Ultrasound Guidance During Radiation Delivery: Confronting the Treatment Interference Challenge

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The team

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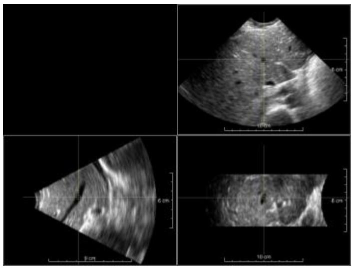
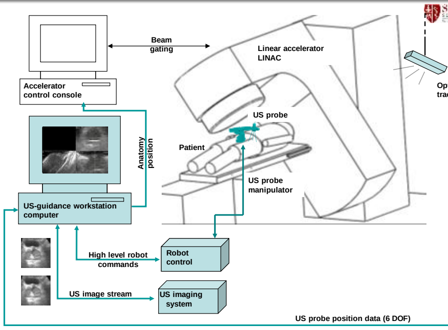
  - NIH STTR grant to Sonitrack Systems
  - NSF
  - Philips Ultrasound
  - Interson
  - Stanford Bio-X IIP

Imaging during beam delivery

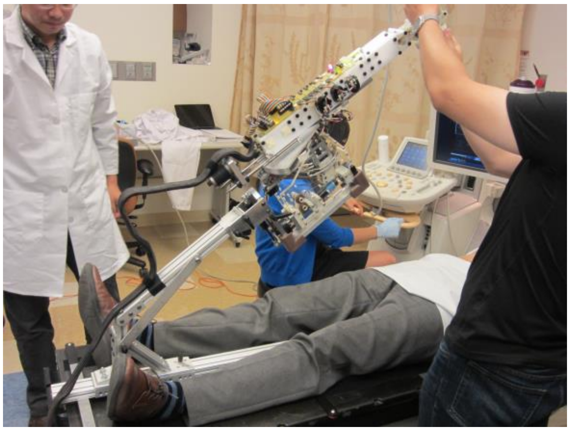


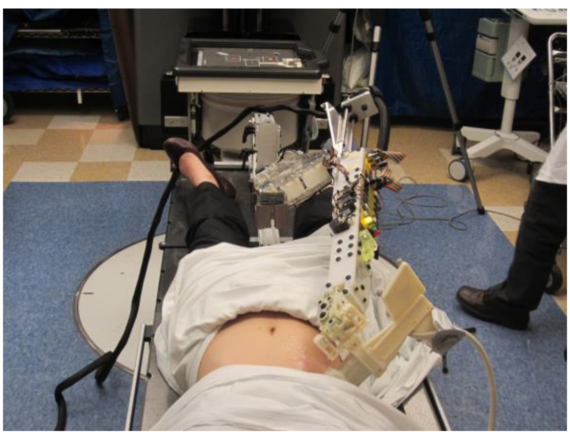
➡ **Add-on**, real-time, **volumetric, soft-tissue** guidance during radiation beam delivery is largely unmet challenge

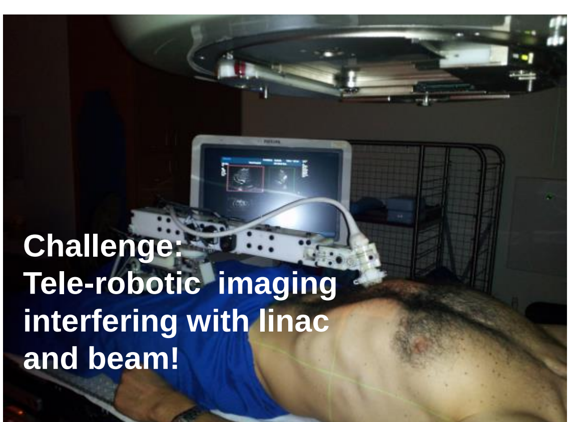
Image guidance architecture



Schlosser J, Salisbury K, Hristov D, **Telerobotic system concept for real-time soft-tissue imaging during radiotherapy beam delivery**, Med Phys. 2010 Dec;37(12):6357-67






Challenge:
Tele-robotic imaging
interfering with linac
and beam!

Approaches to the treatment interference challenge

- ❖***Avoid beams*** through probe and robot
  - ❖Can we assure resulting plan is clinically acceptable for a given patient?
- ❖***Include*** probe and robot in plan
  - ❖Can they be modelled sufficiently accurately?
- ❖***Make*** probe and robot disappear
  - ❖Has Dimitre gone mad?

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Avoid beams through probe and robot

CT simulation

- ❖***Guide*** device placement to potential non-interfering imaging positions
- ❖***Confirm*** adequate image quality

Augmented reality system for ultrasound guided radiation therapy
Renhui Gong, Ralf Bruder, Achim Schweikard, Jeff Schlosser, and Dimitre Hristov International Journal of Computer Assisted Radiology and Surgery, June 2015, Volume 10, Issue 1 S31

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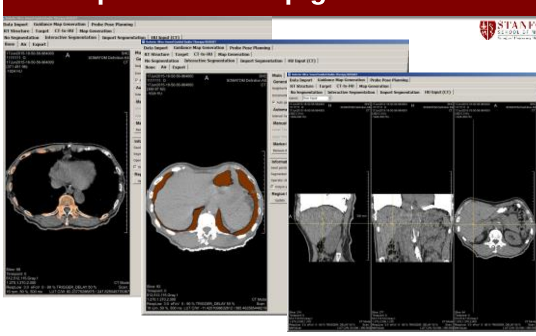
Probe placement map generation



Ralf Bruder, Floris Ernst and Achim Schweikard, SU-D-220-02: Optimal transducer positions for 4D ultrasound guidance in cardiac IGRT, in: 53rd Annual Meeting of the AAPM, pages 3390, 2011

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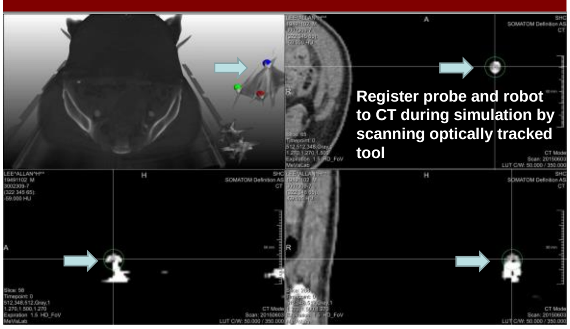
Probe placement map generation

Define target and map attenuation to target from surface

CT simulation



Guide probe placement towards non-interfering positions during simulation: probe placement map

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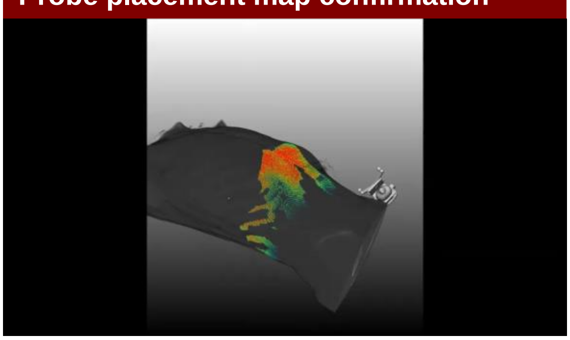
Probe placement map confirmation



Visualize probe in virtual space during actual imaging.

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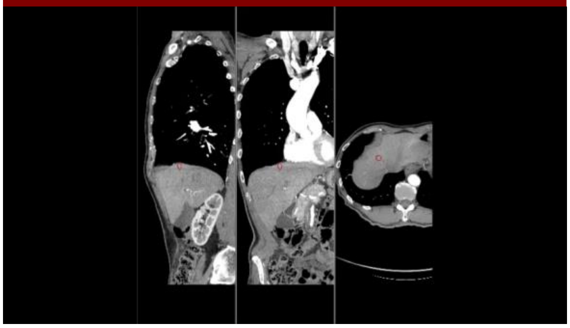
Probe placement map confirmation



Visualize live US images fused with CT and target.

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Avoid beams through probe and robot

Planning

- ***Verify*** non-interference of designed plan
- ***Suggest*** slight changes of robot placement if necessary
- ***Design*** *plan trajectories to avoid robot*

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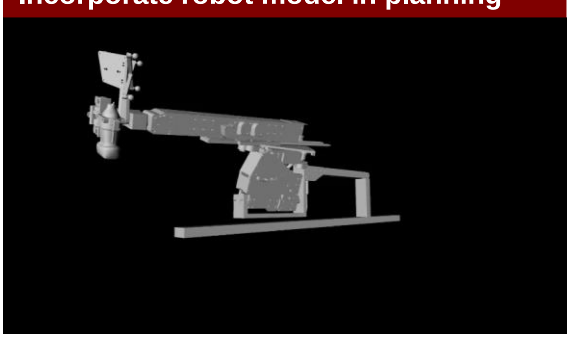
Incorporate robot model in planning



Custom xml descriptor defining joints and limits

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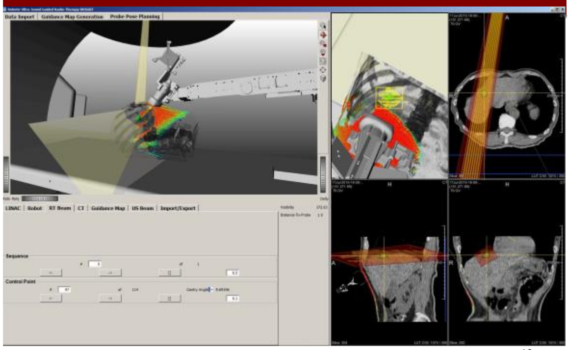
Virtual simulation environment



Robot placement

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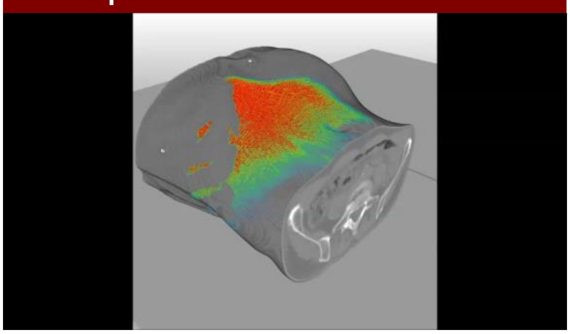
Robot placement in 3D



Recorded joint positions during simulation or interactive setup

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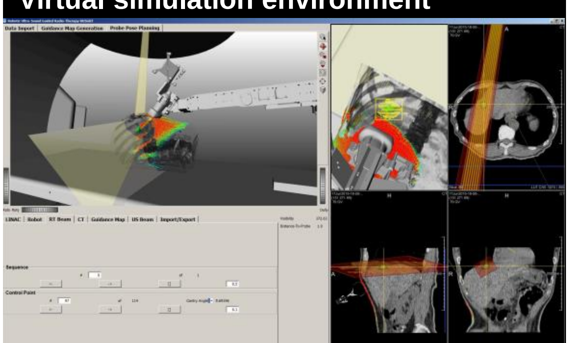
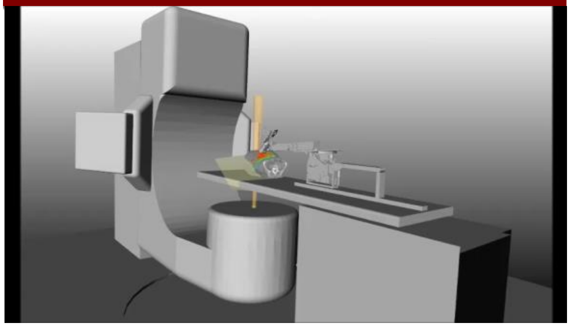
Virtual simulation environment



Plan interference evaluation by loading RT objects

Collision evaluation



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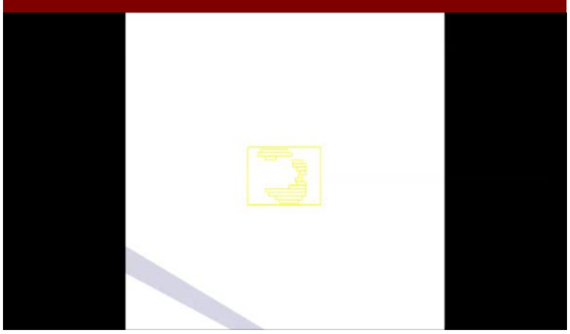
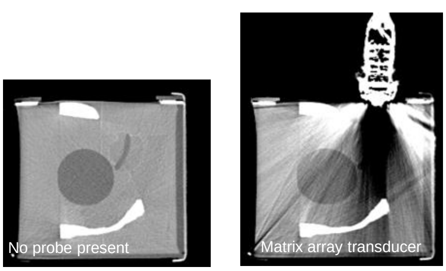
Beam evaluation



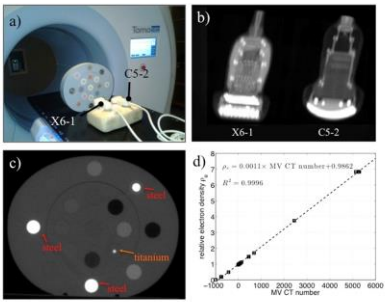
Beam eye-view to monitor entrance through probe/robot

Include probe and robot in plan



➡ ***Severe CT artifacts preclude CT-based modeling.***

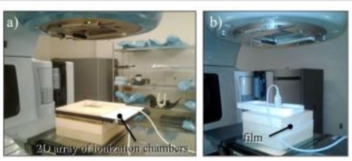
Megavoltage CT for electron density calibration

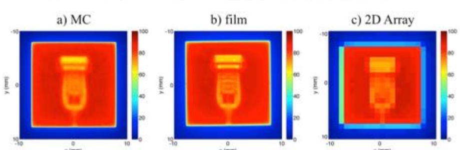


Electron density models of X6-1 and C5-2 ultrasound probes built with a Tomotherapy 3.5 MV CT scan.

Monte Carlo modeling of ultrasound probes for image guided radiotherapy
Magdalena Bazalova-Carter, Jeffrey Schlosser, Josephine Chen, and Dimitre Hristov
Submitted to Medical Physics

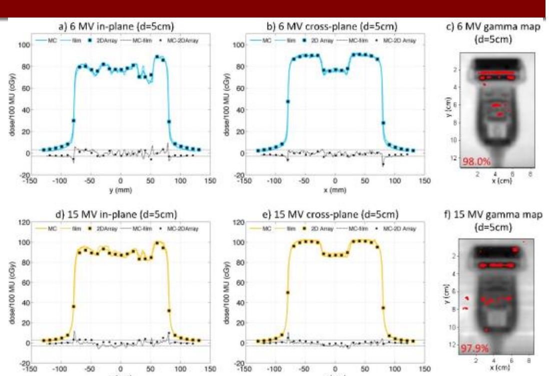
Experimental setup





Note detail differences between MC, film, and 2D array.

X6-1 Probe Horizontal Position

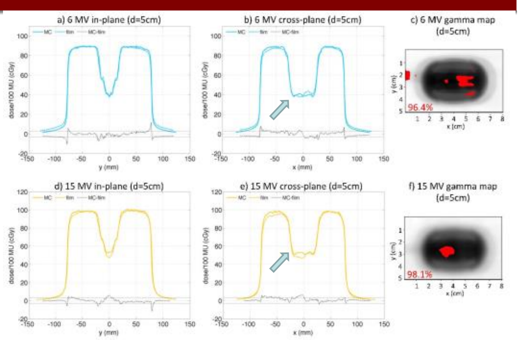


MC versus 2D array

Table 2: Statistics of local dose difference comparison between MC simulations and 2D Array measurements for US probes in horizontal orientation.

	X6-1		C5-2	
	6 MV	15 MV	6 MV	15 MV
Mean (%)	0.3	-0.3	0.1	0.0
Standard deviation (%)	1.3	1.4	1.2	1.2
Max (%)	5.3	3.6	5.9	4.3
Voxels with <3% local difference	95.7	96.6	97.4	99.1

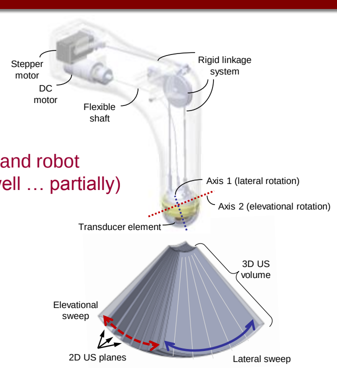
X6-1 Probe Vertical Position

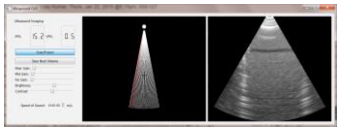


Cable placement introduces dose discrepancies.

Remotely-Actuated Ultrasound Scanning (RUSS)

Make probe and robot disappear (well … partially)





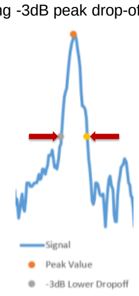
Frame rate and Field of View

For ~1 slice per elevational degree:

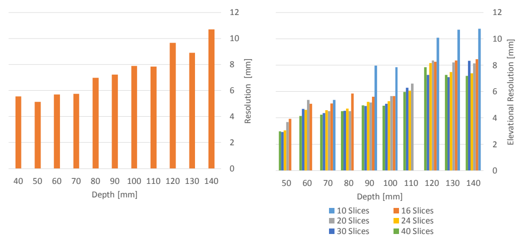
Elevational Sweep Angle	Lateral Sweep Angle	Imaging Depth	Axial Slice Field of View	# of Elevational Slices	Volumes Per Second	Planes Per Second
15º	19º	15 cm	5.0 cm x 4.0 cm	15	3.3	48
23º	**29º**	**10 cm**	**5.0 cm x 4.0 cm**	**22**	**2.2**	**48**
45º	60º	5 cm	5.0 cm x 4.0 cm	44	1.1	48
15º	60º	15 cm	15.0 cm x 4.0 cm	15	1.1	16
23º	**60º**	**10 cm**	**10.0 cm x 4.0 cm**	**22**	**1.1**	**24**
45º	60º	5 cm	5.0 cm x 4.0 cm	44	1.1	48

Spatial Resolution

- Method:
  - Lateral/elevational: point spread using -3dB peak drop-off
  - Axial: minimum resolvable spacing

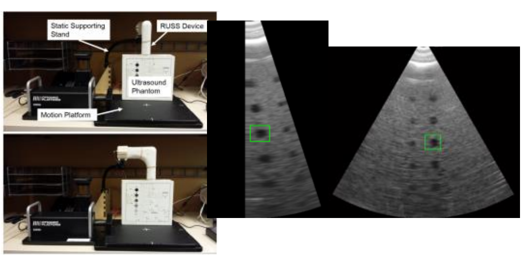


Spatial Resolution: Results

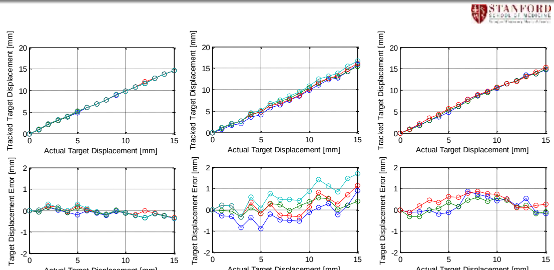


	Axial	Lateral	Elevational
Resolution @ **5 cm** depth	**1 mm**	**5.1 mm**	**3.7 mm**
Resolution @ **10 cm** depth	**1 mm**	**7.9 mm**	**5.7 mm**

Tracking Resolution

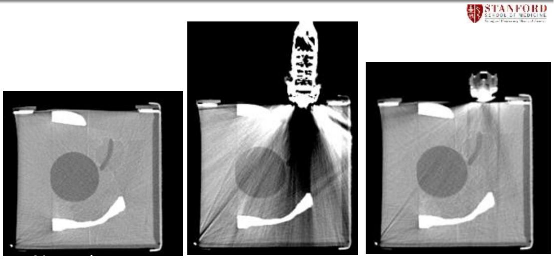


Tracking Resolution: Results



	Axial	Lateral	Elevational
Mean Target Tracking Error	**0.2 mm**	**0.4 mm**	**0.3 mm**
Max Target Tracking Error	0.4 mm	1.7 mm	0.9 mm

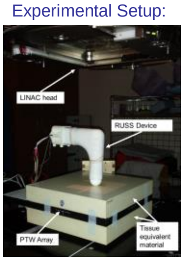
CT Compatibility

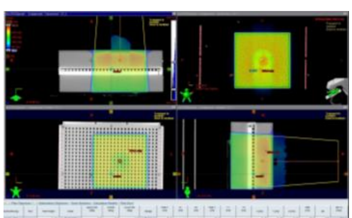


Radiotherapy Beam Compatibility

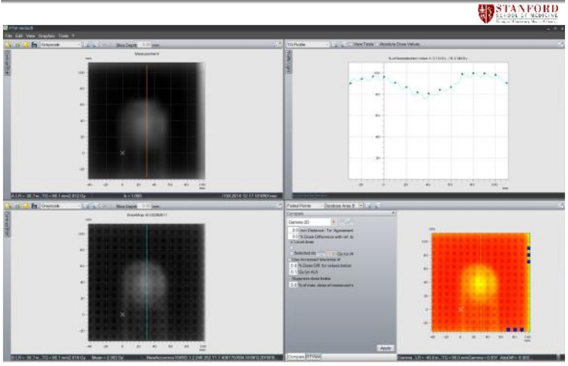
- Method 1: Compare planned and delivered dose through RUSS probe
- Method 2: Image-based tracking during beam delivery

Experimental Setup: Accuros Plan:



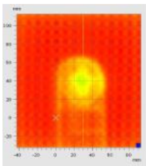


Radiotherapy Beam Compatibility: Results

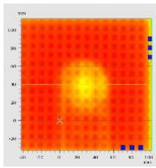


Radiotherapy Beam Compatibility: Results

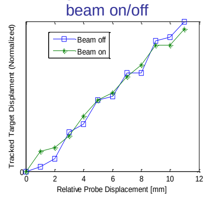
6MV PTW Measurements



15MV PTW Measurements



Tracking Performance with beam on/off



All points met 2.0 mm / 3.0% dose deviation criteria

RUSS summary

Metric	Target: Intrafractional Liver Radiotherapy Guidance	Result with RUSS probe
Framerate and Field of View (FOV)	6.5 cm x 4 cm FOV at 5-15 cm depth; 1 volume per second	**@ 10 cm depth: 5.0 cm x 4.0 cm FOV, 2.2 Hz volume rate, 48 Hz plane rate**
Tracking Resolution	2 mm in each direction	**≤0.4 mm mean resolution**
Imaging during radiation delivery	No statistically significant difference between tracking performance with beam on/off	***p=0.52***
Radiotherapy planning compatibility	±3.0% / 2.0 mm agreement between computed and measured dose distributions	**All points agree within ±3.0% / 2.0 mm**

- RUSS performance meets requirements for intrafractional radiotherapy motion management
- Low CT artifacts, beam compatibility, and low cost

Conclusions

- ***Addressing treatment interferences by tele-robotic US imaging requires simulation tools for avoidance or inclusion strategies***
- ***Inclusion strategy feasible but possibly less practical than avoidance***
- ***Dedicated "radiolucent" ultrasound probes may greatly facilitate RT ultrasound guidance but careful evaluation of performance trade-offs is necessary***