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Clinical applications

in the pelvis:

Verification using deformable phantoms

SCIENTIFIC PROGRAM: Symposium – THERAPY
The Promise and Potential Pitfalls of Deformable Image Registration in Clinical Practice

AAPM Annual Meeting 2014

Disclosure

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UCSF DIR Team

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Sarah Geneser, PhD
Neil Kirby*, PhD
I-Chow Hsu, MD

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Presentation Layout

- **Applications and dependencies of DIR**
- **Clinical Needs / Applications:**
  3 Examples, 3 challenges
- **DIR Evaluation using deformable phantoms**

All references available at the end

DIR Applications

Auto-Segmentation
- Atlas-based segmentation:

Contours Propagation
- Replanning for Adaptive RT
- Compensate distortion due to probe: MRSI DIL to CT, MR - US
- PET/CT - Planning CT

Dose Mapping and Accumulation
- Different fractions
- Different treatment modalities
- Previous irradiation (salvage therapy)

Organ Evolution
- Tumor shrinkage and Dose response
- Level of complications and side effects

Motion Compensation
- Real-time imaging

DIR Performance Dependencies

The performance of deformable image registration algorithms varies widely and is influenced by many factors:

- Image quality (noise, artefact, slice thickness, etc)
- Image modality (CT, CBCT, MRI, US, etc.)
- Multi-image modalities (a key factor for ART as the planning and daily patient images are typically not of the same type)
- Imaging protocol and reconstruction
- Clinical application (contour propagation, dose mapping, dose summation, motion compensation, tumor evolution)
- Clinical site (head & neck, pelvis, lung, etc.)
- Vendor implementation.

Clinical Applications (Pelvis)

3 Examples, 3 challenges

- **Prostate ART (CT-CBCT)**
- **HDR Brachytherapy DIL Boost from MRSI information (MRSI – MRI - CT)**
- **Dose mapping and accumulation**

1- Adaptive Radiation Therapy

Concurrent treatment of prostate and pelvic nodes with IMRT or VMAT

Challenge: Independent movements of prostate vs nodes

Several solutions have been proposed, But they all require contour propagation

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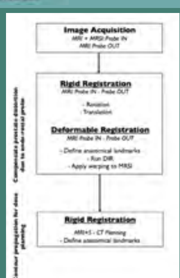
2- Probe Distortion Compensation



- **Difficult to adjust DIR pliability at different locations in the image**
- **Presence / absence of probe not considered by DIR**
- **DIR should focus on Region of Interest only (Zone propagation).**

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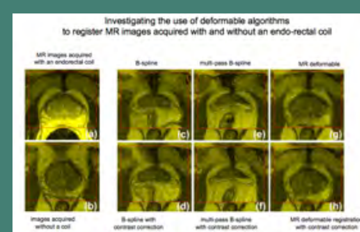

Courtesy of O. Utako Ueda and Josephine Chen

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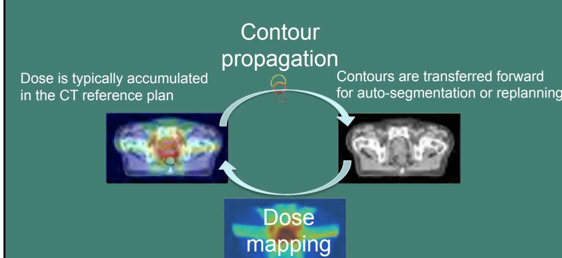
3- Dose mapping and accumulation



- Voxel to Voxel Mapping
- Transformation in each direction is needed

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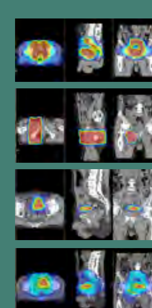
A Clinical Example: Salvage Therapy

Mass outside bladder, IMRT 10/10

Bone mets treatment, 3D 12/11

Lesion inside bladder, Cyberknife 03/12

Composite dose using deformable registration



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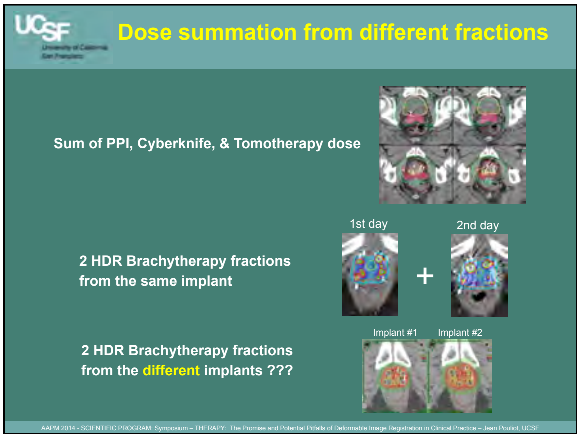
Dose summation from different fractions
Sum of PPI, Cyberknife, & Tomotherapy dose
1st day
2nd day
2 HDR Brachytherapy fractions from the same implant
+
Implant #1
Implant #2
2 HDR Brachytherapy fractions from the different implants ???
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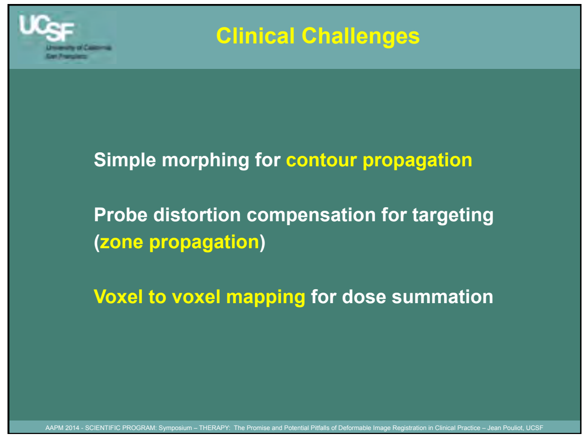
Clinical Challenges
Simple morphing for contour propagation
Probe distortion compensation for targeting (zone propagation)
Voxel to voxel mapping for dose summation
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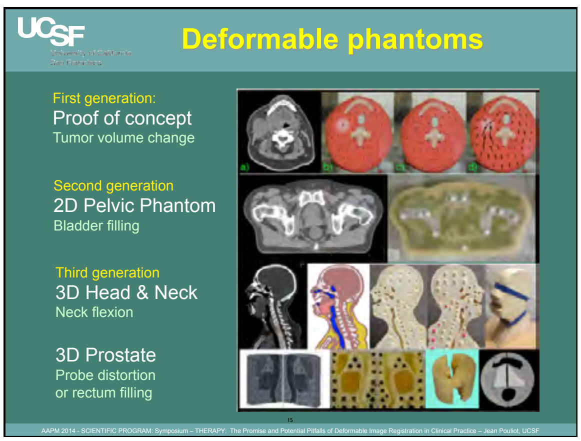
Deformable phantoms
First generation:
Proof of concept
Tumor volume change
Second generation
2D Pelvic Phantom
Bladder filling
Third generation
3D Head & Neck
Neck flexion
3D Prostate
Probe distortion
or rectum filling
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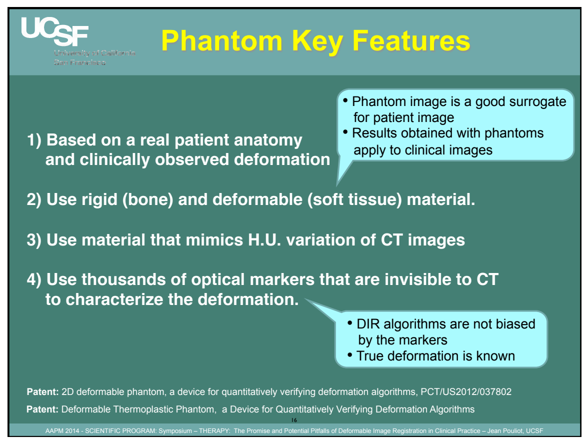
Phantom Key Features
1) Based on a real patient anatomy and clinically observed deformation
• Phantom image is a good surrogate for patient image
• Results obtained with phantoms apply to clinical images
2) Use rigid (bone) and deformable (soft tissue) material.
3) Use material that mimics H.U. variation of CT images
4) Use thousands of optical markers that are invisible to CT to characterize the deformation.
• DIR algorithms are not biased by the markers
• True deformation is known
Patent: 2D deformable phantom, a device for quantitatively verifying deformation algorithms, PCT/US2012/037802
Patent: Deformable Thermoplastic Phantom, a Device for Quantitatively Verifying Deformation Algorithms
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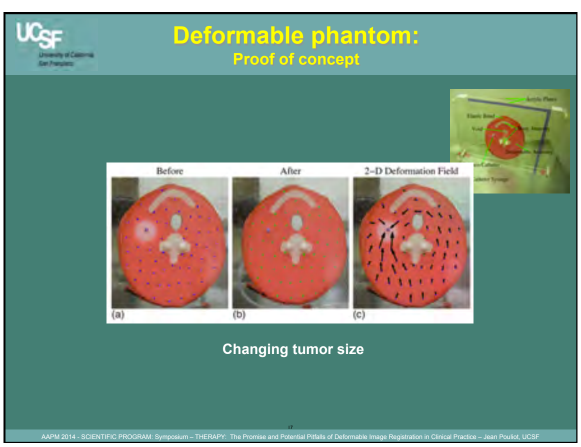
Deformable phantom:
Proof of concept
Before
After
2-D Deformation Field
(a)
(b)
(c)
Changing tumor size
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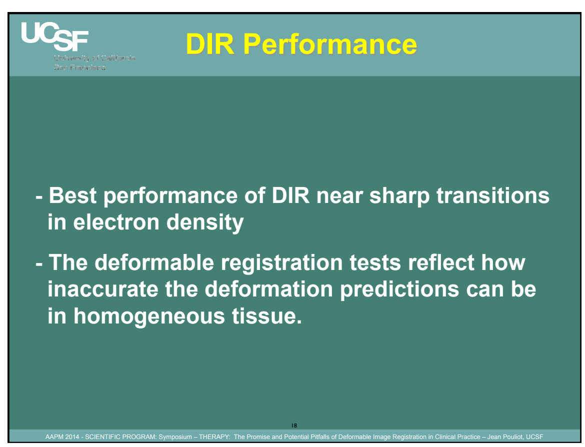
DIR Performance
- Best performance of DIR near sharp transitions in electron density
- The deformable registration tests reflect how inaccurate the deformation predictions can be in homogeneous tissue.
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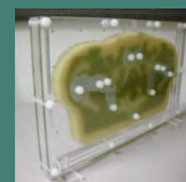
DIR Performance

DIR algorithm optimized only for its ability to transfer anatomical contours will yield large deformation errors in homogeneous regions, a problem for dose mapping.

Pelvic deformable phantom

Phantom based on patient pelvic anatomy. Includes: bones, muscles, organs & fat

- Realistic CT numbers
- Landmarks invisible on CT but glow in the dark
- 2 phantoms: one deformed from the other by changing bladder filling



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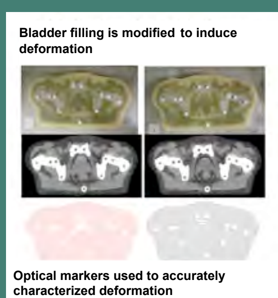
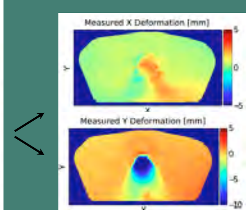
The Ground Truth





Use your **favorite DIR** on the two phantom images and compare predicted deformation with ground truth

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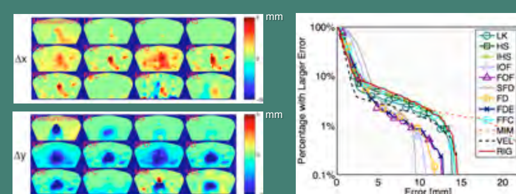
Use your favorite DIR

on the two phantom images and compare predicted deformation with ground truth



- Different DIR generate very different results.
- DIR algorithms require quality assurance.

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DIR Performance

All tested algorithms but two have produced errors ≥ 3 mm for at least 5% of the pixels.

Highest Error (E_{1cm^2}) that occupies 1 cm^2 (0.17%) varies from 8 to 20 mm.

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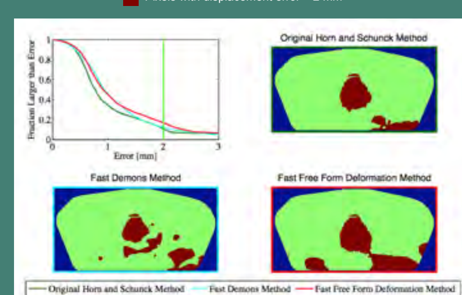
Physical Deformation ?

Pixels with displacement error ≥ 2 mm



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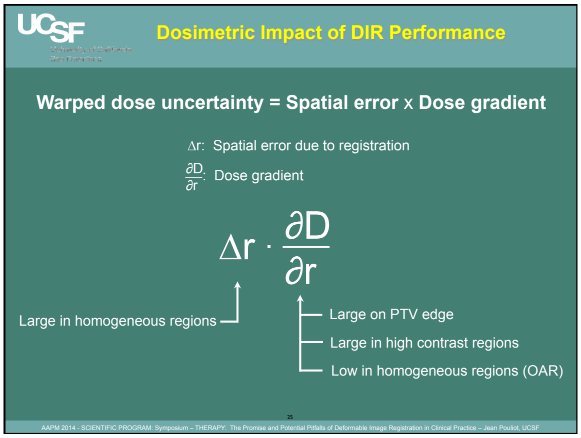
UCSF
Dosimetric Impact of DIR Performance
Warped dose uncertainty = Spatial error x Dose gradient
Δr: Spatial error due to registration
∂D/∂r: Dose gradient
Δr · ∂D/∂r
Large in homogeneous regions
Large on PTV edge
Large in high contrast regions
Low in homogeneous regions (OAR)
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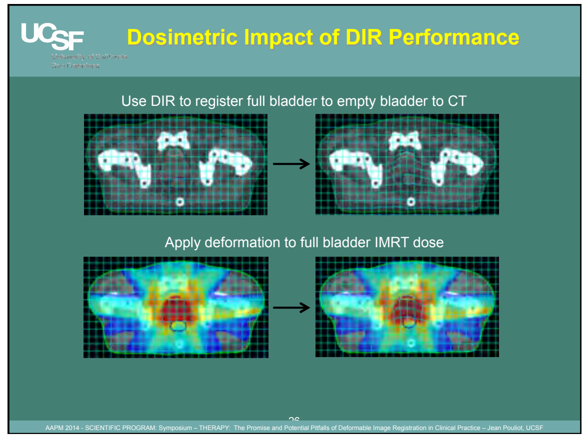
UCSF
Dosimetric Impact of DIR Performance
Use DIR to register full bladder to empty bladder to CT
Apply deformation to full bladder IMRT dose
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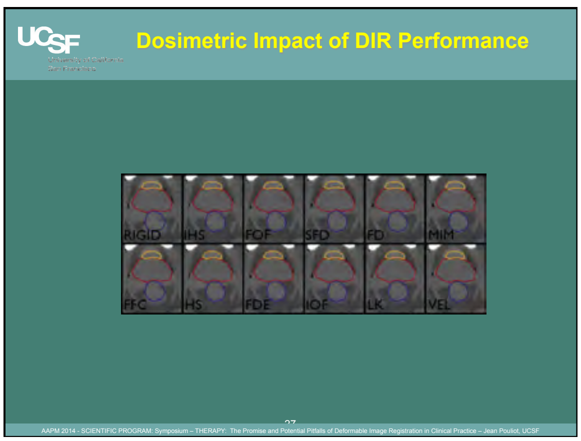
UCSF
Dosimetric Impact of DIR Performance
RIGID
IHS
FOF
SFD
FD
MIM
FFC
HS
FDE
IOF
LK
VEL
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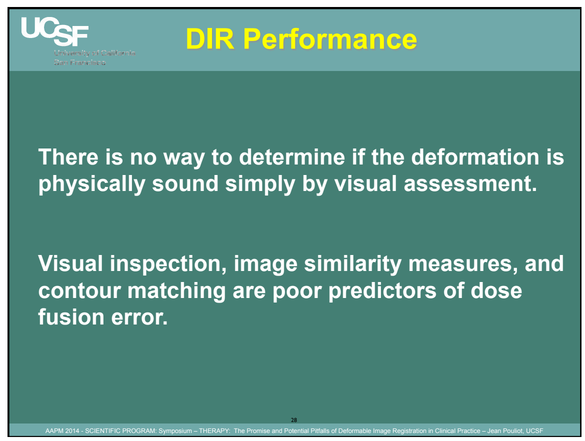
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DIR Performance
There is no way to determine if the deformation is physically sound simply by visual assessment.
Visual inspection, image similarity measures, and contour matching are poor predictors of dose fusion error.
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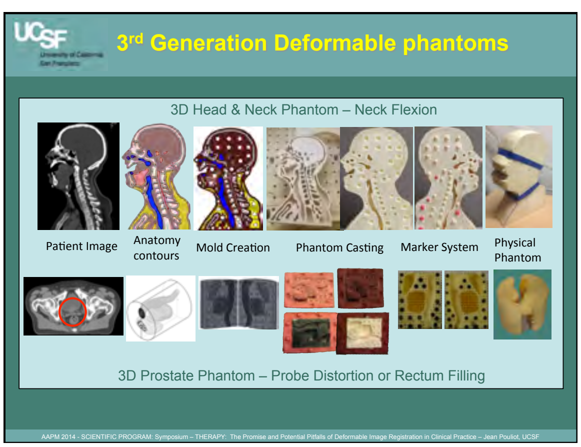
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3rd Generation Deformable phantoms
3D Head & Neck Phantom – Neck Flexion
Patient Image
Anatomy contours
Mold Creation
Phantom Casting
Marker System
Physical Phantom
3D Prostate Phantom – Probe Distortion or Rectum Filling
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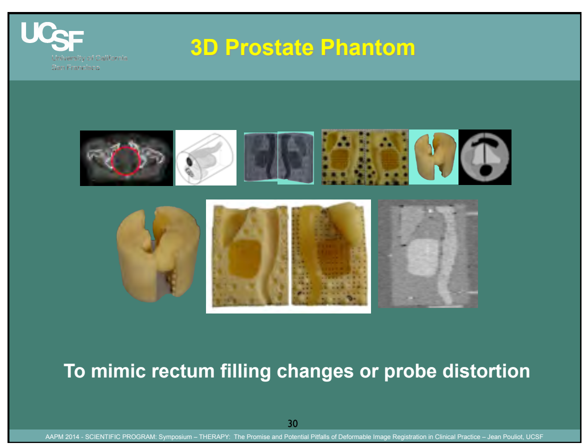
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3D Prostate Phantom
To mimic rectum filling changes or probe distortion
30
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Examples of Results from Phantom Analysis

B-Spline-type algorithms produce smooth, physically plausible deformation, but also may not fully deform one image to the other: Large average errors.

Demon-type algorithms produce beautiful image similarity, but may produce non-physical deformation fields: Large maximum errors.

Performance varies widely between CT-CT, CT-MVCT, or MVCT-MVCT, and even for different slice thicknesses (e.g. 1.5 vs. 3.0 mm).

Spatial DIR accuracy comes from a combination of close image similarity and physical plausible deformations

31

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DIR Use

Assumption: if two images are being registered, every point of one image corresponds appropriately to some point in the other image.

The assumption is **NOT VALID** in presence of:

- Cell killing
- Changes of rectum & blad... ...gs
- Air cavity or Bowel ga...
- Tumor shrinkag...
- Swelling an... ...ma
- Weigh...
- P... ...e/absence of brachytherapy devices (c...theters, balloons, applicators, etc.)

They ALL apply to the pelvis area

32

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Conclusions

DIR -> Contour Propagation & Atlas-based segmentation

DIR based on bio-mechanical properties -> Dose mapping
(Automated landmark-guided DIR)
(Structure-Guided Non-rigid Registration)

Inspection methods must be developed to facilitate and enable assessment of dose fusion accuracy on a patient-specific basis.

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Thank You!

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