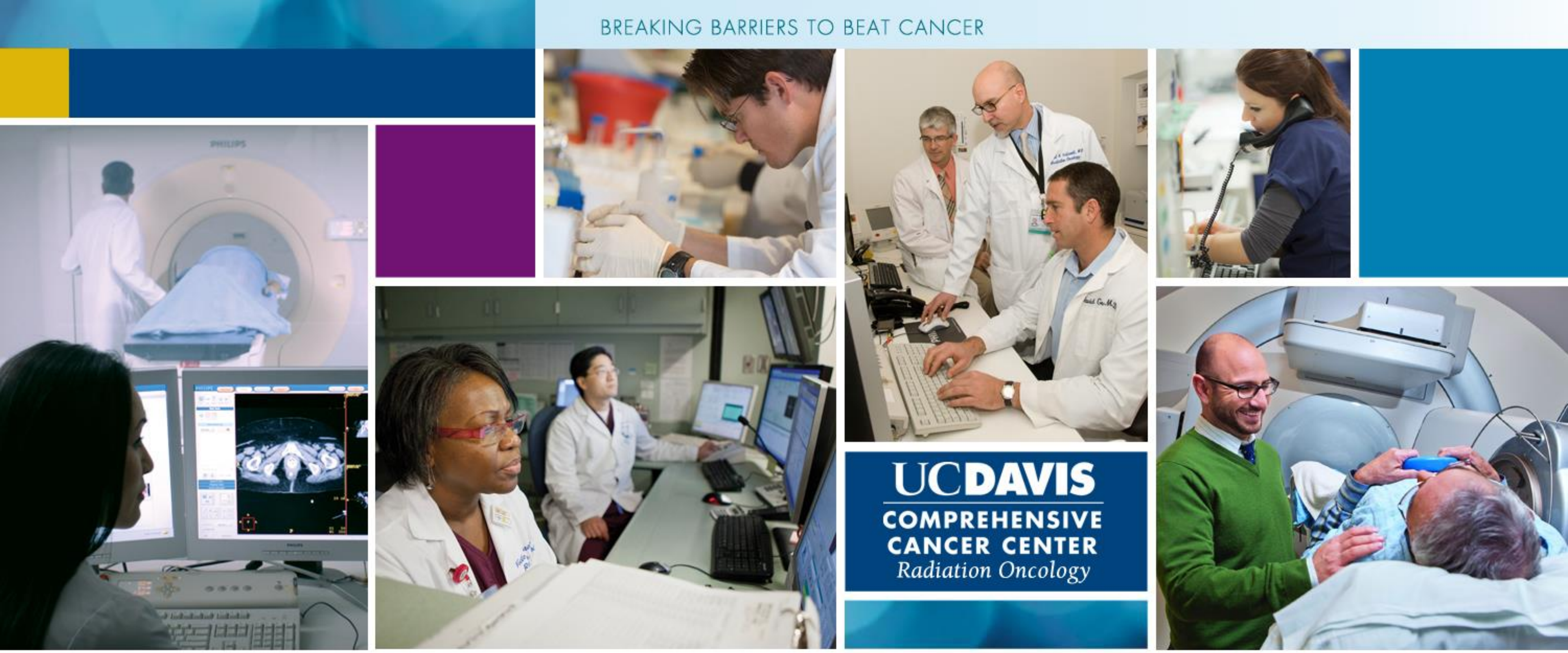


Real-Time Monitoring of Treatment Delivery

Sonja Dieterich, Ph.D., FAAPM
Professor

Disclosures

- UC Davis has a contract with Sun Nuclear for beta-testing PerFraction
- Scientific Advisor, MGS Research

IS WEEKLY PORT FILMING ADEQUATE FOR VERIFYING PATIENT POSITION IN MODERN RADIATION THERAPY?

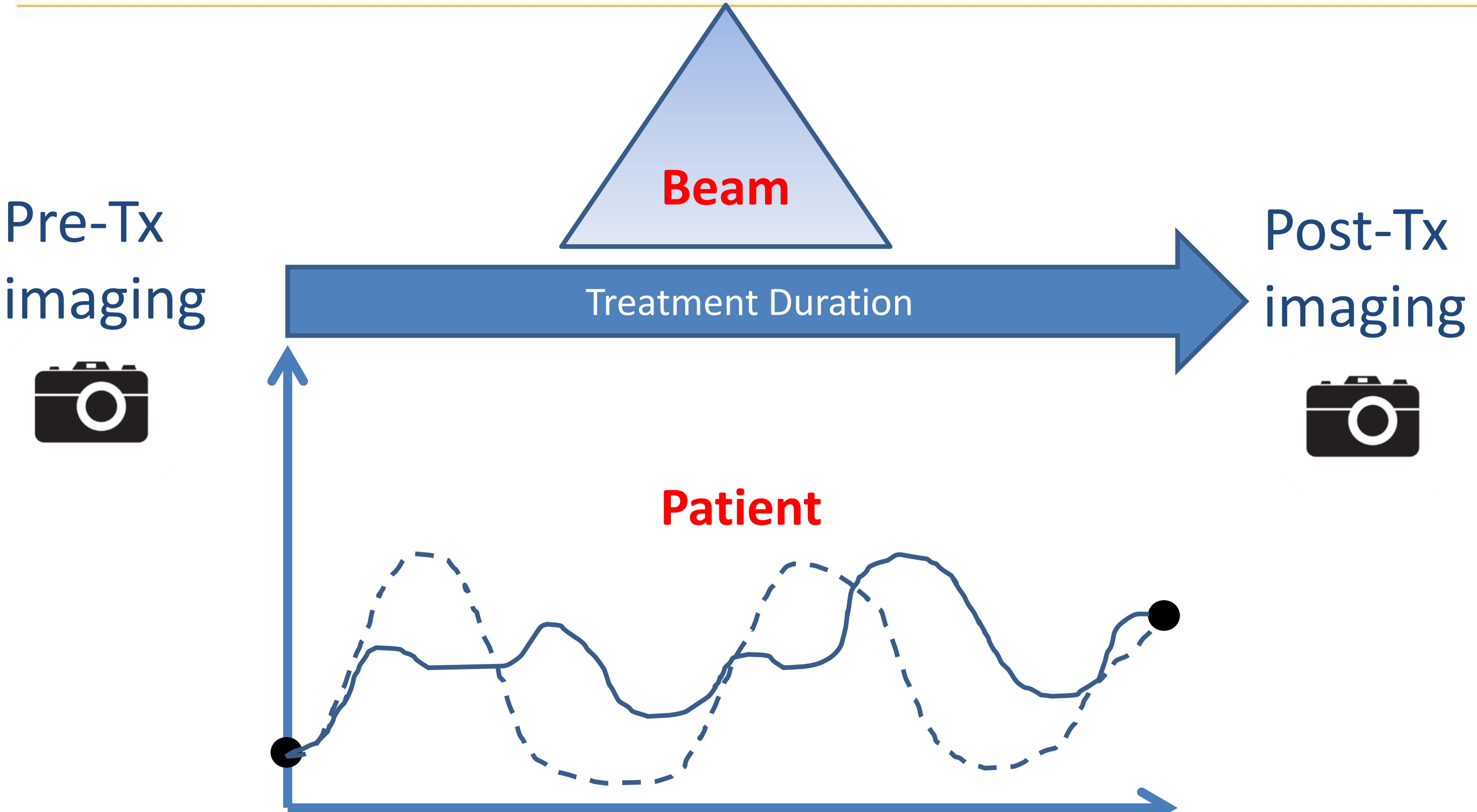
RICHARD K. VALICENTI, M.D., JEFF M. MICHALSKI, M.D., WALTER R. BOSCH, D.SC., RUSSELL GERBER, M.S., MARY V. GRAHAM, M.D., ABEL CHENG, M.S., JAMES A. PURDY, PH.D. AND CARLOS A. PEREZ, M.D.

Radiation Oncology Center, Mallinckrodt Institute of Radiology, Washington University School of Medicine, St. Louis, MO

Purpose: The objective of this study is to use daily electronic portal imaging to evaluate weekly port filming in detecting patient set-up position.

Int. J. Radiation Oncology Biol. Phys., Vol. 30, No. 2, pp. 431–438, 1994

What are we trying to observe?



Beam Monitoring

Existing Beam Monitoring Devices

- Ion chamber
- MLC controller system
- Log files

➢ Log file analysis software

- Litzenberg, Dale W., Jean M. Moran, and Benedick A. Fraass. "Verification of dynamic and segmental IMRT delivery by dynamic log file analysis." *JACMP* 3.2 (**2002**): 63-72.
- Teke, Tony, et al. "**Monte Carlo** based, patient-specific RapidArc QA using Linac log files." *Medical physics* 37.1 (2010): 116-123.
- And many, many more papers ….

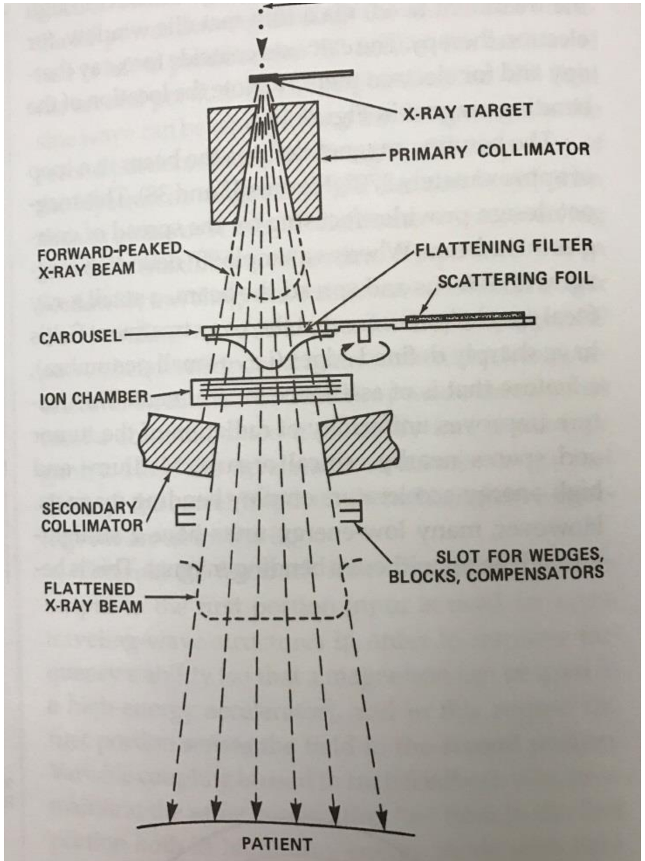


Figure 39. Beam subsystem for x-ray beam therapy.

More Direct Method for Real-Time Beam Monitoring

Transmission Detector Technology

In alphabetical order:

- COMPASS
- DAVID: translucent multi-wire transmission chamber
- IQM
- Magic Plate
- Optical transmission
- Vanilla

COMPASS

PATIENT-SPECIFIC 3D PRETREATMENT AND POTENTIAL 3D ONLINE DOSE VERIFICATION OF MONTE CARLO–CALCULATED IMRT PROSTATE TREATMENT PLANS

RAMESH BOGGULA, M.SC., LENNART JAHNKE, M.SC., HANSJOERG WERTZ, PH.D., FRANK LOHR, M.D., AND FREDERIK WENZ, M.D.

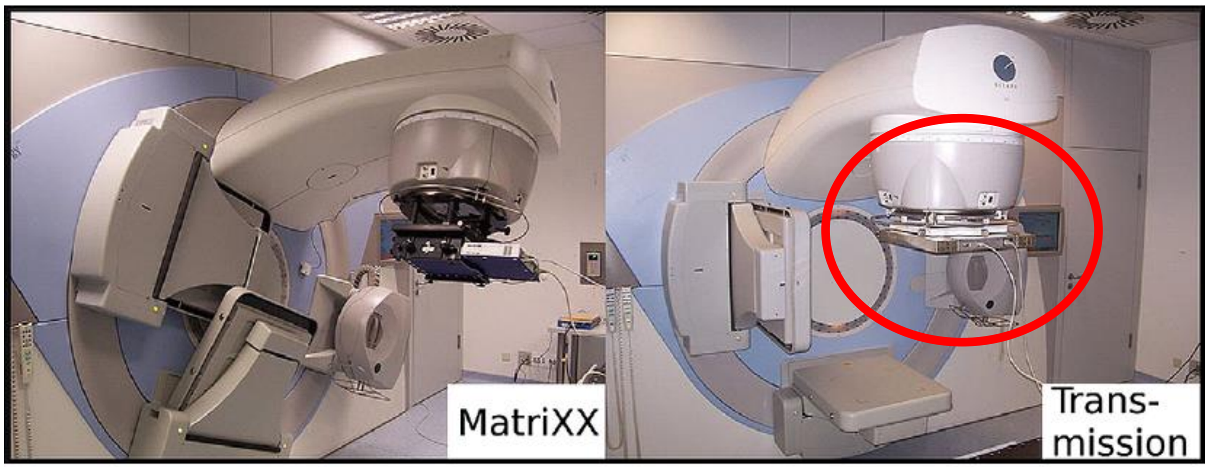
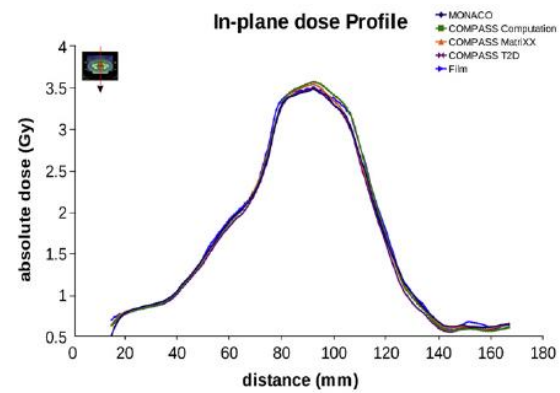
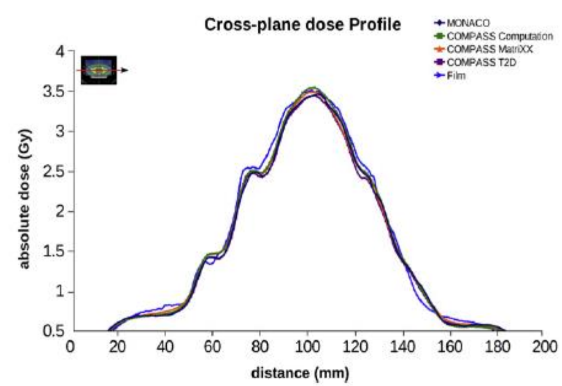


Fig. 1. Setup of MatriXX Evolution (IBA Dosimetry, Germany) detector and transmission detector.





- 1600 vented parallel-plate ion chambers
- 3.1 mm water

DAVID

- Flat, 80-wire chamber
- IMRT DQA serves as reference data set
- During Tx, DAVID gives warning if measurement exceeds tolerance
- ≤1 mm leaf position error

DAVID—a translucent multi-wire transmission ionization chamber for *in vivo* verification of IMRT 1239

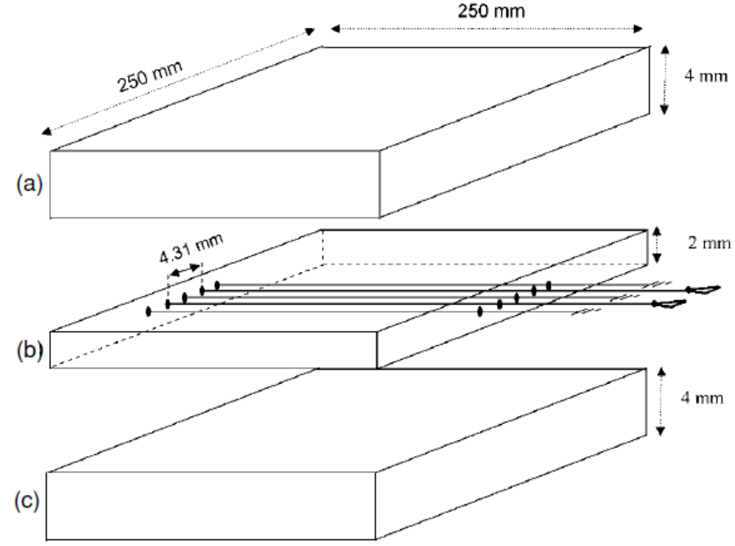


Figure 1. Schematic drawing of the multi-wire ionization chamber in the DAVID system. The blow up sketch illustrates (b) the air-filled collection volume with two of the 29 detection wires connected to the amplifiers and three of the 30 grounded wires, (a) and (c) the 4 mm PMMA cover plates, which carry the translucent chamber voltage electrodes on their inner sides.

DAVID

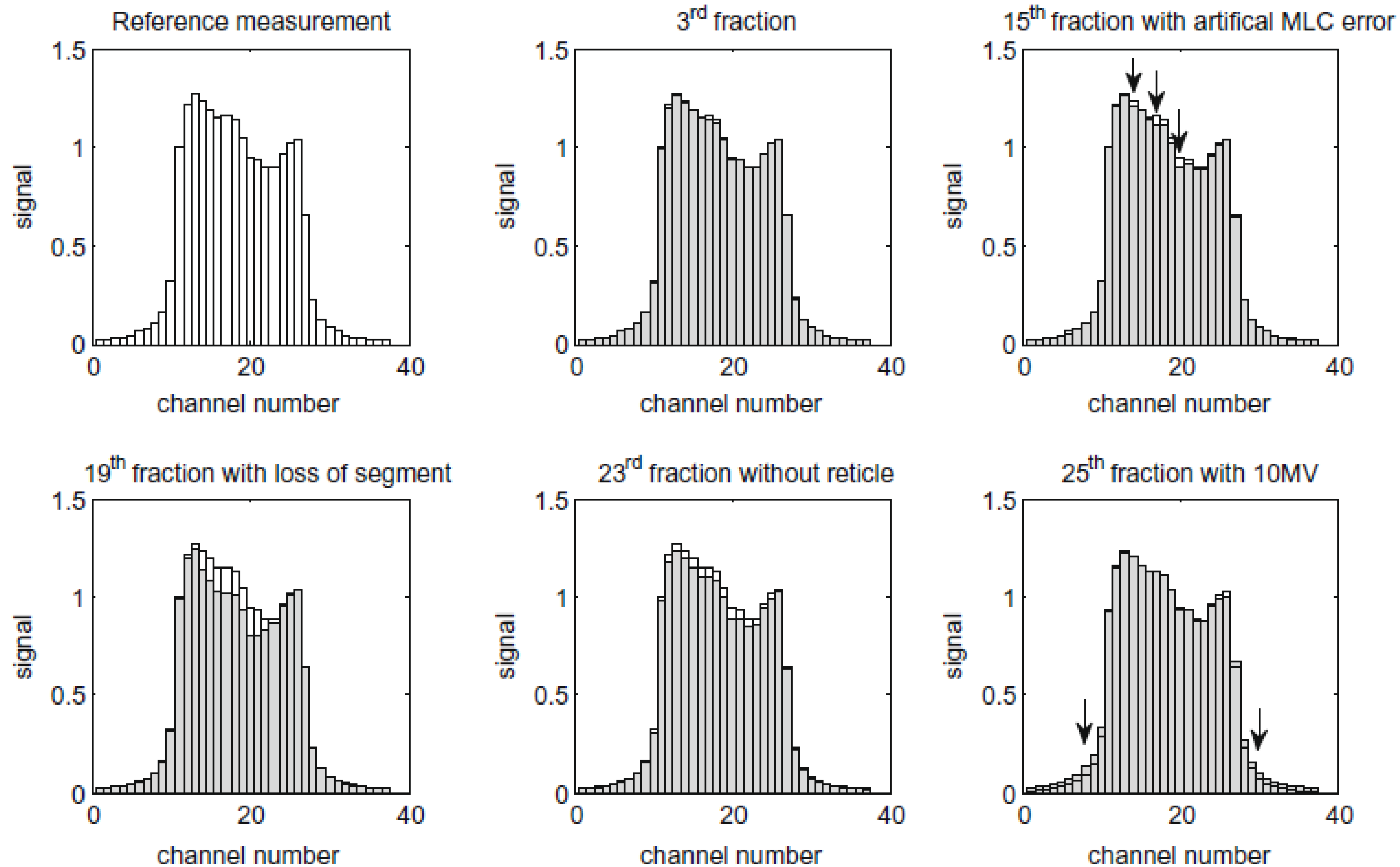


Fig. 3. Examples of the measured DAVID channel signals at 6 MV and at gantry angle 0° for some selected fractions. Artificial errors, introduced in the 15th, 19th, 23rd and 25th fraction, were detected as deviations from the reference signals.

IQM (Integral Quality Monitoring System)

- Developed at PMH (M. Islam, D. Jaffray, et al.)
- Large area ionization chamber with gradient along MLC motion axis

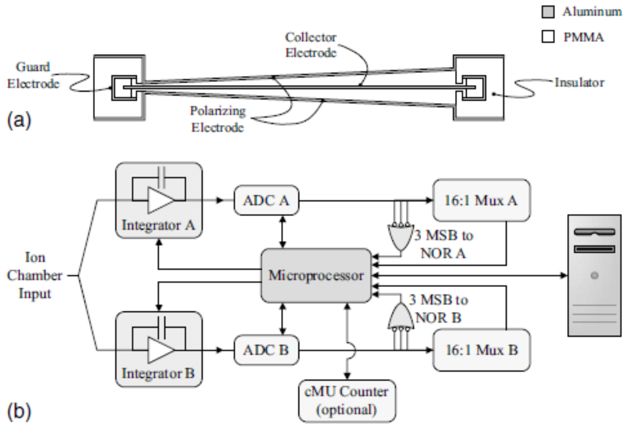


FIG. 2. (a) Schematic diagram of the prototype spatially sensitive large area (22×22 cm^2) ionization chamber; outer electrode (polarizing electrode) separations vary linearly from 2 to 20 mm. (b) Functional block diagram of the dosimetry system, which includes a wide dynamic range dual integrator electrometer and a microprocessor. The microprocessor controls the integration and readout of signals in synchronization with beam segments.

Medical Physics, Vol. 36, No. 12, December 2009

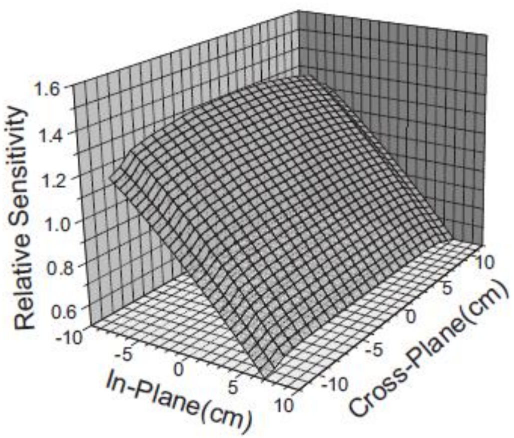


FIG. 5. The spatial response function $\sigma(x,y)$ of the chamber for a jaw setting of 14×24 cm^2. The response values are normalized with respect to the value at the beam central axis. The in plane and cross plane dimensions refer to the directions along and perpendicular to the MLC leaf motions, respectively.

IQM (Integral Quality Monitoring System)

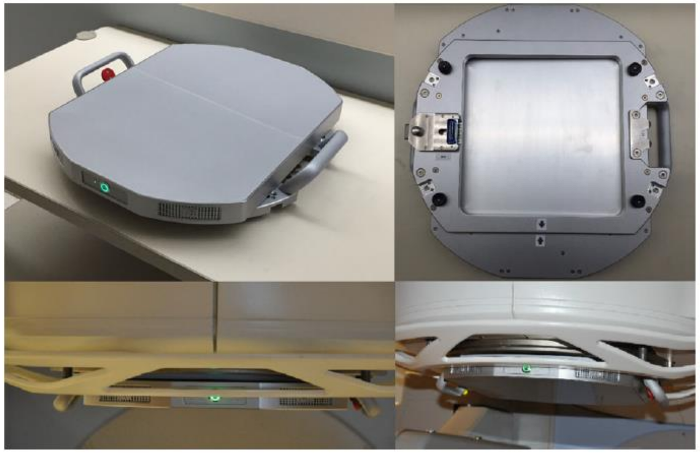


FIG. 1. The Integral Quality Monitor (IQM) is a large area ion chamber (top left) with a gradient of the ion chamber thickness in the axis of MLC motion. It attaches to the accessory tray holder, similar to an electron cone (top right). The device has a low profile from the linac head (bottom left and right) and connects wirelessly to a transceiver and the controlling computer.

- Extensive validation test of newer model (D. Hoffman, UCD resident)
- Impact on beam parameters small
- 1.5 mm leaf shift causes 1% change in 10x10 field

TABLE 1 The percentage change of IQM signal when the baseline 6 MV photon beam, 10 × 10 cm^2 field and 100 MU, is changed with the listed modifications. For modifications that result in less than a 1% signal change, the magnitude of modification to give 1% signal change is recorded.

Modification	% signal change	Magnitude of modification for 1% change
1% decreased MU	−0.99 ± 0.01%	-
1% increased MU	1.00 ± 0.03%	-
1 mm single MLC leaf into field	−0.05 ± 0.01%	13 mm
1 mm single MLC leaf out of field	0.01 ± 0.01%	25 mm
1 mm field shift in MLC motion axis	0.42 ± 0.06%	3 mm
1 mm field shift in MLC nonmotion axis	0.20 ± 0.13%	Not sensitive
Incorrect energy (10 MV)	0.8 ± 0.02%	-
Incorrect energy (15 MV)	2.85 ± 0.01%	-

Magic Plate

- Epitaxial diode technology developed at University of Wollongong
- Technical and dosimetric evaluation very thorough
- No publication on patient plans yet

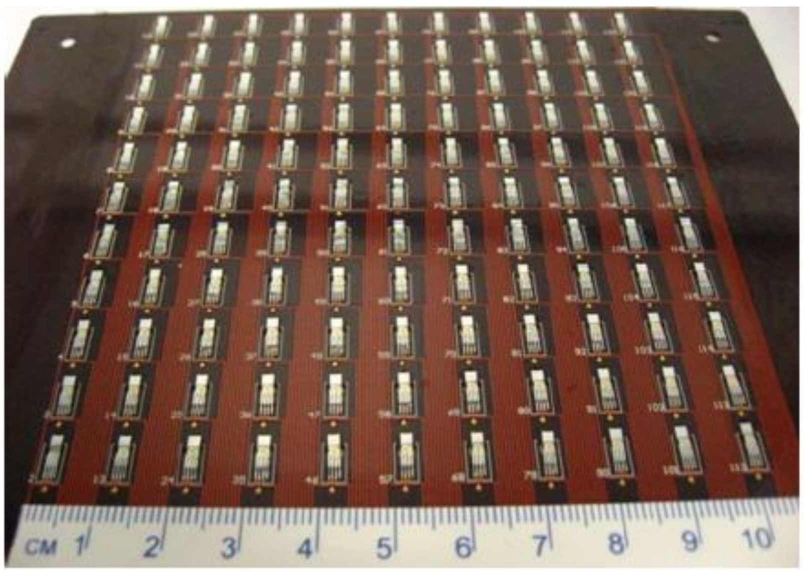


FIG. 1. Magic plate.

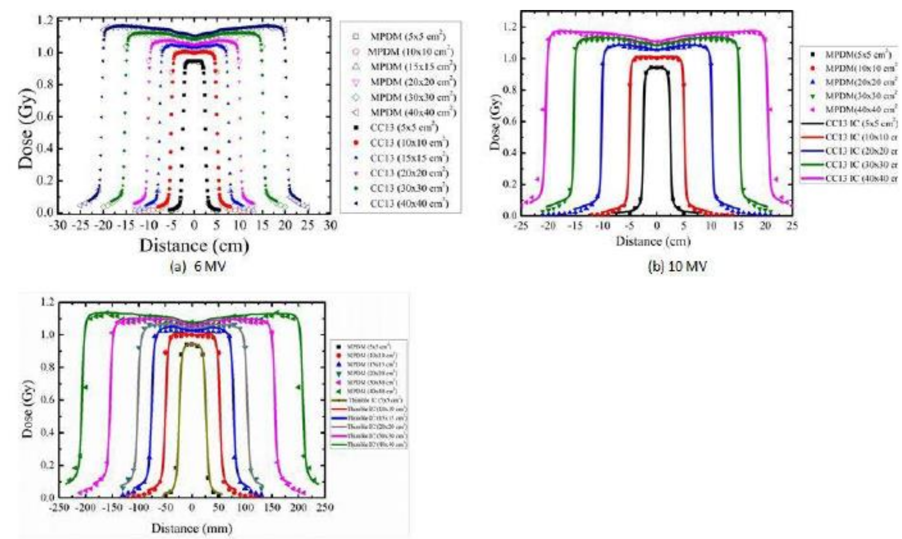


Figure 2. (a-c): Comparison between measured doses using ion chambers (CC13 and PTW Thimble chambers) and measured doses using Magic Plate in solid water phantom (MPDM) at dmax. 6 MV, 10 MV and 18 MV were used for this study.

Optical attenuation

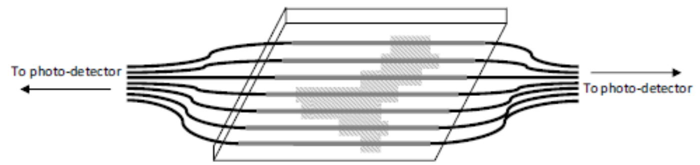


FIG. 2. Simplified schematic of the experimental prototype used. Scintillating fibers (gray) were aligned with respect to the radiation field (hatched lines) to match each multileaf collimator leaf to a single fiber. The light was guided by clear optical fibers (black) and collected by a photodetector. The prototype was located in the accessory tray.

- Prototype detected leaf placement errors <0.8 mm
- Best performance if compared to a gold standard delivery

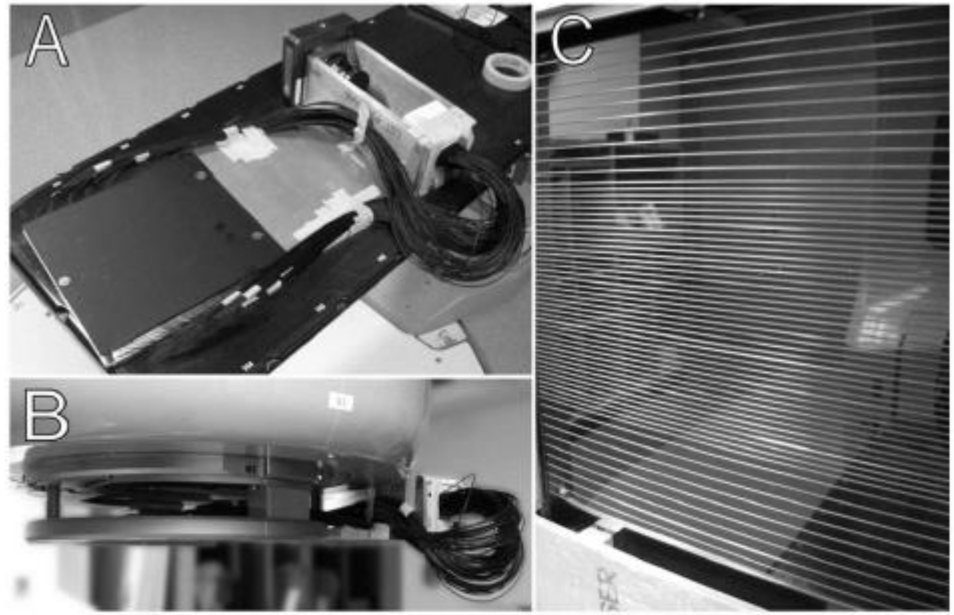


FIG. 3. Actual view of the experimental prototype used. The device is aimed to be placed in the accessory tray of the linac so that fluence verification can take place during the treatment delivery. (a) Top view of the unmounted prototype, (b) prototype mounted in the accessory tray, and (c) bottom view of the prototype, where the parallel scintillating fibers are shown.

Vanilla

- Monolithic active pixel sensor

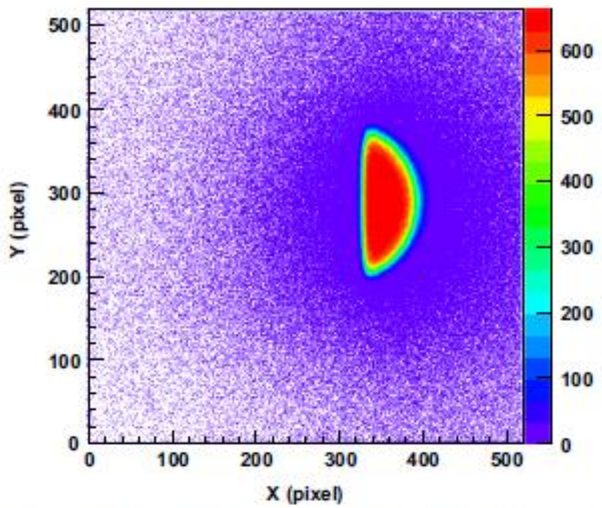


Fig. 4. Summed hit map using the lead brick to block part of the beam. Here a threshold of 350 ADC counts was used.

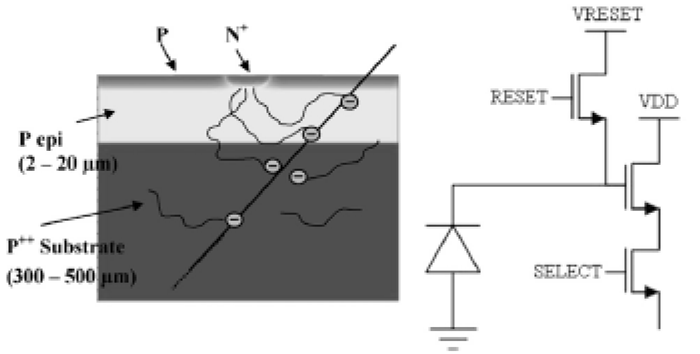


Fig. 1. Schematic cross section of a Monolithic Active Pixel Sensor (*left*) and the in-pixel circuitry of a standard 3T MAPS device (*right*).

Technical note

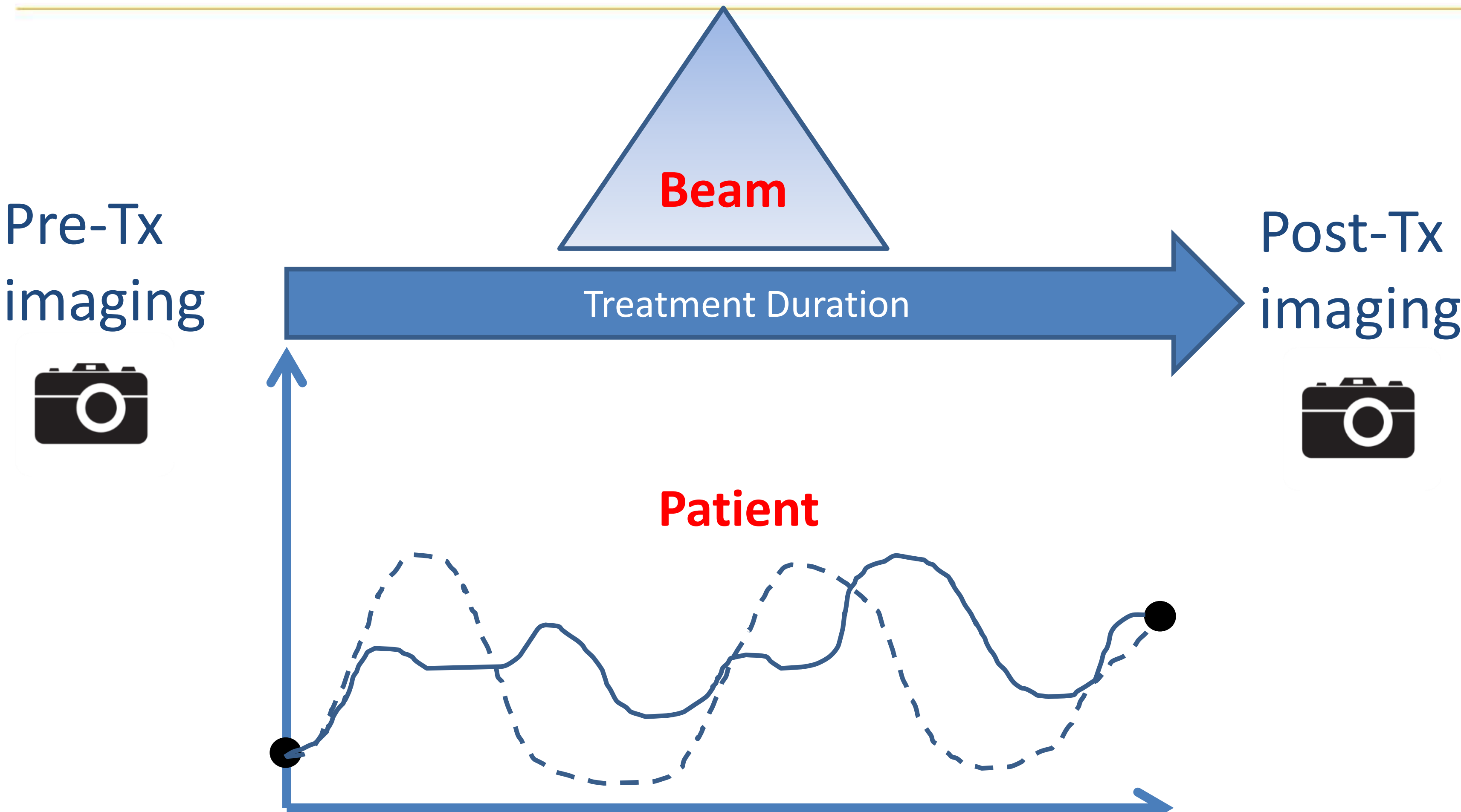
The VANILLA sensor as a beam monitoring device for X-ray radiation therapy

J.J. Velthuis [a,*], R.P. Hugtenburg [b], D. Cussans [a], M. Perry [a], C. Hall [c], P. Stevens [c], H. Lawrence [c], A. McKenzie [c]

"Patients can just get off the couch and walk out of the room!"
John Adler, MD , about linacs ~2003

Patient Monitoring

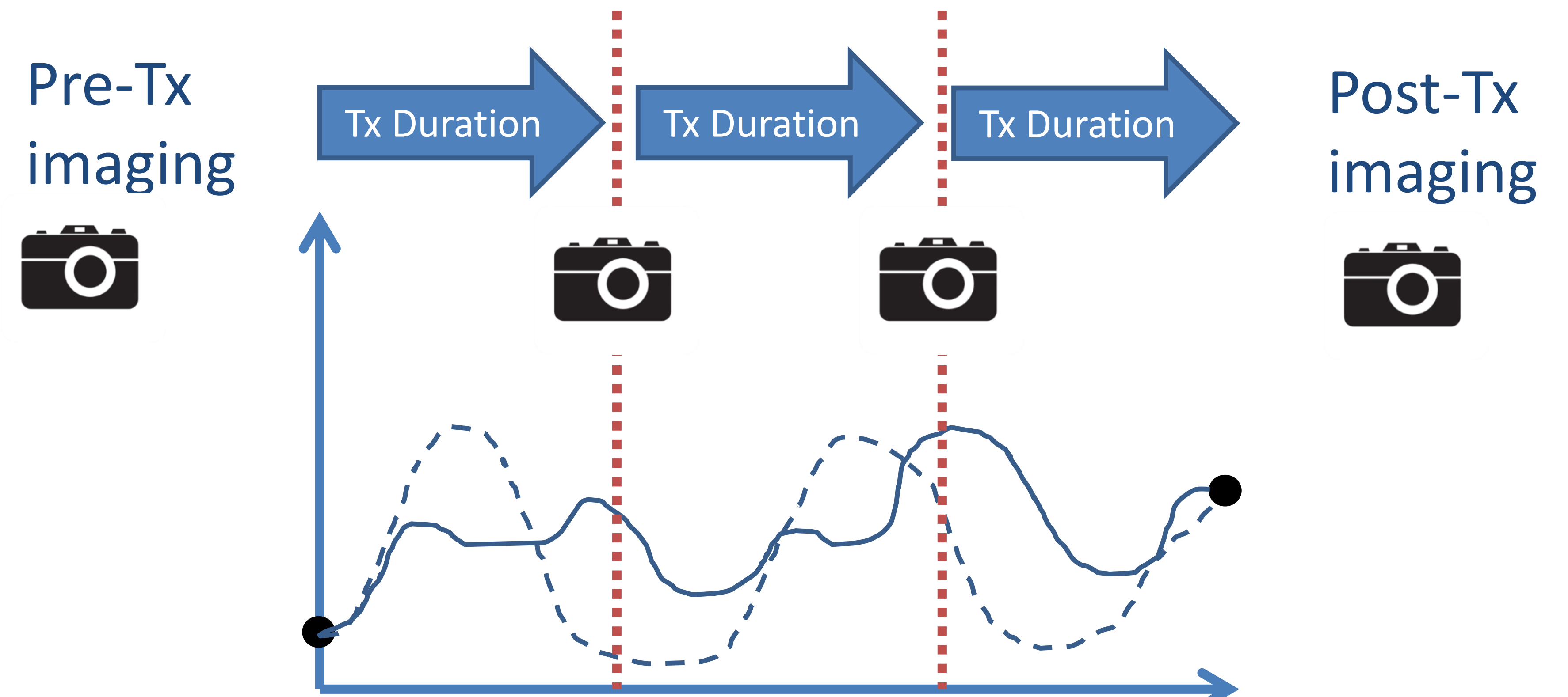
What are we trying to solve?



Patient Imaging

- 2D (+time) Ionizing Imaging options
  - Single kV, Fluoro
  - Orthogonal kV (CK, BrainLab)
  - Orthogonal kV/MV combinations
  - MV beam-line
- 3D/4D Ionizing Imaging options
  - kV CBCT
  - MV CBCT
- 2D (+time) Non-Ionizing Imaging
  - External 2D surrogate (belt, flow meter, RPM cube, CK beacons)
  - Optical imaging in 3D (Vision RT, C-Rad)
  - Electromagnetic (Calypso)
- 3D/4D Non-ionizing Imaging: MRI
- And various combinations of these …

The Salami Solution: treat, stop, image, repeat



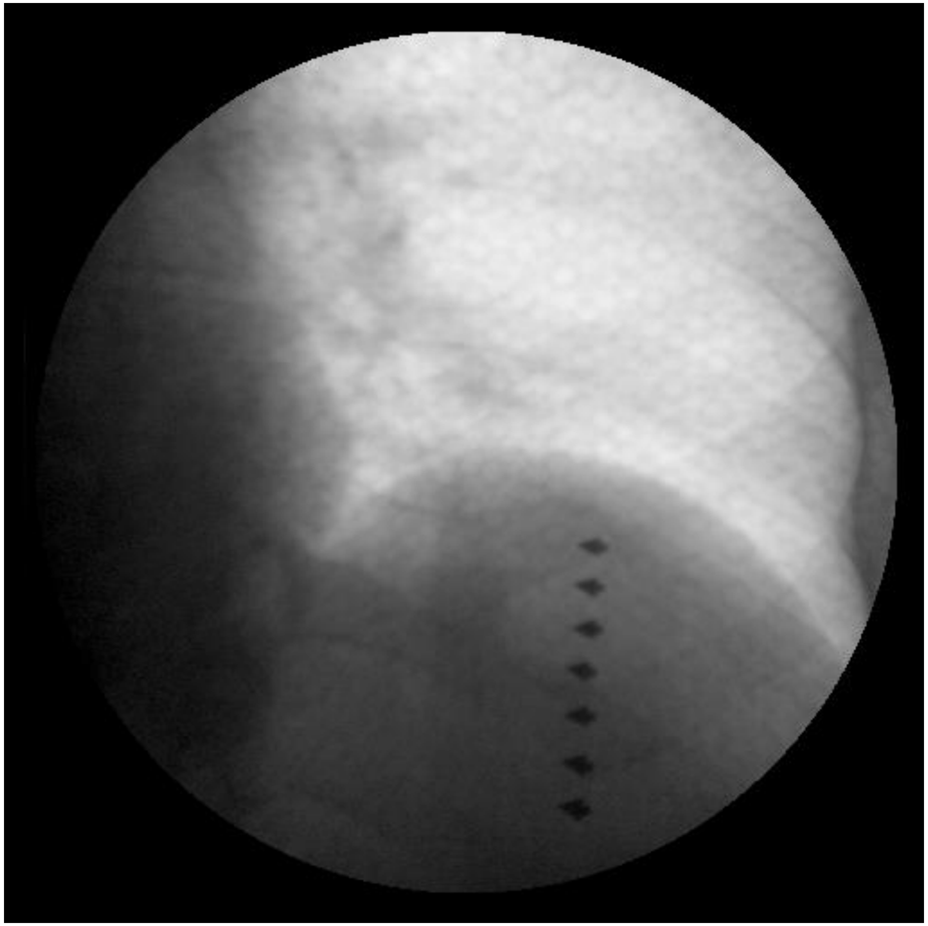
Salami Solution Early Examples

BrainLab

CyberKnife

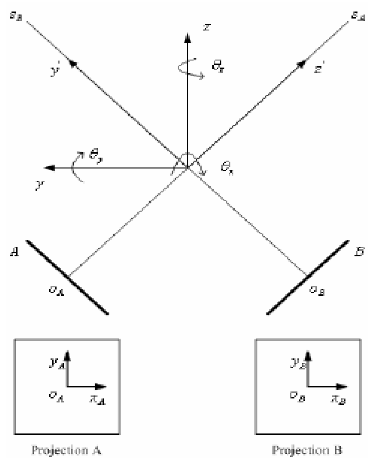
Ionizing Imaging

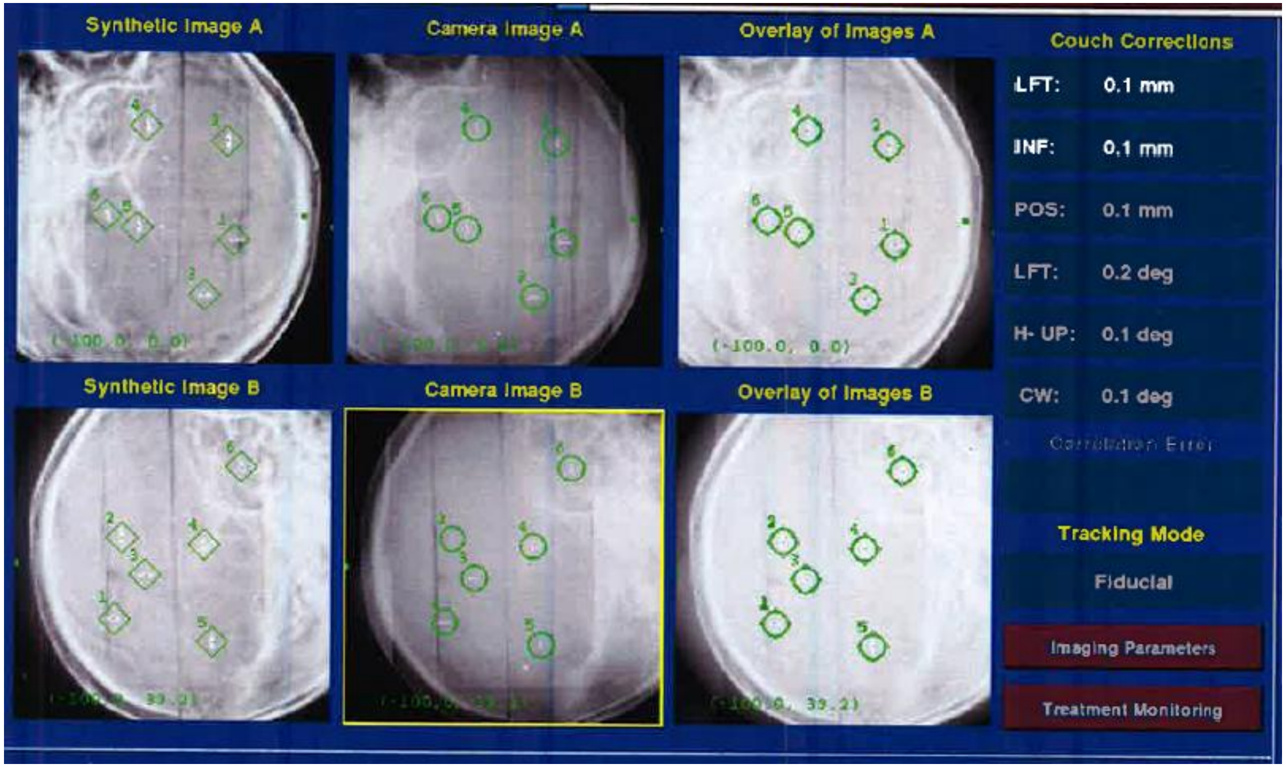
Fluroscopy



- Imaging dose

Orthogonal Imaging





The Principle of 2D-3D registration

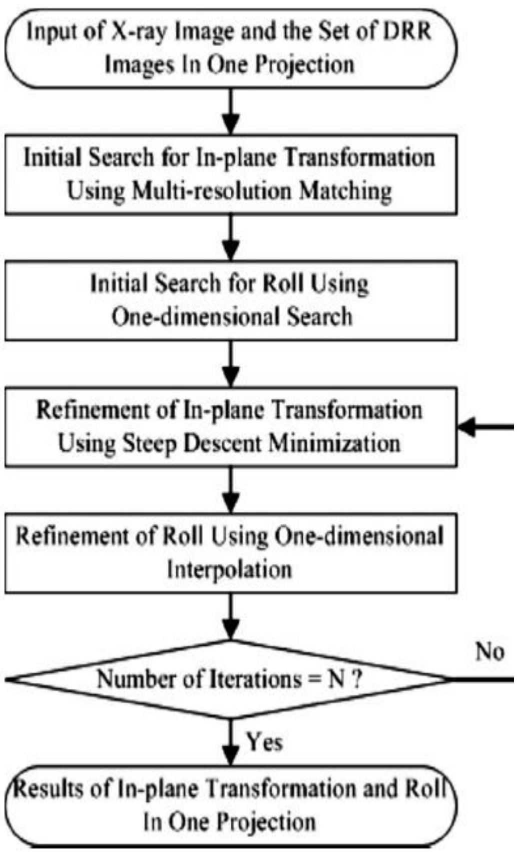
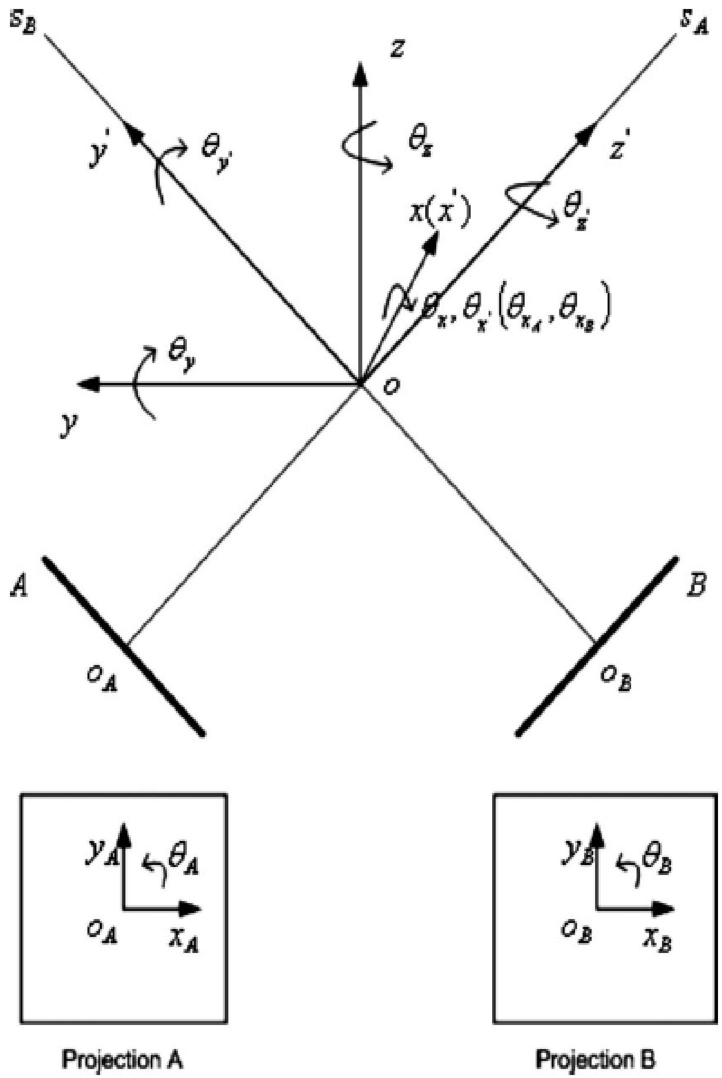
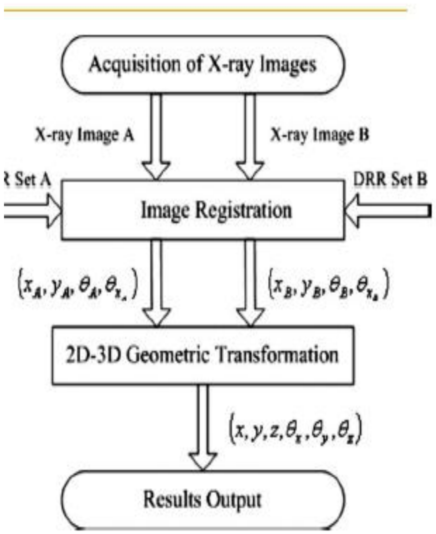


FIG. 4. The flowchart of image registration of an x-ray image and t
DRRs in one projection.





2. The workflow of the 2D–3D image registration.

Requirements for Orthogonal Imaging

- Image registration algorithm:
  - Fast
  - Reliable
- Feedback loop:
  - Automatic Tx stop based on patient position tolerance
  - And/or adjustment of beam to new patient position

Cherenkov Imaging (!!!)

Volume 89 • Number 3 • 2014 Cherenkoscopy for breast radiation therapy 617

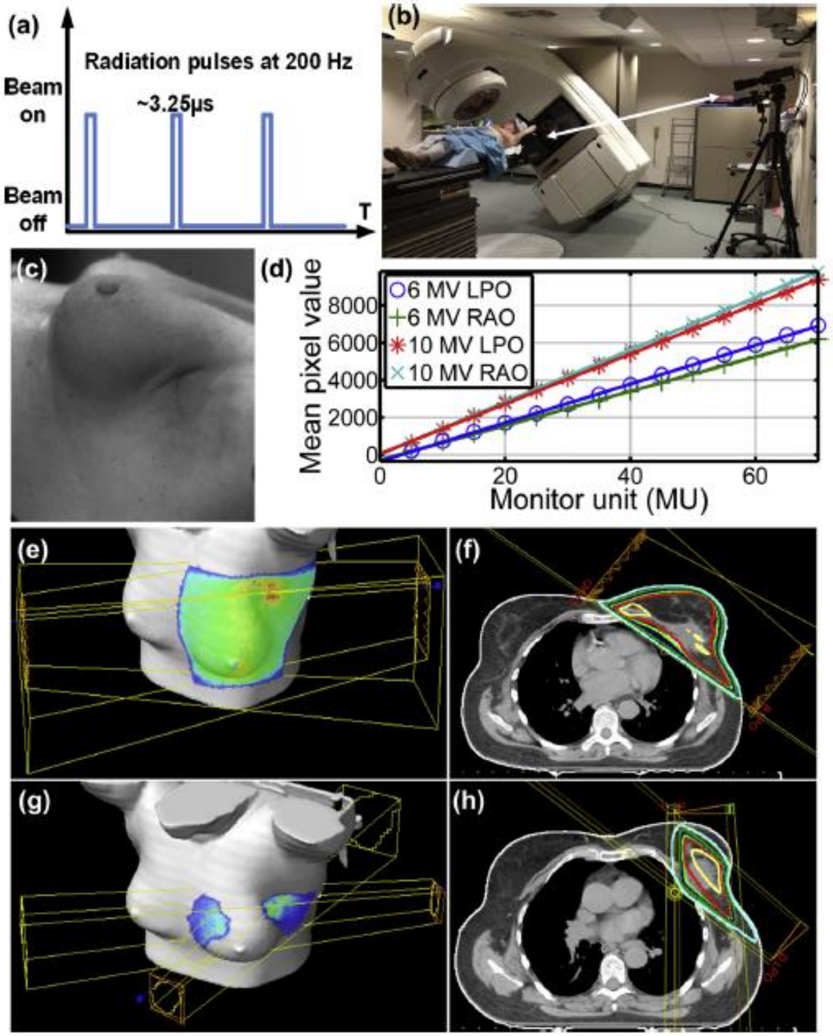


Fig. 1. Integration of ICCD camera into a radiation treatment unit for clinical detection of Cherenkov emission images. (a)

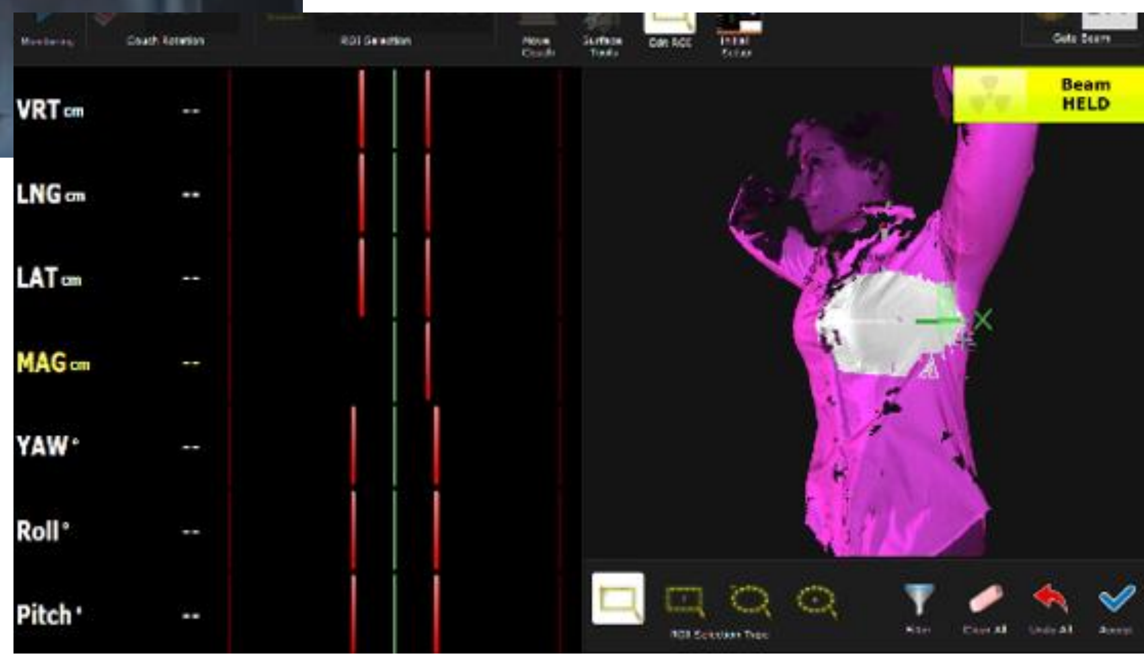
Non-ionizing Imaging

Non-Ionizing Technologies

- Surface Imaging
- US imaging
- Electromagnetic imaging
- MRI

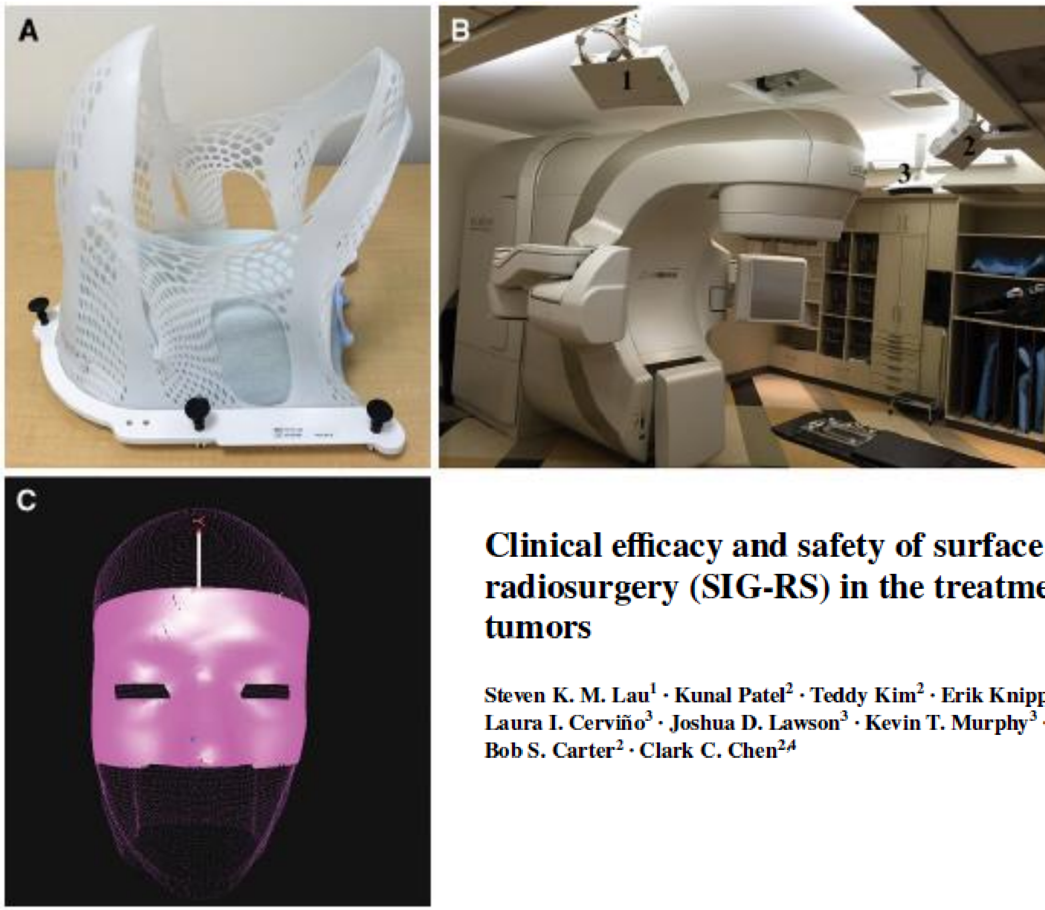
Many additional technologies since AAPM TG-147 provided QA guidance!

Optical Surface Imaging



Surface Imaging for Frameless SRS

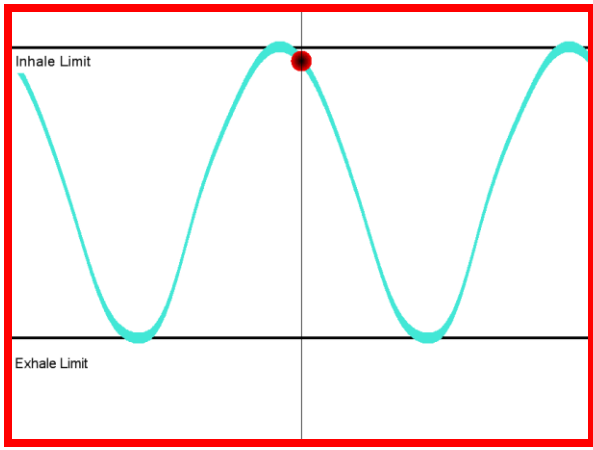
Fig. 1 Adaptation of surface imaging-guided technology to radiosurgery (SIG-RS). **a** Representative customizable open-face thermoplastic mask used for immobilization. **b** Three ceiling-mounted nonionizing camera pods track the patient's facial topography. **c** Three dimensional reconstruction of facial topography is used to identify the region of interest. Facial topography and region of interest are monitored in real-time to detect intrafraction deviations of patient positioning

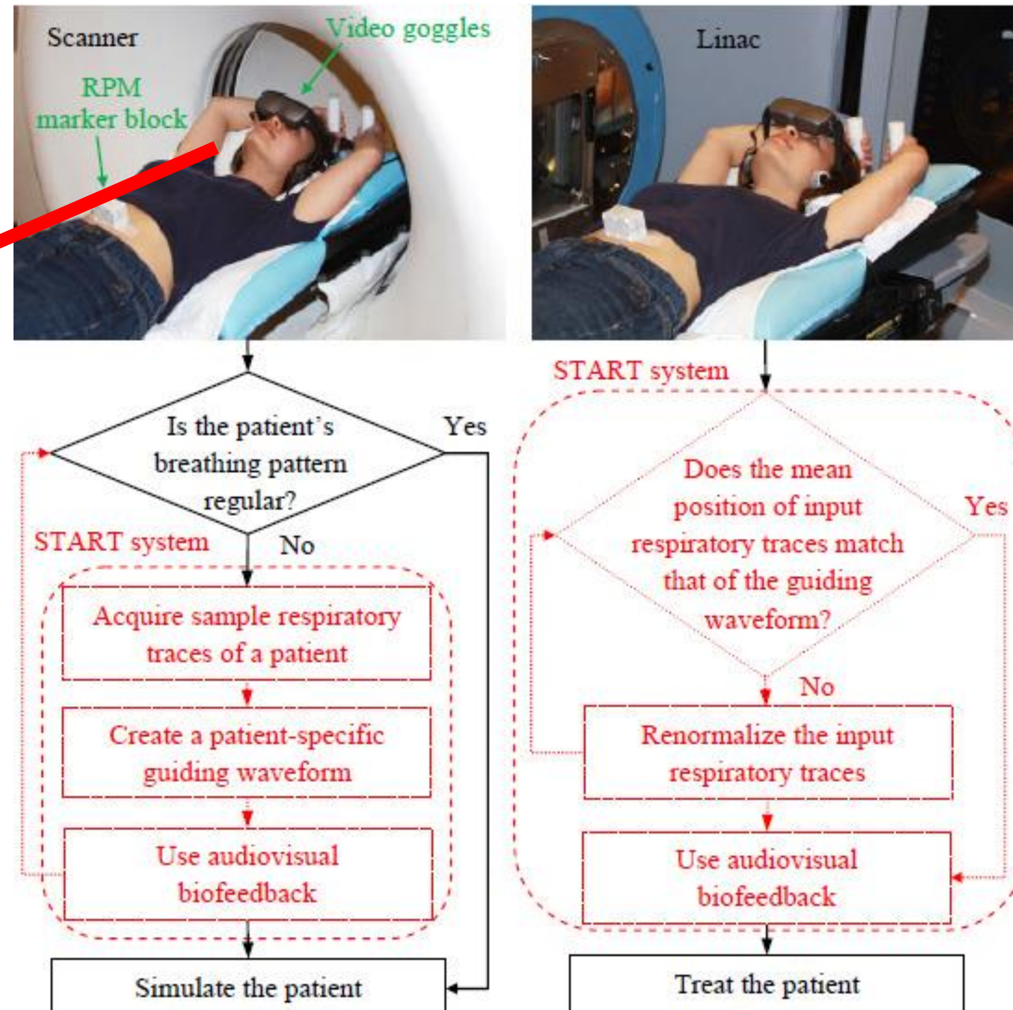


Clinical efficacy and safety of surface imaging guided radiosurgery (SIG-RS) in the treatment of benign skull base tumors

Steven K. M. Lau[1] · Kunal Patel[2] · Teddy Kim[2] · Erik Knipprath[2] · Gwe-Ya Kim[3] · Laura I. Cerviño[3] · Joshua D. Lawson[3] · Kevin T. Murphy[3] · Parag Sanghvi[3] · Bob S. Carter[2] · Clark C. Chen[2,4]

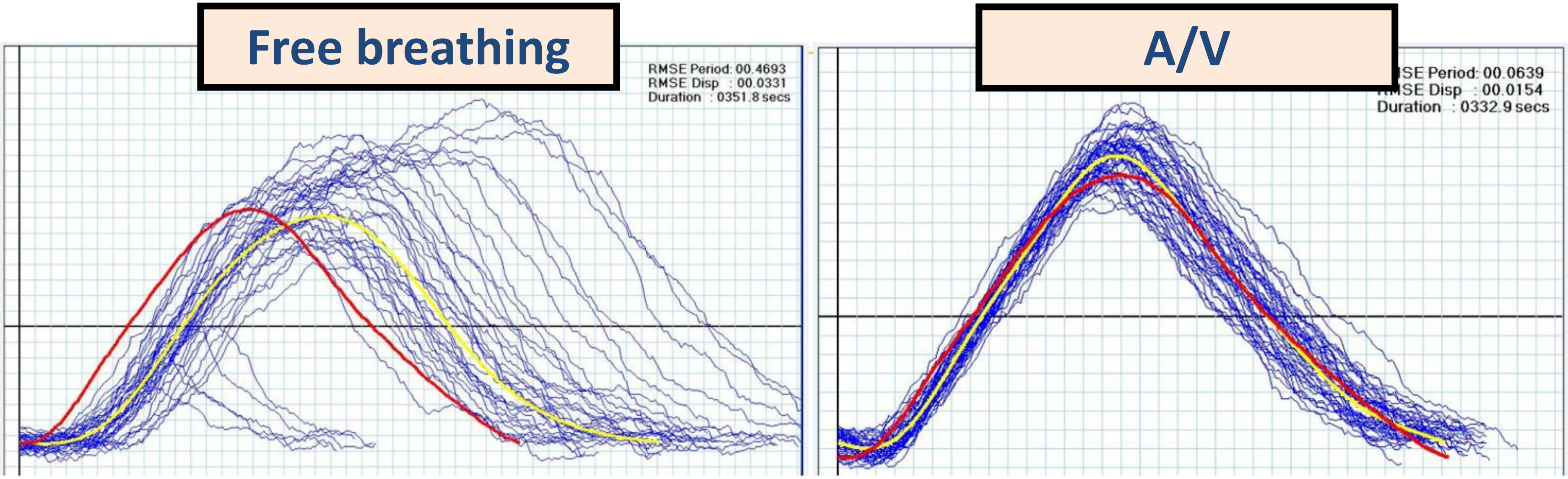
Audiovisual (A/V) Biofeedback





Venkat *et al* (PMB 2008)
Cui *et al* (JACMP 2010)

Impact of A/V Biofeedback



Training type	RMS var^n in displacement (cm)	RMS var^n in period (s)
Free breathing	0.56	0.78
A/V	0.21	0.20

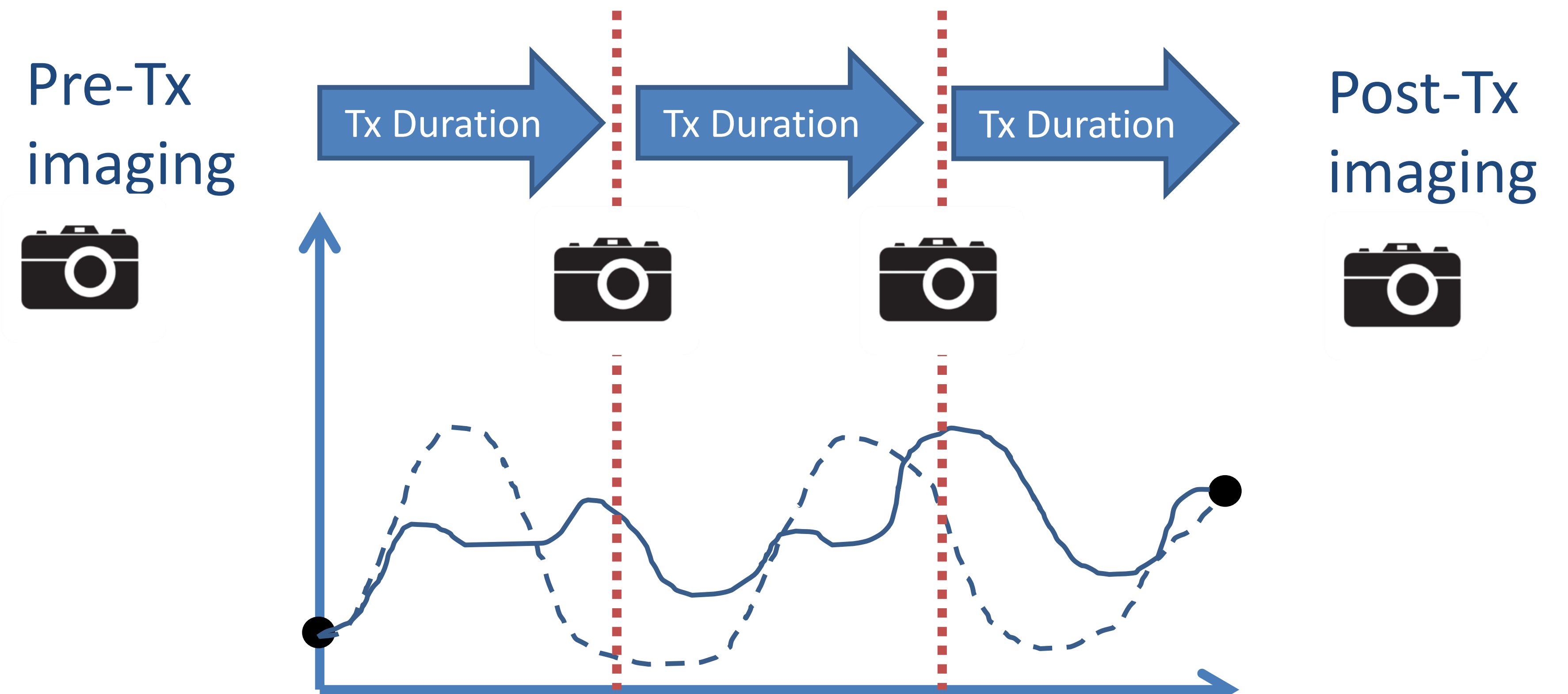
Venkat *et al* (PMB 2008)

Drawback of Non-ionizing Surface Imaging

- External monitoring ONLY
- External-Internal motion correlation is function of phase shift
- One possible solution …

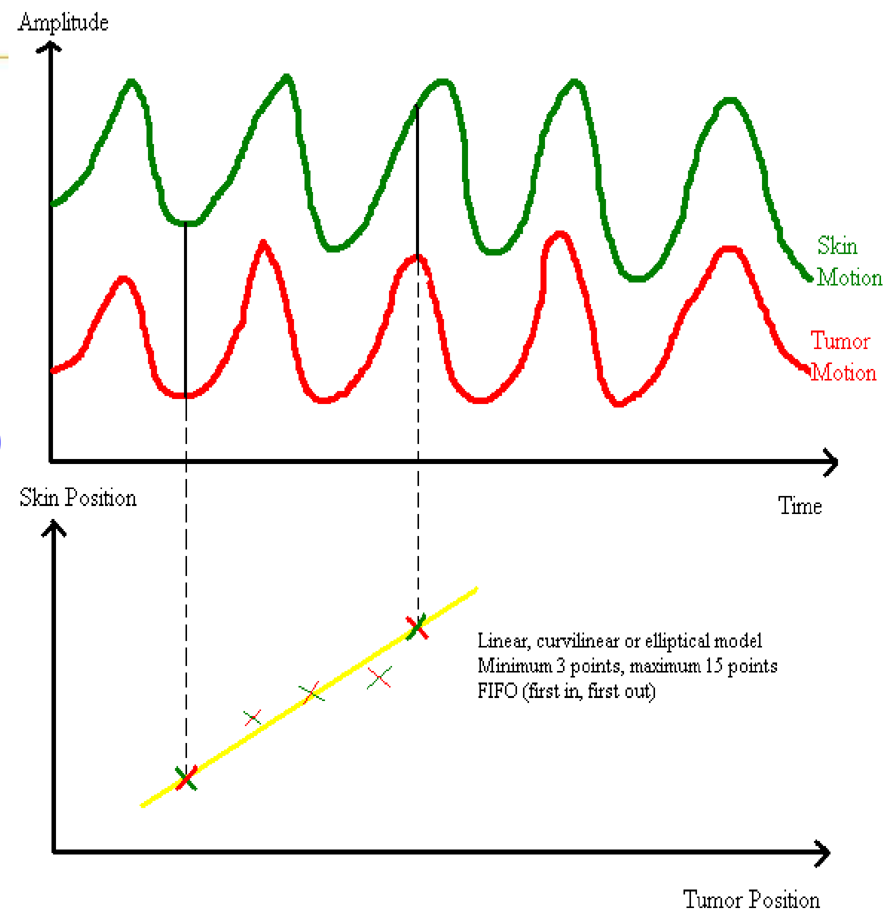
Hybrid (i.e. non-ionizing with ionizing) real-time monitoring

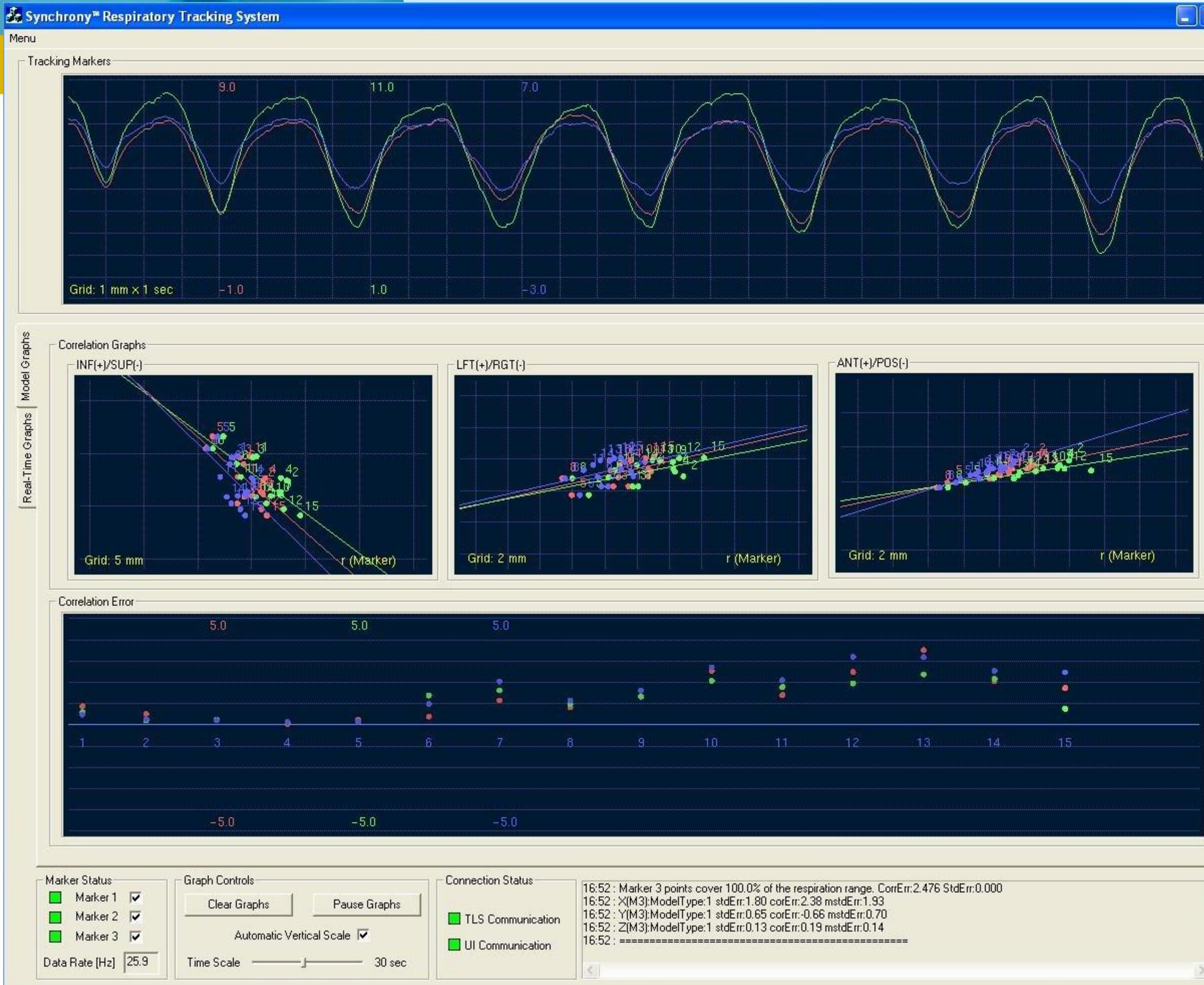
The Salami Solution: treat, stop, image, repeat



Synchrony – Respiratory Tracking

- Beacons on skin to get respiratory motion
- X-rays of tumor (using fiducials or soft-tissue tracking)
- Tumor and skin markers get correlated
- Skin motion predicts tumor motion
- Robot follows the tumor motion





Synchrony™ Respiratory Tracking System
Menu
Tracking Markers
9.0
11.0
7.0
Grid: 1 mm x 1 sec
-1.0
1.0
-3.0
Model Graphs
Real-Time Graphs
Correlation Graphs
INF(+)/SUP(-)
LFT(+)/RGT(-)
ANT(+)/POS(-)
Grid: 5 mm
r (Marker)
Grid: 2 mm
r (Marker)
Grid: 2 mm
r (Marker)
Correlation Error
5.0
5.0
5.0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
-5.0
-5.0
-5.0
Marker Status
Marker 1
Marker 2
Marker 3
Data Rate [Hz]
25.9
Graph Controls
Clear Graphs
Pause Graphs
Automatic Vertical Scale
Time Scale
30 sec
Connection Status
TLS Communication
UI Communication
16:52 : Marker 3 points cover 100.0% of the respiration range. CorrErr:2.476 StdErr:0.000
16:52 : X(M3):ModelType:1 stdErr:1.80 corErr:2.38 mstdErr:1.93
16:52 : Y(M3):ModelType:1 stdErr:0.65 corErr:-0.66 mstdErr:0.70
16:52 : Z(M3):ModelType:1 stdErr:0.13 corErr:0.19 mstdErr:0.14
16:52 : ==

Can be adapted for gated treatment on linacs!

- Setup with CBCT
- Fluoroscopy for 3 breaths
  - Before Tx
  - After Tx
- Fiducial positions determined using template matching algorithm
- Optimize gating window
- Linear relationship between fiducial position and AP signa
- Average change after Tx 1.2 mm (AP) and 0.9 mm (LR)

Medical Physics
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Fifty-eighth annual meeting of the american association of physicists in medicine

SU-F-J-137: Intrafractional Change of the Relationship Between Internal Fiducials and External Breathing Signal in Pancreatic Cancer Stereotactic Body Radiation Therapy

Pettersson N, Murphy J, Simpson D, Cervino L

First published: June 2016 Full publication history

DOI: 10.1118/1.4956045 View/save citation

Non-ionizing 4D internal imaging (Clarity, Calypso, Viewray)

Transperineal US: Clarity

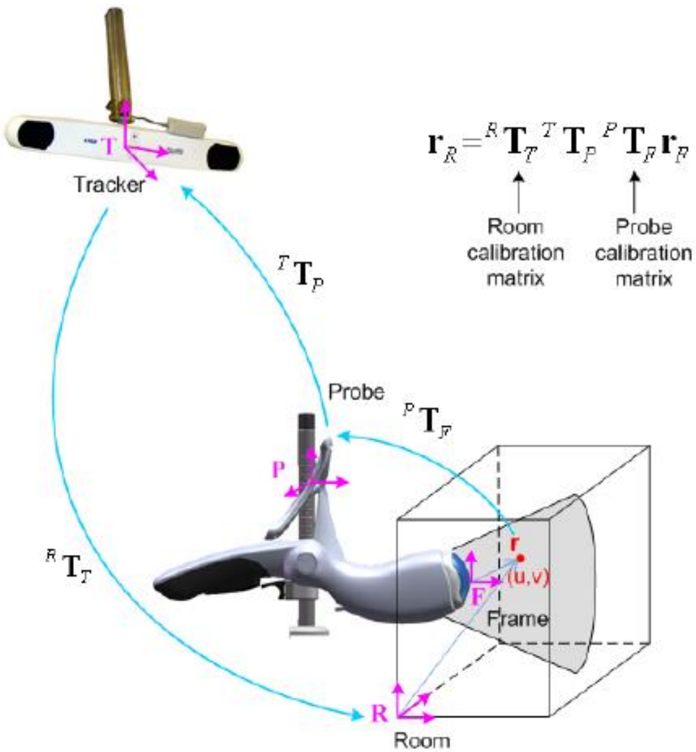
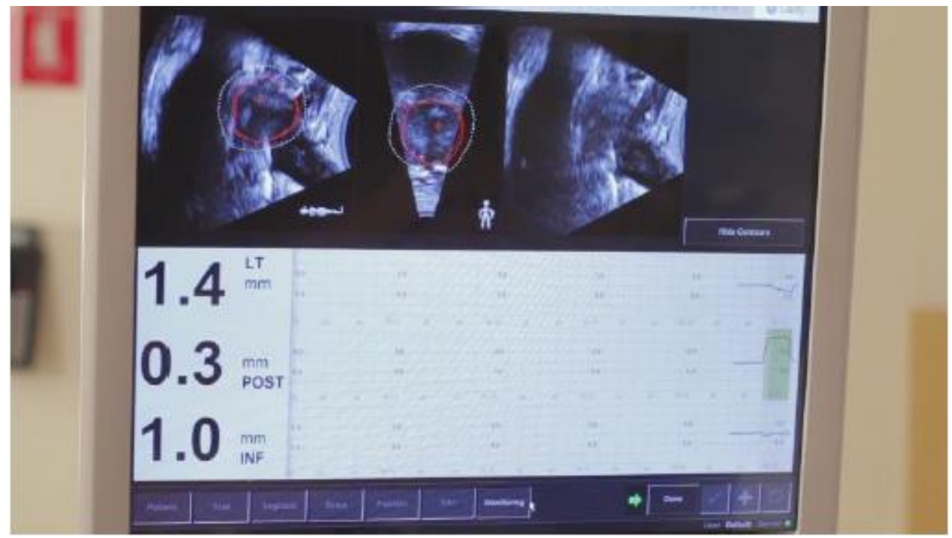


Figure 2. Schematic diagram illustrating coordinate transformations for calibration



Martin Lachaine and Tony Falco

MEDICAL PHYSICS INTERNATIONAL Journal, vol.1, No.1, 2013

Transperineal US localization compared to CT

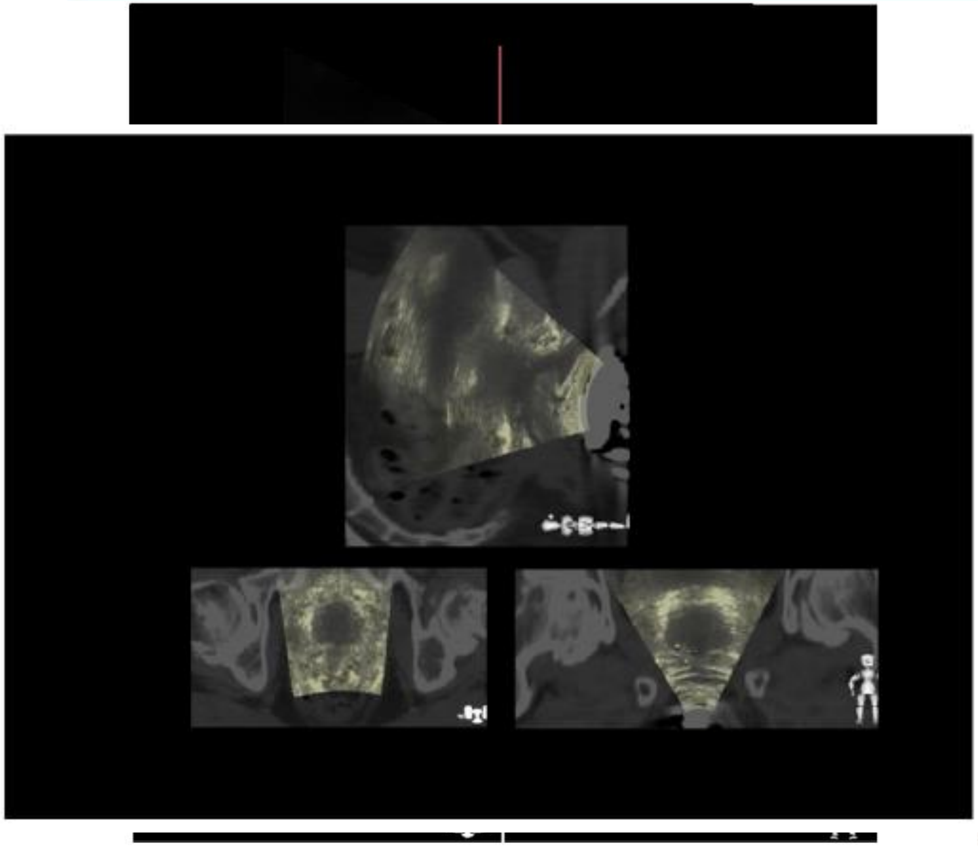


Figure 1 Sagittal (top), axial (bottom left), and coronal (bottom right) transperineal ultrasound images of the prostate.

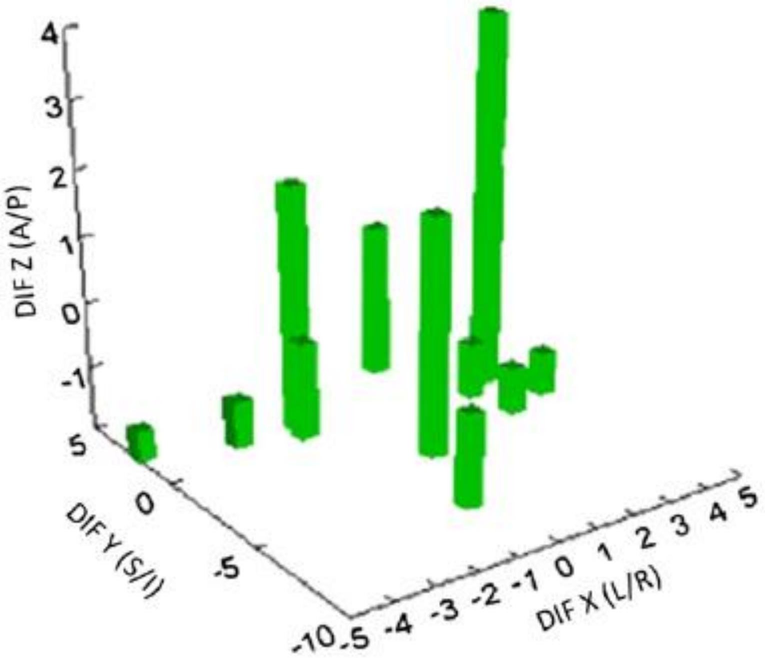


Figure 3 Three-dimensional plot of average differences in computed tomography and transperineal ultrasound-determined position of the prostate gland for each patient.

Electromagnetic imaging

- Langen IJROBP 2008
- Ground-breaking visualization of prostate motiom
- Individual variation between patients
- Adjustments for persistent out of tolerance motion

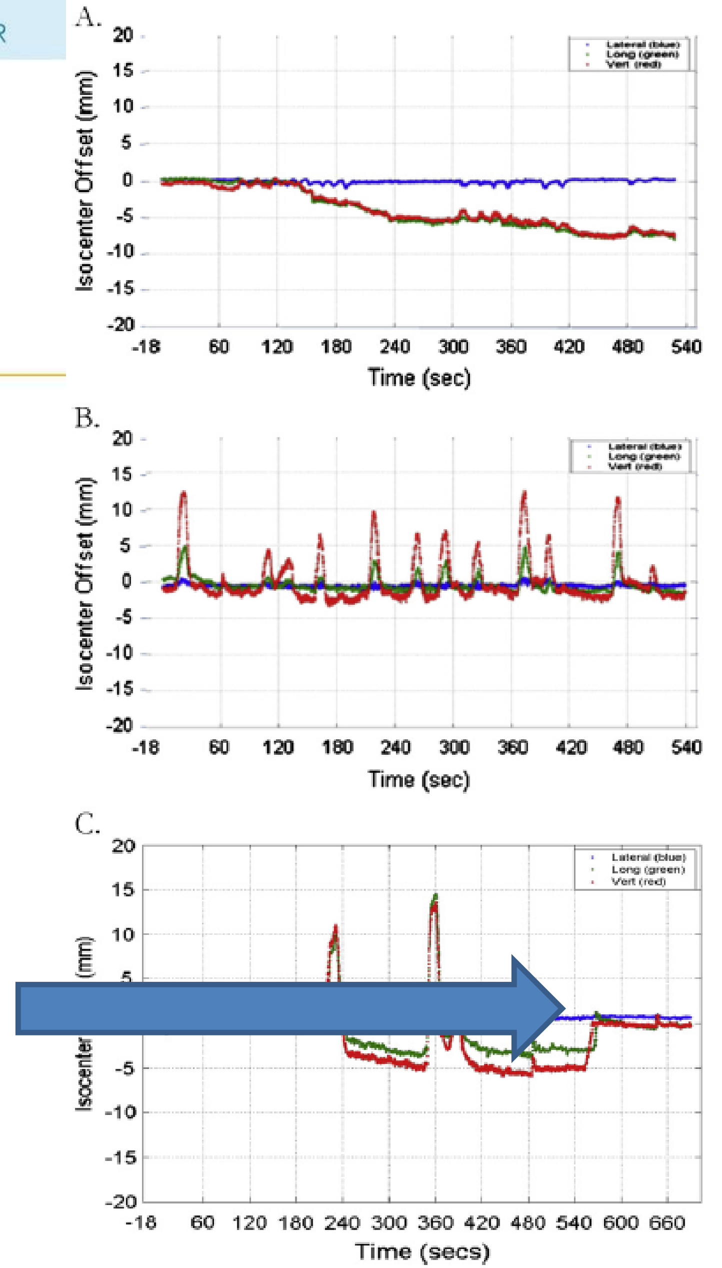


Fig. 1. (A) Drift motion. (B) Transient motion. (C) Drift and transient motion. The track shown in (C) shows an incident when therapists intervened and corrected couch position in response to observed motion (at time, 560 s). For data analysis purposes, these couch corrections were retrospectively eliminated by reintroducing the offset that had been corrected by therapists.

Now add in feedback loop to MLC: Large animal treatments in 2012

- 2012 Large Animal Video from Aarhus (Per Poulsen). Source: Paul Keall's Youtube channel

First Patient in 2013 Followed by Clinical Trial

The first clinical implementation of electromagnetic transponder-guided MLC tracking

Paul J. Keall[a)]
Radiation Physics Laboratory, Sydney Medical School, University of Sydney, NSW 2006, Australia

Emma Colvill
Radiation Physics Laboratory, Sydney Medical School, University of Sydney, NSW 2006, Australia and Northern Sydney Cancer Centre, Royal North Shore Hospital, Sydney, NSW 2065, Australia

Ricky O'Brien and Jin Aun Ng
Radiation Physics Laboratory, Sydney Medical School, University of Sydney, NSW 2006, Australia

Per Rugaard Poulsen
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Thomas Eade, Andrew Kneebone, and Jeremy T. Booth

Multileaf Collimator Tracking Improves Dose Delivery for Prostate Cancer Radiation Therapy: Results of the First Clinical Trial

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Technical requirements
DISCLAIMER: NOT FDA APPROVED

- A way to track tumor position
  - EM tracking (Calypso) considered most accurate at this time
  - Hybrid system will work
- An MLC which can move leaves fast enough (or a robot carrying your linac)
  - Both TrueBeam v2 and Elekta Versa MLCs are capable
- User Interface

Patient Treatment

Physics Contribution

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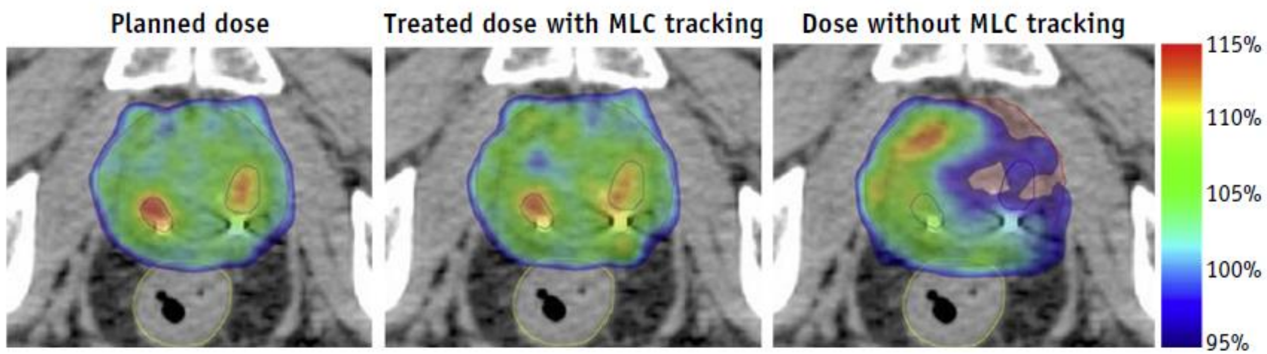

Fig. 3. The 3 dose distributions ($\geq$95% isodose) for a single 2-Gy fraction with a mean displacement of 3.6 mm with the planning target volume (red) and contoured gross tumor volume (blue). The planned dose distribution (left), the treated with MLC tracking dose (center), and the modeled without multileaf collimator (MLC) tracking dose (right). A color version of this figure is available at www.redjournal.org.

Drawbacks of electromagnetic imaging

- Obviously: marker implant
  - Cost
  - Time
  - Anatomical feasibility
- Long-term impact
  - Interference with MRI imaging

MRI Imaging Example: Viewray

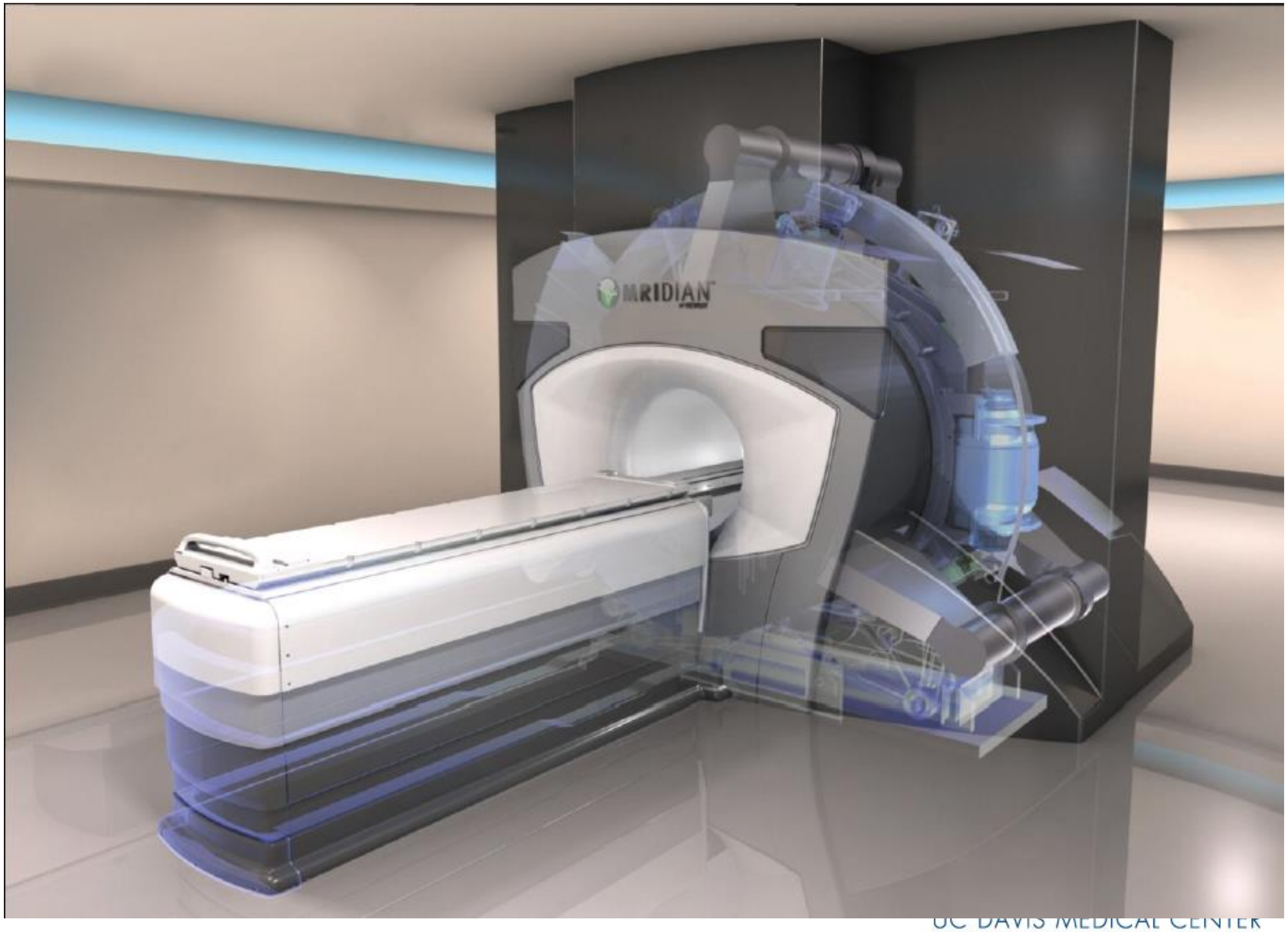

Image courtesy Viewray

Then there is MRI

- Pancreas DIBH
- Tracking during treatment
- Videos provided by Viewray

- ASTRO 2017: look for WashU presentation on adaptive pancreas (P. Parikh)

From Monitoring Beam and Monitoring Patient to doing both at once:

EPID In-Vivo Dosimetry