Patient Positioning Using Optical and Ultrasound Techniques

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Acknowledgements

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  - University of Iowa
  - University of Florida
  - University of Wisconsin
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  - Whitaker Foundation
  - National Cancer Institute
  - ZMed

Objectives

Precision Radiation Therapy

- Optical Tracking in Radiation Therapy
  - What is it?
  - How does it work?
  - How well has it worked?
- Ultrasound Guidance in Radiation Therapy
  - What is it?
  - How does it work?
  - How well has it worked?

What is Optical Tracking?

- Optical tracking is a means of determining in **real-time** the position of an object by tracking the positions of either active or passive infrared markers attached to the object. The position of the point of reflection is determined using a camera system.

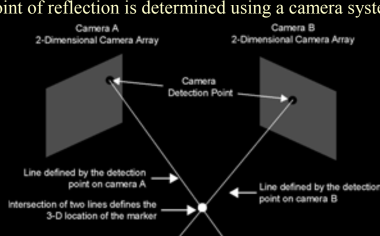
Active markers

Passive markers

Camera

What is Optical Tracking?

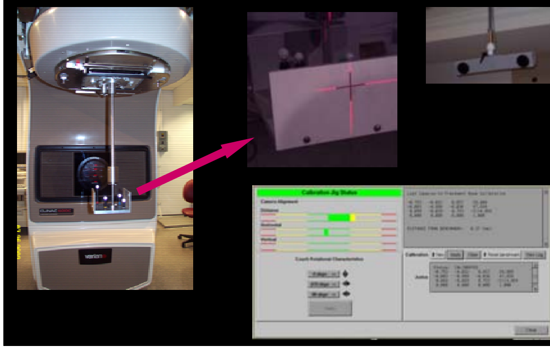
- Optical tracking is a means of determining in **real-time** the position of an object by tracking the positions of either active or passive infrared markers attached to the object. The position of the point of reflection is determined using a camera system.



How Does it Work?

Optical Tracking

How Does it Work?
Calibration of Optical camera



Optical guidance for frameless stereotaxis

- For high-precision intracranial radiotherapy and frameless radiosurgery, we use optical guidance to track the actual patient position using passive markers and a bite-plate linkage.

Frameless Stereotaxis

- Passive Array – Reflective Markers serve as fiducials in both image and real space.

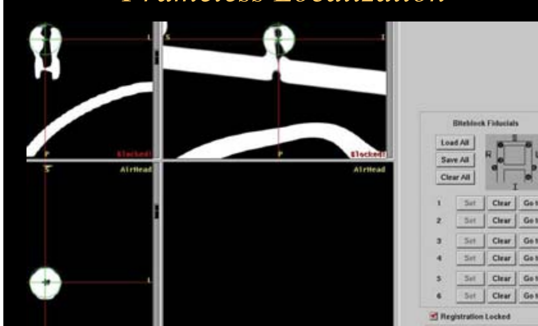
Frameless Stereotaxis
Immobilization During CT Scan

Patients can move – immobilize using custom pillow, aquaplast, etc.

Frameless Stereotaxis
Passive Array – CT Scan

Fiducials must be visible in CT scan – use adequate field of view (typically 35-40 cm depending on distance of bracket from patient).

Frameless Localization



Frameless Stereotaxis

Vector for room coordinates

3x3 rotation matrix

Vector for image coordinates

Translation vector

$$p_{r'} = Rp_i + T$$

Equation can be solved numerically using optimization algorithms (Hook and Jeeves, etc.), or closed form solutions such as single value decomposition or Horn's method (quaternions)

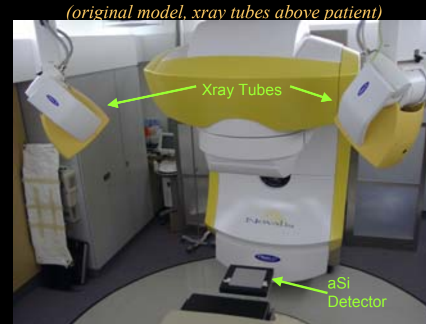
Align Patient

Optical Tracking – BrainLab System

Optical Tracking – BrainLab System

X-ray Guidance Setup

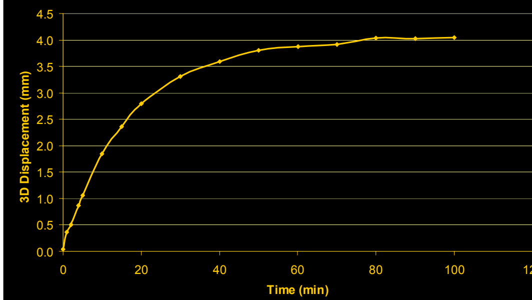
(original model, xray tubes above patient)



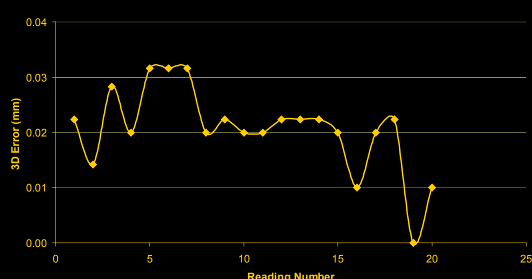
Optical Tracking System QA

- System Commissioning and QA
- Patient Specific QA

Thermal Drift



Reproducibility



Test with Absolute Phantom

- Localize Al target in images (CT)

Frameless Localization Accuracy (Mechanical Standard)

Frameless Localization Accuracy (Mechanical Standard)

No.	AP	Lateral	Axial	RMS
1	0.48	0.48	-0.61	0.91
2	-0.05	0.46	0.50	0.69
3	0.33	-0.20	-0.53	0.65
4	-0.46	-0.15	-0.13	0.50
5	0.43	-0.15	-0.13	0.40

Average **0.65 ± 0.17 mm**

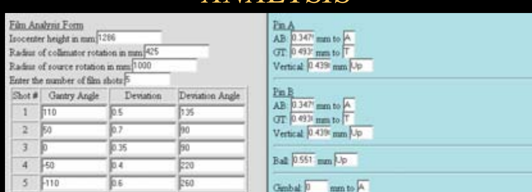
Putting it All Together - Hidden Targets Test with Absolute Phantom

- Localize Al target in images (CT)
- Place on linac using image localized coordinates and optical guidance.

Frameless Localization Accuracy (Film Tests)

- Localize Al target in images (CT)
- Replace Al target with Tungsten target, and place on linac using image localized coordinates.
- Take films from various gantry and table orientations

ANALYSIS



Film Analysis Form

Isocenter height in mm: 1286

Radius of collimator rotation in mm: 425

Radius of source rotation in mm: 1000

Enter the number of film shots: 5

Shot #	Gantry Angle	Deviation	Deviation Angle
1	110	0.5	135
2	50	0.7	90
3	0	0.35	90
4	-50	0.4	220
5	-110	0.6	260

Pin A

AB: 0.347 mm to A

GT: 0.493 mm to T

Vertical: 0.439 mm Up

Pin B

AB: 0.347 mm to A

GT: 0.493 mm to T

Vertical: 0.439 mm Up

Ball: 0.551 mm Up

Gimbal: 0 mm to A

Predicted error:

Z-Pixel Size = 1.25mm

X-Pixel Size = 0.703 mm

Y-Pixel Size = 0.703 mm

Predicted Error = 1.59mm

Results:

Z: 0.49 mm to T

X: 0.35 mm to A

Y: 0.50 mm High

Overall error = 0.789mm

Frameless Localization (Patient)

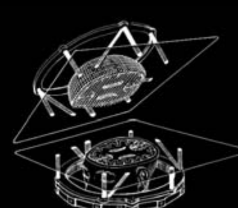
Frameless Localization (10 Patients)

Average ± s.d. **1.1 ± 0.3 mm**

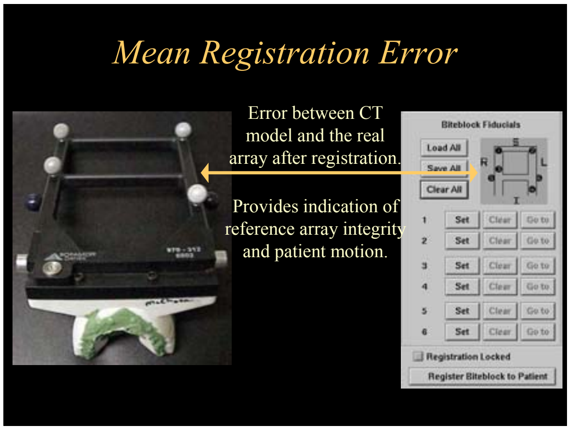
compared to conventional stereotactic localization

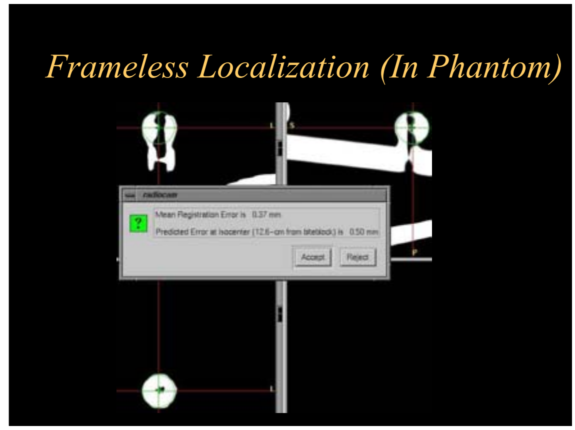
Meeks, Bova et al., IJROBP, 2000

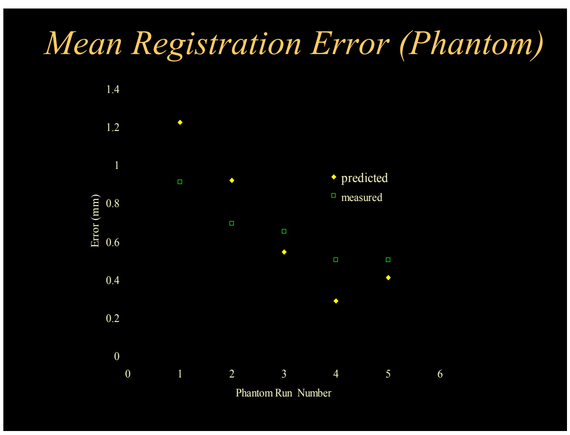
Can we predict localization errors?

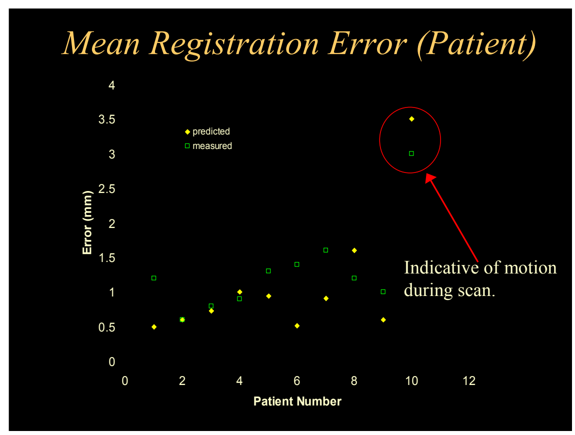


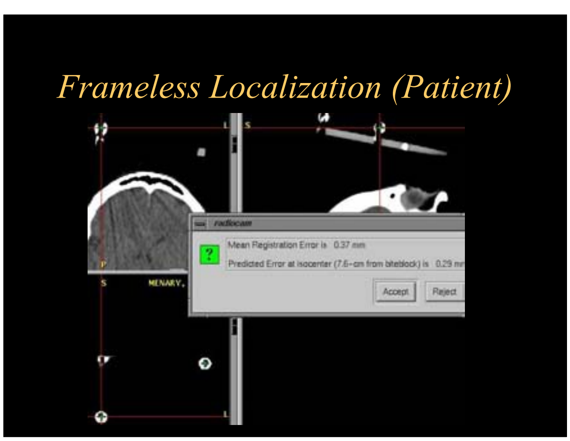
Analogous to frame-based stereotaxis, we have an over-defined fiducial system with a known geometry. Can predict accuracy of patient positioning at isocenter

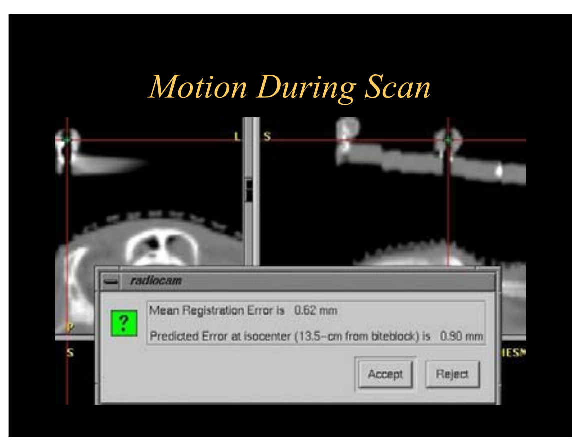

Mean Registration Error
Error between CT model and the real array after registration.
Provides indication of reference array integrity and patient motion.
Biteblock Fiducials
Load All
Save All
Clear All
Registration Locked
Register Biteblock to Patient


Frameless Localization (In Phantom)
radiocam
Mean Registration Error is 0.37 mm
Predicted Error at isocenter (12.6-cm from biteblock) is 0.50 mm
Accept
Reject

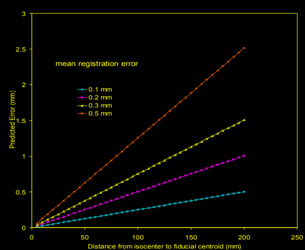

Mean Registration Error (Phantom)
predicted
measured
Error (mm)
Phantom Run Number


Mean Registration Error (Patient)
predicted
measured
Error (mm)
Patient Number
Indicative of motion during scan.


Frameless Localization (Patient)
radiocam
Mean Registration Error is 0.37 mm
Accept
Reject


Motion During Scan
radiocam
Mean Registration Error is 0.62 mm
Predicted Error at isocenter (13.5-cm from biteblock) is 0.90 mm
Accept
Reject

Array placement

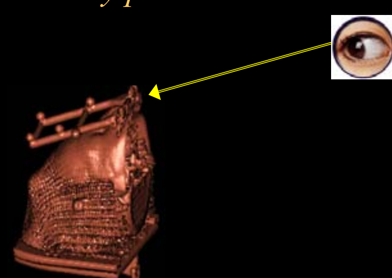


Minimizing the distance from the center of the fiducial array to isocenter minimizes the effect of the mean registration error at isocenter.

Array placement

Bracket allows adjustment of fiducial array relative to patient

Array placement



Keep camera “line of sight” in mind – if you rotate too far back, the fiducials will not be visible to the camera in the treatment room.

Frameless Radiosurgery
Reseat Test

RadioCameras Biteblock Reseat Test Results

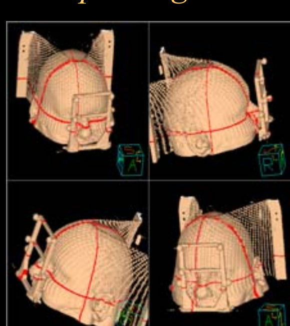
Patient name: Test
Patient id:
Date: Tue Feb 20 13:27:20 CST 2001

Results:

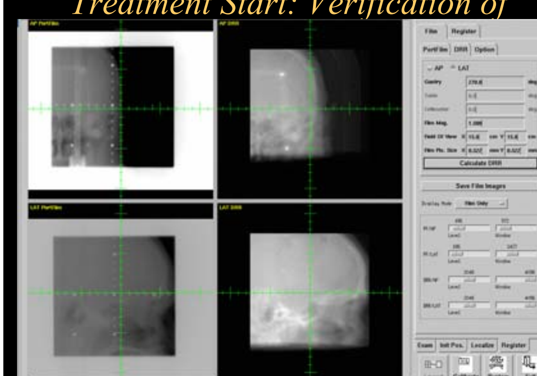
Sample # 1	123.042610
Sample # 2	122.947922
Sample # 3	122.963150
Sample # 4	122.976456
Sample # 5	123.009842
Sample # 6	123.143639
Sample # 7	123.090691
Sample # 8	123.117416
Sample # 9	123.051674
Sample #10	123.051720

Average Difference 0.078497
Maximum Difference 0.159073

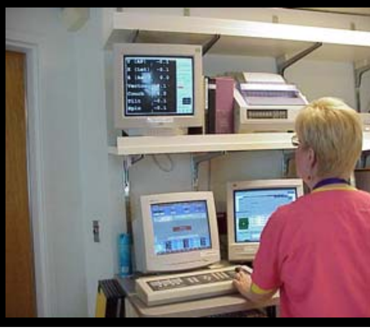
Treatment Start: Verification of Setup Using Laser



Treatment Start: Verification of

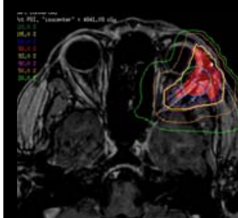


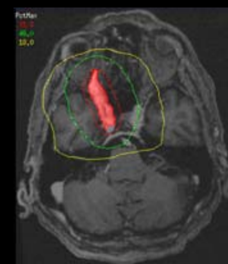
Online Monitoring of Patient Position during Treatment



Optical Guidance in Radiotherapy

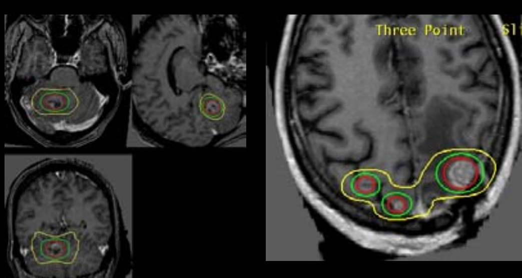
- Long-Term Experience
  - University of Florida – started 1994
- High Accuracy
- Excellent Dose Conformality
- Excellent Clinical Results





- June, 2000 – Frameless Radiosurgery – **Why Not?**

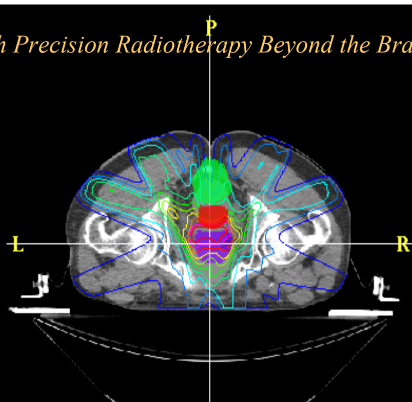
Frameless Radiosurgery



Frameless Radiosurgery

- 64 patients with intracranial metastases treated from June, 2000 -September, 2002
  - 1-6 mets (median 2)
  - Rx Dose = 12.5-20 Gy (median = 17.5 Gy)
  - Local Control = 88%
  - Median Survival = 8.7 Months (Max = 30.1 months)
- Results indistinguishable from framed SRS

High Precision Radiotherapy Beyond the Brain

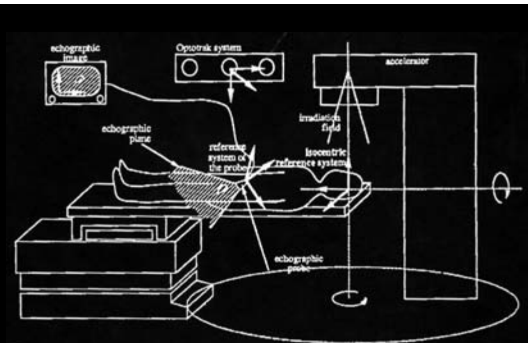


Optical Tracking – BrainLab System

Diaphragmatic Pressure/Optically Guided Body Frame

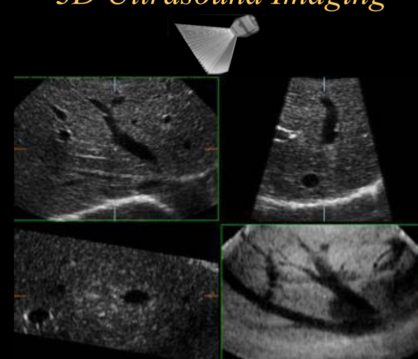
Extracranial Stereotactic Radiotherapy Solution

- Tumor localization using real-time imaging at the treatment machine
  - – Digital X-Ray Images
  - – CT
  - – Ultrasound



Troccaz et al., 1995

3D Ultrasound Imaging



What is 3DUS guided RT?

High-resolution infrared camera
Detects passive and active fiducials

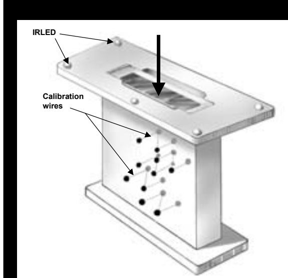
- ➢High-end, Linux custom computer
- ➢Spatial Digitizer linked to Camera
- ➢Image Processing and Localizing Software

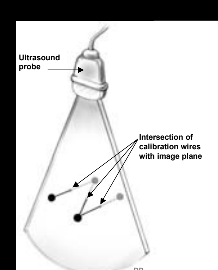
SonoSite Ultrasound:
- Portable
- 3.5MHz abd. probe

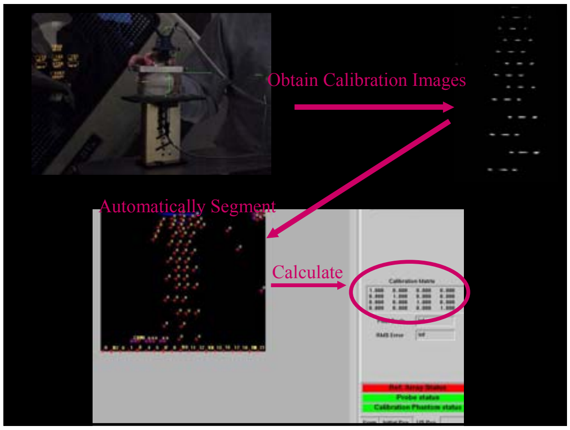
Optically tracked ultrasound probe

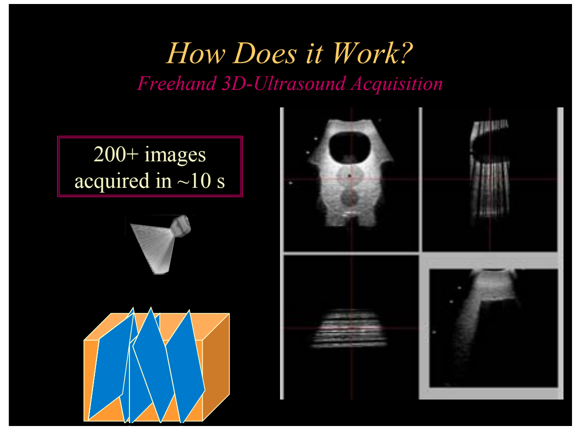
How Does it Work?

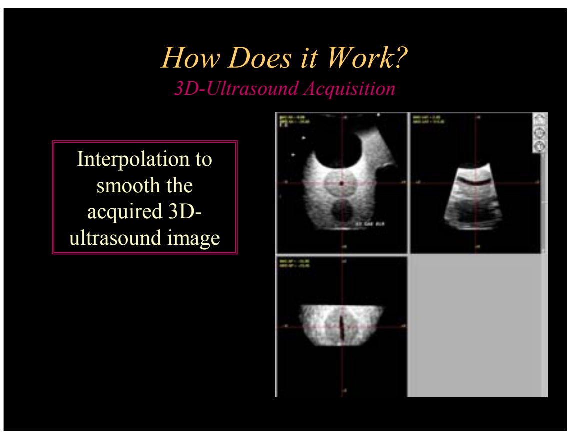
Ultrasound Calibration

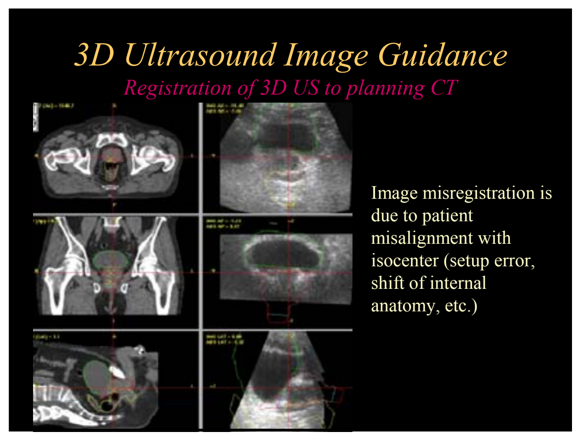


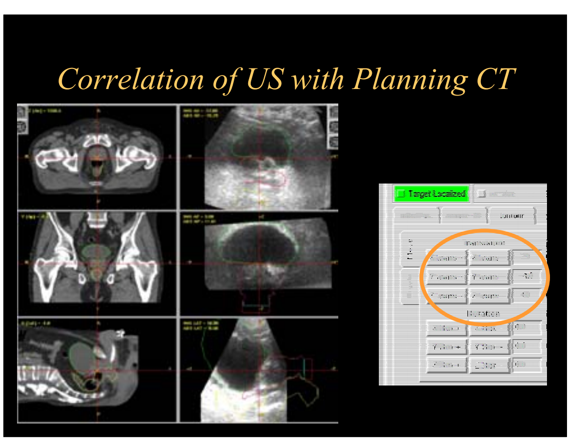


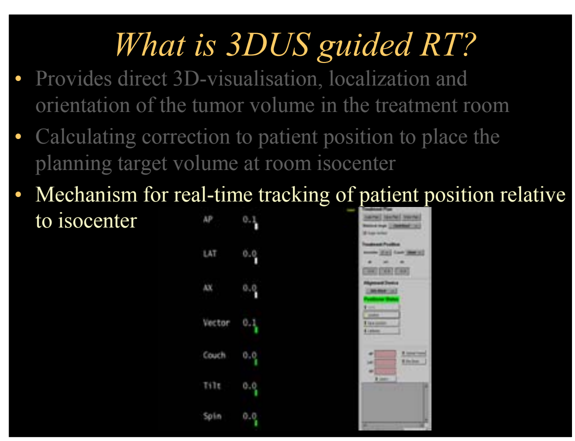

Obtain Calibration Images
Automatically Segment
Calculate


How Does it Work?
Freehand 3D-Ultrasound Acquisition
200+ images acquired in ~10 s

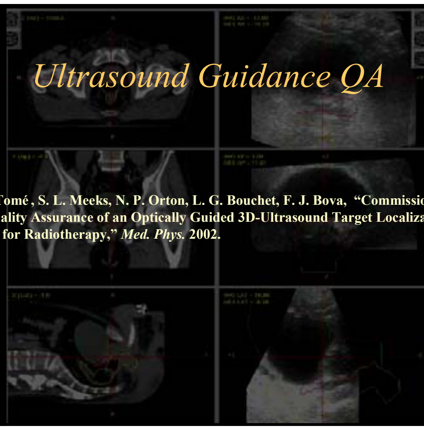

How Does it Work?
3D-Ultrasound Acquisition
Interpolation to smooth the acquired 3D-ultrasound image


3D Ultrasound Image Guidance
Registration of 3D US to planning CT
Image misregistration is due to patient misalignment with isocenter (setup error, shift of internal anatomy, etc.)


Correlation of US with Planning CT
Target Localized


What is 3DUS guided RT?
• Provides direct 3D-visualisation, localization and orientation of the tumor volume in the treatment room
• Calculating correction to patient position to place the planning target volume at room isocenter
• Mechanism for real-time tracking of patient position relative to isocenter
AP
LAT
AX
Vector
Couch
Tilt
Spin

Ultrasound Guidance QA

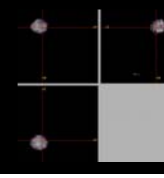


W. A. Tomé, S. L. Meeks, N. P. Orton, L. G. Bouchet, F. J. Bova, "Commissioning and Quality Assurance of an Optically Guided 3D-Ultrasound Target Localization System for Radiotherapy," *Med. Phys.* 2002.

Tracking Accuracy

Using Optical Tracking as Standard

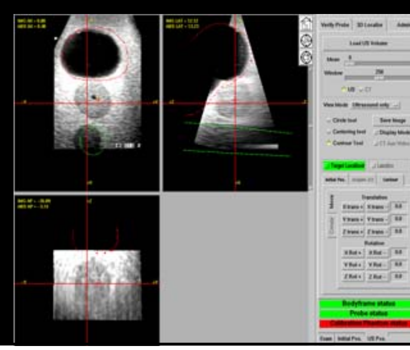
Depth (mm)	AP Distance (mm)	Lateral Distance (mm)	Axial Distance (mm)
All depths	0.03 ± 0.4	-1.2 ± 0.4	-0.7 ± 0.5



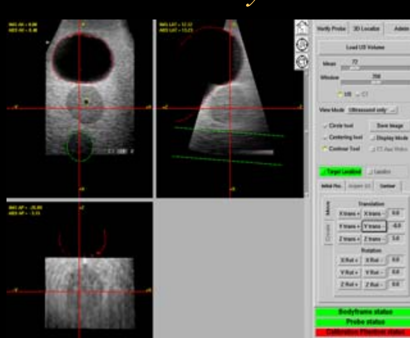
Pre-Clinical Prostate Phantom Tests

- Using Optical Guidance known shifts are introduced using a translation table.
- Optical Guided System is blinded to introduced shifts by recording the position of a fiducial array that is fixed to the couch.

Optically Guided Ultrasound Target Localization for shifted Phantom



Contours are moved to Match US Anatomy



Results

Exp	AP (mm)	Lat (mm)	Ax (mm)	AP_m (mm)	Lat_m (mm)	Ax_m (mm)
1	0.0	0.0	0.0	0.6±0.46	-0.3±0.69	-0.03±0.1
2	0.0	0.0	5.0	0.67±0.52	-0.38±0.61	4.95±0.12
3	0.0	0.0	-5.0	0.55±0.53	-0.25±0.58	-5.3±0.67
4	0.0	-5.0	0.0	0.55±0.53	4.95±0.17	-0.22±0.22
5	0.0	-5.0	5.0	0.25±0.06	-5.85±0.17	5.3±0.27

W. A. Tomé, S. L. Meeks, N. P. Orton, L. G. Bouchet, F. J. Bova, "Commissioning and Quality Assurance of an Optically Guided 3D-Ultrasound Target Localization System for Radiotherapy," *Med. Phys.* 2002.

BAT Tracking Accuracy in Patient

Using CT as Standard

AP Distance (mm)	Lateral Distance (mm)	Axial Distance (mm)
-0.09 ± 2.8	-0.16 ± 2.4	-0.03 ± 2.3

Lattanzi J, McNeeley S, Pinover W, Horwitz E, Das I, Schultheiss TE, Hanks GE. A Comparison of Daily CT Localization to a Daily Ultrasound-Based System in Prostate Cancer. *Int J Radiat Oncol, Biol Phys* 1999; 43(4).

How Do I Use it Clinically?

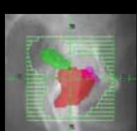
Basic Process

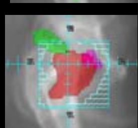
Immobilize and CT Scan → Treatment Planning → Laser patient positioning → 3D-ultrasound acquisition → Target positioning → Treatment Delivery

How Do I Use it Clinically?

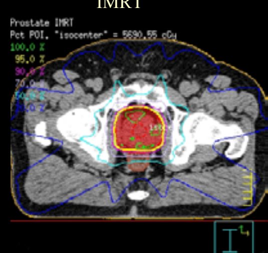
Treatment Planning

BEV Conformal



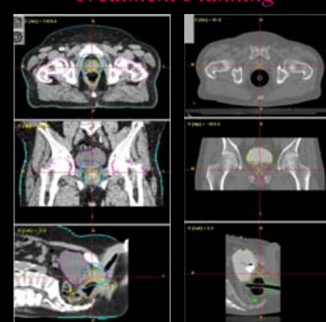


IMRT



How Do I Use it Clinically?

Treatment Planning



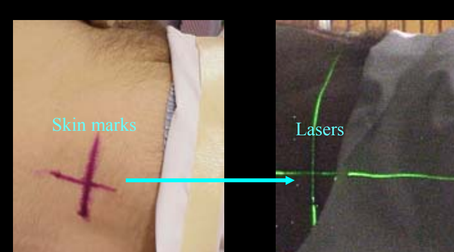
How Do I Use it Clinically?

Treatment Planning

- BEV conformal or IMRT treatment planning using Pinnacle
- CT and structure contours transferred to SonArray using Dicom-RT or RTOG

3D Ultrasound Image Guidance

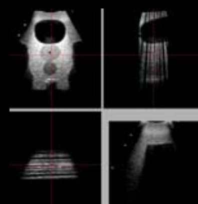
Initial Alignment from CT Simulation



3D Ultrasound Image Guidance

Acquire 3D Ultrasound Data

Analogous to CT acquisition – acquire multiple axial using freehand ultrasound probe manipulation.



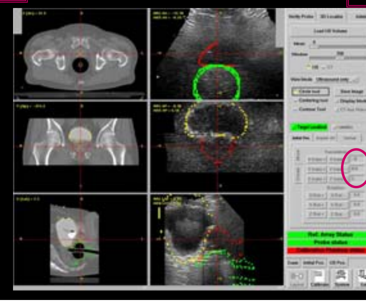
How Do I Use it Clinically?

Target Localization

CT Images and structures contour from treatment plan

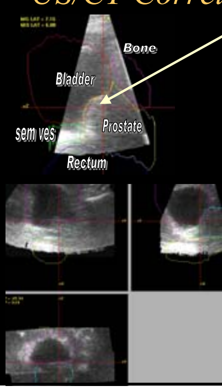
Correlation of 3D-ultrasound image with Treatment PLan

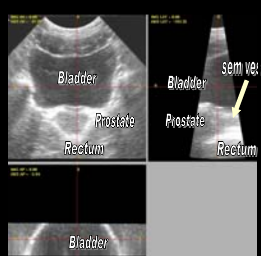
Actual position of target as determined from the 3D-ultrasound



US/CT Correlation - Prostate

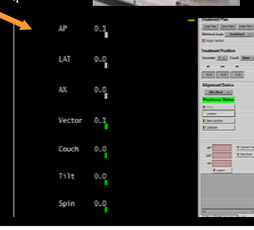
Interface between prostate and bladder
Sem ves
Bladder
Nothing below bone!



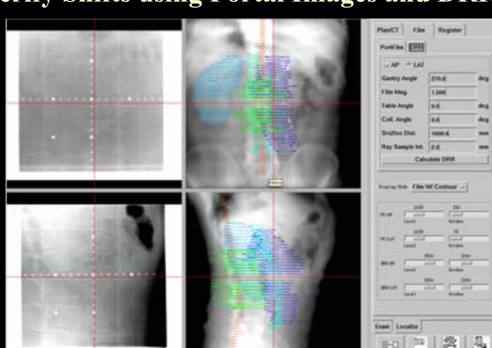


How Do I Use it Clinically?

Patient Positioning



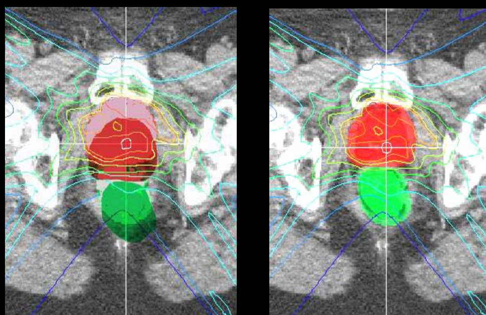
Verify Shifts using Portal Images and DRRs



Proceed With Normal Treatment…

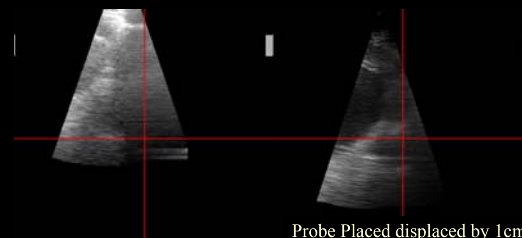
Pitfalls in Ultrasound Guidance

What happens with inter- and intra-fraction organ motion?



Pitfalls in Ultrasound Guidance:

User Variability in Image Quality

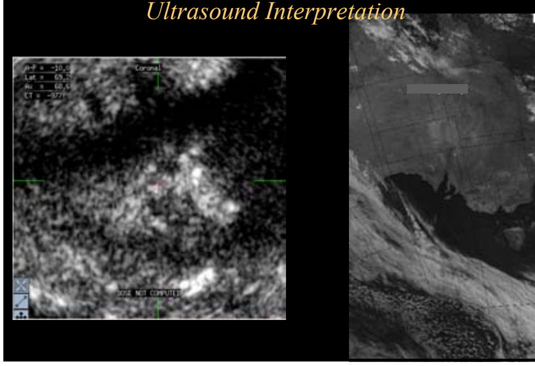


Probe Placed over treatment isocenter

Probe Placed displaced by 1cm superiorly from treatment isocenter.

Pitfalls in Ultrasound Guidance:

Ultrasound Interpretation



Pitfalls in Ultrasound Guidance:

User Variability

Retrospective registration of 15 different data sets by 9 different users; 4 users with experience and 5 trained in use of the software, but not US imaging.

Average Shift

AP (mm)	Lat (mm)	Axial (mm)
3.4	2.7	4.5

Std. Dev. (Trained)

AP (mm)	Lat (mm)	Axial (mm)
1.2	0.9	1.4

Std. Dev. (Not Trained)

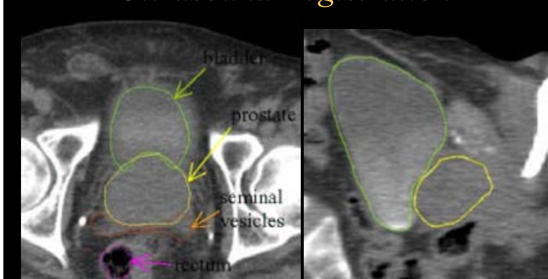
AP (mm)	Lat (mm)	Axial (mm)
3.6	1.5	2.9

Treatment Planning

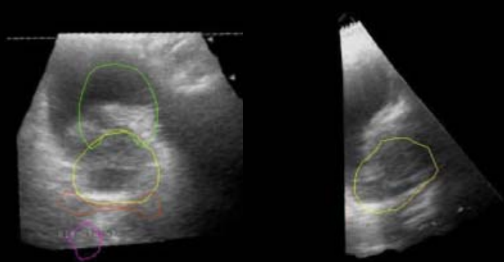
US-Guided Prostate

- ***Sensible*** PTV may be larger than ***Minimum***
- Remember user *variability* can *vary,* which increases required PTV
- In practice, we create a PTV with a variable (5-10 mm) margin on the CTV.

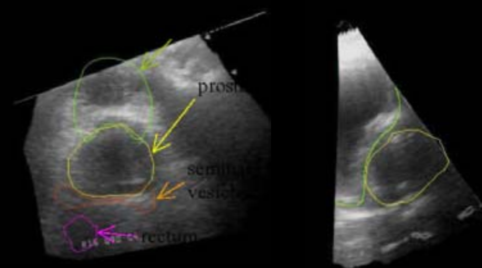
Work in Progress – Automated Ultrasound Registration



Work in Progress – Automated Ultrasound Registration



Work in Progress – Automated Ultrasound Registration



US-Guided Prostate Trial

- NCI-supported Phase III Randomized Multi-Center Clinical Trial
  - Arm 1 - With ultrasound
    - Initial fields: 46 Gy/23 fractions, PTV = 1 cm margins on prostate, seminal vesicles, and nodes
    - 32 Gy/16 fractions, PTV = 2 mm margin on prostate only
  - Arm 2 - With conventional localization
    - Initial fields: 46 Gy/23 fractions PTV = 1.5 cm margins on prostate, seminal vesicles, and nodes
    - 32 Gy/16 fractions, PTV = 1 cm margin on prostate only

US-Guided Prostate Trial

Preliminary Results

Acute GI Toxicity	Arm 1 3DCRT	Arm 2 U/S-3DCRT
Grade 0	25%	89%
Grade 1	0%	11%
Grade 2	75%	0%
	p= 0.014	

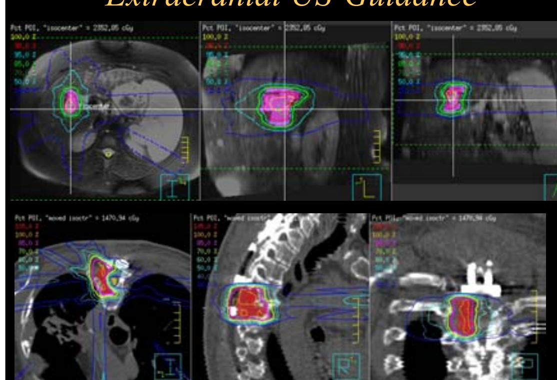
Acute GU Toxicity	Arm 1 3DCRT	Arm 2 U/S-3DCRT
Grade 0	50%	66%
Grade 1	25%	33%
Grade 2	25%	0%
	p=0.45	

3D Ultrasound Image Guidance

Other Applications at UIHC (to date)

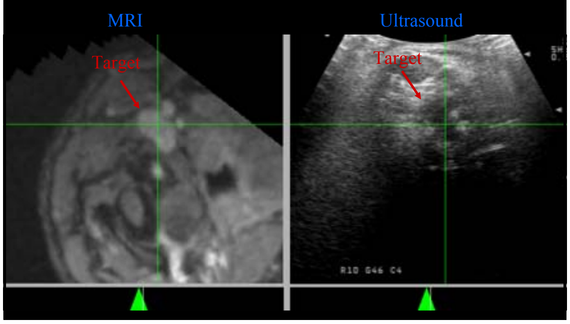
- Liver
- Low neck
- Paraspinal
- Metastatic pelvic lesions
- Chest wall

Extracranial US-Guidance



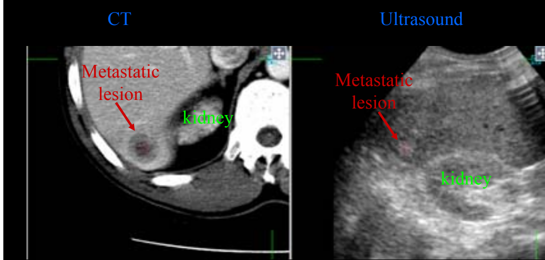
Clinical US Example

Residual neurofibroma at c2-3



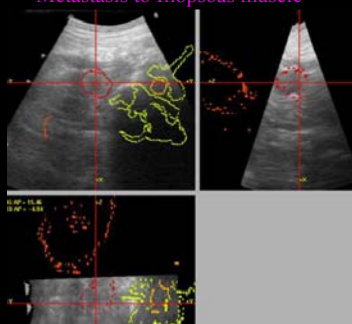
Clinical US Example

Liver



Clinical US Example

Metastasis to Iliopsoas muscle



Future Development/Questions

- Reliable Automated image registration techniques – important for all image registration modalities (CT, x-ray, US)
- Technical improvements in organ motion management
- Clinical Trials defining true benefits of image-guidance and IMRT.
- Defining dose/volume tolerances for hypofractionated regimens – Rigorous Phase I dose-seeking studies are required