

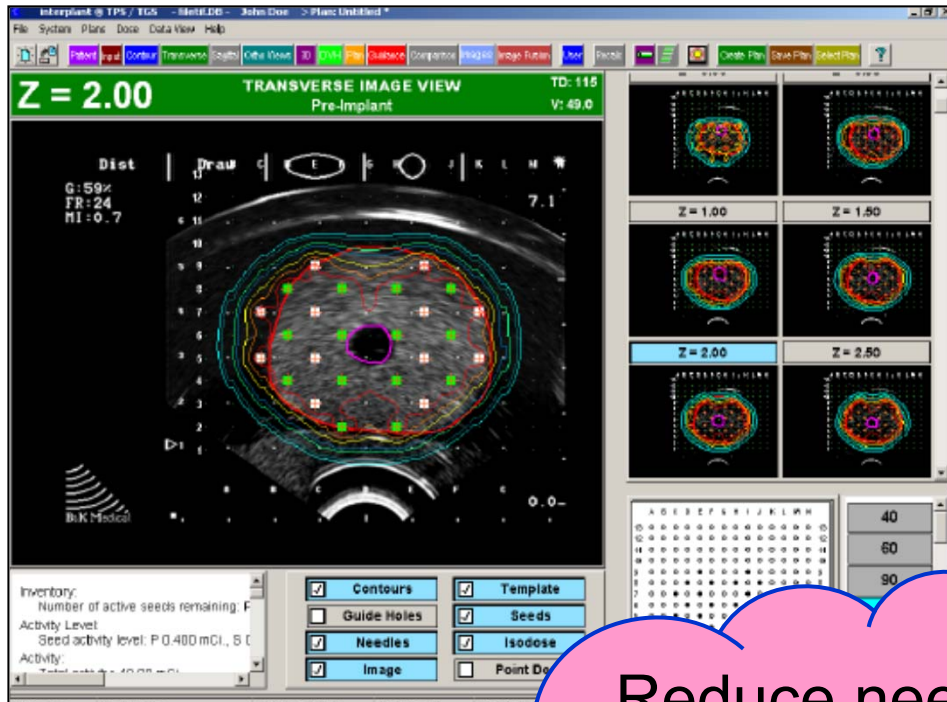
# Robot-assisted Prostate Cancer Interventions in the Perk Lab

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**Professor and Cancer Care Ontario Research Chair  
Queen's University, Canada**

<http://perk.cs.queensu.ca>

# TRUS-guided brachytherapy: Plan v.s. actual implant



Reduce needle  
adjustments &  
needle time in  
prostate

Implants *NEVER*

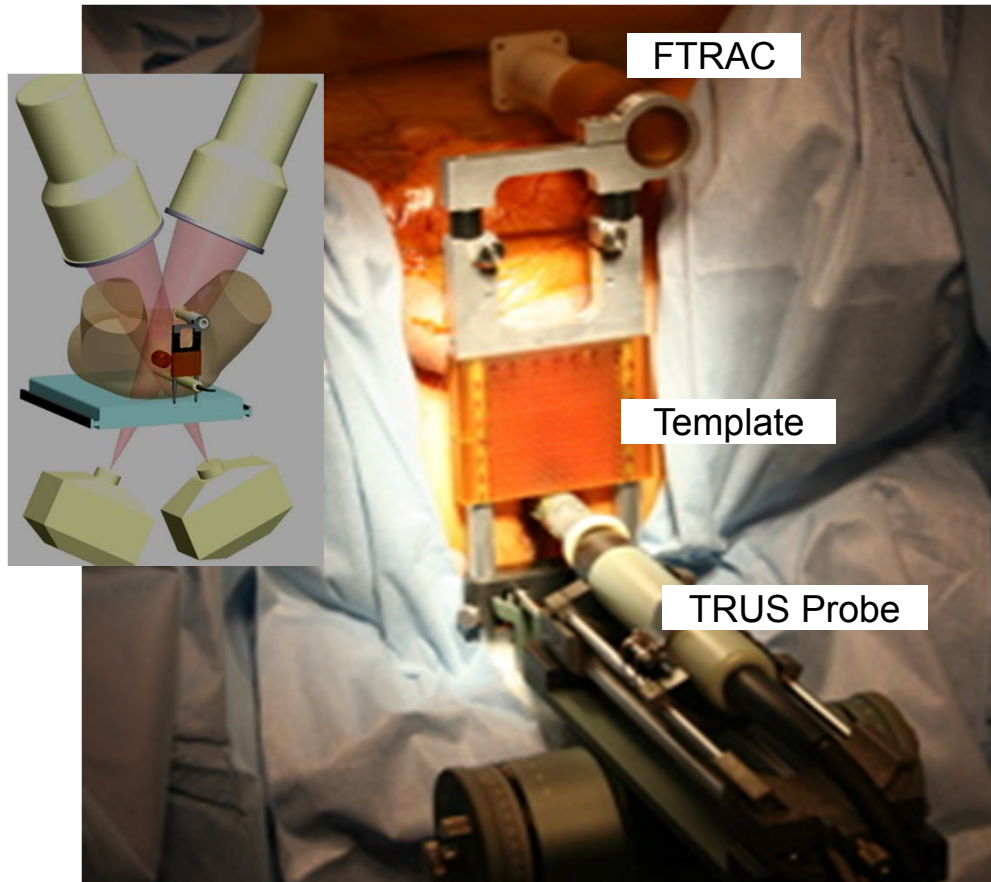
- System mis
- Organ mot
- Needle be
- Edema

planned

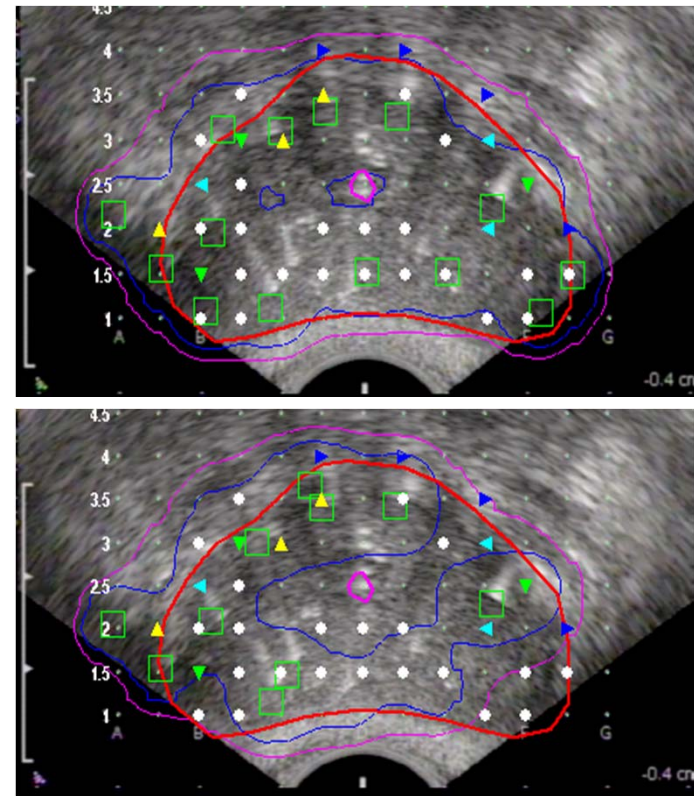


# Intra-operative seed migration

## Intensity-based Registration of TRUS & fluoroscopy (iRUF)



- Colds spots on exit dosimetry
- Average 4 extra seeds (max 9)
- Edema: ~5.0mm (12mm max)



Fallavollita *et al.* Med Phys 2010  
Dehghan *et al.* MICCAI 2011

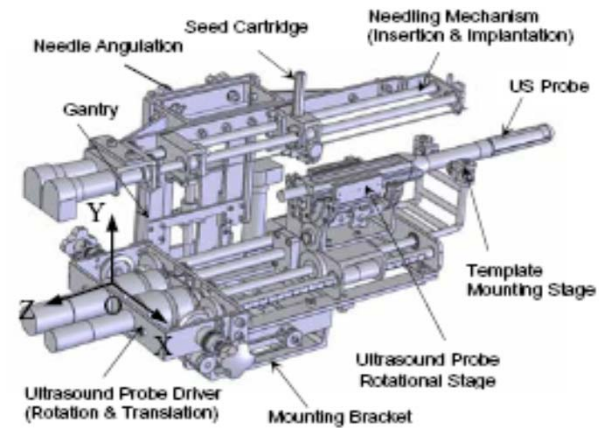
Jain *et al.* MedIA 2011  
Song *et al.* Brachytherapy 2011



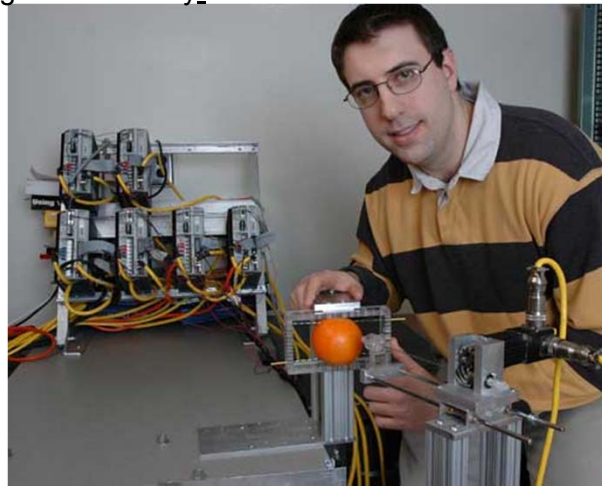
# It's a lot of DOF



Sin *et al.* Nanyang Technological University



Yu & Podder *et al.* MICCAI 2006

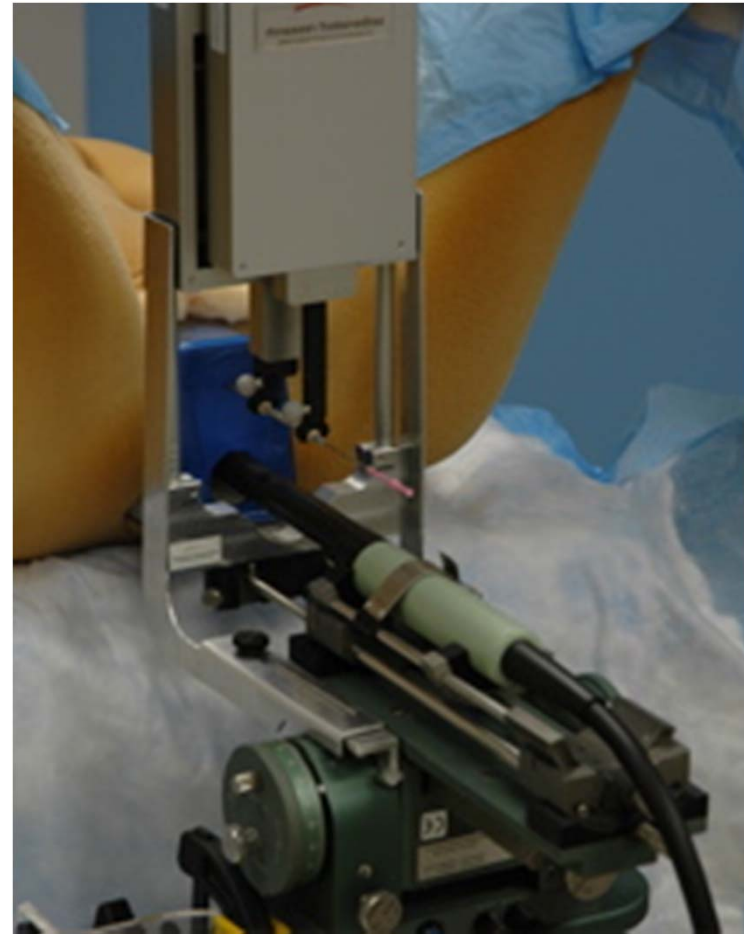
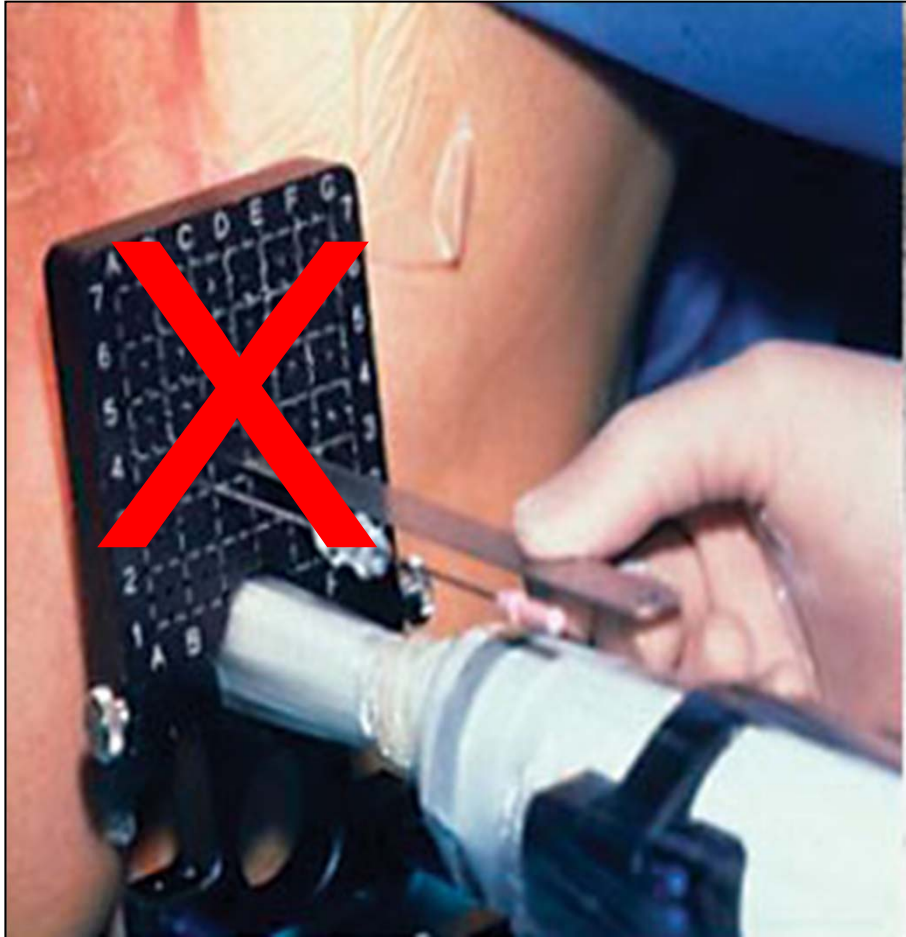


Meltsner *et al* Phys. Med. Biol. 52 6027-6037, 2007



# Replace template w/ robot

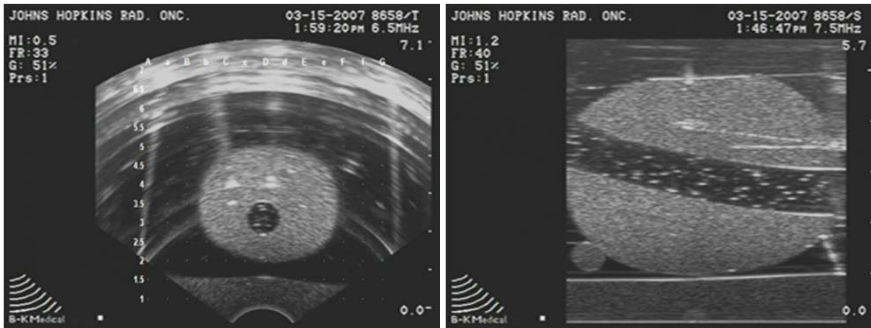
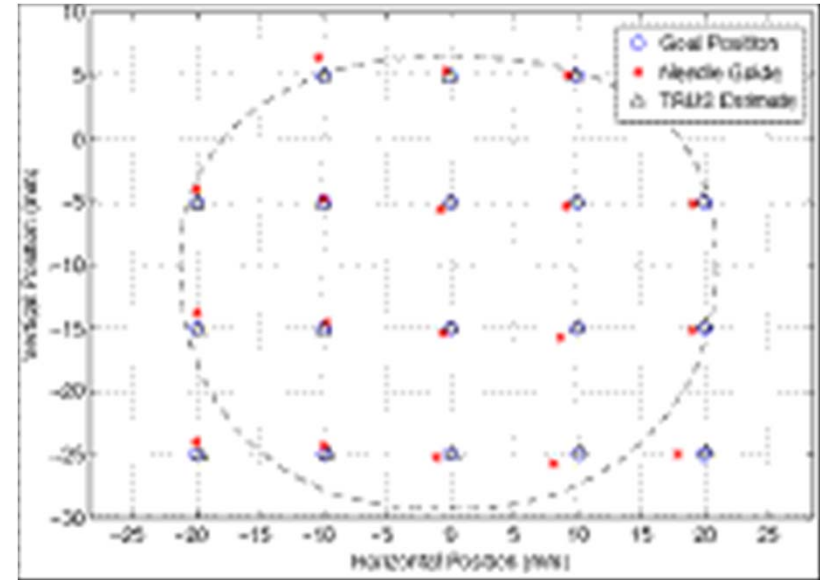
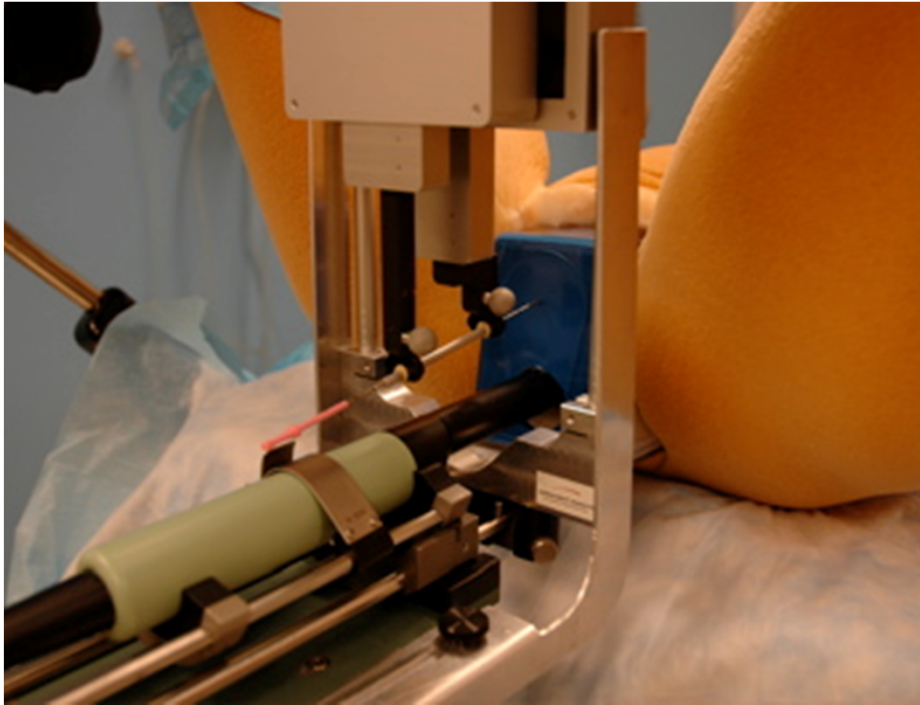
Must not alter clinical setup & workflow



Fichtinger et al. MedIA, 2008



# Accurate needle placement w/ TRUS



- Avg. 1.04 mm (STD=0.50 mm)
- Relative to TRUS
- 18 samples over prostate

Fichtinger *et al.* *MedIA*, 2008

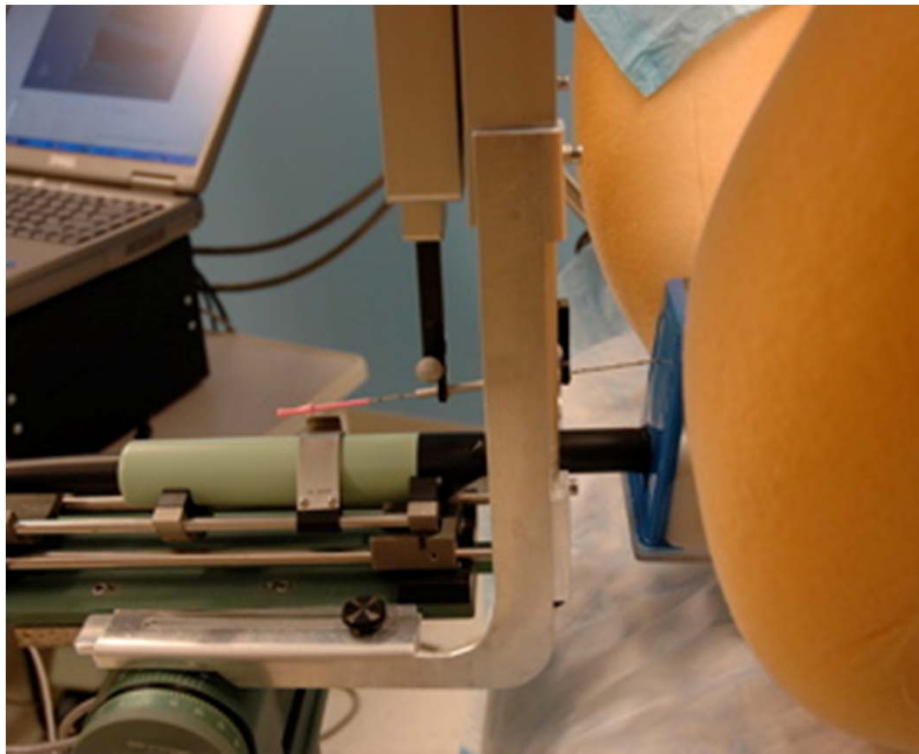


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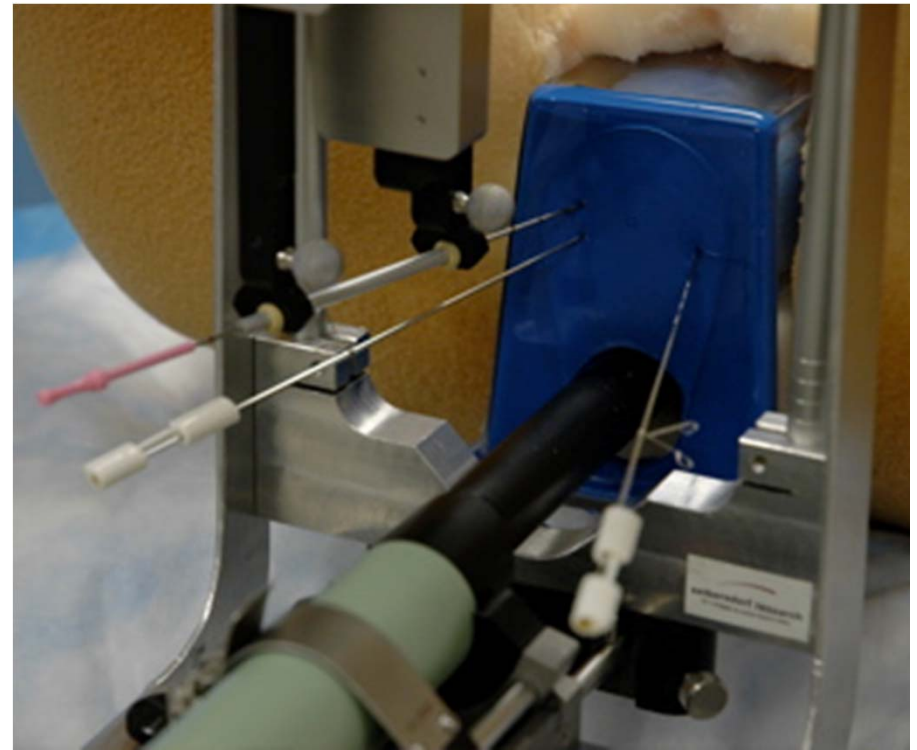
# Additional benefits of robot

**Pubic arch interference reduced  
by slanted needles**



Prostates >55cc, about  $\frac{1}{3}$  of candidates

**No apparent interference with  
stabilization needles**



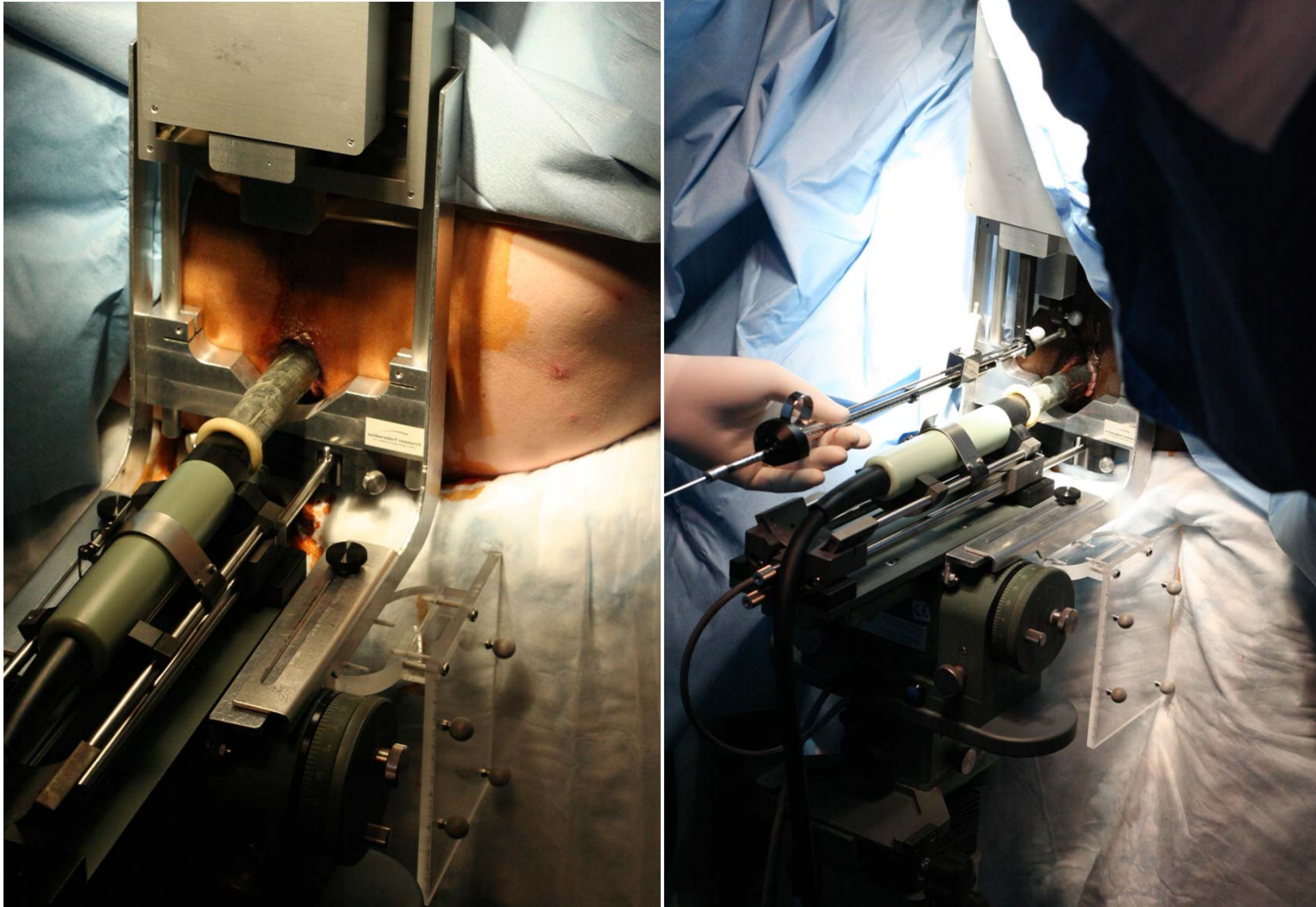
*Fichtinger et al. MedIA, 2008*



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# Phase-I clinical trial



Song et al. Brachytherapy 2011



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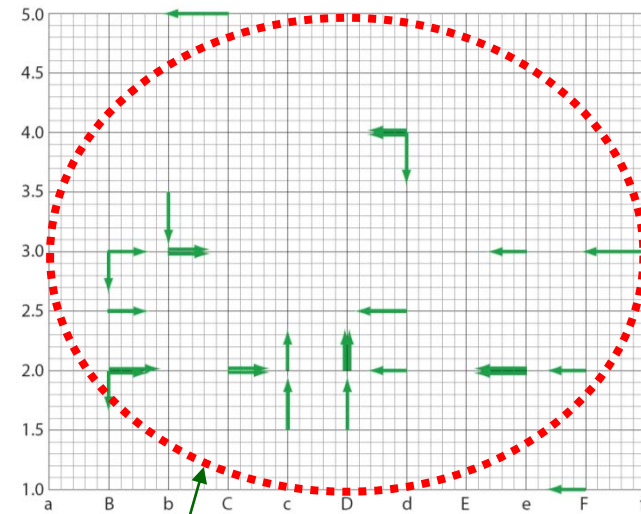


# Surprising results

Summary table

	#1	#2	#3	#4	#5	Total
Prostate volume (cc)	31.1	19.2	28.4	48.2	42.9	
Total needles inserted	35	33	44	31	41	<b>184</b>
Total planned needles	35	31	41	30	38	<b>175</b>
Inserted with robot	30	33	44	31	41	<b>179</b>
Inserted manually	5	0	0	0	0	<b>5</b>
Adjustments to calibration (home)	1	3	2	1	1	<b>8</b>
Adjustments to correct needle pos.	4	12	12	12	14	<b>54</b>
> 2 mm in X	0	5	2	7	6	<b>20</b>
> 2 mm in Y	3	2	3	2	1	<b>11</b>
<b>&gt; 4 mm in X</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>1</b>	<b>0</b>	<b>1</b>
<b>&gt; 4 mm in Y</b>	<b>1</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>1</b>
Adjustments to modify plan	0	0	9	6	8	<b>23</b>
> 2 mm in X	0	0	5	3	5	<b>13</b>
> 2 mm in Y	0	0	4	1	2	<b>7</b>
> 4 mm in X	0	0	3	0	2	<b>5</b>
> 4 mm in Y	0	0	1	0	2	<b>3</b>
Implant time	1:21	0:53	1:04	0:51	1:05	

XY adjustments  $\geq 3$  mm

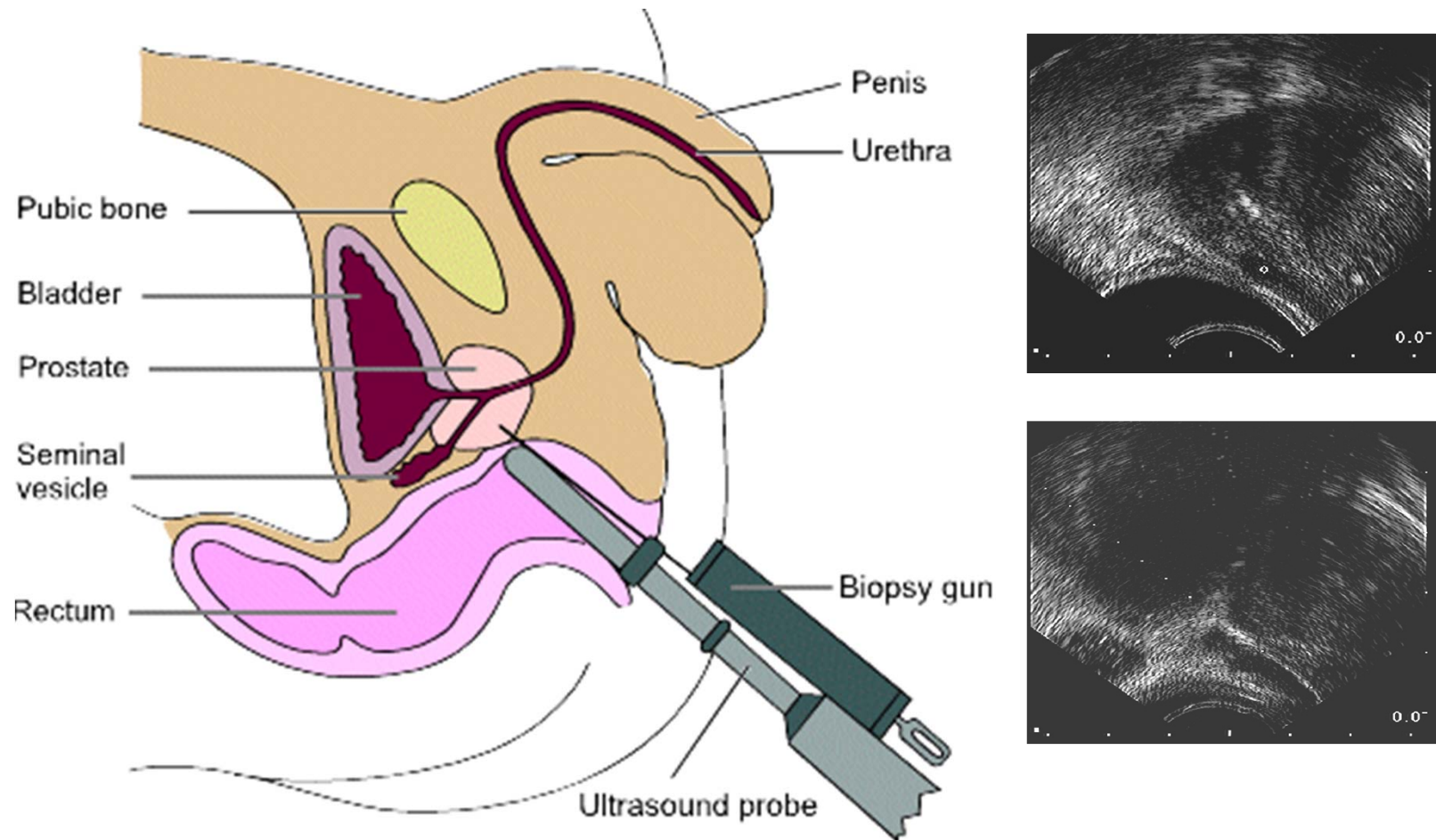


Prostate

Song et al. Brachytherapy 2011



# Standard of care: TRUS biopsy



**Cancers as large as a sugar cube may be missed...**

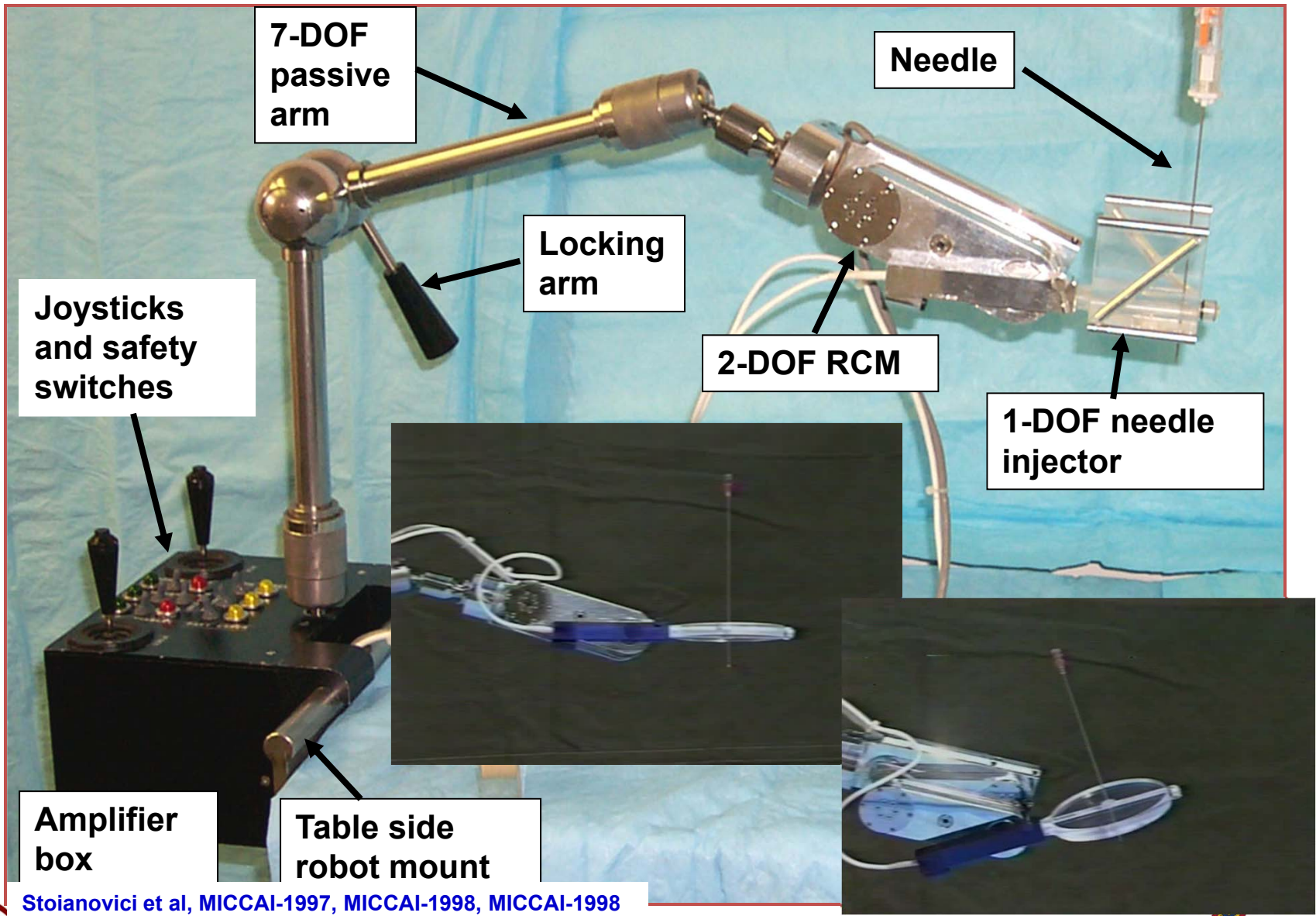


# CT-Guided Prostate Biopsy



Fichtinger et al. Acad Rad, 2002

# Example: 3DOF RCM-PAKY



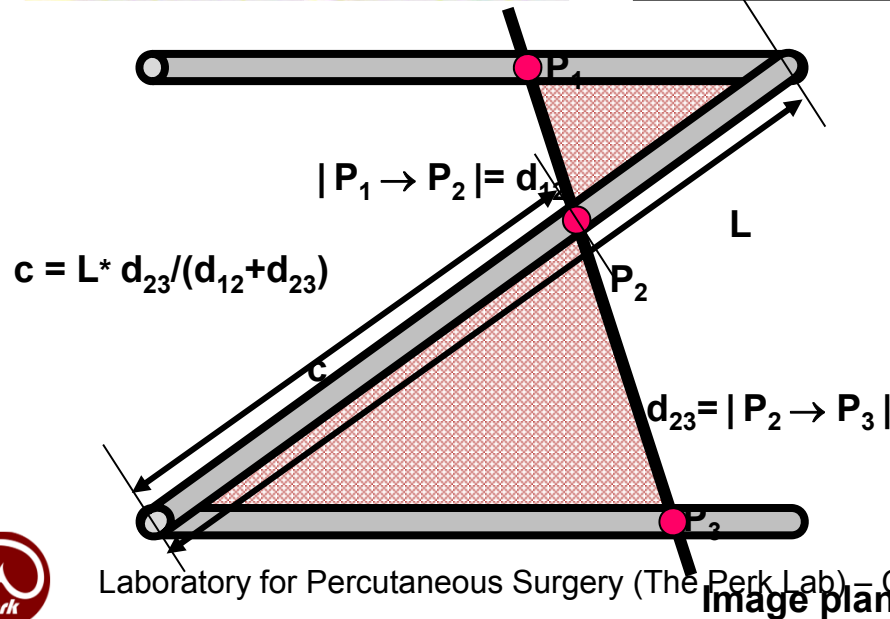
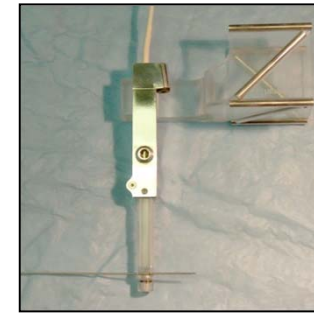
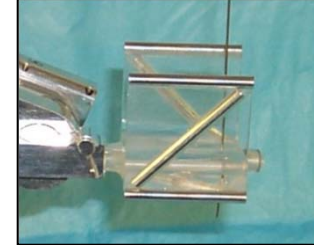
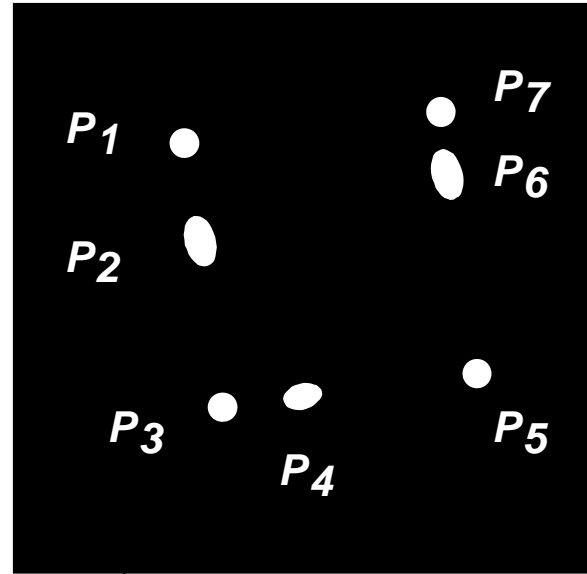
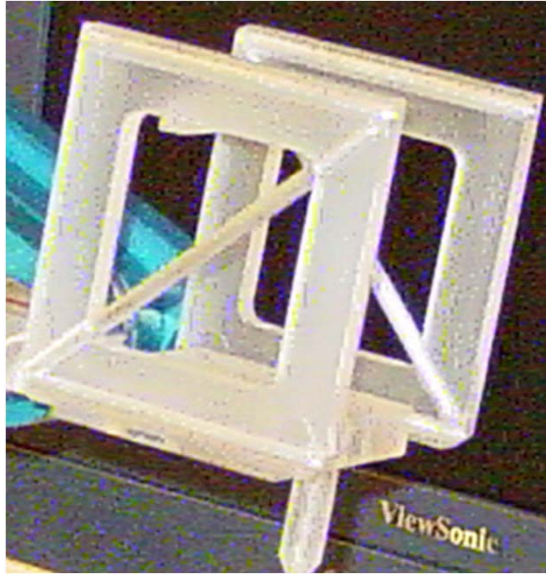
Stoianovici et al, MICCAI-1997, MICCAI-1998, MICCAI-1998



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# Single-slice Registration to CT

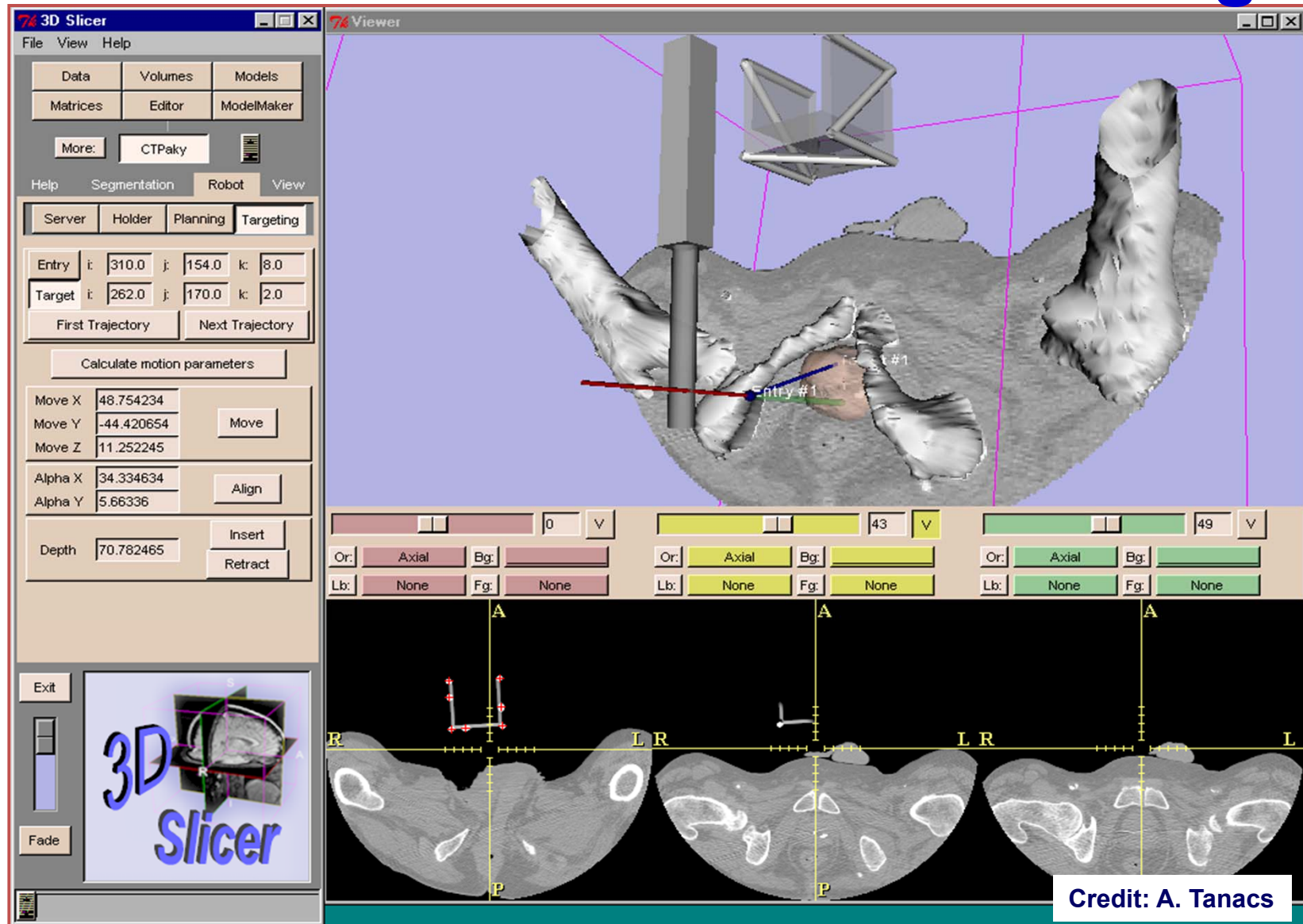


**Closed form: fast and computationally robust**

- Susil et al. MICCAI 1999
- Masamune et al. JCAS 2001
- Lee et al. J. MedPhys 2002

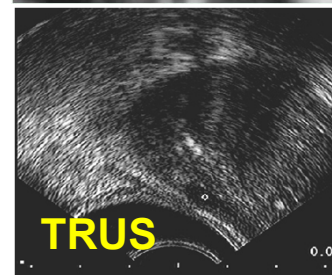
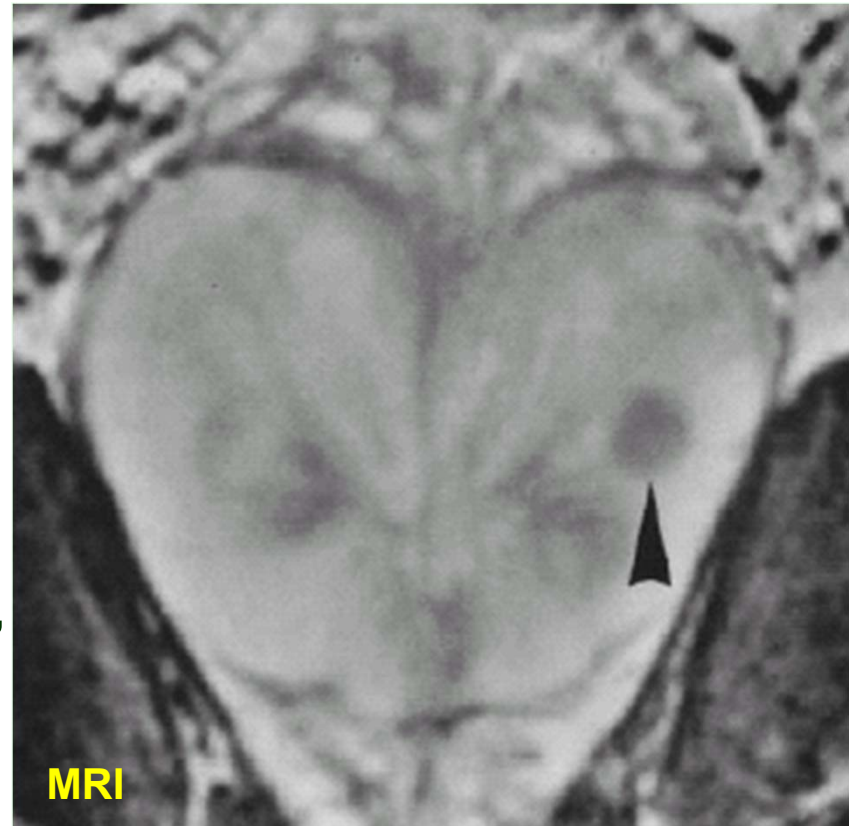


# Slicer-based Treatment Planning



# Why MRI?

- No ionizing radiation
- High soft-tissue contrast
- High resolution imaging
- True 3D volumetric imaging
- Multi-parametric imaging
  - T1/T2 weighting, Functional, Diffusion, Flow, Temperature, Oxygenation, ...
- Can provide “real-time” imaging capabilities



# Extreme environment



**PLAY MOVIE**

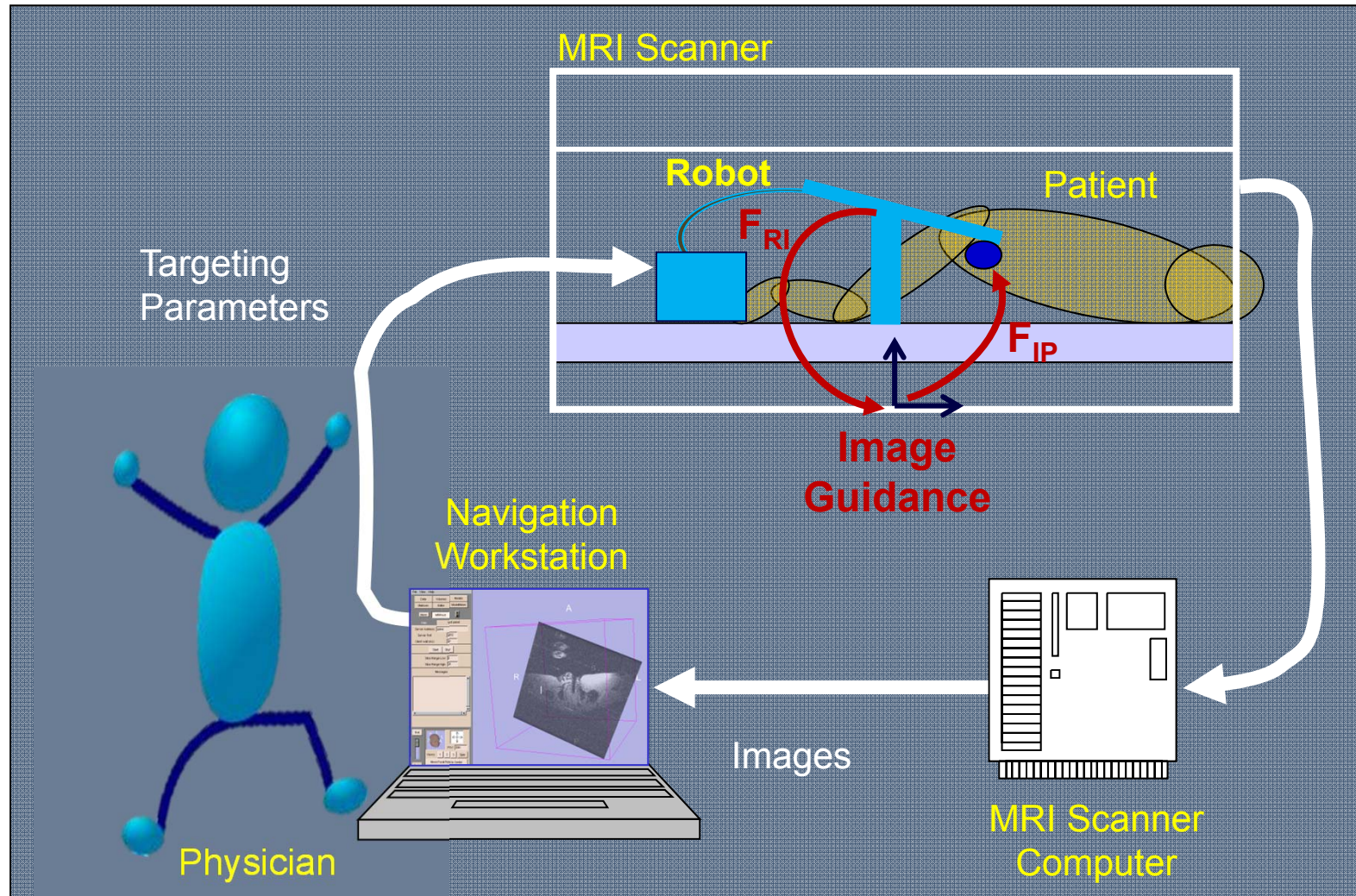


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# Point & click surgery paradigm



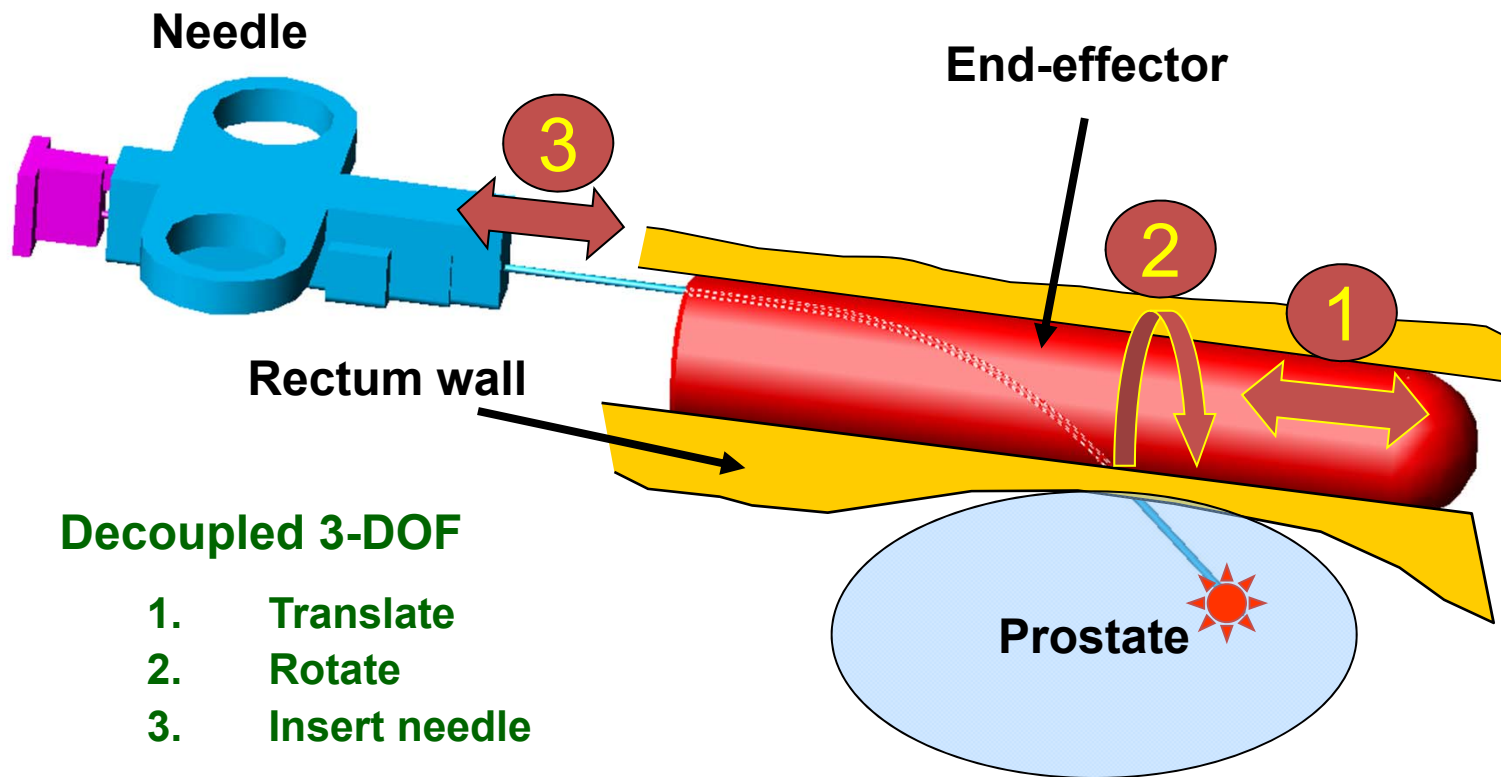
Fichtinger et al. MICCAI, 2002



# Kinematic design

**PROBLEM:** Small tubular space in rectum for end-effector

**APPROACH:** Cylindrical coordinate mapping of prostate → three independent decoupled motions are necessary and sufficient



Fichtinger *et al.* MICCAI, 2002



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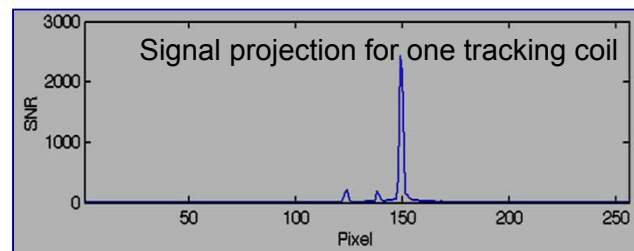
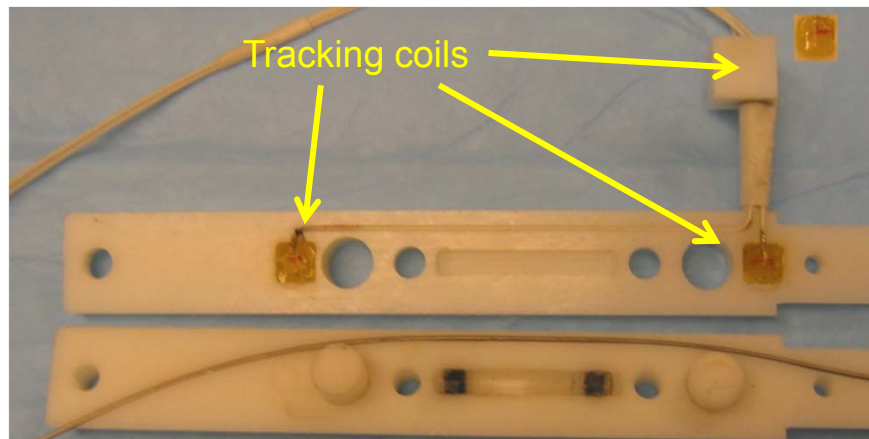


# IG: Robot to MRI registration

**PROBLEM:** Localize the robot in MRI space

**PRIOR ART:** All robots use passive markers – slow update rate

**NEW APPROACH:** Three active imaging antennas in end-effector



- Active antennas localized in MRI space (Dumoulin 1994, Derbyshire 1999)
- Imaging coil around Gad capsule, fast dodecahedral readouts
- 3 markers known in robot and image space allow for coordinate system registration
- **PROS:**
  - High accuracy (0.2 mm, 0.3 deg)
  - High update rate (20 Hz)
- **CONS**
  - Uses up channels, vendor-dependent (gradient dewarping)

Susil *et al.* Radiology, 2003



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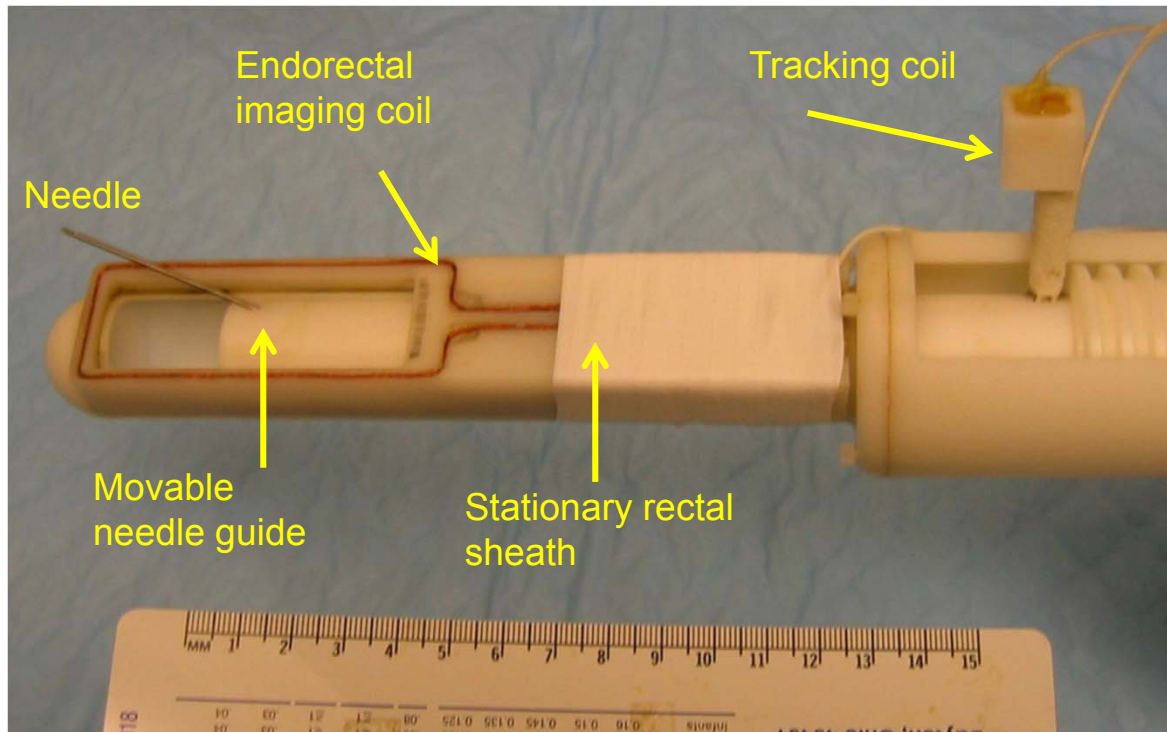
# IG: Anatomical imaging

**PROBLEM:** Signal fading near prostate if only surface coils are used

**NEW APPROACH:** Incorporate endorectal imaging antenna coil in end-effector

**PRIOR ART:** Inflatable endorectal imaging coils are common...

**SALIENT FEATURE:** Sheath holds the antenna; decouples it from moving robot parts; decouples target anatomy from moving parts



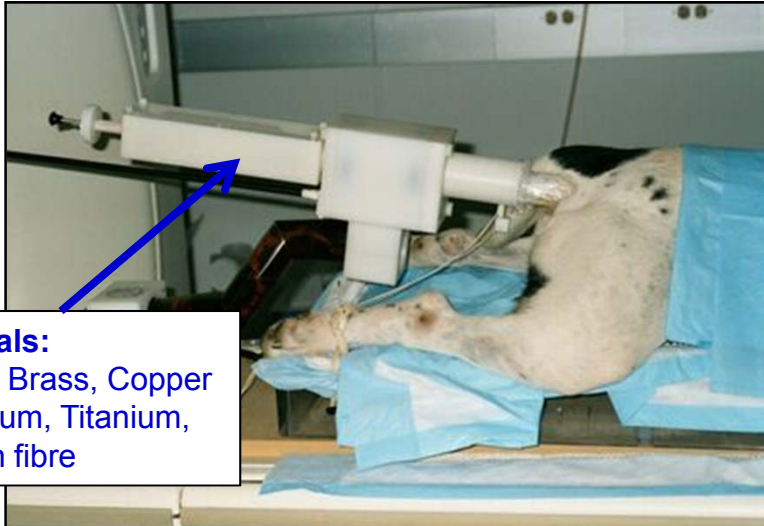
Susil *et al.* Radiology, 2003



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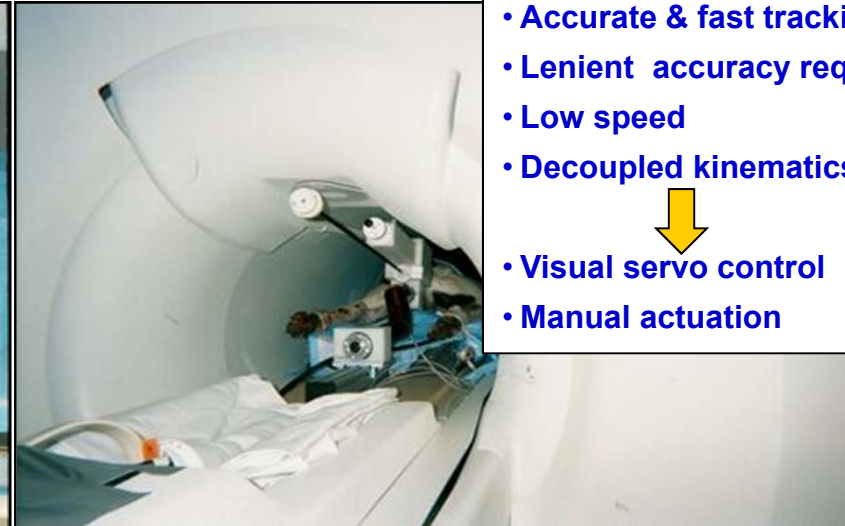


# Actuation, power and control

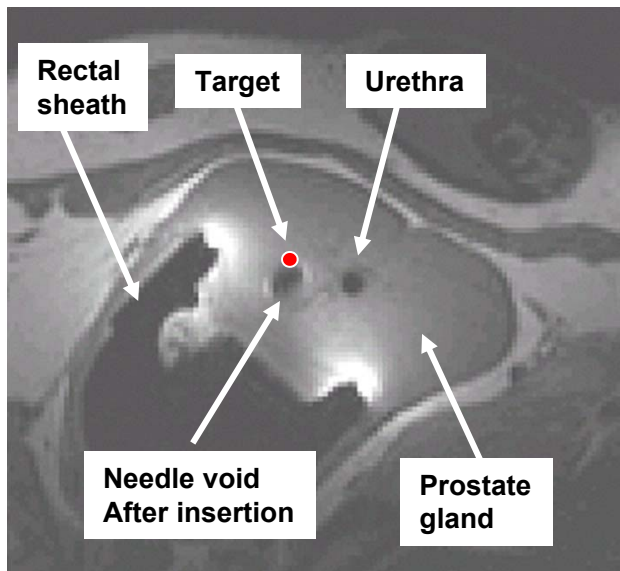


## Materials:

Acetol, Brass, Copper  
Aluminum, Titanium,  
Carbon fibre



- Accurate & fast tracking
  - Lenient accuracy req.
  - Low speed
  - Decoupled kinematics
- ↓
- Visual servo control
  - Manual actuation

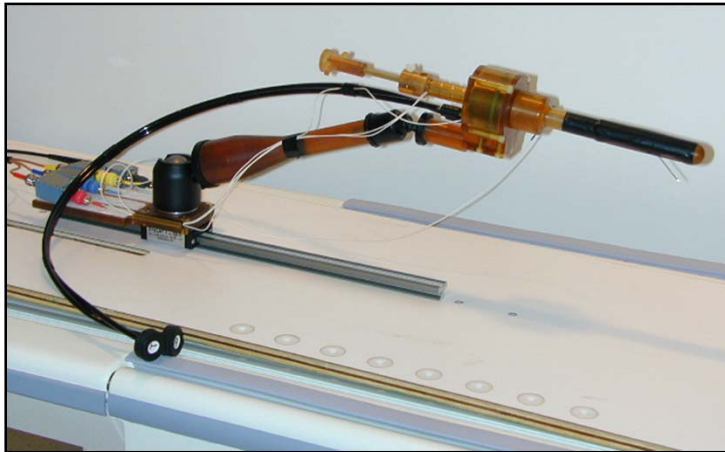


Year 1 from project inception

Susil *et al.* Radiology, 2003



# Human grade system



Year 2 from project inception



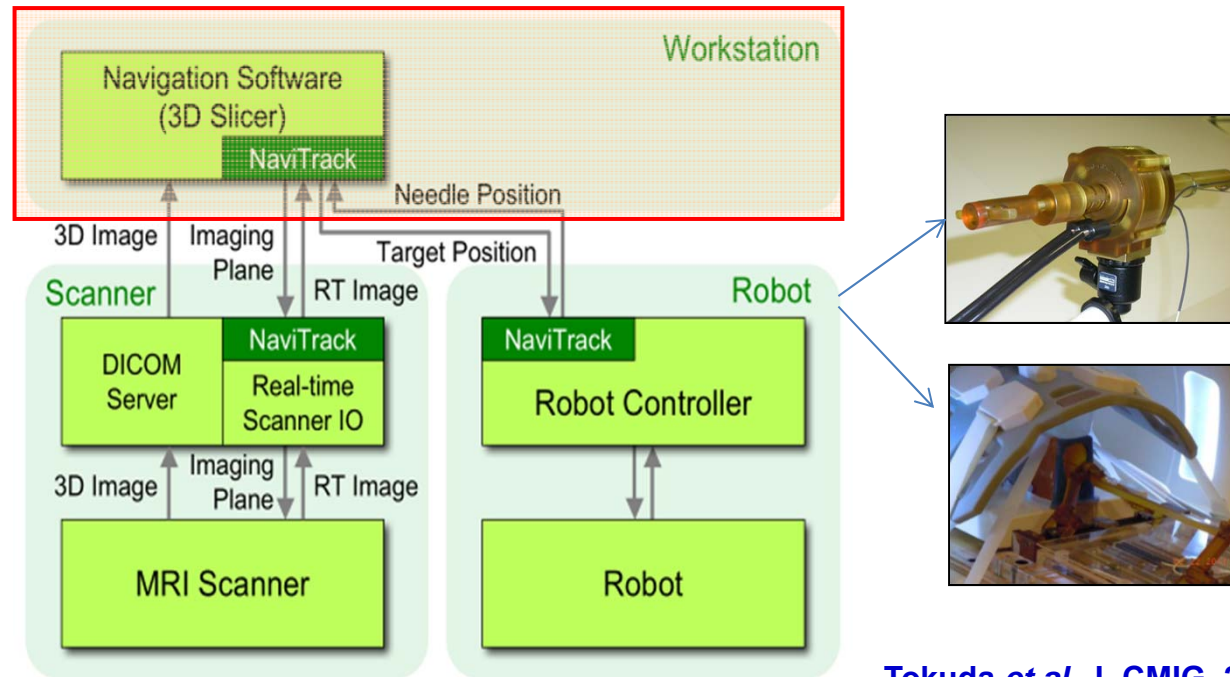
Krieger *et al.* IEEE TMBE, 2005  
[most cited IEEE TBME paper 2005-2010]



# Software system integration

**Objective:** Rapid application prototyping for preclinical and clinical trials

**Approach:** Human Supervisory Control Model instantiated for MRI guided robotic surgery; Build on open source and architecture; take full advantage of 3D Slicer ([www.Slicer.org](http://www.Slicer.org)) and underlying ITK, VTK, etc.



Tokuda *et al.* J. CMIG, 2009  
Lasso *et al.* ImNO, 2011  
Lasso A, PhD Thesis BTU, 2012



# Patient imaging



**Susil et al. J. Urol, 2006**

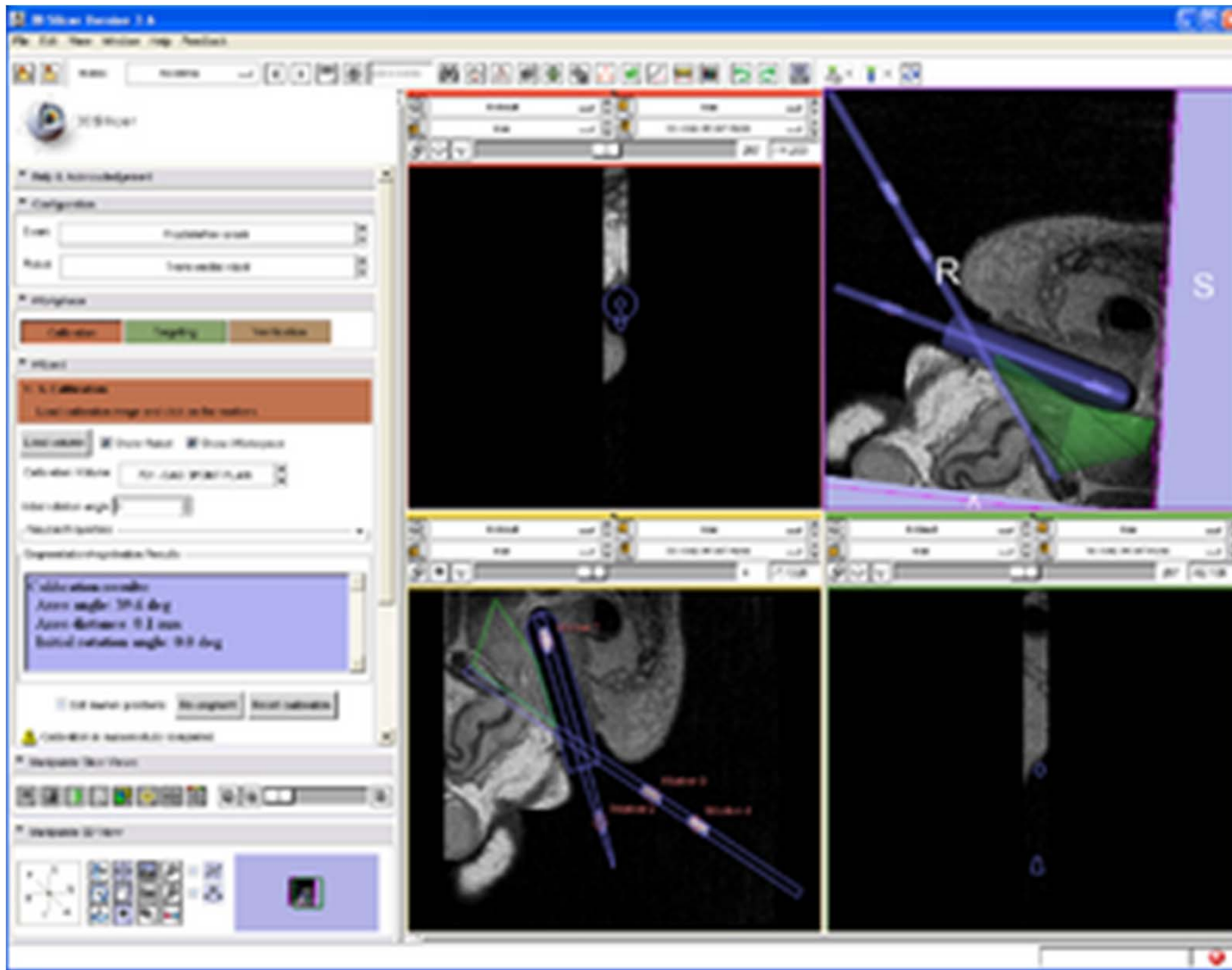


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# Calibration



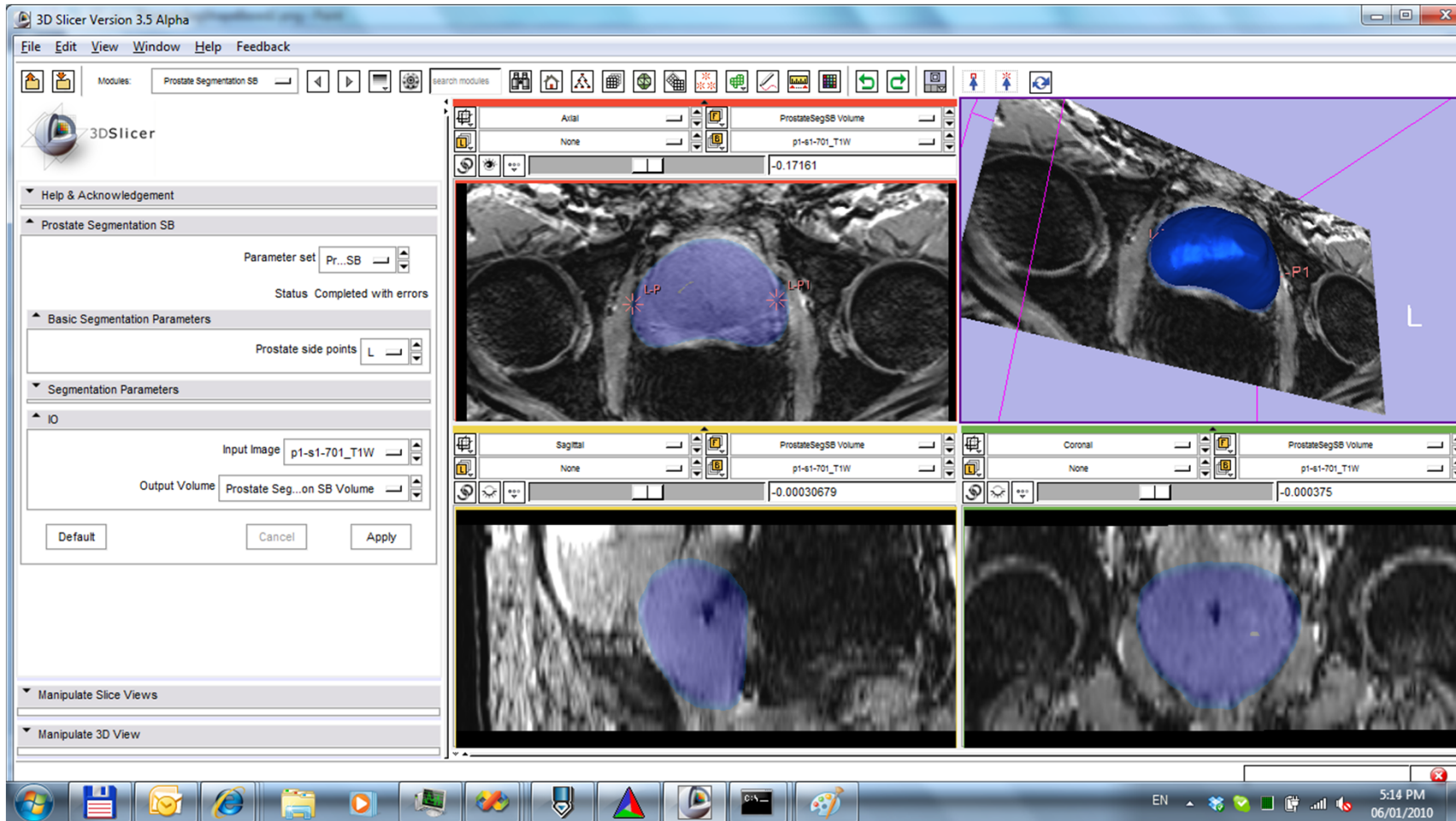
Lasso et al. NAMIC, 2010



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# Modeling



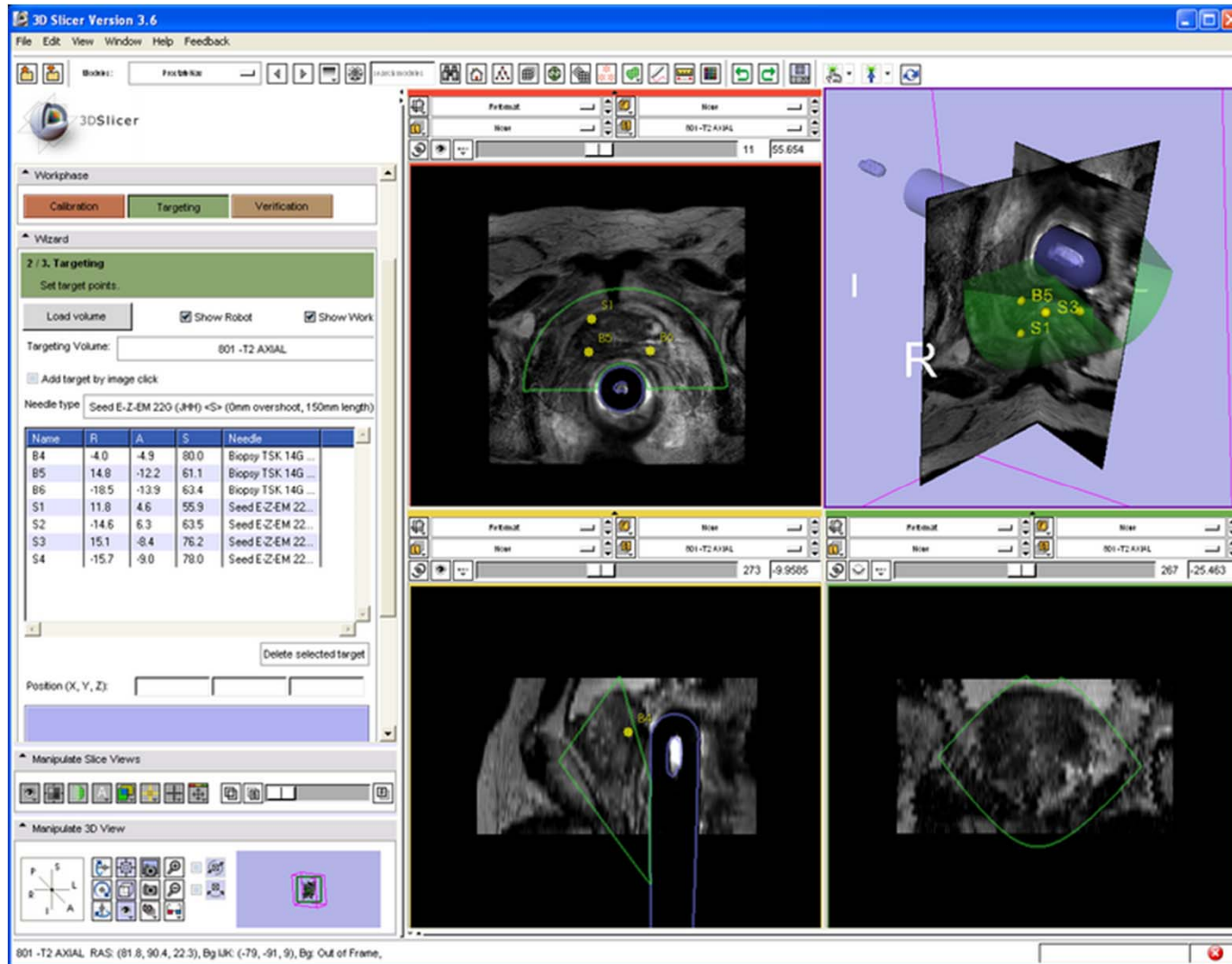
Gao *et al.* IEEE TMI 2010



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# Target planning



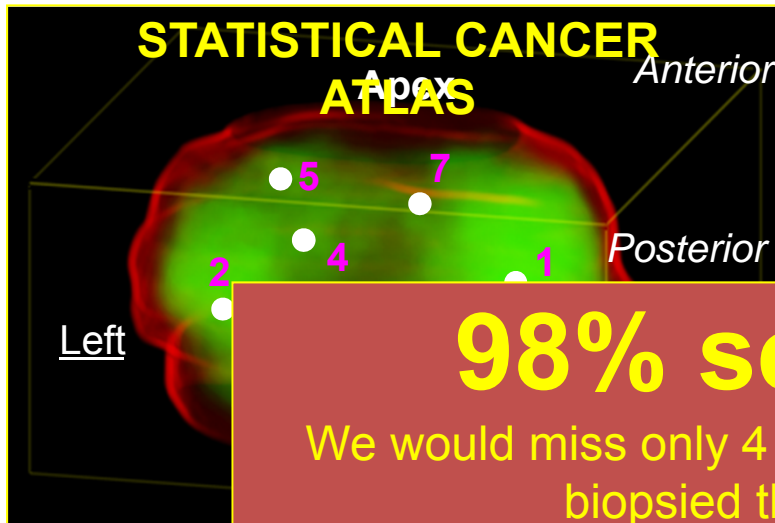
Lasso et al. NAMIC, 2010



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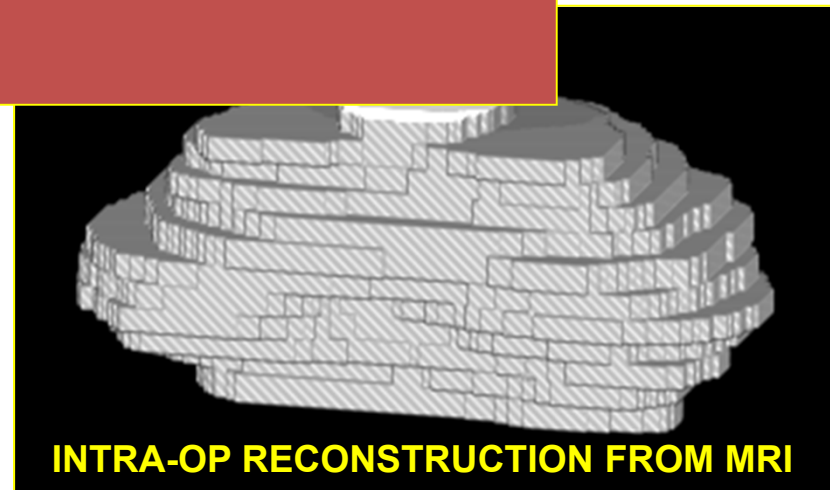
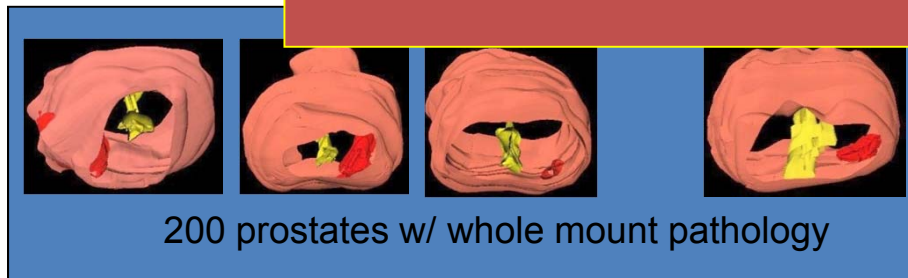


# Population based planning



**98% sensitivity**

We would miss only 4 cancers out of the 200 if we biopsied those men today



Shen *et al.* *MedIA*, 2004  
Zhan *et al.* *IEEE TMI*, 2007  
Zou *et al.* *MedIA*, 2009



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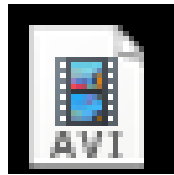
# Execution



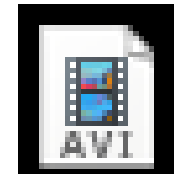
**Susil et al. J. Urol, 2006**



# Real-time monitoring



Good-Injection.avi



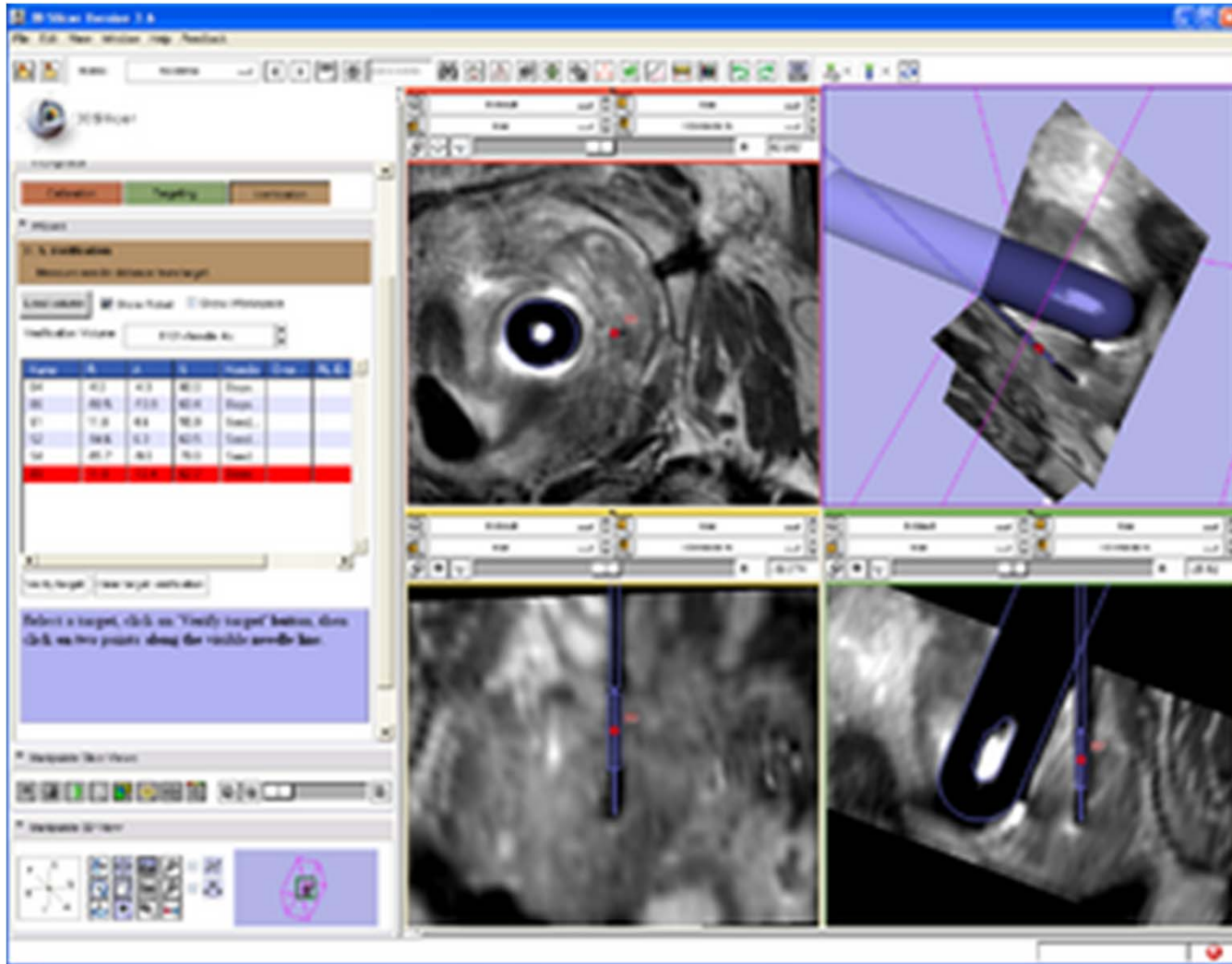
Bad-Injection.avi

- Transrectal robotic needle placement
  - Monitoring at 10fps

**Chowing *et al.* Prostate, 2006**



# Verification



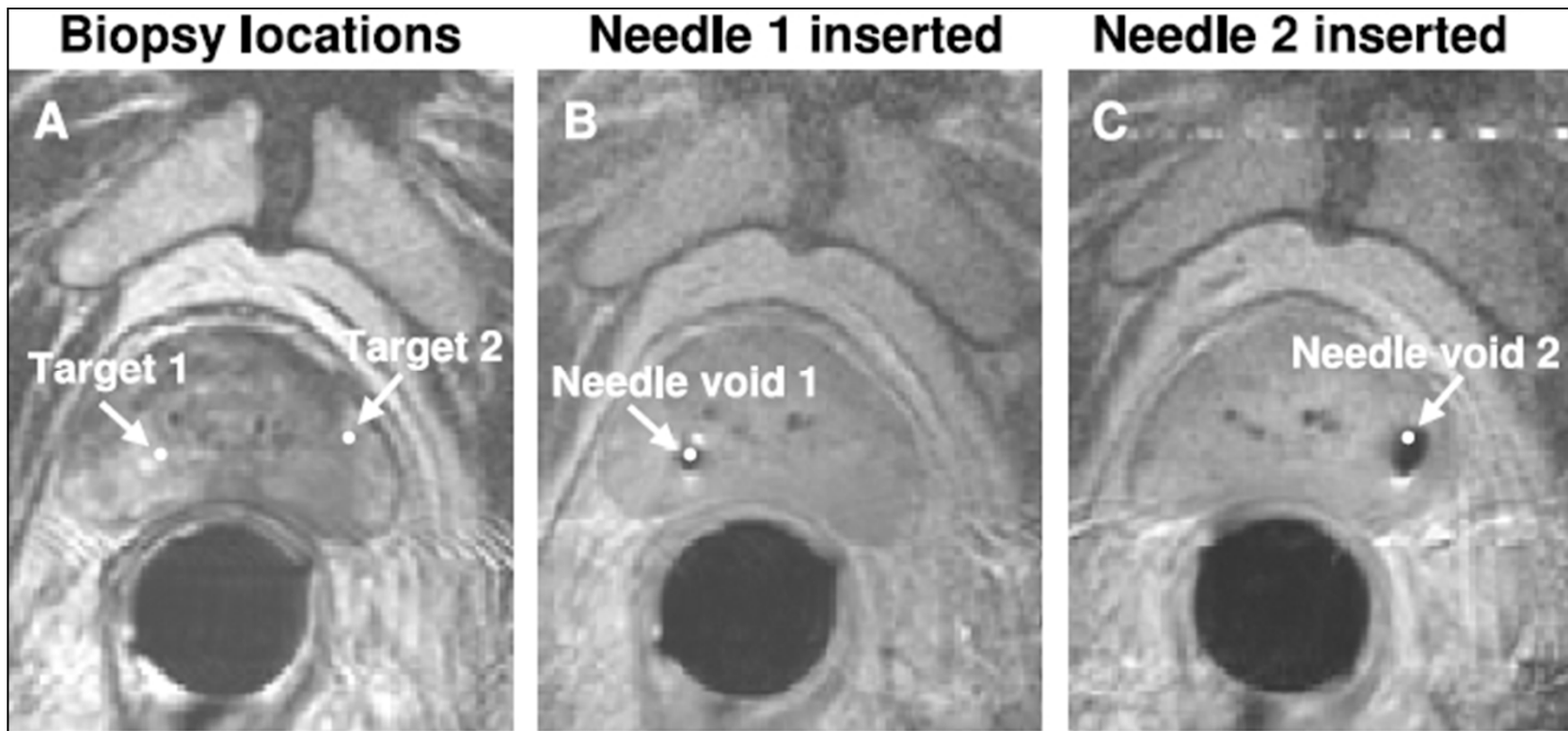
Lasso et al. NAMIC, 2010



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# Verification (close-up)



Susil *et al.* J. Urol, 2006

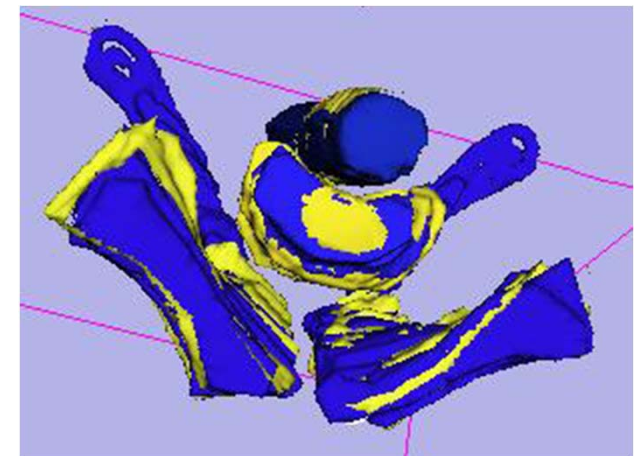
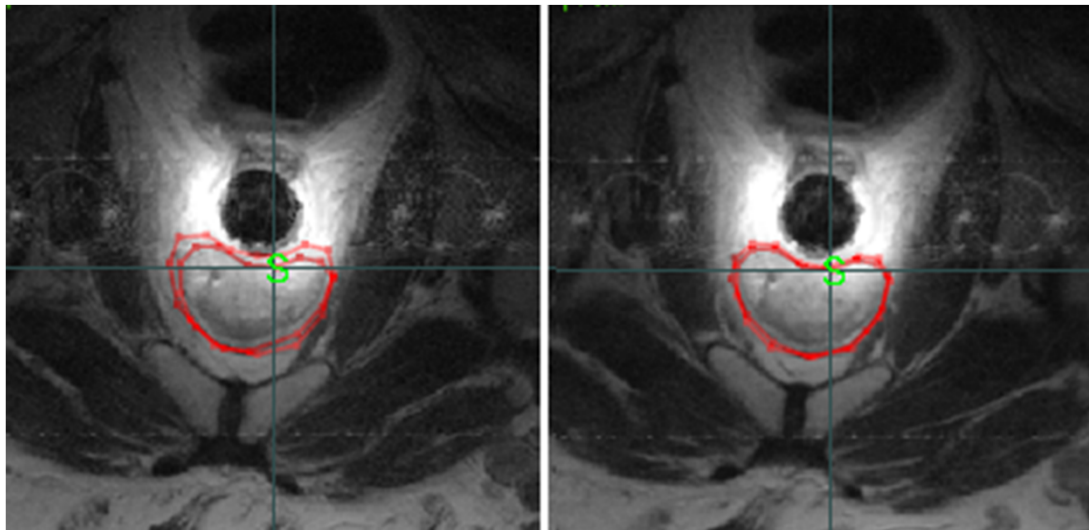
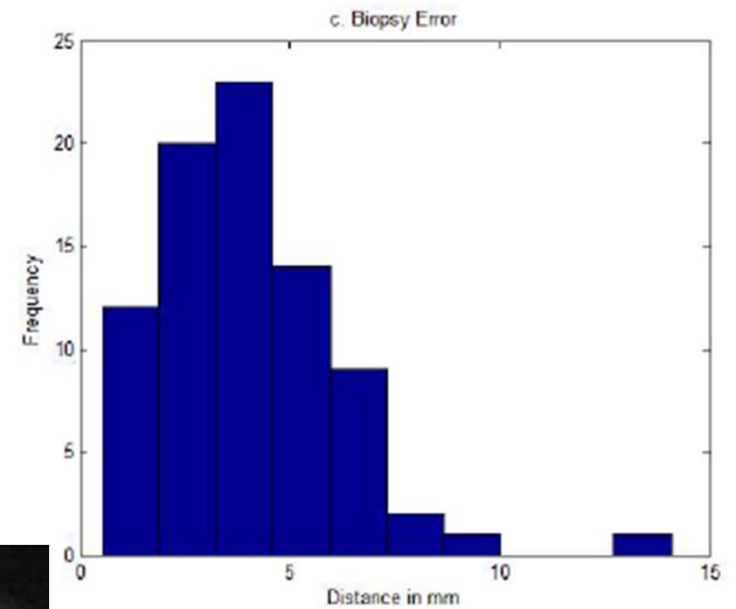
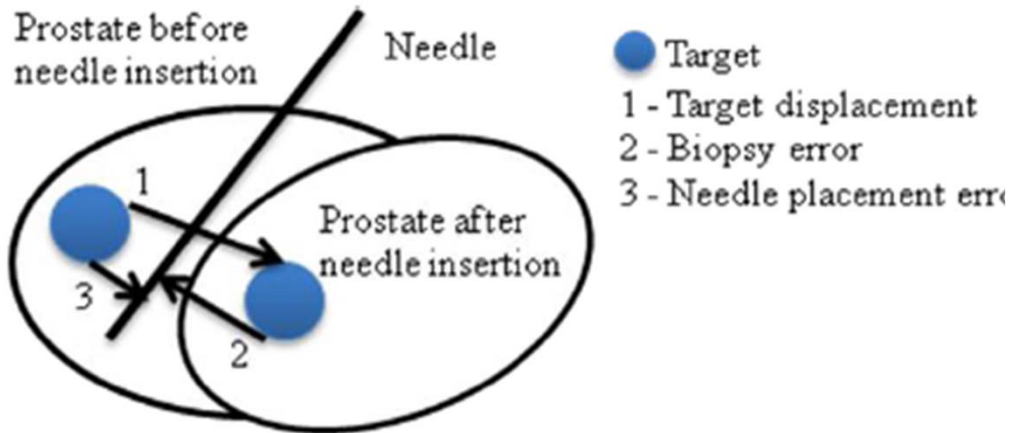


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# Five-year retrospective

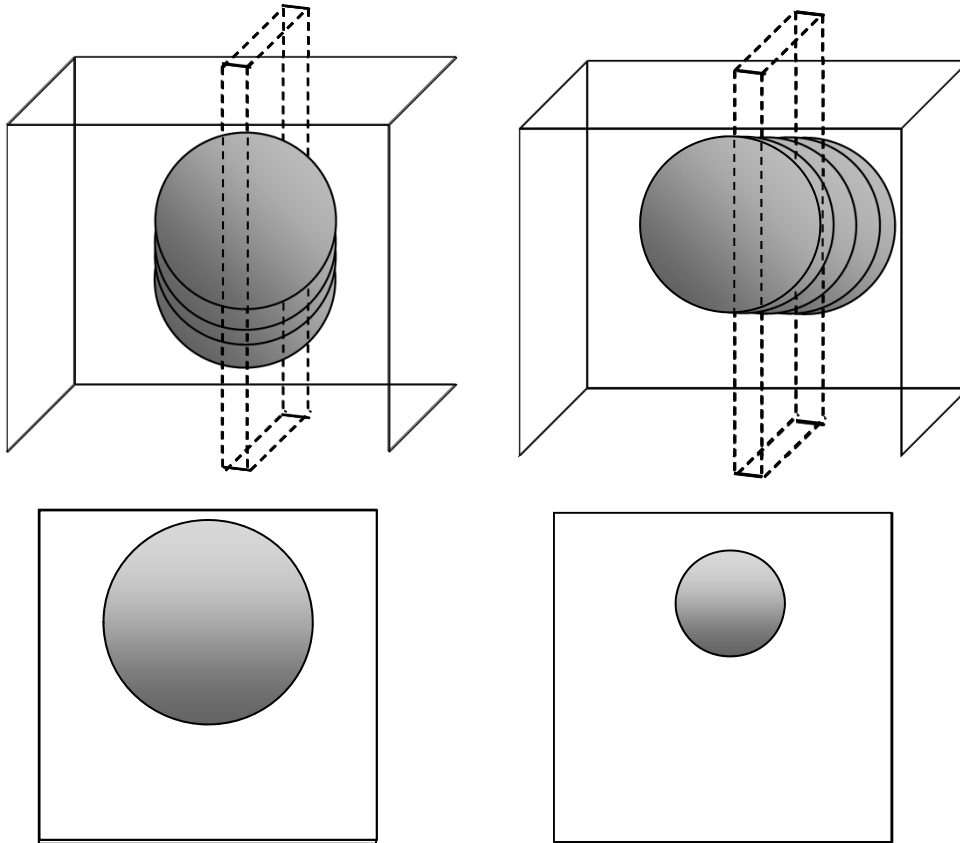


Xu *et al.* MICCAI 2010

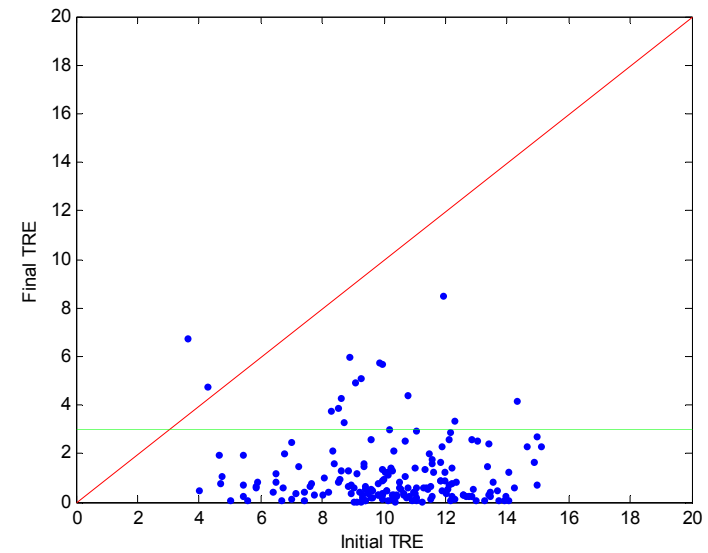


# Target motion tracking

## Moving prostate volume & fixed MRI slices



### Simulation results



Mean TRE: 0.83mm

STD=0.54mm

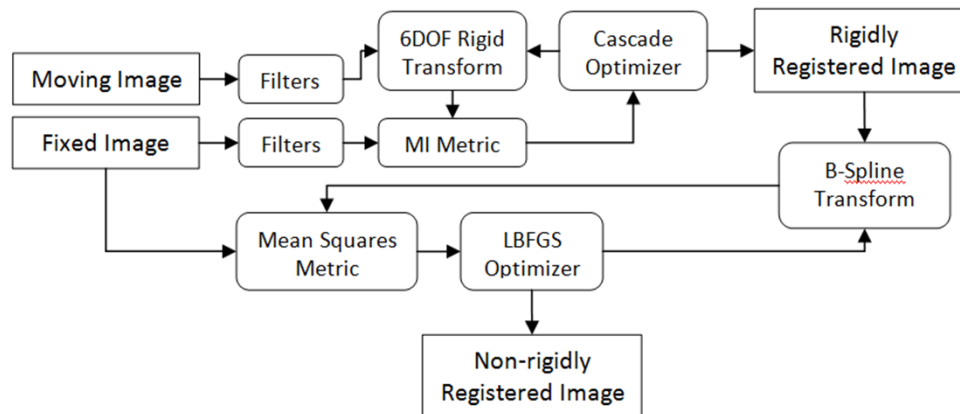
Failure rate on first run: 9%

Final failure rate: 0%

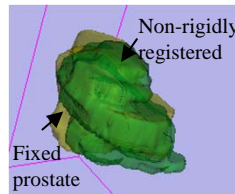
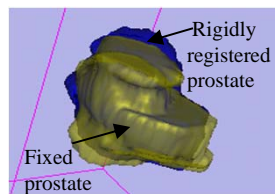
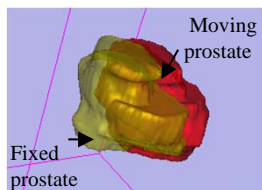
**Gill et al. SMIT 2008**



# Target motion tracking



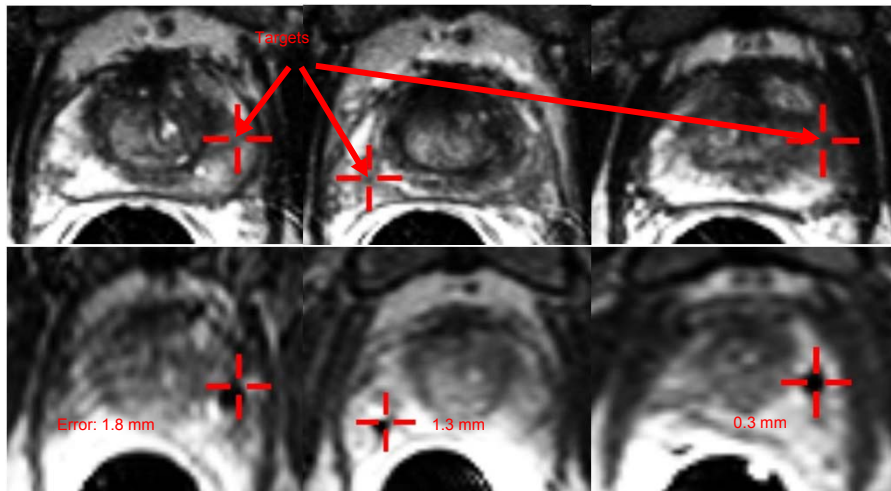
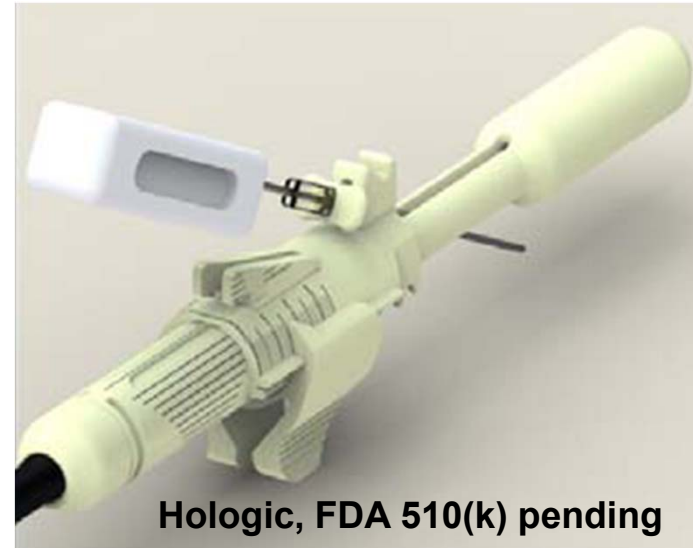
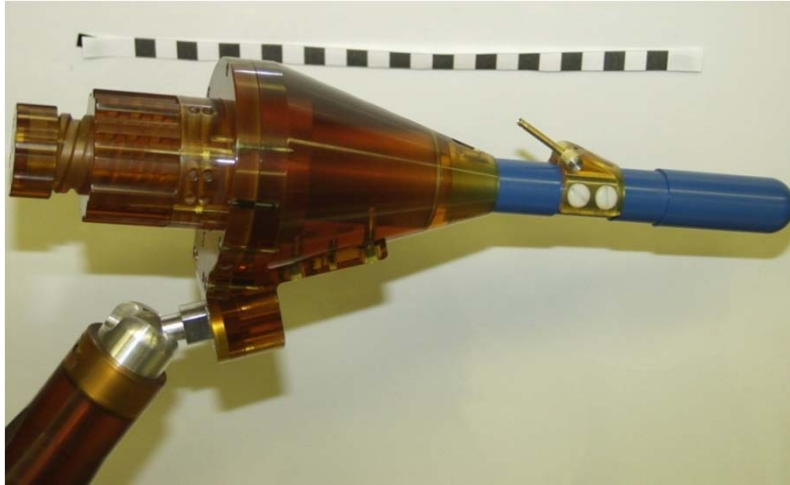
		Patient 1	Patient 2	Patient 3	Overall
	<b>Initial target Displacement</b>	9.85	4.33	17.33	10.50
<b>Rigid</b>	<b>Tracking Error</b>	2.26	2.22	3.65	2.71
	<b>Registration Time</b>	39	60	37	45
<b>Deformable</b>	<b>Tracking Error</b>	2.17	2.24	3.66	2.69
	<b>Registration Time</b>	58	308	147	142



Tadayyon *et al.* SPIE Med Imaging 2010  
 Tadayyon *et al.* IEEE EMBS 2010  
 Tadayyon *et al.* IEEE TBME 2011



# Commercial translation



- **RT tracking antennas are gone**  
Passive markers (for intermittent registration) + optical encoders (for relative motion) + strong mounting
- **Commercial biopsy needle used**  
New kinematics (2 rots, 1 ins)  
All manual insertion  
Patient pulled from the bore

Singh *et al.* Rad Onc, 2007  
Singh *et al.* Eur. J. Rad Onc, 2007  
Krieger *et al.* IEEE TBME, 2011

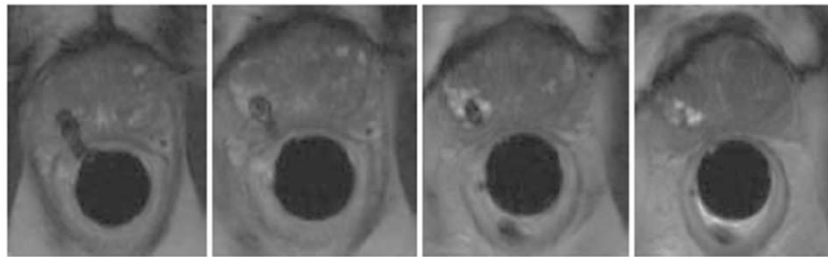


# Needle tracking in MRI

**PROBLEMS:** Needle is seen as a large signal void, the void is displaced depending on needle angle w.r.t.  $B_0$  and  $B_f$

**APPROACH:** Measure needle localization error over the work space (done)  
Analyze data, derive compensation function (in progress...)

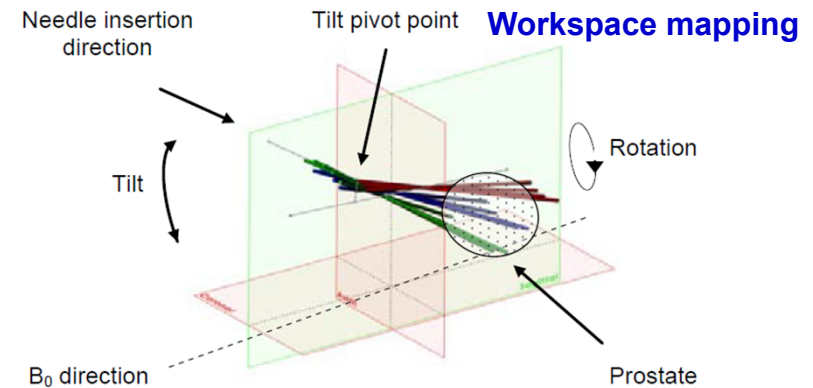
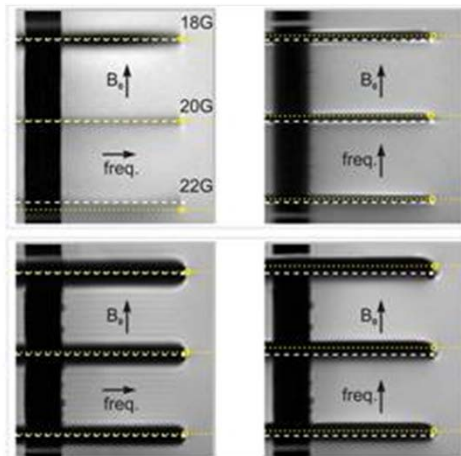
## Patient case: needle artifact extended forward by 9mm



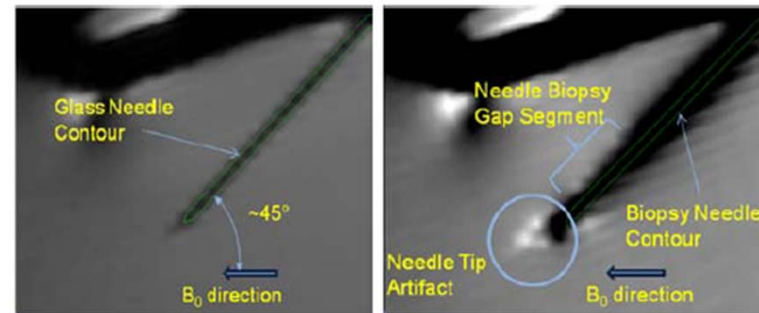
True needle tip

9 mm (3 slices) extended tip artifact

## Needle void displacement for different needles



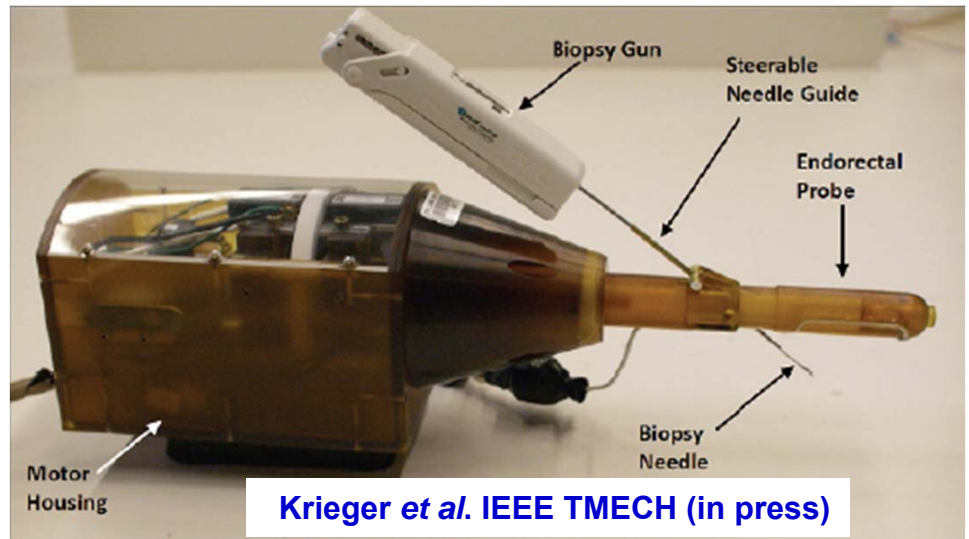
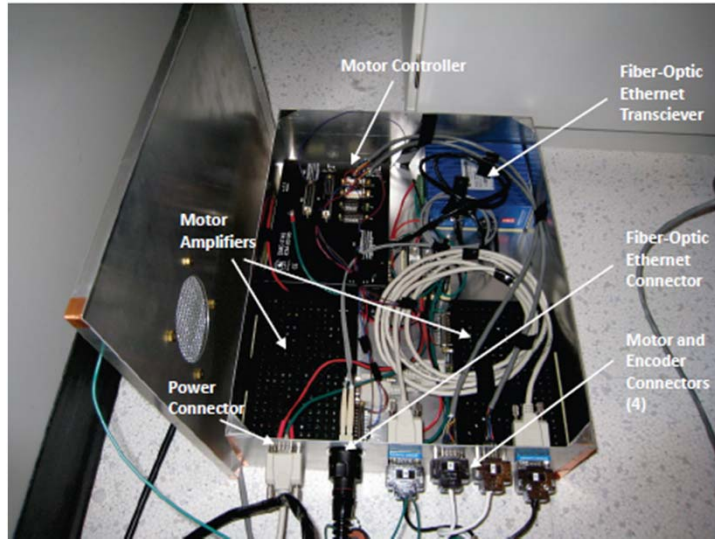
## Glass needle v.s. Titanium needle



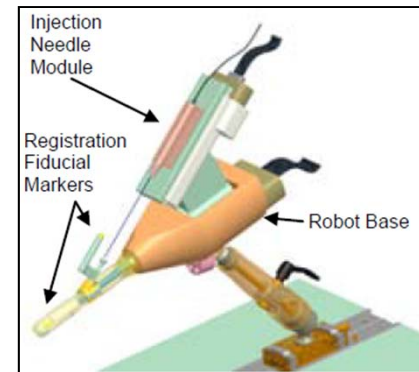
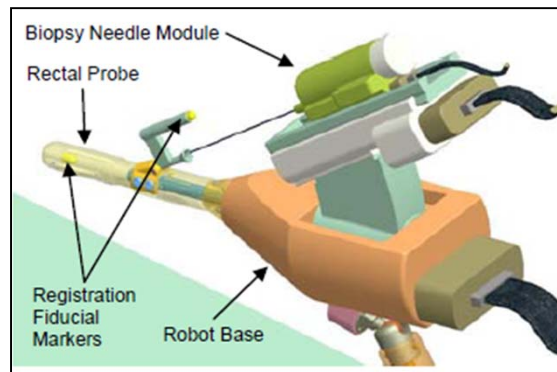
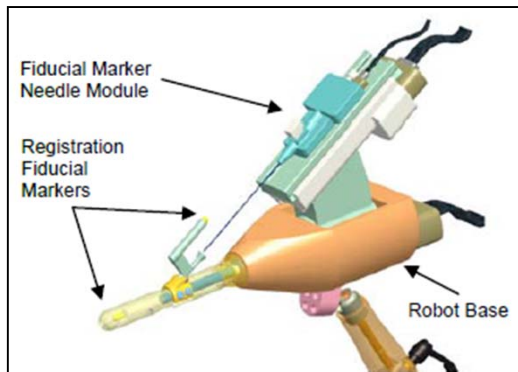
Song et al. IEEE TBME 2012 (accepted)



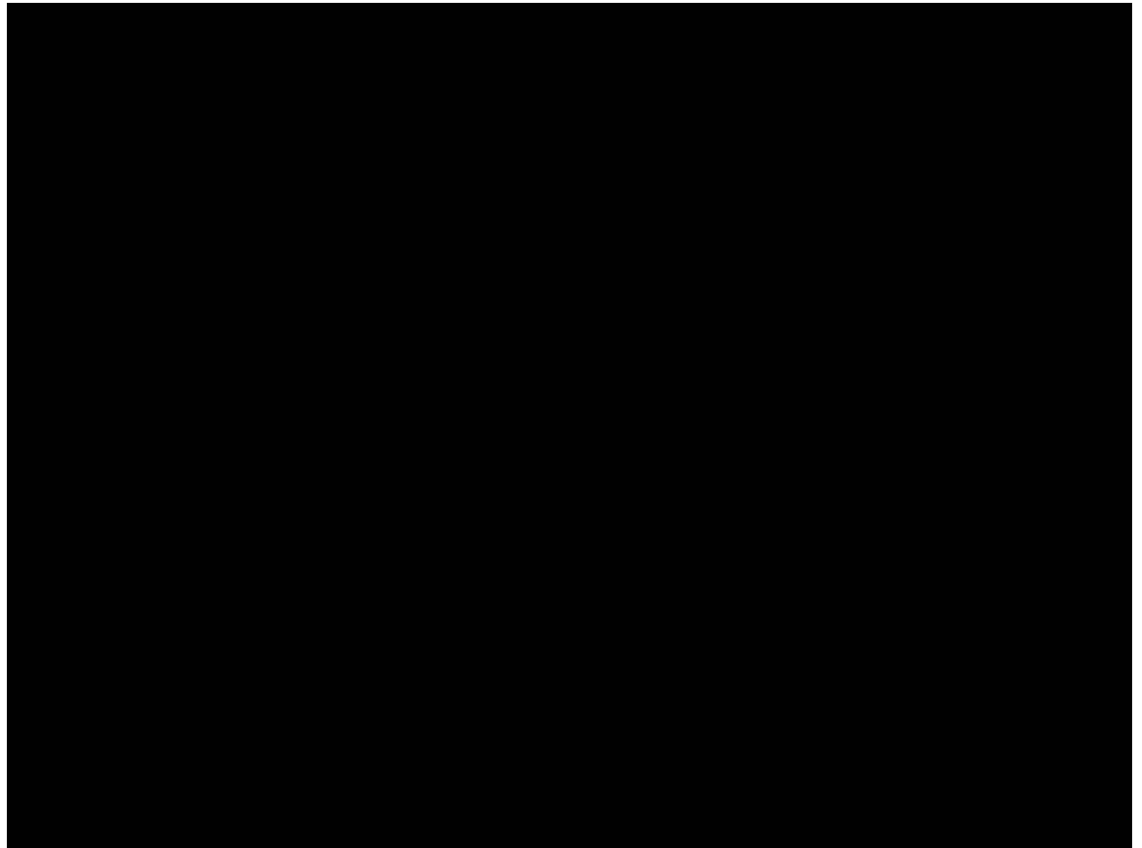
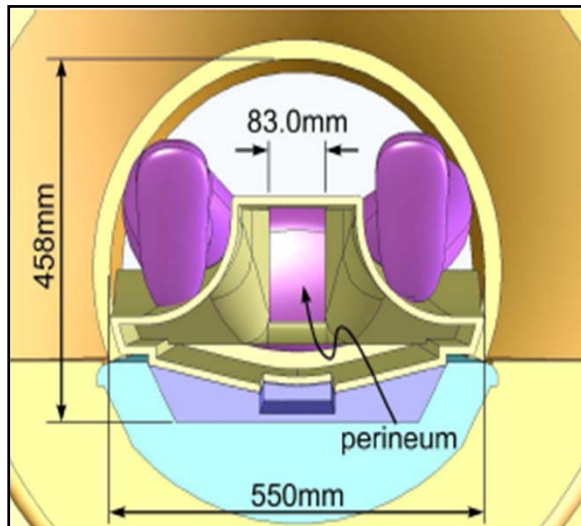
# Fully actuated system



## Smarter end-effectors coming...



# Transperineal in-MR intervention



Fischer *et al.*, IEEE Trans Robotics, 2008



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# How can we get here?

- Committed teams
- Focus on systems
- Address needs
- Be reductionist
- Rapid iteration
- Measurable goals
- Have fun!

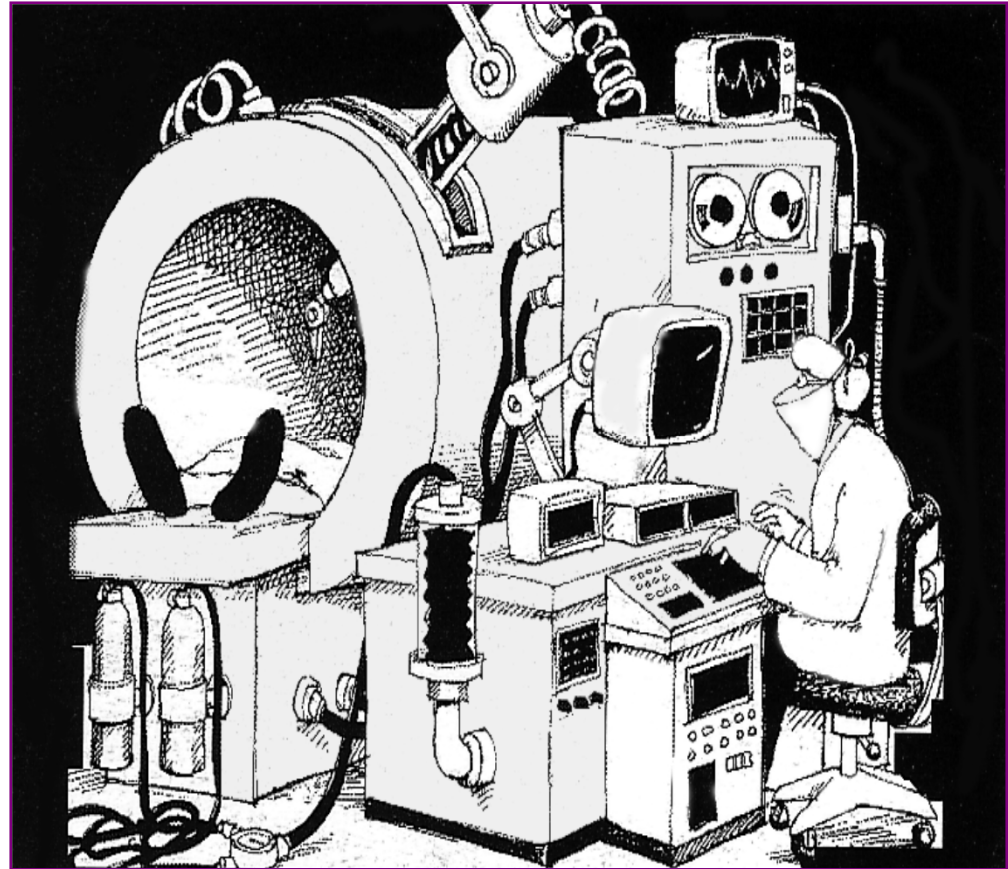


Image borrowed from Russ Taylor





# Thank You!



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