Current and future motion management techniques in imaging for RT simulation

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Disclosures

Honoraria from Philips Healthcare and Siemens Healthineers (not related to this presentation)
Learning objectives

1. Motion management during the RT simulation process
2. Challenges and opportunities with 4D-CT (PET, MR)
3. Emerging technologies and future directions
The radiation therapy process

- Immobilization and motion management
  - CT scan
  - MRI scan
  - PET/CT scan
  - Image registration/fusion
    - Target and OAR contouring

- Treatment planning
- Quality assurance/plan verification
- Patient setup
- Pre-treatment imaging
- Treatment
Motion management in radiation therapy

• Goal in RT is to irradiate the target (tumor) and spare healthy tissue

• Modern treatment planning systems and treatment delivery devices can provide highly conformal radiation plans

• Important to know where the target is (and healthy tissue)

• Critical for hypo-fractionated treatments (for example, lung SBRT)
Why we need motion management

• For best therapeutic effect, give high dose to tumor and as little dose as possible to healthy tissue (OAR – organs-at-risk).

• Limited by achievable dose fall-off and uncertainties.

• If motion is present, position uncertainties can increase or decrease dose.
Motion management in radiation therapy

• Sites most affected by breathing motion:
  • Lung
  • Mediastinum
  • Chest wall / breast
  • Kidney/adrenal
  • Liver
  • T-spine

• Toxicities to organs-at-risk:
  • Lungs / pulmonary system
  • Heart
  • Esophagus
  • Liver
  • Kidneys...
Guidance documents on motion management and QA

• AAPM TG-76 “The Management of Respiratory Motion in Radiation Oncology”, 2006
• AAPM TG-147 “Quality assurance for nonradiographic radiotherapy localization and positioning systems”, 2012
• AAPM TG-290 “Respiratory Motion Management for Particle Therapy”, 2022
• AAPM TG-302 “Surface Image Guided Radiotherapy”, 2022
• AAPM TG-324 “Management of Respiratory Motion in Radiation Oncology: An Update to Task Group 76 (TG324)” – in progress
• AAPM TG-66U1 “Quality assurance for computed-tomography simulators in Radiation Oncology: An Update to the Report of the AAPM Radiation Therapy Committee Task Group No. 66 (TG66U1)” – in progress
Motion management techniques

1. **Breath hold** (freeze motion; forced or voluntary)
2. **Compression devices** (limit motion with forced shallow breathing)
3. **Integrate movement into treatment planning** (requires knowledge of motion trajectory)
4. **Gated treatment on certain phases of respiratory cycle** (free-breathing or breath hold)
5. **Tracking techniques** (during treatment delivery)

Freeze motion with breath hold

Active

Voluntary

image by Elekta

images by DYN’R
Freeze motion with breath hold (DIBH)

- Most commonly applied for left-sided breast cancer
- Spares heart and LAD
- Respiratory surrogate or observation (no BH device)
- Scan triggered manually once BH is stable


Limit motion with compression devices

image by CIVCO

image by orfit

image by ELEKTA

image by CDRSystems
Limit motion with compression devices

• Motion evaluated without compression (4D-CT)
• If motion amplitude exceeds tolerance, apply compression
  • apply maximum force that patient can tolerate
  • acquire 4D-CT with forced shallow breathing

Motion-encompassing methods

• Breath-hold scans (inhale and exhale)
  • Voluntary BH or active breathing control
  • Connect inhale and exhale GTV to get iGTV (ITV)

• Gated scans (inhale and exhale)

• Slow scan (low pitch) → average tumor position

• Multiple fast 3D scans at several (random) phases

• 4D-CT scans (time-resolved 3D volumes)


Use cases for 4D-CT in radiation therapy

- Target motion estimation and delineation of internal target volume (ITV)
  - should be done in all three dimensions
- Selecting respiratory states for gated treatments
- 4D dose calculation
- More recently: Lung ventilation studies

Early work on 4D-CT:
Manage motion with gated treatments

• Purpose: select thresholds for gated treatments
• Acquire respiratory surrogate trace and 4D-CT
• Preselect gating thresholds and export gating protocol to TPS / R&V / LINAC
Respiratory-gated 4D-CT

- Respiratory signal acquired from a respiratory surrogate
  - Spirometer
  - Surface movement
    - marker block+IR camera,
    - laser reflected off skin
    - abdominal belt with strain gauge / pressure sensor
- Tagging/sorting of projection data
- Reconstruction into spatiotemporal motion bins
  - time/phase-based
  - amplitude-based
- Assumption: correlation exists between respiratory surrogate signal and internal target motion (in reality, this assumption is not always met)
Respiratory gating

Images by Philips

Images by Anzai

UMaryland
Respiratory-gated 4D-CT: benefits and challenges

Benefits

• Patient can breathe normally

• Provides full motion information (typically 10 bins)

• More accurate amplitude estimate vs inhale/exhale breath hold

• Can be combined with abdominal compression to reduce motion

Challenges

• Correlation between surrogate and tumor

• Takes longer (slow-pitch scan)

• Artifacts due to breathing irregularities

• Setting optimal scan parameters (mostly automatic these days)
Respiratory-gated 4D-CT

- At each position, acquire data from a complete breathing cycle
- Tag projection data to corresponding phase/amplitude bin
- Sort projection data according to phase/amplitude bin

(simplified for illustration purposes)
Binning in respiratory-gated 4D-CT

time (phase)-based binning

amplitude-based binning
Assumptions in conventional respiratory-gated 4D-CT

1. The breathing pattern is regular

2. There is a constant relationship between the external surrogate and the internal target motion

3. There is sufficient data to reconstruct images at all requested breathing states

! Artifacts can occur if these assumptions are violated

! Most often, the source for artifacts is irregular breathing and inadequate scan parameters

Retrospective 4D-CT: choice of acquisition parameters

- In helical 4D-CT, the maximum pitch factor (table speed) depends on the breathing rate

- Slower (higher) BPM → slower (higher) speed

![Graph showing Maximum pitch vs. BPM for different FOVs](image-url)
Retrospective 4D-CT motion artifacts

- In practice, no patient breathes perfectly regular
- The majority (75%–90%) of clinical 4D-CT’s have artifacts[1], [2], [3]
  - changes in amplitude
  - changes in frequency
  - baseline drift
  - coughing
  - breathing stops temporarily
  - inadequate scan settings (e.g., slow gantry rotation speed for patient with fast breathing rate)

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Retrospective 4D-CT: motion artifacts

- Irregular amplitude
- Irregular frequency (long pauses, sudden rapid breathing)

Interpolation artifacts

Irregular amplitude

Image source: 4D CT cookbook 2.1, Siemens Healthcare GmbH siemens-healthineers.com/radiotherapy/ct-for-rt
4D-CT motion artifacts – duplicate structure / stacking

- Very common with irregular breathing amplitude
- Most obvious near diaphragm
4D-CT motion artifacts – interpolation artifact

extreme example of multiple interpolation artifacts — unusable for planning purposes
Implications of motion artifacts for radiation therapy

- Overestimate or underestimate target motion and target size
- Inaccurate pixel values (inaccurate dose calculation)
- May lead to under-irradiation of the intended target or to over-irradiation of organs-at-risk
- Potentially unfavorable treatment outcomes


- Target volume RMSE up to 19% and target position RMSE up to 2.5 mm [1]
- Uneven distribution of ITV, banding artifacts. Reduction of ITV volume up to 20% for small (15 mm) lesions and motion amplitude 4 cm and ITV length reduction up to 7mm [2]
- Impact on local tumor control if target is not adequately irradiated [3]

Challenges with motion management

• Irregular breathing (irregular amplitude, irregular frequency)
• Periods of shallow breathing
• Reproducibility (breathing pattern or amplitude different between simulation and treatment)
• Patient coaching may be necessary (visual coaching devices may be beneficial)
Adaptive 4D-CT

Example: “intelligent 4D-CT” (*)
• Sequential scanning (‘cine’ mode, ‘step-and-shoot’)
• Automatic scan setting adjustment based on patient’s breathing
• Analyze breathing between scan segments
  • beam-on only if breathing is consistent with reference trace


artifact-free images despite long breathing pause
Prospective respiratory-gated 4D-CT

- Cine mode with acquisition triggered on certain gating window only
- Useful for gated treatments
- Limited availability on commercial CT simulators

4D-PET/CT

• CT is fast (seconds), PET is slow (minutes)
• Impact of motion on PET:
  • Reduction of SUV (risk of missing lesion on PET images)
  • Apparent change in lesion size
  • Mismatch in PET/CT fusion
• Average from PET is usually assumed to encompass the complete motion due to slow PET acquisition.
• Use of 3D PET/CT for target definition may underestimate full motion envelope and lead to under-irradiation of the target.

4D-MRI

• External surrogates difficult to synchronize with pulse acquisition
• Internal surrogates work better
• Current MR-linacs only offer 2D cine MRI
• Full 4D-MRI is still investigative (prior information + motion model + deformable registration).

Summary and outlook

• Proper motion management during RT sim is essential for high-quality radiation treatment

• Respiratory management technique used during simulation should complement the technique used for treatment

• Irregular and non-reproducible breathing poses the biggest challenges

Future directions

• Automatic adaptation to changes in breathing pattern

• Patient-specific motion modeling

• AI/ML solutions

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