Clinical Impact and Applications of 4D Imaging (in RT)

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Disclosures

- Employee of Virginia Commonwealth University / Washington University
- Research Grants: NIH, Varian Medical Systems
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All radiation therapy is inherently 4D.

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- Simulation to treatment time
- Delivery time
- Fractionation

But what do we really mean by 4D?

- Volumetric (3D plus time) measurement
- of (quasi)periodic respiration in thorax and upper abdomen.
- Incorporation into radiation therapy planning and delivery.

4D Imaging - some terms

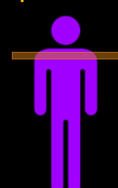
- ***4D Image***: the complete spatial and temporal image
- ***Frame***: One instantaneous time or phase point in the image.
- A 4D image is composed of multiple 3D frames (3D + time).

Almost any modality can be 4D

- CT, MRI, PET, ultrasound, etc.
- Rarely is 4D collected through subsequent rapid 3D frames
- Mainly, collect portions of image over multiple breathing cycles, and stitch these together

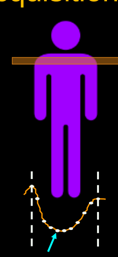
Example 4D(CT) Image Acquisition

- Slice acquired – few 100 ms



Example 4D(CT) Image Acquisition

- Slice acquired – few 100 ms
- Breathing cycle – 5-7 s
- Acquire ~10-12 frames over breathing cycle



Example 4D(CT) Image Acquisition

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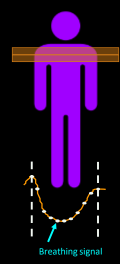
- Move to next slice position, repeat



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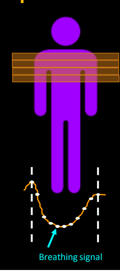
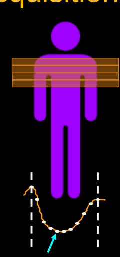


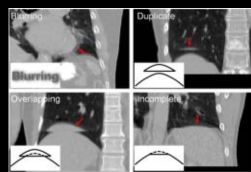
Example 4D(CT) Image Acquisition

- Slice acquired – few 100 ms
- Breathing cycle – 5-7 s
- Acquire ~10-12 frames over breathing cycle
- Move to next slice position, repeat
- Finally, stack slices into a 3D frame, frames into a 4D image



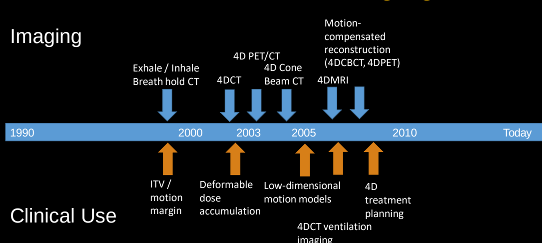
Considerations with 4D Imaging

- So 4D is not really 4D
  - In the sense of 3D + time
  - Rarely a true '3D cine' image
- This can lead to:
  - Artifacts
  - Incomplete representation of motion
- Keep this in mind – clinical applications

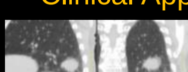


Yamamoto, IJROBP, 2008

A Brief Timeline of 4D Imaging in RT

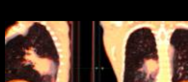


Clinical Applications of 4D Imaging

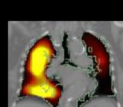


4D Treatment Planning

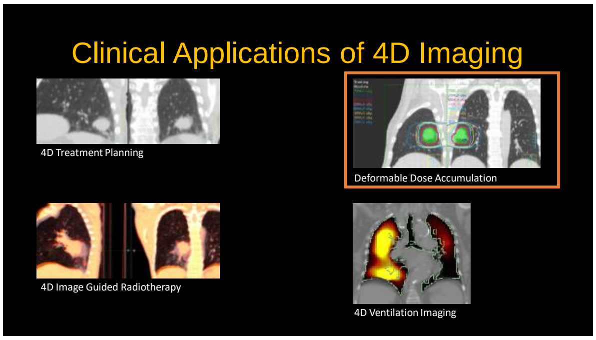
Deformable Dose Accumulation



4D Image Guided Radiotherapy



4D Ventilation Imaging


Clinical Applications of 4D Imaging
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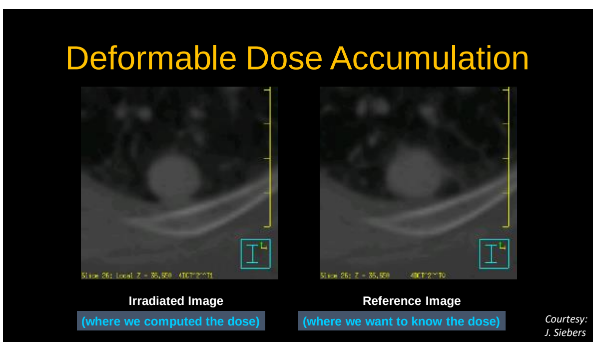
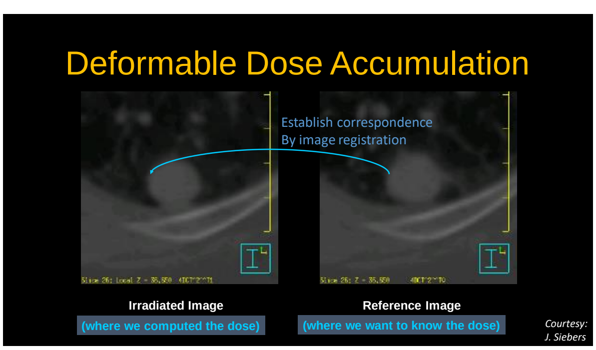
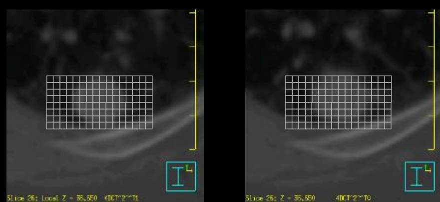

Deformable Dose Accumulation
Irradiated Image
(where we computed the dose)
Reference Image
(where we want to know the dose)
Courtesy:
J. Siebers


Deformable Dose Accumulation
Establish correspondence
By image registration
Irradiated Image
(where we computed the dose)
Reference Image
(where we want to know the dose)
Courtesy:
J. Siebers

Deformable Dose Accumulation

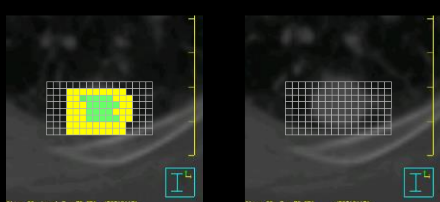


Irradiated Image (where we computed the dose)

Reference Image (where we want to know the dose)

Courtesy: J. Siebers

Deformable Dose Accumulation

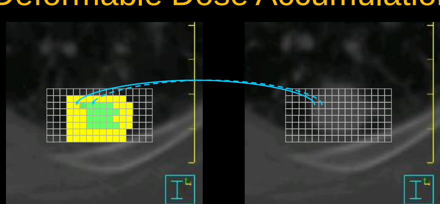


Irradiated Image

Reference Image

Courtesy: J. Siebers

Deformable Dose Accumulation



Irradiated Image

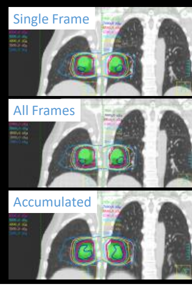
Reference Image

Courtesy: J. Siebers

Deformable Dose Accumulation

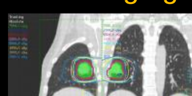
- Register all frames to reference
- Compute dose on irradiated frames
- Deform dose to reference frame
- Accumulate all deformed doses

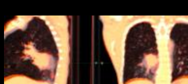
- Uses:
  - Improve prediction of delivered dose
  - Outcomes modeling, margin analysis, etc.
  - 4D treatment planning

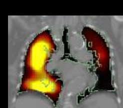


Clinical Applications of 4D Imaging


4D Treatment Planning


Deformable Dose Accumulation

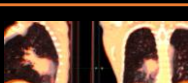

4D Image Guided Radiotherapy


4D Ventilation Imaging

Clinical Applications of 4D Imaging


4D Treatment Planning


Deformable Dose Accumulation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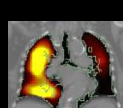
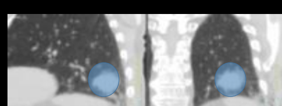

4D Ventilation Imaging

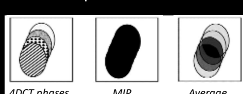
Motion Management in Planning – Static Delivery

- Free breathing CT (not recommended)
  - Simple
  - Imprecise, introduces systematic error in IGRT
- Motion Envelope / Internal Target Volume (ITV)
  - Simple, given 4DCT
  - Doesn't allow proper (quadratic summation) margins
- Mid-ventilation
  - Properly handles margins
  - Smaller margin than ITV
  - Requires margin formula (with assumptions)

ITV Generation

- 4DCT -> Maximum Intensity Projection (MIP) -> Contour MIP
  - Only contour one image
  - May be difficult to define motion envelope





Underberg, IJROBP 63(1) 2005

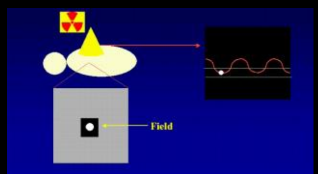
Glide-Hurst, J Thorac Disease 6(4) 2014

Motion Management in Planning – Dynamic Delivery

- Breath hold
  - Requires a breath hold CT, not truly 4D
- Gating
  - Limit the beam delivery to only particular phases or amplitudes of breathing
- Tracking
  - 'Chase' the target motion with a dynamic beam delivery

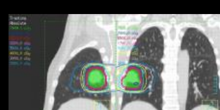
Respiratory Gating

- Beam is turned on only during a particular phase / amplitude / position
- 4D imaging can be used for gated planning to set gating window, assess dosimetric coverage
- Traditionally, had to rely on external motion signal (surrogate).
- Now, onboard MRI, 2D + time imaging allow for more direct assessment of target position



Target Tracking

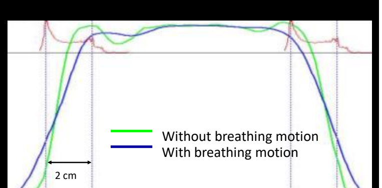
- Beam aperture continually chases target phase / amplitude / position
- 4D imaging can be used to assess dosimetric coverage
- Similar to gating, more direct assessment of tumor position is emerging (implanted markers, MRI, etc.)



Courtesy: P. Keall

4D Inverse Planning

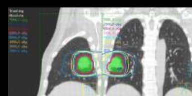
- Incorporate the motion into inverse planning
- design a fluence distribution which compensates for the expected blurring of dose
- Concerns:
  - Sensitivity to motion changes
  - Quality assurance



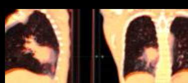
Courtesy: D. Yan

Clinical Applications of 4D Imaging

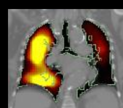
4D Treatment Planning



Deformable Dose Accumulation



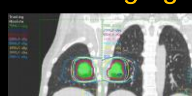
4D Image Guided Radiotherapy



4D Ventilation Imaging

Clinical Applications of 4D Imaging

4D Treatment Planning



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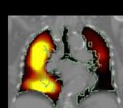
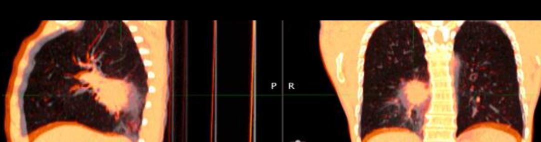
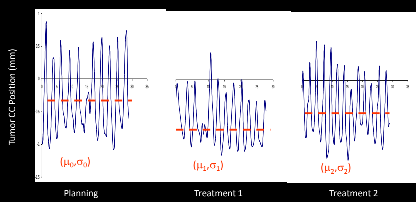


4D Ventilation Imaging

Baseline Variation

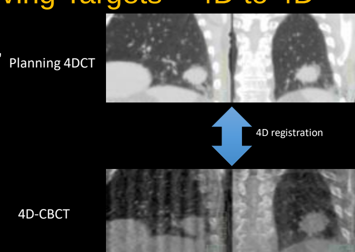


Breathing Pattern Changes



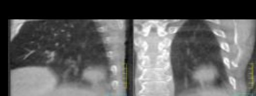
IGRT for Moving Targets – 4D to 4D

- Options:
  - Register each frame, then average
  - Register a reference frame (e.g., end inhale)
  - Depends on delivery technique (free breathing, gating, tracking, etc.)

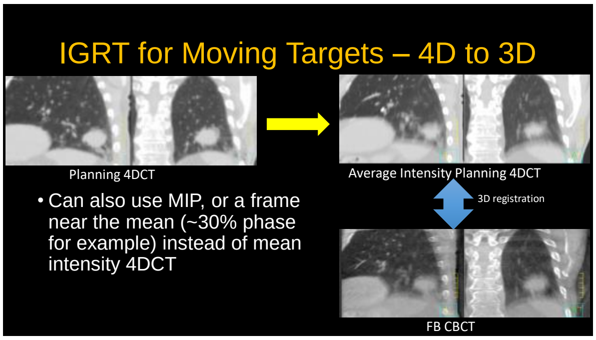


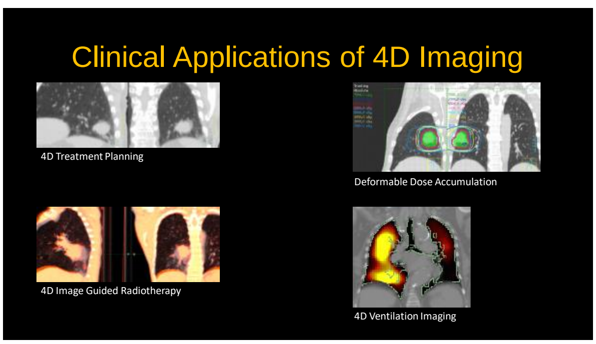
IGRT for Moving Targets – 4D to 3D

- Free-breathing CBCT blurs moving anatomy
- Due to periodicity of respiration, tends to show mean position of the moving anatomy, including tumor



FB CBCT


IGRT for Moving Targets – 4D to 3D
Planning 4DCT
Average Intensity Planning 4DCT
3D registration
• Can also use MIP, or a frame near the mean (~30% phase for example) instead of mean intensity 4DCT
FB CBCT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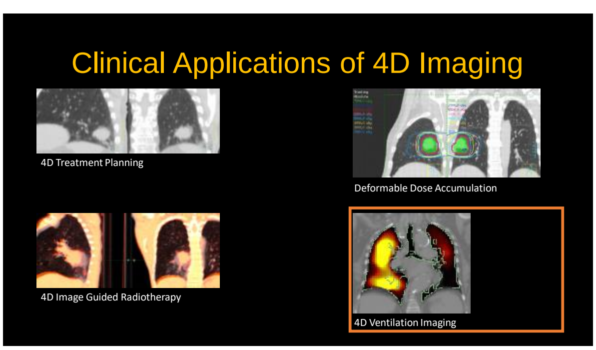
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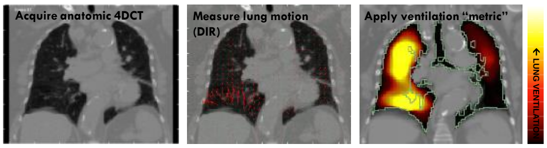


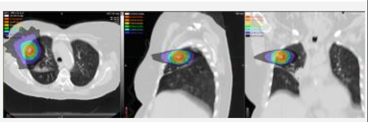
Advantages over nuclear medicine and hyperpolarised gas MRI:

- ✓ 4DCT is already widely available in radiotherapy departments
- ✓ No added scan time or imaging dose

Courtesy: J. Kipritidis, Univ. Sydney

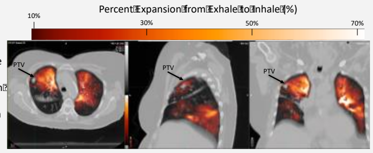
Initial Planning Process

Step 1: Create Conventional Plan



Percent Expansion from Exhale to Inhale (%)

Step 2: Create Jacobian transformation based CT-ventilation map



Ding K, Bayouth JE, Buatti JM, Christensen GE, Reinhardt JM. 4DCT-Based Measurement of Changes in Pulmonary Function Following a Course of Radiation Therapy. Med. Phys. 2010;37(3):1261-1272.

Courtesy: J. Bayouth, UW

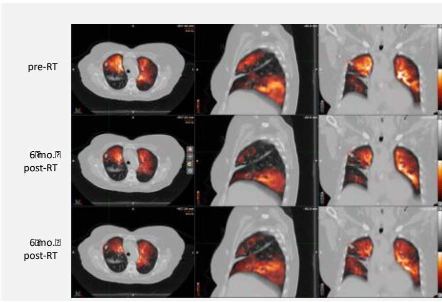
Step 5: Create Plan Designed to Improve Pulmonary Function (IPF)

Conventional Plan

IPF Plan

Courtesy: J. Bayouth, UW

Ventilation Response to IPF Treatment

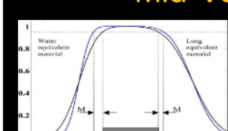


Courtesy: J. Bayouth, UW

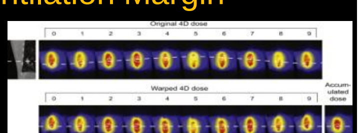
Summary

- 4D images widely available and widely used in RT
- Applications emerge quickly after new imaging developments
- Much new development in planning, guiding, assessing therapy with 4D imaging

Mid-Ventilation Margin



Sonke, Sem Rad Onc 20(2) 2010

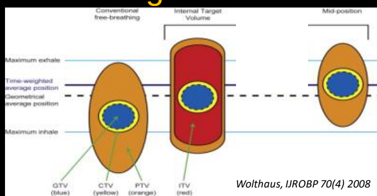


Mexner, IJROBP 74(4) 2009

Periodic respiration

- is a random error, has a blurring effect on dose from photons
- has a relatively minor effect on the delivered vs. planned dose, relative to other geometric errors (setup error, target delineation, etc.)
- only really true for photons, not particles

Motion Management in Planning

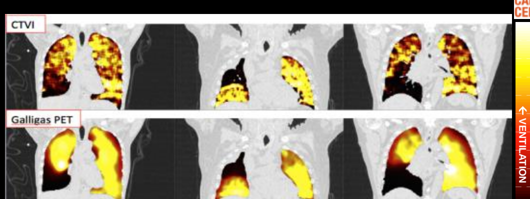


Wolthaus, IJROBP 70(4) 2008

ITV encompasses entire range of motion (as measured by 4DCT)
Mid-ventilation considers motion as a random error
ITV margin will commonly be larger than mid-ventilation margin

Clinical validation of 4D Ventilation Imaging

NORTHERN SYDNEY CANCER CENTRE



Courtesy: J. Kipritidis, Univ. Sydney