Optimization of an On-Board Imaging System for Rapid Radiotherapy

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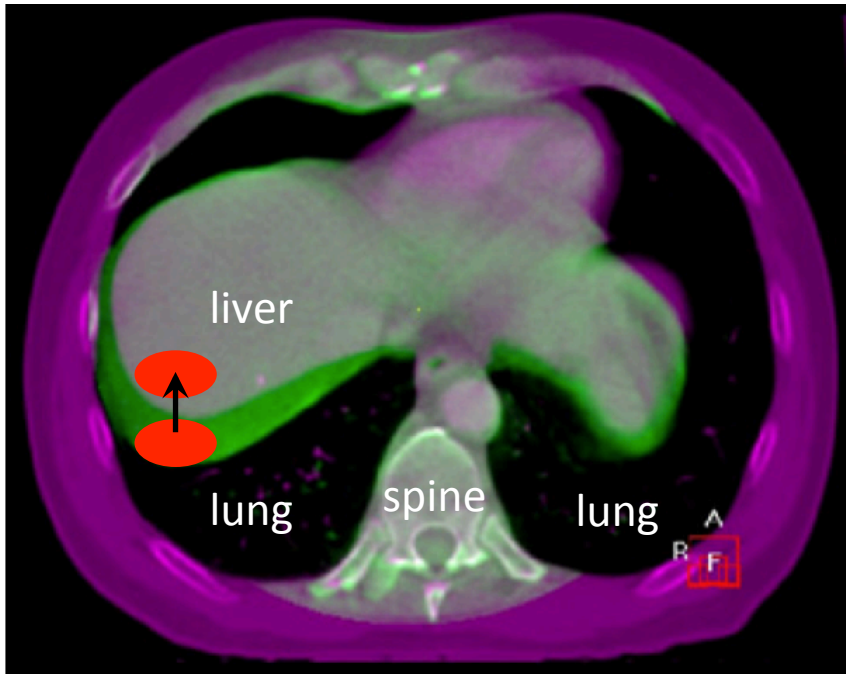
Problem: motion during treatment

Two overlapping thorax views during normal breathing

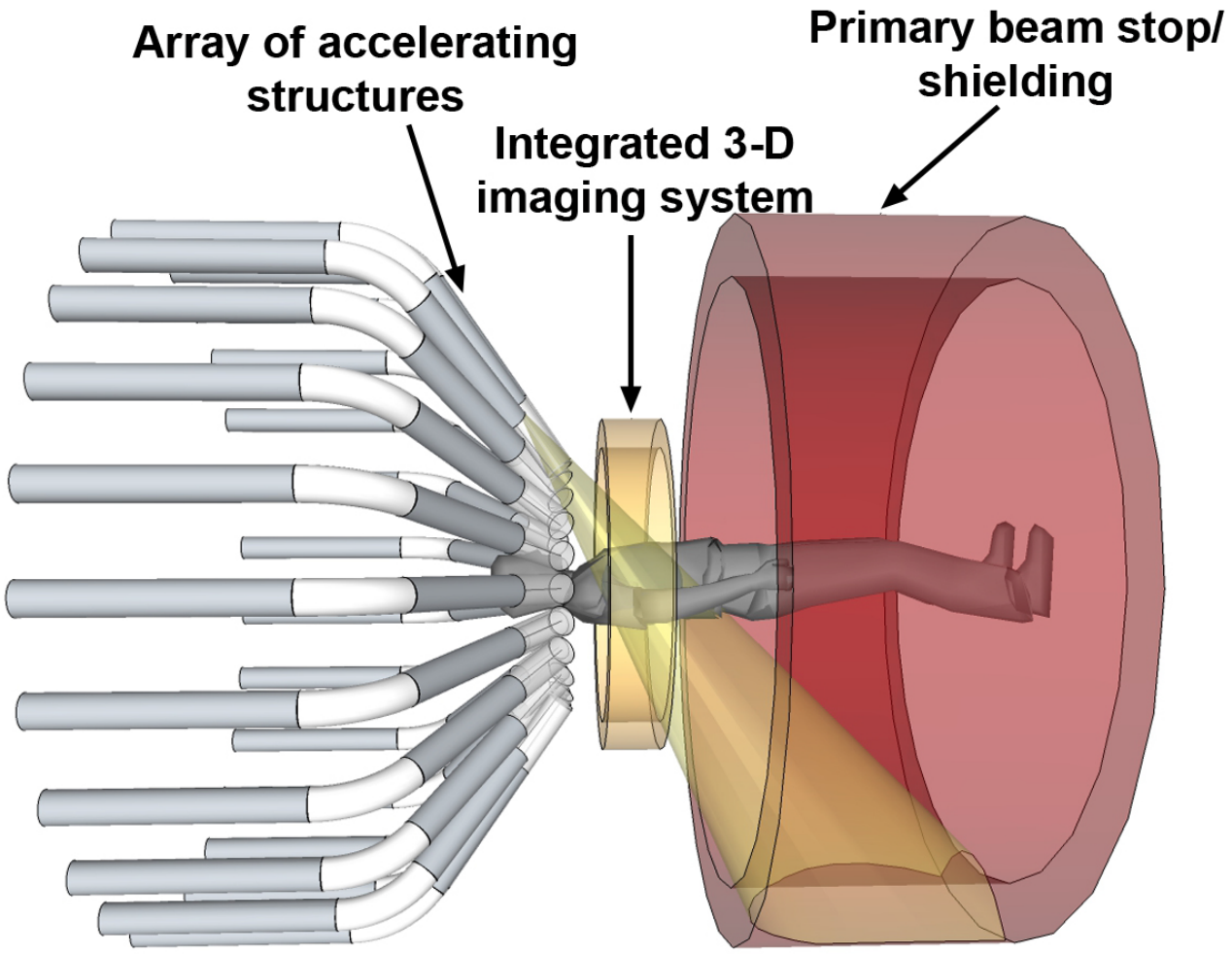


K.K. Brock, "Imaging and Image-Guided Radiation Therapy in Liver Cancer," 2011

Fix: PHASER

- PHASER = Pluridirectional High-Energy Agile Scanning Electron Radiotherapy
- Basic idea: deliver entire radiation treatment in a few seconds to effectively freeze motion
- Mechanism: use high-energy electrons, which can be steered electronically (no moving parts)
- 100 MeV electrons can deliver a dose with similar accuracy to 2 MeV photons (mean energy)

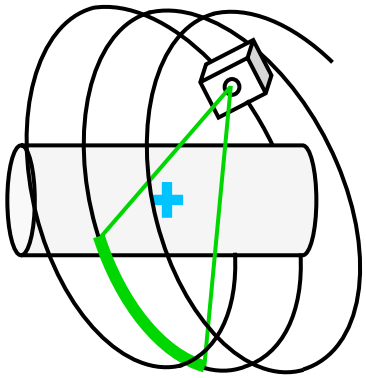
PHASER Setup



Why do we need on-board imaging?

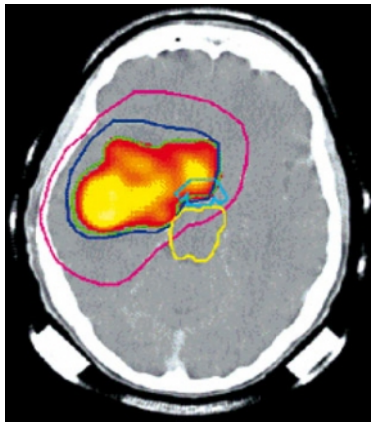
- The patient changes between treatment planning and treatment delivery (interfraction motion/ deformation)
- Must align patient and treatment plan
- CT system works best for this
  - Fast imaging
  - Hardware won't interfere with the accelerator hardware
- Q: What kind of CT system should we use?
- A: Whatever allows us to accurately register the treatment plan to the patient's current position

Work Flow

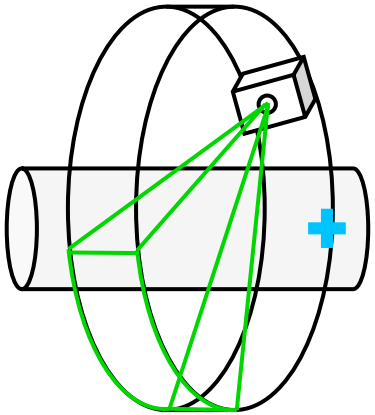


Acquire helical scan data: high quality, 40 cm axial FOV

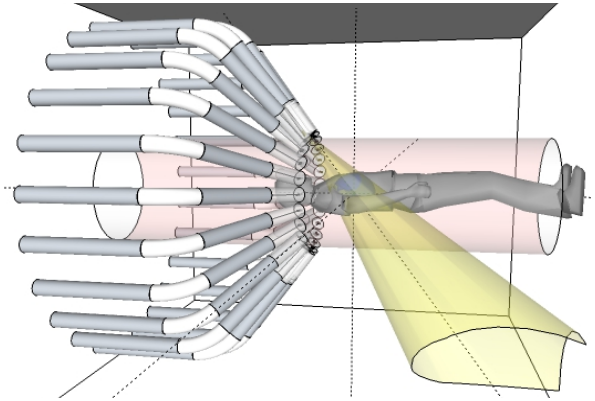
Reconstruction



Registration, choosing plan, verifying choice



axial scan and tumor position verification: FAST, 10 cm axial FOV



Deliver therapy

Not shown: Diagnostic-quality CT taken with clinical system for treatment planning

CT Detector design optimization

- Limiting our imaging system to include ONE custom part will reduce overall cost
- Detector is the most expensive part of the system
- Possible detector designs
  - Low resolution: 48 rows, all 4x4 mm pixels
  - Medium resolution: 64 rows, 16 4x4 mm pixels + 32 2x2 mm pixels + 16 4x4 mm pixels (better resolution in center, use only high-quality section for helical scan)
  - High resolution: 192 rows, all 1x1 mm pixels

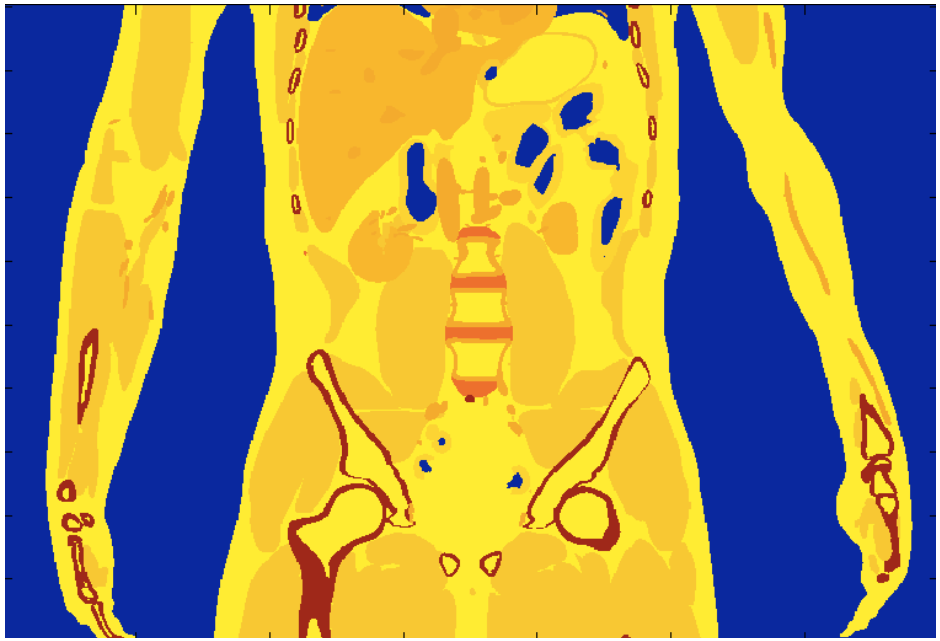
Optimization Procedure

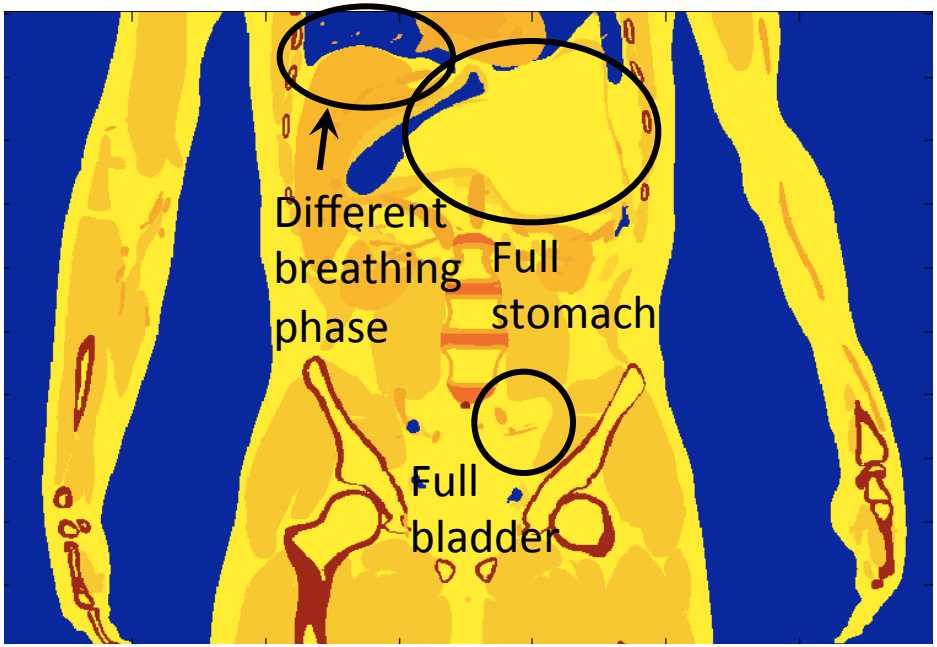
- Make three numerical anthropomorphic phantoms with realistic deformations
- Generate realistic CT data for each imaging step
- Register helical data to clinical data and axial data to helical data
- Evaluate “goodness” of registration to determine which detector designs meet image quality requirements

Phantoms

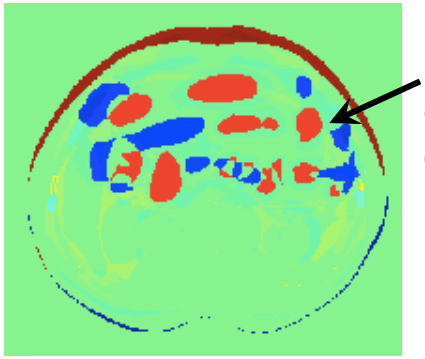
Patient on day of clinical scan

Patient on day of treatment



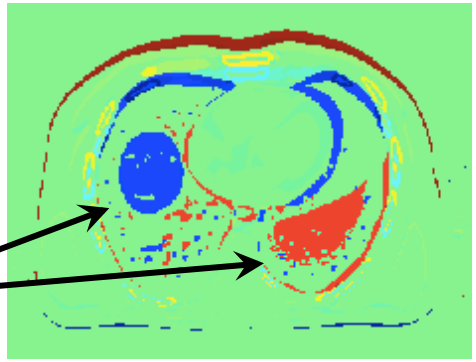


Sample phantom difference image axial slices



Bowel has moved to accommodate organ expansion

Lungs and liver have deformed



Liver Lesions

Question: Can we accurately register small liver lesions with deformation?

Spherical liver lesions of different densities in original phantom

Spherical liver lesions in deformed phantom (axial distance between top and bottom slices is 2 cm)

Primary Simulation

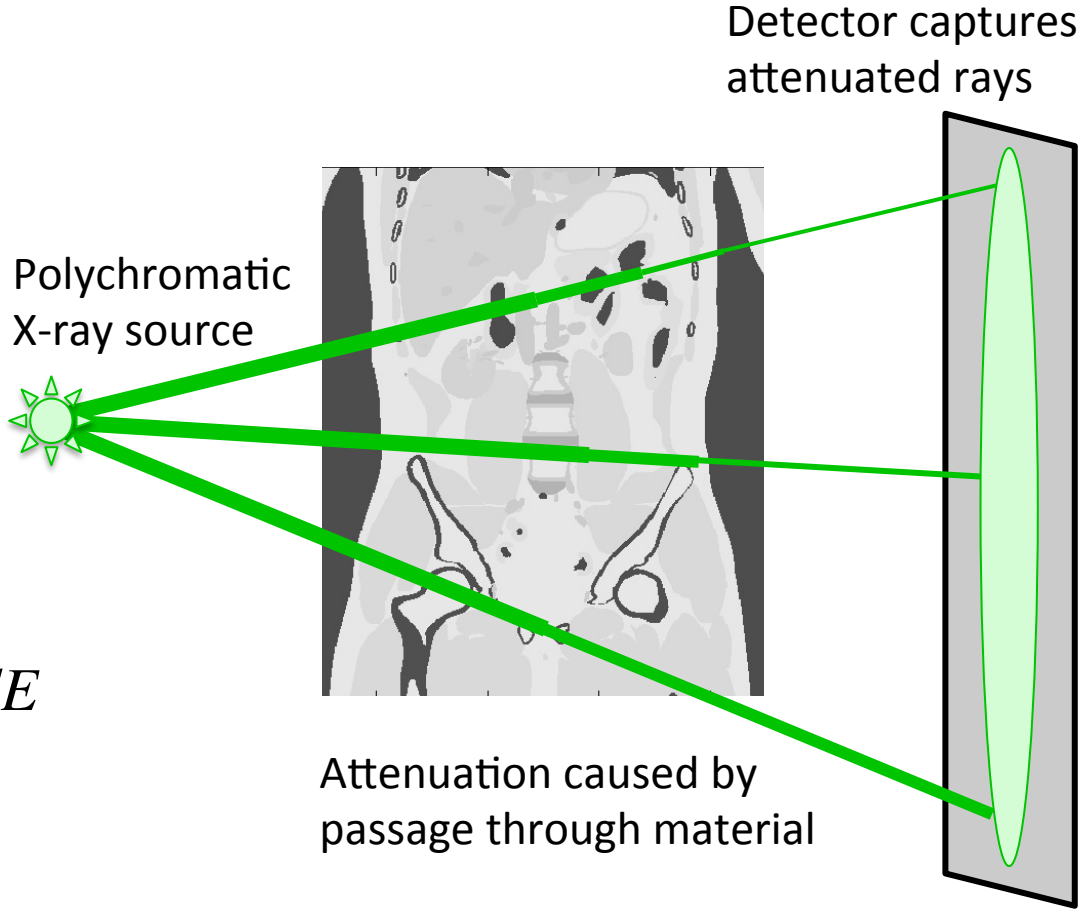
Software generates cone beam projection images, includes tools for 3D volume reconstruction, DOES NOT include scatter

X-ray attenuation, one energy, one material

$$I(L) = I_0 \exp(-\mu L)$$

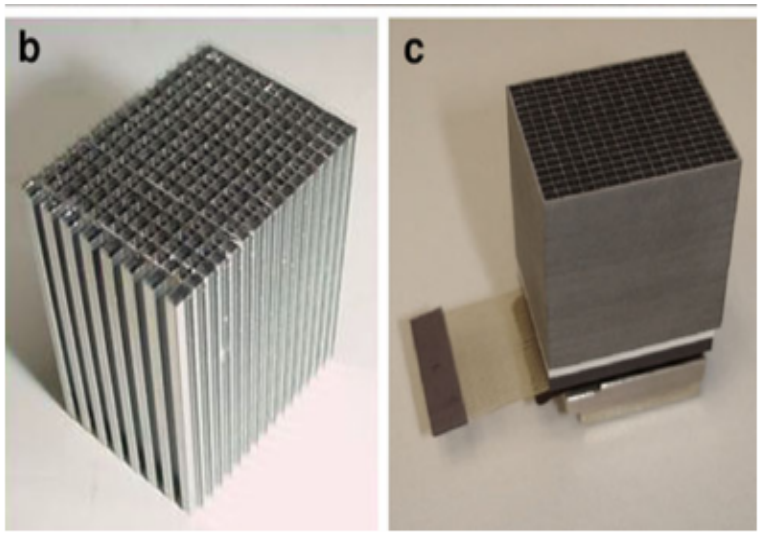
X-ray attenuation, polyenergetic, several materials

$$I(x_{tot}) = \int_{E\min}^{E\max} I_{0,E} \prod_{i=1}^{n} \exp(-\mu_{iE} L_i) dE$$

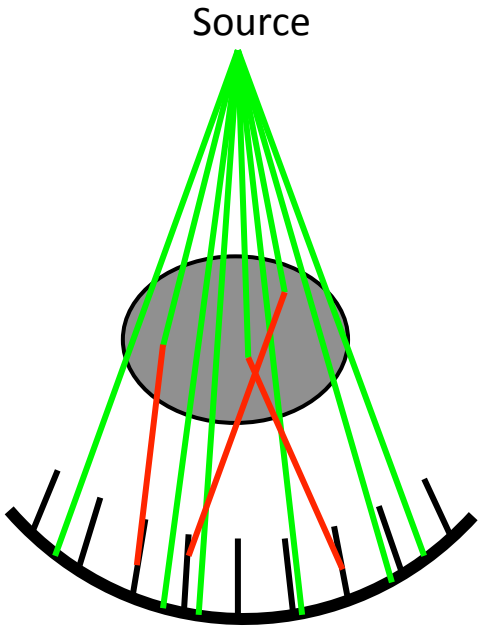


Scatter Simulation

- Monte Carlo simulation accounts for random physical processes responsible for scattering
- MC-GPU open-source scatter simulation software
- Scatter can be reduced with an anti-scatter grid

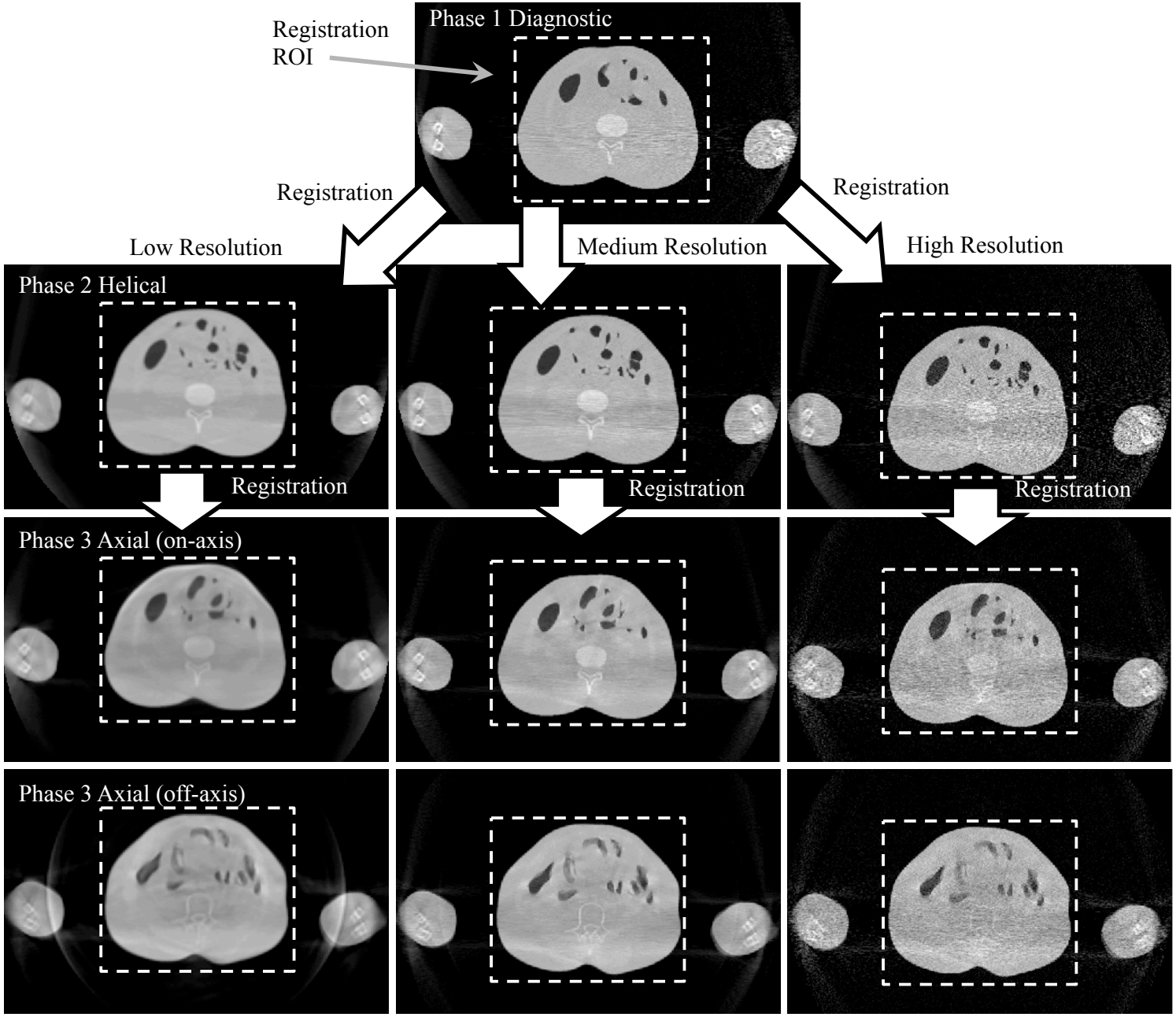


2D anti-scatter grid, *Philips*



Curved detector with anti-scatter grid

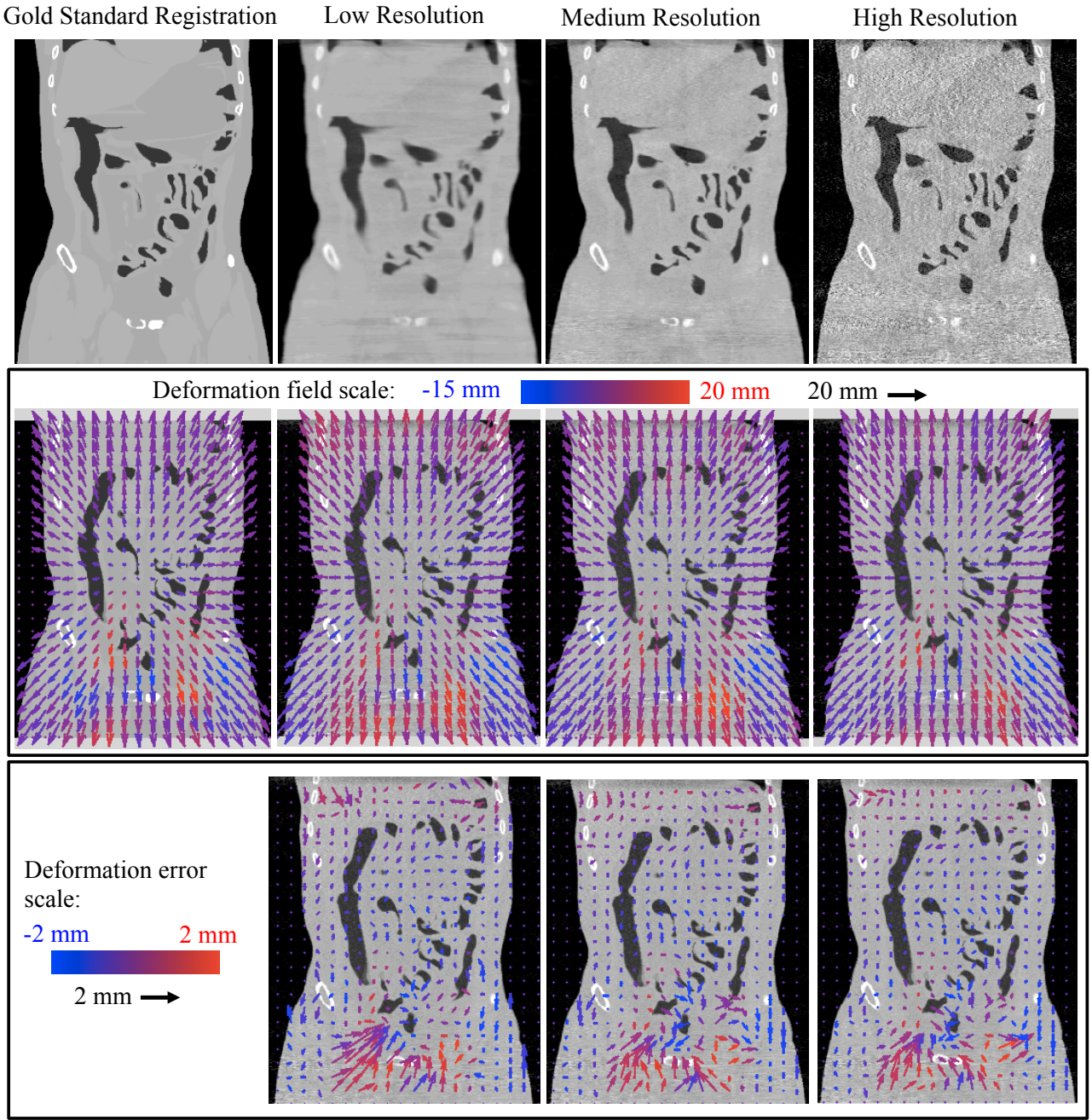
Sample Data


Registration
ROI
Phase 1 Diagnostic
Registration
Registration
Low Resolution
Medium Resolution
High Resolution
Phase 2 Helical
Registration
Registration
Registration
Phase 3 Axial (on-axis)
Phase 3 Axial (off-axis)

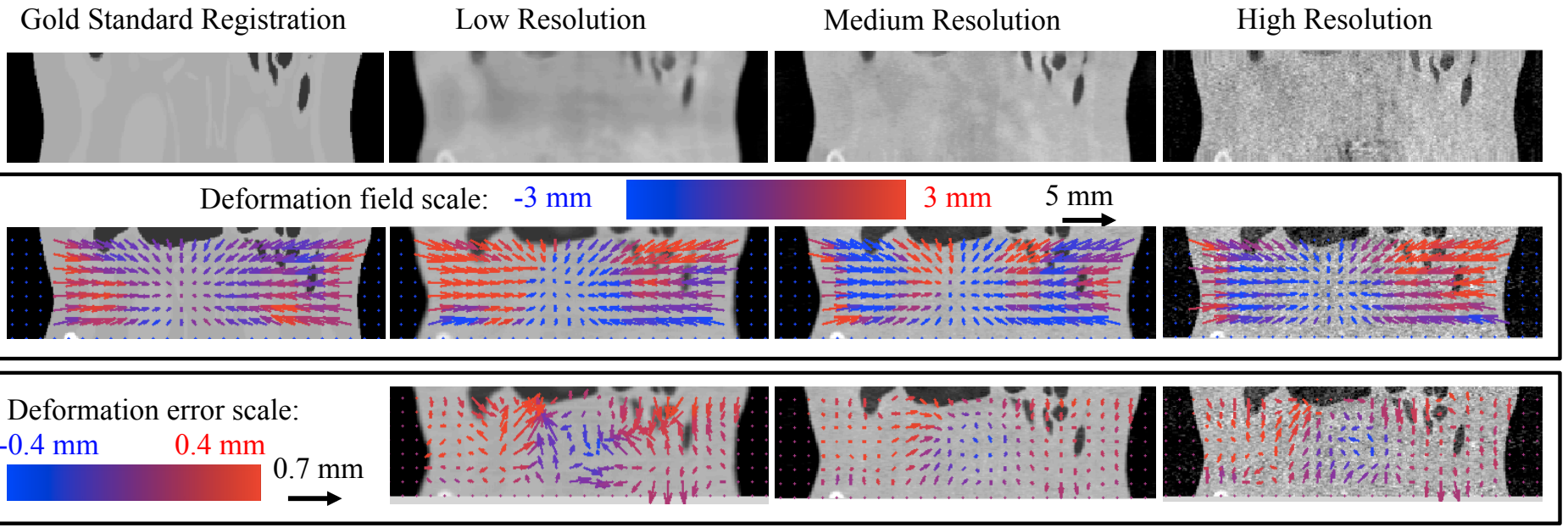
“Gold Standard” for Registration

- We want to evaluate the imaging system, not the registration algorithm
- We don’t have the ground truth deformation field anyway
- Solution:
  - Convert different imaging phase phantoms to HU
  - Register them using the same workflow
  - Compare “gold standard registration” deformation field with deformation fields

Diagnostic-Quality/Helical Registration



Helical/Axial Registration



Global Registration Results

Distances are between real data registration deformation field and gold standard data registration deformation field

$$D_{a,b}(x,y,z) = \sqrt{(a_x(x,y,z) - b_x(x,y,z))^2 + (a_y(x,y,z) - b_y(x,y,z))^2 + (a_z(x,y,z) - b_z(x,y,z))^2}$$

Detector	Diagnostic/helical registration mean pointwise distance (mm)	Helical/axial registration mean pointwise distance (mm)
Low Resolution	3.1	4.8
Medium Resolution	2.6	3.9
High Resolution	2.0	3.9

Liver Lesion Registration Results

Distances are between real data registration deformation field and gold standard data registration deformation field

Detector	Diagnostic/helical registration mean pointwise distance (mm)	Helical/axial registration mean pointwise distance (mm)
Low Resolution	3.4	4.3
Medium Resolution	1.7	2.5
High Resolution	1.8	3.3

Conclusions

- Low resolution detector is worse than the other two by pretty much every metric
- Medium and high resolution detectors are virtually interchangeable
- Use of medium resolution detector is recommended because it is much more economical than high resolution detector

Goals for Future Work

- Investigate possible dose reduction in imaging system
- Develop algorithm for fast treatment plan adaptation
- Build custom CT and integrate it with other PHASER hardware

Acknowledgements

- Thanks to Meng Wu and He Yang for their work on this project
- Thanks to the Fahrig group and the PHASER team
- Thanks to SCIT for supporting me
- Thanks to the Weston Havens Foundation, the Department of Radiation Oncology, the School of Medicine, and the Office of the Provost of Stanford University for supporting PHASER

Thank you, RSL!

- New job: faculty position at Tufts University
- New email address: erica.kemmerling@tufts.edu
- When you look me up, don't forget that my name is Erica Kemmerling, not Erica Cherry!!

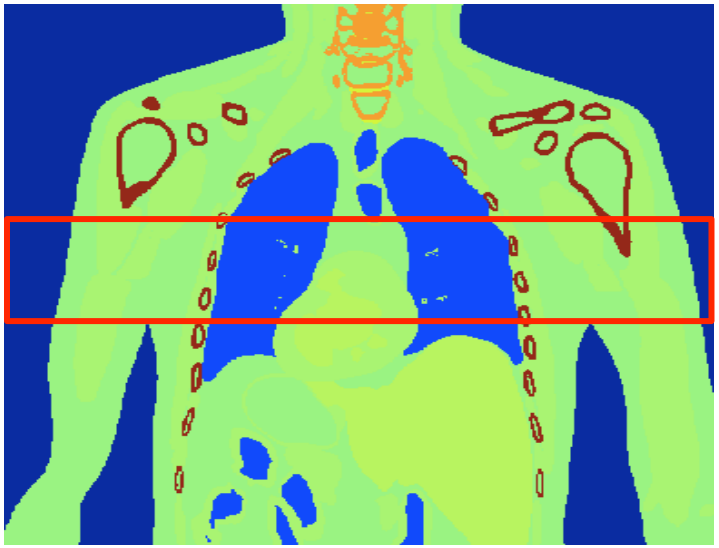
Questions?

EXTRA SLIDES

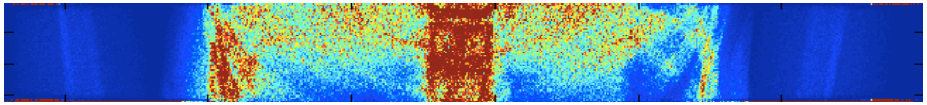
Custom CT Parameter Summary

Parameter	Clinical Scanner	On board CBCT	Custom scanner
Source to detector distance (mm)	1040 (too small– can't shift patient)	1400-1700	1300
Typical scan time (sec)	10	100 (too slow– patient must breathe)	10 helical, 1 axial
In-plane field of view (mm)	500	240-400 (too small– truncation artifacts)	500
Maximum axial field of view at isocenter (mm)	32 (too small– can't acquire data quickly enough)	175	100

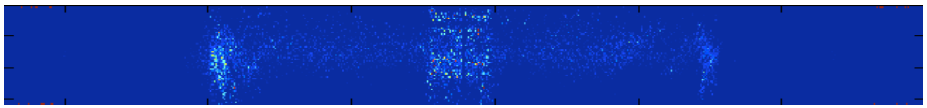
Scatter-to-primary ratio (SPR)



No anti-scatter grid



1-cm-tall 2D anti-scatter grid



SPR 0 2