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

Geoff Hugo, Ph.D.
Virginia Commonwealth University
Washington University School of Medicine
gdhugo@wustl.edu

Disclosures
• Employee of Virginia Commonwealth University / Washington University
• Research Grants: NIH, Varian Medical Systems
• Royalties: Varian Medical Systems

All radiation therapy is inherently 4D.
All radiation therapy is inherently 4D.

• 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
- Breathing cycle – 5-7 s
- Acquire ~10-12 frames over breathing cycle
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

A Brief Timeline of 4D Imaging in RT

Clinical Applications of 4D Imaging
Clinical Applications of 4D Imaging

4D Treatment Planning

4D Image Guided Radiotherapy

4D Ventilation Imaging

Deformable Dose Accumulation

Irradiated Image
(where we computed the dose)

Reference Image
(where we want to know the dose)

Establish correspondence
by image registration

Deformable Dose Accumulation

Courtesy: J. Siebers
Irradiated Image
(where we computed the dose)

Reference Image
(where we want to know the dose)

Deformable Dose Accumulation

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
- 4D Image Guided Radiotherapy
- Deformable Dose Accumulation
- 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

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.)

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
Clinical Applications of 4D Imaging

- 4D Treatment Planning
- 4D Image Guided Radiotherapy
- Deformable Dose Accumulation
- 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
IGRT for Moving Targets – 4D to 3D

Planning 4DCT

- Can also use MIP, or a frame near the mean (~30% phase for example) instead of mean intensity 4DCT

Average Intensity Planning 4DCT

3D registration

FB CBCT

Clinical Applications of 4D Imaging

4D Treatment Planning

Deformable Dose Accumulation

4D Image Guided Radiotherapy

4D Ventilation Imaging

Deformable Dose Accumulation

4D Ventilation Imaging
CT ventilation imaging (CTVI) transforms 4DCT from purely anatomic imaging into functional imaging that visualizes breathing induced air volume change (“ventilation”).

Advantages over nuclear medicine and hyperpolarised gas MRI:

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

Acquire anatomic 4DCT
Measure lung motion (DIR)
Apply ventilation “metric”

4D Ventilation Imaging

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

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

Conventional Plan

IPF Plan

Step 2: Create Jacobian transformation based CT-ventilation map


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

Conventional Plan

IPF Plan

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

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

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

Wolthaus, IJROBP 70(4) 2008

Reliably good voxel level correlations (r~0.65) correlations between CTVI and PET for 18 lung cancer patients.

Clinical validation of 4D Ventilation Imaging

Courtesy: J. Kipritidis, Univ. Sydney