Integrated on-board CBCT-US imaging system for soft tissue IGRT and real-time intra-fraction monitoring

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Challenges of Soft Tissue IGRT

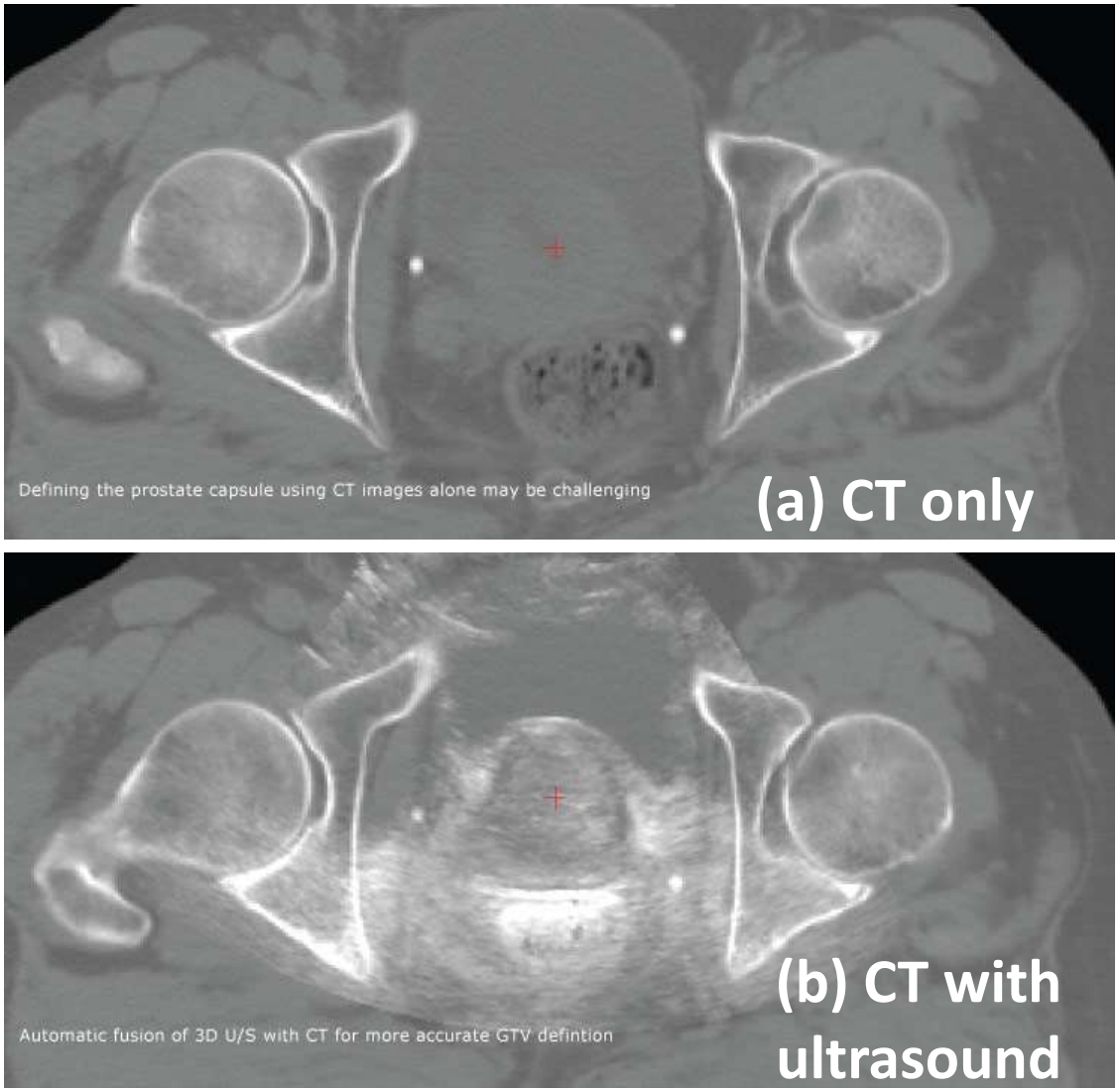
Inter-fraction methods: Cone beam CBCT, MV CT			
Pros	Volumetric information	**Cons**	Snap shot
	Adaptive Radiation Therapy		Ionizing radiation
			Image Quality
Inter-fraction methods: Intra-modal ultrasound imaging			
Pros	Soft tissue information	**Cons**	Snap Shot (at present)
	Non-ionizing		Expertise/operator dependence
Intra-fraction methods: Implanted Markers			
Pros	Real-time monitoring	**Cons**	Invasive
	Non-ionizing option		Ionizing radiation
			Soft tissue surrogate (truth?)

- Emergence of MRI-Radiation Machines

Integrated 3D ultrasound/CBCT imaging for soft tissue IGRT

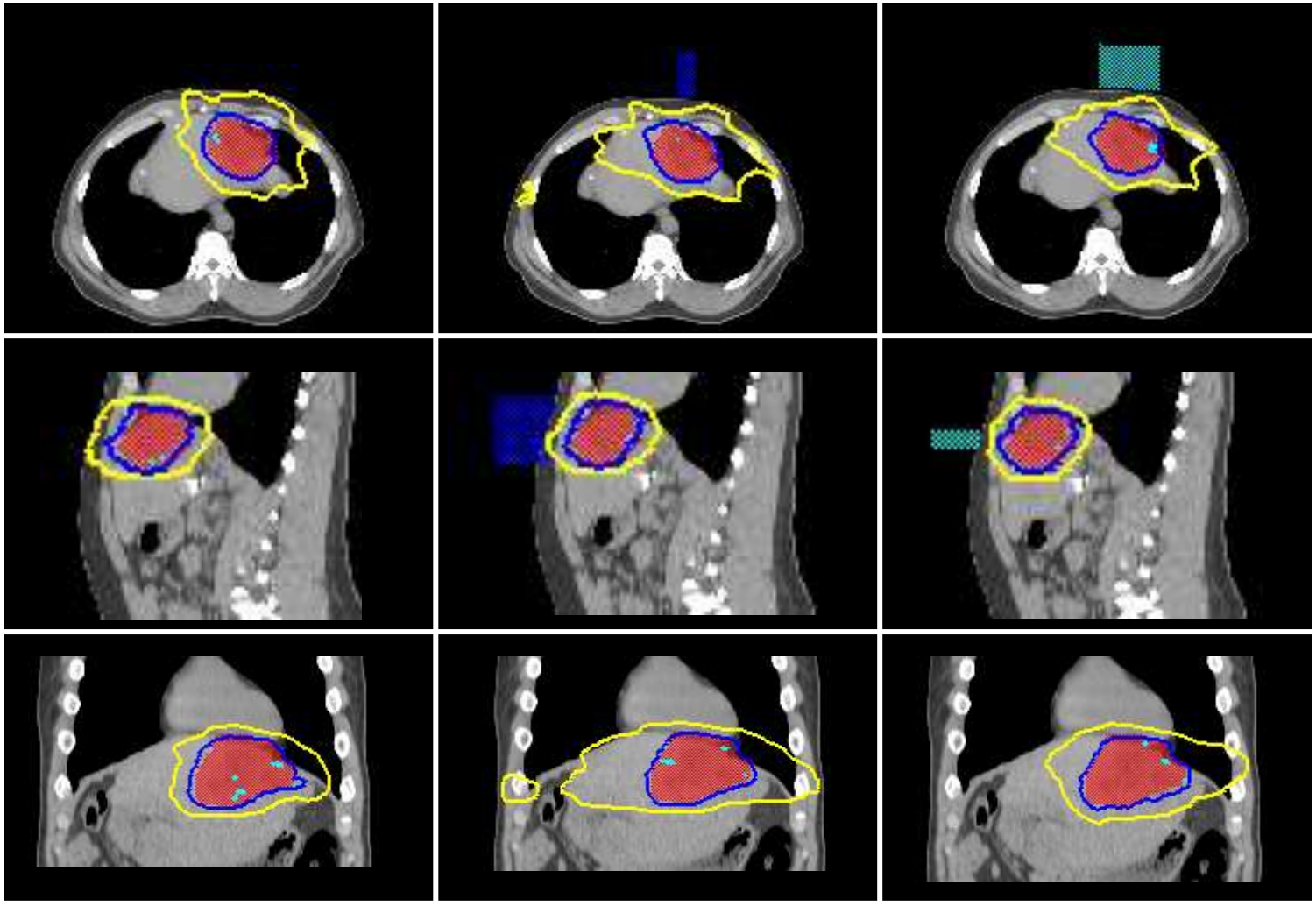
Hypothesis:

- US-CBCT offers an non-ionizing, non-invasive inter- and intra-fraction solution for soft tissue targets
- Prostate, liver, pancreas



Challenges of US imaging	Solutions
Reproducibility / operator dependence	Robotic placement of a 3D probe
Deformation of anatomy	Keep US probe in place during irradiation while avoiding beams → Intra-fraction monitoring
Soft tissue registration	By definition, auto-fusion of CBCT and real-time US
Require simulation/planning of patient in treatment position with the ultrasound/CBCT system in place	

SBRT Liver Planning Studies with Probe on Patient (n=10)



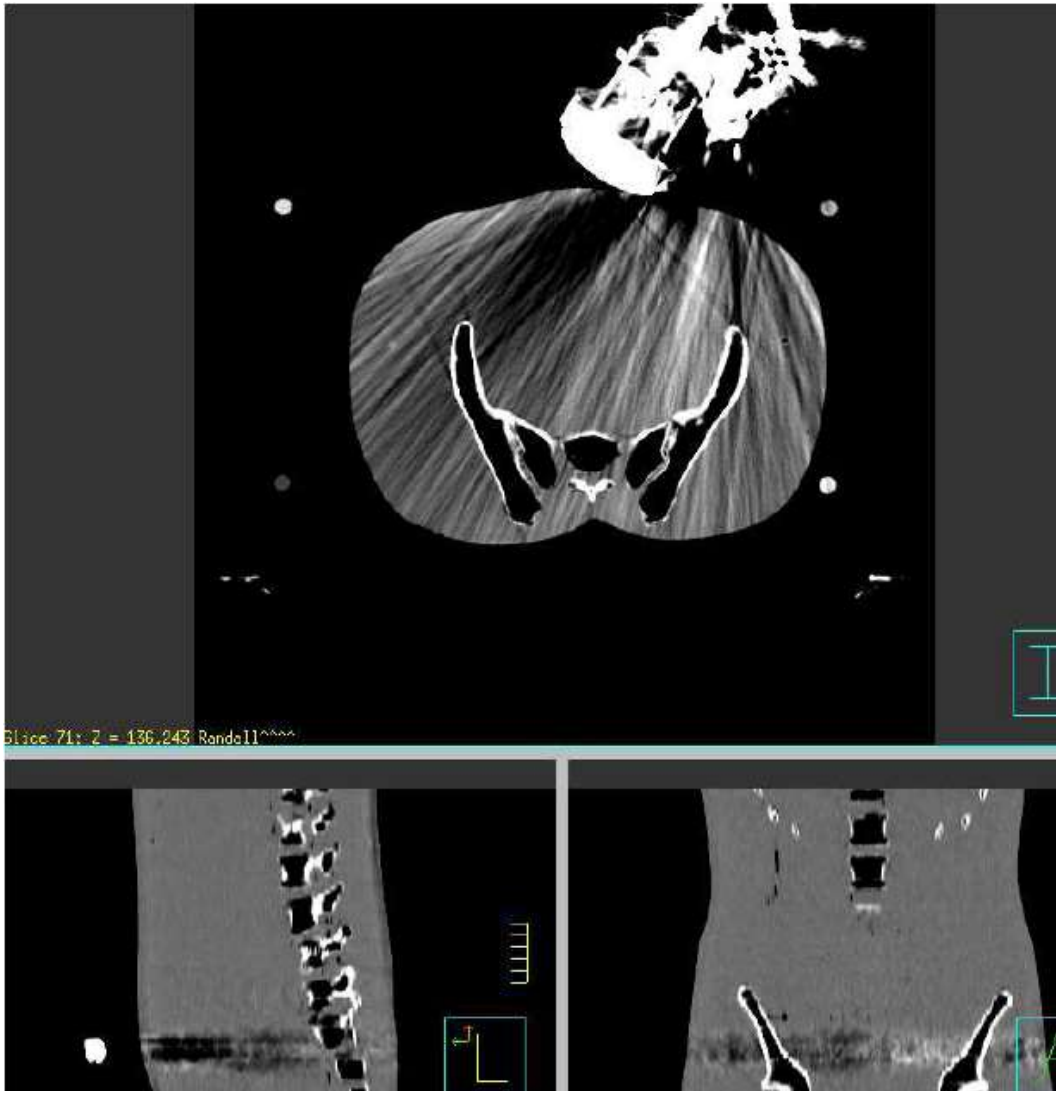
Plan-Clinical | Probe-Parallel | Probe-Vertical

Liver SBRT Dosimetric Endpoint Comparing

	Plan-Clin	US-Para	US-Vert	
D95 - PTV (Gy)	**38.72 ±0.14**	**38.63 ± 0.14**	**38.48 ± 0.31**	**P>0.05**
V15 - Liver (cc)	**363 ± 38**	**355 ± 48**	**367 ± 39**	**P>0.05**

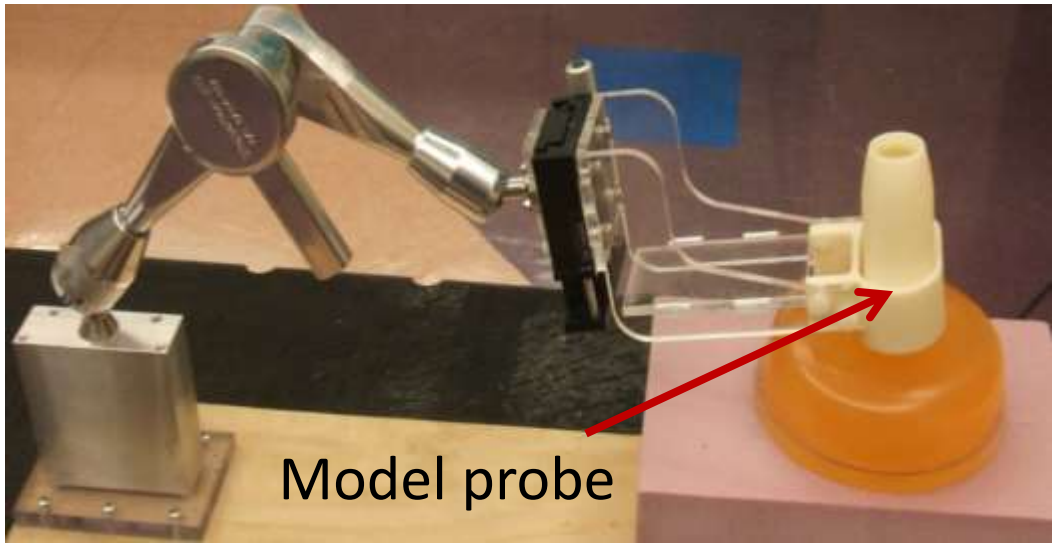
- Except for the superficial lesions of 2patients, the remaining 8 can be treated with probe in place.
- Probe-parallel allows 7 coplanar/1 non-coplanar treatments
- Probe-vertical allows 2 coplanar/6 non-coplanar treatments

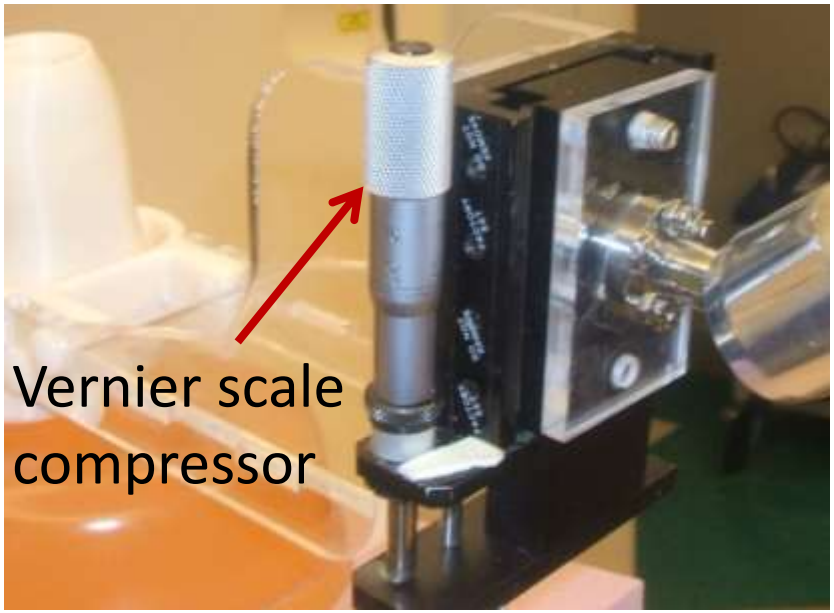
CT artifacts from Ultrasound Probe



- Need a ***model probe*** to avoid planning CT artifacts for planning and CBCT setup
- Require probe exchange
- Need to demonstrate reproducible placement and deformation

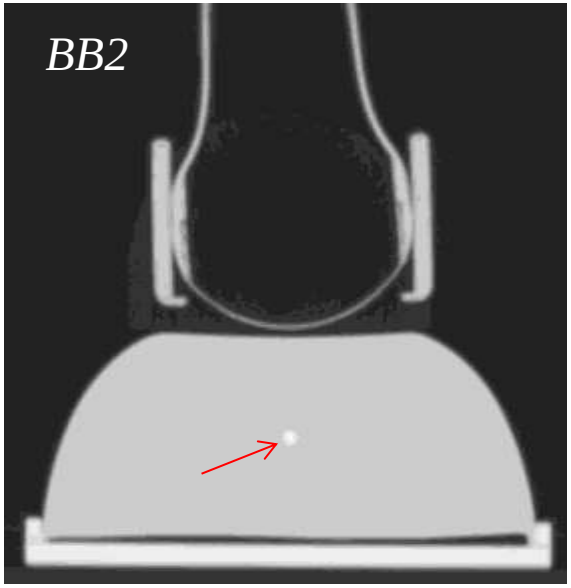
Reproducibility of model probe using CT: Passive (1D) robotic arm and gel phantom

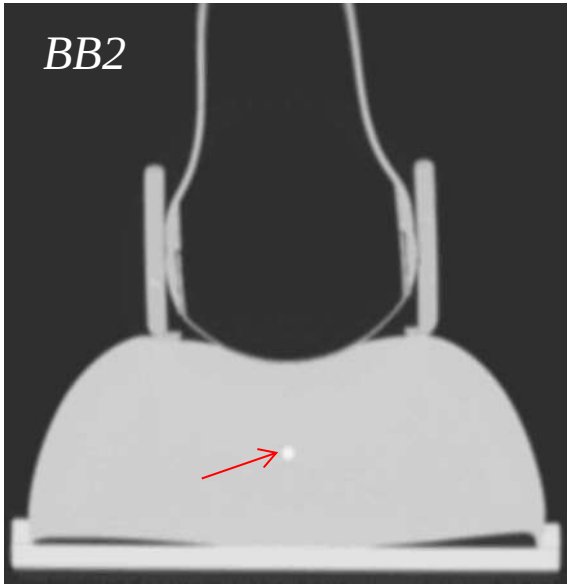




- Deformable gel phantoms with 12 embedded PMMA beads (1.2, 2.8, 3.2 mm in diameter)
- Compression Force ~ 5 N (~0.5 kg)

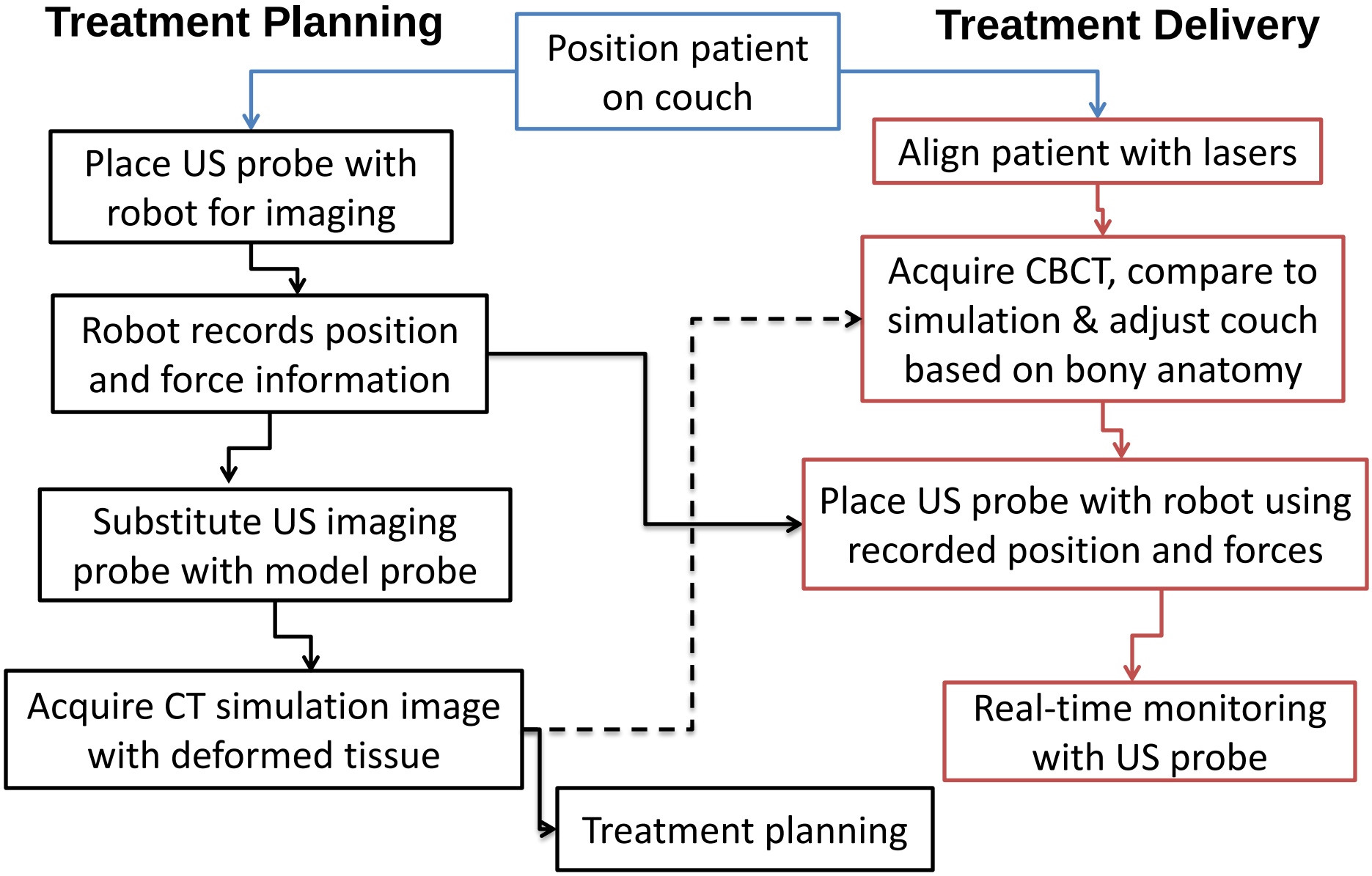
Reproducibility studies with model probe



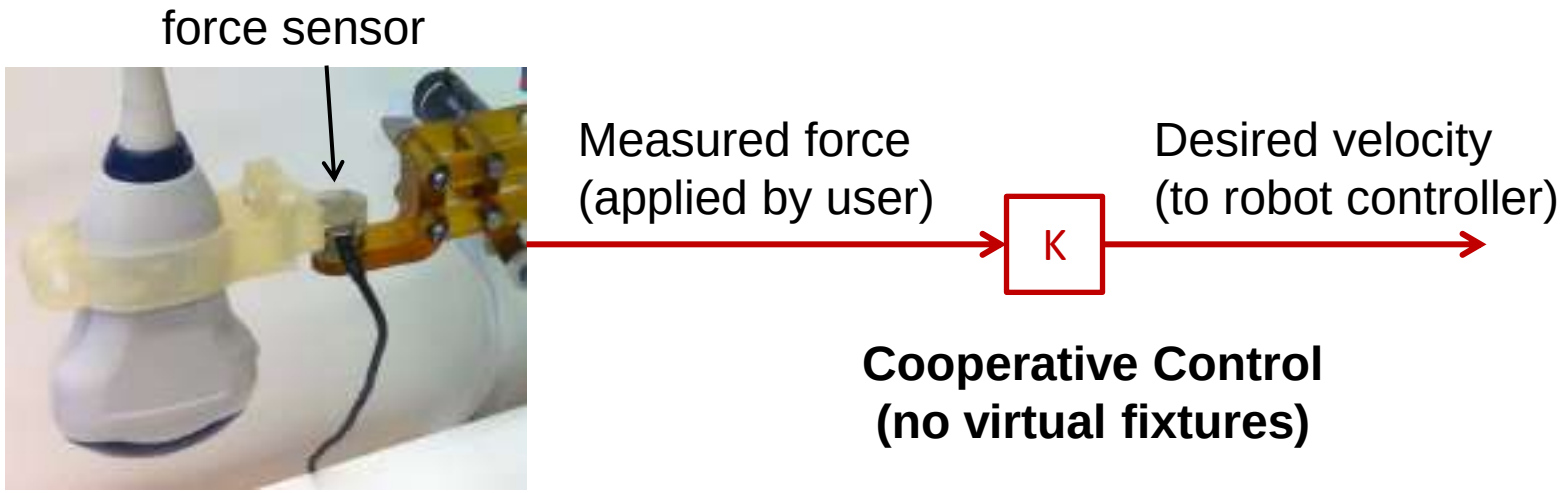


- CT (1 mm) slice scans of repeat cycles of w/wo compression
- Intra-scan: Compare displacement due to compression
- Inter-scan (1 day apart): Compare the difference of two separate measurements after accounting for setup error
- All beads' positions were reproducible to *within 1 mm*

Workflow: Robotic Assistance



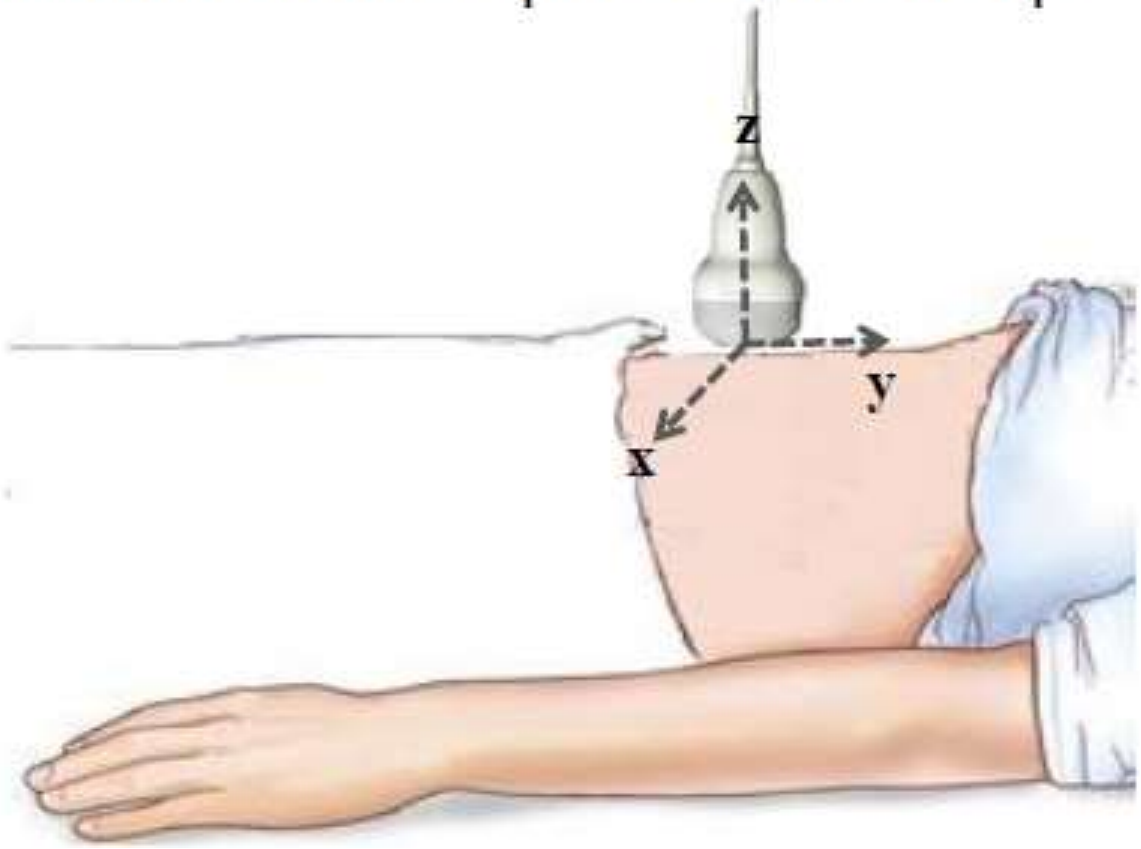
Cooperatively Controlled Robotic Placement



- Safety concerns regarding autonomous motion
- The need to adjust for setup error, anatomical changes, etc.
  - Human operator will be involved
- Implementation of virtual fixtures:
  - Enable less-skilled user to reproduce deformation (e.g., similar position/force) during inter-fraction treatment

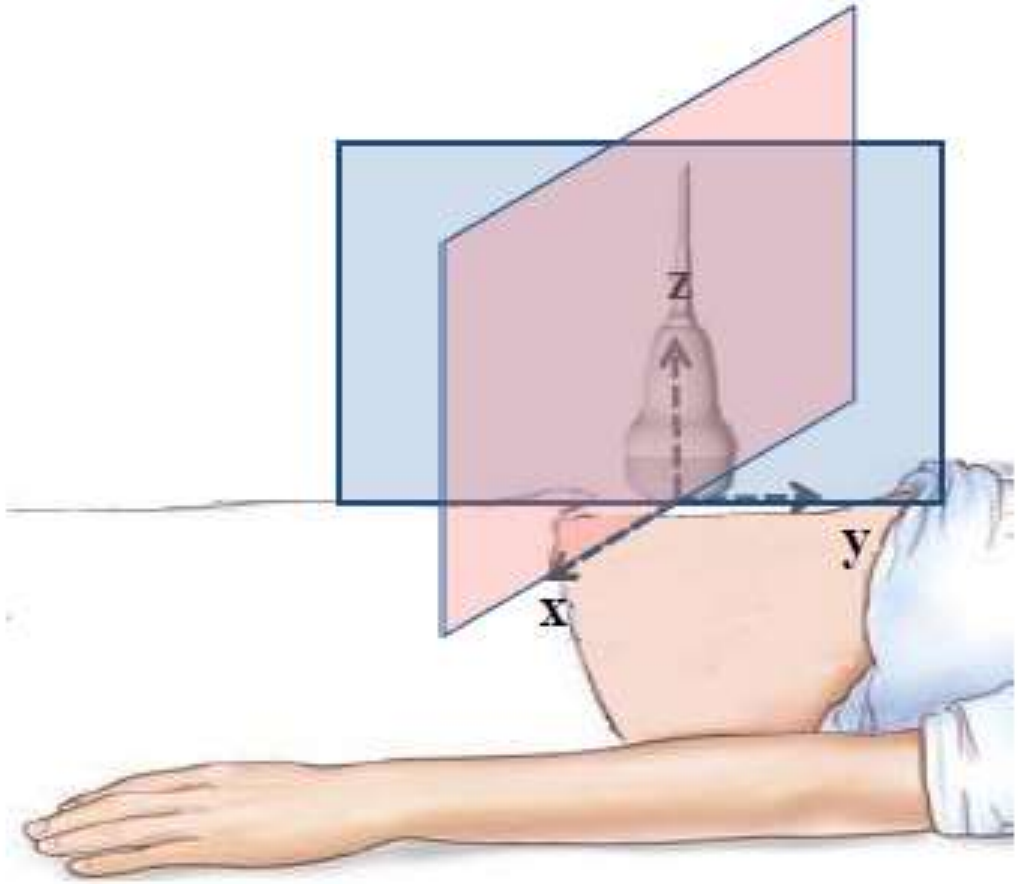
Placing the probe

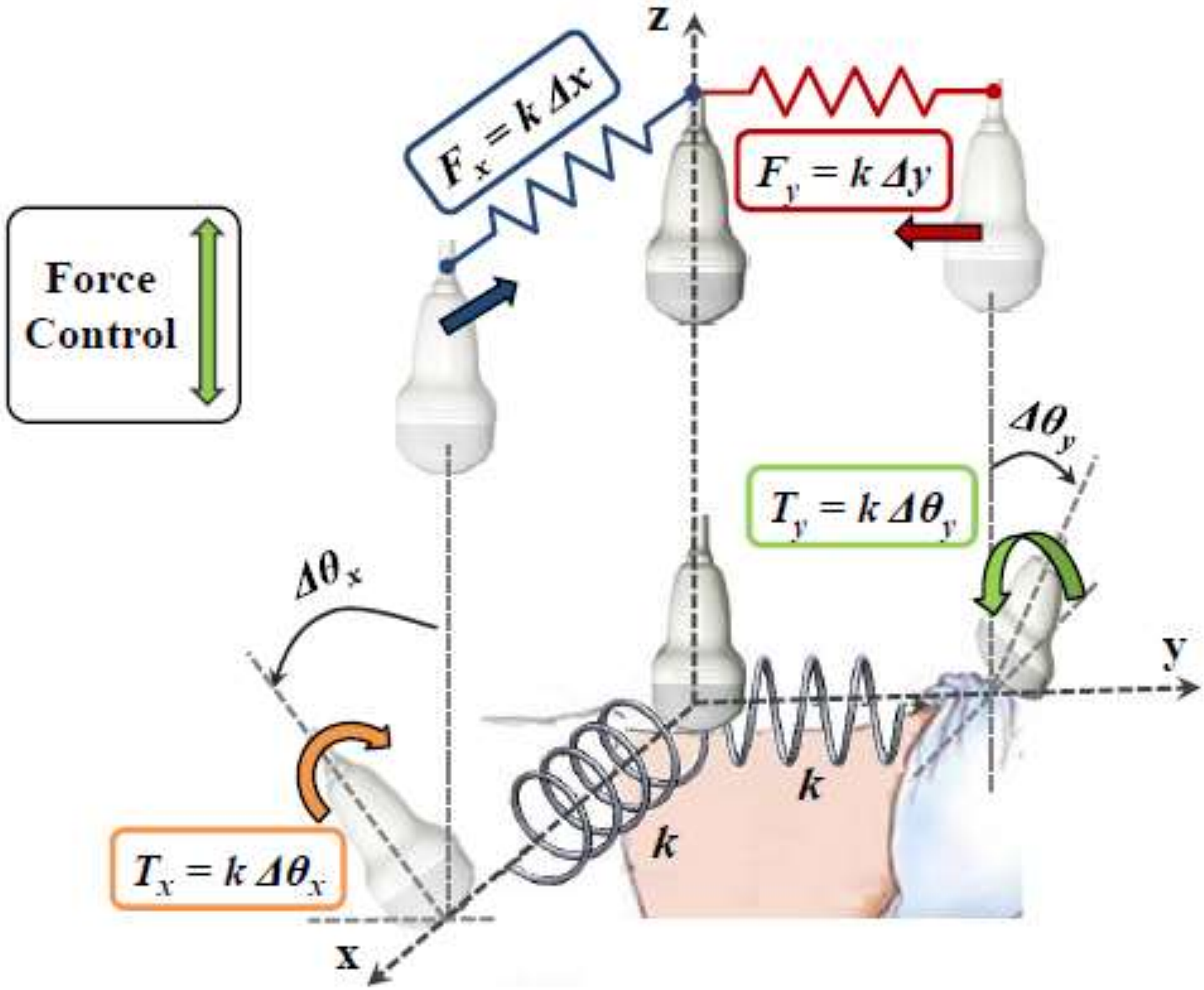
- ✓ Target area is found
- ✓ A coordinate frame is placed at the US tip



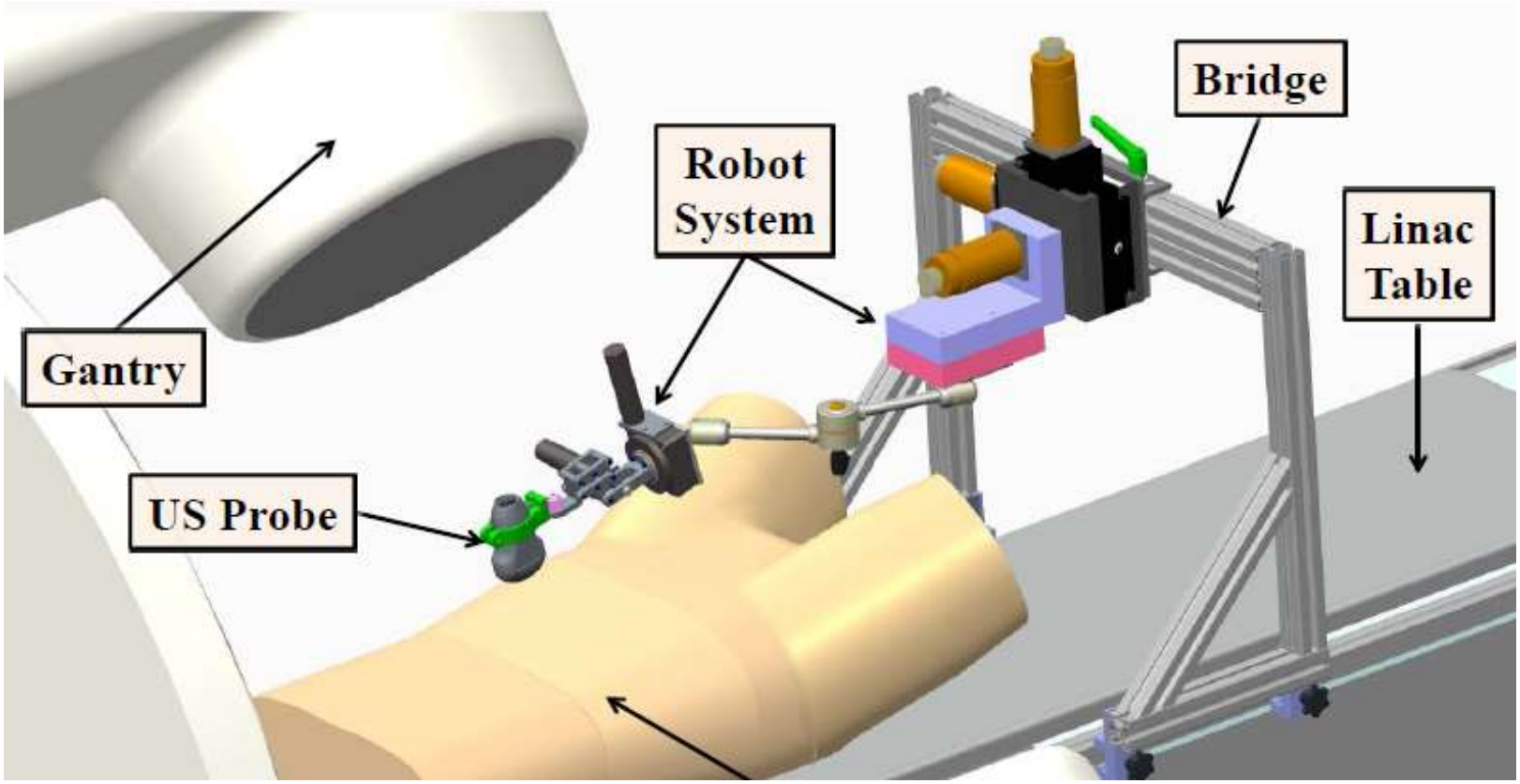
Control Algorithm

- ✓ After probe is placed, virtual planes are created

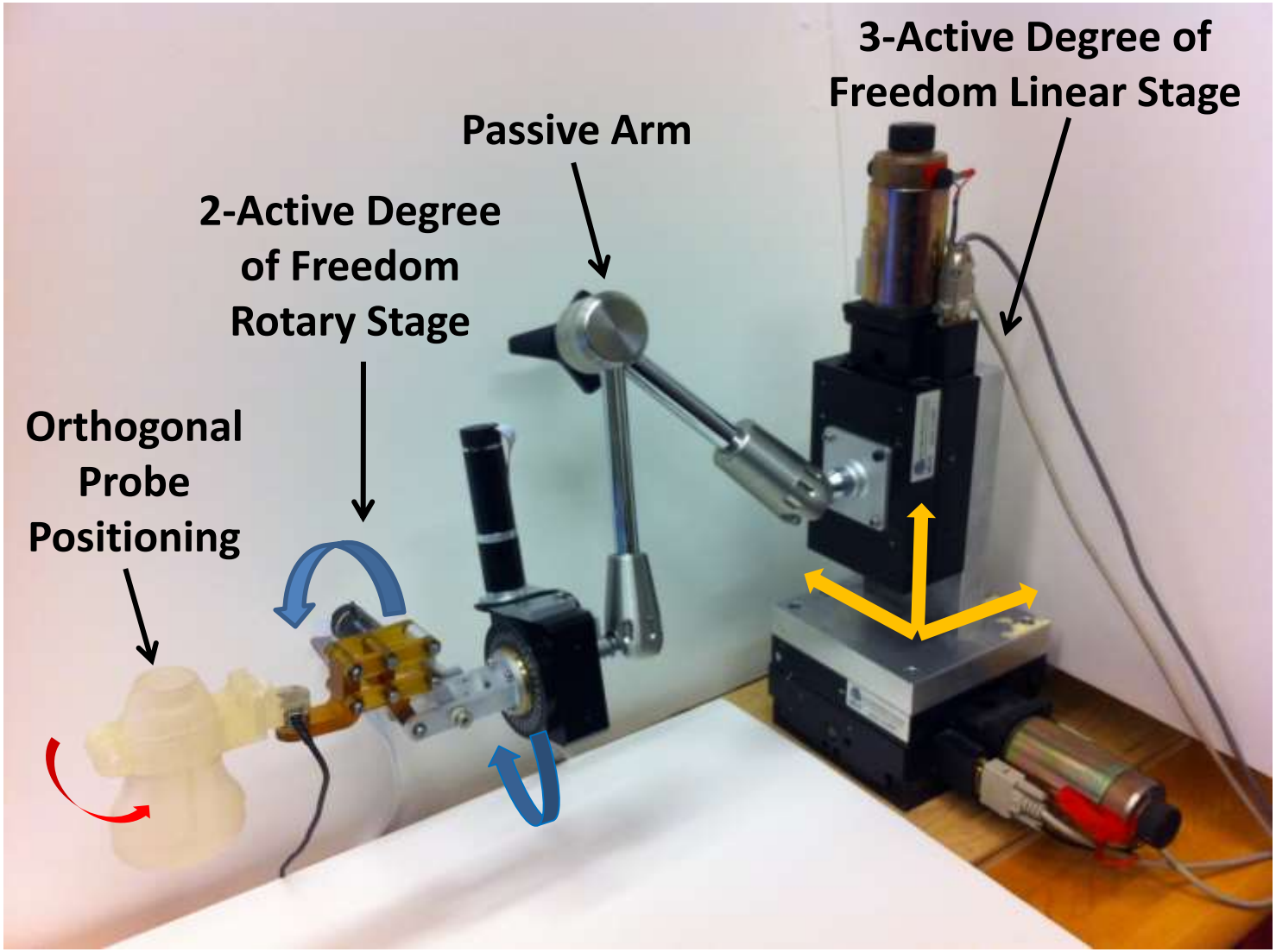



Force Control
$F_x = k\,\Delta x$
$F_y = k\,\Delta y$
z
$\Delta\theta_y$
$T_y = k\,\Delta\theta_y$
$\Delta\theta_x$
y
k
k
$T_x = k\,\Delta\theta_x$
x

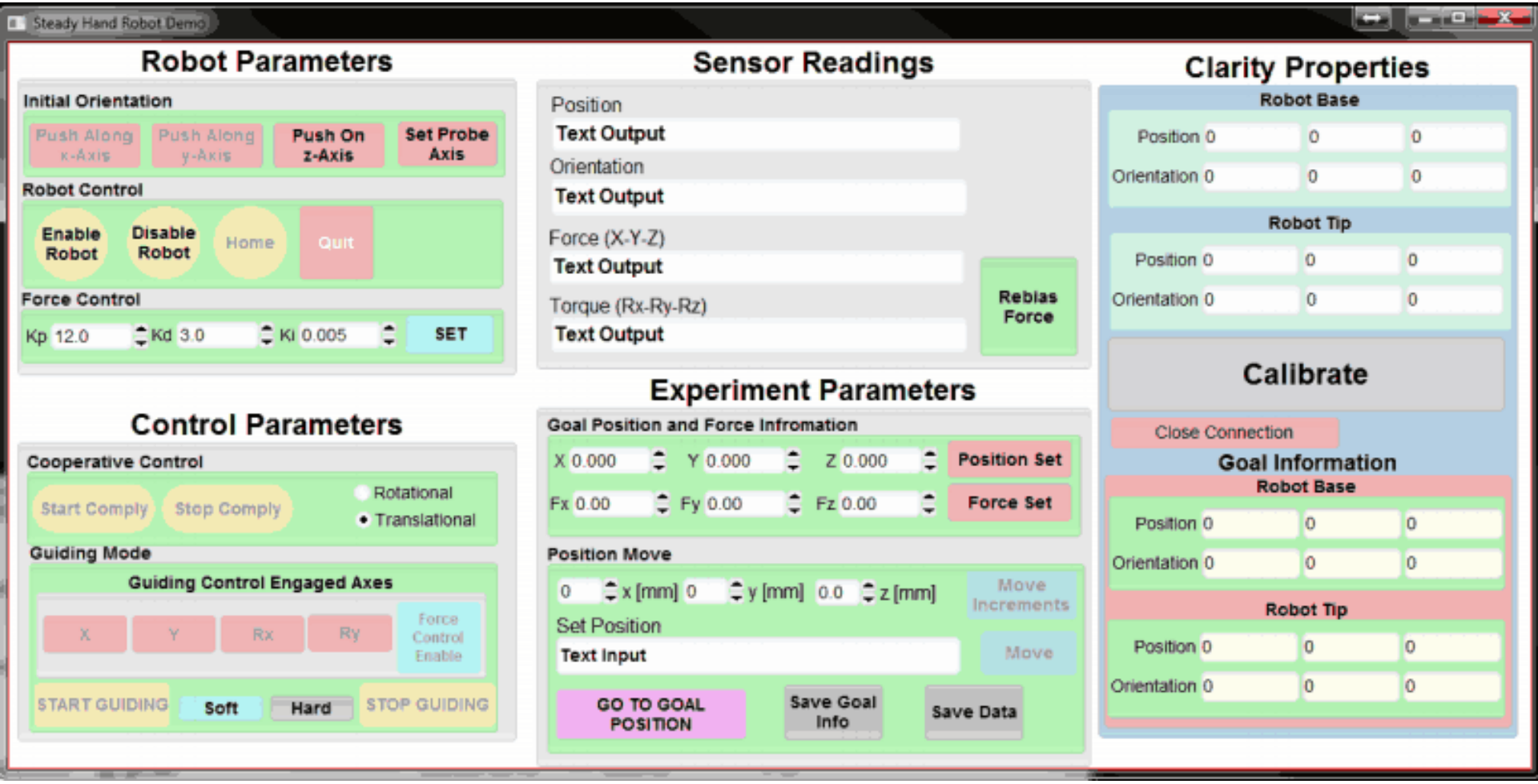
Cooperative Robotic Arm for Probe Placement



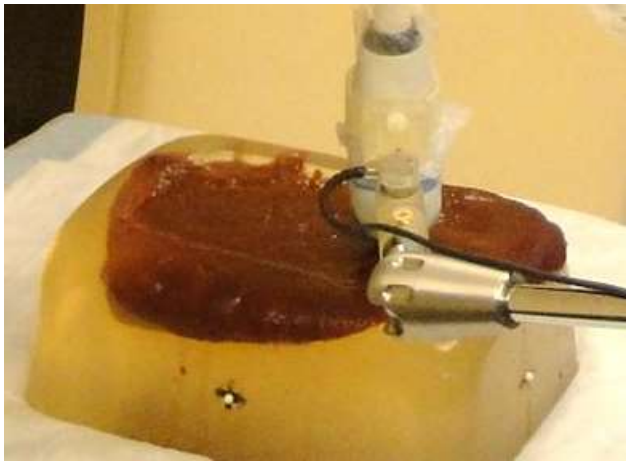
Prototype Cooperative Robot for Probe Placement

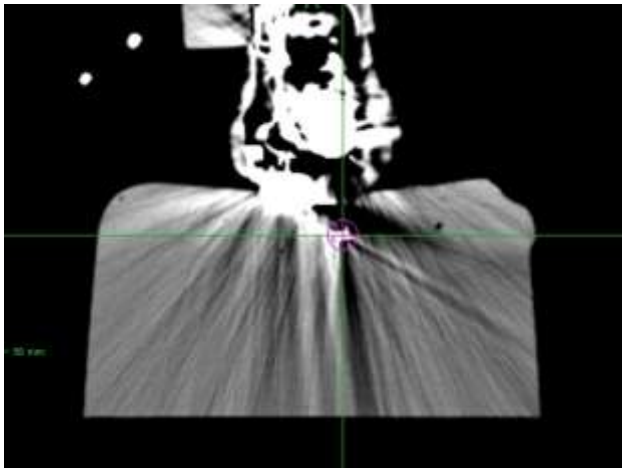


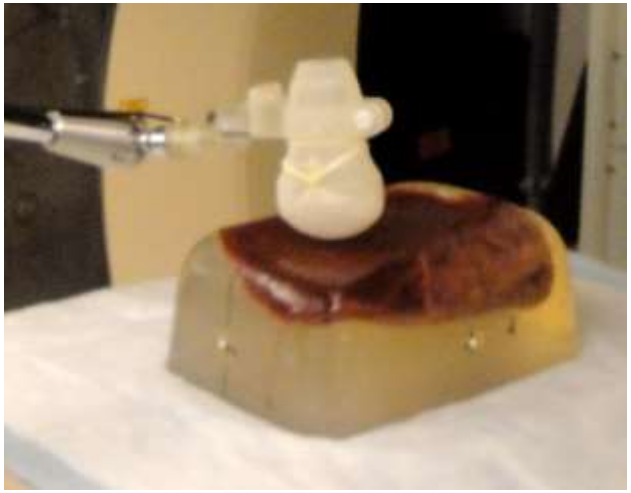
R&D Robot GUI:
Study of positional or force control

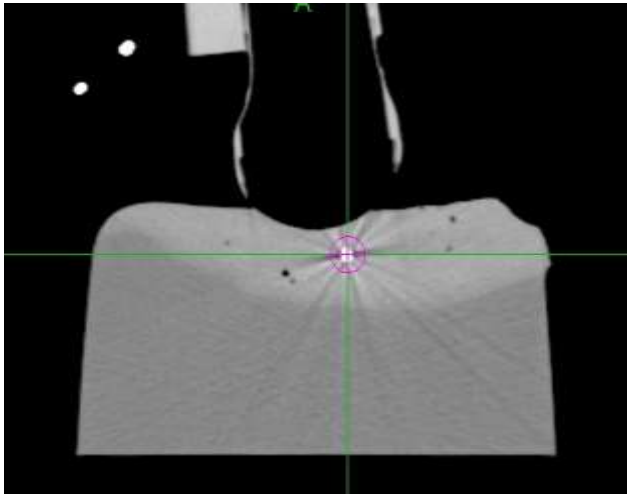


Ex-vivo Bovine Liver in gel phantom



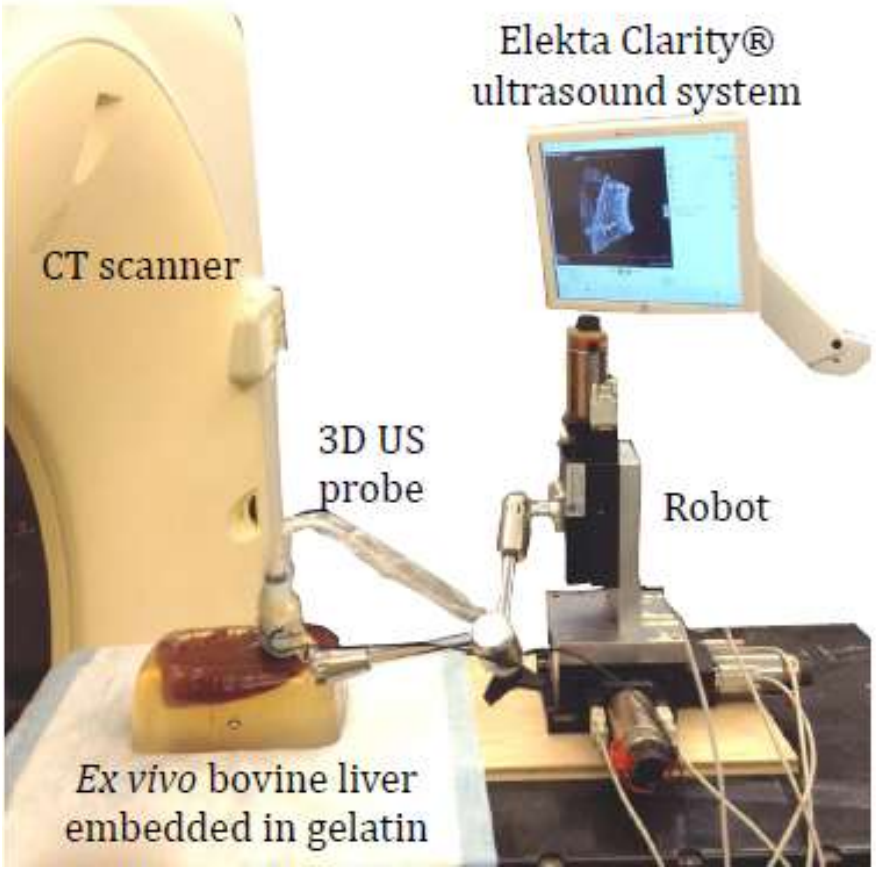


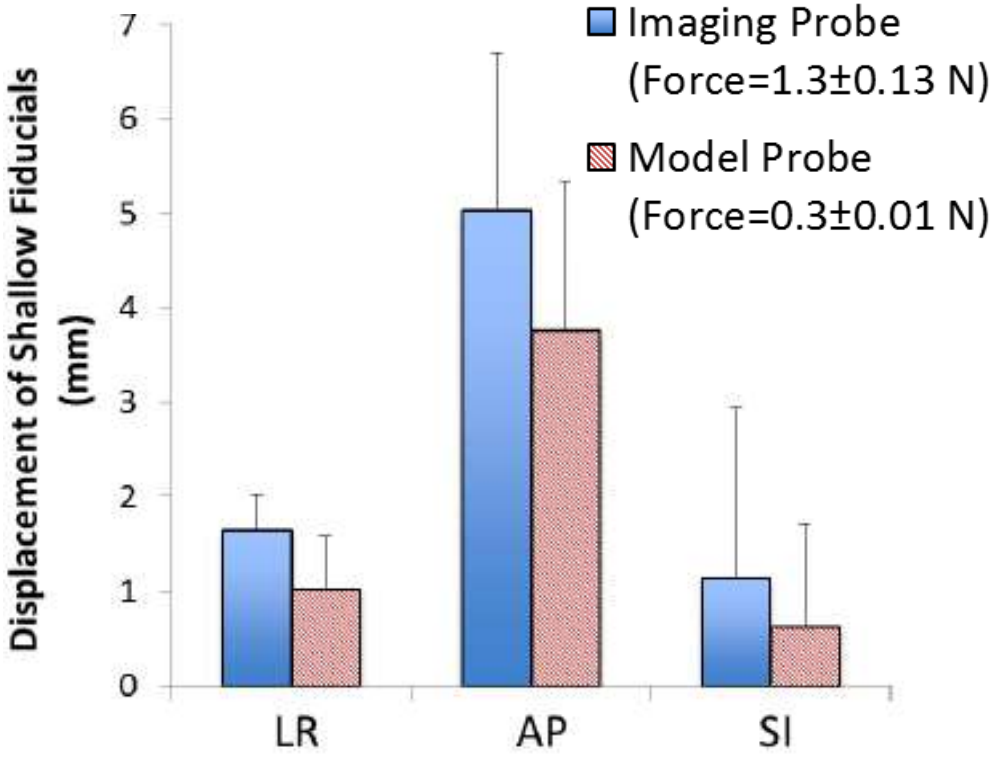




- Gel phantom was overly simplistic with uniform deformation
- A more realistic ex-vivo liver phantom was devised
- Comparison of deformation was made between ultrasound and model probe.

Reproducibility of Deformation





Contact forces lower with model probe
The robotic arm needs to be stiffened

- Significant compression force differences between gel and liver phantom
- Suitability of phantom material is of concern

X-ray CT – Ultrasound IGRT : In vivo feasibility studies

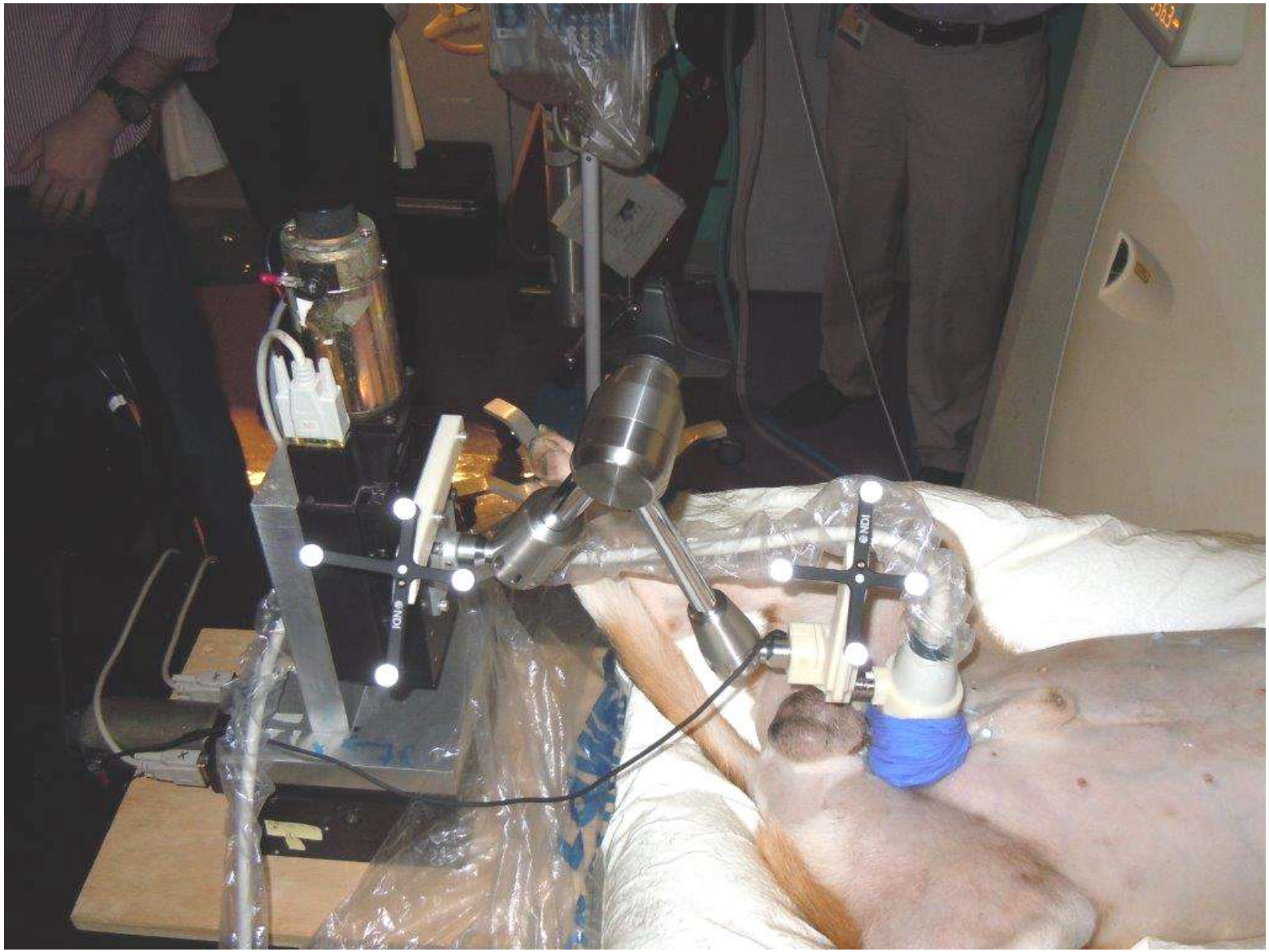
- DO13M143: “Reproducibility of probe placement for combined US-CT imaging”
  - Most realistic subject
- Reproducibility of induced deformation
  - Between clinical US probe and model probe
  - Intra-fraction during a treatment/simulation session
  - Inter-modality from simulation to treatment
  - Inter-fraction on different days (analysis in progress)

DO13M143

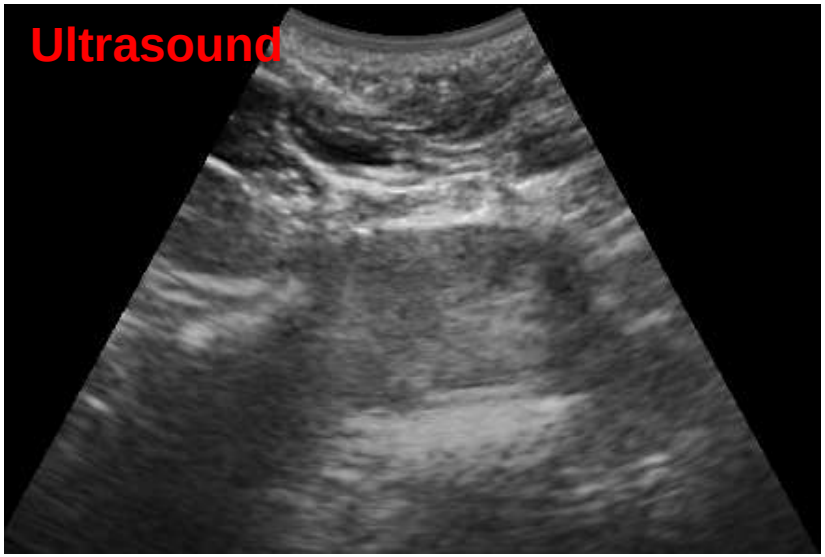
- Laboratory dogs: 4 planned, 1 studied
- Three spherical stainless steel markers (2.38 mm dia) implanted in the prostate, liver, pancreas
  - 1-2 organs were studied per week
- Helical CT of displaced marker positions due to robotic placement of imaging and model probe
  - no probe, imaging probe, model probe
- Focus of first dog study over 4 weeks:
  - Workflow; system configuration; …
  - Intra-fraction variation

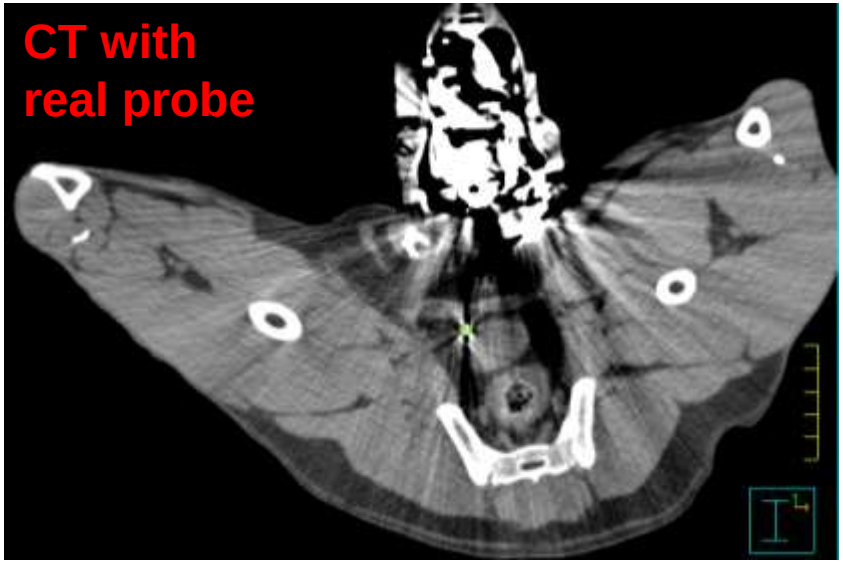

PHILIPS

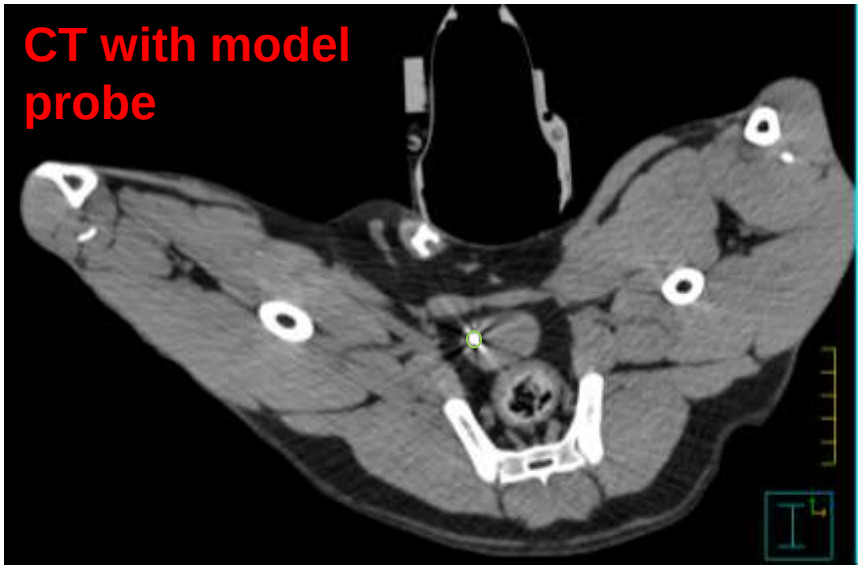
Prostate (Force = 14 N)



Prostate Images

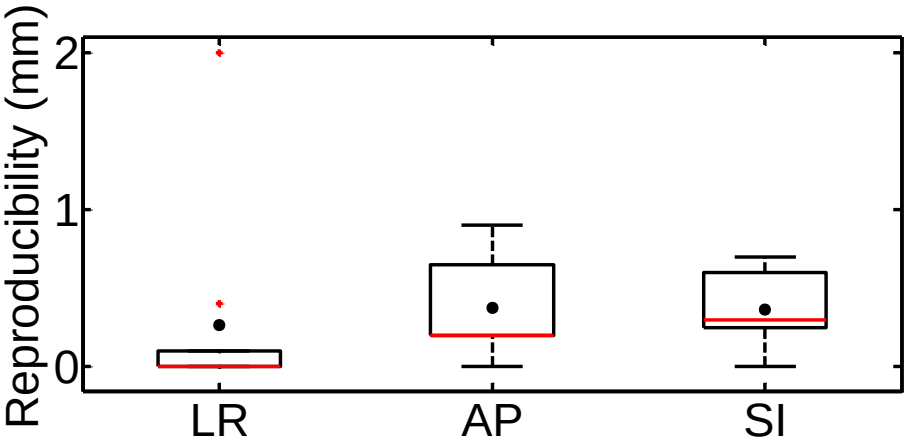




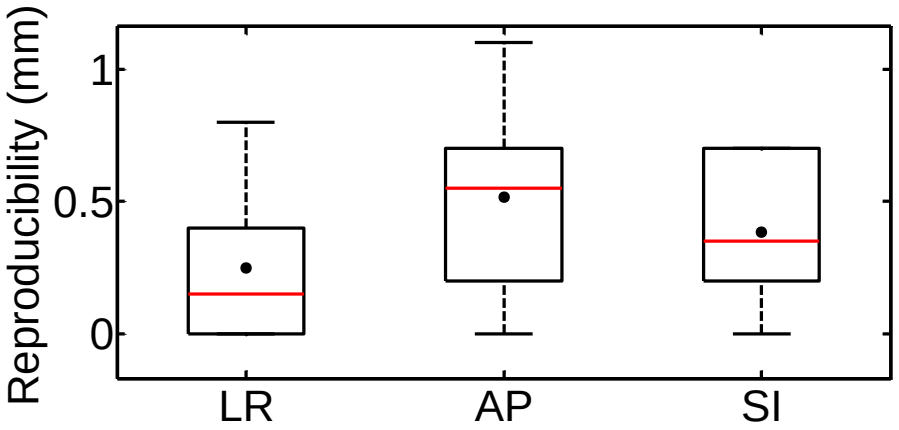


Prostate (Force = 14 N; 10 N ~ 1 kg): Marker Position Reproducibility in Interquartile Range

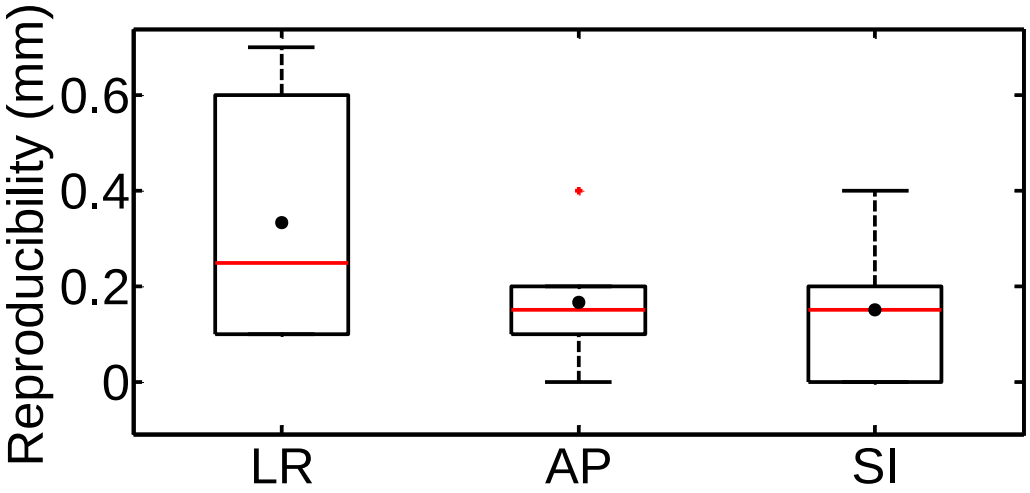
Real Probe: 3D mean error=0.6 mm



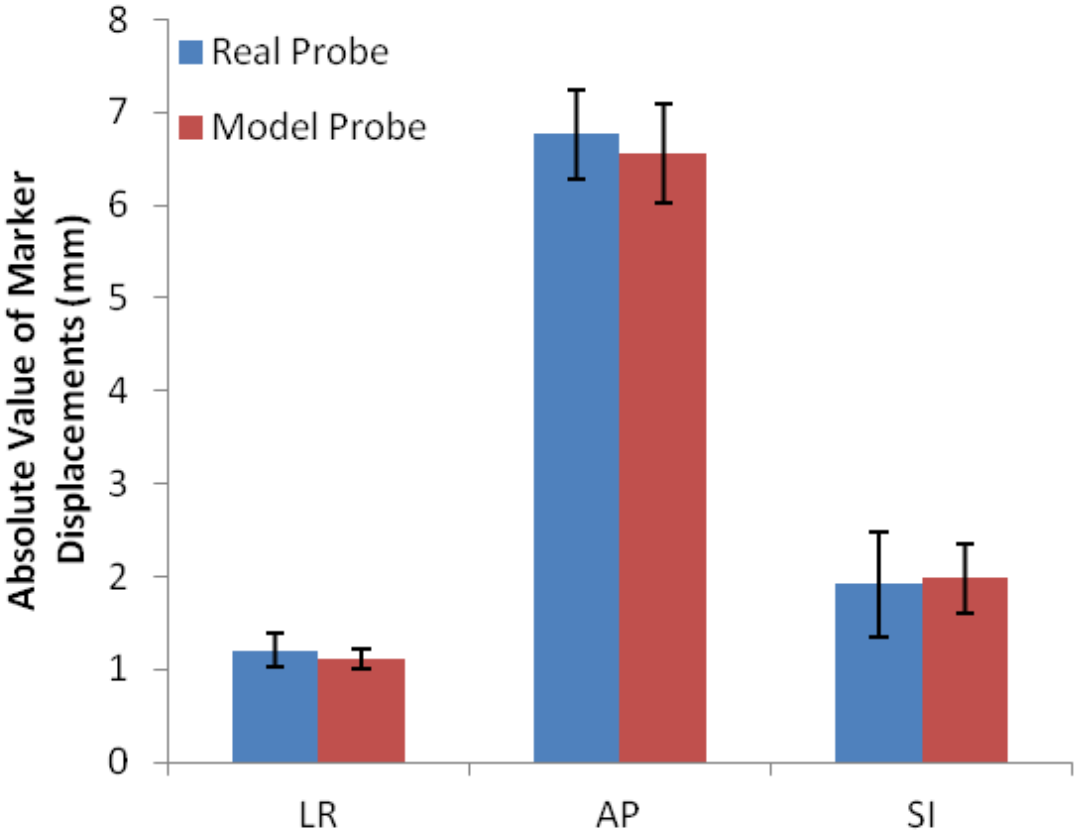
Model Probe: 3D mean error = 0.7mm

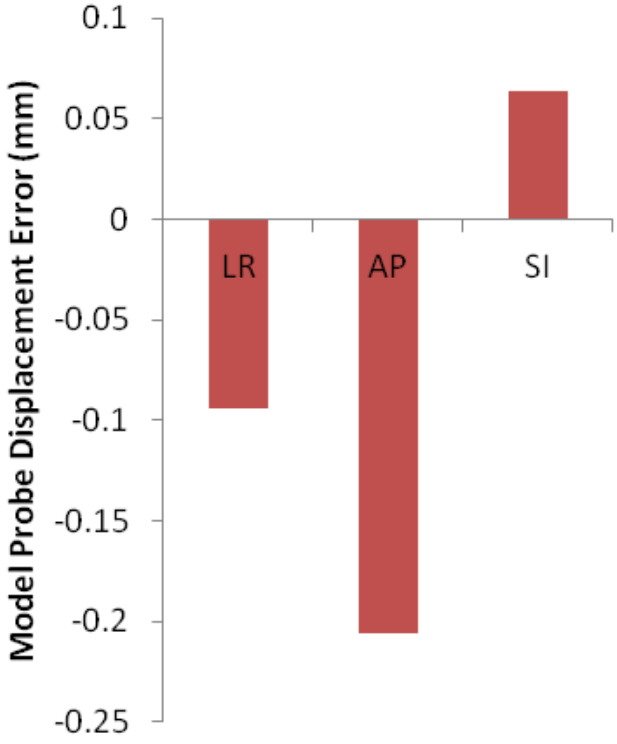


No Probe: 3D mean error = 0.4mm



Prostate:
Probe-Induced Marker Displacement (from no probe)

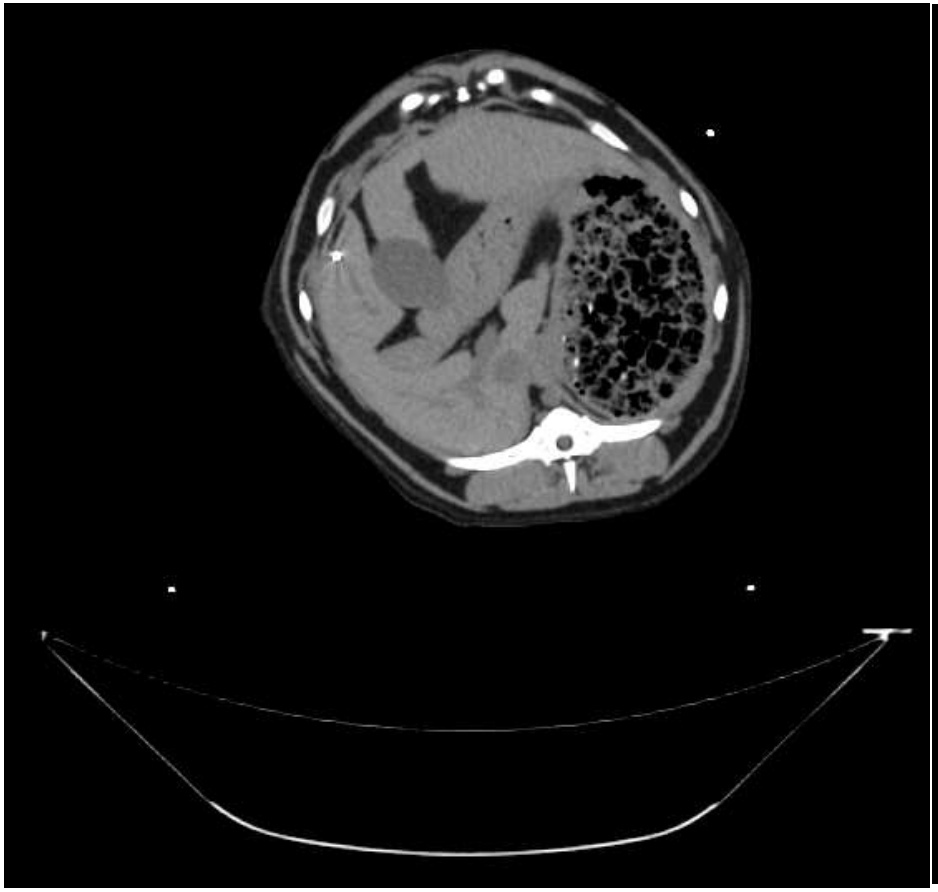




3D mean error
= 0.2mm

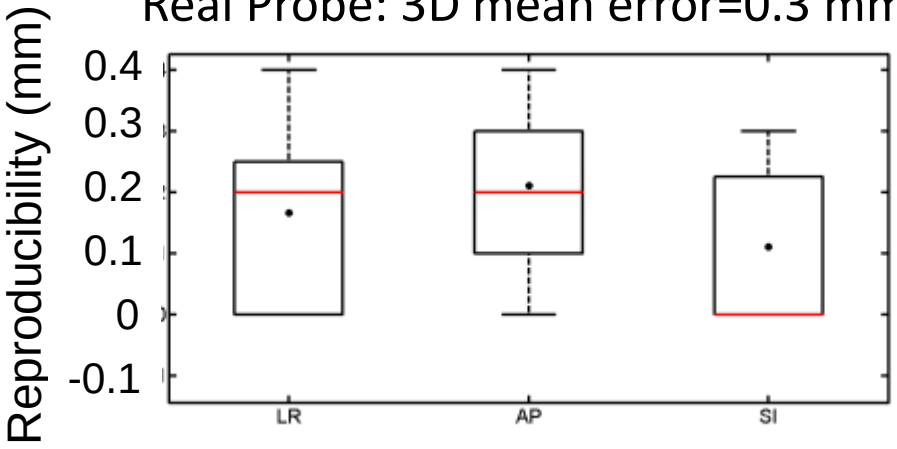
Liver at Breath-hold (Force = 40 N)

Liver CT and Ultrasound Images

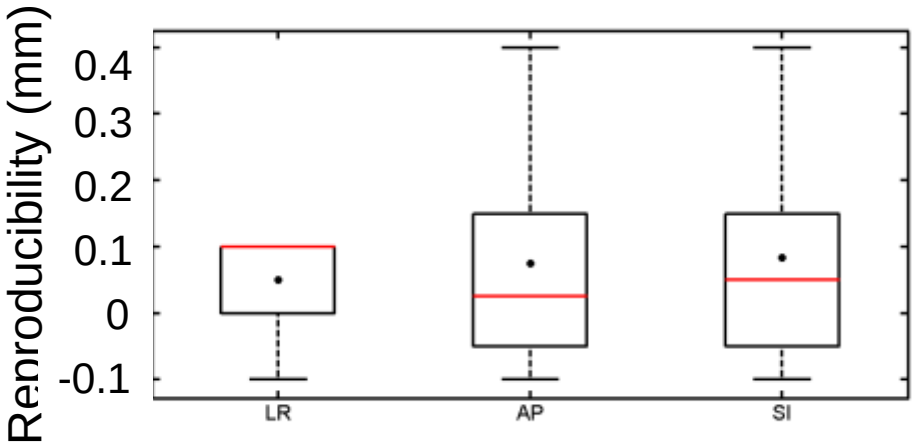


Liver (Breath-hold):
Marker Position Reproducibility in Interquartile Range

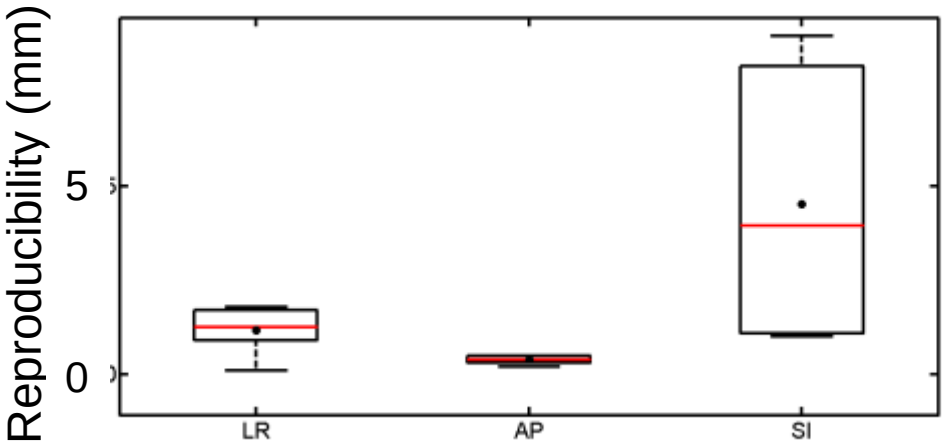
Real Probe: 3D mean error=0.3 mm



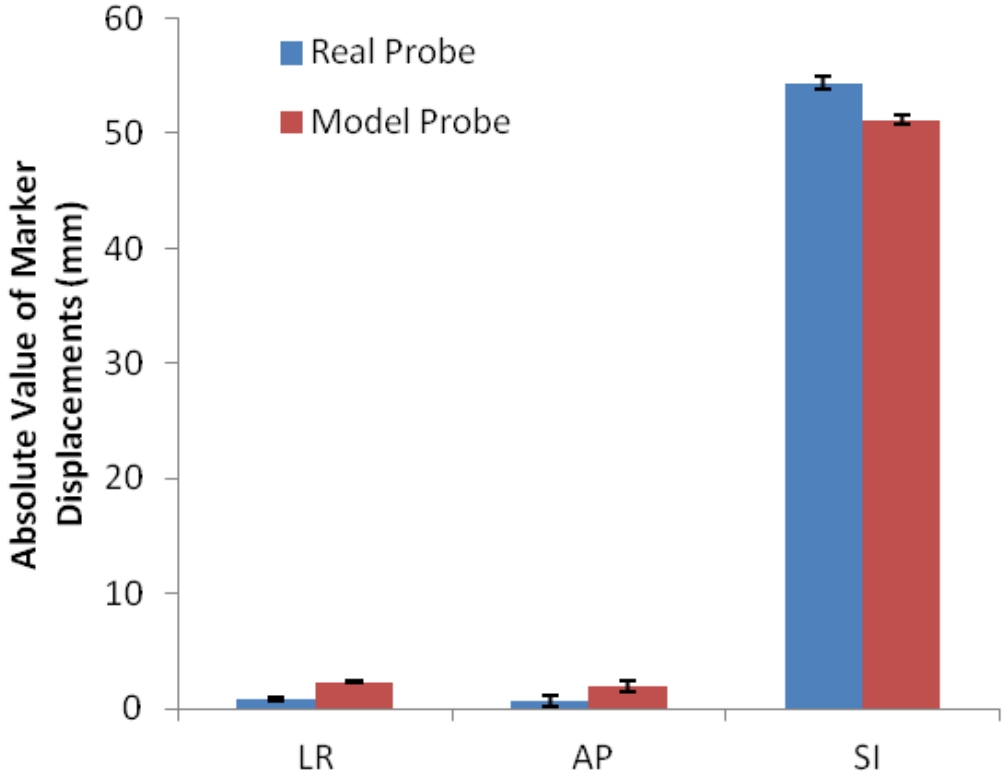
Model Probe: 3D mean error=0.6 mm

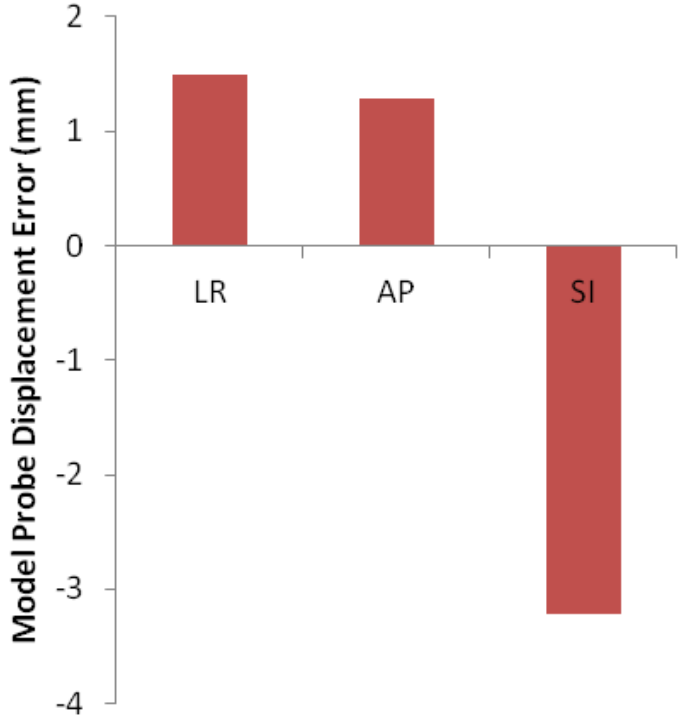


No Probe: 3D mean error = 4.7mm



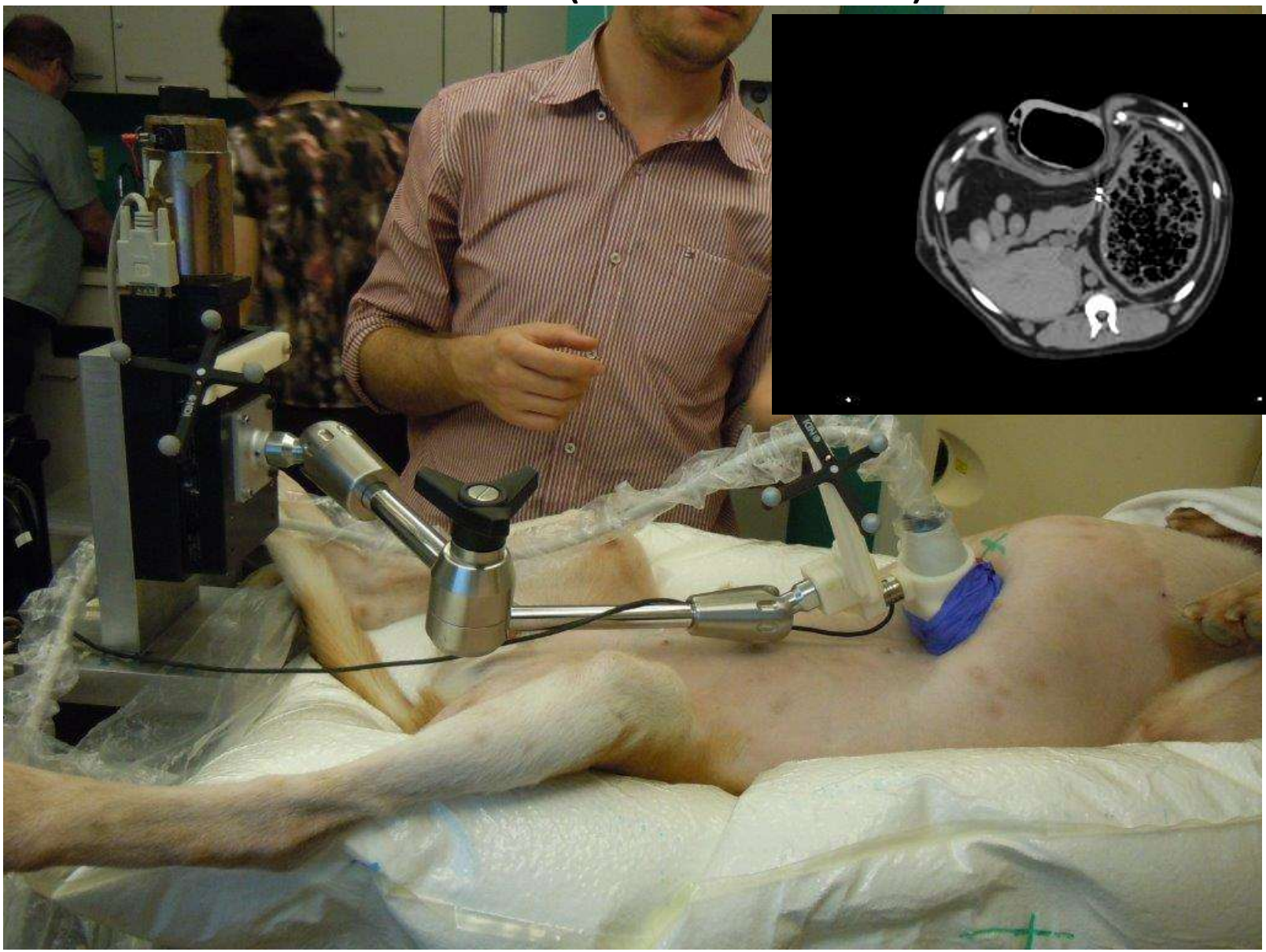
Liver (at Breath-hold): Probe-Induced Marker Displacement





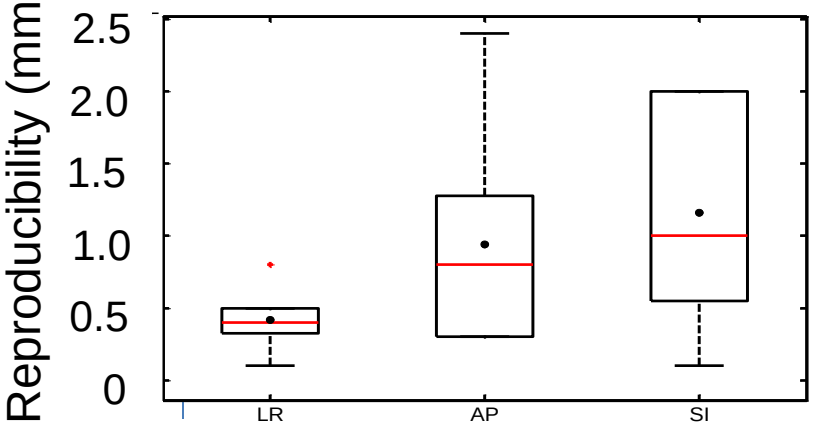
3D mean error
= 4.1 mm

Pancreas (Force = 34.5N)

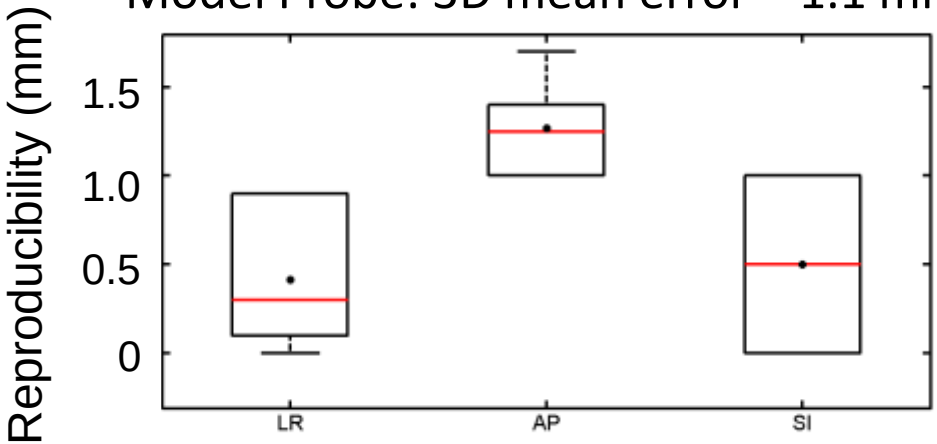


Pancreas (at Breath-hold): Probe-Induced Marker Displacement

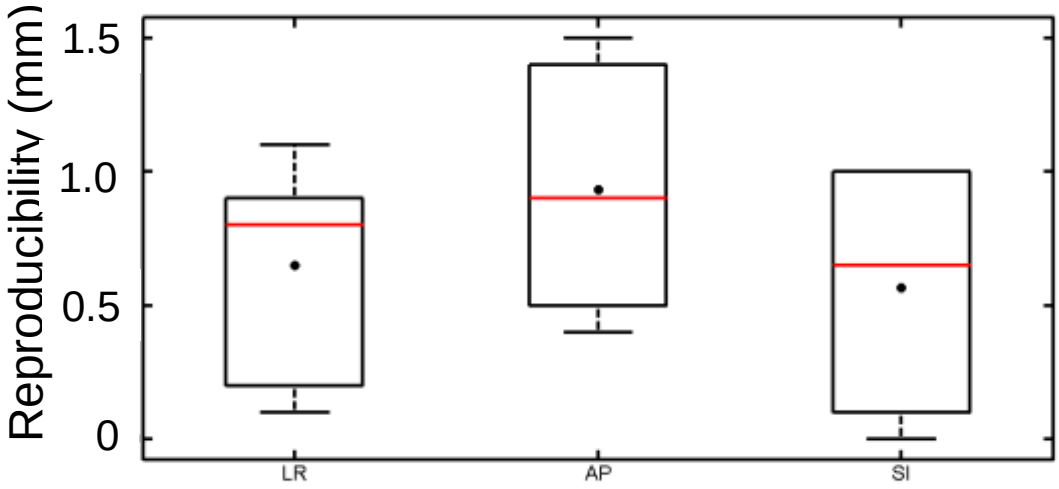
Real Probe: 3D mean error = 1.6 mm



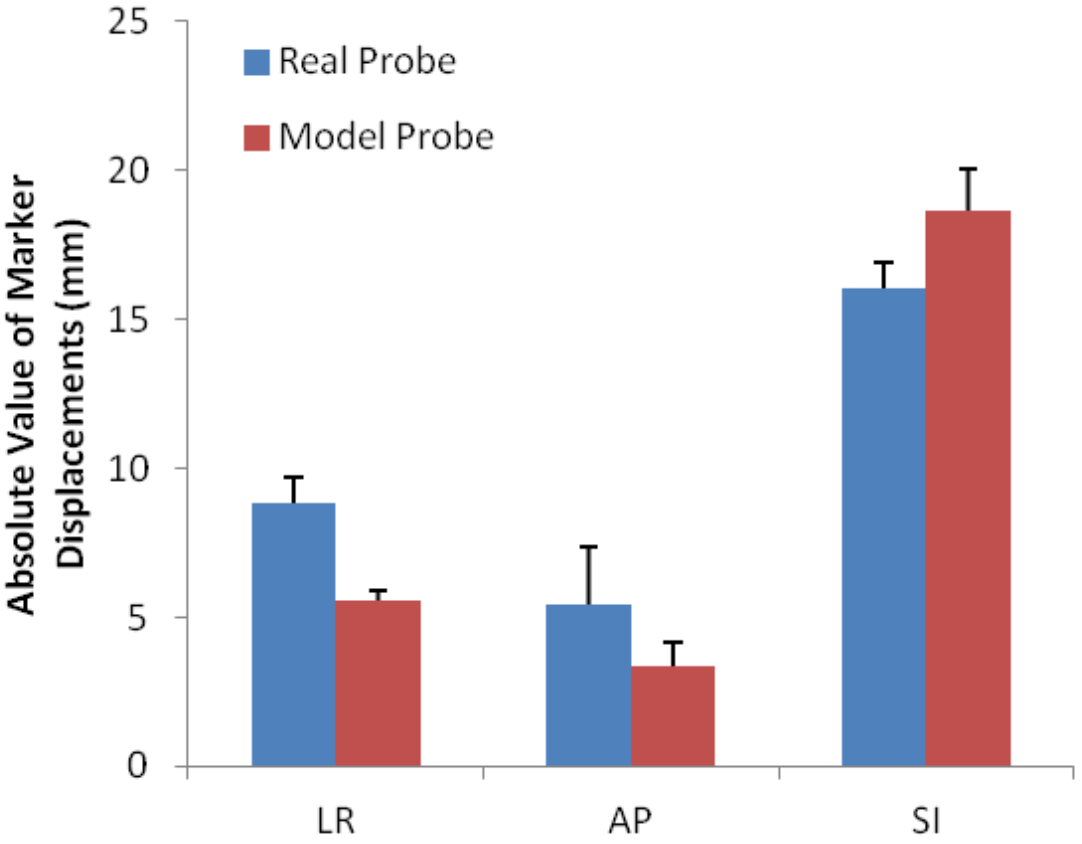
Model Probe: 3D mean error = 1.1 mm

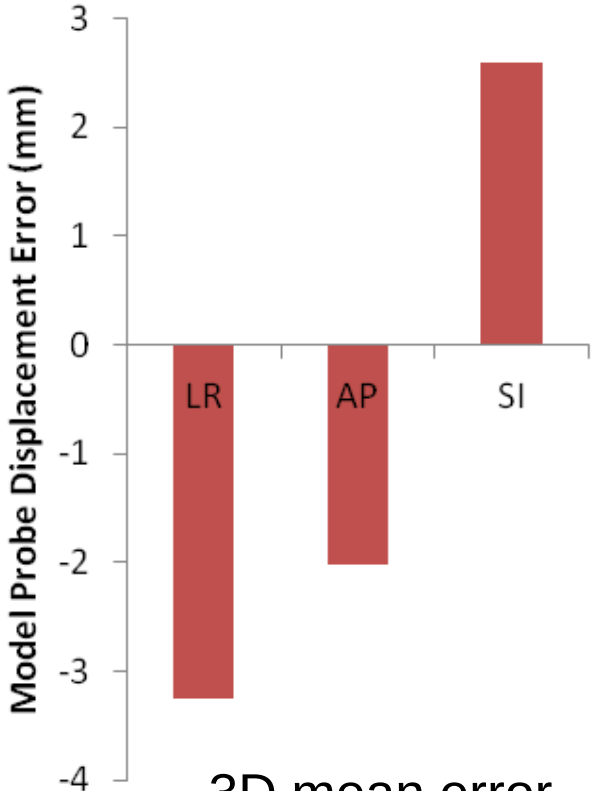


No Probe: 3D mean error = 1.3mm



Pancreas (at Breath-hold): Probe-Induced Marker Displacement





3D mean error = 4mm

Conclusions

- CT of implanted markers provides a direct validation of reproducible deformation due to probe
- Choice of phantom is important to study reproducibility for ultrasound guidance (Force: 1 to 40N)
- Prostate deformation is reproducible to within 1 mm
- Results for liver and pancreas can be improved
  - Experience; no visual feedback; un-optimized system

- More in vivo (dog) IGRT studies to:
  - refine the system
  - Inter-fraction study on a CBCT machine

Robot System Requirements

- Repeatable mounting of US probe and model probe
- Record probe position and contact force (in simulation)
- Enable operator to reproduce position and force when switching between US and model probes
- Hold model probe in place during CT or CBCT acquisition
- Enable less-skilled user to reproduce deformation (e.g., similar position/force) during inter-fraction treatment
- Hold US probe in place during treatment
- Sufficient workspace to scan abdominal organs: prostate, liver, kidney, pancreas *(as we discover!!!)*

Dose Volume Histograms