Robot-Assisted Image-Guided Prostate Interventions

Gabor Fichtinger, PhD

Director of Engineering,

Associate Research Professor of Computer Science and Radiology

NSF-Funded Engineering Research Center for Computer-Integrated Surgical Systems and Technology

Copyright © CISST ERC, 1999-2003

Long List of Contributors…

Dan Stoianovici, Louis Whitcomb, Clif Burdette, Alex Patriciu, Dumitru Mazilu, Attila Tanacs, Ergin Atalar, Rob Susil, Axel Krieger, Cynthia Menard, Emese Balogh, Allison Okamura, Chad Schneider, Ameet Jain, Tabish Mustufa, Keenan Wyrobek, Greg Chirikjian, Sangyoon Lee, Yu Zhou, Emese Balogh, Anand Vishwanathan, Anton Deguet, Herve Mathieu, Russ Taylor, Jim Anderson, Vincent Lerie, Ted DeWeese, Lee Myers, and many others…

Copyright © CISST ERC, 1999-2003

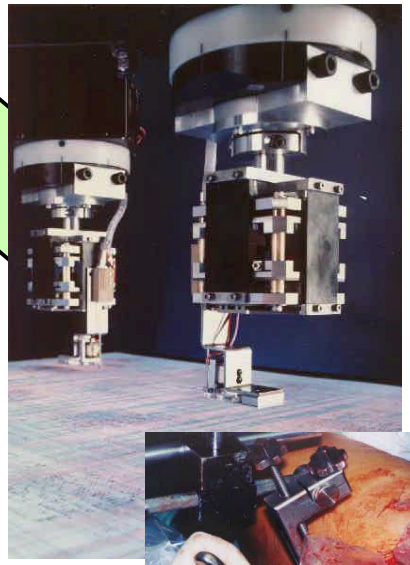
NSF Engineering Research Center for Computer-Integrated Surgical Systems and Technology

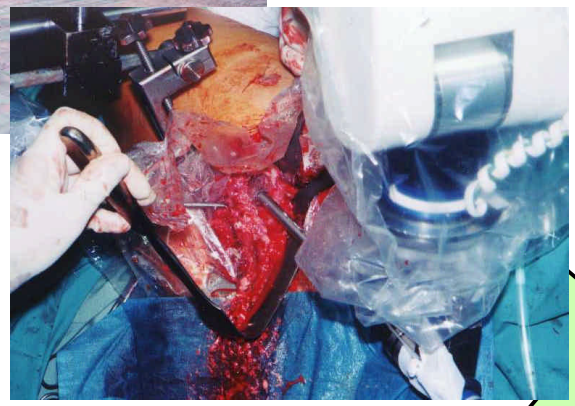
- Multi-institution, multi-disciplinary center
  - **Johns Hopkins University** + Medical Institutions
  - MIT + Brigham & Women's Hospital
  - CMU + UPMC
  - Others: Morgan State, Georgetown, Harvard, UPenn
- Current funding $6.8M/year

Copyright © CISST ERC, 1999-2003

ERC Mission Statement

Develop basic science, technology, and systems working cooperatively with physicians to significantly change the way surgical interventions are carried out in the 21st century.

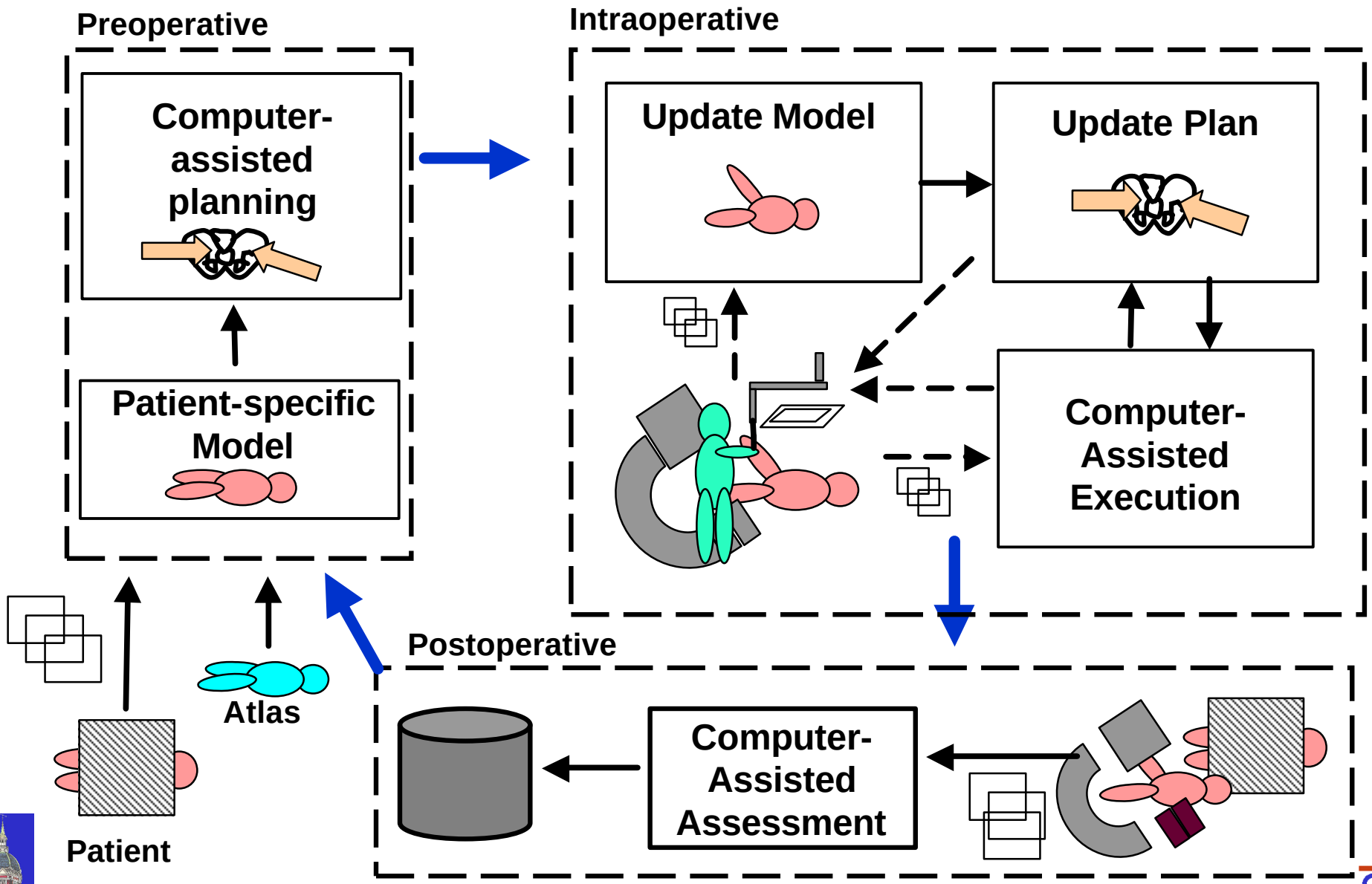




Couple Information to Action

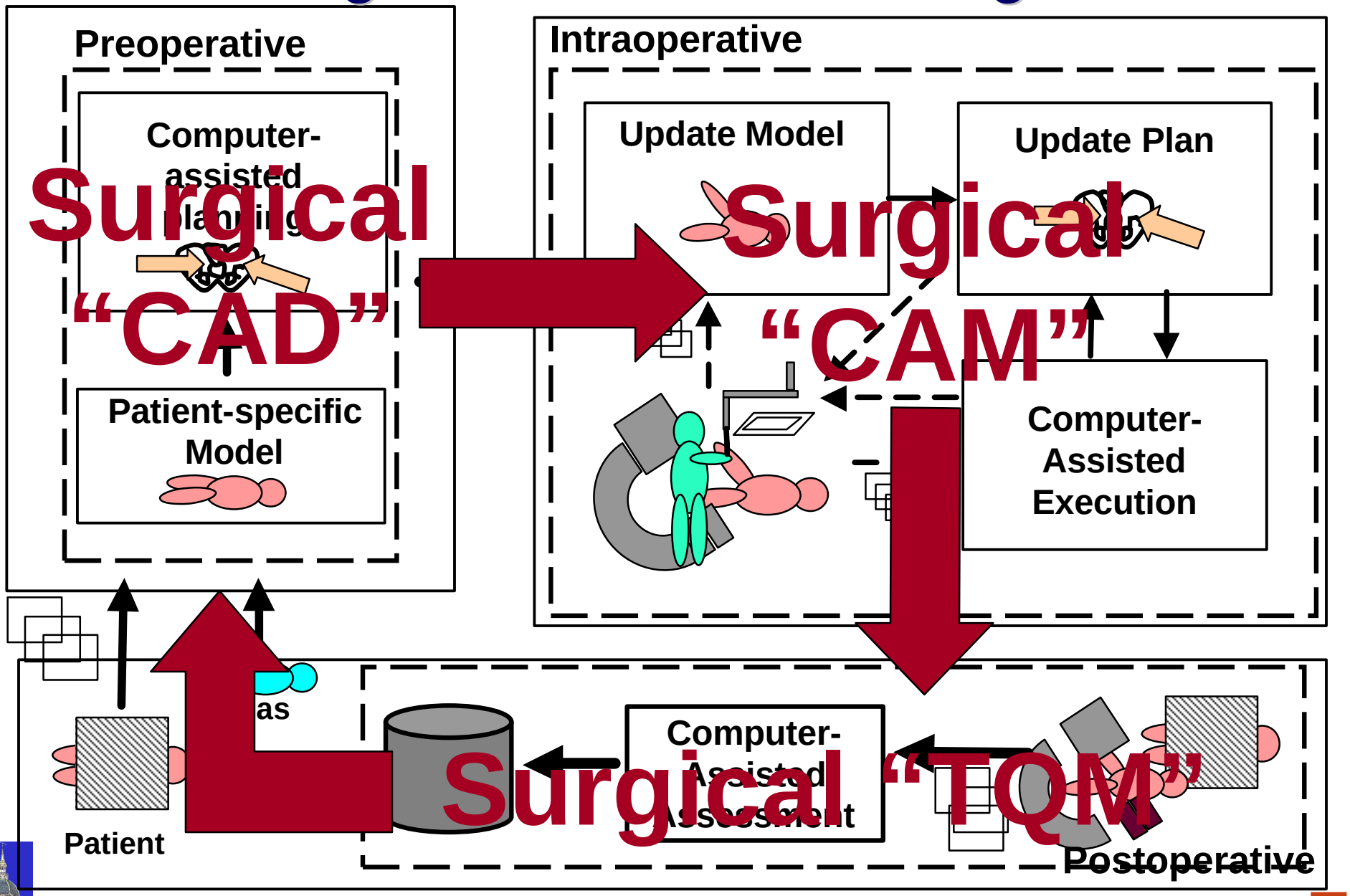
Copyright © CISST ERC, 1999-2003

Computer Integrated Surgery



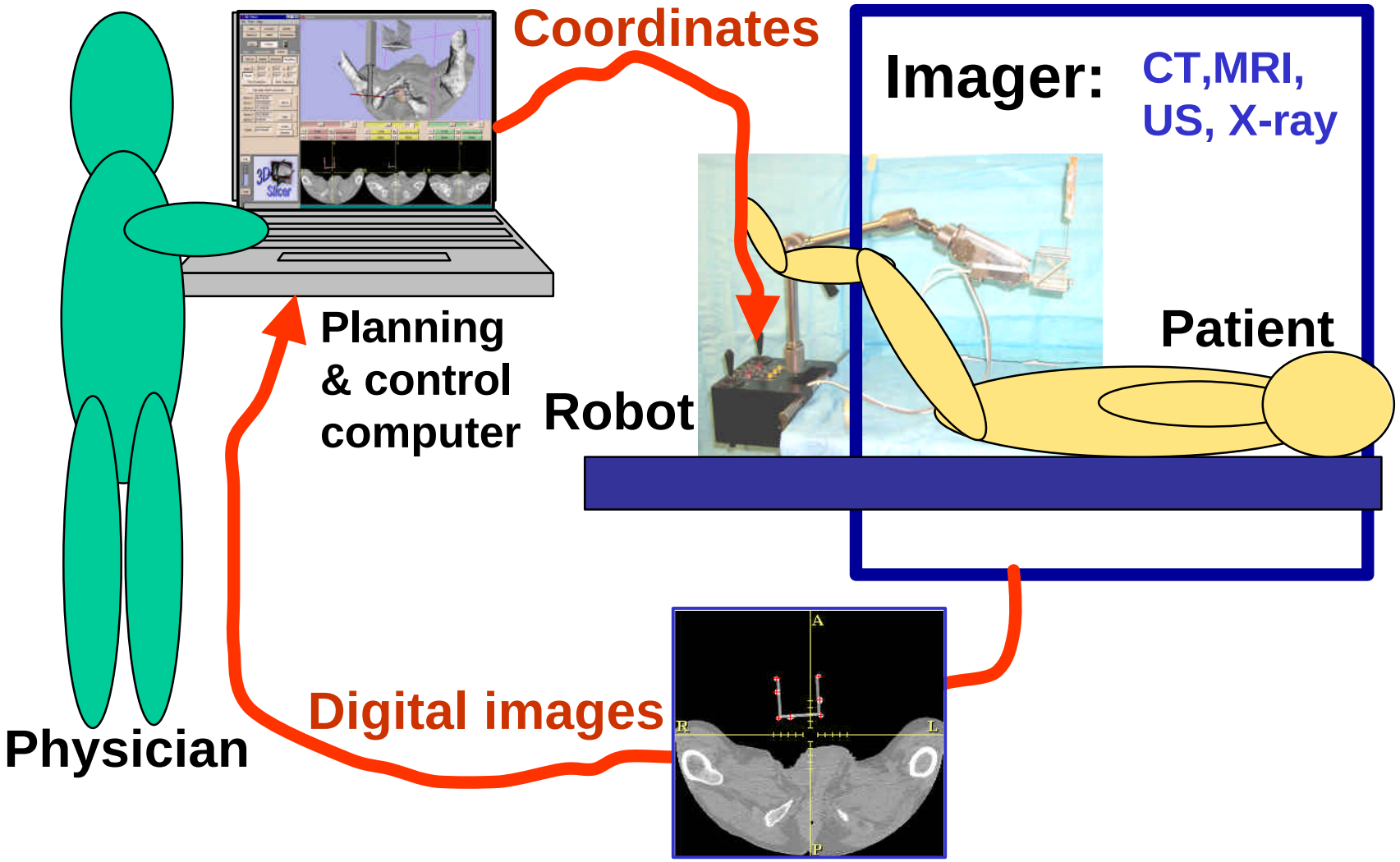
Copyright © CISST ERC, 1999-2003

Surgical CAD/CAM Paradigm



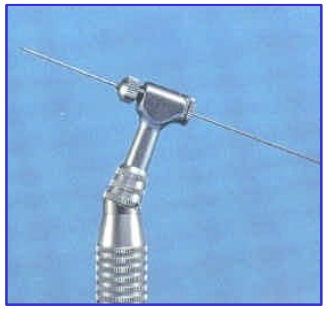
Copyright © CISST ERC, 1999-2003

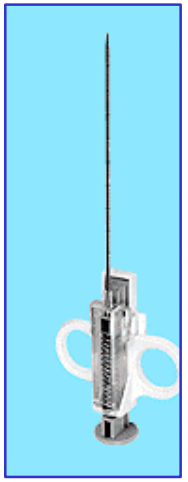
Close The Loop in OR: Robot-Assisted "Point & Click" Surgery

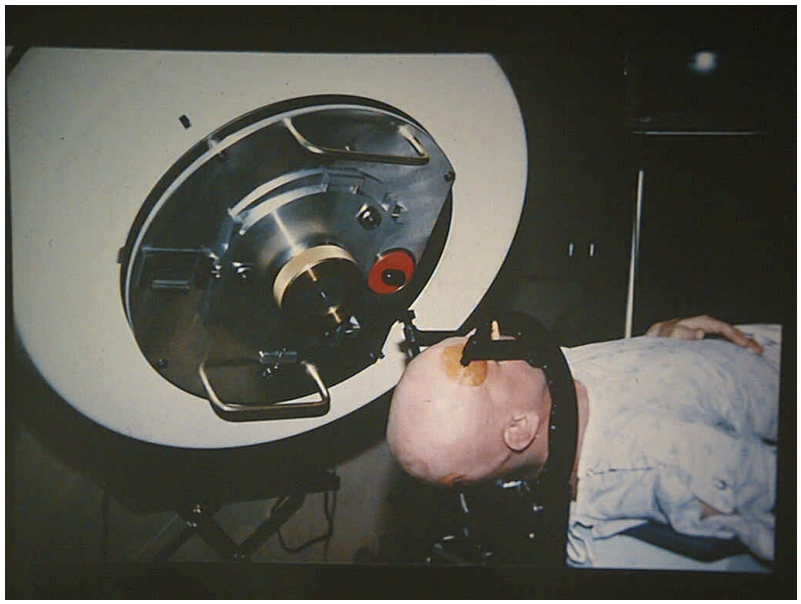


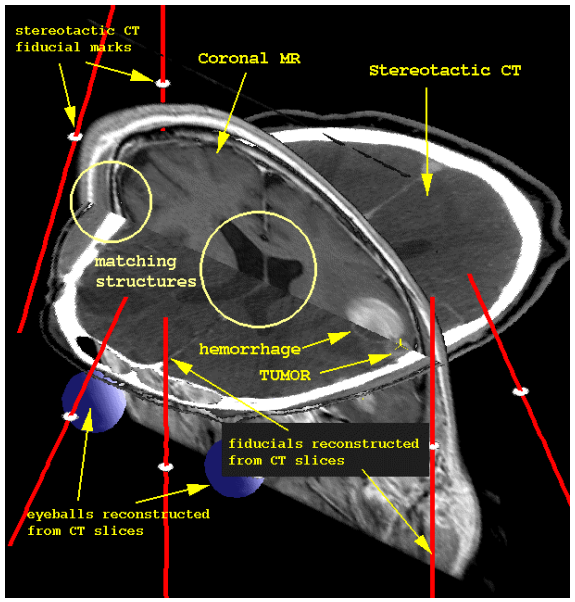
Copyright © CISST ERC, 1999-2003

Current Focus: Conceptually “Needle-Based” Localized Procedures









Copyright © CISST ERC, 1999-2003

Why Needles?

- **Potentially significant impact on medical practice**
  - **Minimally invasive (compared to open surgery)**
    - Faster recovery
    - Less morbidity
    - Fewer complications
    - Lower cost
    - Repeatable in many indications
  - **Sharply increasing number of procedures**

- **Challenging but doable**
  - ***Constrained process – formally describable***
  - **Major challenges (in addition to open/lap surgery):**
    - **no visibility**
    - **no access**
    - **no room to maneuver**
    - **no room to recover**

Copyright © CISST ERC, 1999-2003

Clinical Scope of Our Investigation

Prostate	Liver	Spine
200,000 cancers/year	Metastasis from colorectal cancer	$120 billion cost
1M biopsies /year	130,000 new /year	70% of population affected in lifetime
10M BPH currently	60,000 death /year	**Bone**
25% of men affected in lifetime	Hepatitis worldwide	400,000 metastatic cases/year

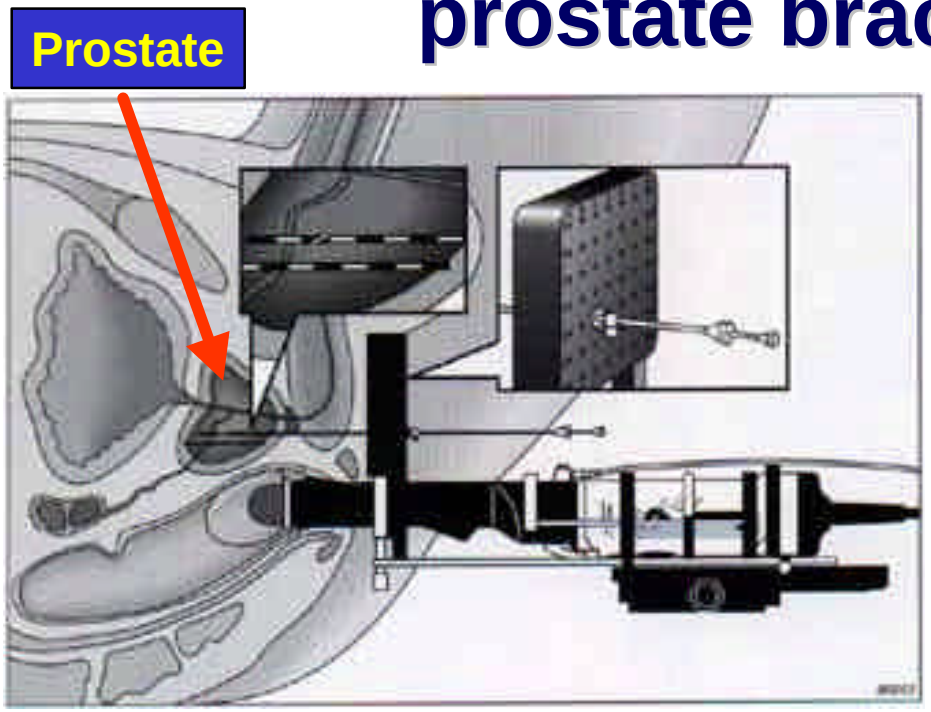
United States numbers

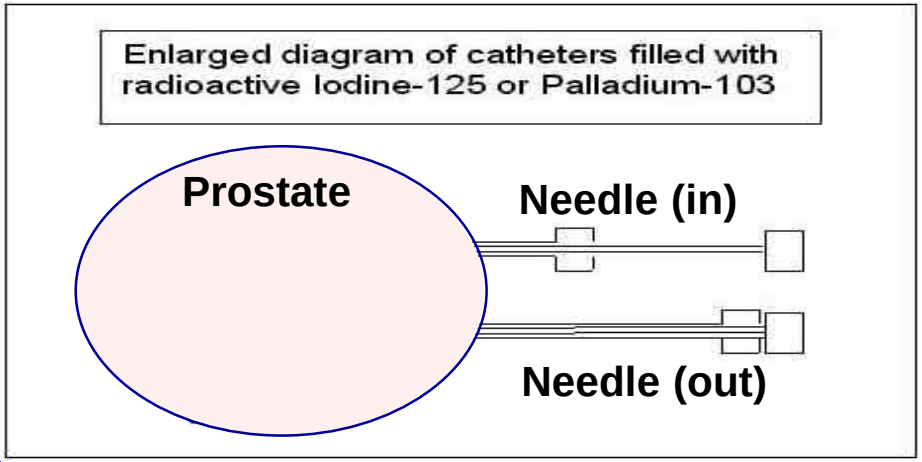
Why these?

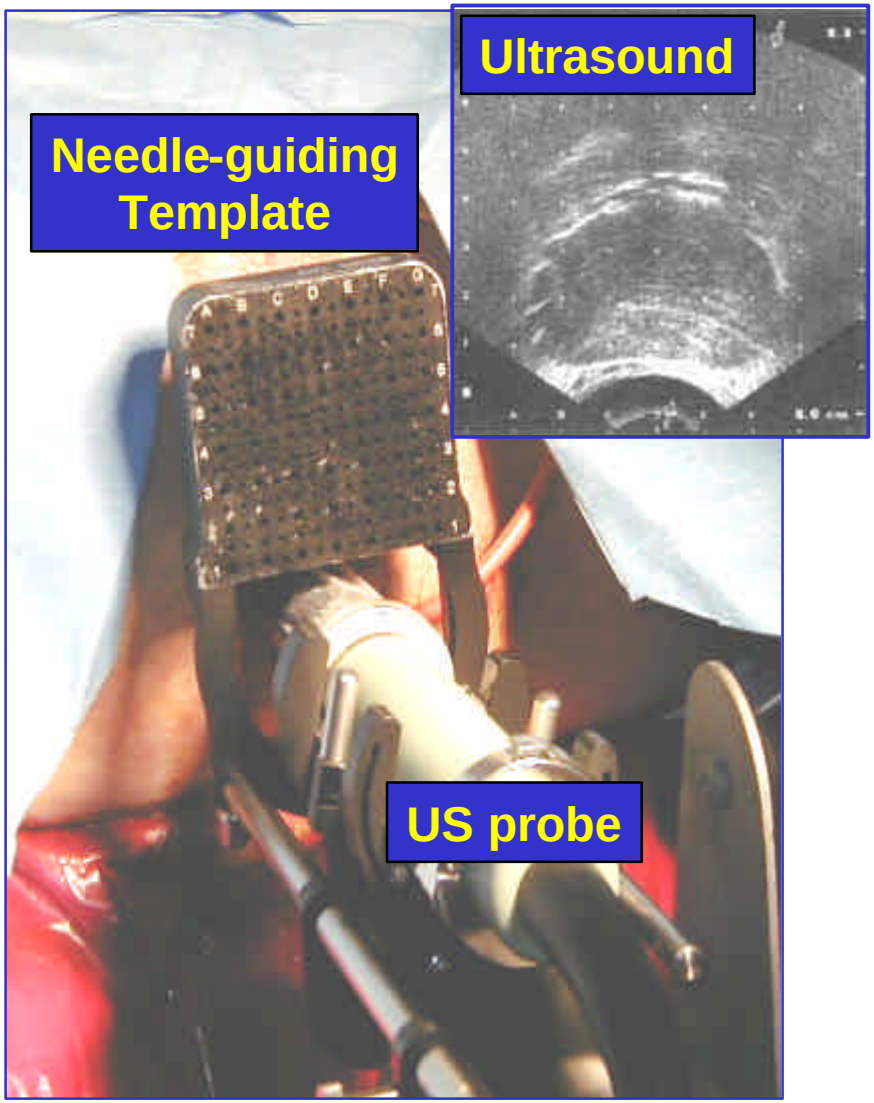
- Significant health problems
- Right mix of challenge and doability
- Clinical buy-in
- Experience of investigators
- Funding opportunities

Copyright © CISST ERC, 1999-2003

Benchmark procedure: TRUS-guided prostate brachytherapy



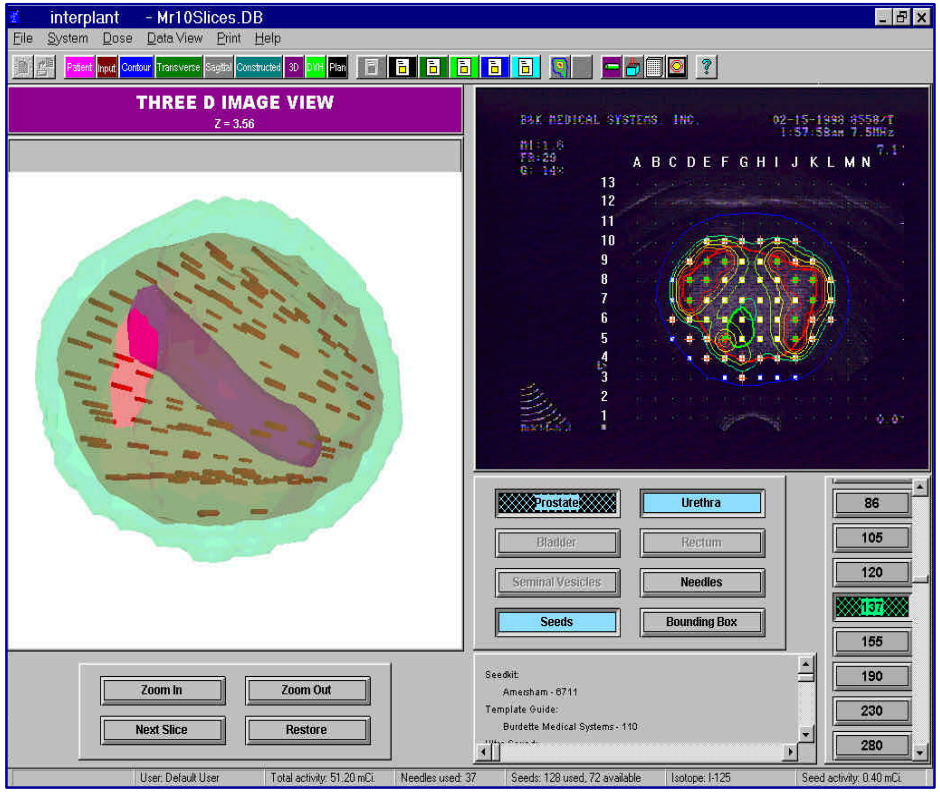




Copyright © CISST ERC, 1999-2003

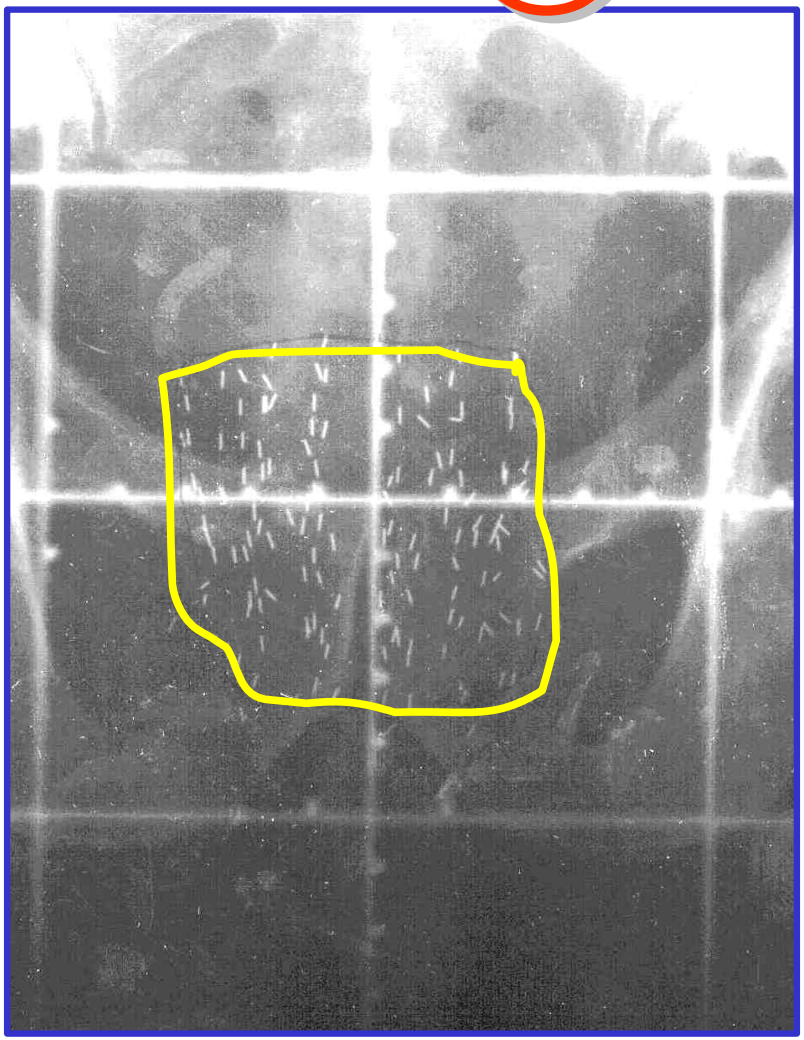
Plan versus result

PRE-OP PLAN



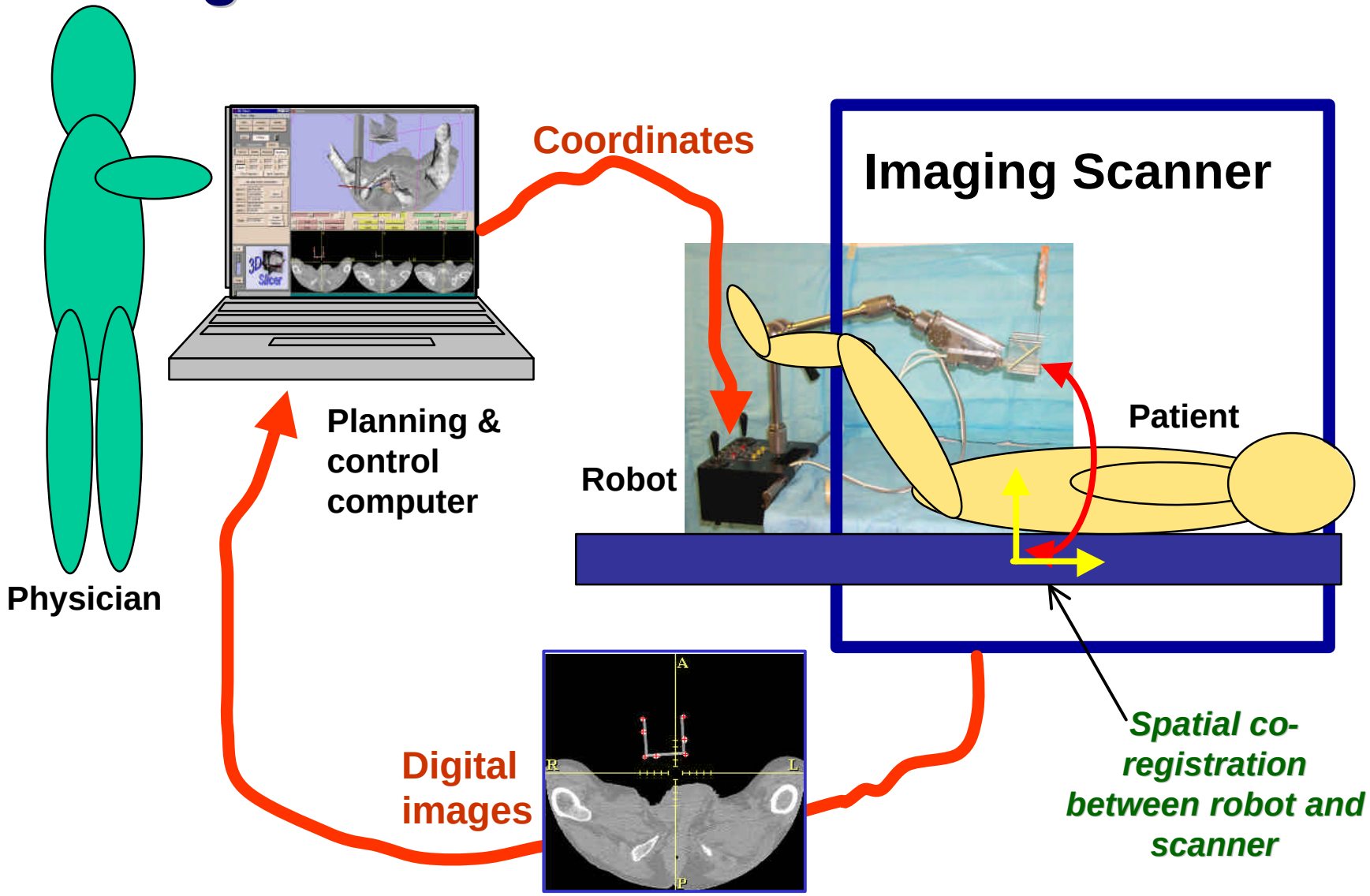
Courtesy of Burdette Medical Systems, Inc.

POST-OP RESULT



Copyright © CISST ERC, 1999-2003

Accuracy, Consistency, Optimization – Image-Guided Robot Inside Scanner

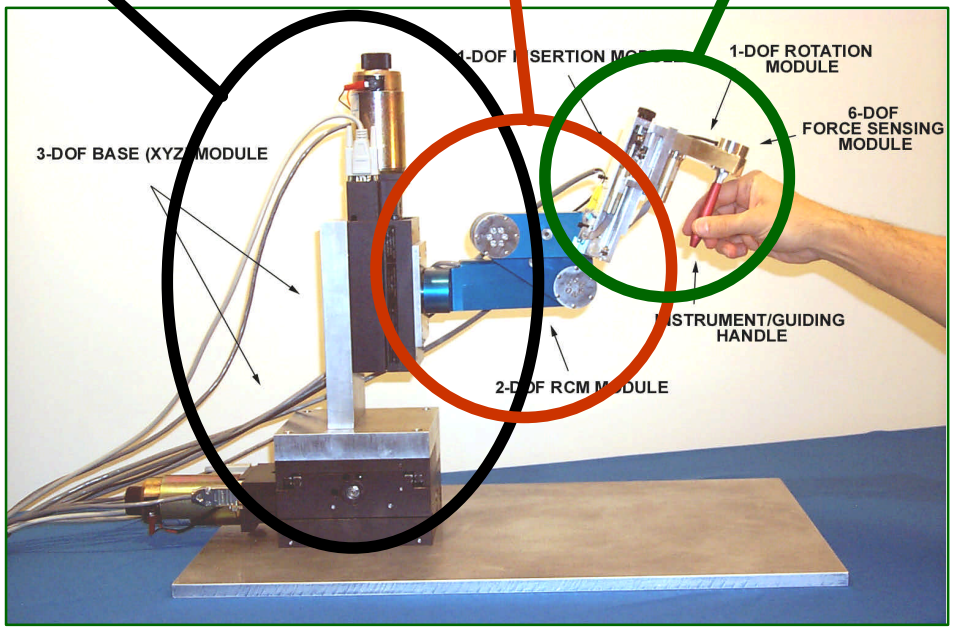


Copyright © CISST ERC, 1999-2003

Remote Center of Motion for Needle Placement

Rotation about stationary fulcrum point

1. 3D translation "move needle to entry"
2. 2D Rotation "orient needle"
3. 1D/2D Insertion "drive needle"

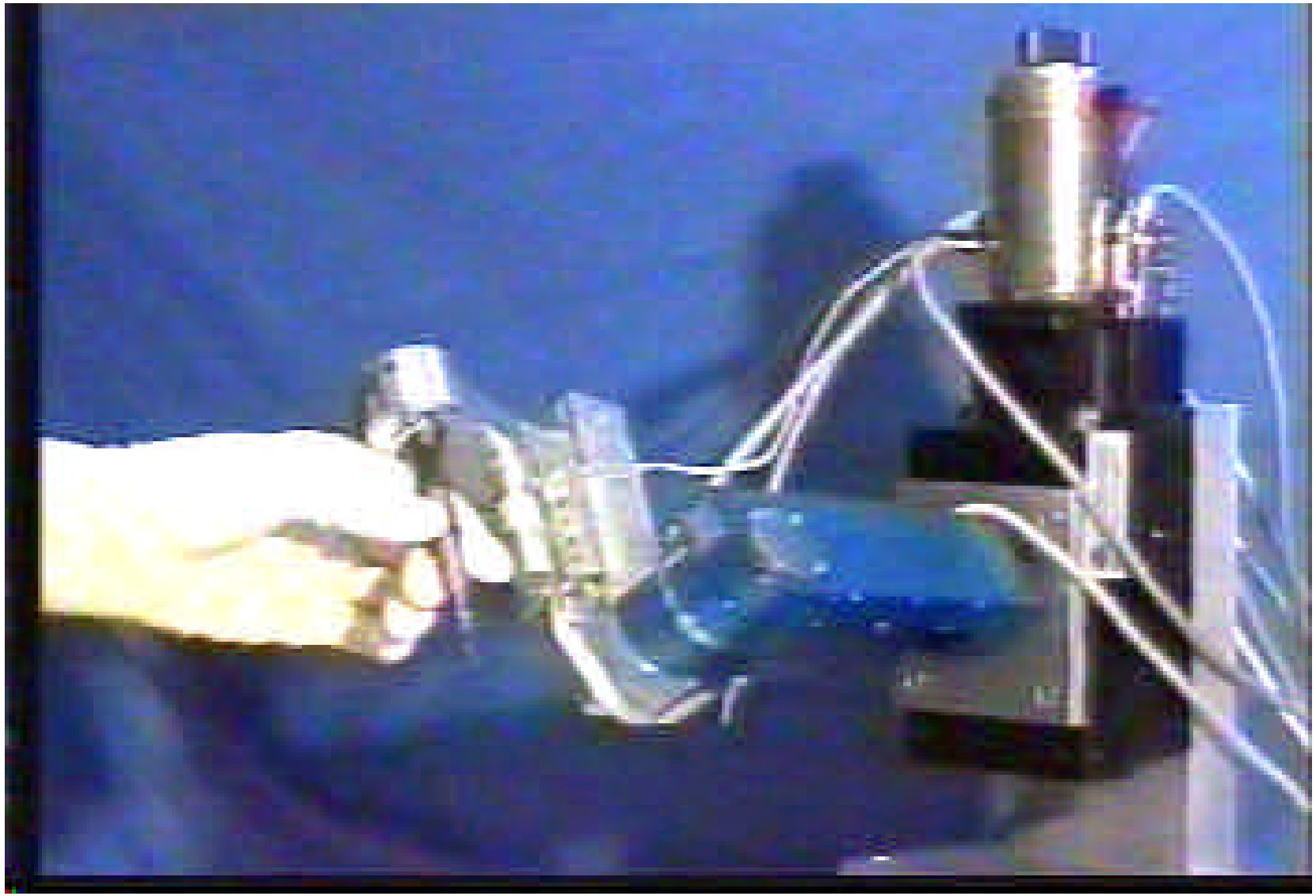


Benefits

- Suits workflow
- Decoupled motion
- Safe
- Modular

Copyright © CISST ERC, 1999-2003

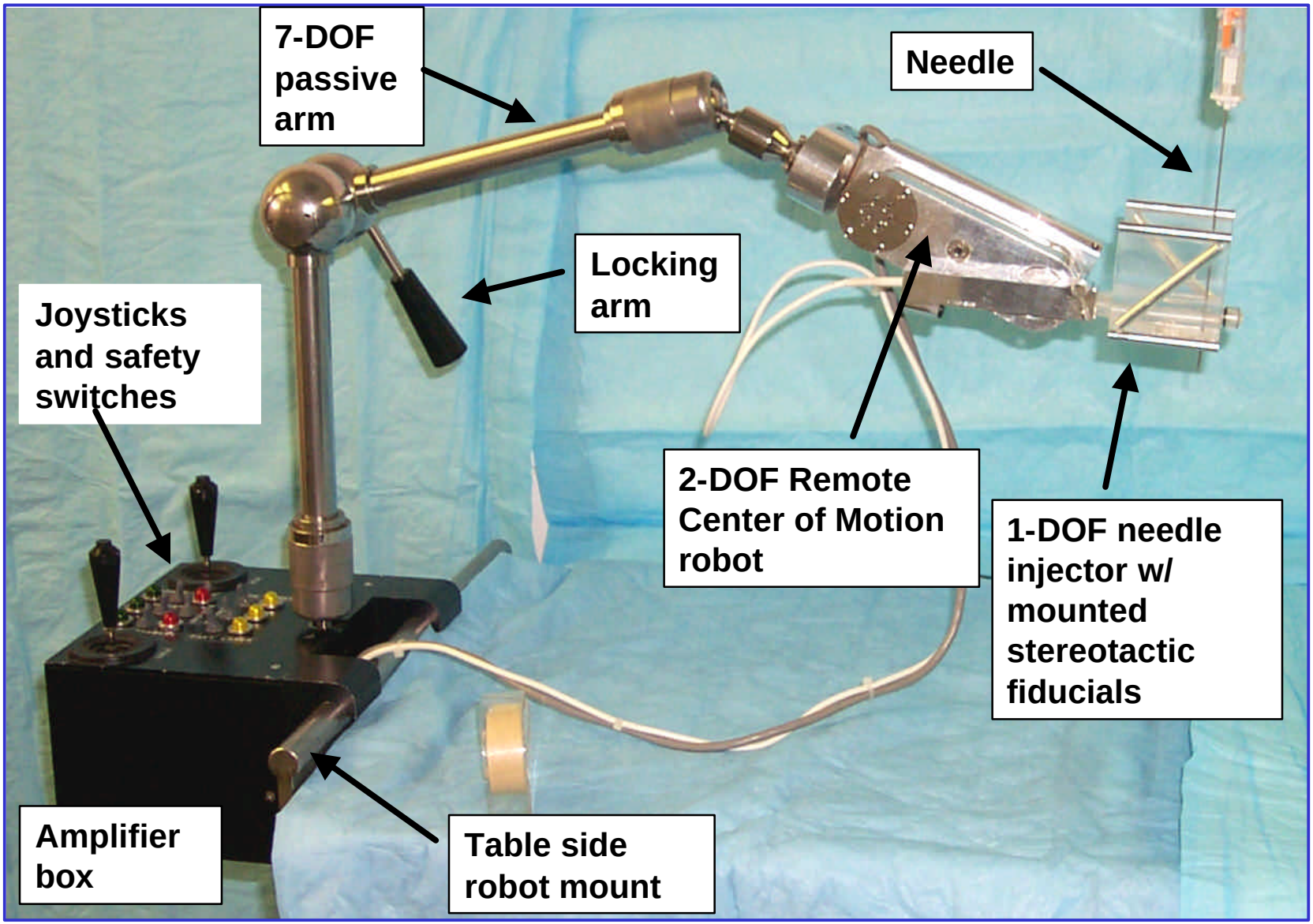
SteadyHand Microsurgery Robot



R. Taylor, D. Stoianovici, L. Whitcomb, A. Barnes

Copyright © CISST ERC, 1999-2003

3-DOF Version



Robot: D. Stoianovici

Copyright © CISST ERC, 1999-2003

Patient and robot on the table

Copyright © CISST ERC, 1999-2003

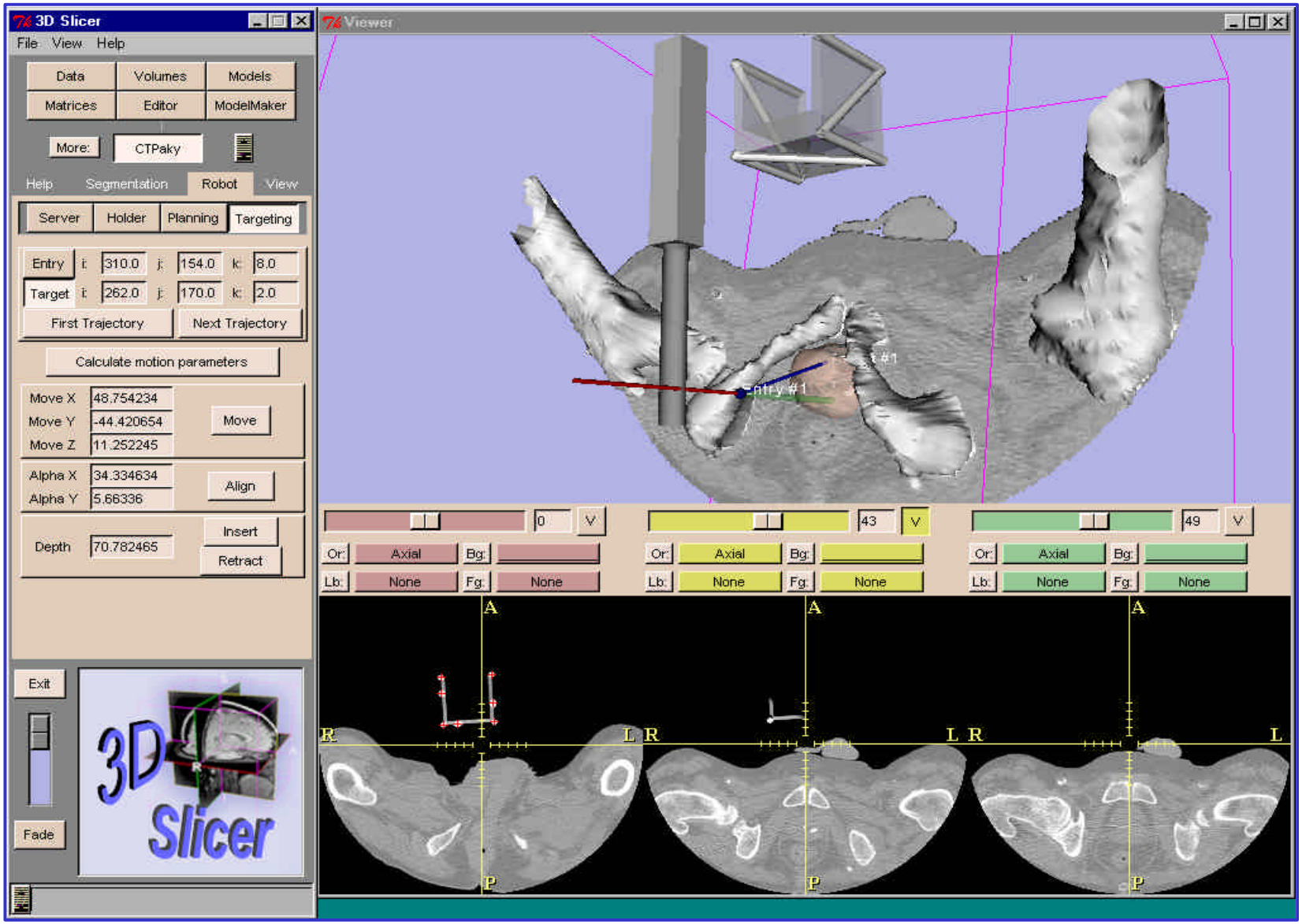
Patient and robot in CT scanner

Copyright © CISST ERC, 1999-2003

Stereotactic adapter in place

Copyright © CISST ERC, 1999-2003

Intra-op treatment planning

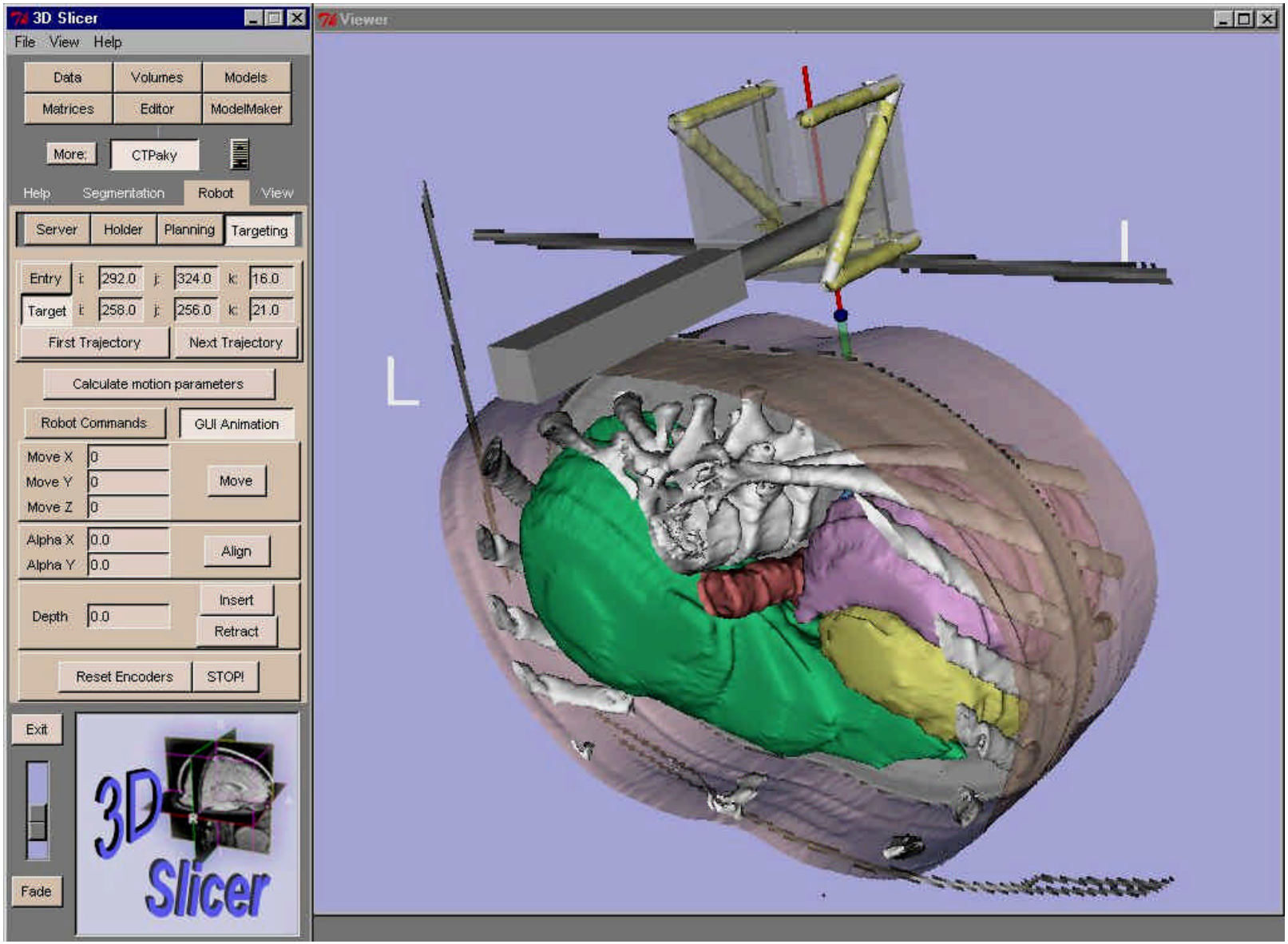


Copyright © CISST ERC, 1999-2003

Tilted insertion of a needle

Copyright © CISST ERC, 1999-2003

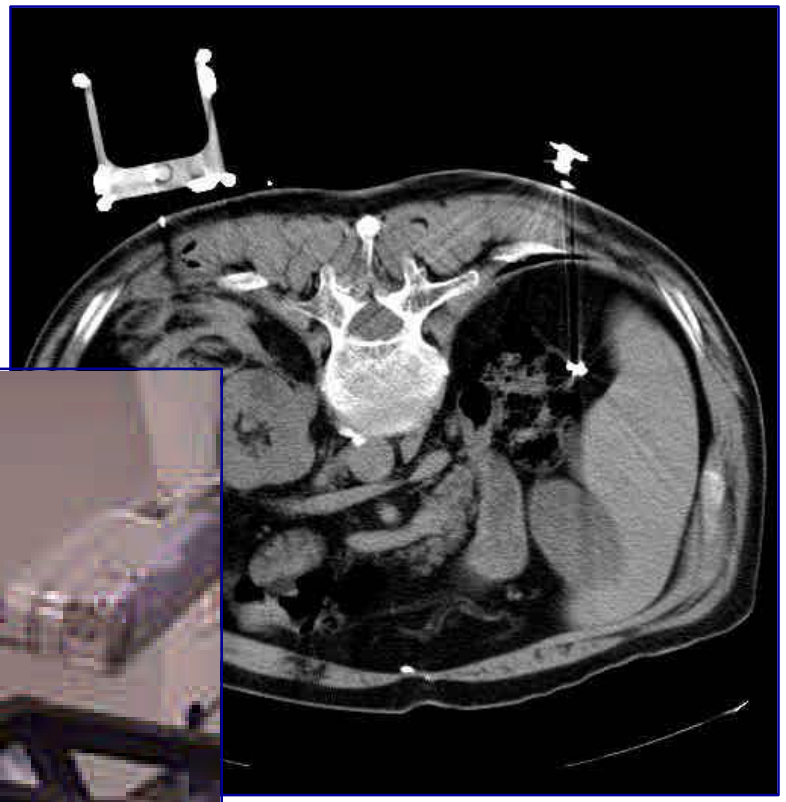
Works the same way for kidney, lung…



Copyright © CISST ERC, 1999-2003

Transfer to kidney biopsy

Robot registered to CT from a single image using stereotactic frame on the end-effector



Credit: D. Stoianovici, L. Kavoussi, A. Patriciu, S. Solomon (JHU Bayview)

Copyright © CISST ERC, 1999-2003

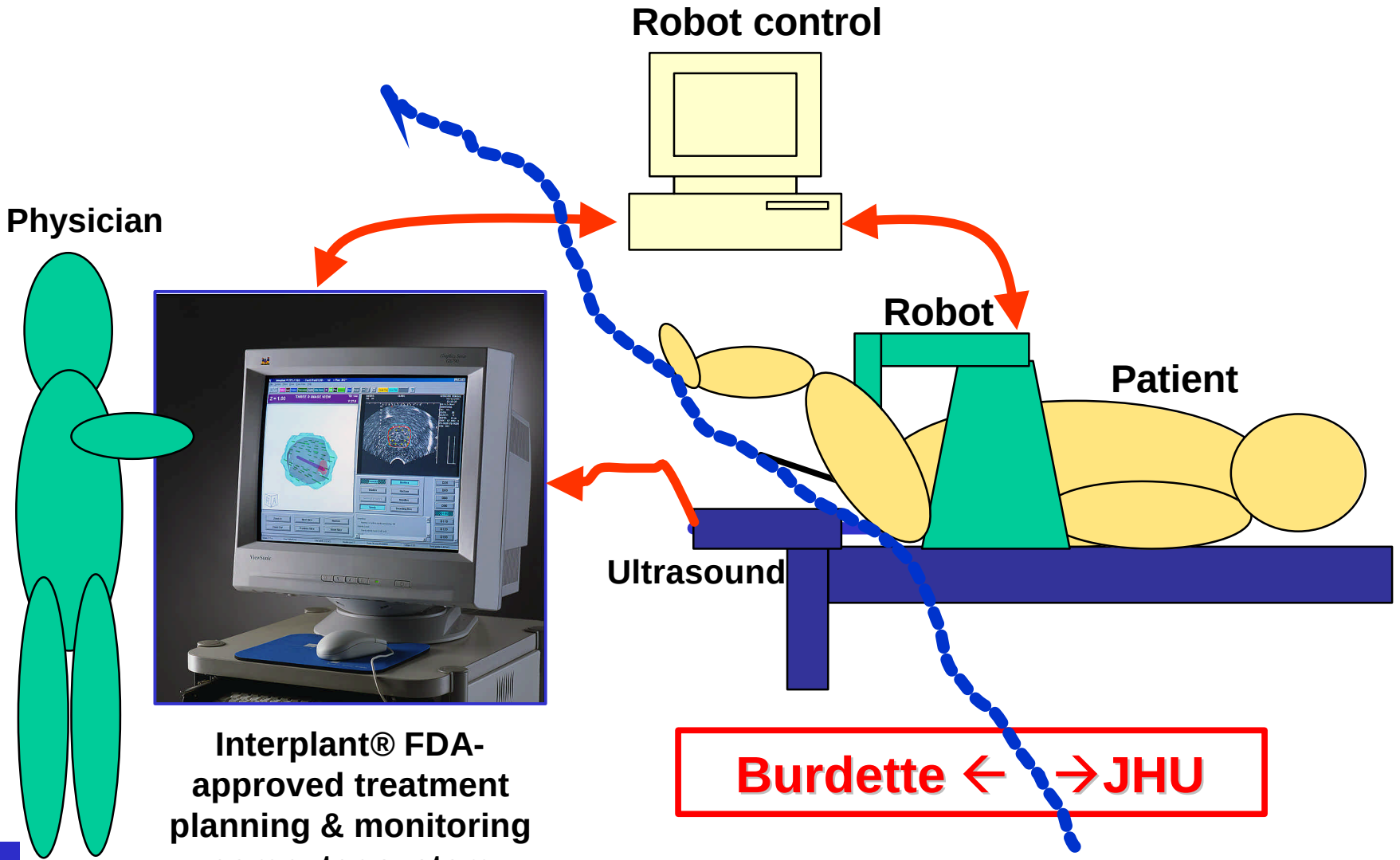
Transfer to lung biopsy

Robot registered to CT using the scanner's alignment laser

Credit: D. Stoianovici, L. Kavoussi, A. Patriciu, S. Solomon, JHU Bayview and G. Fichtinger, ERC

Copyright © CISST ERC, 1999-2003

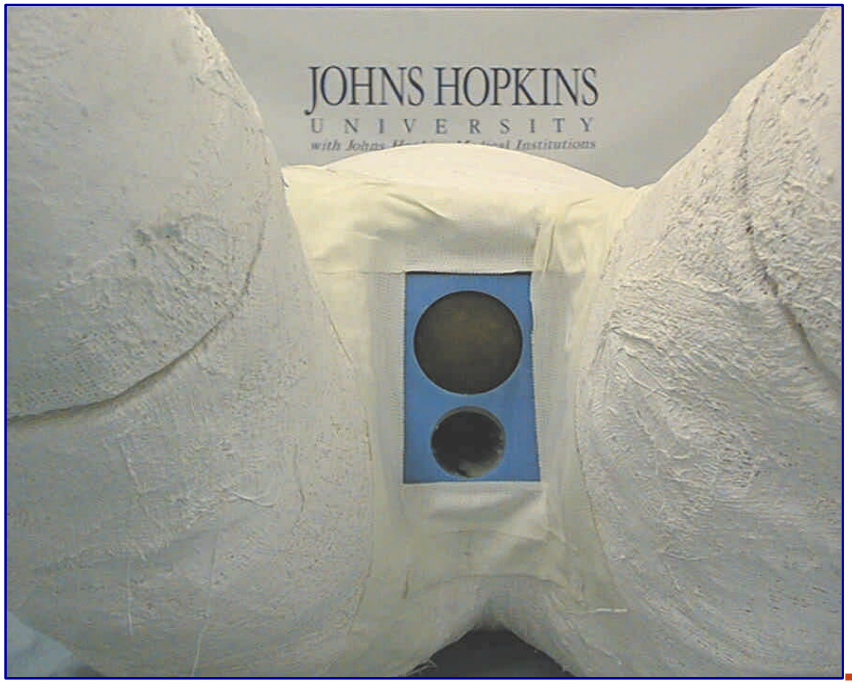
TRUS-guided brachytherapy robot merged with Burdette's Interplant®



NIH SBIR grant with Burdette

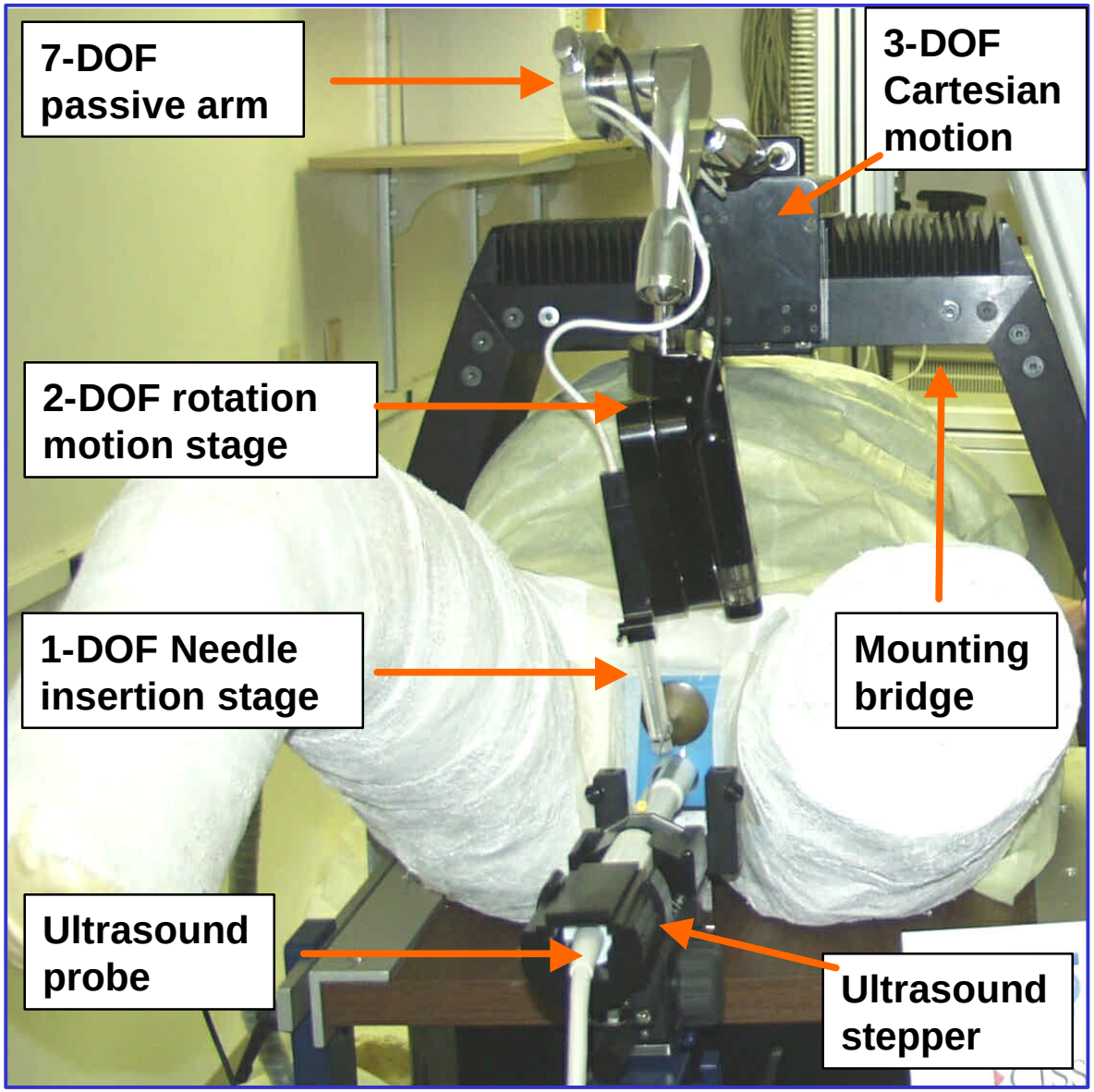
Copyright © CISST ERC, 1999-2003

Practiced on custom-built phantom



Copyright © CISST ERC, 1999-2003

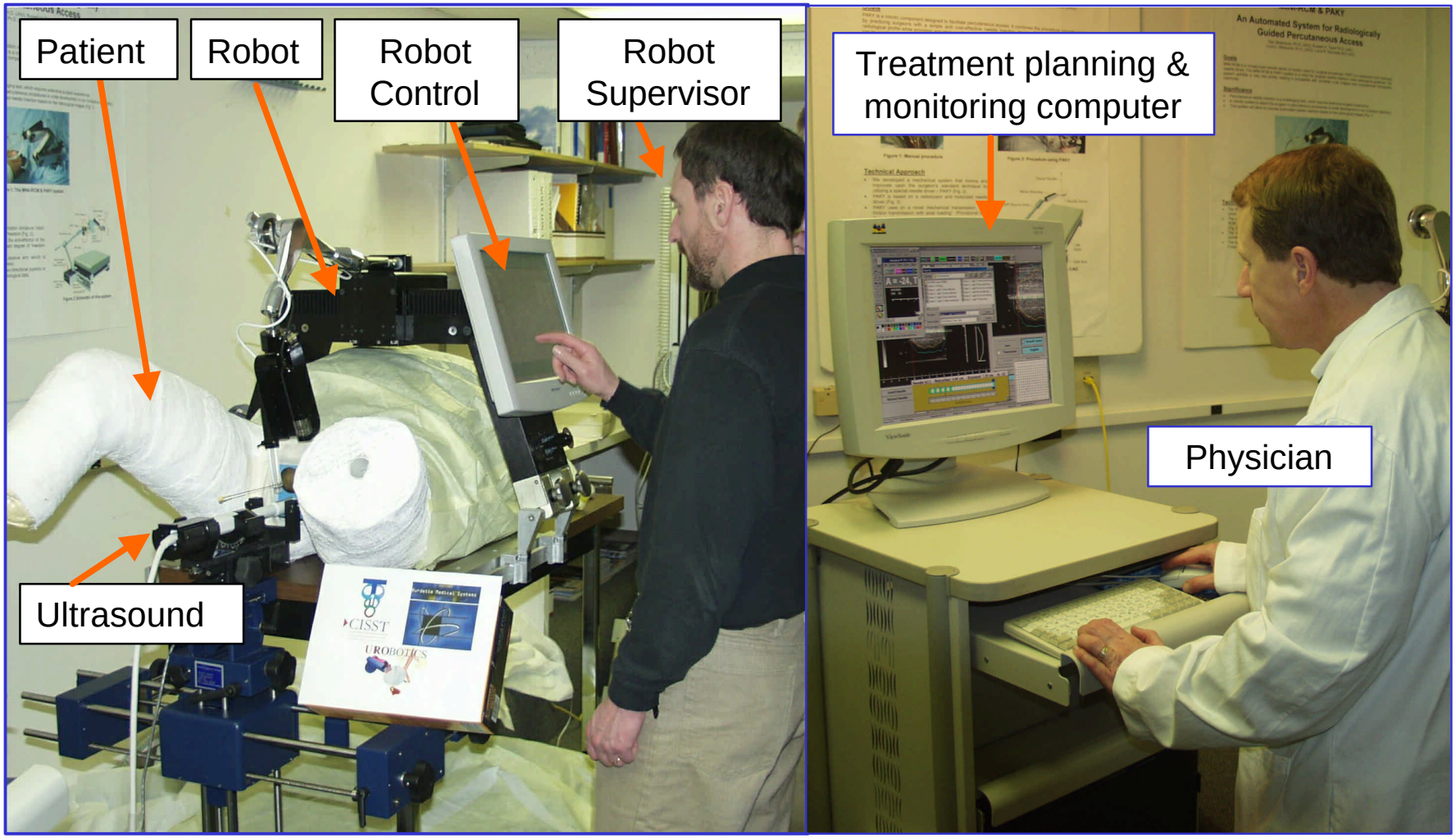
The URobotics Accubot™ robot



Robot: D. Stoianovici

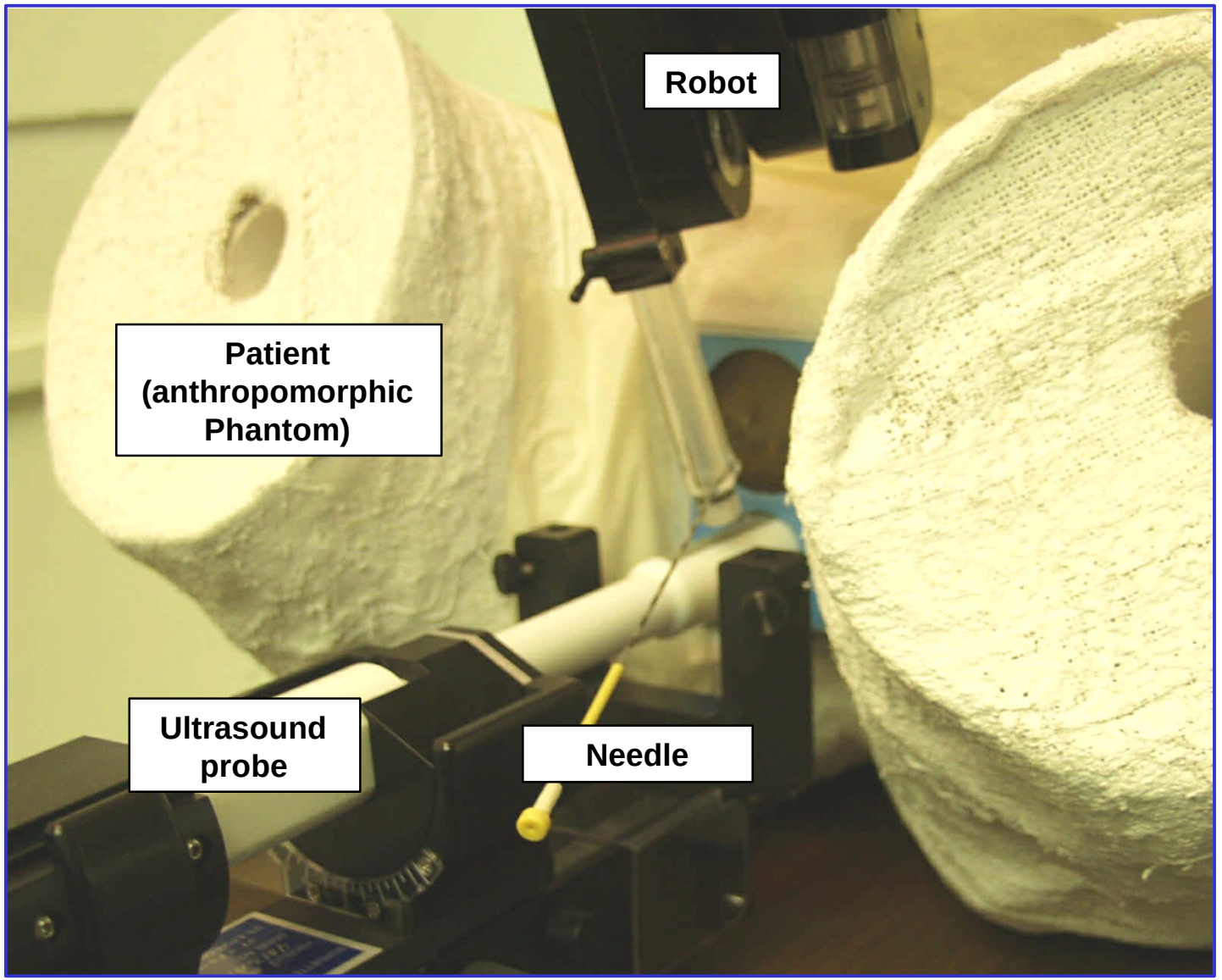
Copyright © CISST ERC, 1999-2003

The integrated Phase-1 system



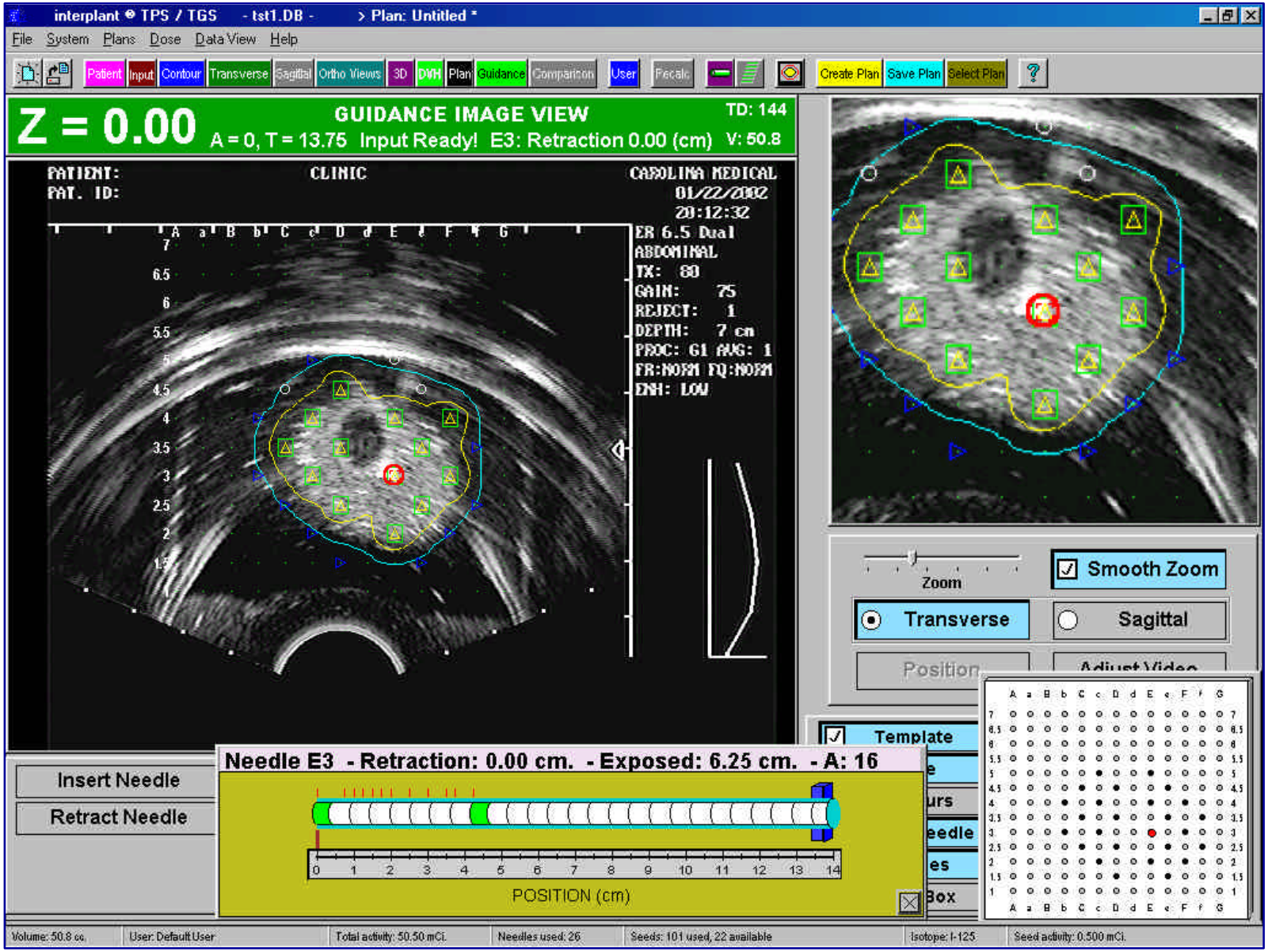
Copyright © CISST ERC, 1999-2003

Tilted needle to avoid pubic arch interference



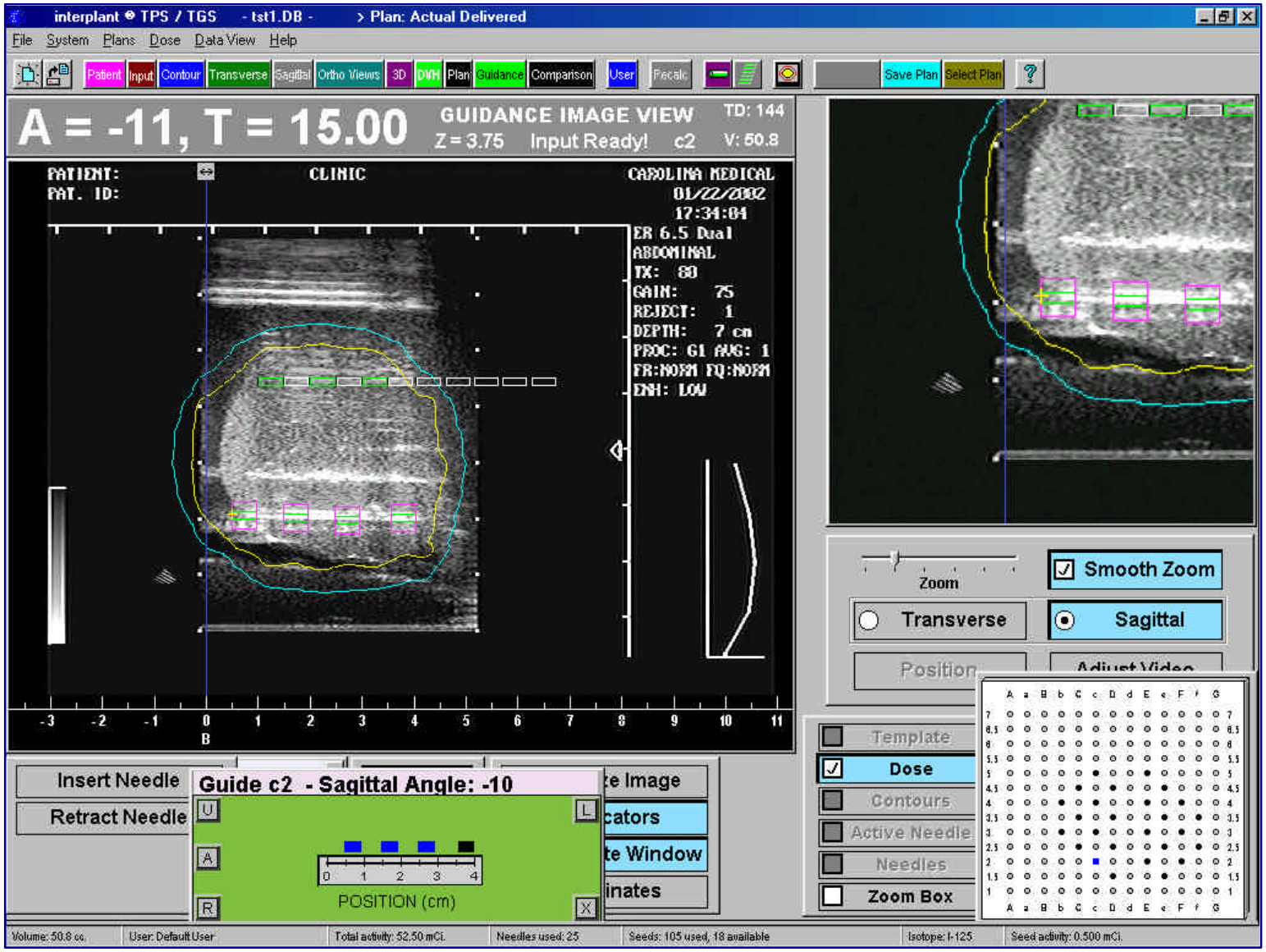
Copyright © CISST ERC, 1999-2003

Needle tracked in live US image



Copyright © CISST ERC, 1999-2003

Real-time dosimetry upon release of seed



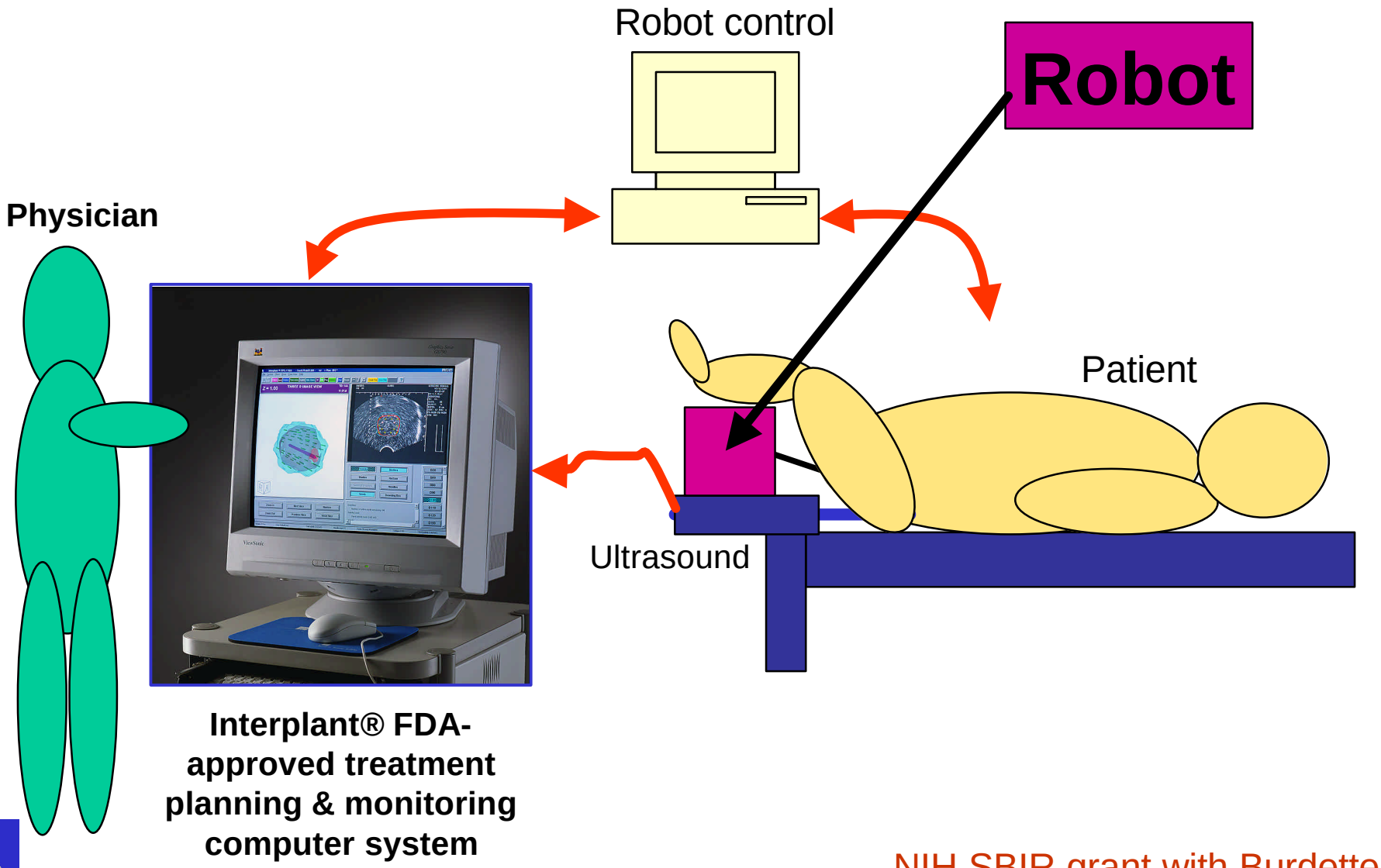
Copyright © CISST ERC, 1999-2003

Phase-1 results

- Reached all relevant locations
- Demonstrated arbitrary entry and angle
- Aiming error:
  - ~ 2.0 mm
  - worst case 2.5 mm
  - 80% in 2 mm margin
- Depth error:
  - ~ 2.5 mm
  - worst case 5.0 mm
  - 70% in 2.5 mm margin

Copyright © CISST ERC, 1999-2003

Phase-2 NCI grant to build compact robot

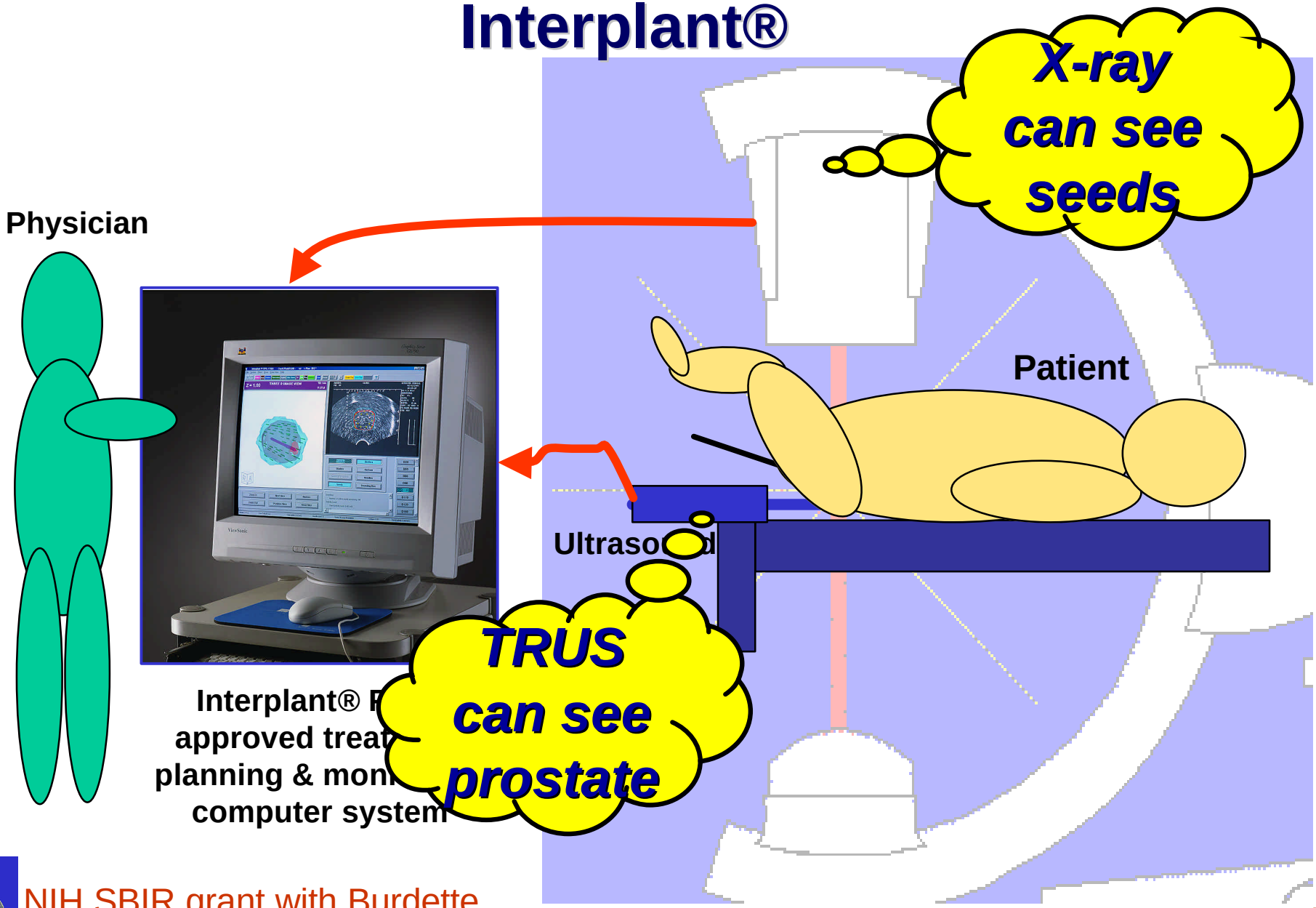


Interplant® FDA-approved treatment planning & monitoring computer system

NIH SBIR grant with Burdette

Copyright © CISST ERC, 1999-2003

Fusion of C-arm and TRUS in Burdette's Interplant®

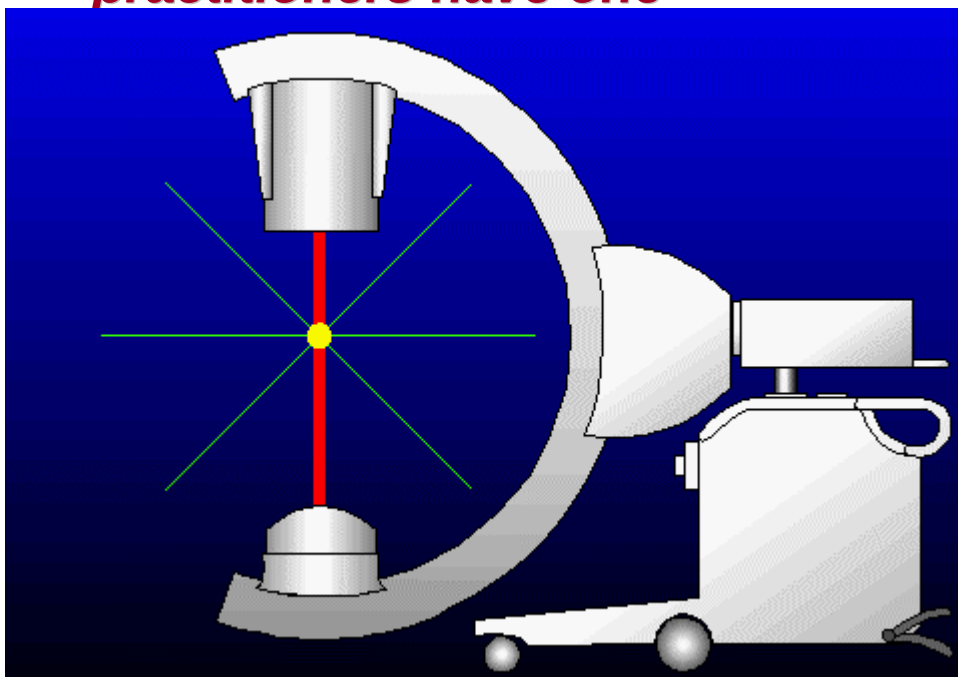


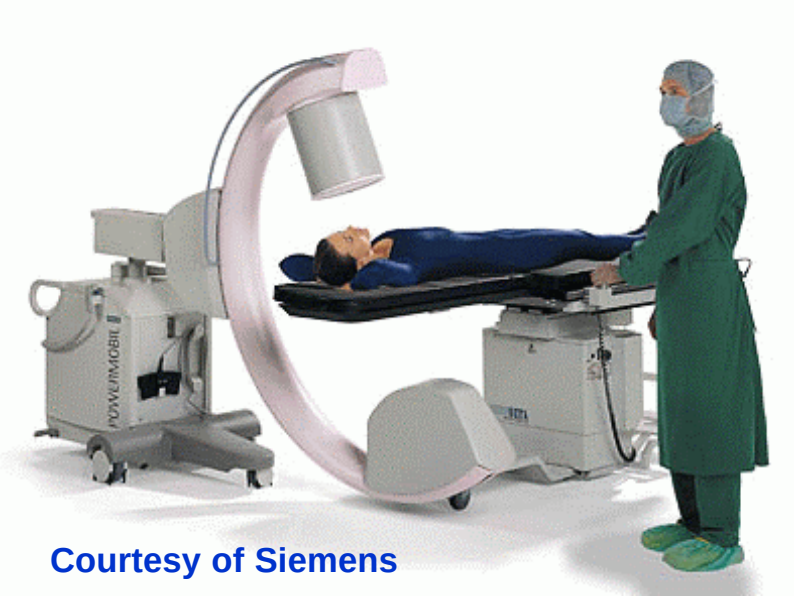
NIH SBIR grant with Burdette

Copyright © CISST ERC, 1999-2003

C-arm in surgery

- Mobile
- Real-time
- Inexpensive
- Broad coverage
- *60% of brachytherapy practitioners have one*



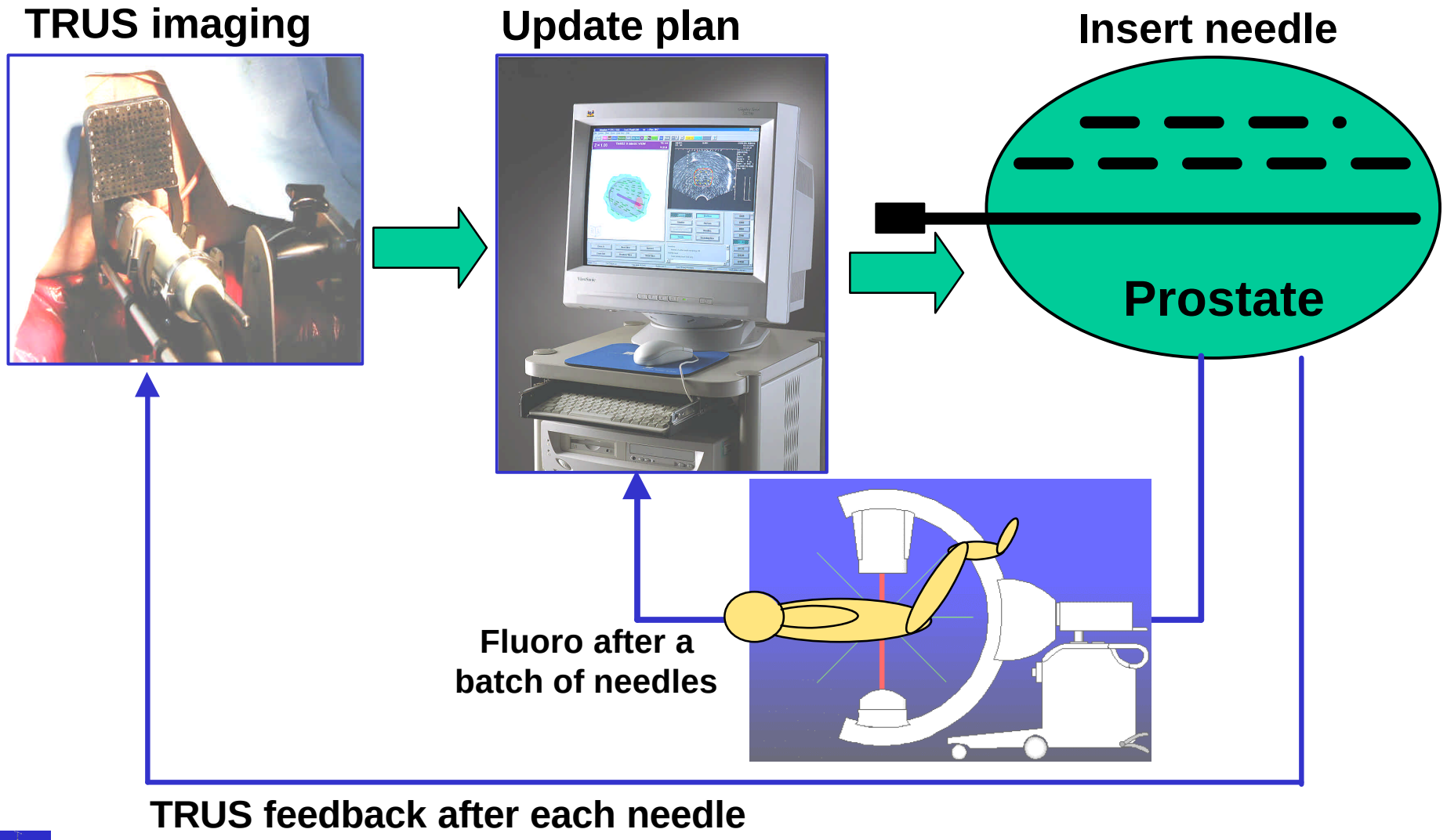


Courtesy of Siemens

- Limited rotation
- X-ray dose
- Need for calibration
- Low soft tissue contract
- Need for tracking

Copyright © CISST ERC, 1999-2003

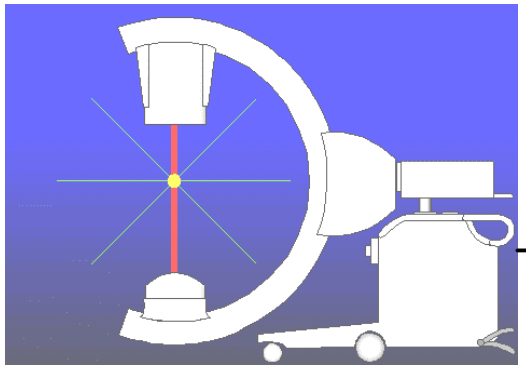
Procedural flow with C-arm augmentation



Copyright © CISST ERC, 1999-2003

Integrated System Design

Pre-op Calibration



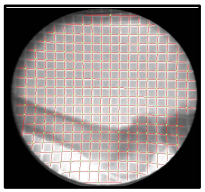


Image processing pipeline

C-arm calibration

Intra-op Fluoro

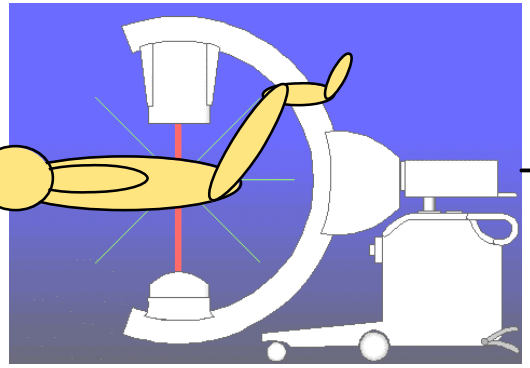


Image processing pipeline

Fiducials

Registration

Seeds

Seed Matching

3D Cloud of Seeds

Intra-op TRUS

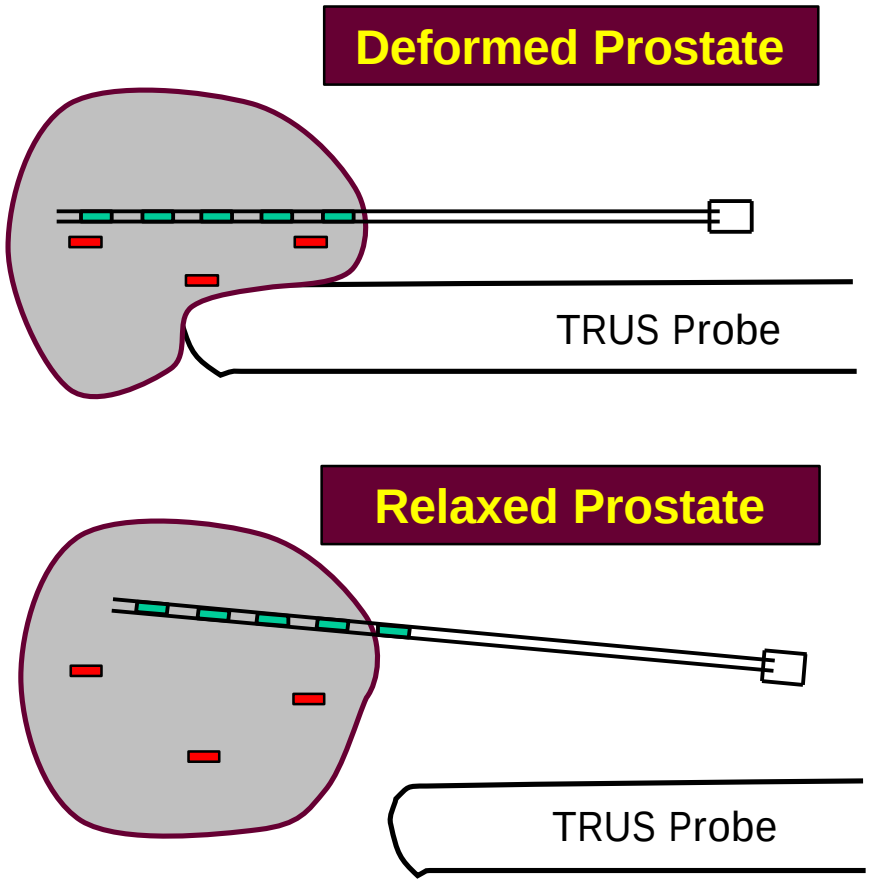
3D US Reconst ruction

3D Dosimetry

Currently available in Interplant®

Copyright © CISST ERC, 1999-2003

Problem 1: Organ motion and deformation during TRUS imaging



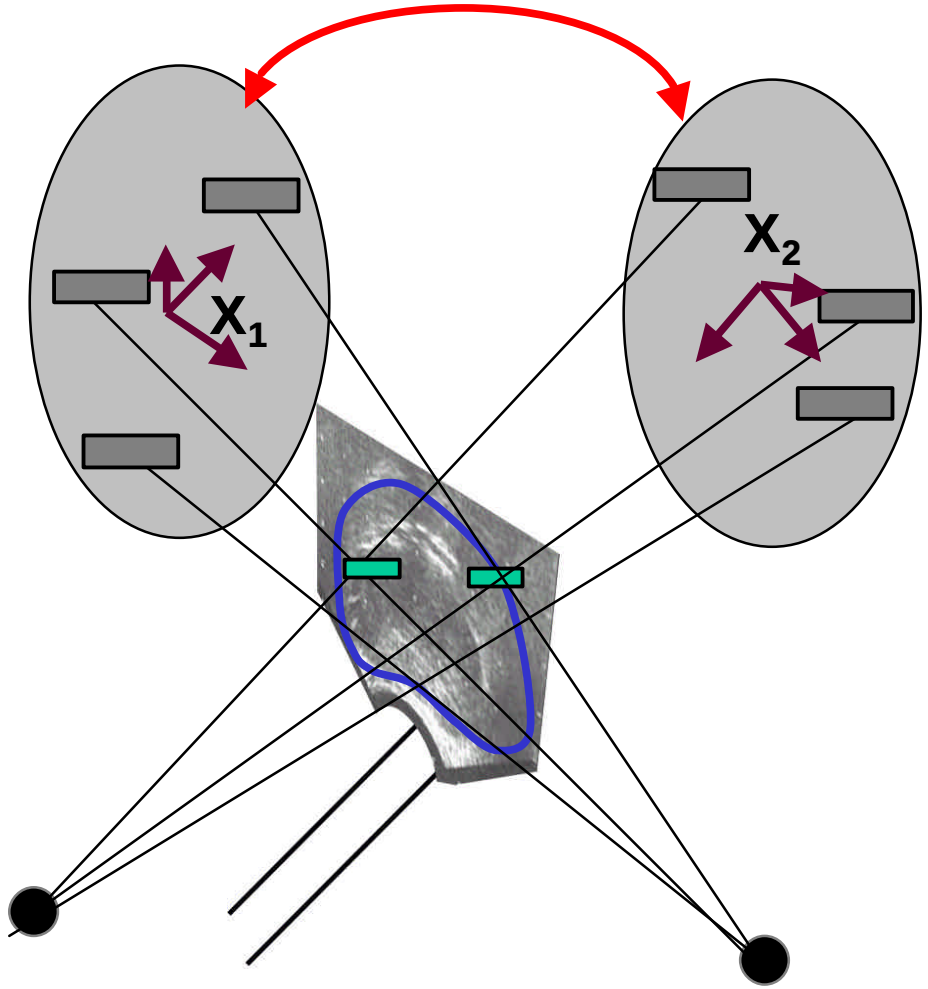
Few possible fiducials:

- **Active seeds**
- **Marker seeds**
- **Implant needles**
- **Stabilizer needles**
- **Urethral catheter**

Fiducials dislocate relative to prostate anatomy

Copyright © CISST ERC, 1999-2003

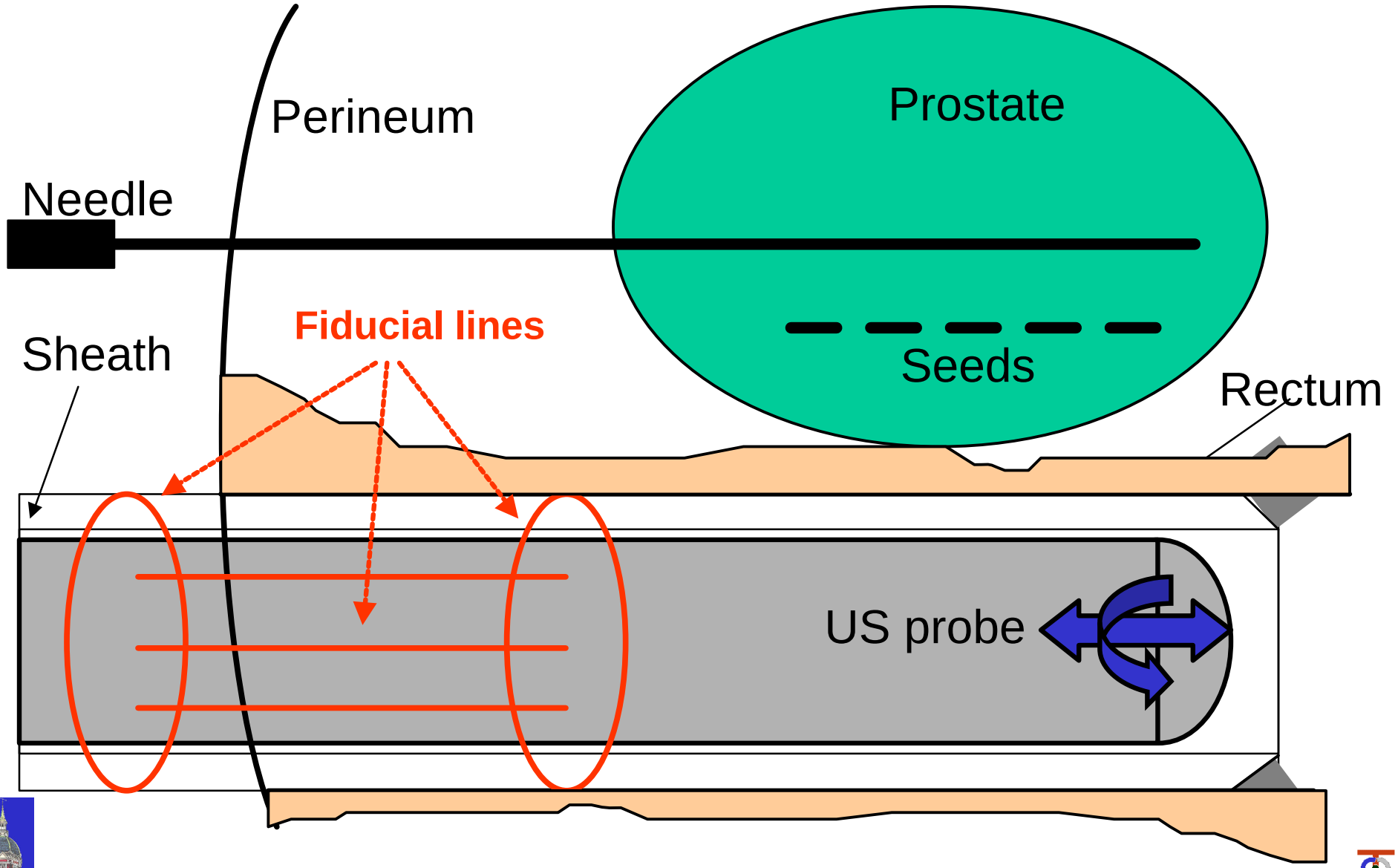
Problem 2: C-arm tracking a.k.a. pose encoding



Need to know where the X-ray shots are coming from relative to one to another

Copyright © CISST ERC, 1999-2003

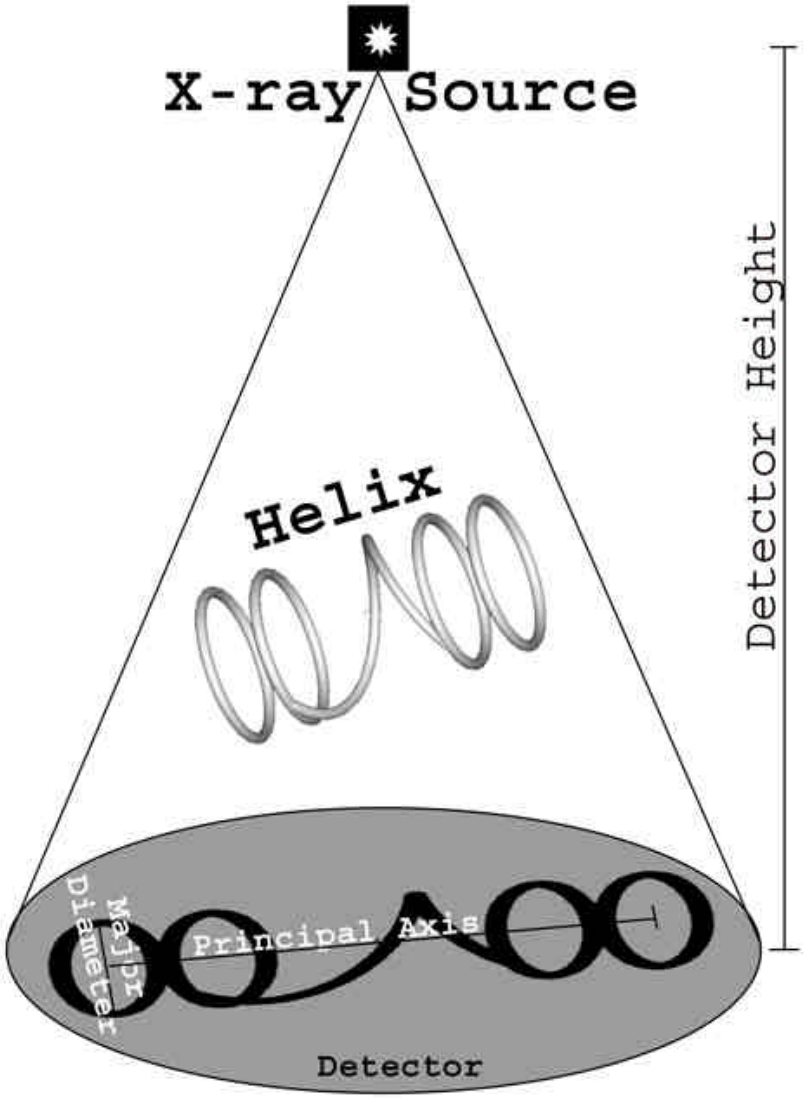
Our approach: transrectal sheath with mounted 6-DOF fiducials



Copyright © CISST ERC, 1999-2003

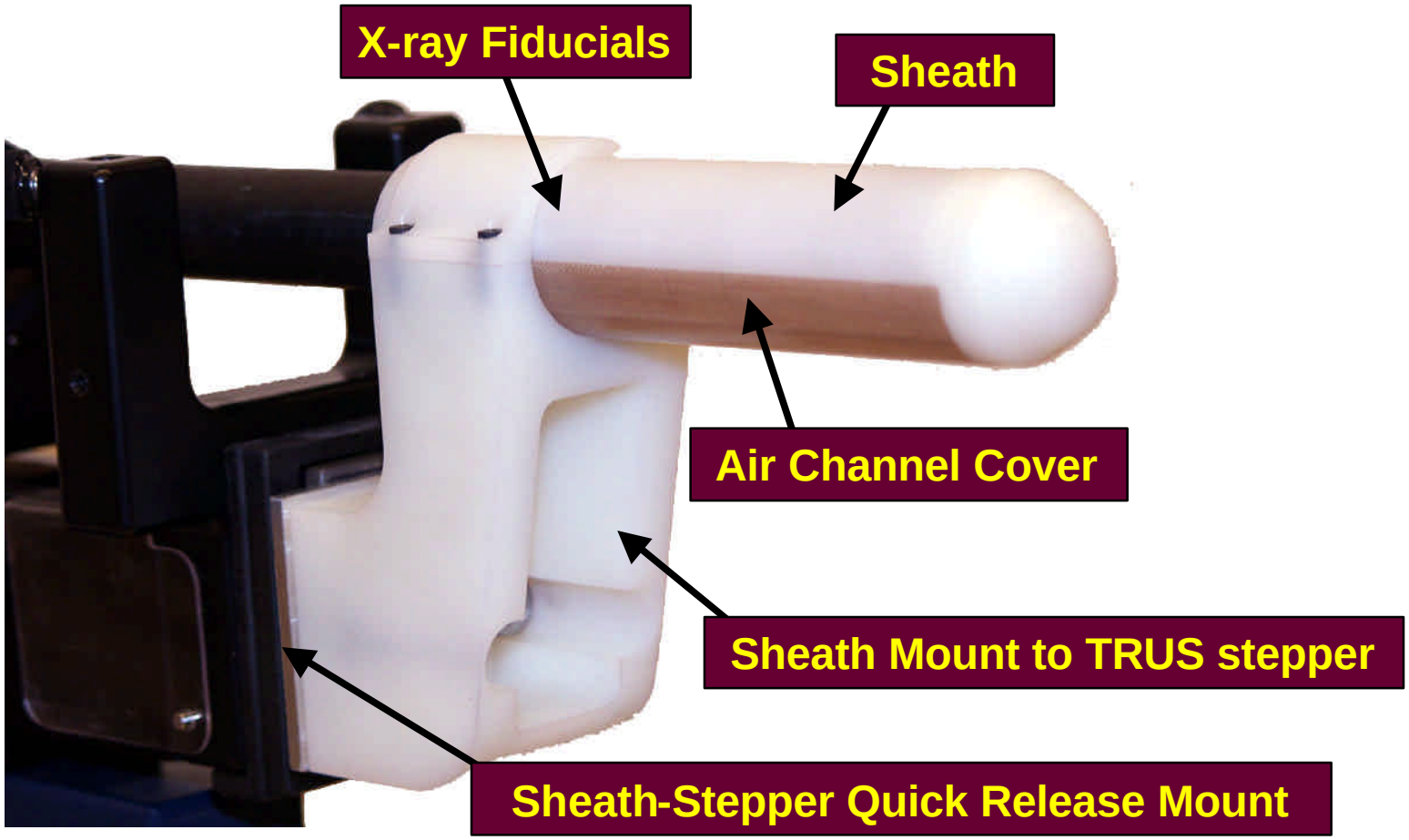
Pose encoding with helical fiducial

- All six degrees of freedom of the helix can be computed from one projection of the Helix
- By Fixing the Helix to the TRUS stepper → Know transformation between every X-ray picture and TRUS.



Copyright © CISST ERC, 1999-2003

Sheath fixed to TRUS stepper base



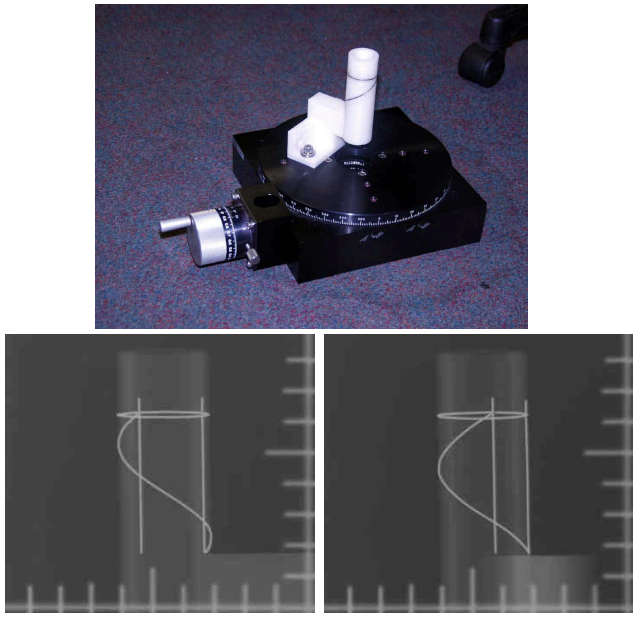
Copyright © CISST ERC, 1999-2003

Pose encoding validation results

Z-axis Rotation

Average Error 0.2°

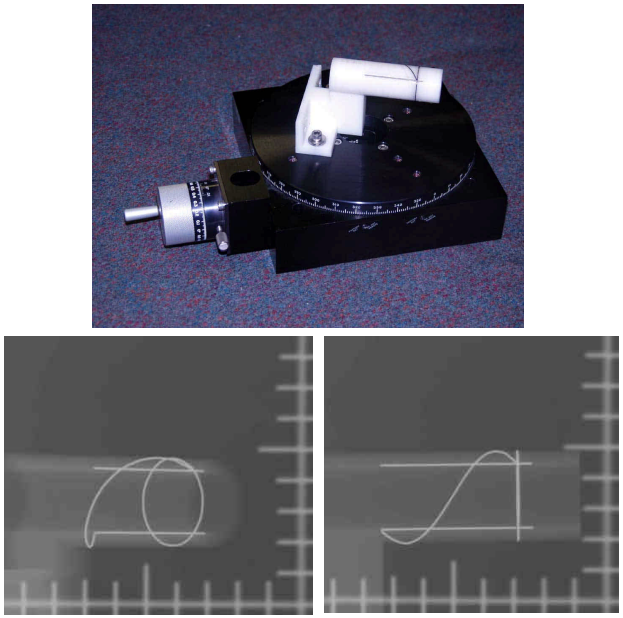
Max Error 0.7°



Y-axis Rotation

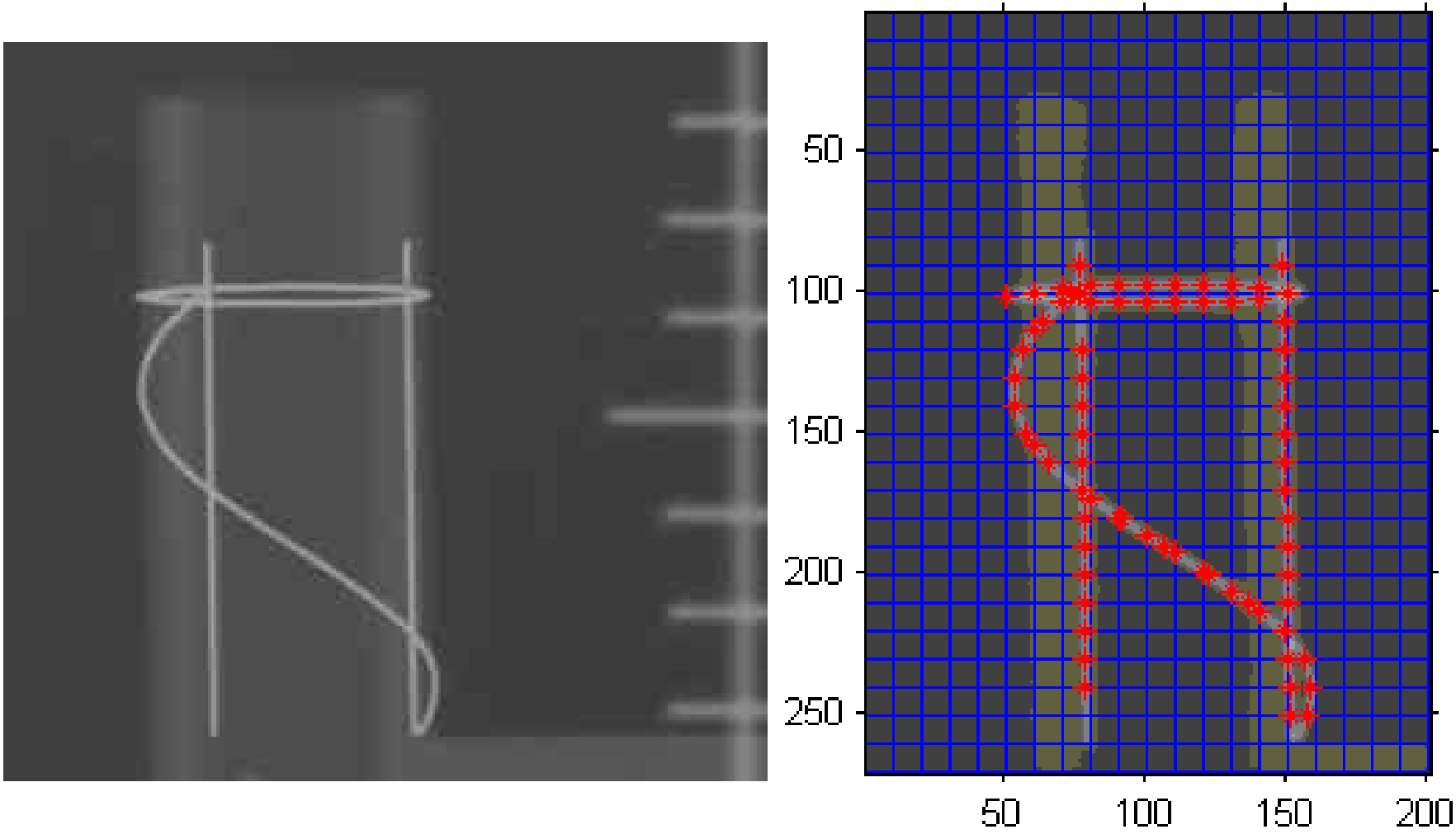
Average Error 0.58°

Max Error 1.7°



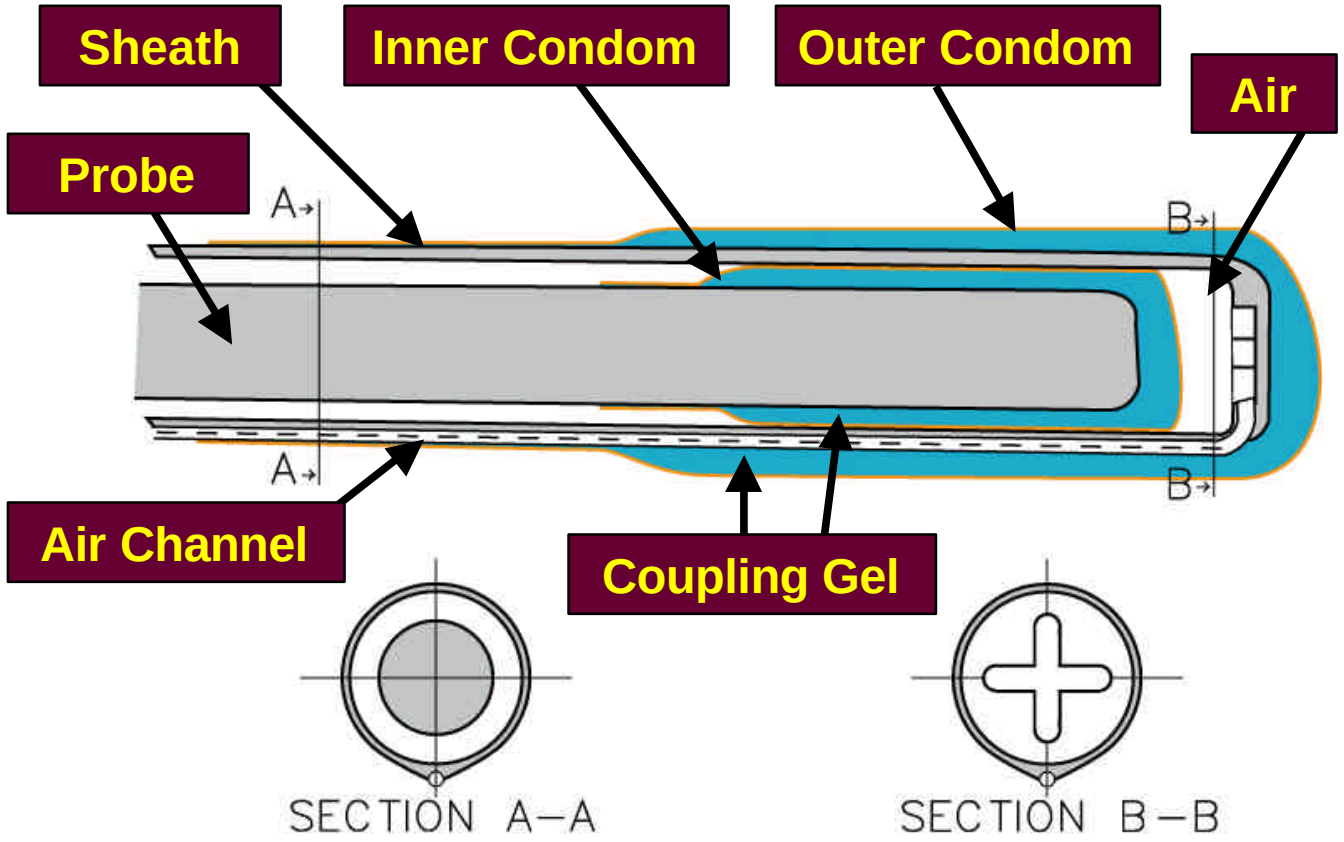
Copyright © CISST ERC, 1999-2003

Auto-segmentation of RUF fiducials



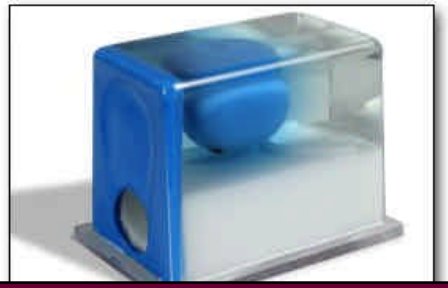
Copyright © CISST ERC, 1999-2003

Acoustic coupling in sheath with condom and gel



Copyright © CISST ERC, 1999-2003

Acoustic coupling experiments on standard phantom



Prostate Phantom

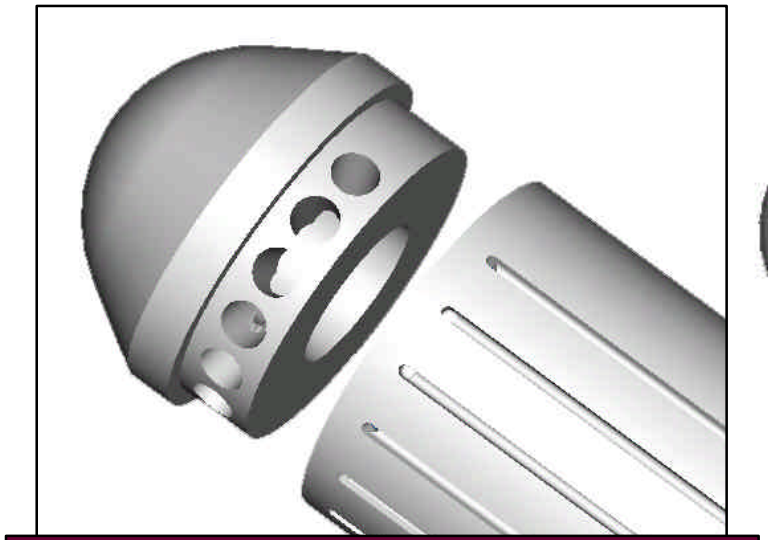
Bare TRUS Probe

Probe w/ condom

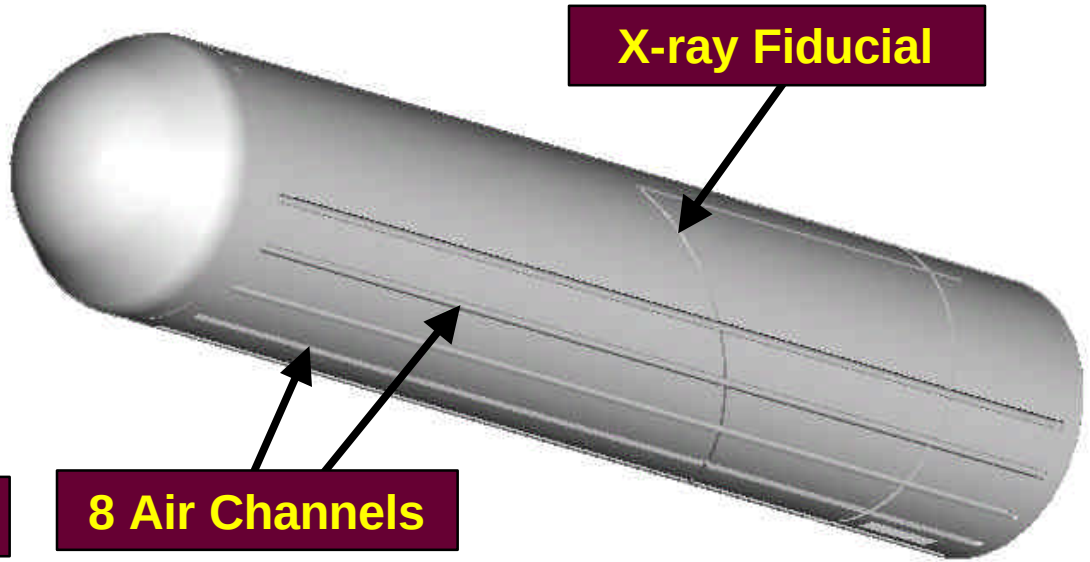
Probe w/ condom + Sheath

Copyright © CISST ERC, 1999-2003

Sheath with depressurizing air channels

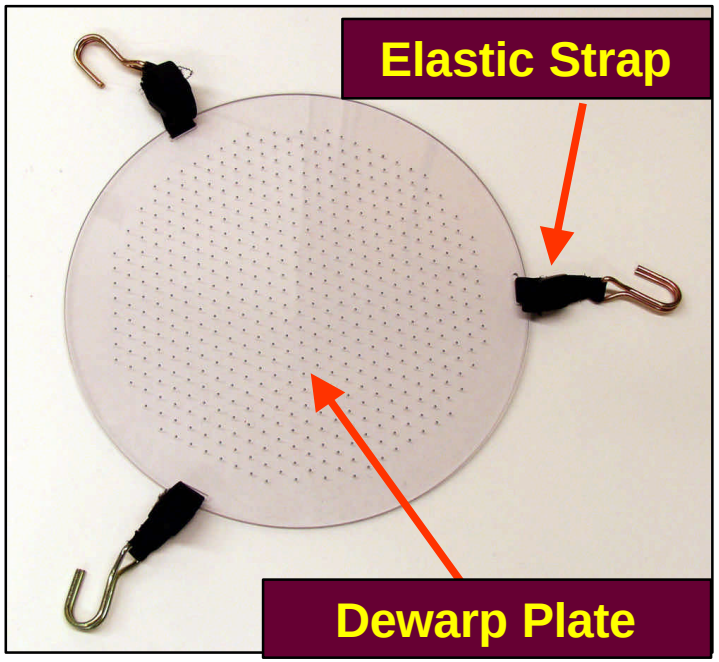


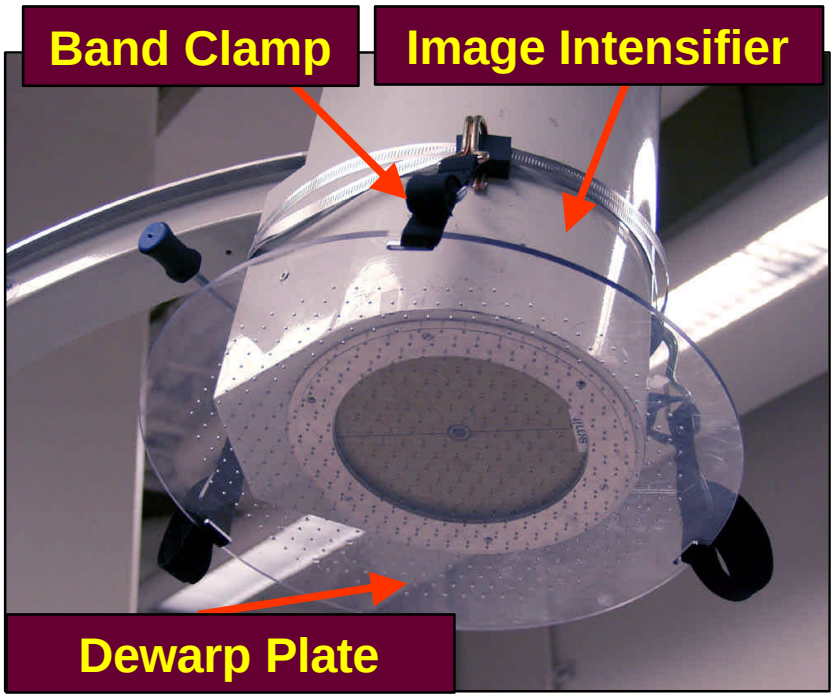
Exploded View of Channels



Copyright © CISST ERC, 1999-2003

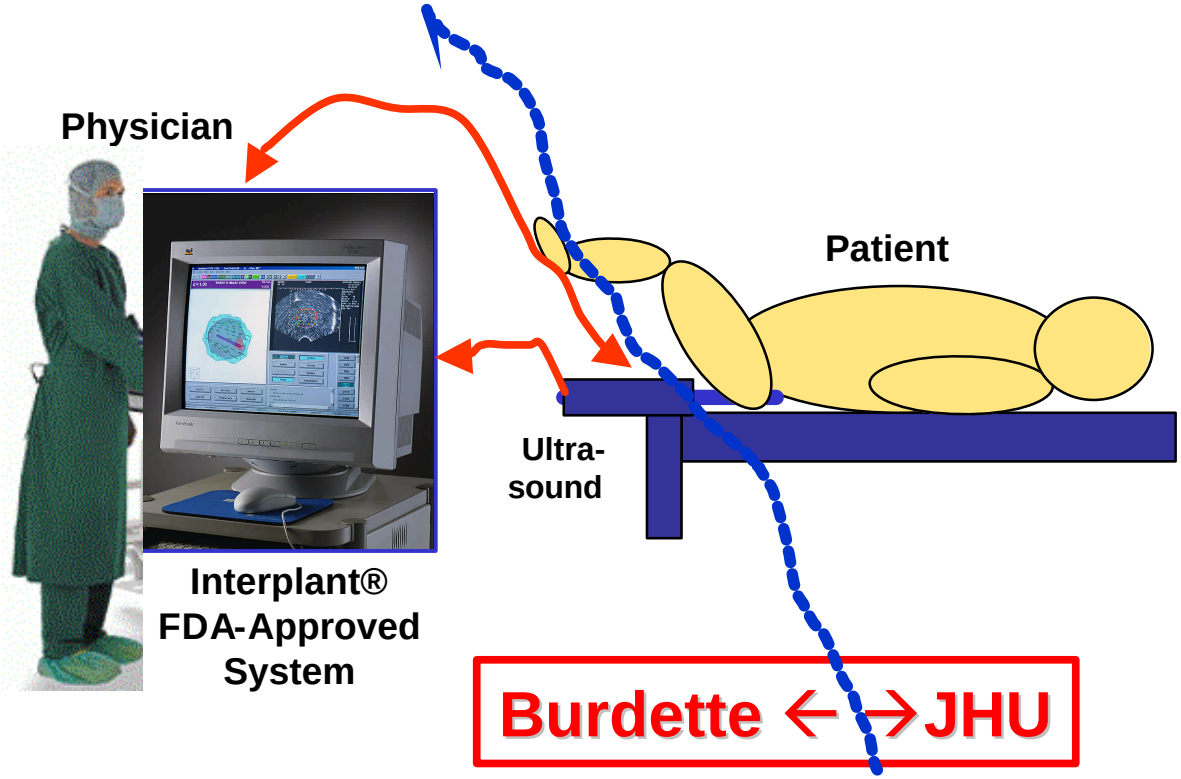
Universal C-Arm dewarping/calibration kit

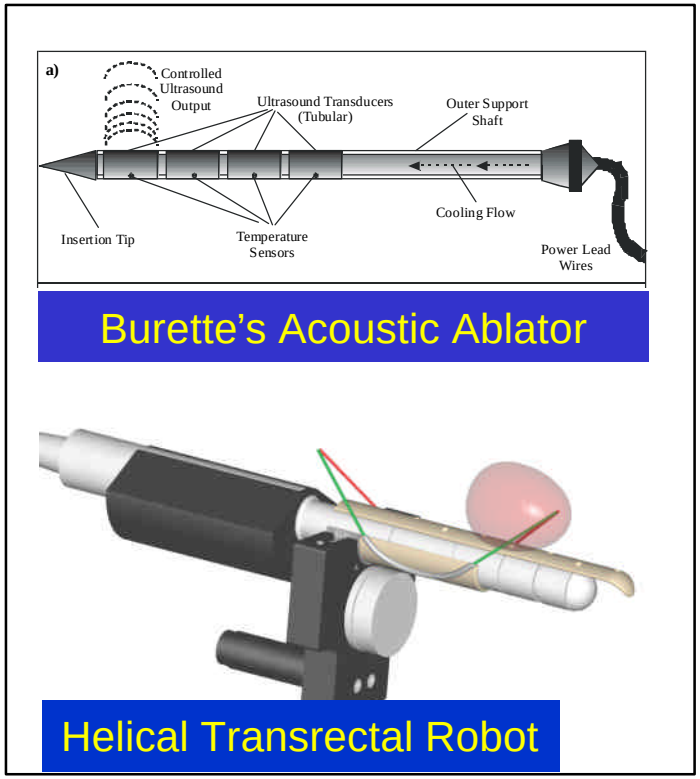




Copyright © CISST ERC, 1999-2003

TRUAP – Transrectal Ultrasound-Guided Ablation of the Prostate



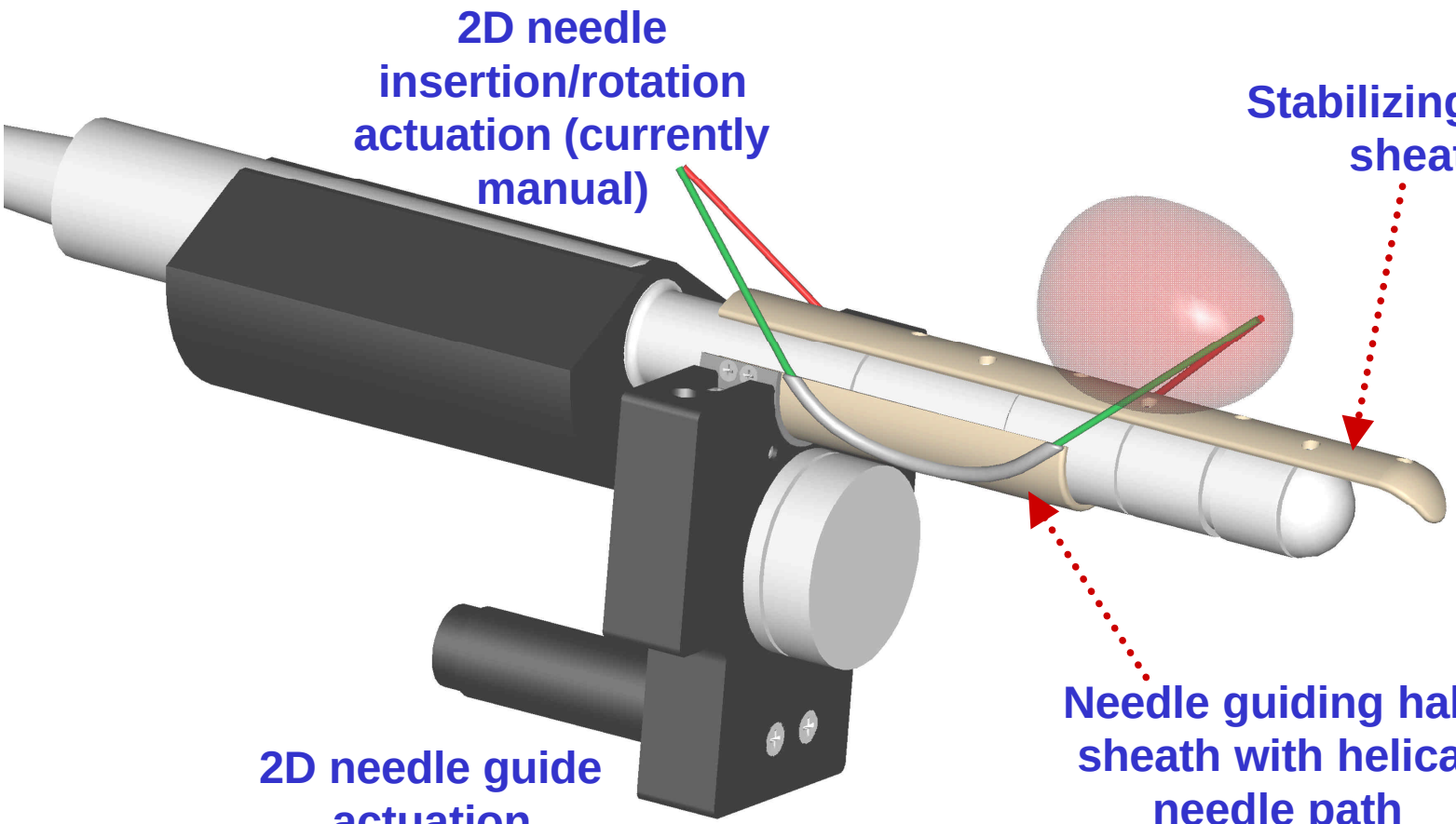


Industry Partner: Acoustic MedSystems / Burdette Medical

Funded by Acoustic MedSystems / Burdette Medical
NIH Fast-Track STTR pending w/ Burdette

Copyright © CISST ERC, 1999-2003

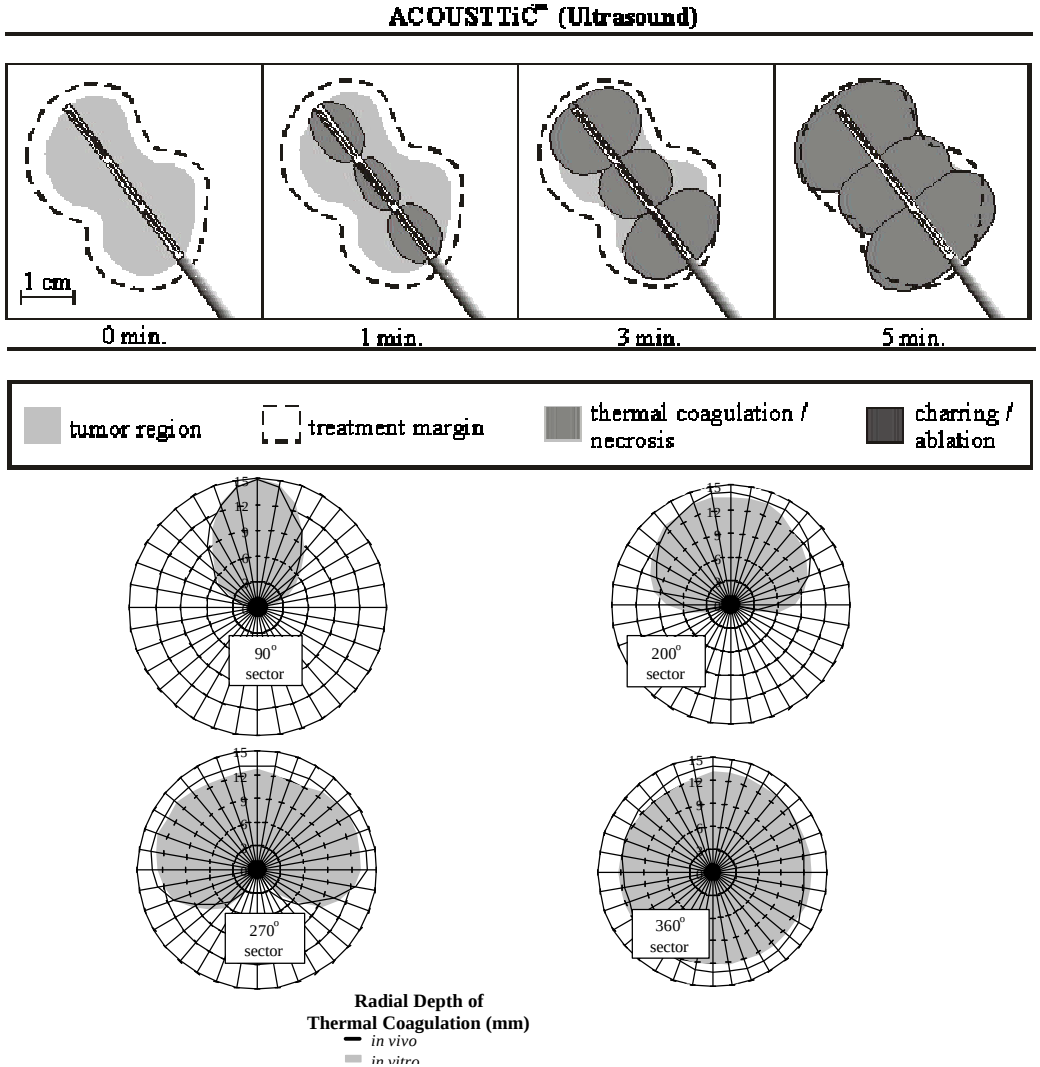
Helical 4-DOF transrectal robot built around the TRUS probe

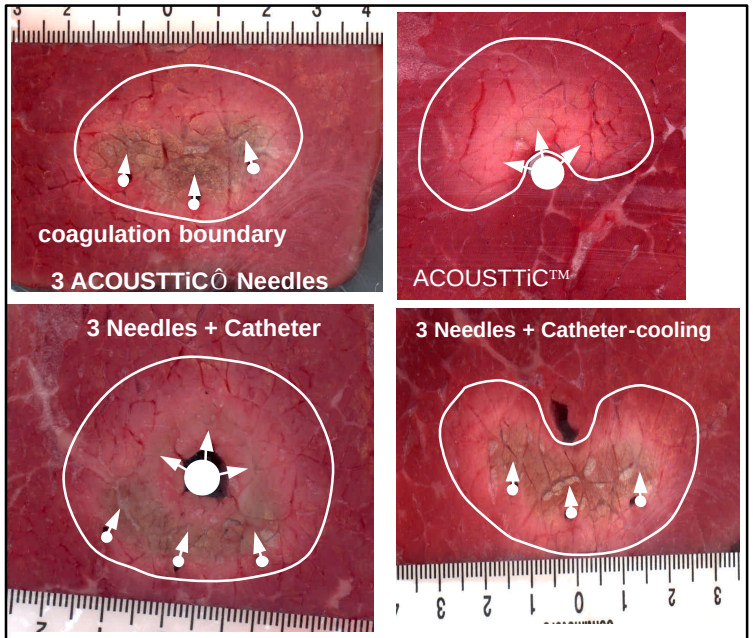


The needle can be driven through a curved path (even beyond the limit of elasticity) as long as it comes out in a controlled trajectory)

Copyright © CISST ERC, 1999-2003

Burdette's HIIU Ablator





Lesions of thermal coagulation produced *in vitro* with three applicators demonstrating conformal control of energy and heating (cross-sectional slices), in bovine muscle, in-vivo. Note the clear demarcation of thermal coagulation achieved in 5 minutes.

It is enough to deliver the needle nearby the target volume, because the placement error is compensated electronically

Copyright © CISST ERC, 1999-2003