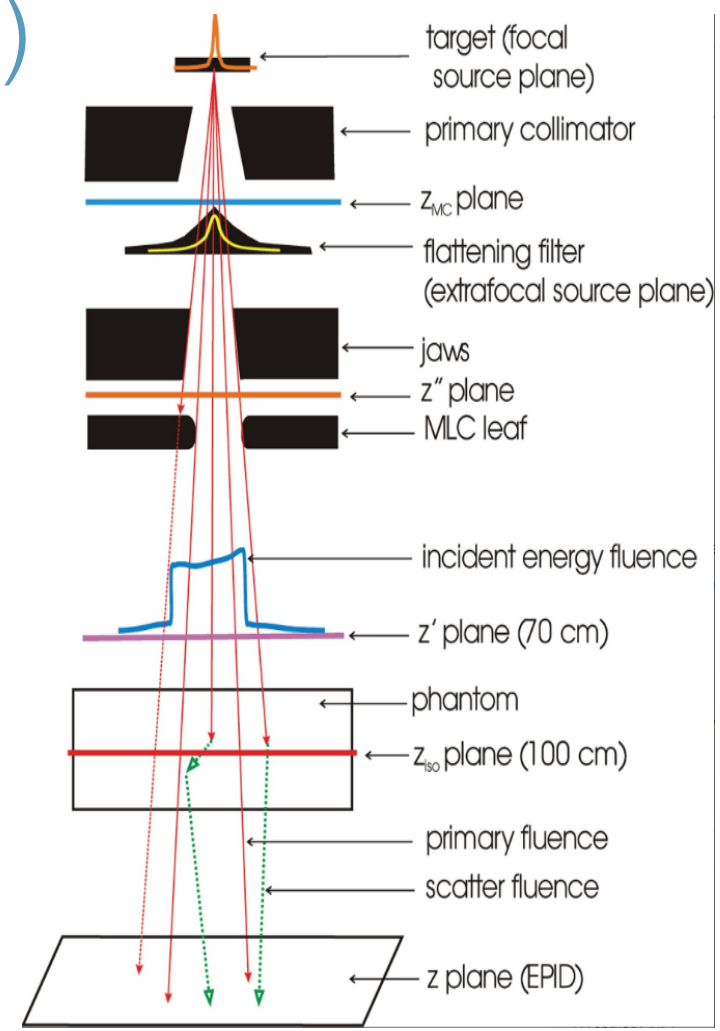
- **2016 AAPM Annual Meeting - Session: The EPID Strikes Back.**
  - Peter Greer, PhD
  - https://www.aapm.org/education/vl/vl.asp?id=11449
- **Clinical 3D Dosimetry in Modern Radiation Therapy.**
  - In Press, Edited by Ben Mijnheer, PhD

Thank You

Additional Materials

Transit Dosimetry (forward projection)

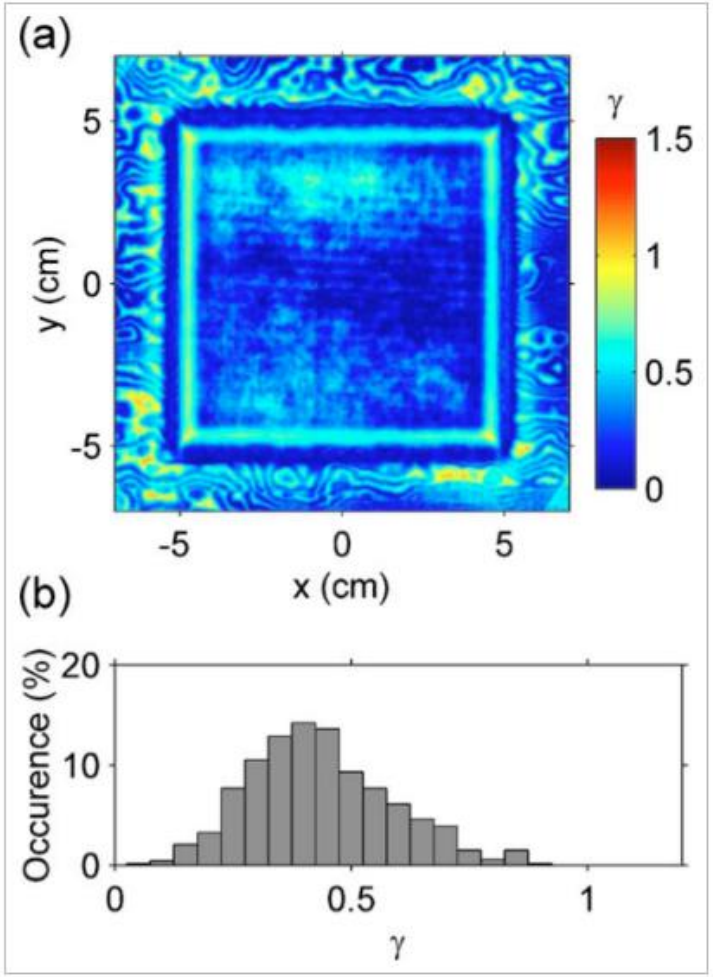
- Use MC methods or empirical calculations.



Chytyk et al Med Phys 2013

Back Projection (0D,2D)

- Determination of dose at point in patient (iso)
- Estimation of planar dose
  - Related imager response to radiological thickness of patient/phantom.

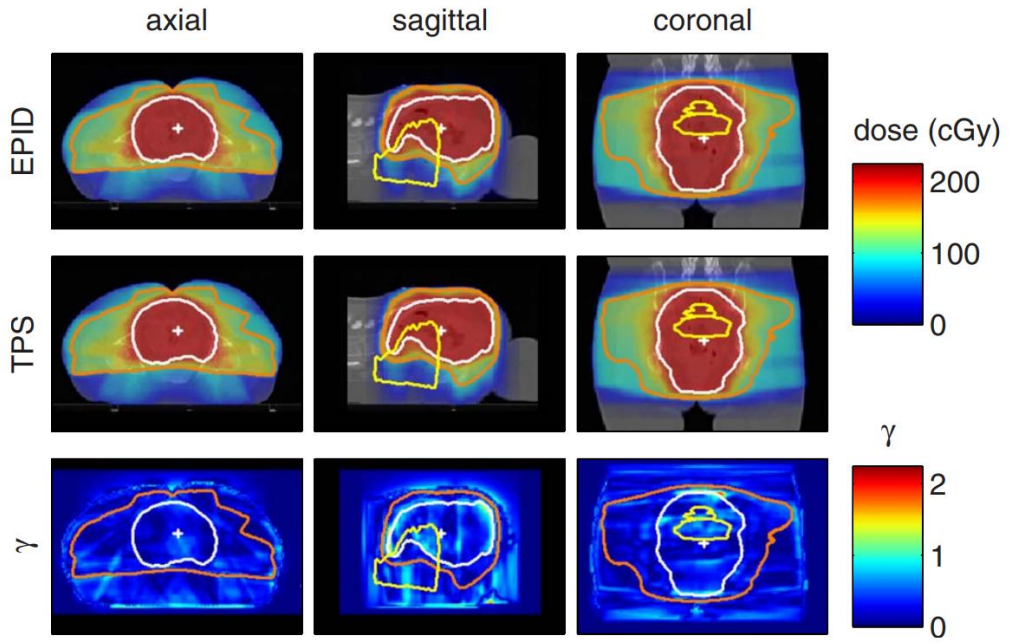


Piermattei et al Med Phys 2008.

Wendling et al Med Phys 2006

Back Projection (2D-3D)

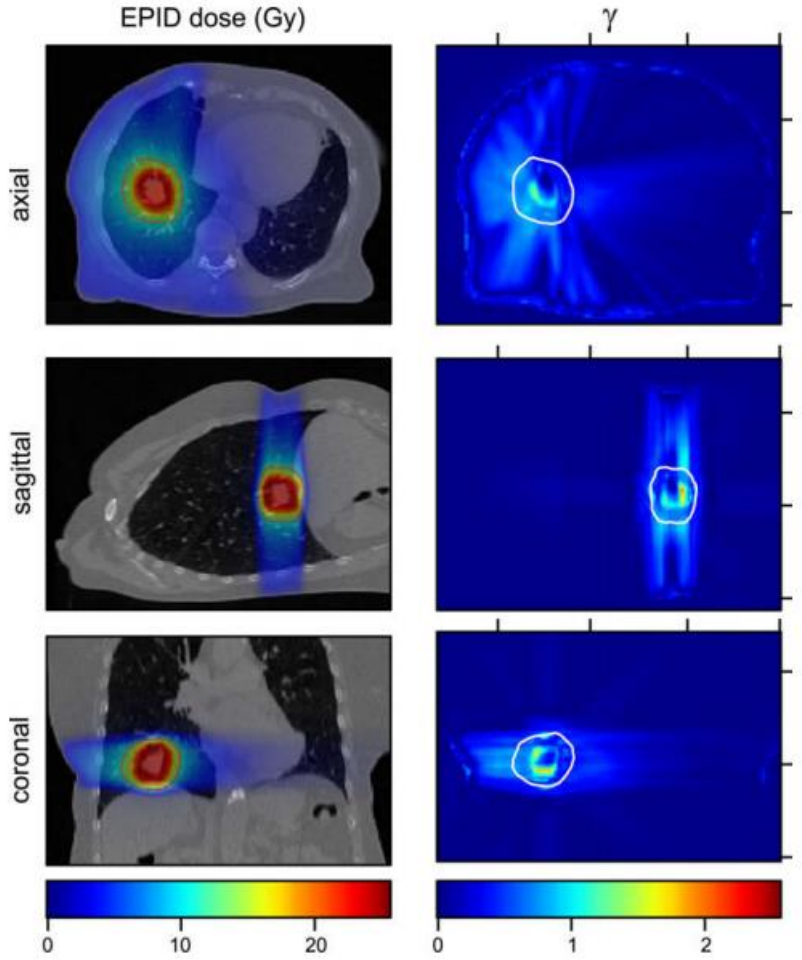
- Requires collection of open beam image
- Use EPID image to estimate primary and scatter fluence
- Model attenuation of primary fluence through patient CT
- Reconstruction of 2D dose planes, interpolated to reconstruct 3D dose



Wendling et al Med Phys 2008

Back Projection VMAT

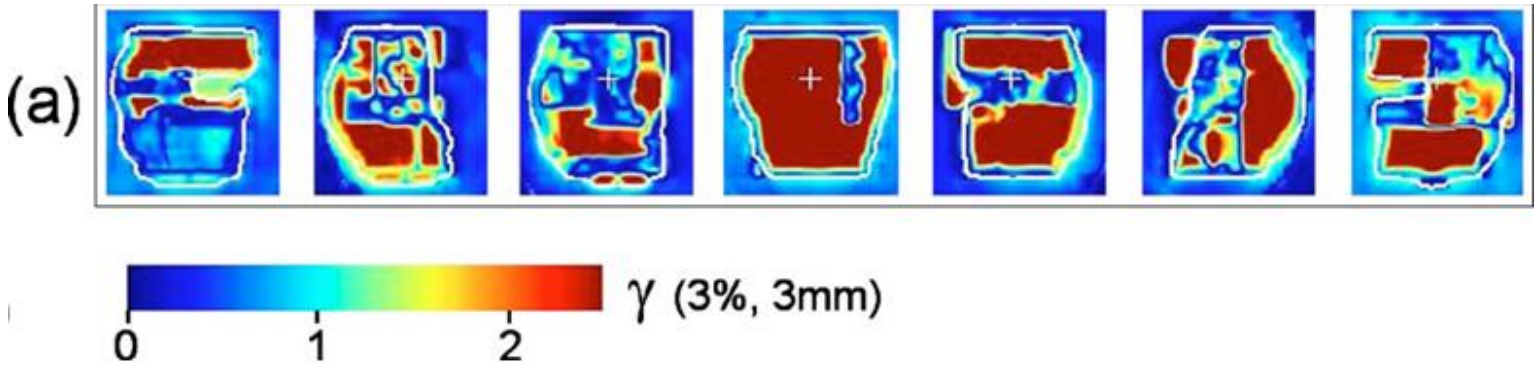
- Information is washed out over VMAT Arc
- Use Cine images recording gantry angle to backproject dose at various angles
- Technical challenges
  - Gantry angle lag, missing frames, interplay between pulsing and readout.



*Mans et al Radiother. Oncol 2010.
McCurdy et al Medical Physics 2009

Case Study

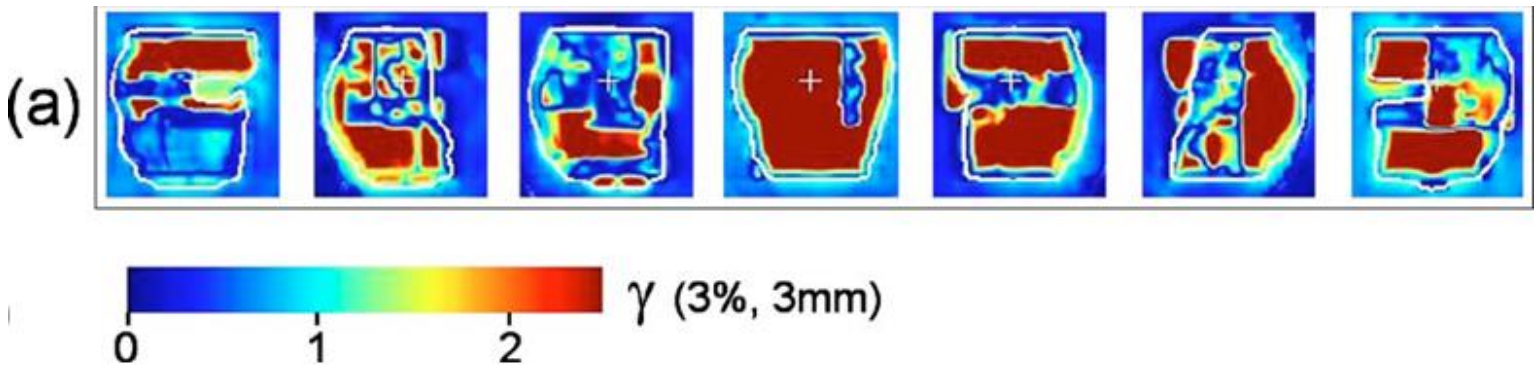
- Rectum cancer patient (NKI)
  - Prescribed 25 Gy to target volume in 5 fractions.
  - 7 IMRT beams
  - Plan transferred to Mosaiq, all protocols followed, no abnormalities observed. Majority of control points corrupted (27 out of 35)
  - MLC positions and jaw positions mismatched



Mans et al. Med Phys. 37(6) 2010

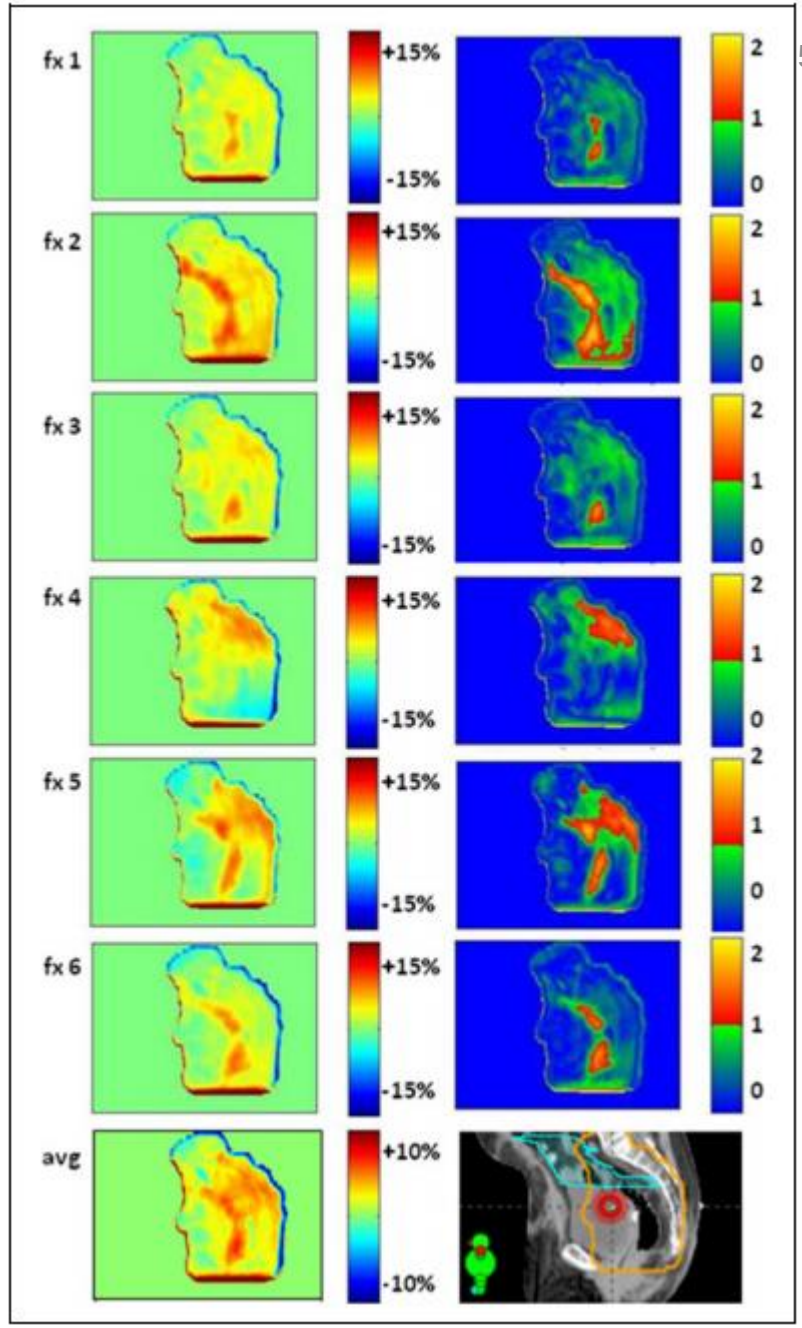
Case Study

- EPID dosimetry done during first fraction, analysis done after first fraction
- Would have been detected pre-treatment
- EPID data used to reconstruct dose, used to inform decisions on continuation of plan



Rectum

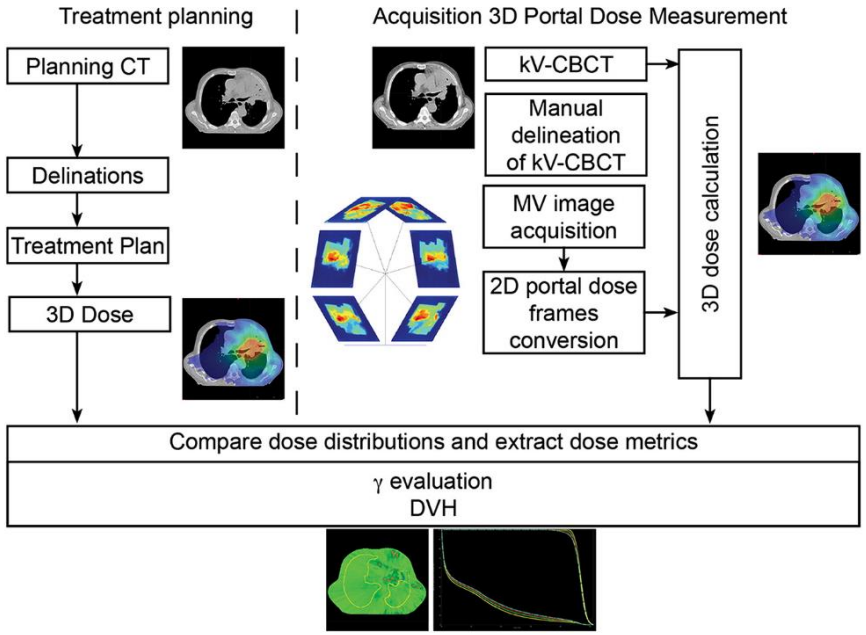
- Prone rectal treatments
  - Reconstruction of planar dose at isocenter.
  - Persistent bowel gas, changes to bowel dose



Peca et al. Technol Cancer Res Treat 2017

Automation: Maastro

- 3D dose reconstruction using kv CBCT image. 3D portal dose compared to planned dose. Automatically flagged if gamma criteria is not passed.
- 3D calculated for all patients.
- Study done on atelectasis adaptive protocol
  - If significant change observed CTV is re-delineated on CBCT.
  - Discrepancies and changes over time for lung cancer treatments.



Persoon et al. Acta Oncol 2013