UNIVERSITY of MARYLAND
SCHOOL OF MEDICINE

Current and future motion management techniques in imaging for RT simulation

Jochen Cammin, Ph.D.

AAPM 2022, 64th Annual Meeting & Exhibition
SAM Therapy Educational Course

RESPECT *and* **INTEGRITY** | **WELL-BEING** *and* **SUSTAINABILITY** | **EQUITY** *and* **JUSTICE** | **INNOVATION** *and* **DISCOVERY**

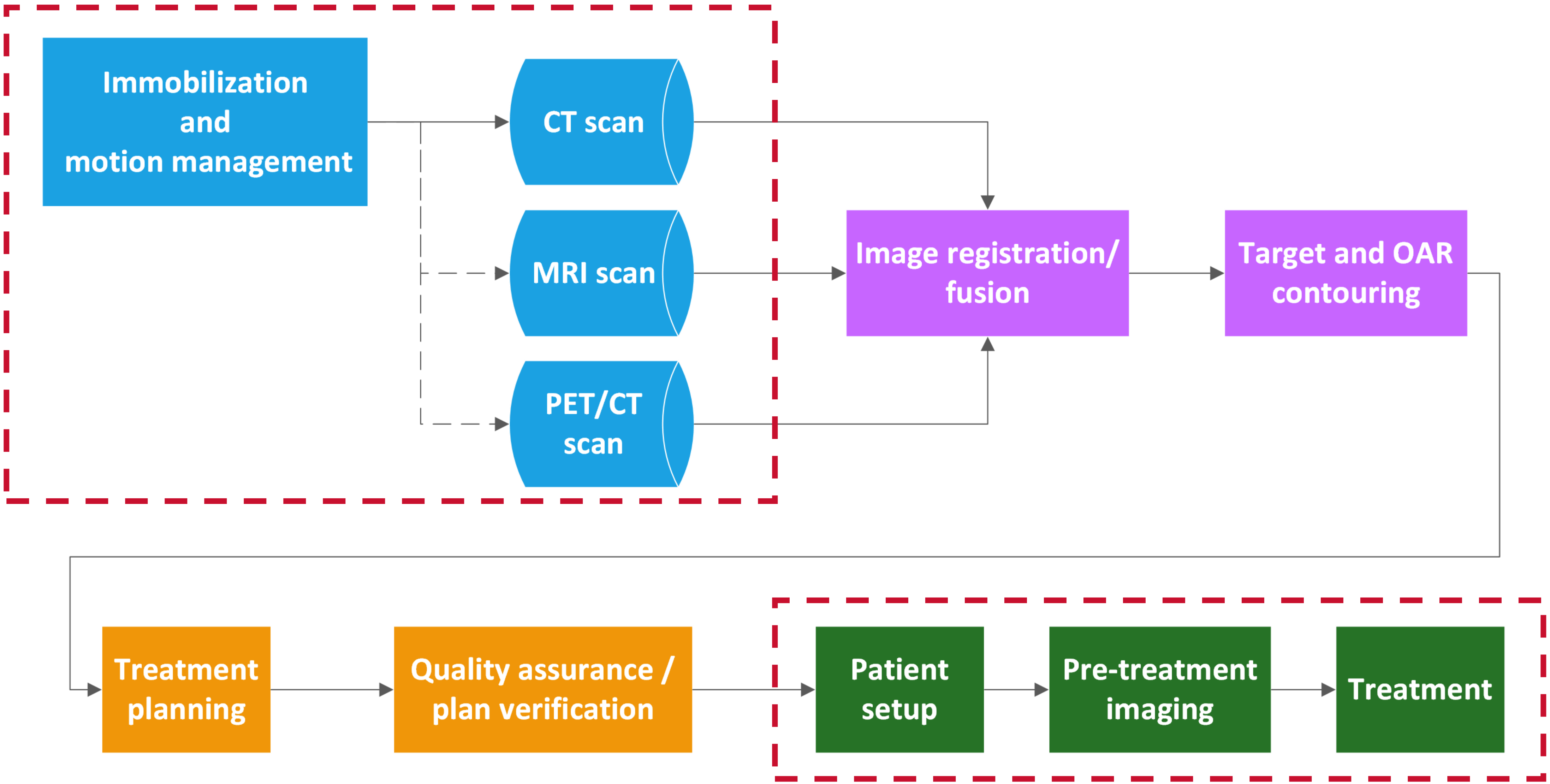
Disclosures

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

Learning objectives

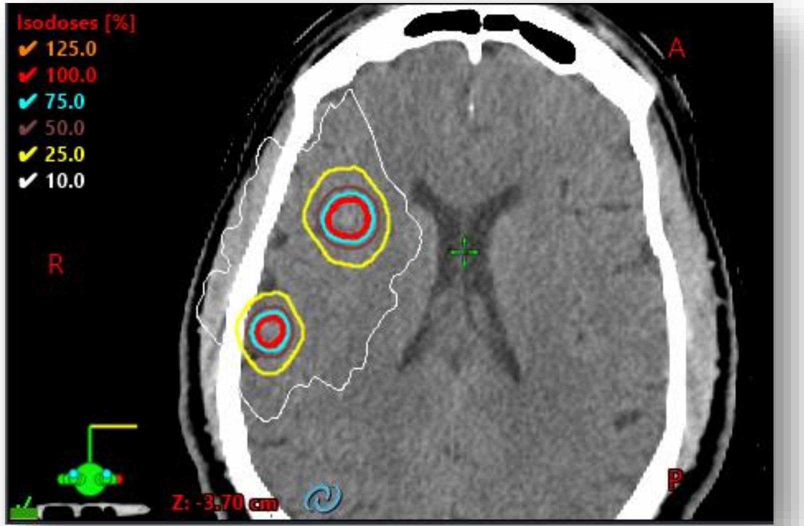
1. Motion management during the RT simulation process
2. Challenges and opportunities with 4D-CT (PET, MR)
3. Emerging technologies and future directions

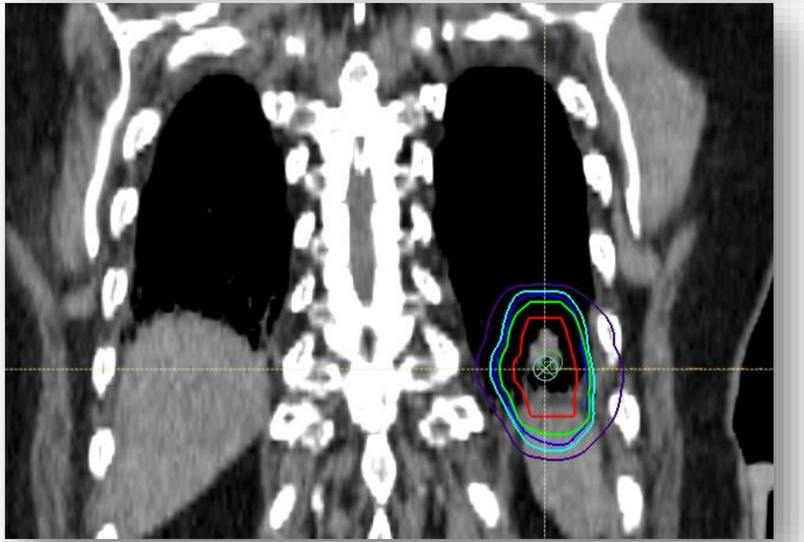
The radiation therapy process



Motion management in radiation therapy

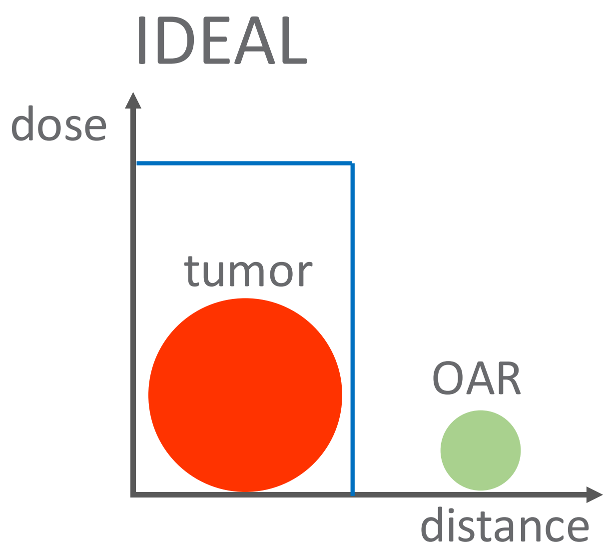
- Goal in RT is to irradiate the target (tumor) and spare healthy tissue
- Modern treatment planning systems and treatment delivery devices can provide highly conformal radiation plans
- Important to know where the target is (and healthy tissue)
- Critical for hypo-fractionated treatments (for example, lung SBRT)

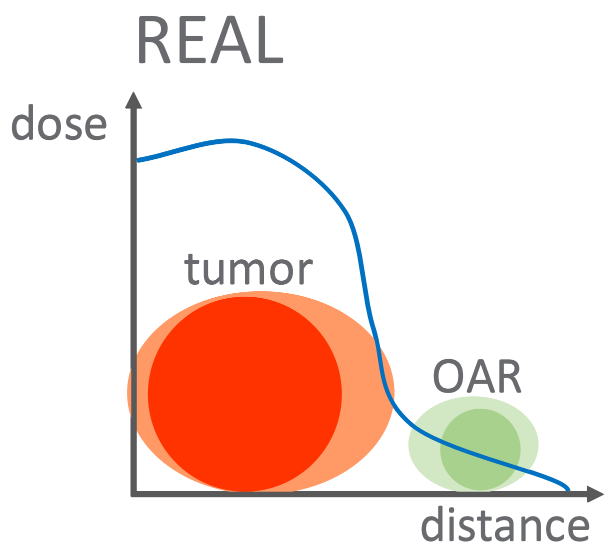




Why we need motion management

- 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



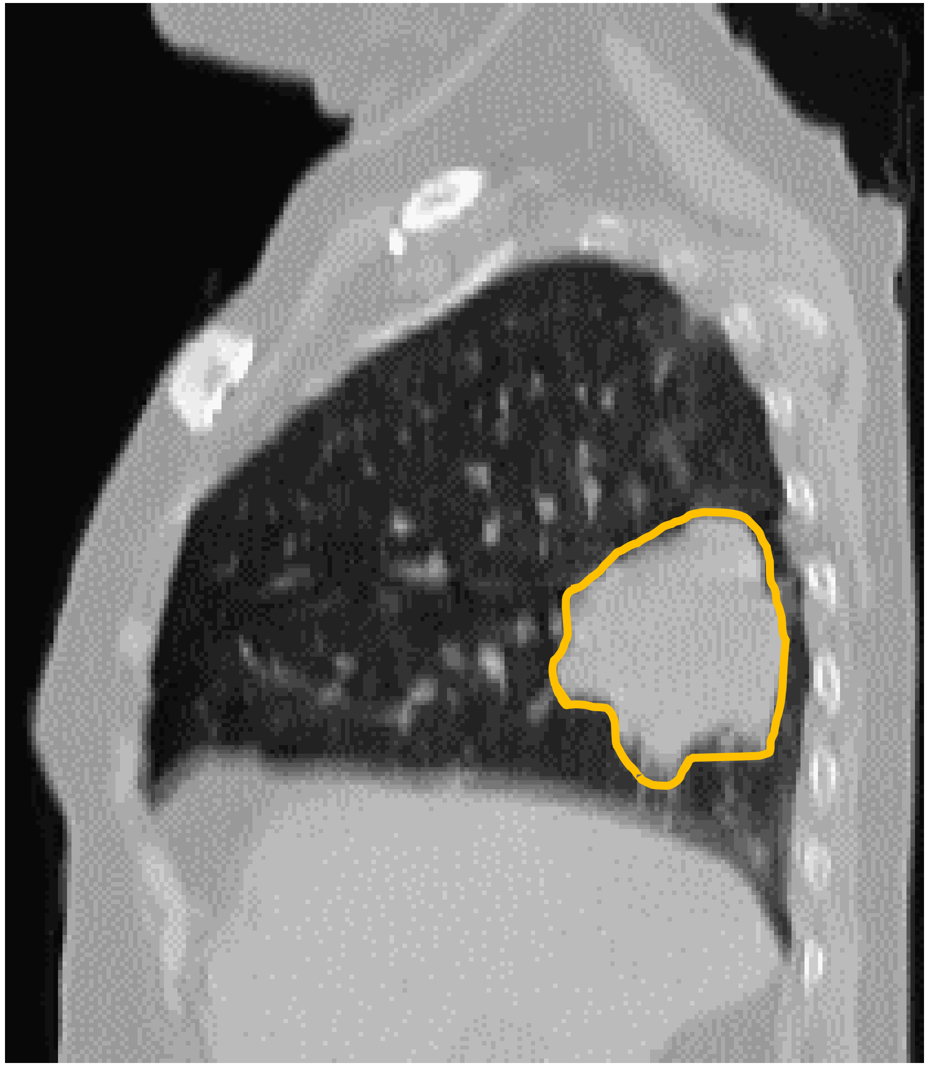


Motion management in radiation therapy

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

(Lung, Mediastinum, Chest wall / breast: thorax; Kidney/adrenal, Liver, T-spine: abdomen)

- 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)

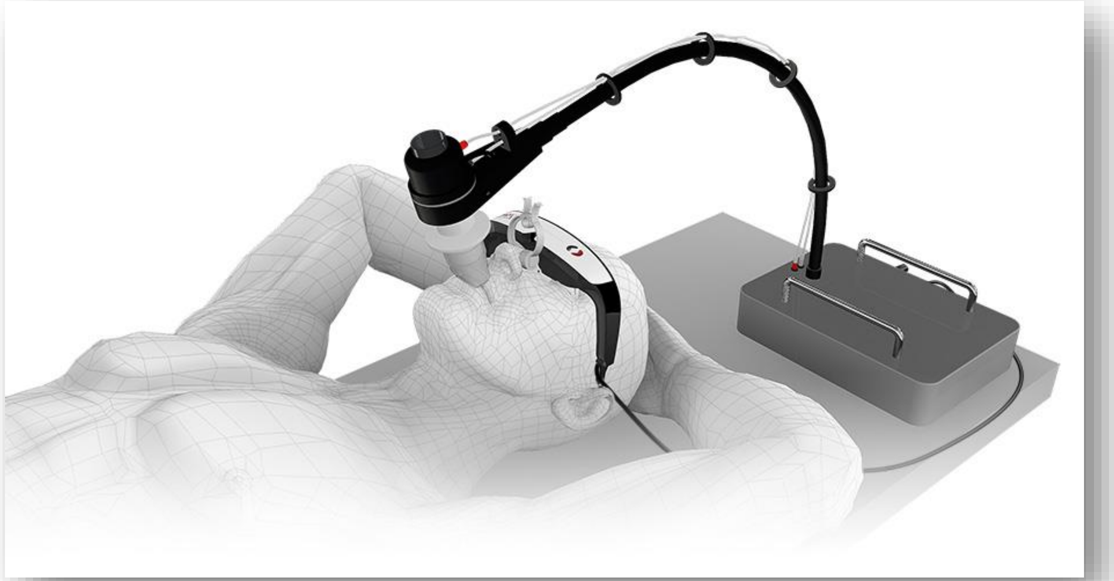
P. Giraud, A. Houle, "Respiratory Gating for Radiotherapy: Main Technical Aspects and Clinical Benefits", ISRN, vol. 2013, Article ID 519602, 2013. doi.org/10.1155/2013/519602

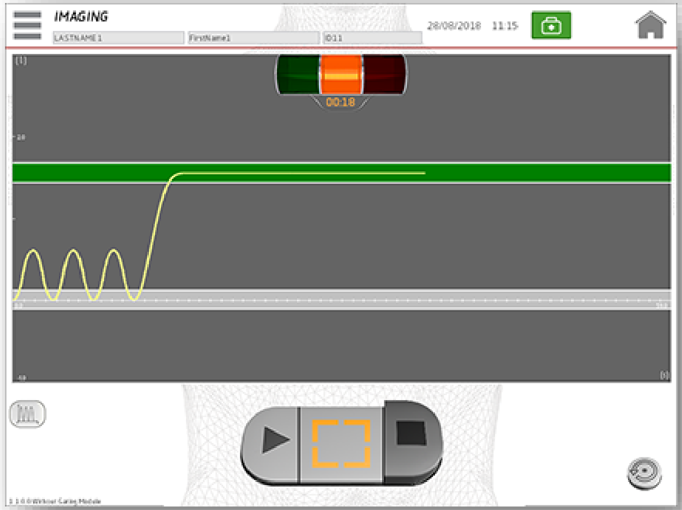
Freeze motion with breath hold

Active

image by Elekta

Voluntary

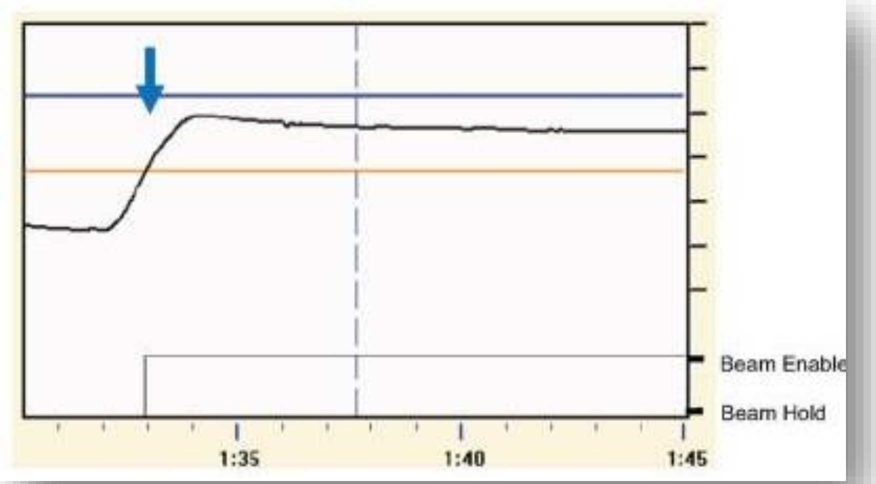




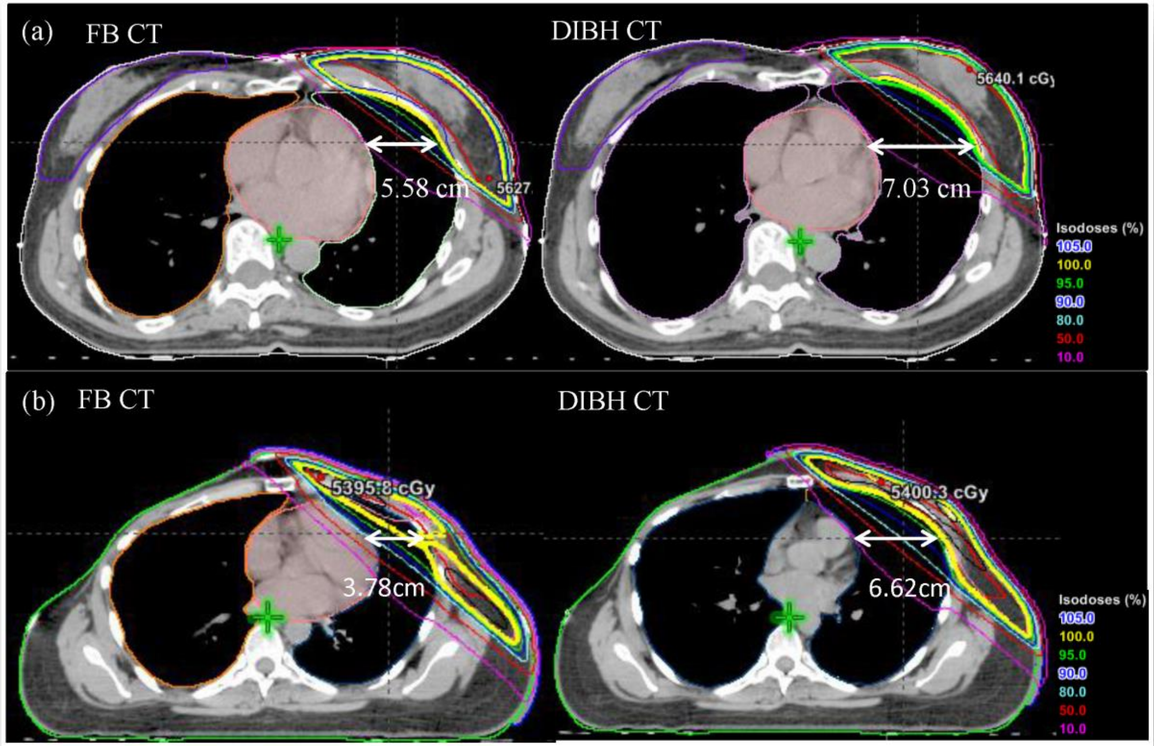
images by DYN'R

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



Bergom C, Currey A, Desai N, Tai A, Strauss JB. Deep Inspiration Breath Hold: Techniques and Advantages for Cardiac Sparing During Breast Cancer Irradiation. Front Oncol. 2018 Apr 4;8:87. doi: 10.3389/fonc.2018.00087. PMID: 29670854; PMCID: PMC5893752.

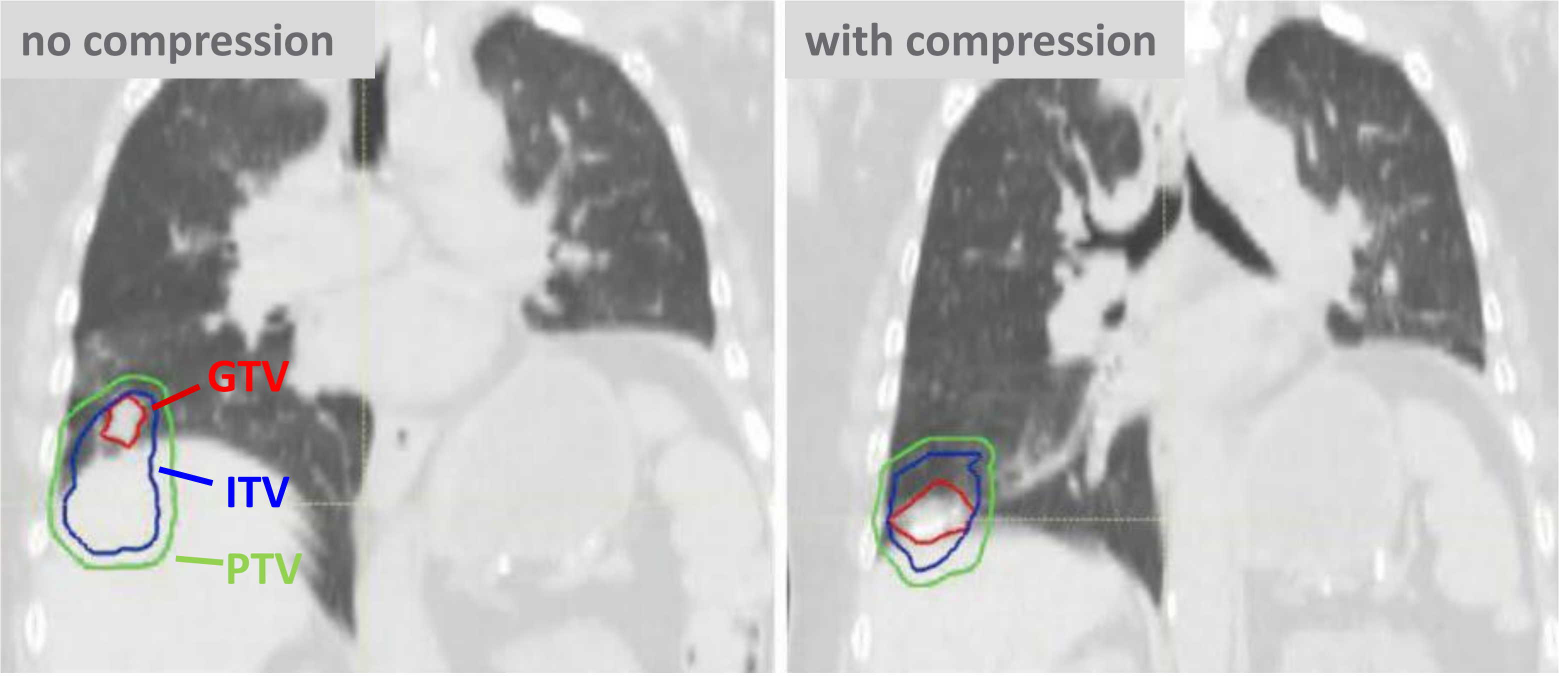


Rong Y, Walston S, Welliver MX, Chakravarti A, Quick AM (2014) Improving Intra-Fractional Target Position Accuracy Using a 3D Surface Surrogate for Left Breast Irradiation Using the Respiratory-Gated Deep-Inspiration Breath-Hold Technique. PLoS ONE 9(5): e97933. doi.org/10.1371/journal.pone.0097933

Limit motion with compression devices

Limit motion with compression devices

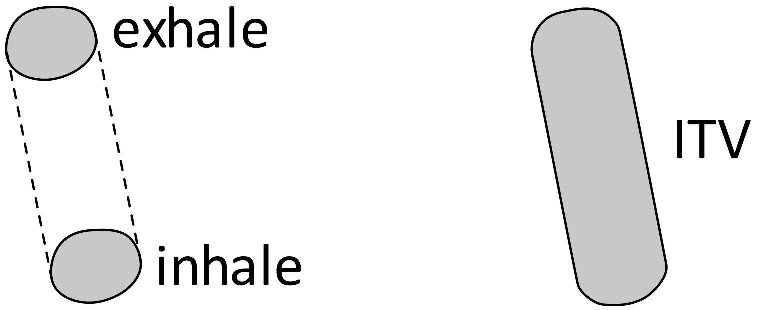
- Motion evaluated without compression (4D-CT)
- If motion amplitude exceeds tolerance, apply compression
  - apply maximum force that patient can tolerate
  - acquire 4D-CT with forced shallow breathing

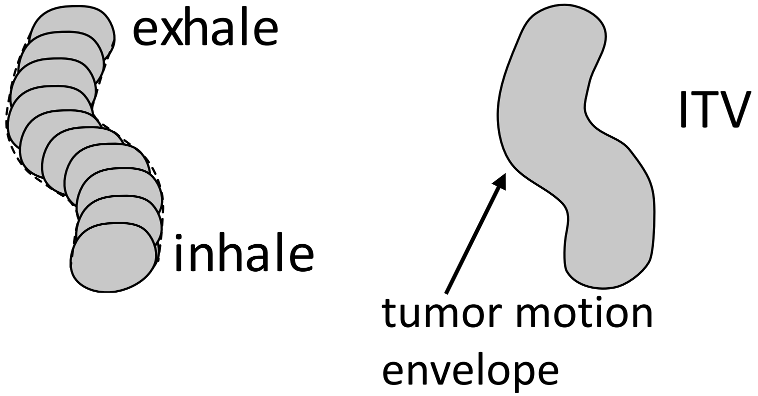


Molitoris J., et.al., Transl Lung Cancer Res. 2019 Feb;8(1):24-31. doi:10.21037/tlcr.2018.09.25.

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)**



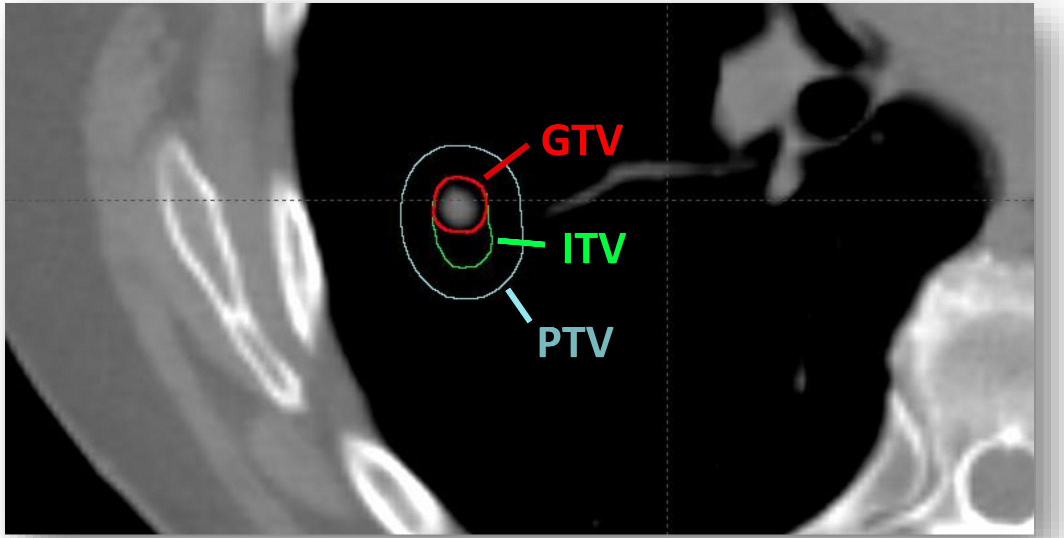


Thomas D., et al. A novel fast helical 4D-CT acquisition technique to generate low-noise sorting artifact-free images at user-selected breathing phases. Int J Radiat oncol Biol Phys. 2014;89: 191–8

Thomas D.H., et al. Is there an ideal set of prospective scan acquisition phases for fast-helical based 4D-CT? Phys Med Biol. 2016;61(23):632–41.

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

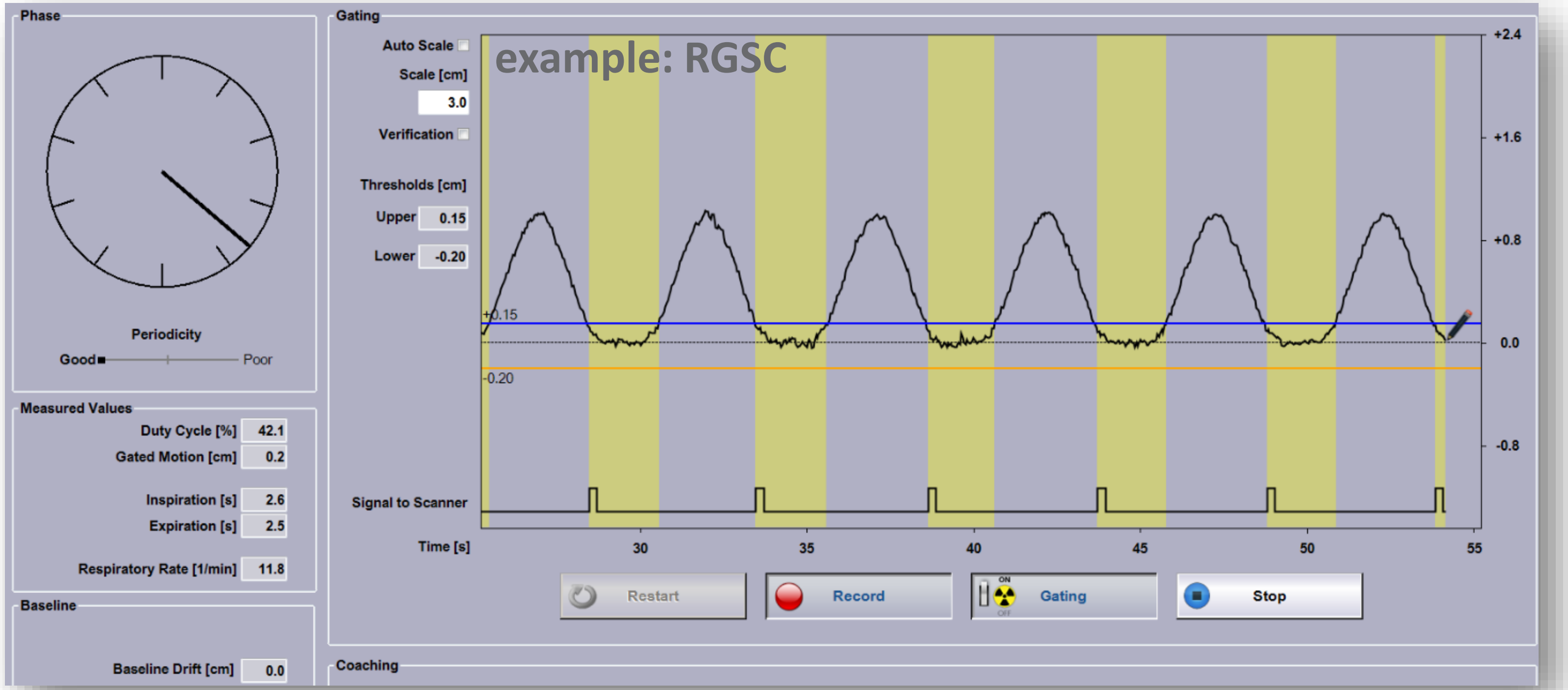


Early work on 4D-CT:

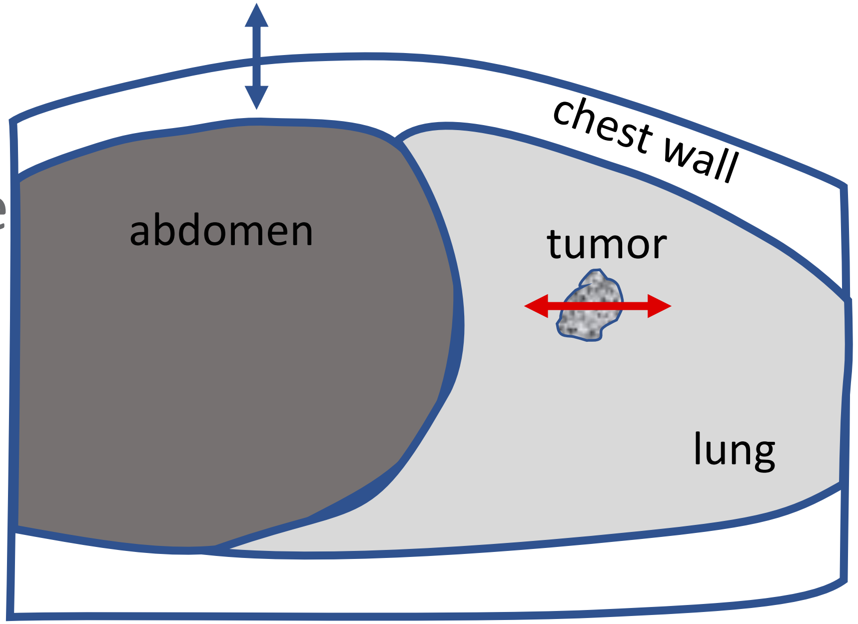
1. Ford EC, Mageras GS, Yorke E, Ling CC. Respiration-correlated spiral CT: a method of measuring respiratory-induced anatomic motion for radiation treatment planning. Med Phys. 2003;30:88–97. doi: 10.1118/1.1531177.
2. Low DA, Nystrom M, Kalinin E, et al. A method for the reconstruction of four-dimensional synchronized CT scans acquired during free breathing. Med Phys. 2003;30:1254–63. doi: 10.1118/1.1576230.
3. Vedam SS, Keall PJ, Kini VR, Mostafavi H, Shukla HP, Mohan R. Acquiring a four-dimensional computed tomography dataset using an external respiratory signal. Phys Med Biol. 2003;48:45–62. doi: 10.1088/0031-9155/48/1/304.

Manage motion with gated treatments

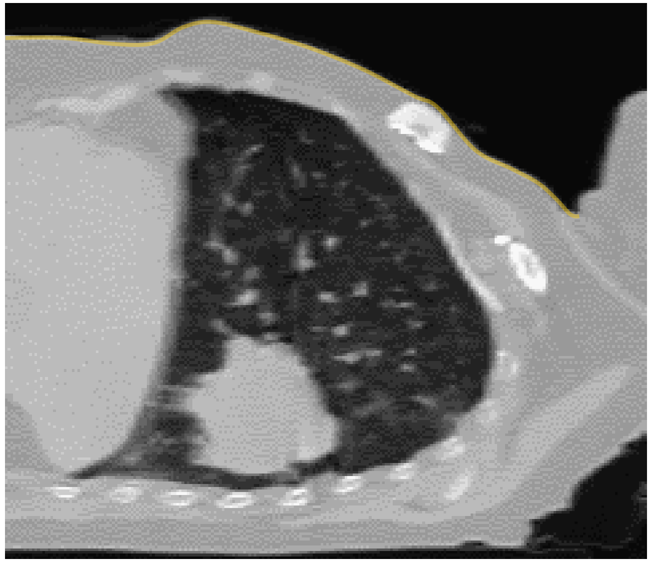
- Purpose: select thresholds for gated treatments
- Acquire respiratory surrogate trace and 4D-CT
- Preselect gating thresholds and export gating protocol to TPS / R&V / LINAC



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

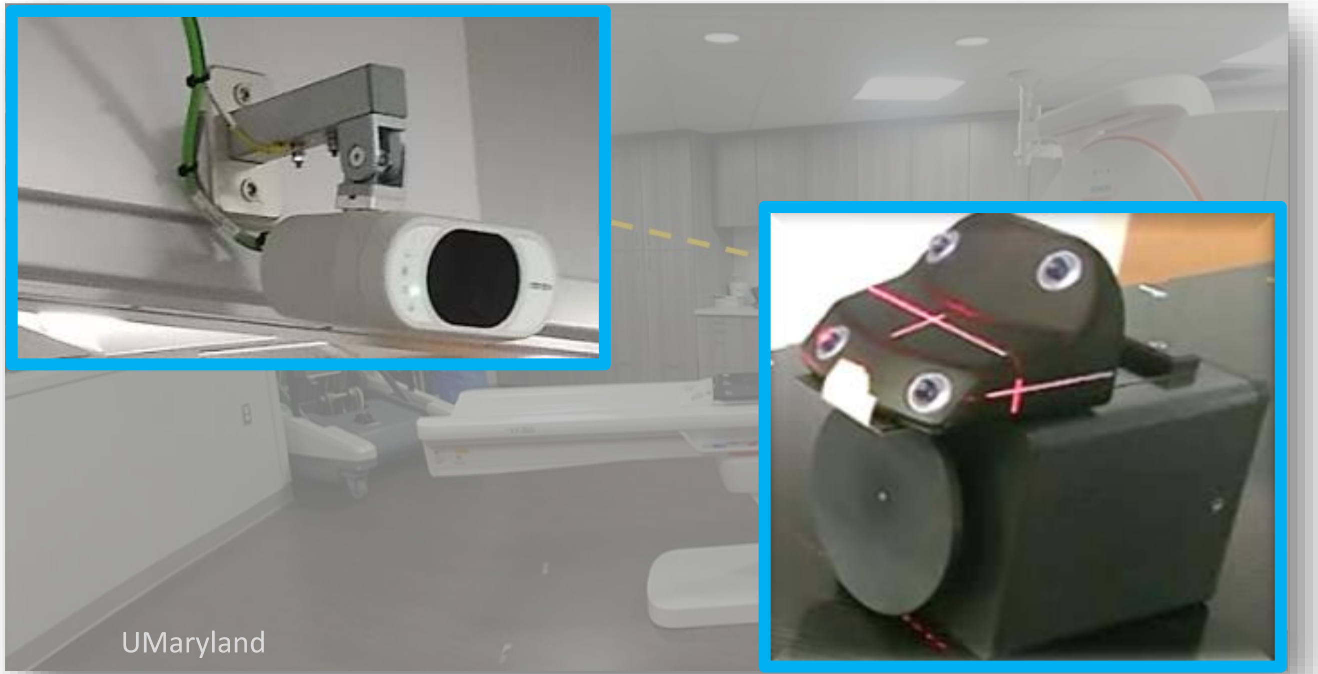


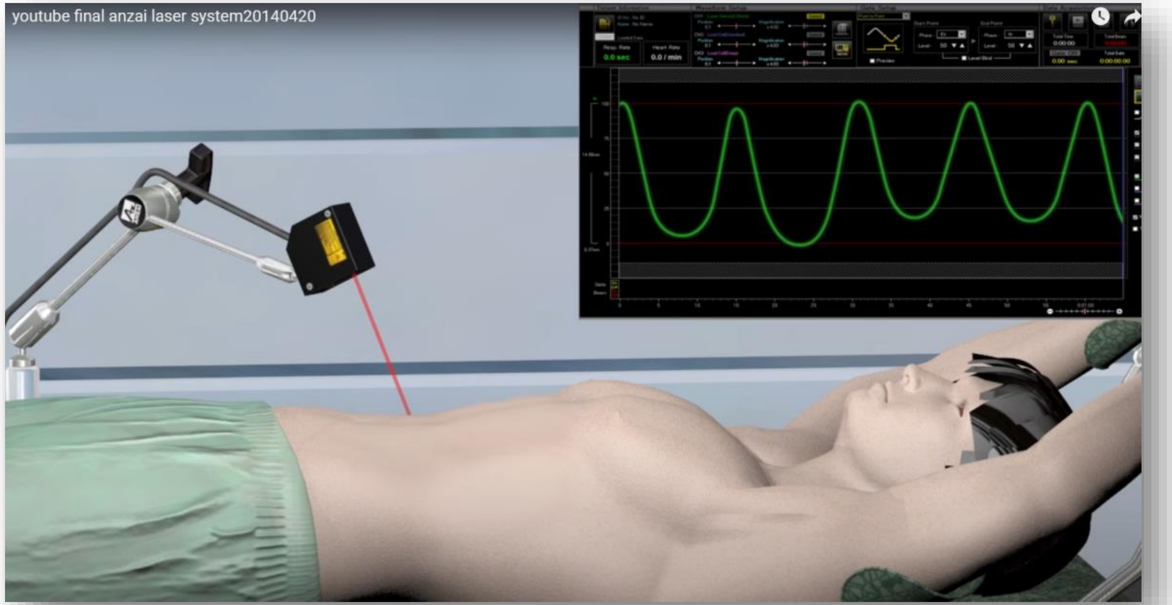
- Assumption: correlation exists between respiratory surrogate signal and internal target motion (in reality, this assumption is not always met)

Respiratory gating

image by Philips

images by Anzai





Respiratory-gated 4D-CT: benefits and challenges

Benefits

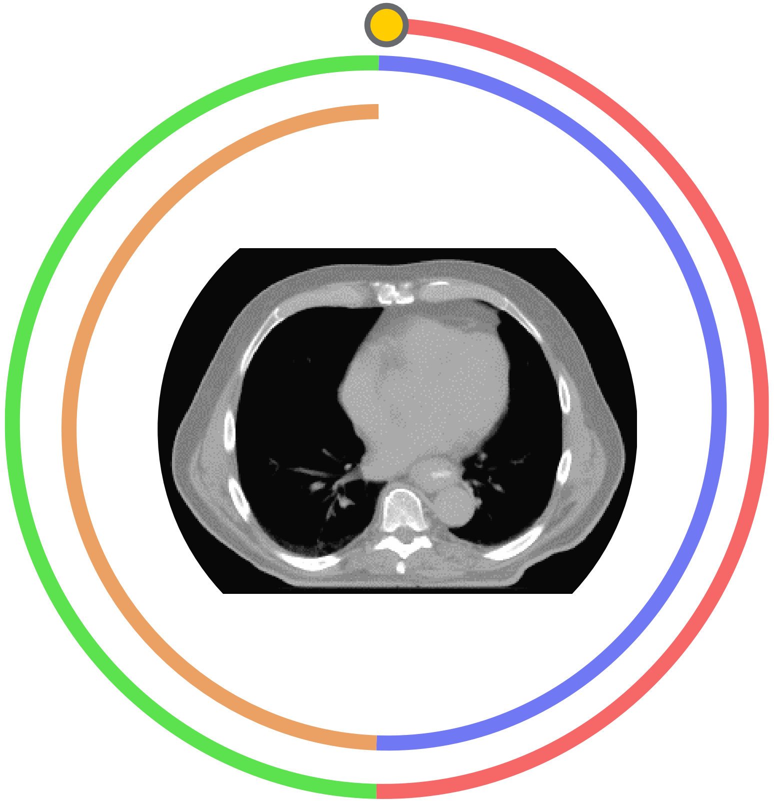
- Patient can breathe normally
- Provides full motion information (typically 10 bins)
- More accurate amplitude estimate vs inhale/exhale breath hold
- Can be combined with abdominal compression to reduce motion

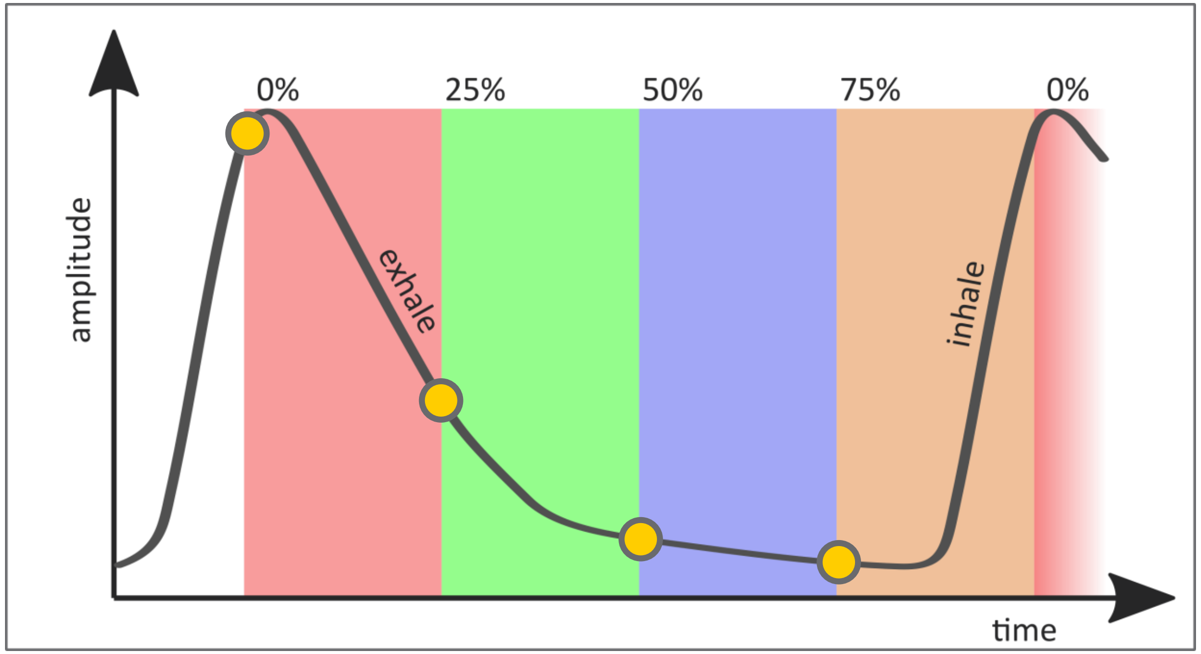
Challenges

- 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

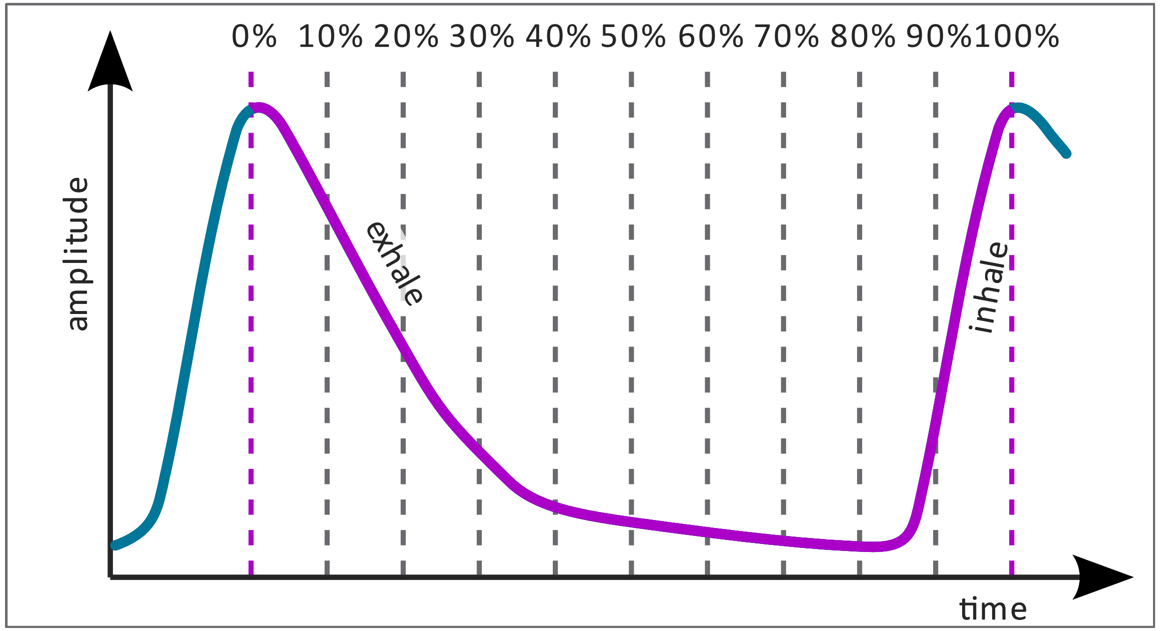




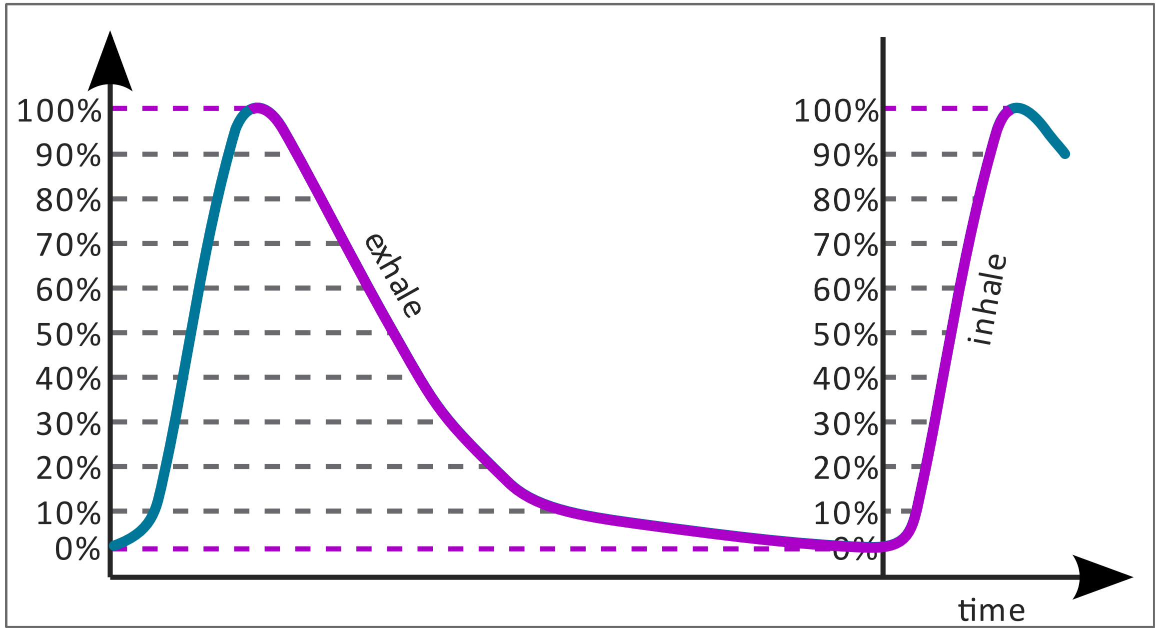
(simplified for illustration purposes)

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

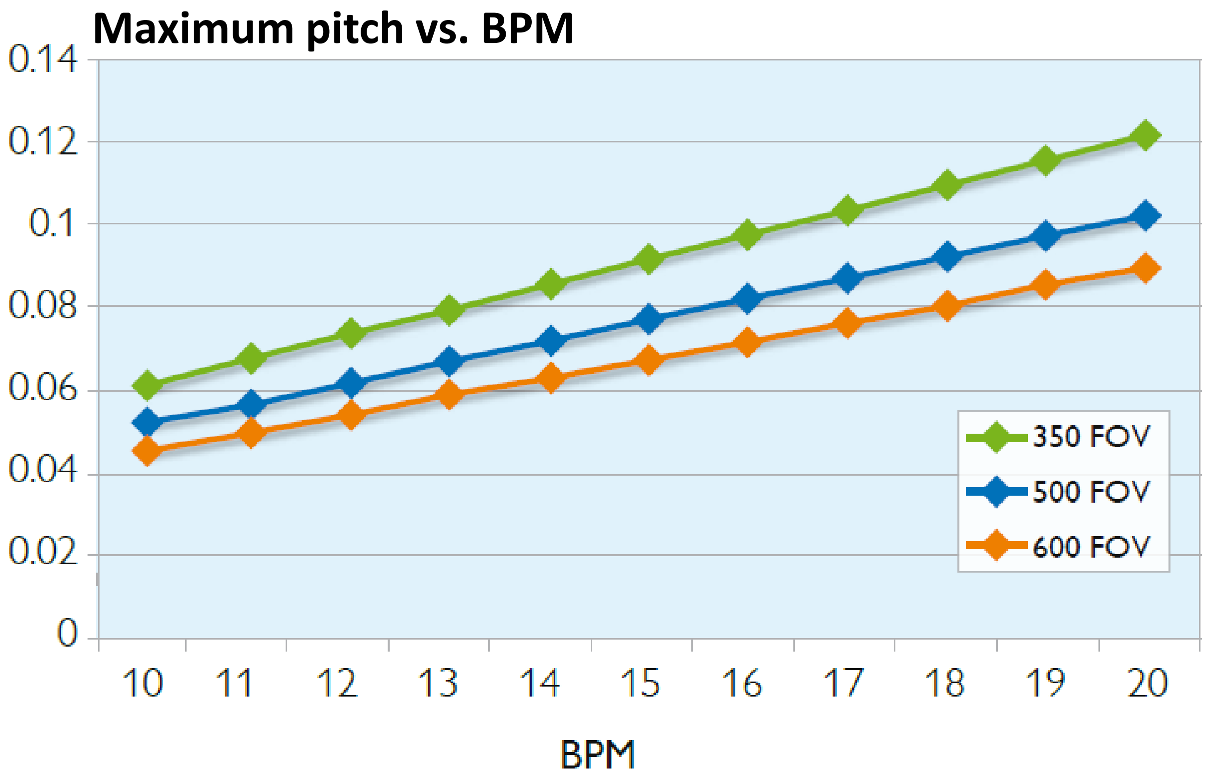
! Artifacts can occur if these assumptions are violated

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

Werner, René, Christian Hofmann, Eike Mücke, and Tobias Gauer. "Reduction of Breathing Irregularity-Related Motion Artifacts in Low-Pitch Spiral 4D CT by Optimized Projection Binning." *Radiation Oncology (London, England)* 12 (June 19, 2017): 100. doi.org/10.1186/s13014-017-0835-7.

Retrospective 4D-CT: choice of acquisition parameters

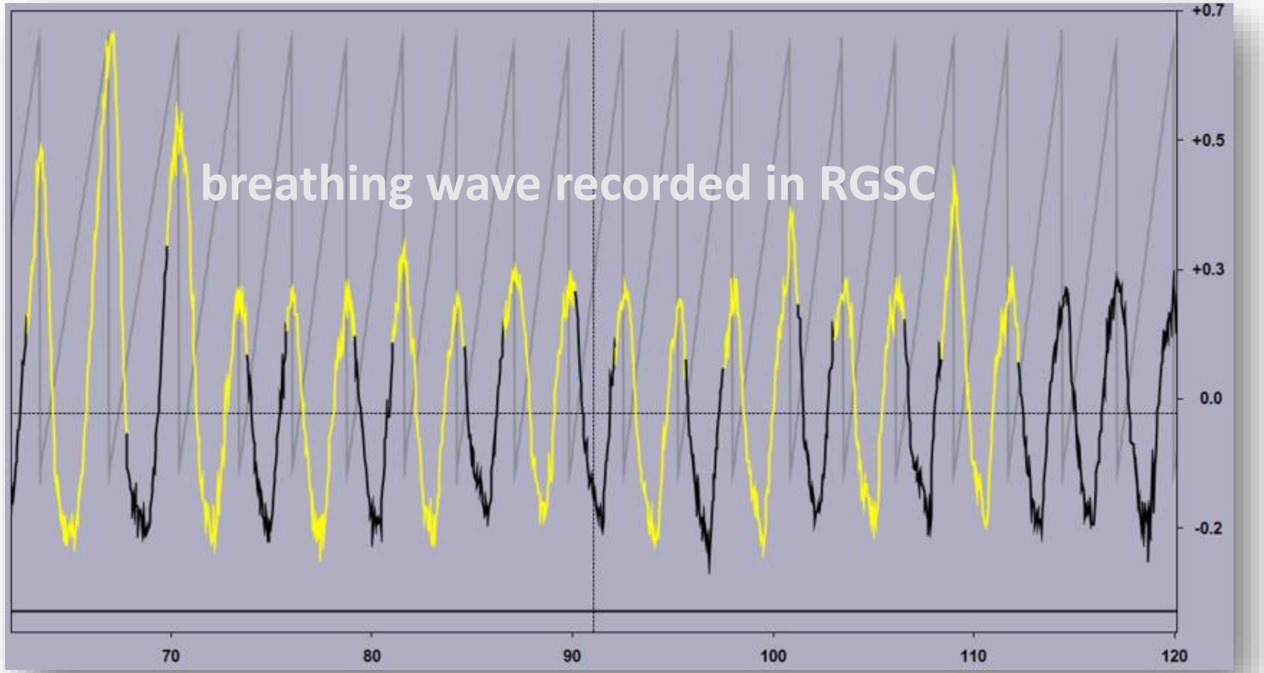
- In helical 4D-CT, the maximum pitch factor (table speed) depends on the breathing rate
- Slower (higher) BPM → slower (higher) speed



Philips whitepaper on respiratory motion management for CT

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)

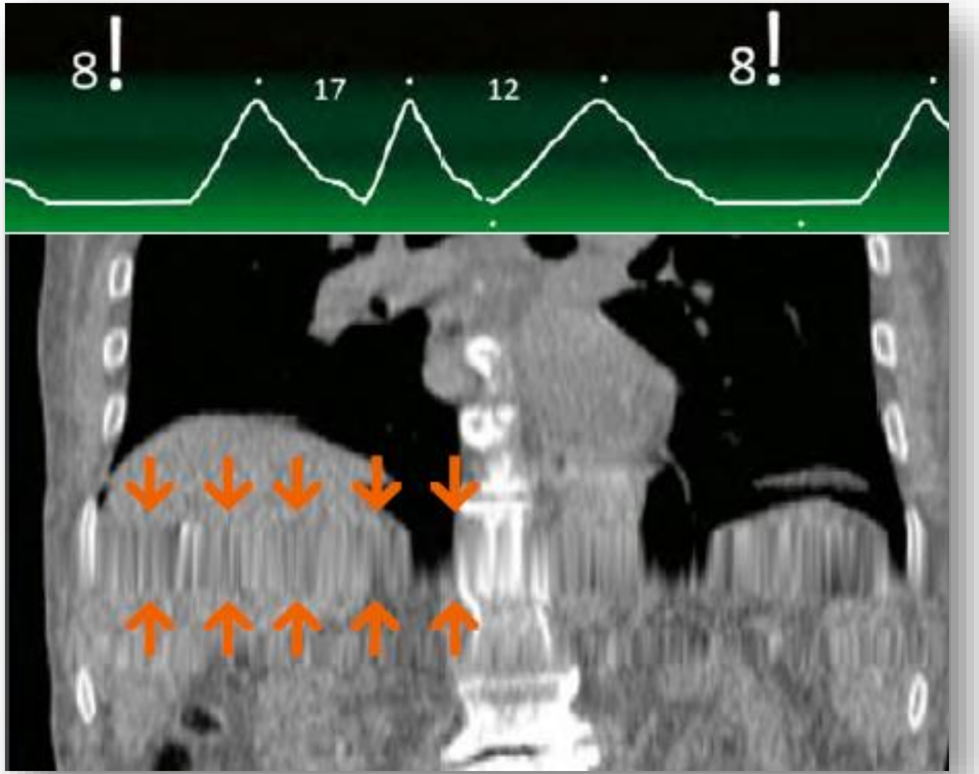


[1] Yamamoto T, Langner U, Loo BW Jr, Shen J, Keall PJ. Retrospective analysis of artifacts in four-dimensional CT images of 50 abdominal and thoracic radiotherapy patients. Int J Radiat Oncol Biol Phys. 2008 Nov 15;72(4):1250-8. doi: 10.1016/j.ijrobp.2008.06.1937. Epub 2008 Sep 25. PMID: 18823717.
[2] Keall PJ, Vedam SS, George R, Williamson JF. Respiratory regularity gated 4D CT acquisition: concepts and proof of principle. Australas Phys Eng Sci Med. 2007 Sep;30(3):211-20. doi: 10.1007/BF03178428.
[3] Wulfhekel E, Grohmann C, Gauer T, Werner R. EP-1743: Compilation of a database for illustration and automated detection of 4DCT motion artifacts. Radiother Oncol 2014;111:S266

Retrospective 4D-CT: motion artifacts

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

Interpolation artifacts



Irregular amplitude

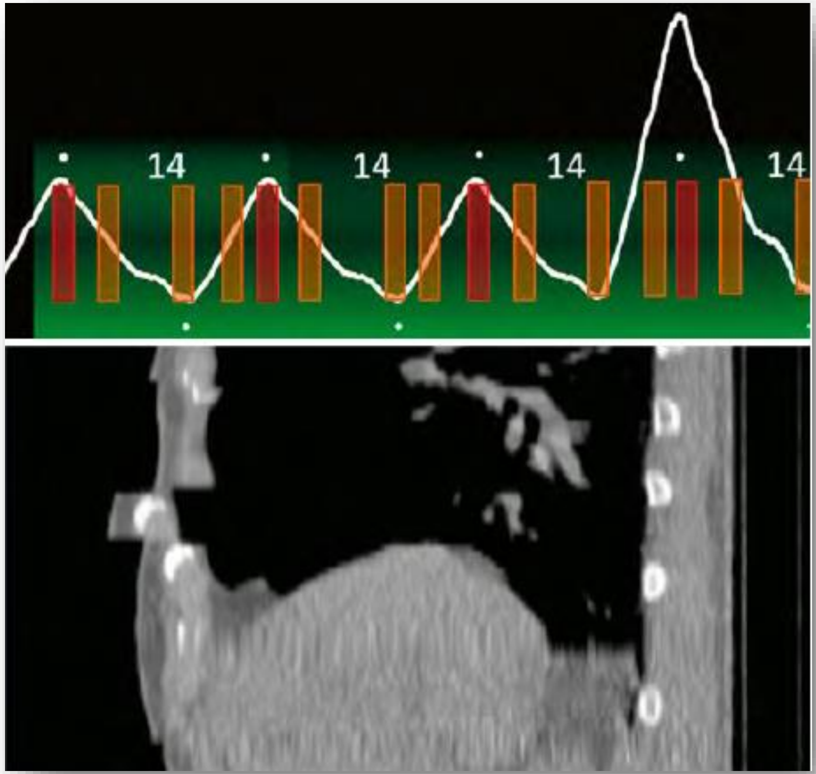
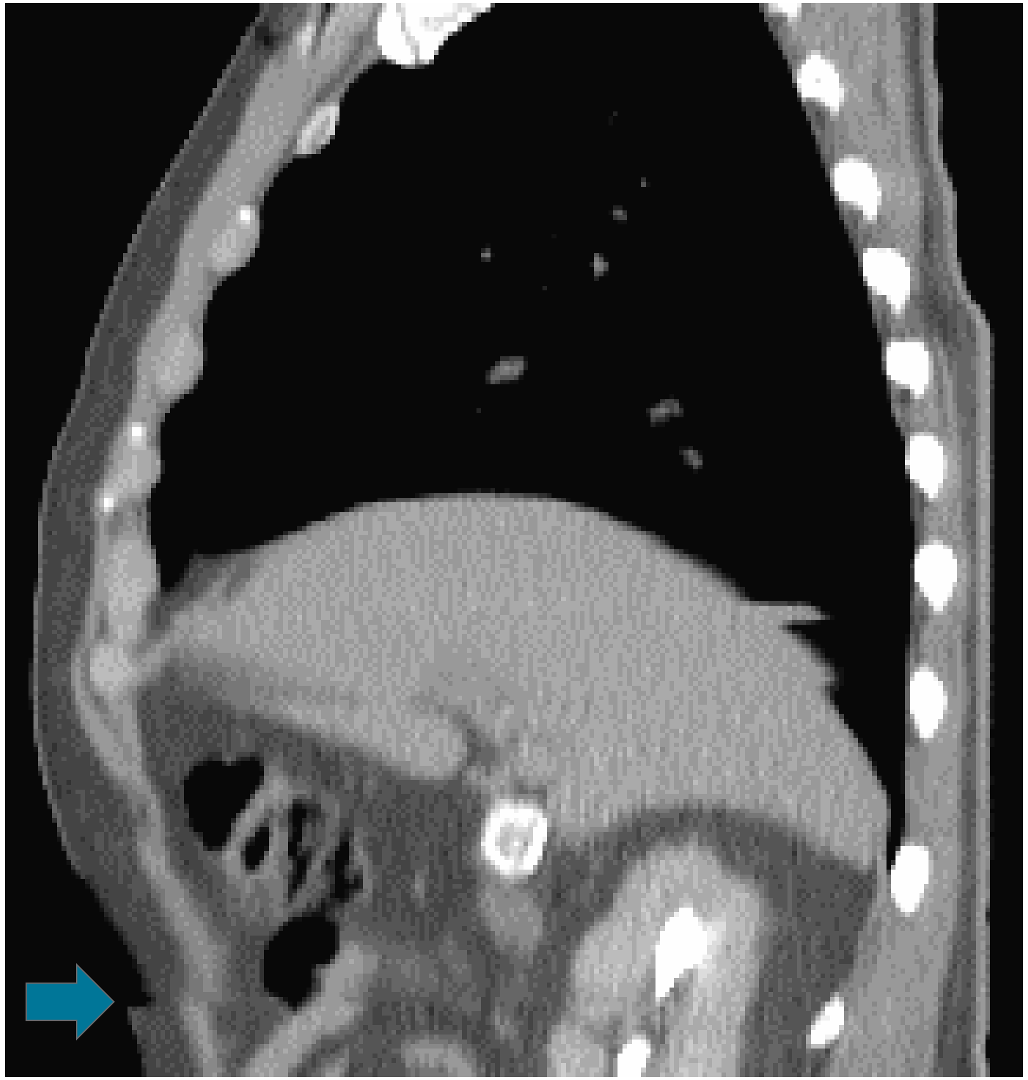
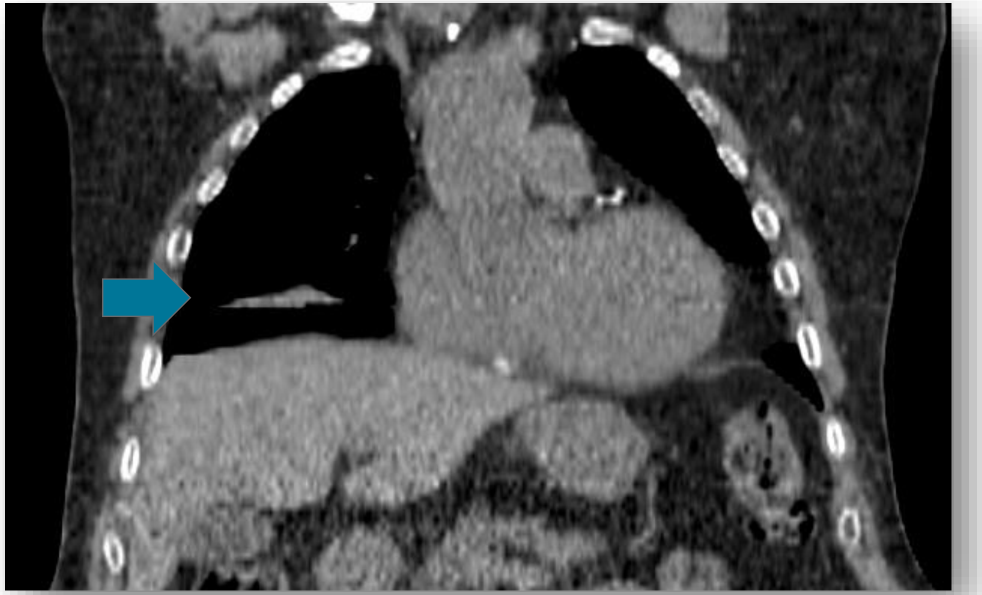


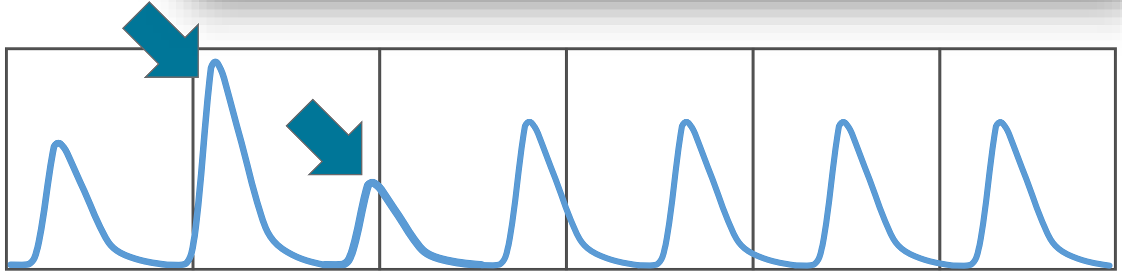
image source: 4D CT cookbook 2.1, Siemens Healthcare GmbH siemens-healthineers.com/radiotherapy/ct-for-rt

4D-CT motion artifacts – duplicate structure / stacking



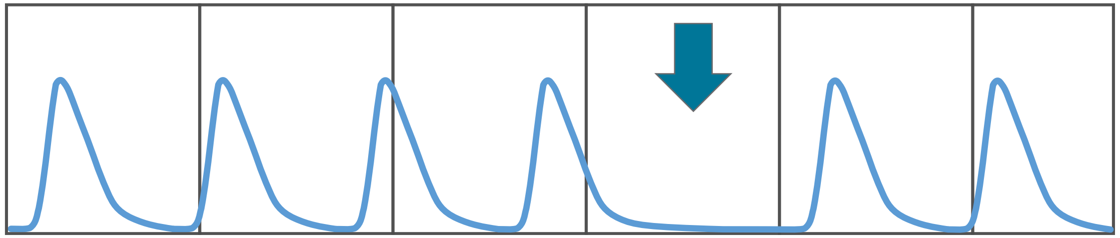
- Very common with irregular breathing amplitude
- Most obvious near diaphragm





4D-CT motion artifacts – interpolation artifact

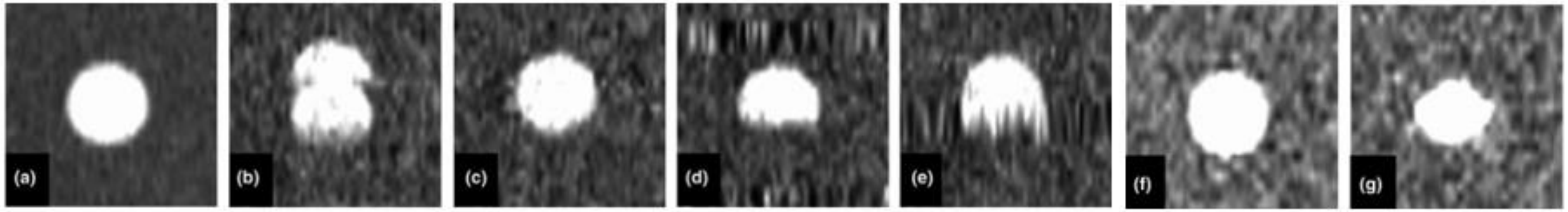
extreme example of multiple interpolation artifacts — unusable for planning purposes



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

Clements et.al., Med Phys. 2013; 40: 021904
Pan et.al., J Appl Clin Med Phys 2019, 20: 109-120



Miyamae Y, et. al., J Appl Clin Med Phys. 2020;21(1):11-17. 10.1002/acm2.12692

- 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]

[1] Miyamae Y, et.al. Variation in target volume and centroid position due to breath holding during four-dimensional computed tomography scanning: a phantom study. J Appl Clin Med Phys. 2020;21(1):11-17.
[2] Clements N, et.al. The effect of irregular breathing patterns on internal target volumes in four-dimensional CT and cone-beam CT images in the context of stereotactic lung radiotherapy. Med Phys. 2013;40(2):21904.
[3] Sentker T, et. al., 4D CT image artifacts affect local control in SBRT of lung and liver metastases. Radiother Oncol. 2020 Jul;148:229-234. doi: 10.1016/j.radonc.2020.04.006. Epub 2020 Apr 9.

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)

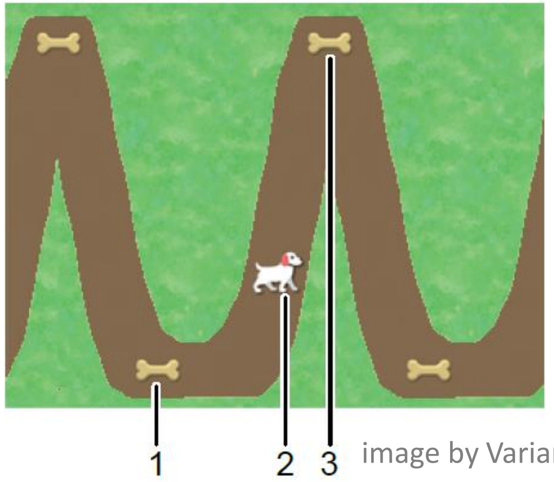


image by Varian

1. Expiration peak target (optional)
2. Current breathing position
3. Inspiration peak target (optional)

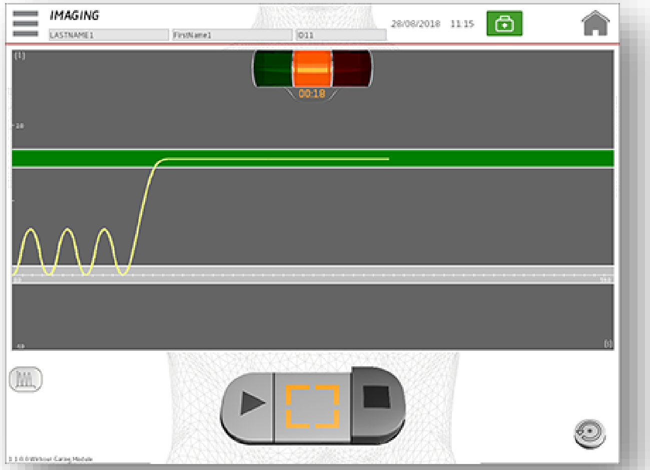
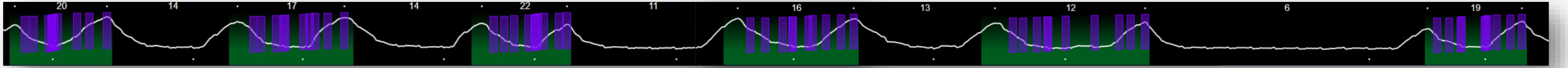


image by DYN'R

Adaptive 4D-CT

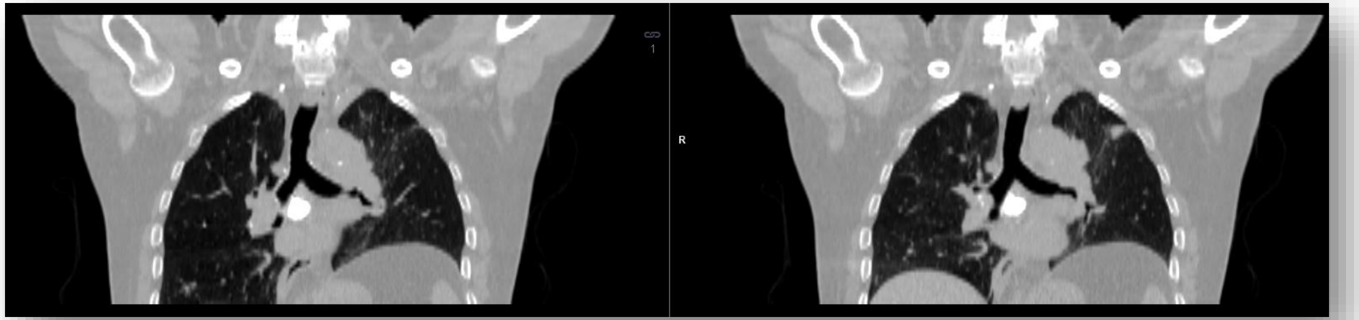
Example: “intelligent 4D-CT” (*)

- 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



end inhale

end exhale

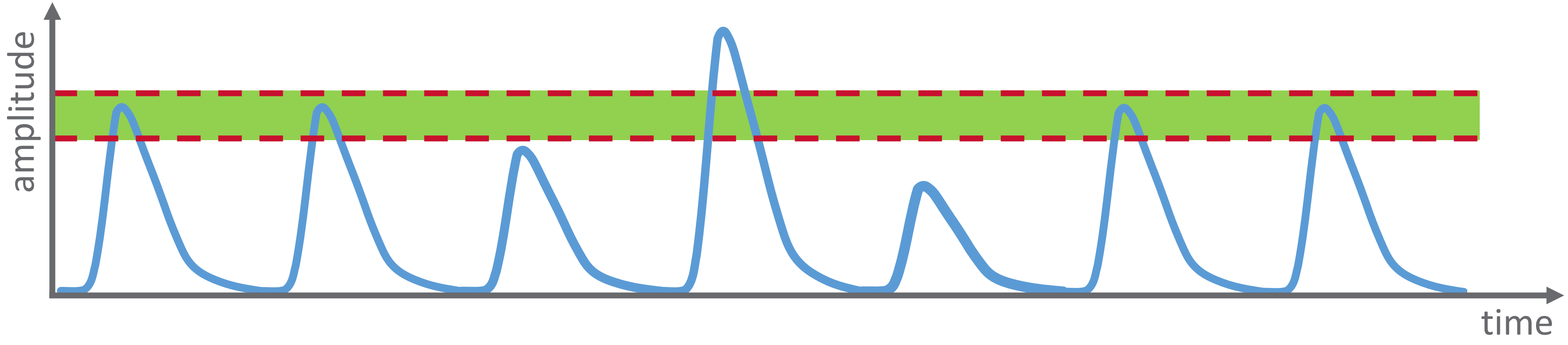


artifact-free images despite long breathing pause

(*)Werner, R., Sentker, T., Madesta, F., Gauer, T. and Hofmann, C., Med Phys. 2019 Aug;46(8):3462-3474. doi: 10.1002/mp.13632

Prospective respiratory-gated 4D-CT

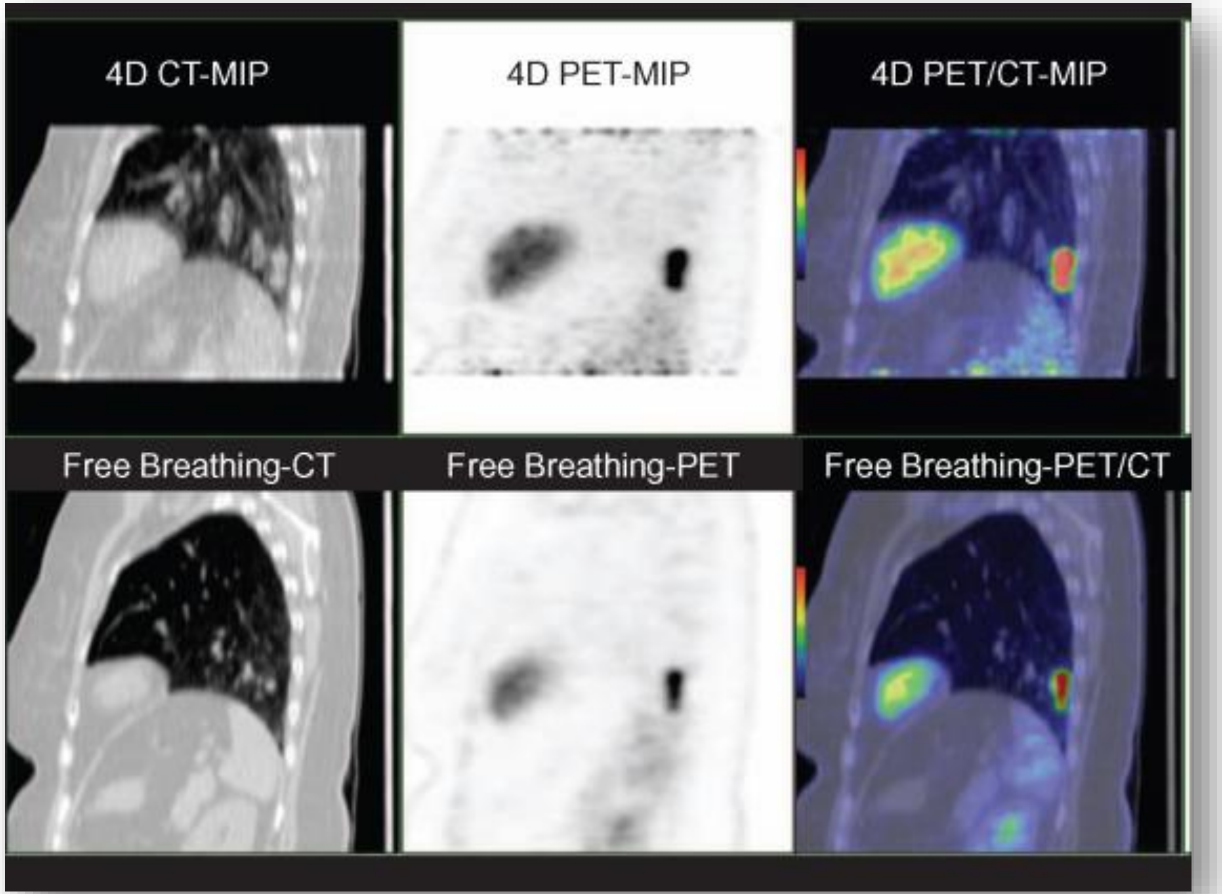
- Cine mode with acquisition triggered on certain gating window only
- Useful for gated treatments
- Limited availability on commercial CT simulators



Bernatowicz, K., P. Keall, P. Mishra, A. Knopf, A. Lomax, and J. Kipritidis. "Quantifying the Impact of Respiratory-Gated 4D CT Acquisition on Thoracic Image Quality: A Digital Phantom Study." *Medical Physics* 42, no. 1 (2015): 324–34. doi.org/10.1118/1.4903936.

4D-PET/CT

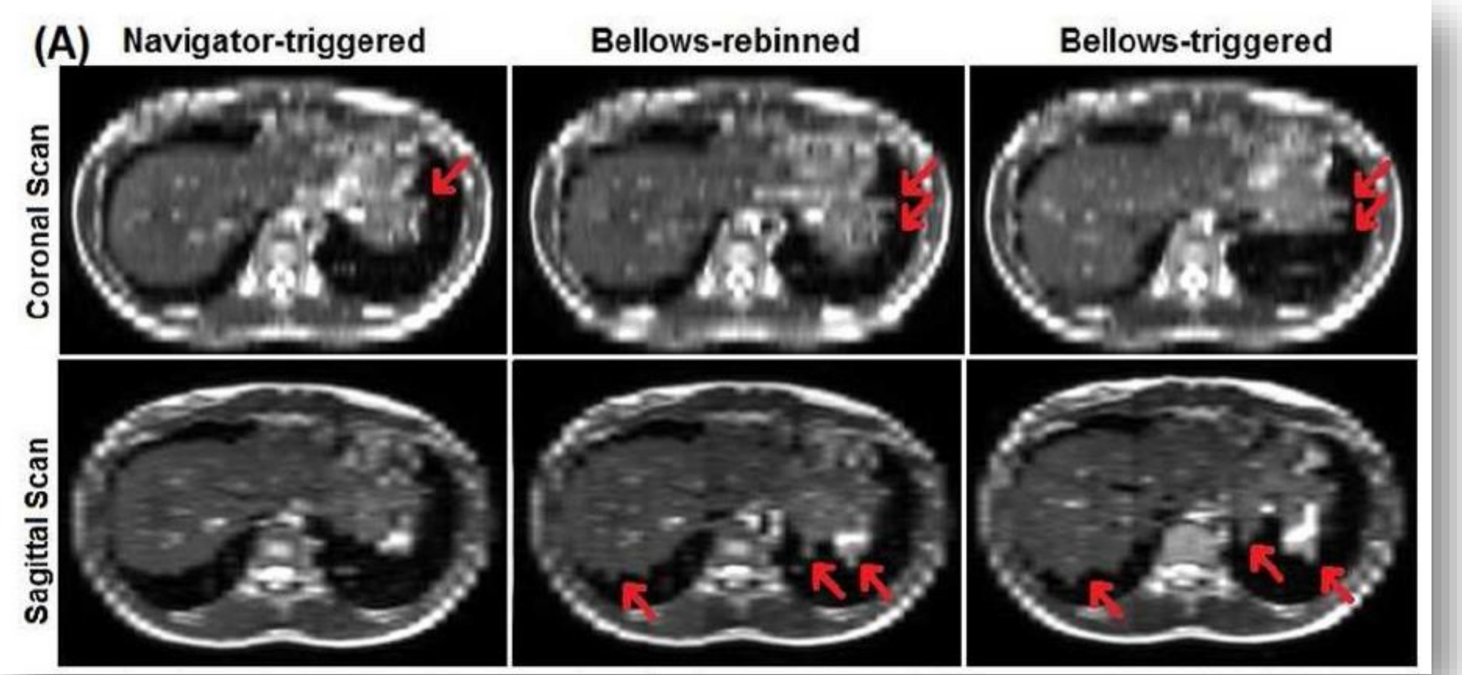
- CT is fast (seconds), PET is slow (minutes)
- Impact of motion on PET:
  - Reduction of SUV (risk of missing lesion on PET images)
  - Apparent change in lesion size
  - Mismatch in PET/CT fusion
- Average from PET is usually assumed to encompass the complete motion due to slow PET acquisition.
- Use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



S. Siva et.al., Journal of Thoracic Oncology, Volume 10, Issue 7, 2015, p. 1112-1115, doi.org/10.1097/JTO.0000000000000555

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).



Li G, Wei J, Olek D, Kadbi M, Tyagi N, Zakian K, Mechalakos J, Deasy JO, Hunt M. Int J Radiat Oncol Biol Phys. 2017 Mar 1; 97(3):596-605. doi: 10.1016/j.ijrobp.2016.11.004.

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

contact: jcammin@som.umaryland.edu