Model-Augmented Image Guidance for Soft-Tissue Surgeries and Interventions

Advances in Image-Guided Interventions

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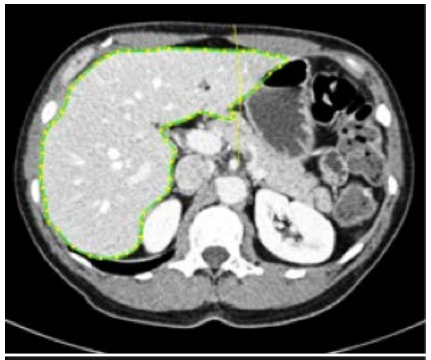
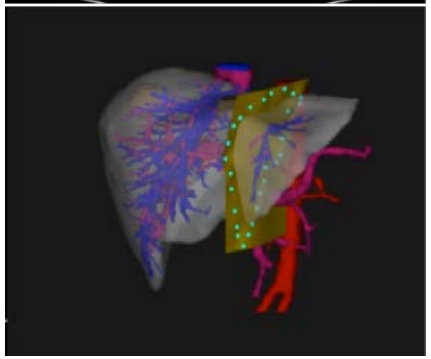
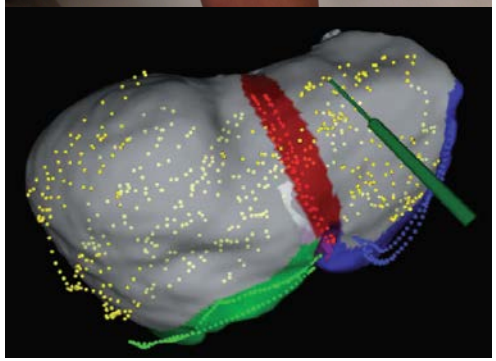
Discussion points for today's talk

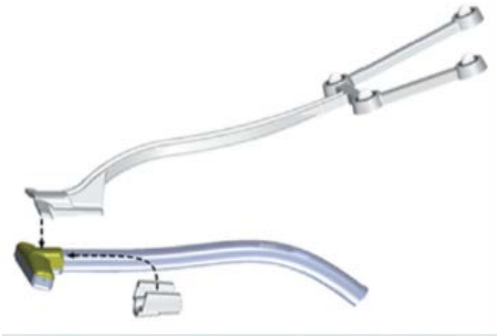
- Modeling as a Scaffold for Intraoperative and Interventional Data
  - We can't measure everything!
  - Biophysical models offer: ease of integration, accurate estimation, and constraint
  - Result is the *enables of sparse data-driven assistance to therapy*
- Examples of Model-Augmented Image Guidance
  - Enhancing localization with soft-tissue biomechanics
  - Predicting thermal dose extent with soft-tissue bioelectric/bioheat transport
- Available Challenge Data for the Community

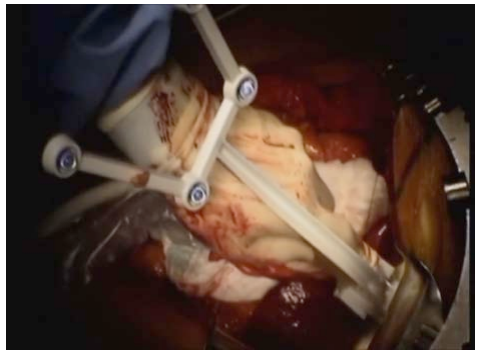
… evolving image guidance technology …











Segmentation & Planning → Intraoperative Surface-based Registration → Tracked Ultrasound

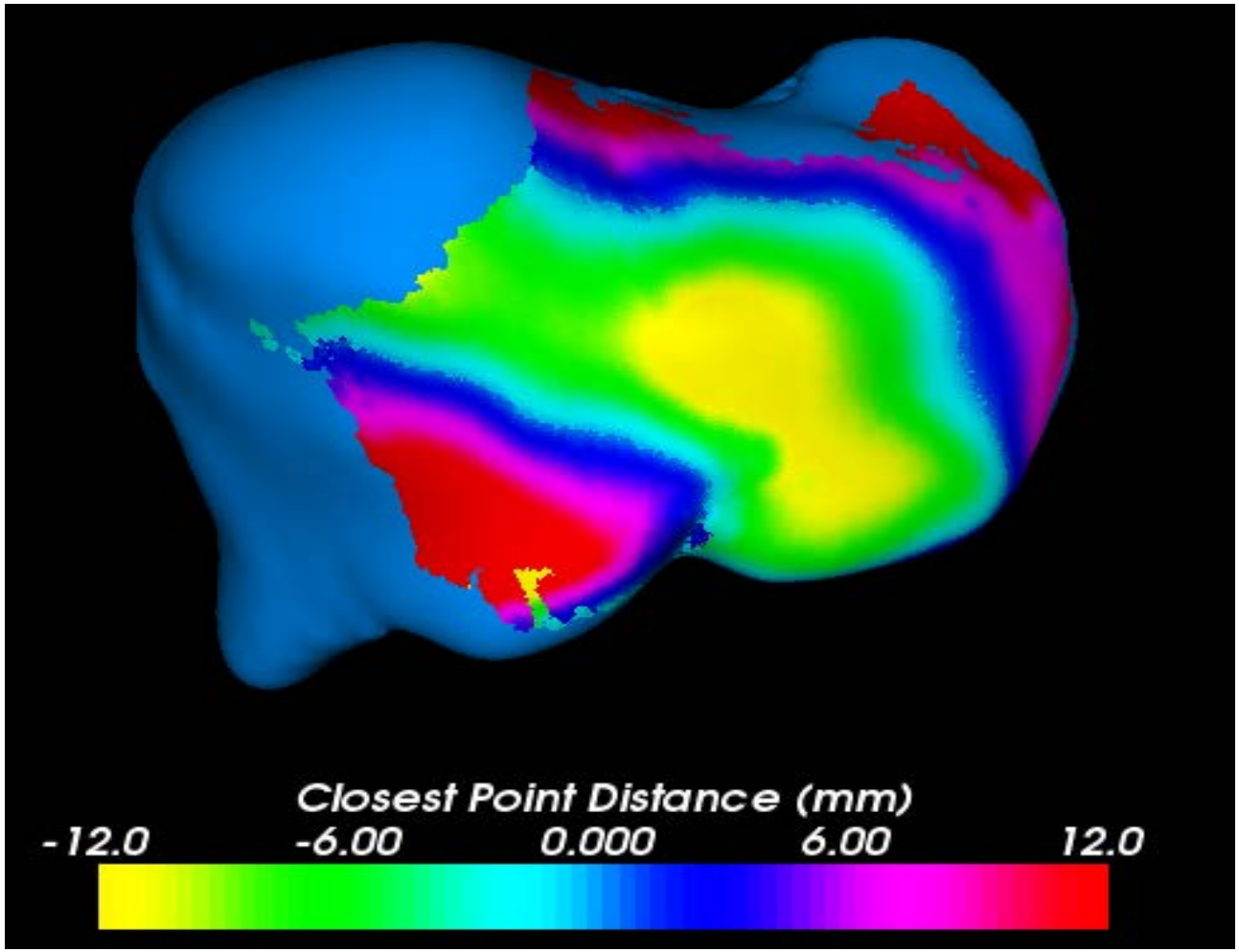
… evolving image guidance technology …

Imaging/Information

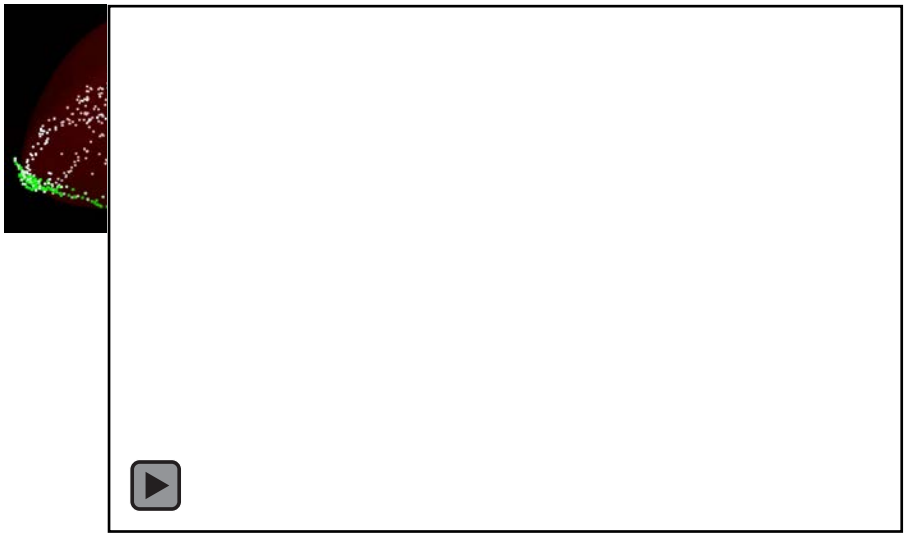
Localization/Digitization

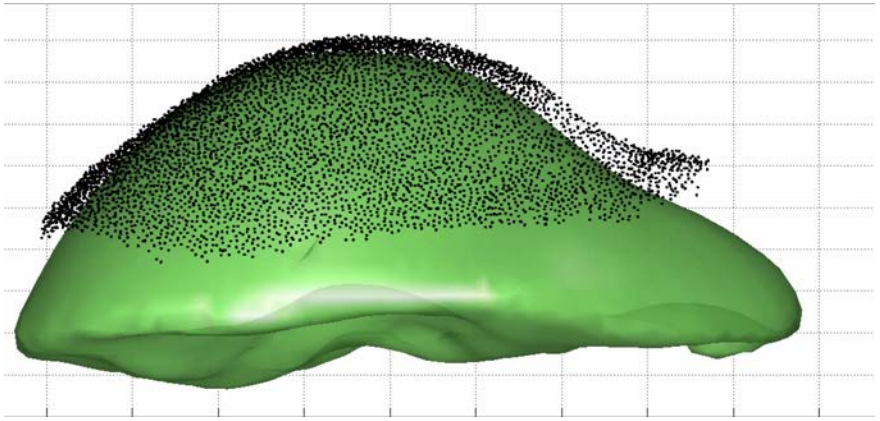
Registration

… evolving image guidance technology …



Model-based augmentation …

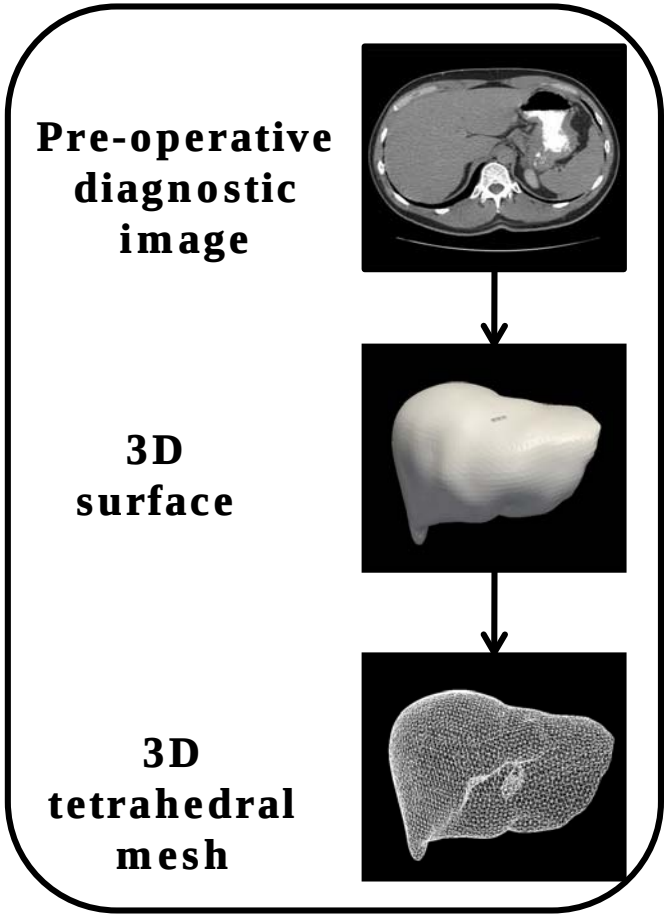


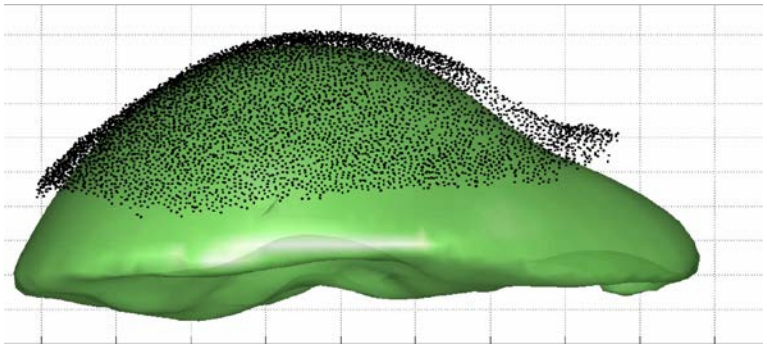


Intraoperative Data

Model-based Deformation Correction

Sparse-data driven image-to-physical registration





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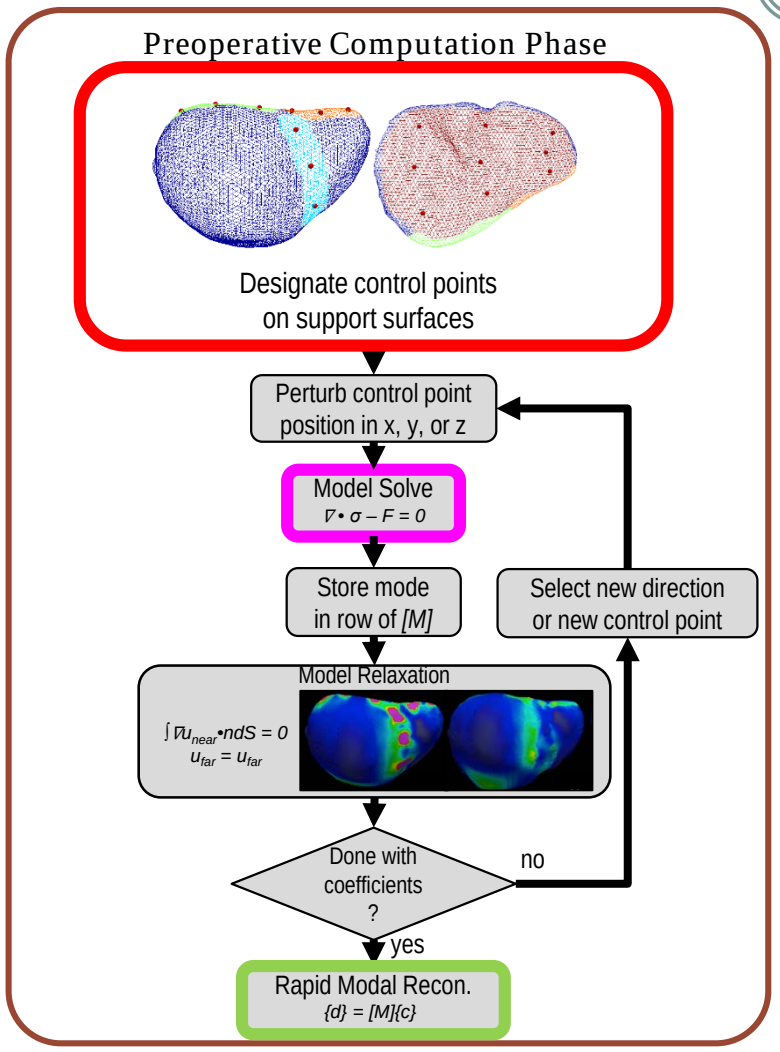
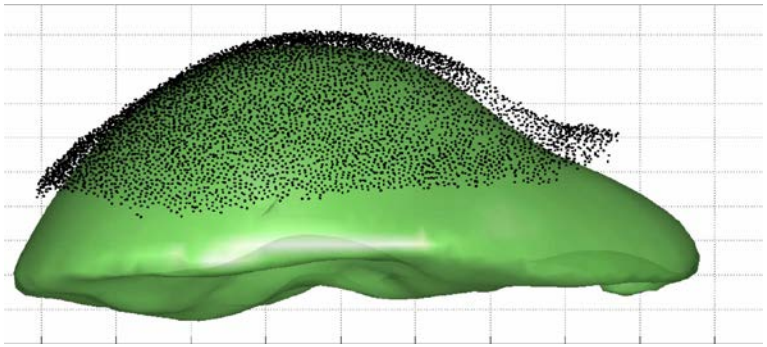
J. S. Heiselman, et al., "Characterization and correction of intraoperative soft tissue deformation in image-guided laparoscopic liver surgery," *Journal of Medical Imaging*, vol. 5, no. 2, Apr 2018.

Sparse-data driven image-to-physical registration





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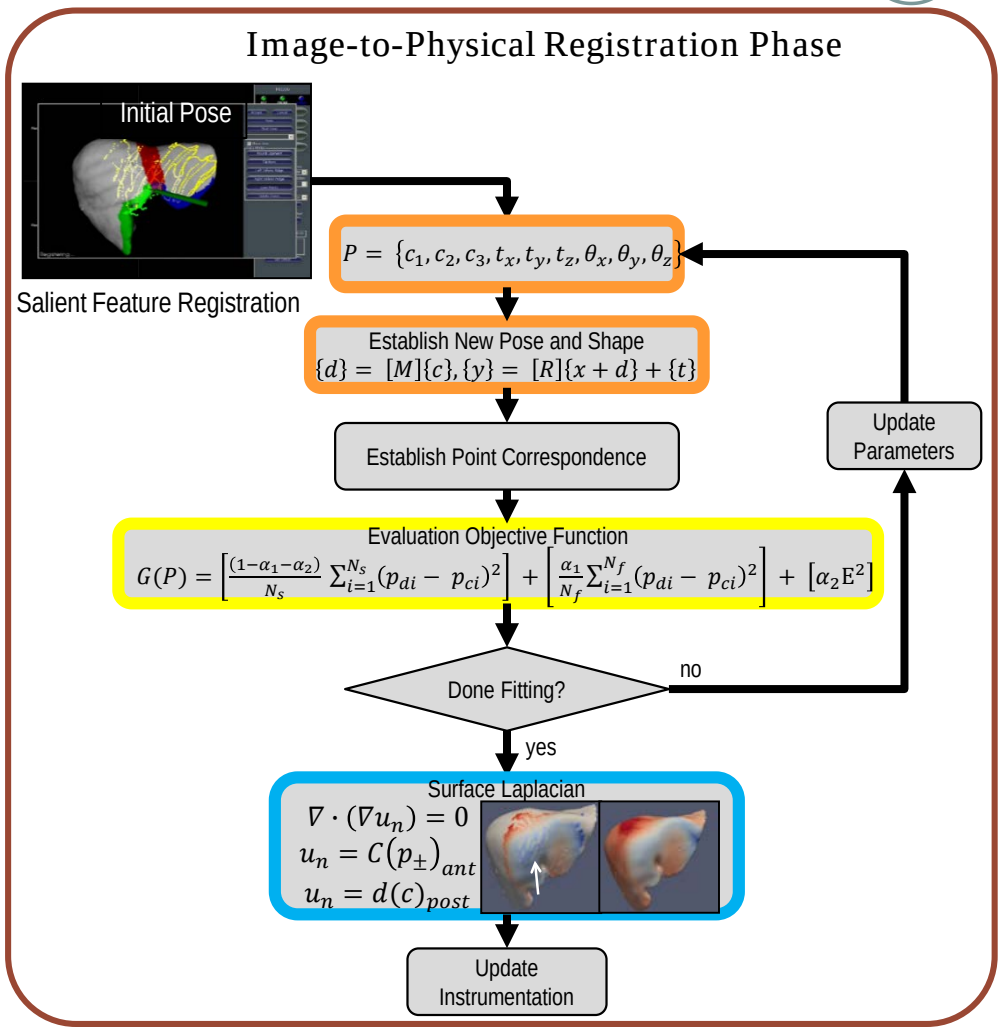
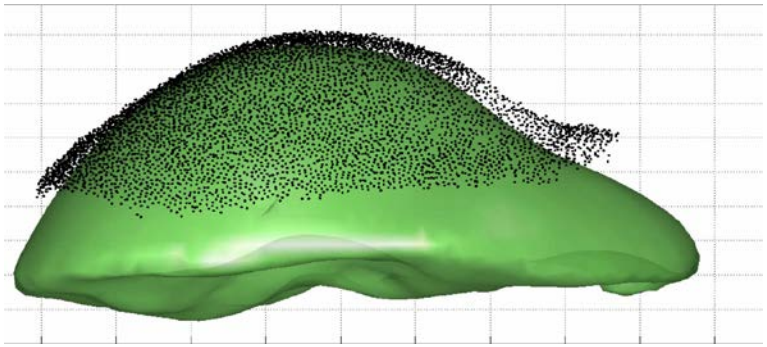
Sparse-data driven image-to-physical registration





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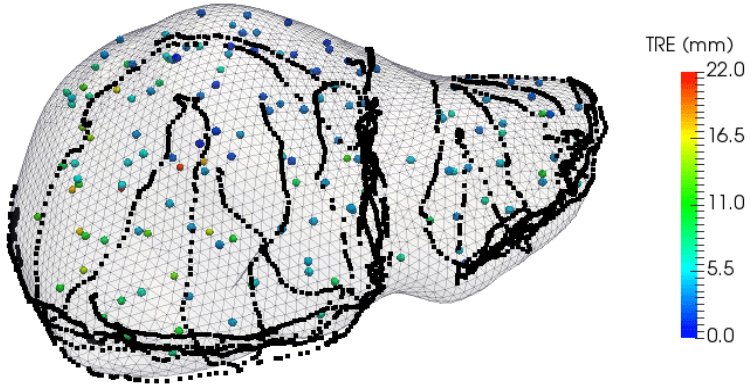
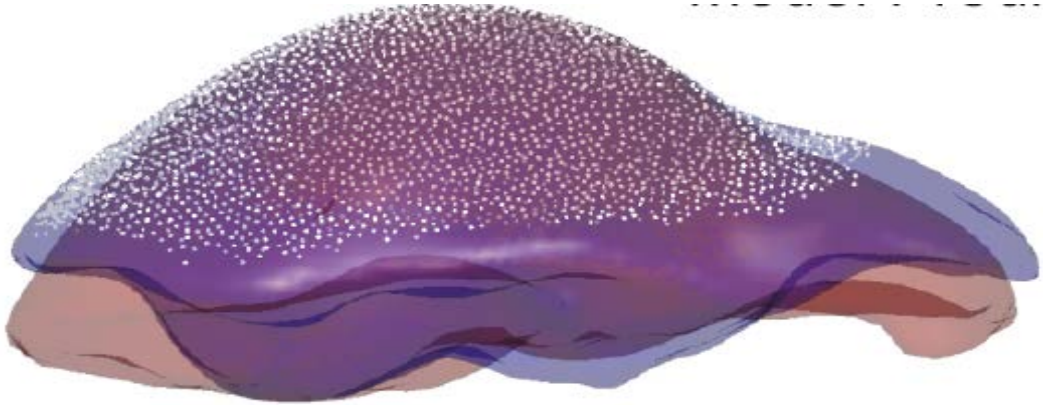
Human-to-phantom study …

J. A. Collins, et al., 'Improving registration robustness for image-guided liver surgery in a novel human-to-phantom data framework', *IEEE Transactions on Medical Imaging*, Vol. 36, No. 7, pp. 1502-1510, 2017



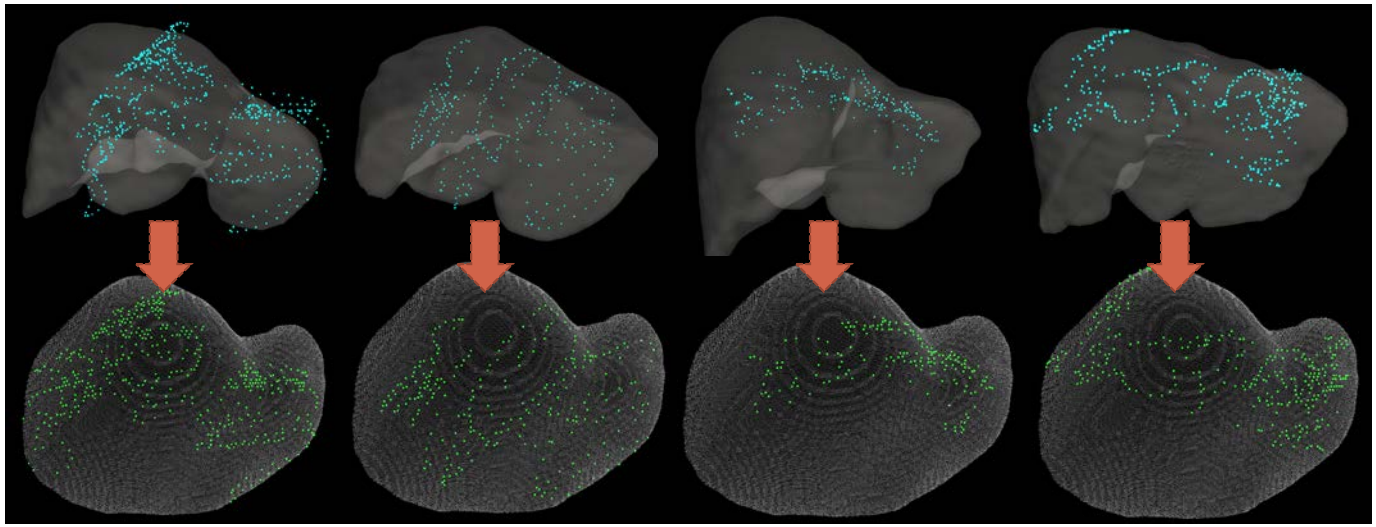
Phantom has known volumetric deformation



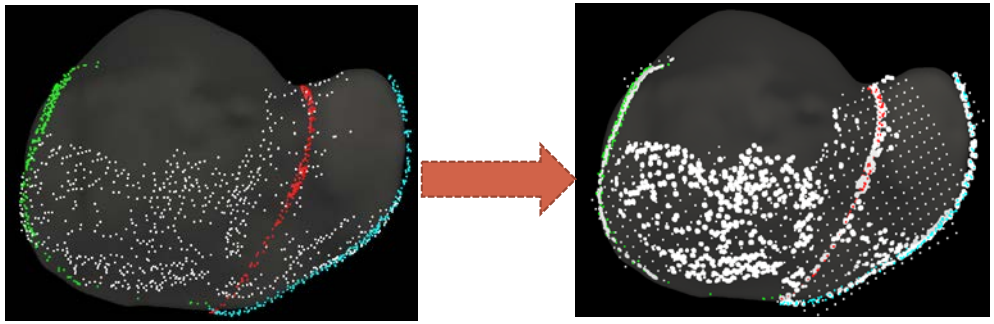
Human-to-phantom study …

N=13

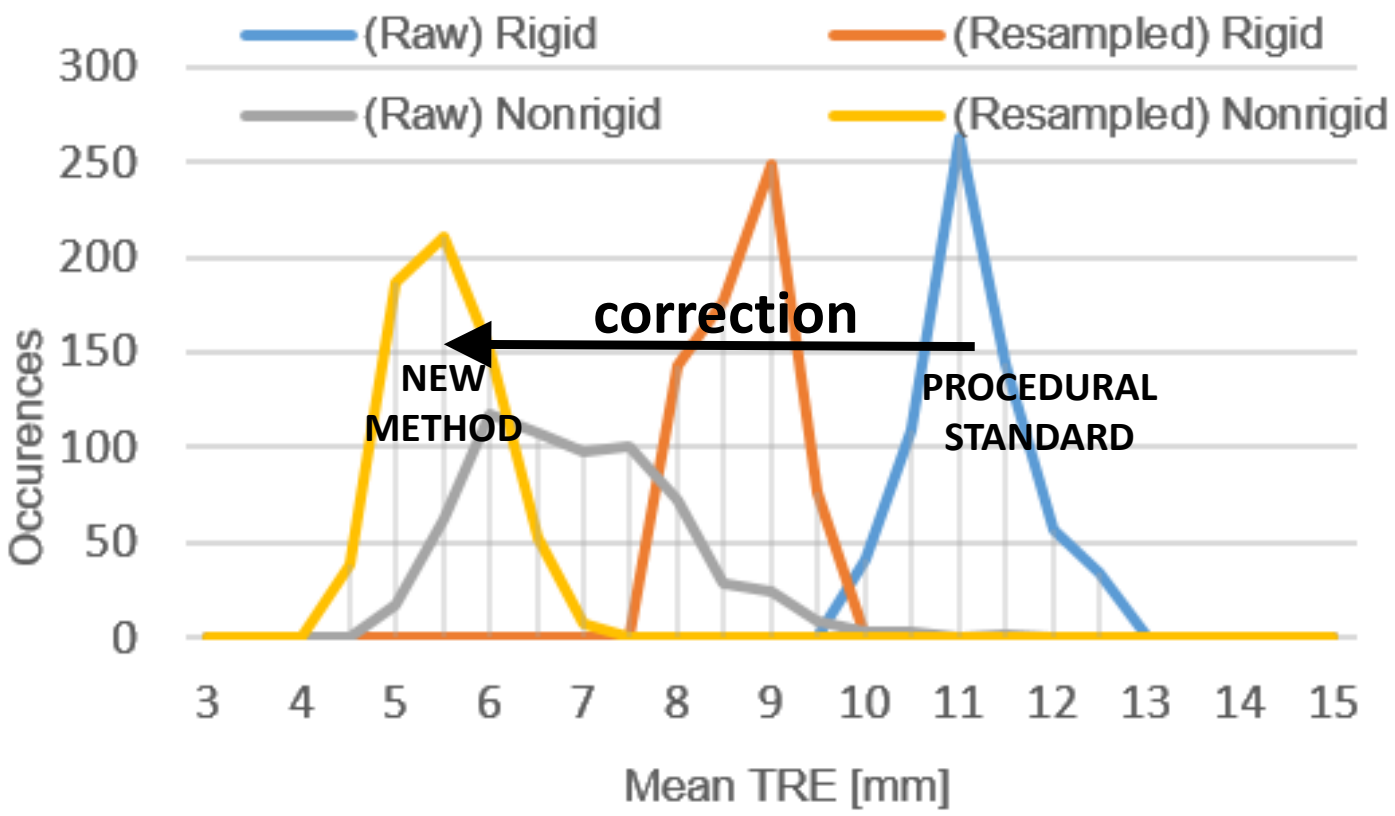
Transpose OR pattern on quantitative phantom



Develop Sampling Strategy to Improve Robustness

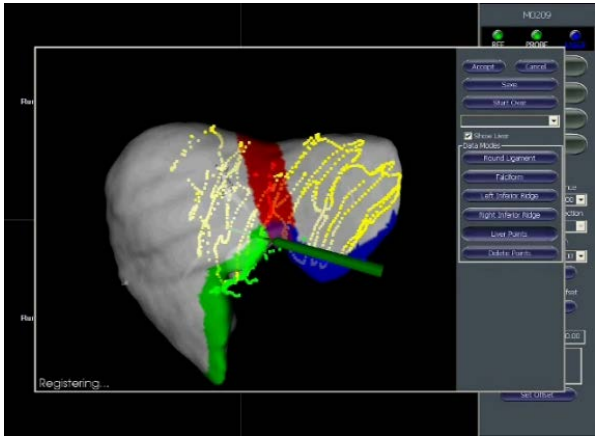


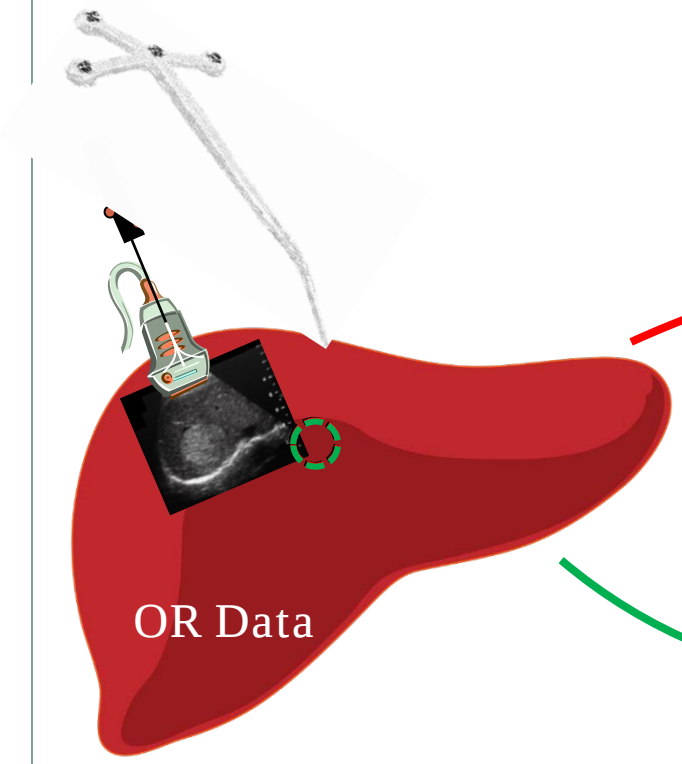
Human-to-phantom study … Results



Interventional ultrasound study …

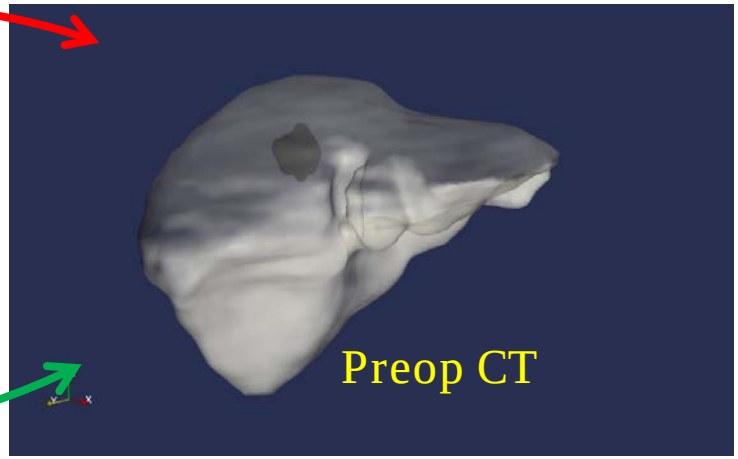
L. W. Clements, et al., 'Towards validation of model-based deformation correction in image-guided liver surgery via tracked intraoperative ultrasound', *Journal of Medical Imaging*, Vol. 3, No. 1, pp. 015003, 2016.





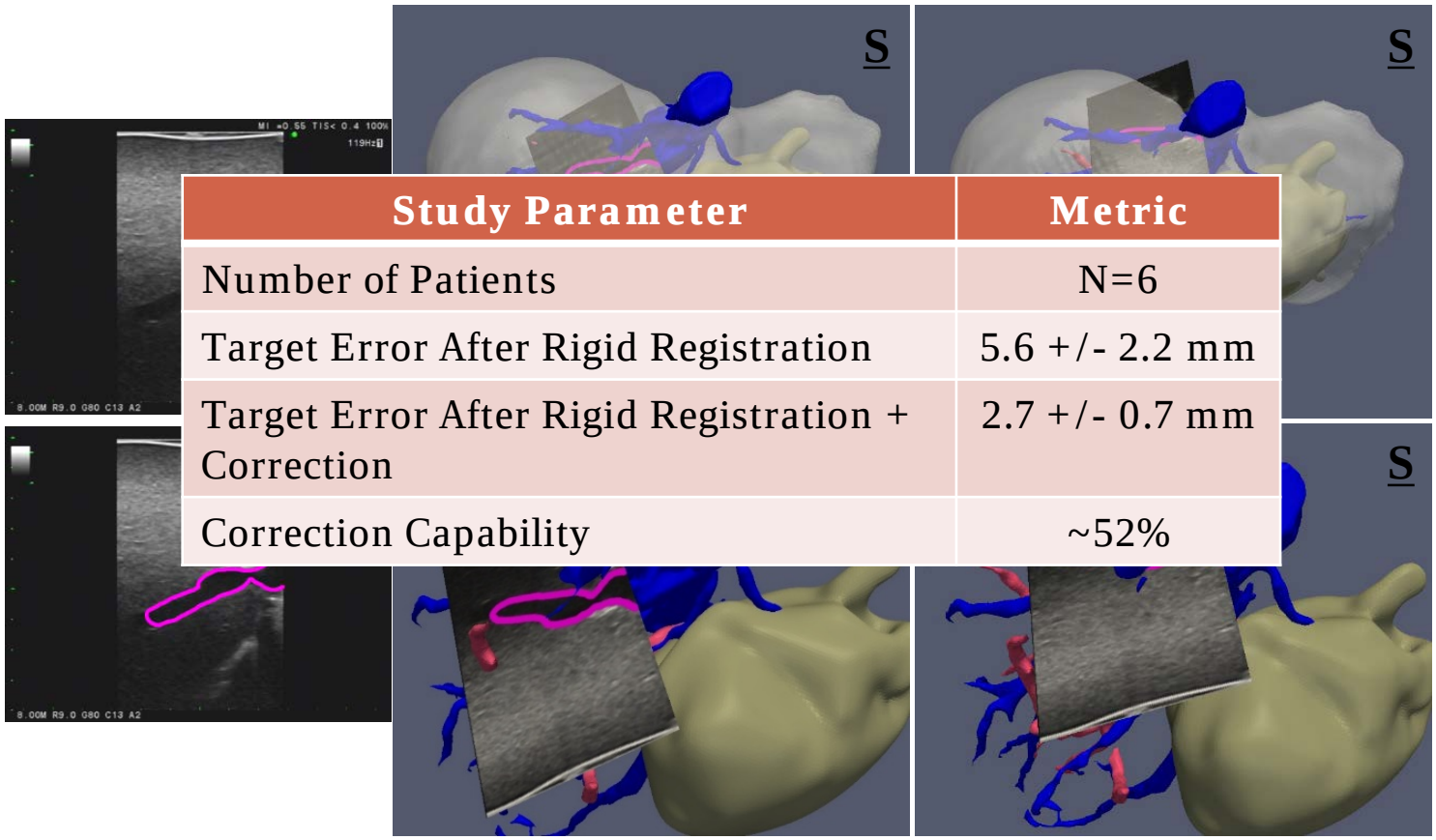
$[T]_{Rigid}$

$[T]_{Rigid} + [\Delta]_{Correction}$



Interventional ultrasound study … Results

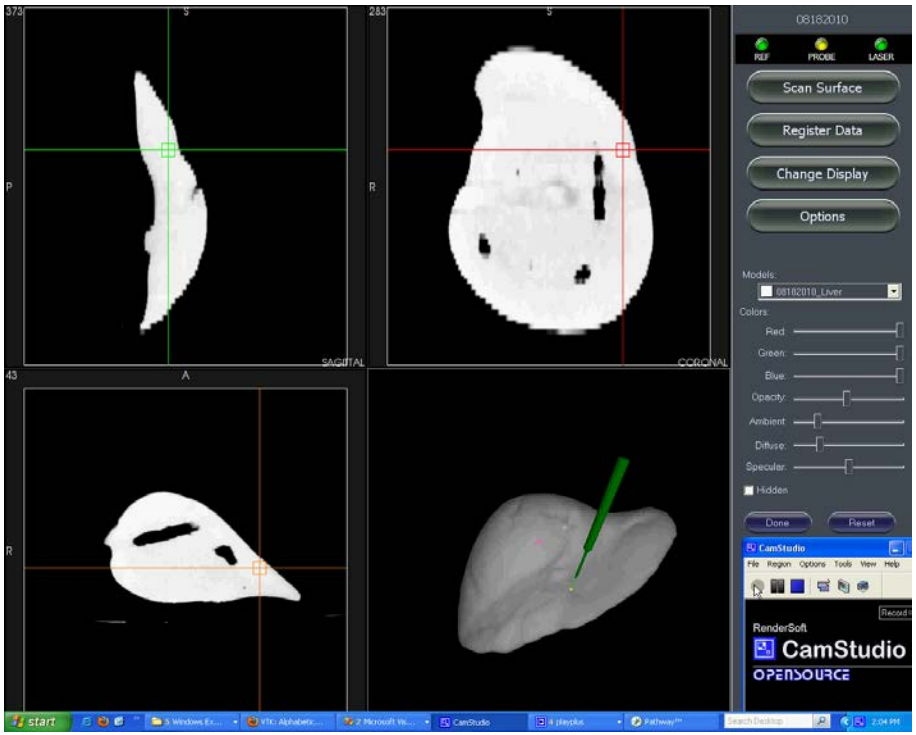
Rigid Registration | Post-Correction



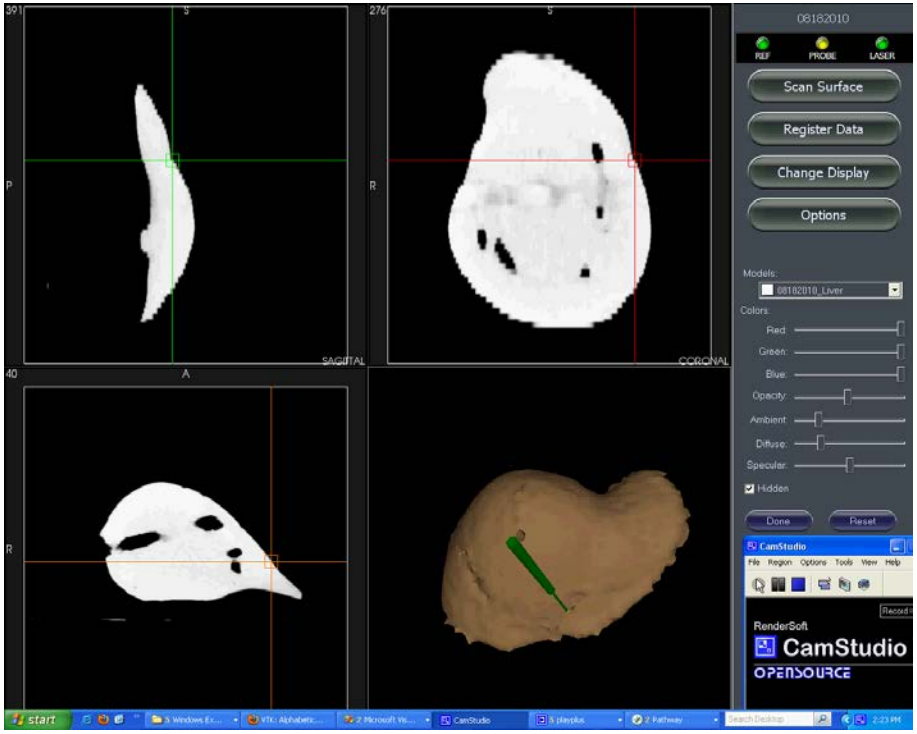
Study Parameter	Metric
Number of Patients	N=6
Target Error After Rigid Registration	5.6 +/- 2.2 mm
Target Error After Rigid Registration + Correction	2.7 +/- 0.7 mm
Correction Capability	~52%

L. W. Clements, et al., 'Towards validation of model-based deformation correction in image-guided liver surgery via tracked intraoperative ultrasound', *Journal of Medical Imaging*, Vol. 3, No. 1, pp. 015003, 2016.

Novel bystander study …



Conventional Stylus Transform



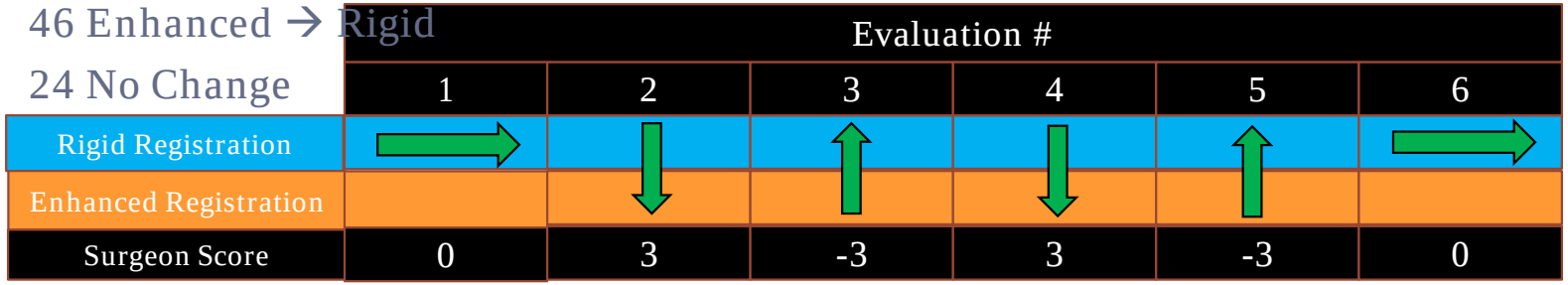
Non-rigid Stylus Transform

A. L. Simpson, P. Dumpuri, J. E. Ondrake, J. A. Weis, W. R. Jarnagin, and M. I. Miga, 'Preliminary study of a novel method for conveying corrected image volumes in surgical navigation', *International Journal of Medical Robotics and Computer Assisted Surgery*, Vol. 9, pp. 109-118, 2013.

Novel bystander study …

- N=20 Patients Undergoing Standard of Care Liver Surgery
- Two Participating Surgeons
- Rigid Registration & Corrected Registration Determined
- 6-7 Sequential display evaluations in the operating room
- Display order **<u>randomized and blinded</u>** to surgeon & operator
- +3/-3 Display rating from highly improved to highly worsened
- Total of 125 evaluations
  - 55 Rigid → Enhanced
  - 46 Enhanced → Rigid
  - 24 No Change

Score	Description
+3	Highly Improved
+2	Moderately Improved
+1	Slightly Improved
0	No Improvement
-1	Slightly Worse
-2	Moderately Worse
-3	Highly Worsened



L. W. Clements, et al.. 'Deformation correction for image-guided liver surgery: An intraoperative assessment of fidelity.' *Surgery*, 2017.

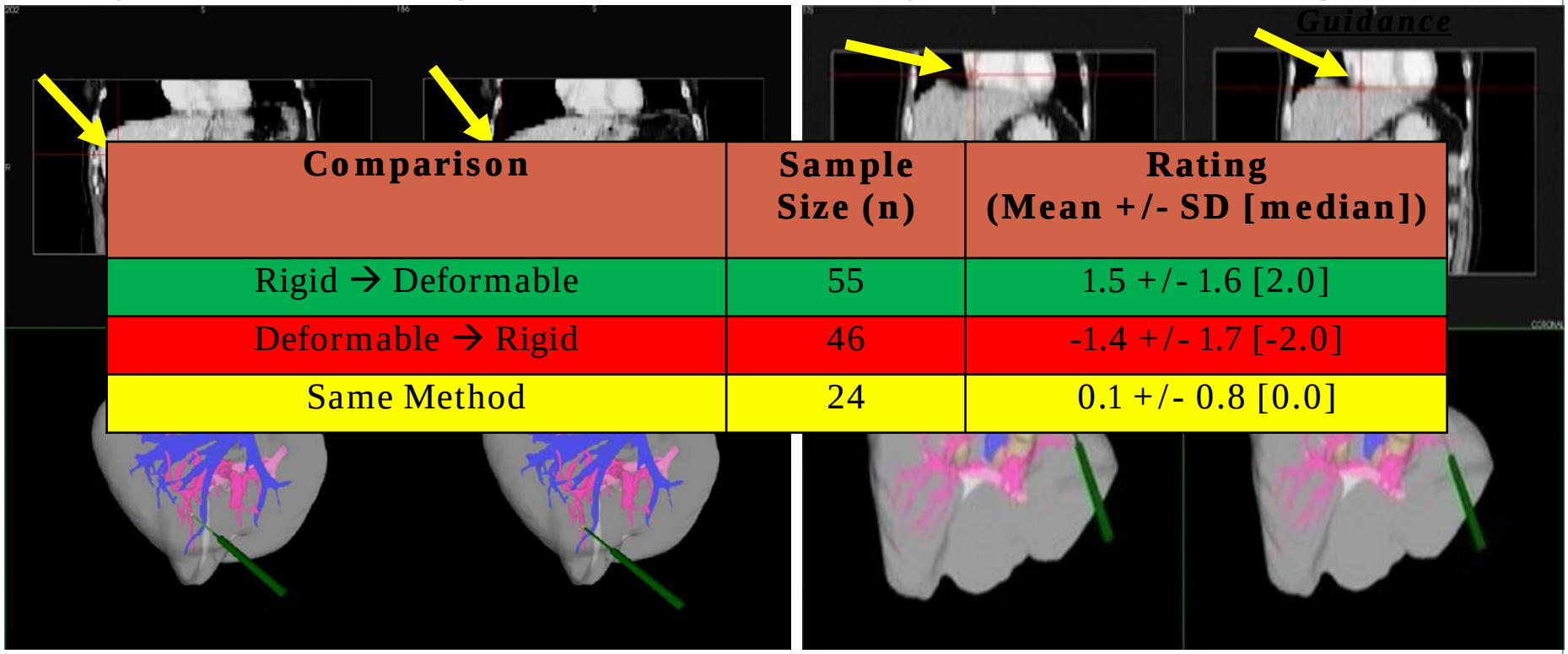
Novel bystander study … Results

Patient 11

Rigid Guidance ***Deformable Guidance***

Patient 17

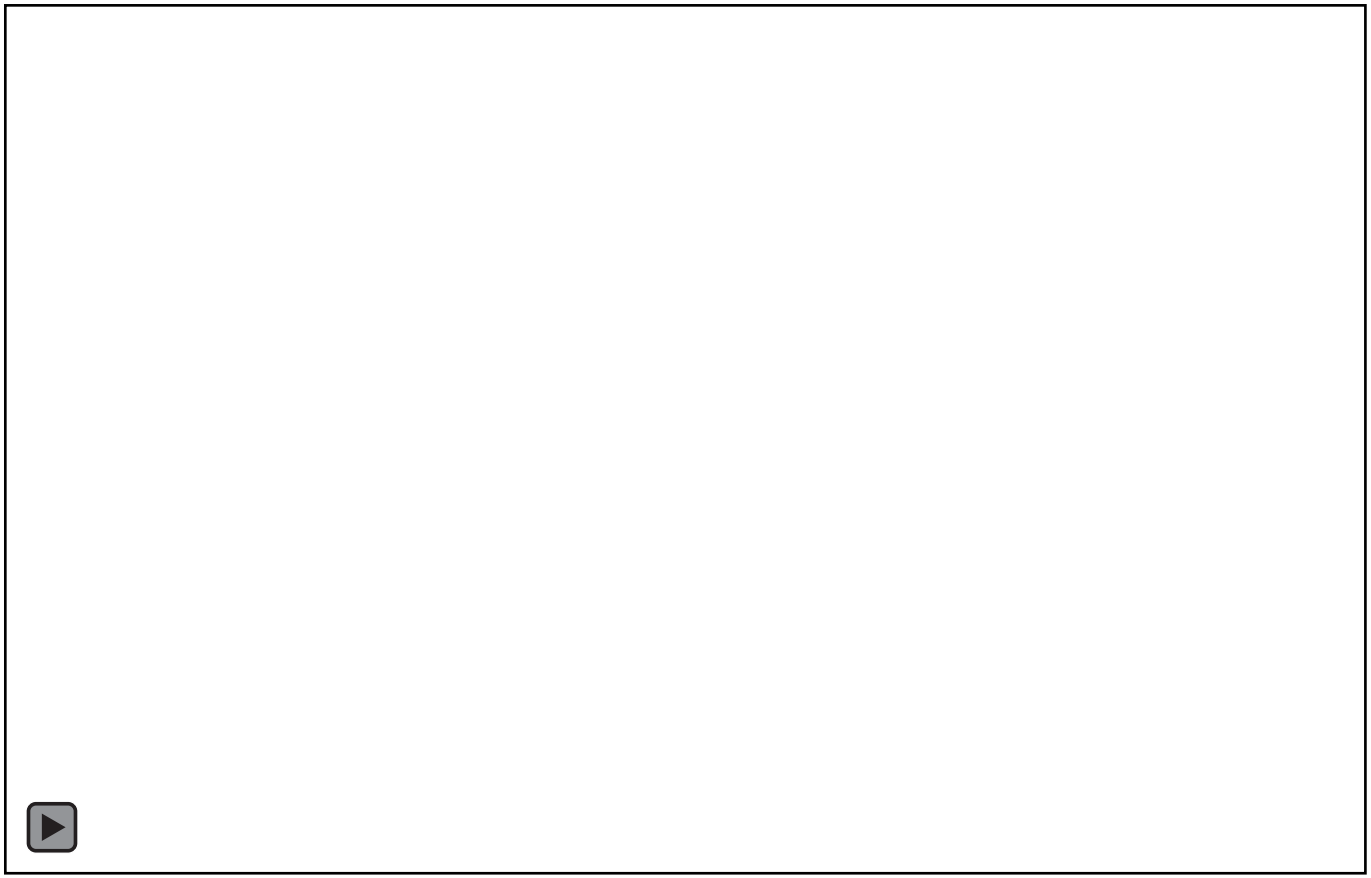
Rigid Guidance ***Deformable Guidance***



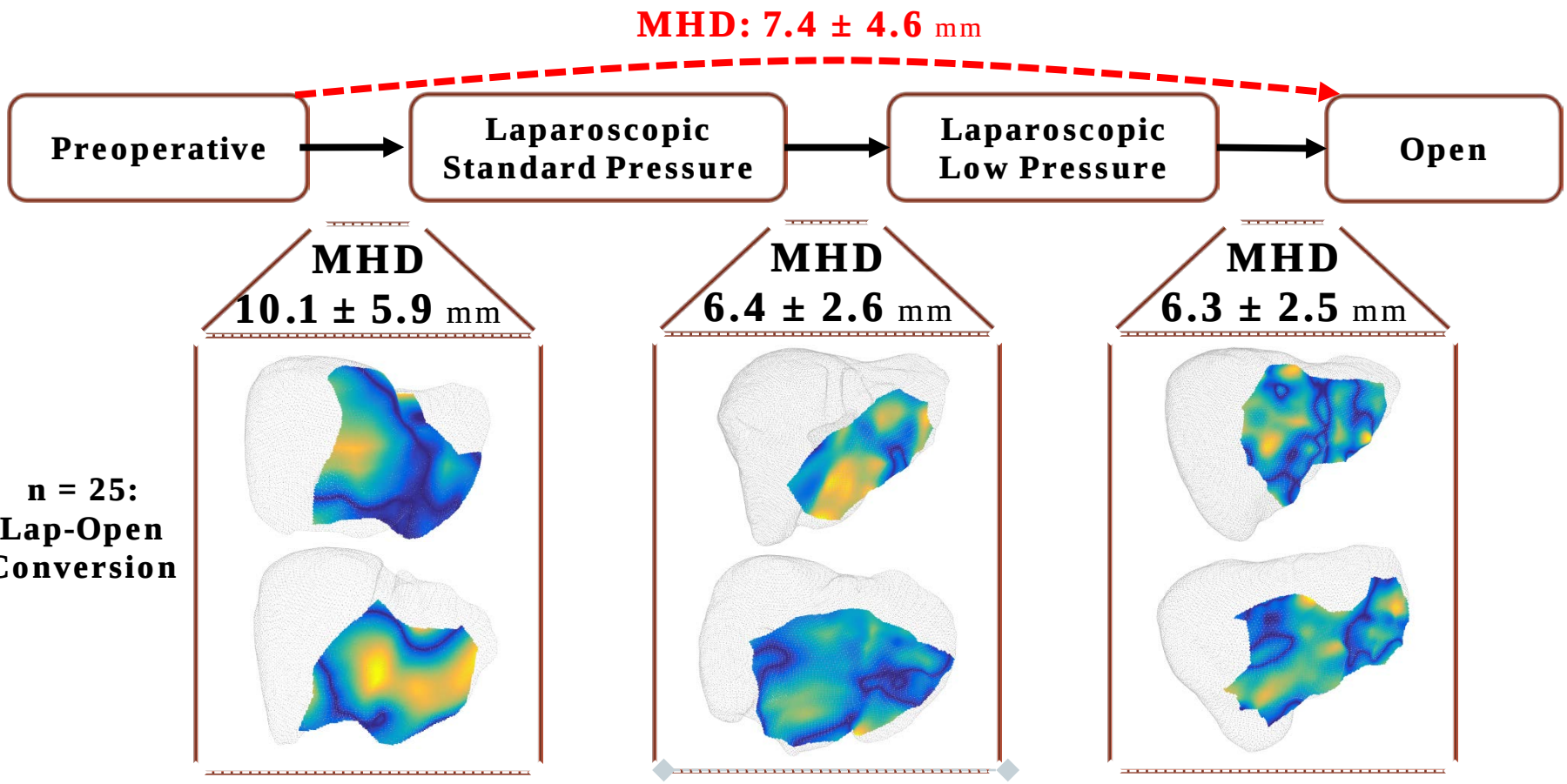
Comparison	Sample Size (n)	Rating (Mean +/- SD [median])
Rigid → Deformable	55	1.5 +/- 1.6 [2.0]
Deformable → Rigid	46	-1.4 +/- 1.7 [-2.0]
Same Method	24	0.1 +/- 0.8 [0.0]

L. W. Clements, et al.. 'Deformation correction for image-guided liver surgery: An intraoperative assessment of fidelity.' *Surgery*, 2017.

… extending framework for other sparse data

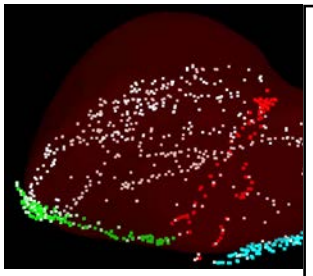


… extending framework to less invasive

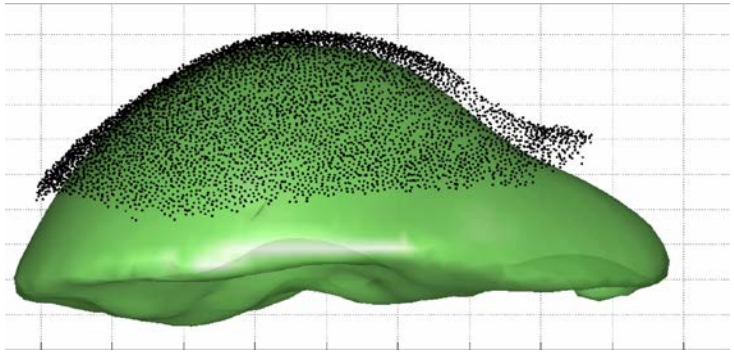


J. S. Heiselman et al., "Characterization and correction of intraoperative soft tissue deformation in image-guided laparoscopic liver surgery," *Journal of Medical Imaging*, vol. 5, no. 2, Apr 2018, Art. no. 021203.

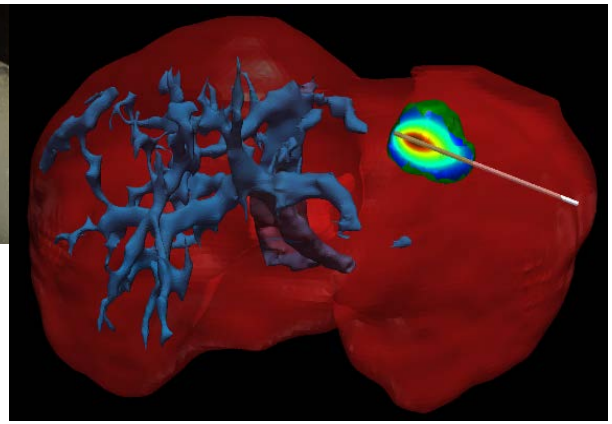
Multi-physics model-based augmentation …



Intraoperative Data



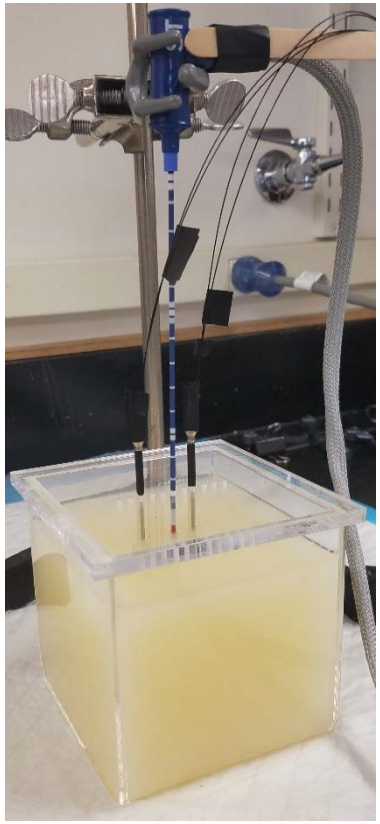
Model-based Deformation Correction



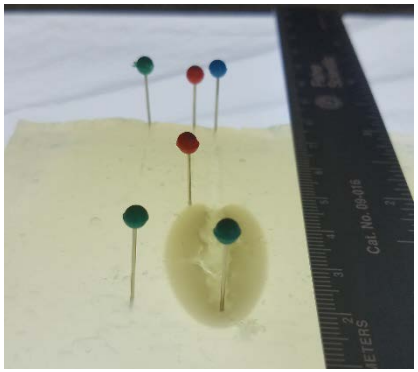
Model-based Microwave Ablation Prediction

Multi-Physics Model-based Approach for Improving Localization of Antenna and Estimating Thermal Dose

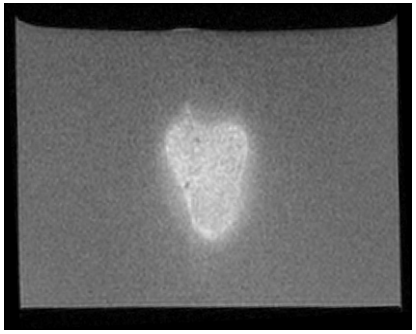
Ablation fitting and localization study …



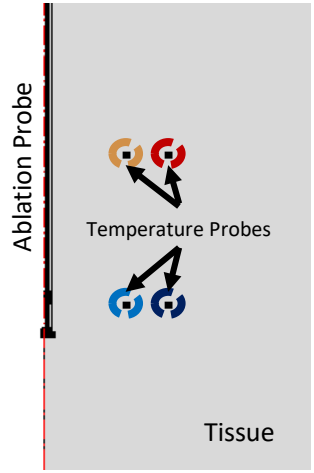
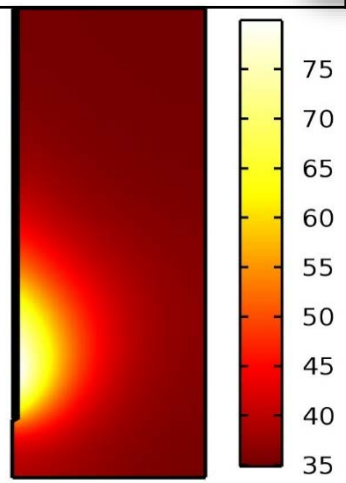
Post-ablation mock histology



Post-ablation MRI



2D Axisymmetric Model

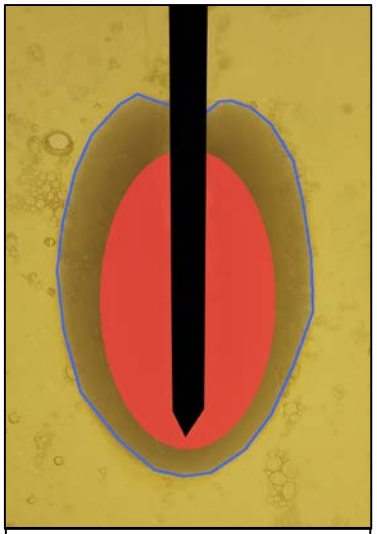
Model	*Result (T [°C])*
	

$(\nabla^2 + \omega^2 \mu \varepsilon_c)\vec{E} = 0$	E.M.
$\rho c \frac{\partial T}{\partial t} = \nabla \cdot k\nabla T + Q - Q_p + Q_m$	Thermal

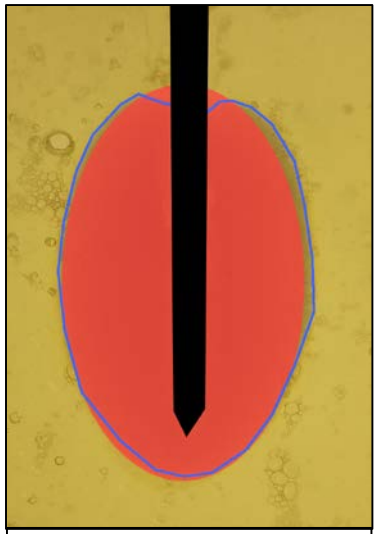
A Testing and Simulation Environment

J. A. Collins, J. S. Heiselman, L. W. Clements, D. B. Brown, and M. I. Miga, "Multiphysics modeling towards enhanced guidance in hepatic microwave ablation: A preliminary framework", *Journal of Medical Imaging*, vol. 6, no. 2, pp. 025007:1-10, 2019.

Ablation fitting and localization study …



Initial ablation zone solution



Optimal ablation zone solution

Choose property values
$P = [\sigma, \varepsilon, k, c]$

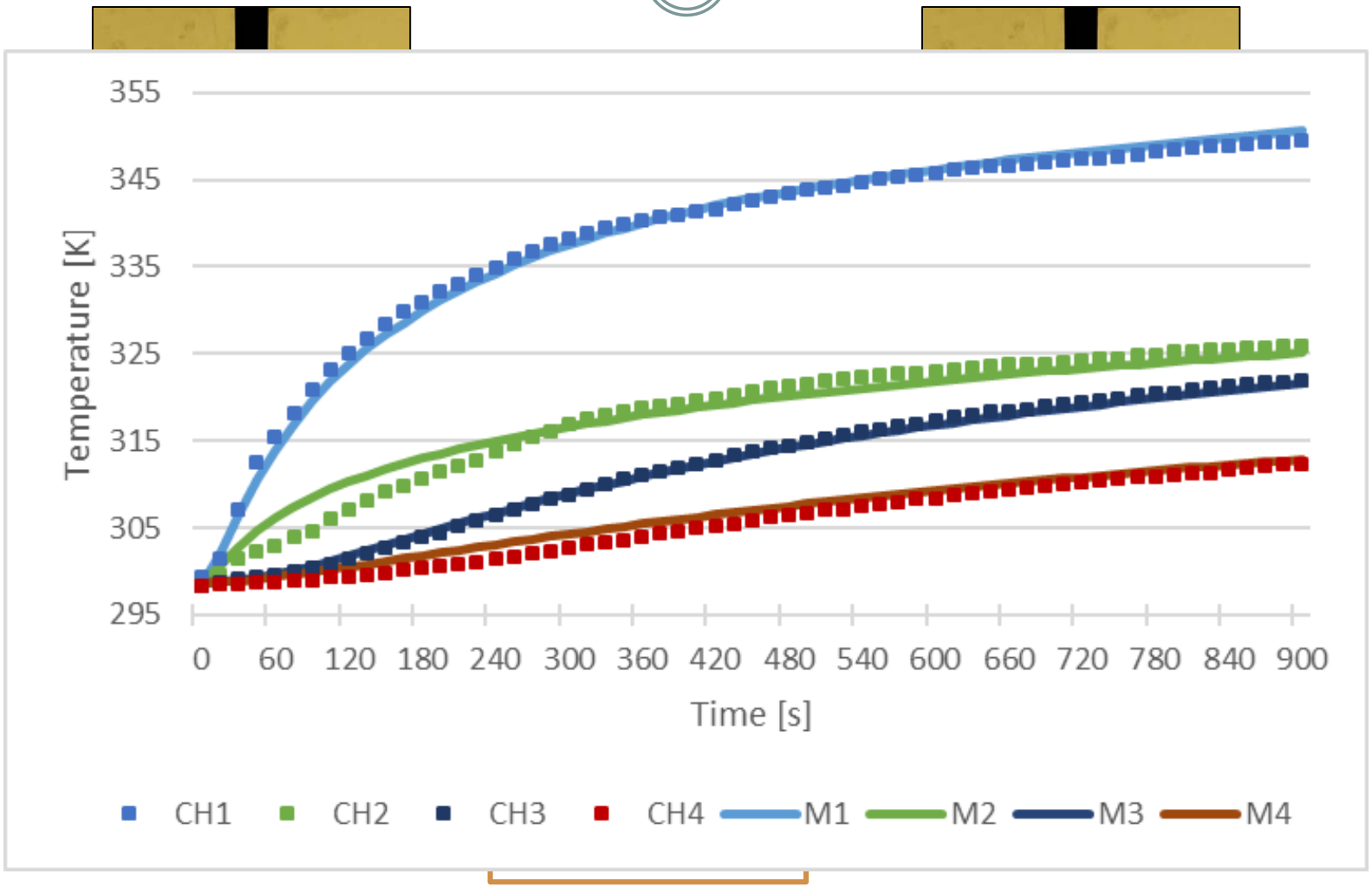
Solve forward ablation model

Does the predicted ablation fit the observed ablation?

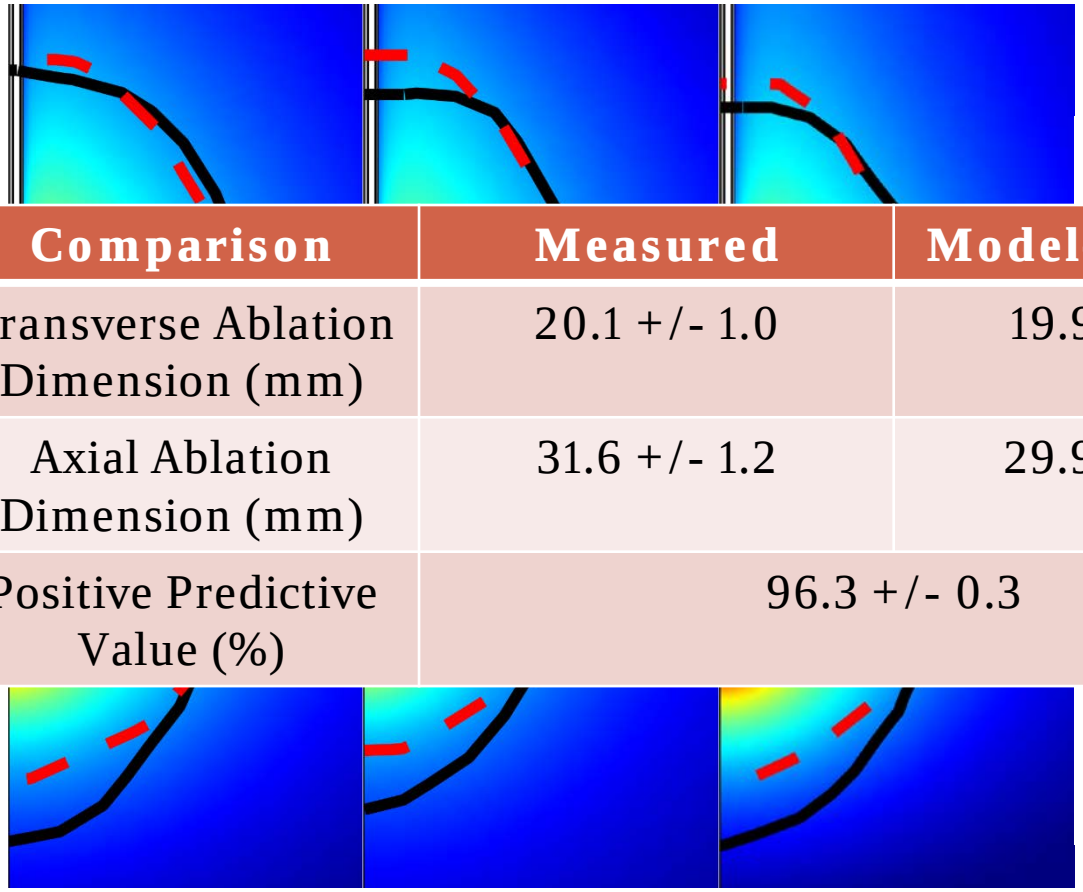
No

Yes

Ablation fitting and localization study …



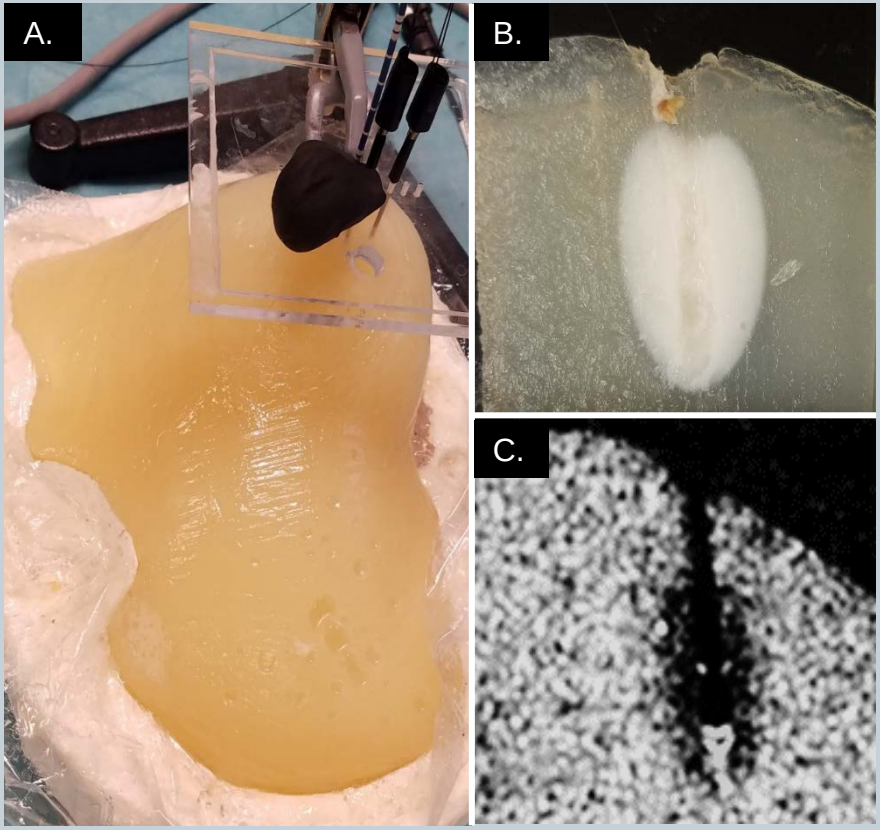
Ablation fitting and localization study … Results



Comparison	Measured	Model-Predicted
Transverse Ablation Dimension (mm)	20.1 +/- 1.0	19.9 +/- 1.8
Axial Ablation Dimension (mm)	31.6 +/- 1.2	29.9 +/- 0.6
Positive Predictive Value (%)	96.3 +/- 0.3	

Ablation fitting and localization study …

- N=3 Phantoms
- 3 ablations per phantom
- 4 deformations per phantom
- Metrics
  - 3 targets (ablation centroid, needle insertion point, needle tip)
  - Positive predictive value



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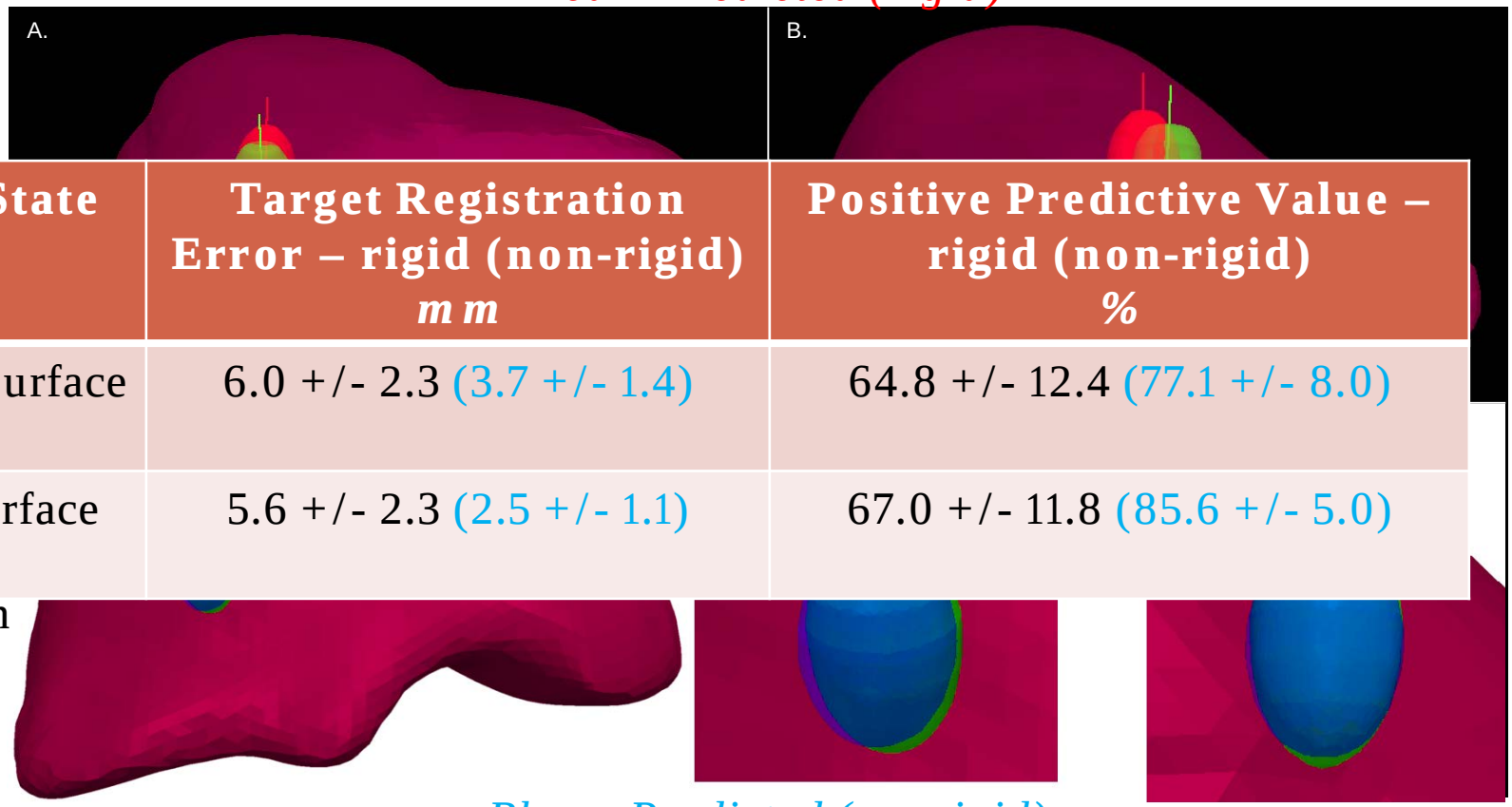
Ablation fitting and localization study … Results

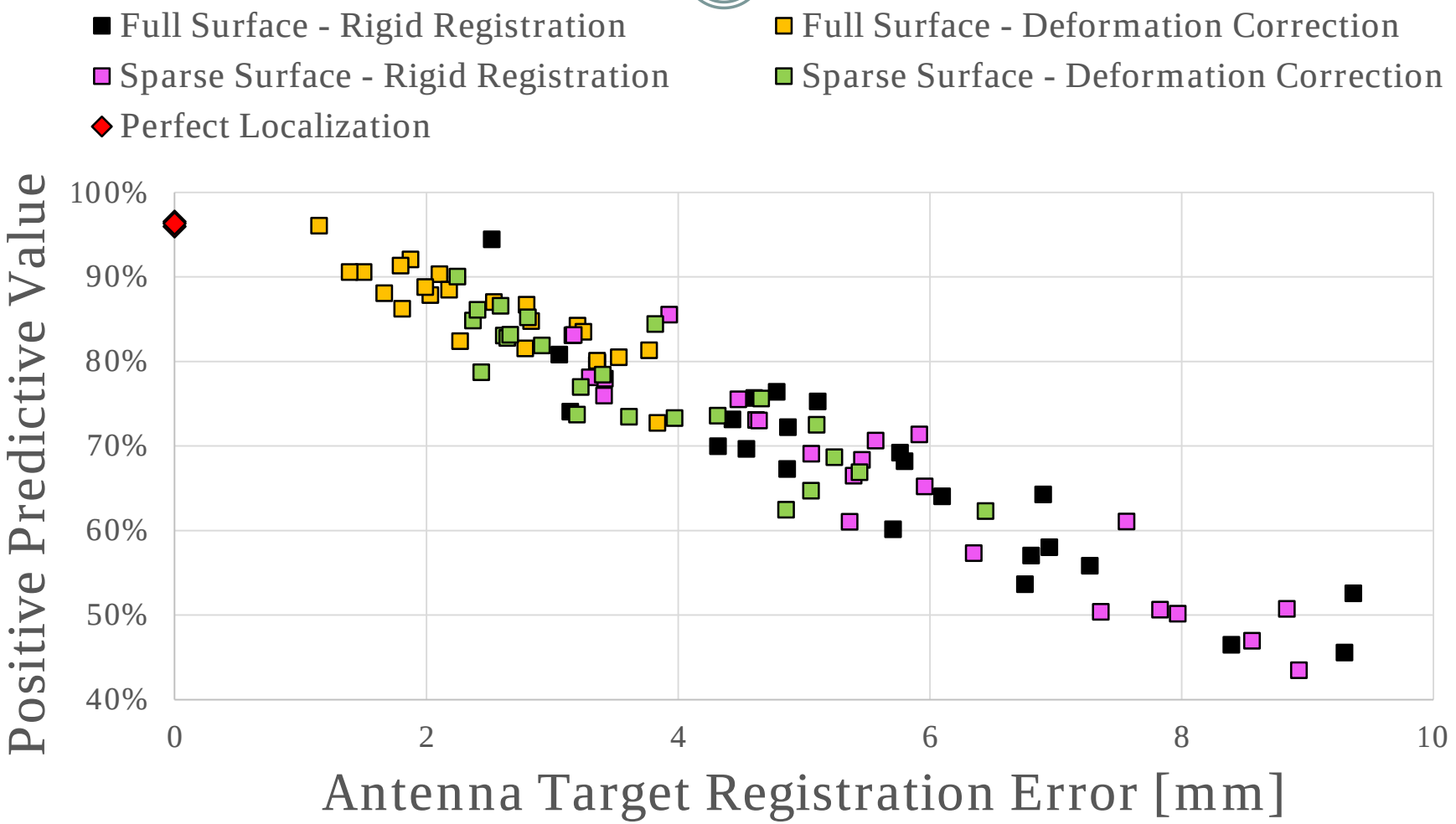
Green – Ground Truth
Red – Predicted (rigid)



Data State	Target Registration Error – rigid (non-rigid) *mm*	Positive Predictive Value – rigid (non-rigid) *%*
Partial Surface	6.0 +/- 2.3 (3.7 +/- 1.4)	64.8 +/- 12.4 (77.1 +/- 8.0)
Full Surface	5.6 +/- 2.3 (2.5 +/- 1.1)	67.0 +/- 11.8 (85.6 +/- 5.0)

Blue – Predicted (nonrigid)
Green – Ground Truth

Ablation fitting and localization study … Results



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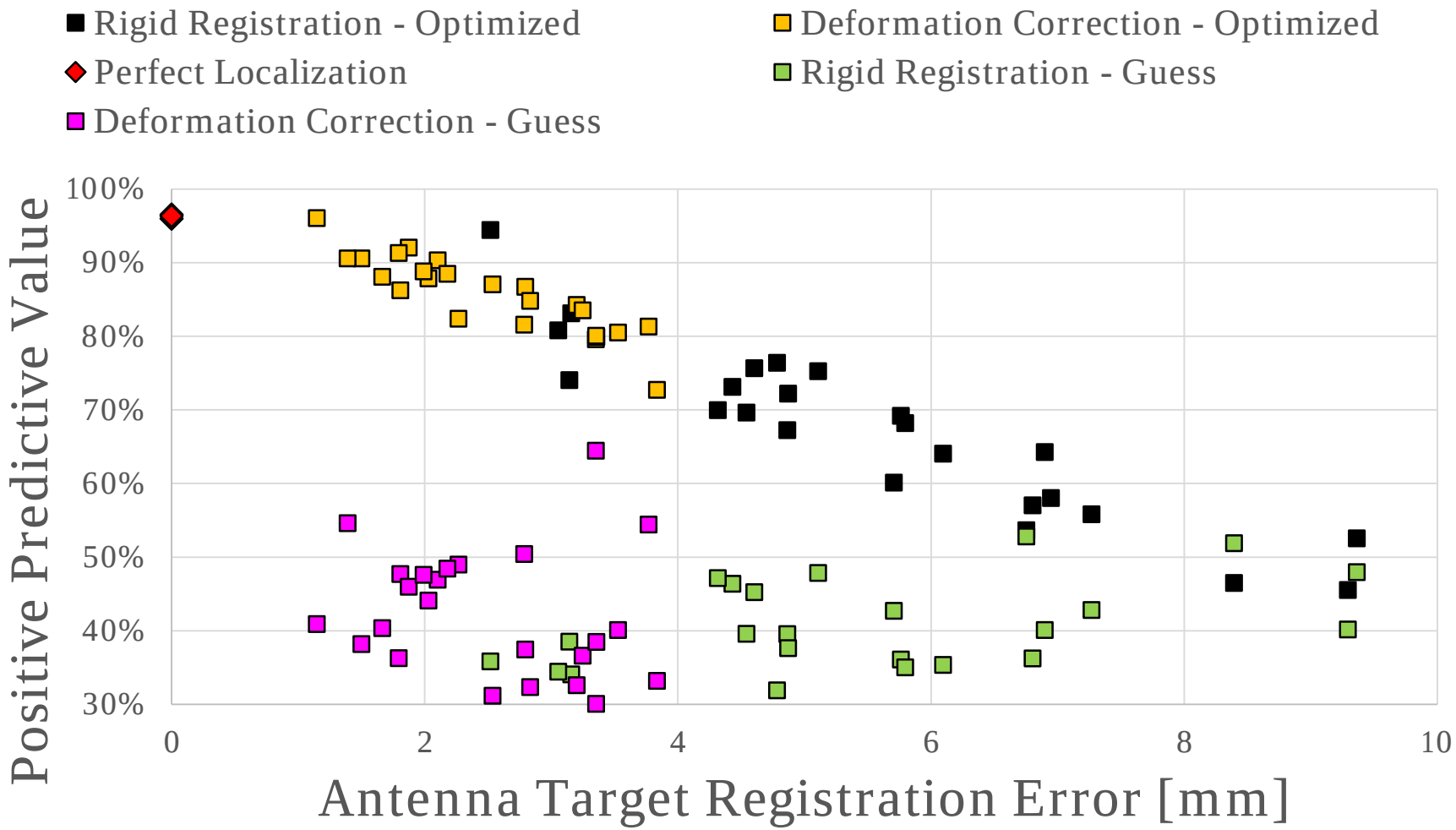


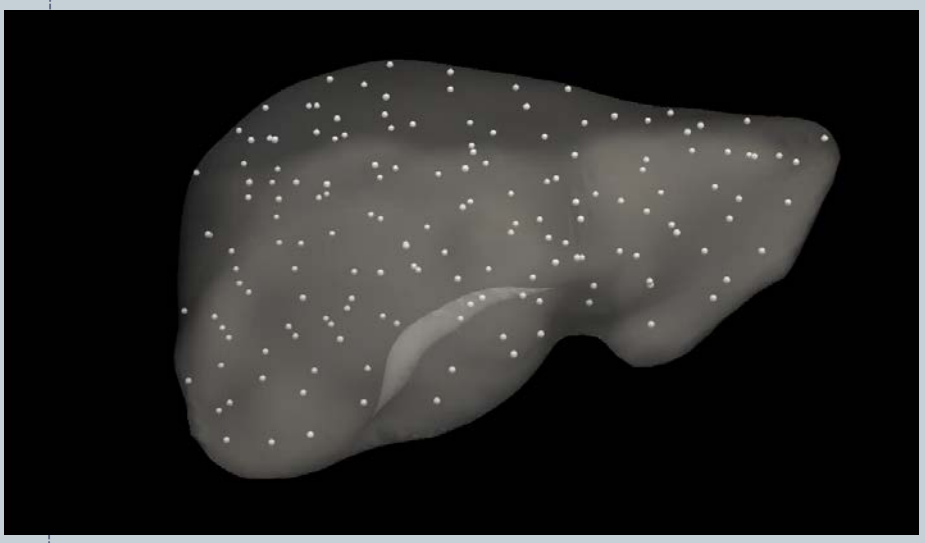
… key question remaining …

Previous work suggests: *Better localization accuracy and PPV is achieved with appropriately 'tuned' models.*

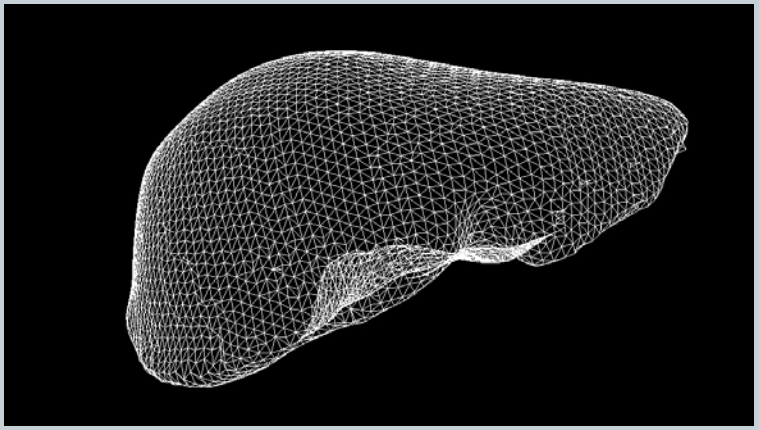
Hypothesis: *MR image-data-derived surrogate biomarkers can provide 'tuning' for driving predictive modeling to forecast microwave thermal ablation therapy*

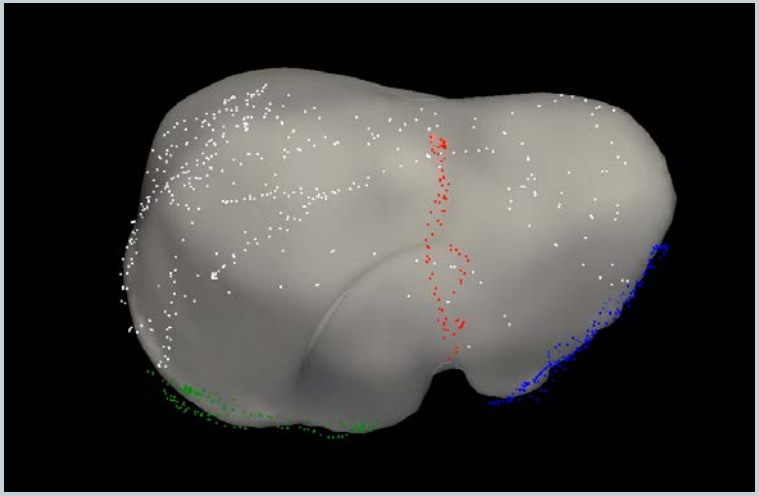
Image-to-Physical Liver Registration Sparse Data Challenge

- Data Set Generation Methods
  - 80% Ecoflex® 00-10 platinum-cure silicone mixed with 10% Silicone Thinner® and 10% Slacker® Tactile Mutator (Smooth-On Inc., Pennsylvanina)
  - N=159 CT-visible targets
  - Baseline CT, and 4 deformations under posterior side of liver



… sparse data description…

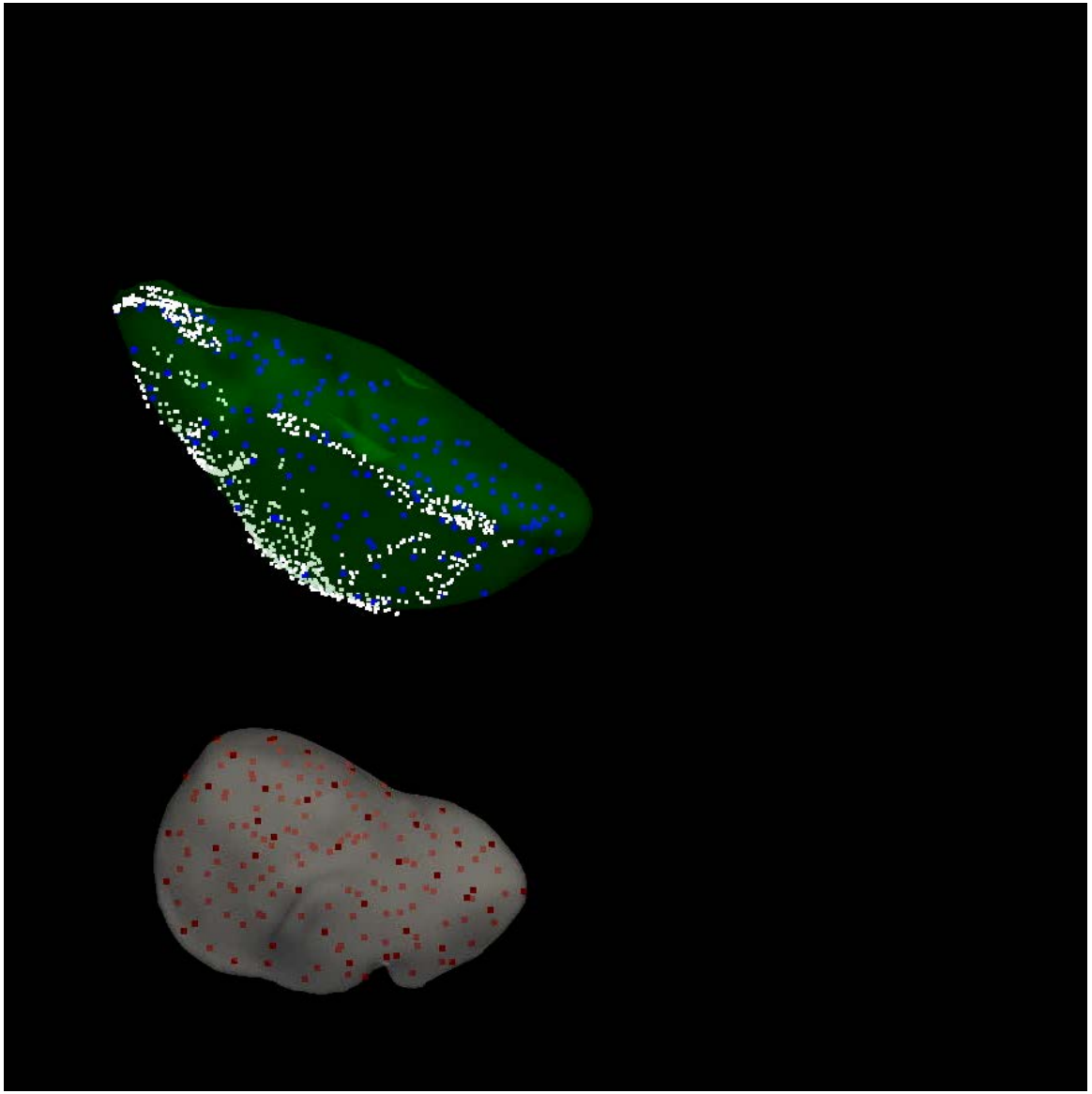




- Sparse Data Challenge Sets
  - Mesh & binary mask
  - 84 surface contact-swabbed sets
    - 21 OR patterns of anterior surface
    - extent 20-44%
    - 4 deformations sets
  - 28 anterior surface non-contact swabbed sets
  - General surface, falciform, left & right inferior ridge (112 sets)

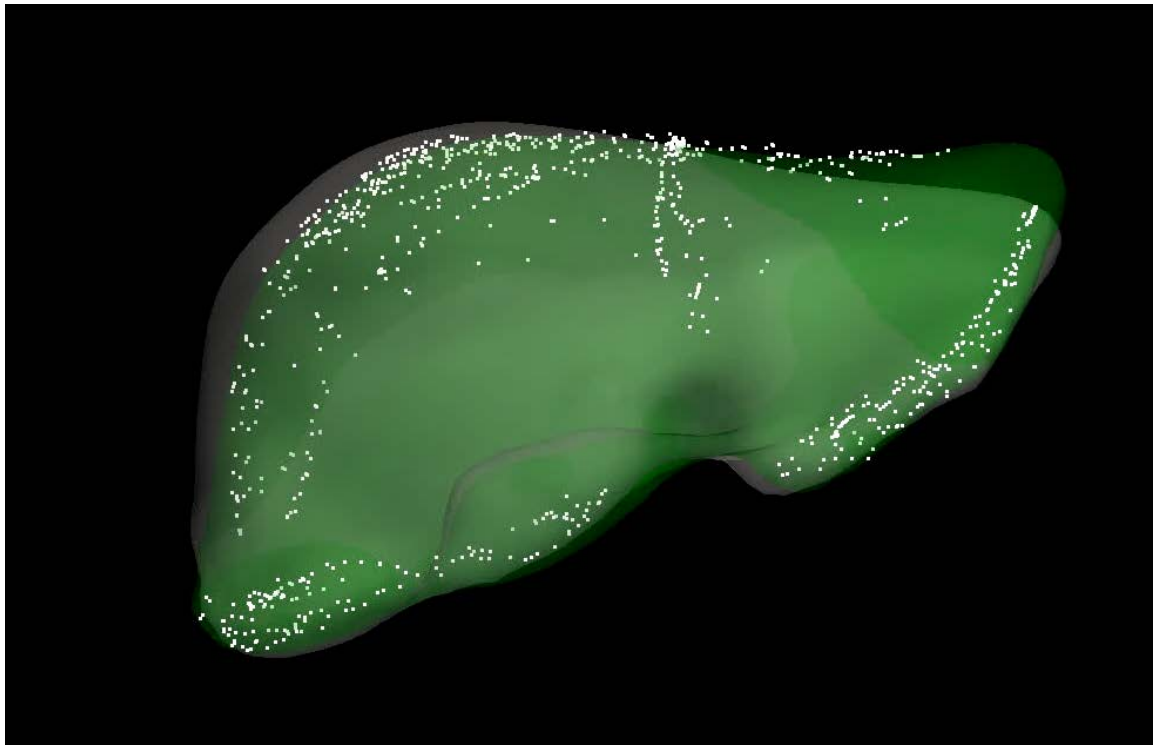
… example results …

All sets have varied initial poses



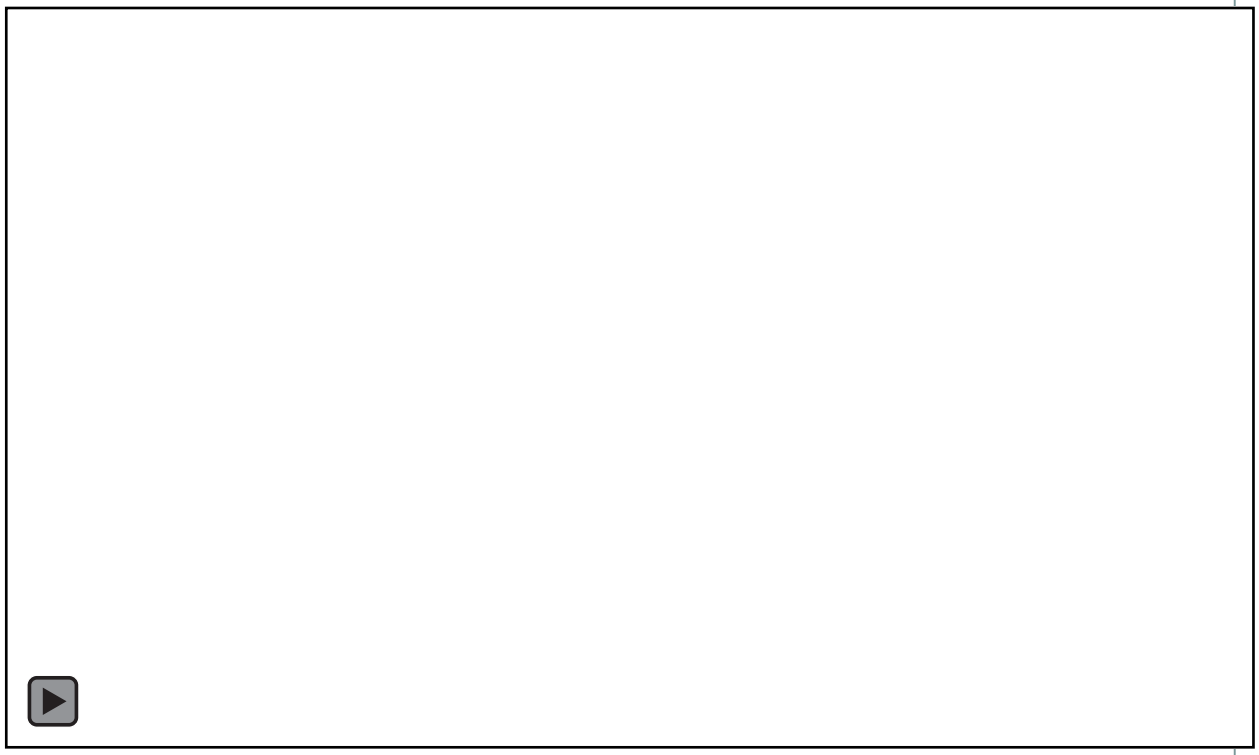
… example results …

- All sets have varied initial poses
- Requires initial alignment strategies



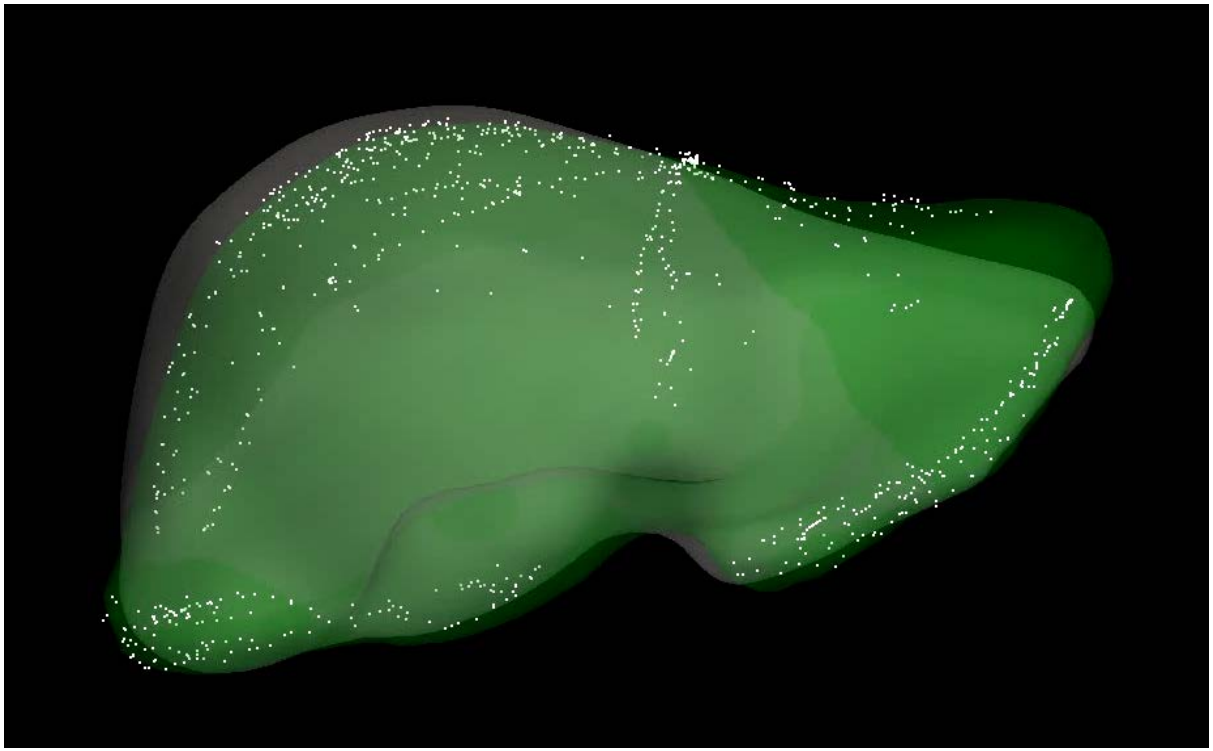
… example results …

- All sets have varied initial poses
- Requires initial alignment strategies
- Deformation spans moderate to high deformations



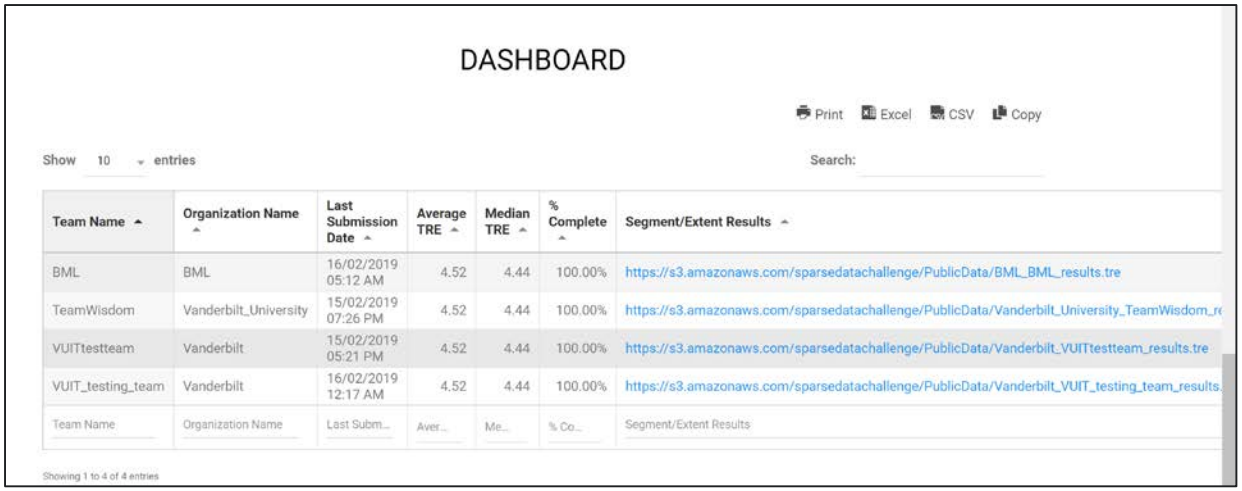
… example results …

- All sets have varied initial poses
- Requires initial alignment strategies
- Deformation spans moderate to high deformations
- Nonrigid registration using sparse anterior data



What are the steps for participating?

1. Go to sparsedatachallenge.org
2. Register your team (PI biosketch approval)
3. After approval, go to site and Login
4. Go into Data Site tab and download data
5. When done, Login, go back to Data Site and upload results
6. Check Dashboard on Gateway



Folks Past and Present


Bill Jarnagin


Peter Kingham


Dan Brown


Michael Miga


Amber Simpson


Logan Clements


Sunil Geevarghese

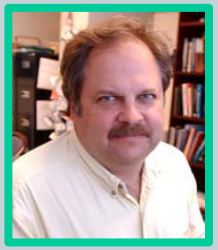

Jon Heiselman


Derek Doss


Alice Ding


Caleb Rucker


Jared Weis


Bob Galloway


Tom Pheiffer


Prashanth Dumpuri


Jarrod Collins

VANDERBILT UNIVERSITY

VANDERBILT UNIVERSITY MEDICAL CENTER

Memorial Sloan Kettering Cancer Center

Questions