Motion and Margins in Radiotherapy

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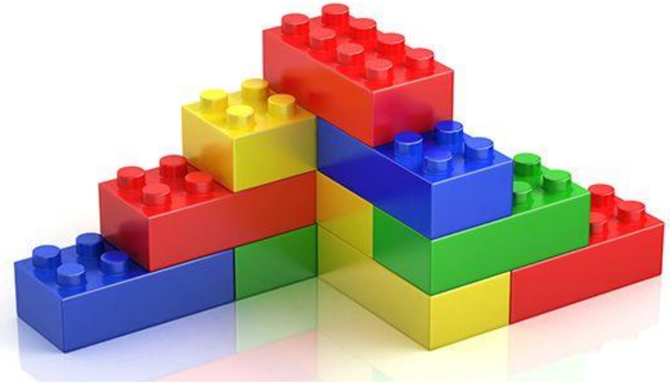

Peter MacCallum Cancer Centre, Melbourne

- 5 campuses
- 16 linacs, 1 GammaKnife, 4 SXR
- 7 CT, 1 PET/CT
- HDR, LDR and eBrachytherapy
- SRS, SBRT, TBI, TSET, intraop.
- About 7000 RT patients per year
- Varian Eclipse in the cloud (+ iPlan, Gammaplan, Oncentra brachy)

- Tumour stream organisation
- Many technology driven RT clinical trials

Main campus Melbourne

Modern Radiotherapy

time → margin reduction

1960s	Fixed SSD RT		Hand planning
1970s	Isocentric RT	better set-up	Computer planning
1980s	Conformal RT	better targeting	3D planning
1990s	Stereotactic RT	more beams	inverse planning
2000s	IMRT, VMAT	better sparing	4D planning
2010s	IGRT, Motion management	better and more frequent personalization	Fast computer assisted (AI) based adaptive re-planning
2020s	Adaptive RT		

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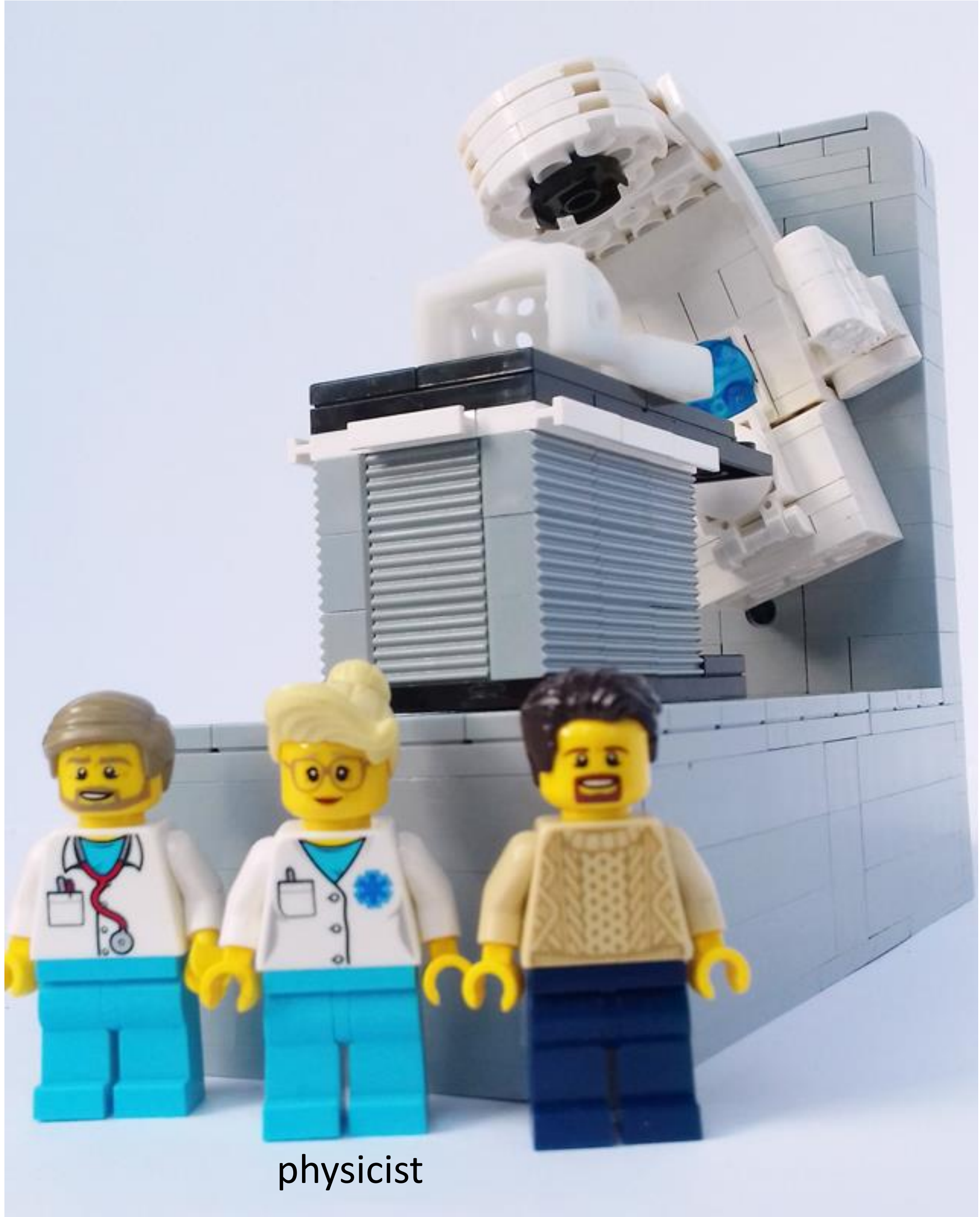
Objectives of the presentation

- To introduce image guidance as a enabler of motion management in radiotherapy
- To explore what type of motion management is possible
- To discuss how the use of image guidance influences margins

- To illustrate why medical physicists are essential in this context



Key take home messages

- Motion management requires imaging
- Effective motion management starts in treatment planning
- Radiotherapy is a 4D problem and CT is a good starting point
- Patient involvement is essential for most motion management strategies (comfort, breath hold, regular breathing, …)
- Medical physicists have the skills and competence required to support and lead motion management in radiotherapy

Imaging and Motion Management

Treatment Planning

- Identifies targets and critical structures
- Assesses motion to determine motion management approach
- Defines target volumes
- Generate reference images

Treatment Delivery

- Confirms no significant changes to planning
- Verifies correct patient set-up
- Guides the radiation delivery
- Monitors position and motion
- Verifies delivery

Imaging and Motion Management

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- delivery

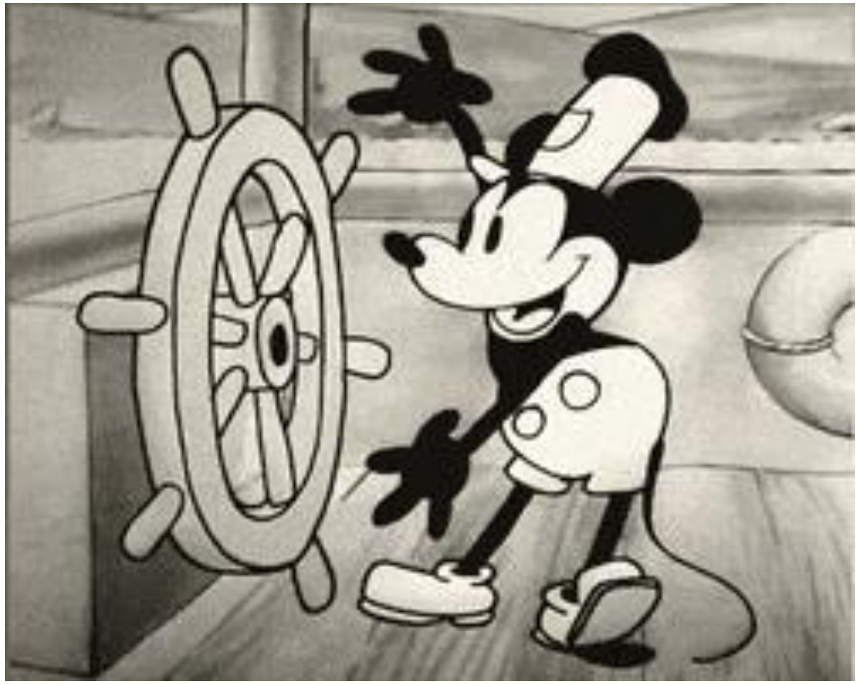
Adaptive radiotherapy combines both in a single session

Imaging for treatment planning

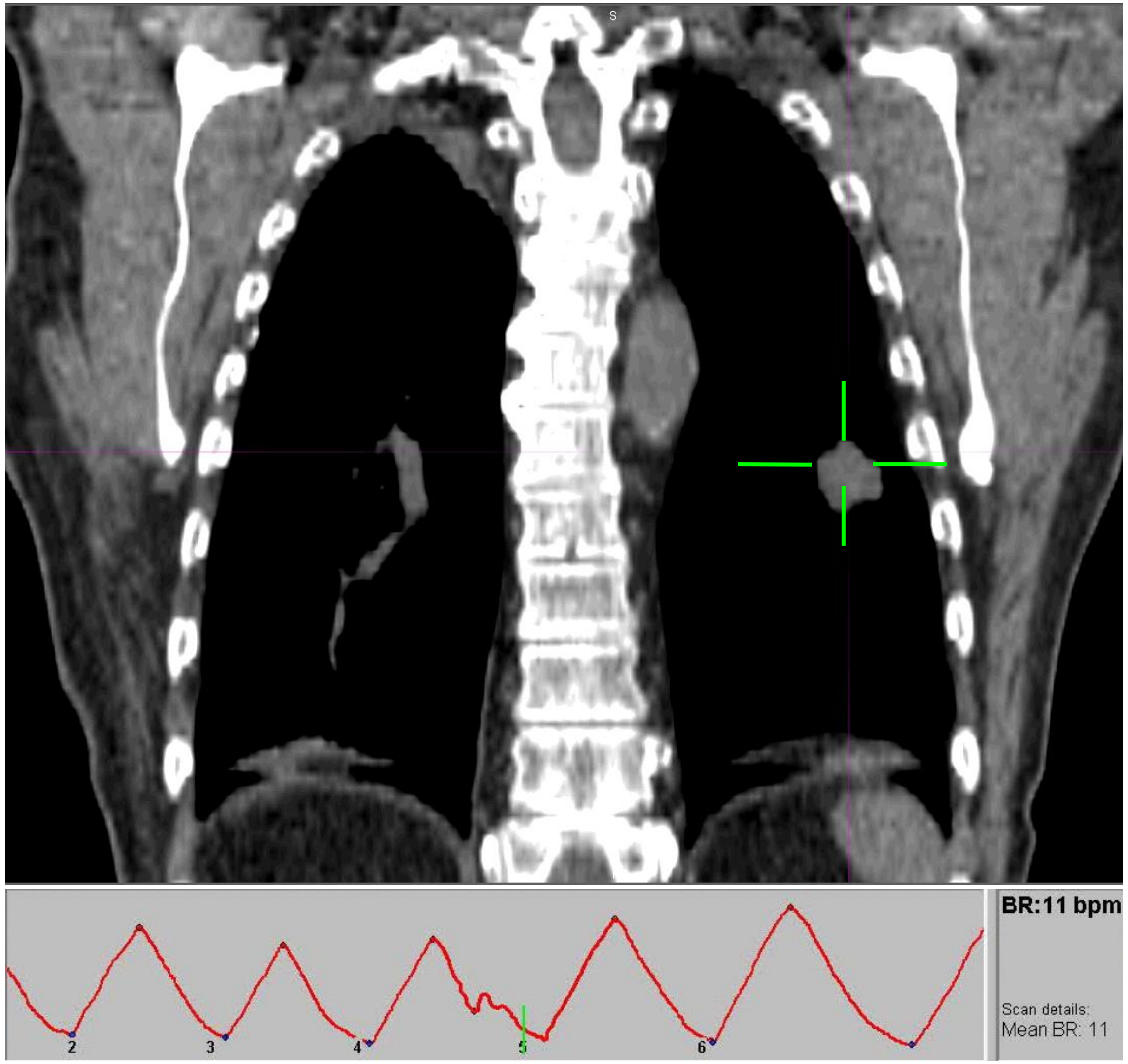
- Needs to be able to visualise the target and relevant critical structures
- Needs to address a 3 dimensional problem
- Needs to provide a basis for dose calculation
    - CT is the most important tool
    - Contrast agents are increasingly used
    - MRI, PET, SPECT can add anatomical and functional information
- Often several images are combined

Imaging for treatment planning

- Needs to allow to assess and predict motion and expected changes between treatment fractions
- Needs to address a 4 dimensional problem
  - 4D CT is the most important tool
  - Contrast agents are tricky to use
  - MRI, PET, SPECT can add information on integral target/organ location over time
- In practice breathing motion is most important



Breathing creates a moving target…



Motion management in planning

- **Planning**
  - Assessment of motion
- Tools
  - Immobilisation
  - Set-up (comfort)
  - Fluoroscopy
  - Breath hold CT(s)
  - Coaching
  - 4D CT
  - MRI
  - Slow scan/PET
  - 4D PET
  - Ultrasound
  - Compression

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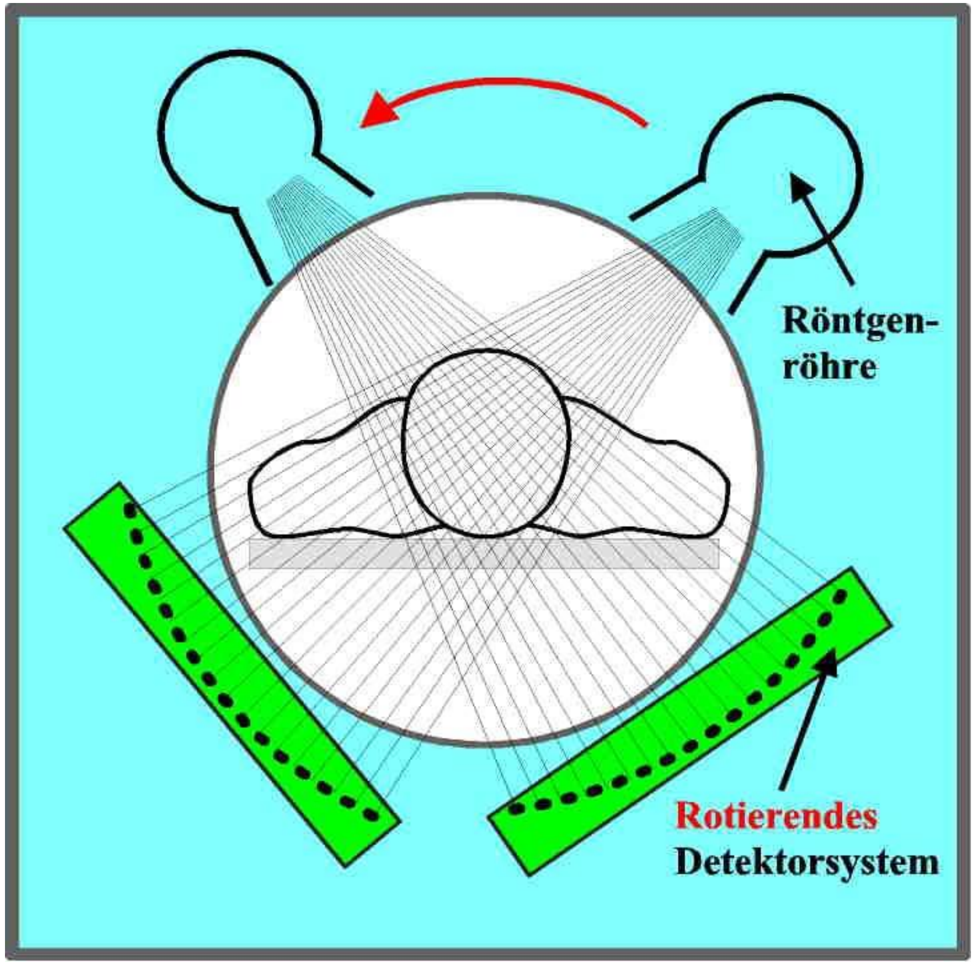
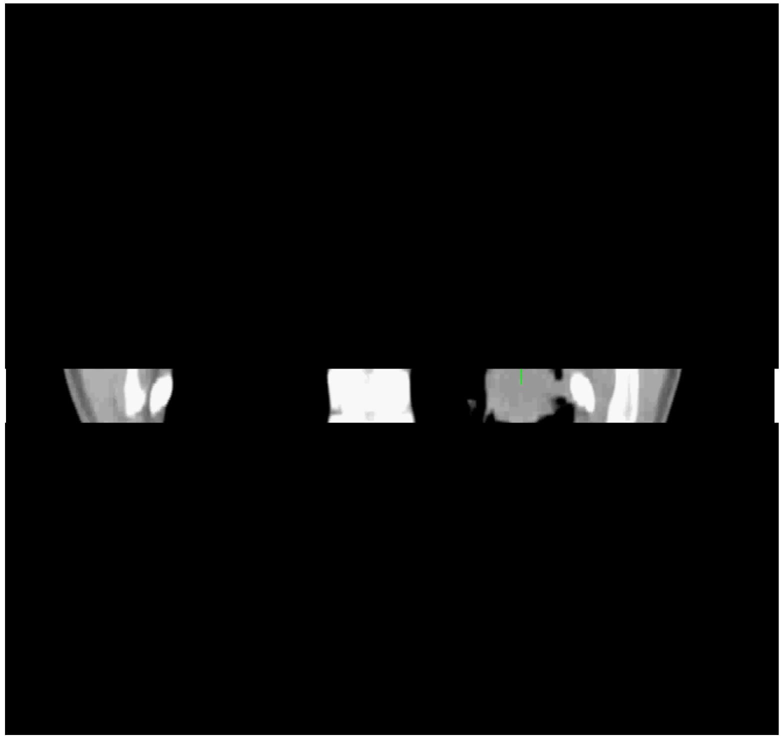
How can we take motion into account in treatment planning?

- Fluoroscopy
- Time resolved CT: 4D CT - Relies on acquiring data from each part of the anatomy for each phase of the breathing cycle



CT fluoroscopy approach

- Continuos rotation around the patient
- Typically multi-slice
- Typically reduced mAs
- Need to 'stitch' many slices together



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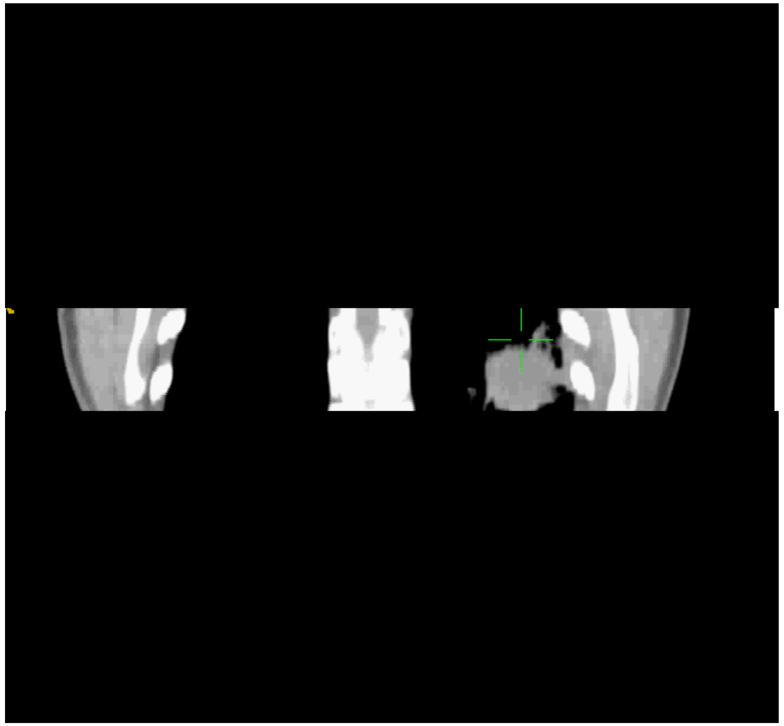

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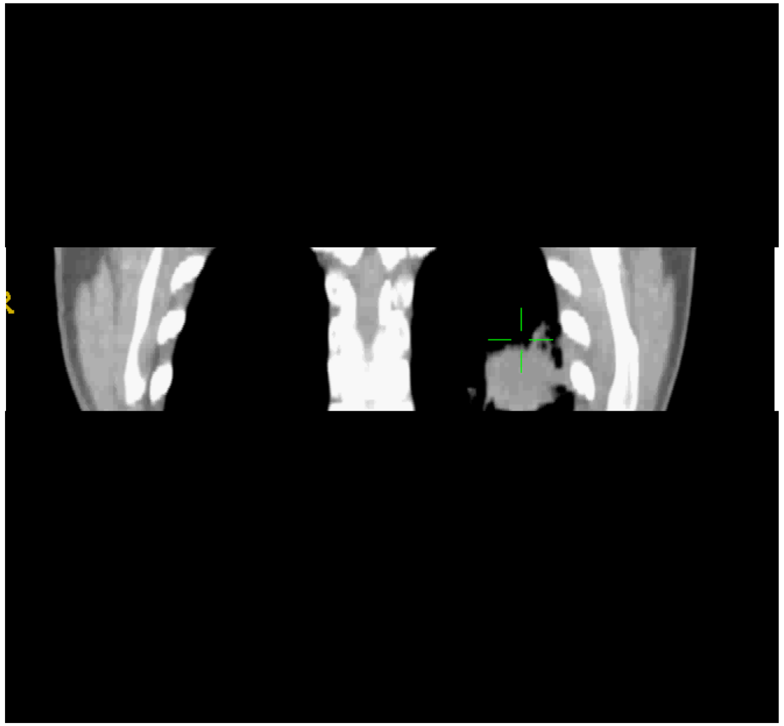
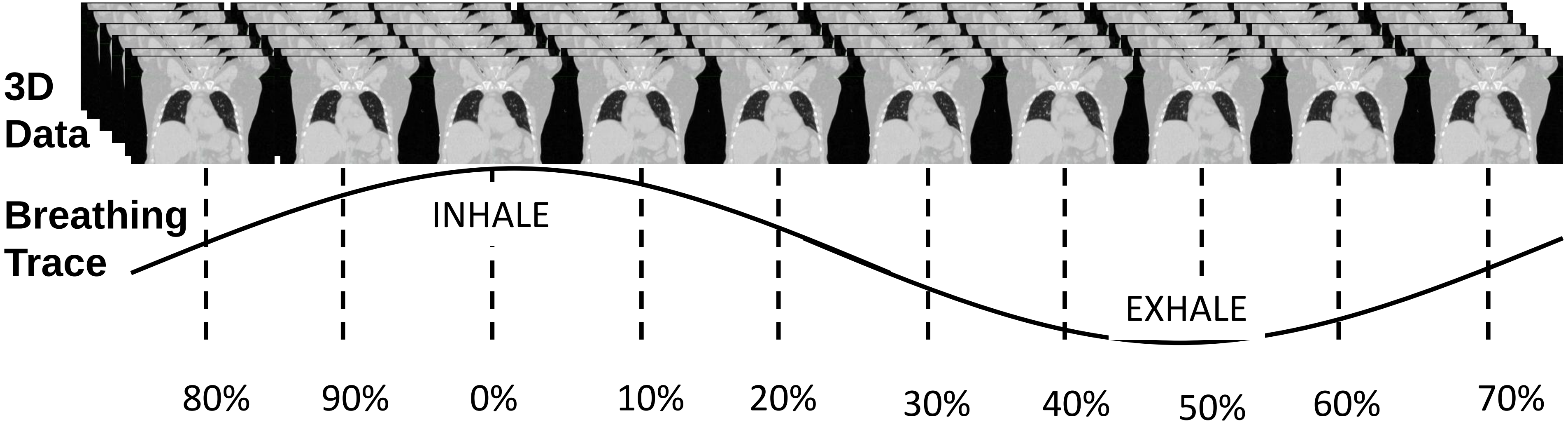
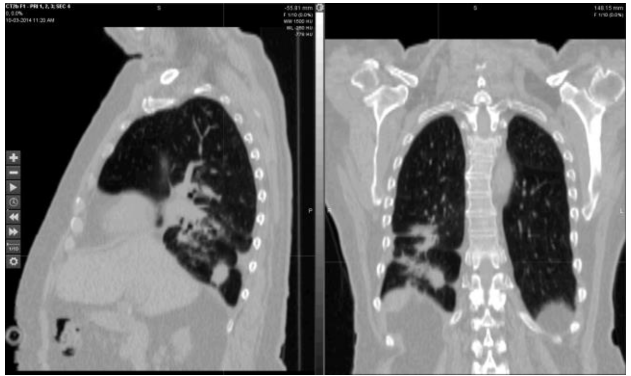


4DCT is the most important tool for breathing motion

A series of 3DCT images of the same volume, each of which represents the anatomy in a different phase of the breathing cycle



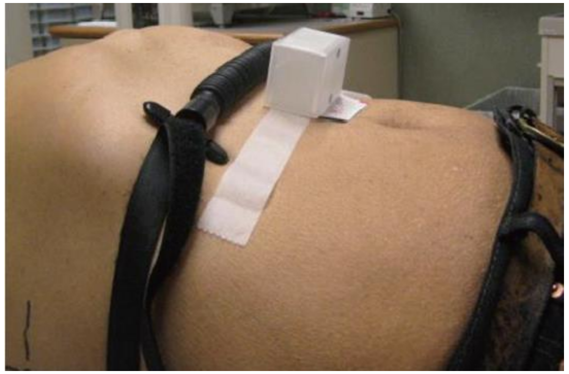


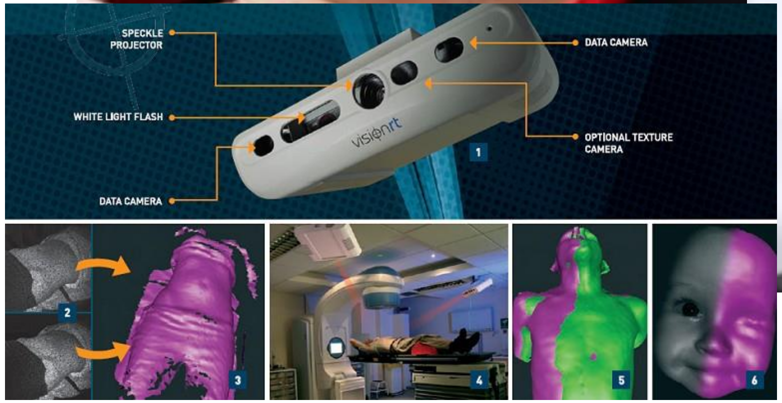
Requires

- A CT scanner
- A respiratory signal

Many breathing monitoring and controlling options

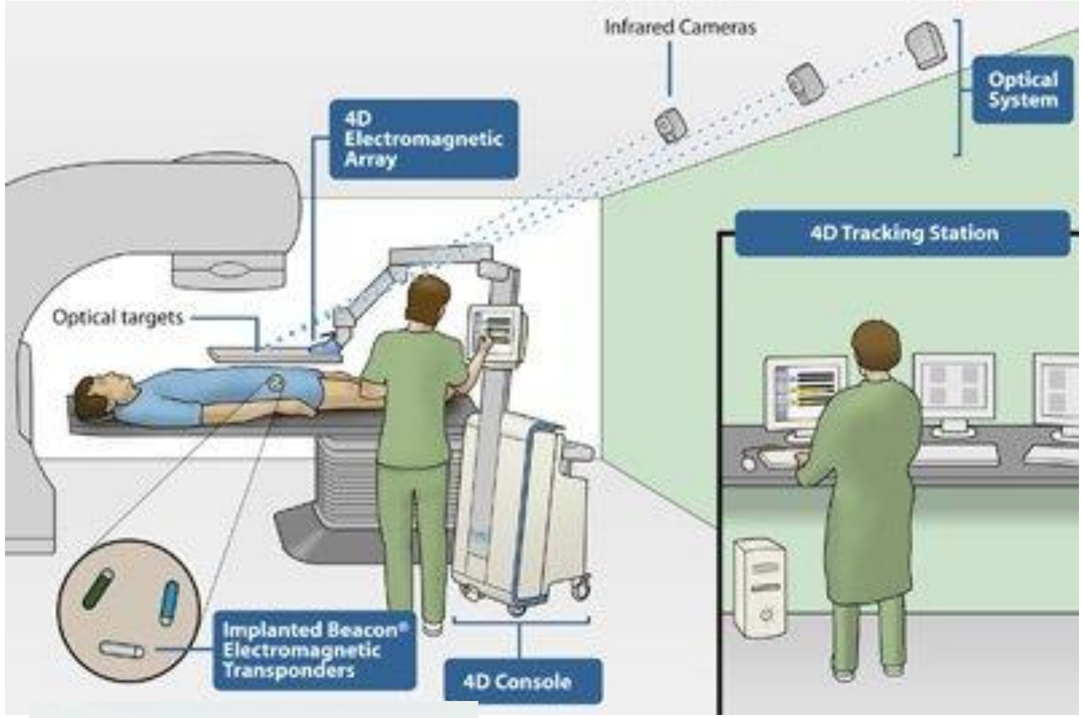
- None
- Elekta ABC
- Varian RPM
- Optical systems (eg Vision RT)
- Breathe-well
- Internal anatomy

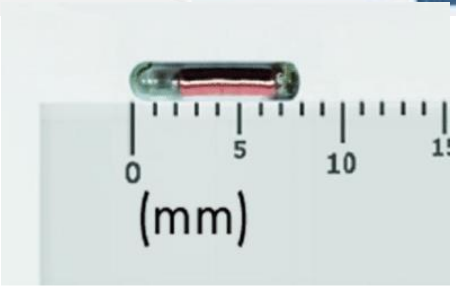




A few comments on surrogate markers

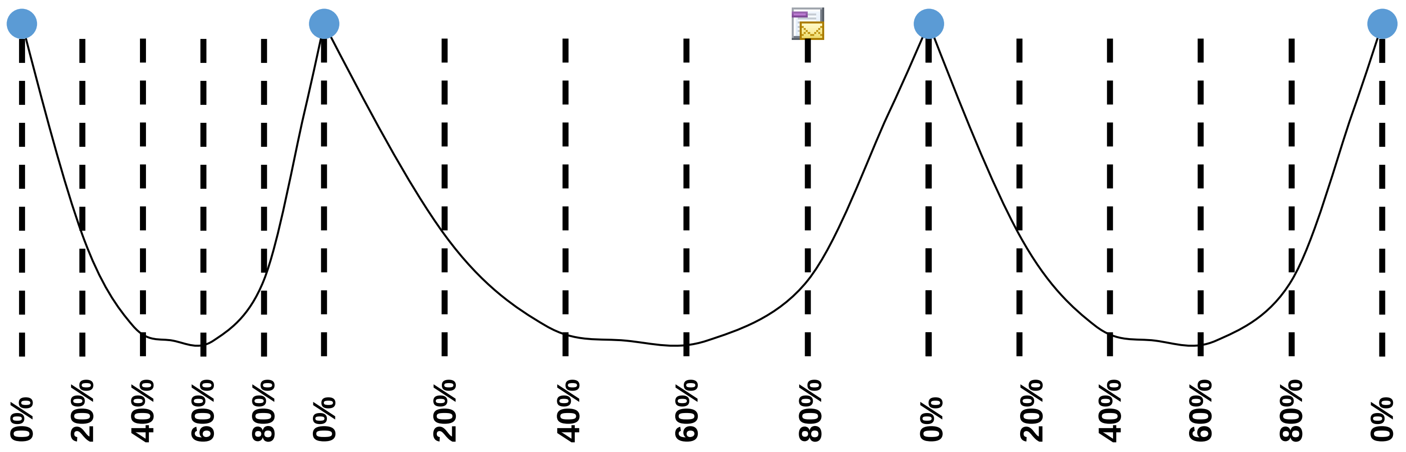
- Can be external or internal
  - Gold seeds
  - Surgical clips, lipiodol
  - Mirco-calcifications
  - Infrared markers on the skin
  - Skin (surface guidance)
- May not need imaging





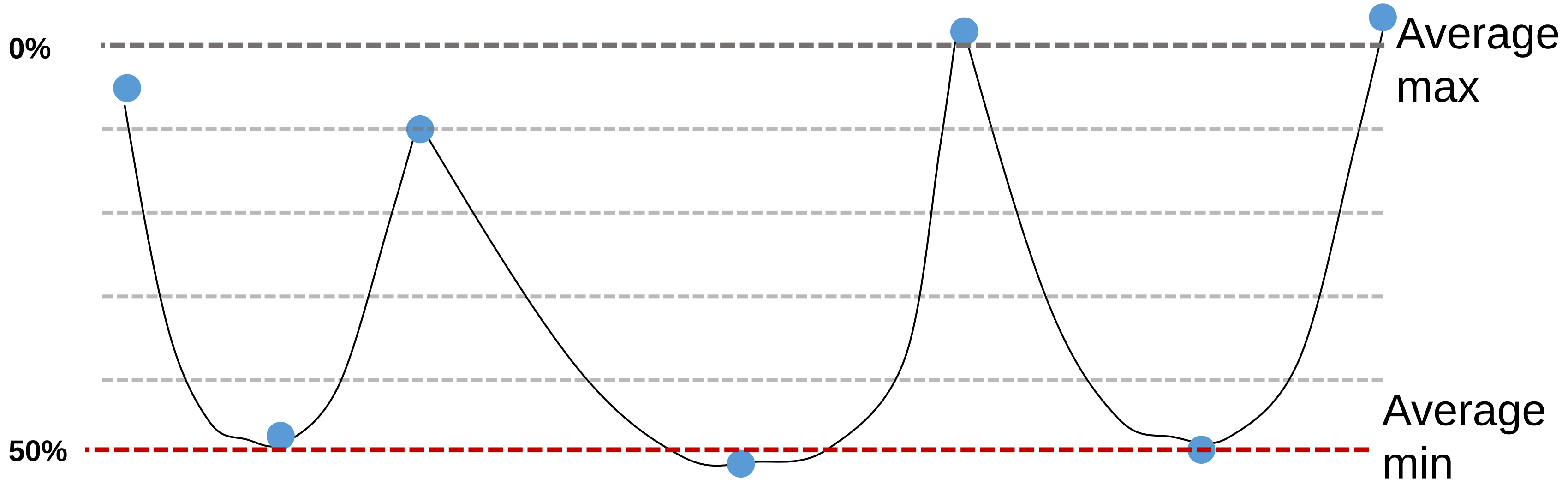
Phase binning

- Define the peaks (or other features of the breathing trace) as a specific phase
- Distribute evenly the time (and corresponding image data) between each peak
- When respiratory signal is not uniform, can result in mismatches of phases



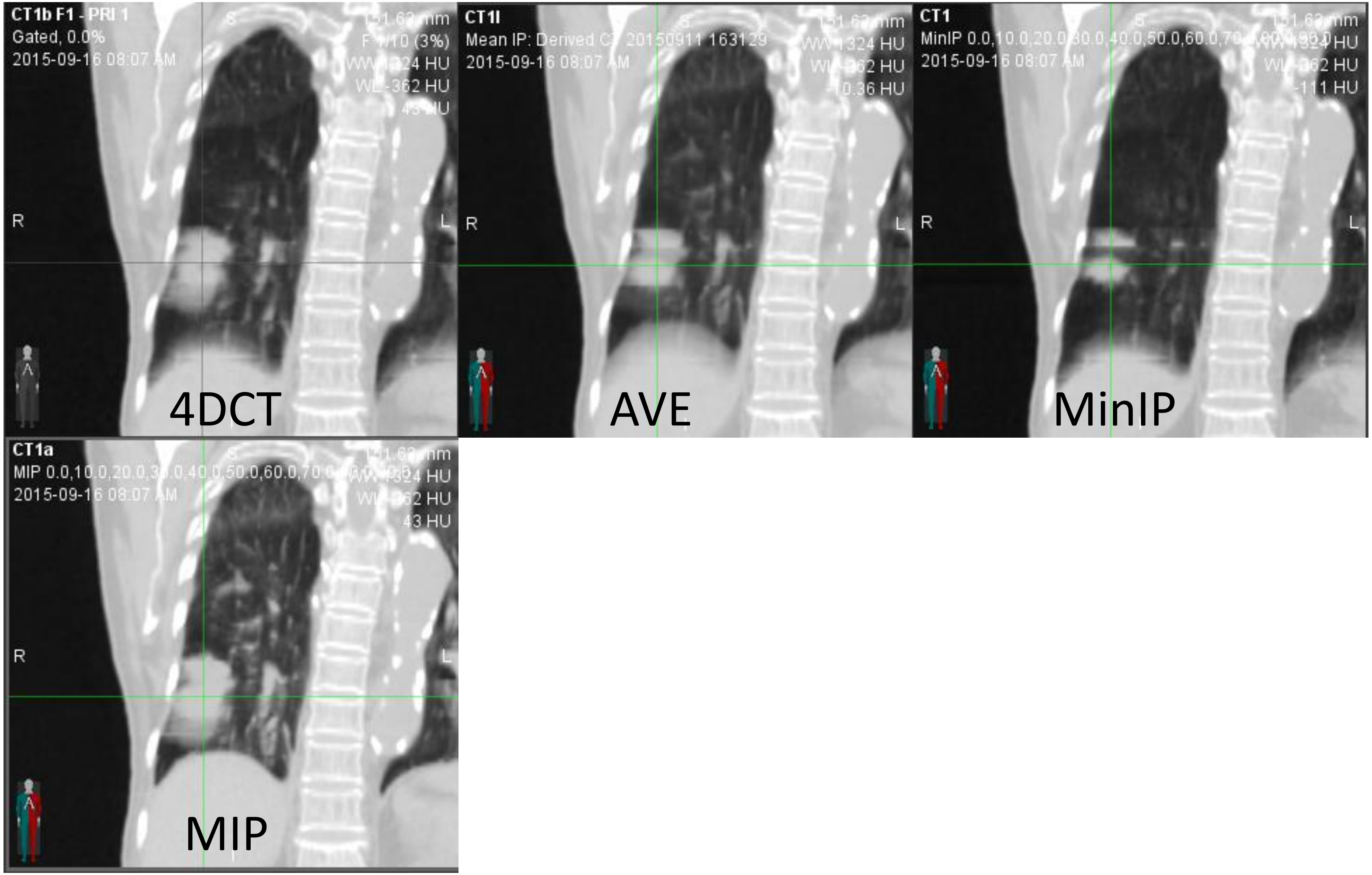
Amplitude binning

- Divide respiratory signal evenly between average max and min displacements
- Each phase is then image data from a specific portion of the average amplitude
- Should in theory result in fewer motion artefacts than phase sorting (but potential for missing slices)

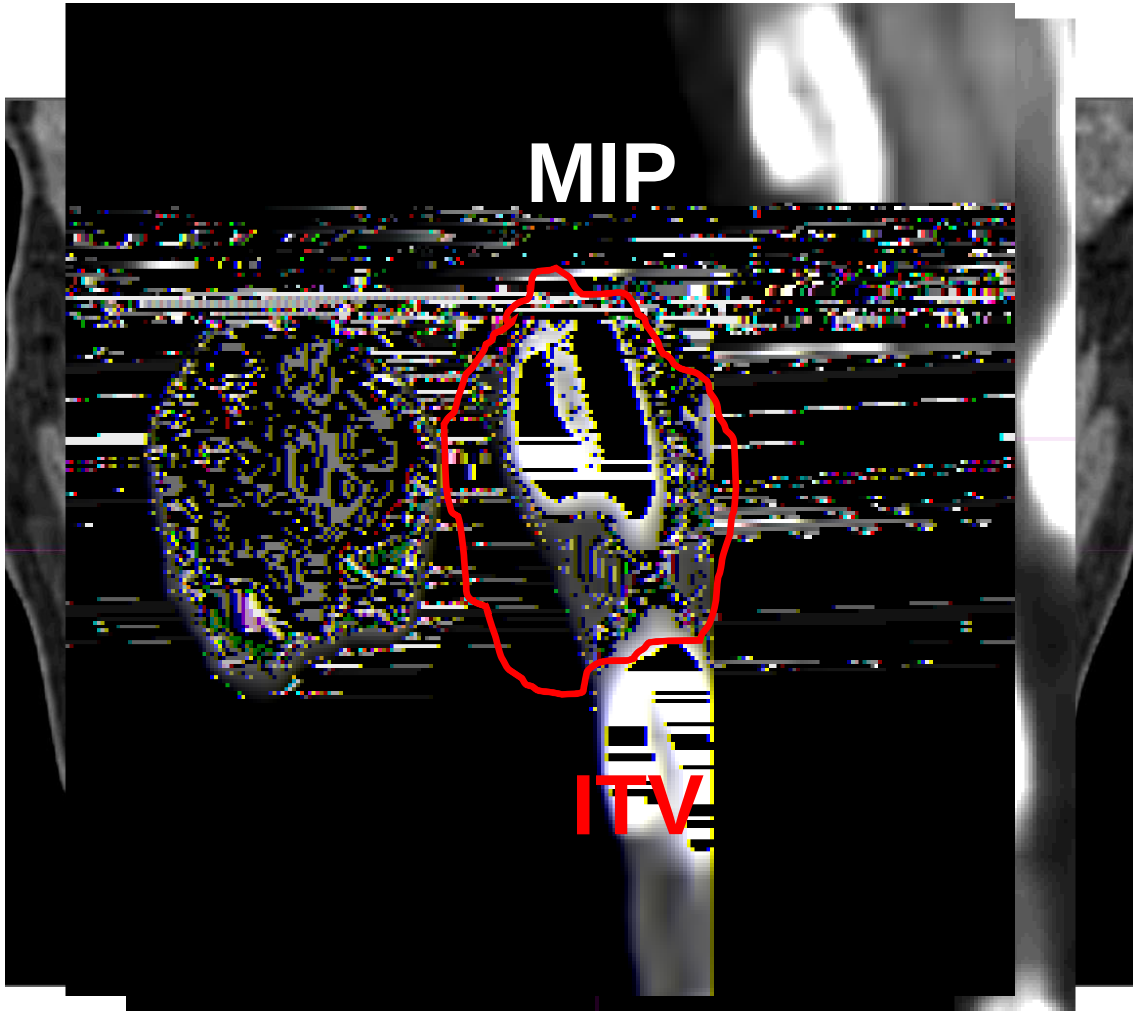


Li H et. al. Clinical evaluations of an amplitude-based binning algorithm for 4DCT reconstruction in radiation therapy, Med. Phys. 39 2012 p922

4DCT and its derivatives: intensity projections

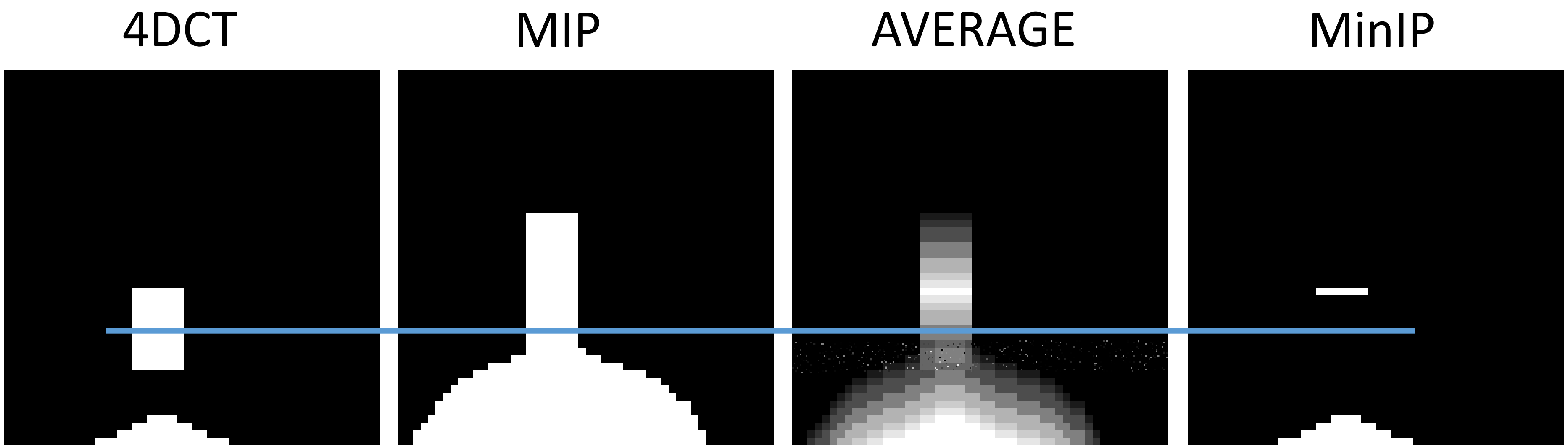


MIP -> internal target volume



- We outline everywhere the tumour goes
- Respiratory motion is treated as a systematic error therefore we encompass the whole (known) excursion of the tumour
- Potentially overestimates the influence of motion on the tumour dose

A simple physics picture to highlight issues



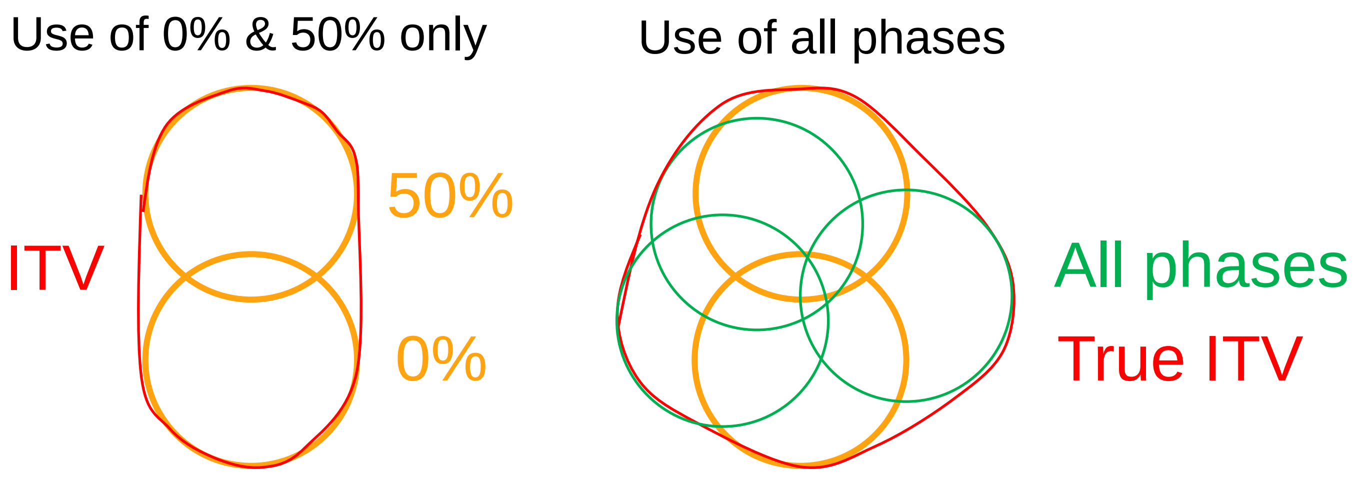
- 10 phases, each needing a minimum of 180 degrees of projections for reconstruction
- CT rotation period <= 0.5s → each phase is representing 250ms
- Breathing cycle 2 to 8s – a lot can happen in 250ms

- 4D CT sees the target in each phase of the breathing cycle only once

Internal target volume & hysteresis

- If there is hysteresis, then the maximum inhale and exhale phases alone are not suitable to generate ITV. All phases, or the MIP, should be used

- If possible you should verify MIP derived ITV using all phases



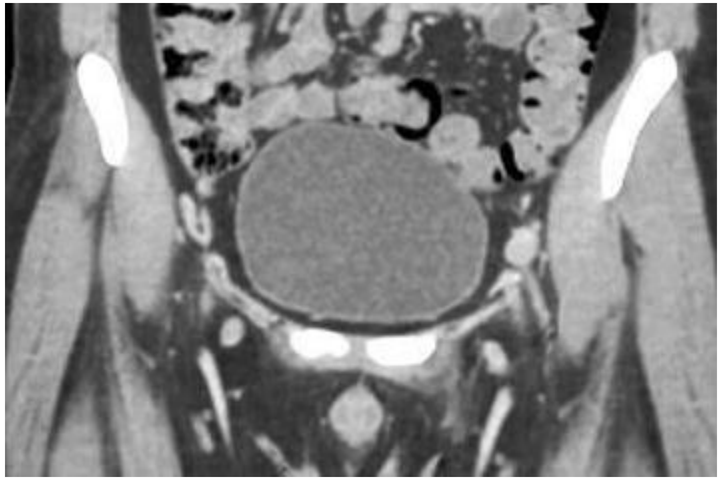
4DCT artefacts

- Can manifest differently from 3DCT
- Are a particular problem with
  - Breathing pauses or slow breathing: If the lesion is not moving enough while the lesion axial plane is moving through the scan plane, the full extent of motion is not captured
  - Irregular breathing: Mismatches in phases or amplitudes lead to discontinuities in the image data

SCANNING THE PATIENT AGAIN…

Patient set-up also matters

- Lung, Breast
  - Arms up
- Breast
  - Deep inhalation breath hold (DIBH)
- Prostate
  - Bladder ‘comfortably’ full
- Lung, breast, lymphoma
  - DIBH
- Liver
  - Exhale breath hold



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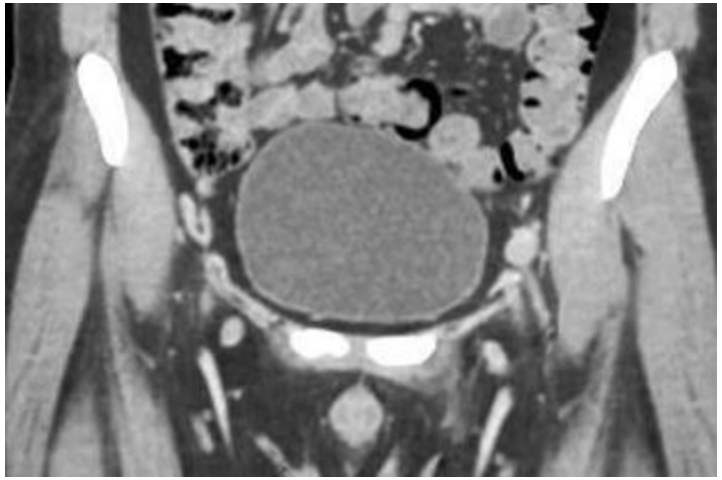
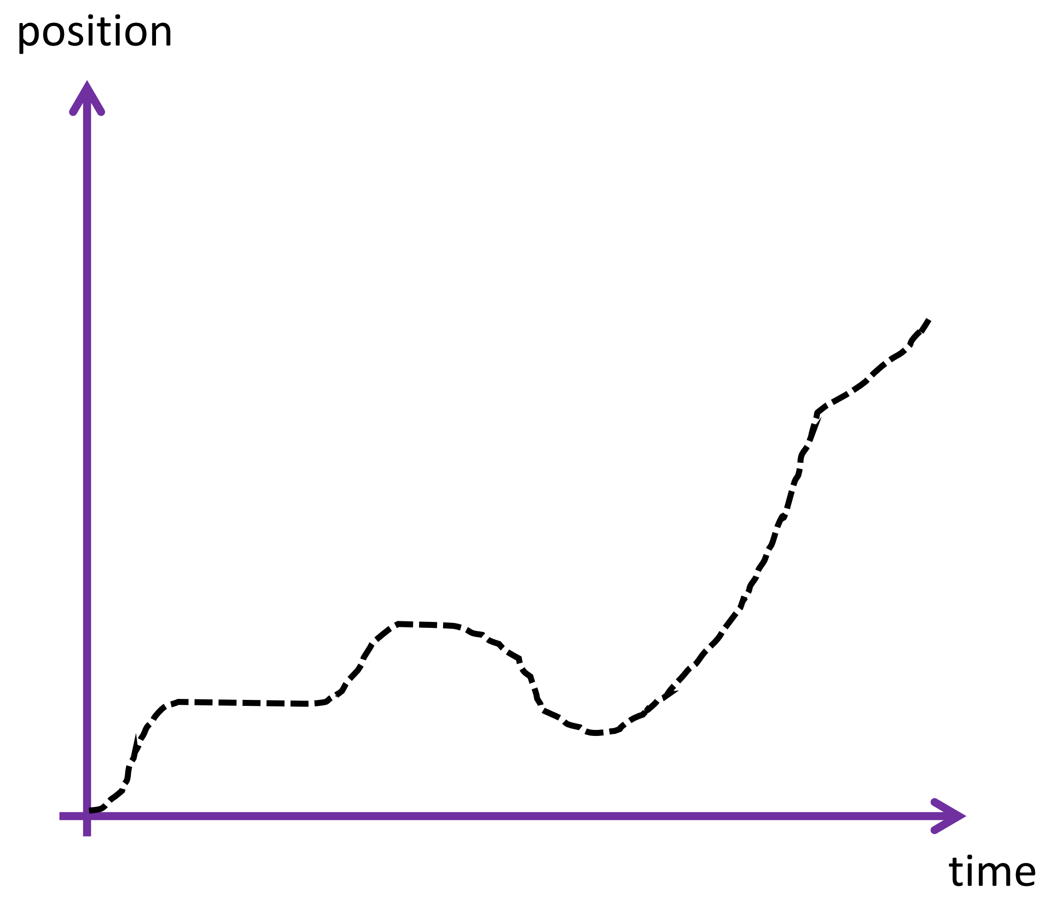
  - DIBH
  - breath hold

Patient comfort is VERY important as it ensures reproducibility

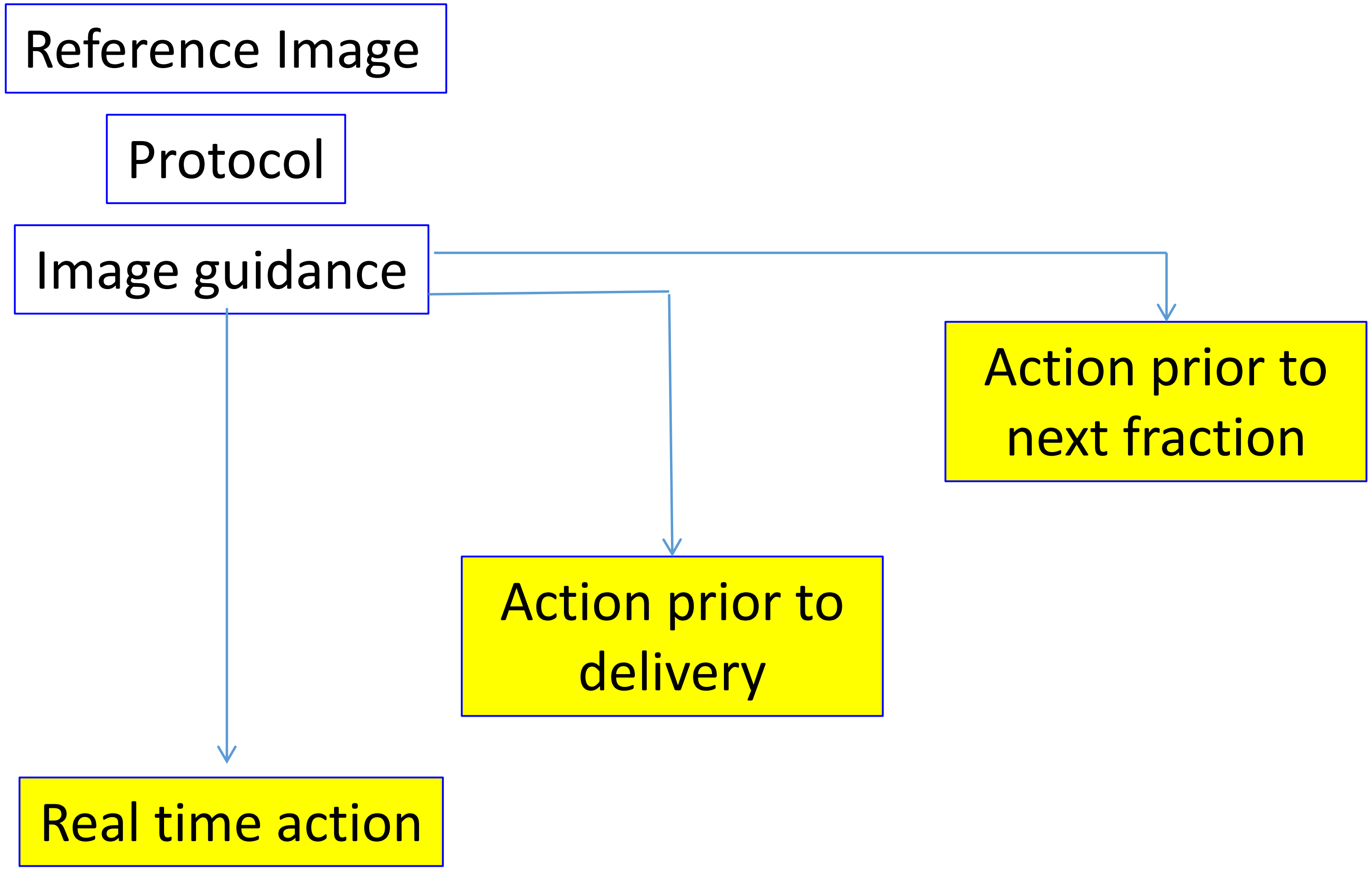


Motion is position as a function of time

- Different time scales
  - Day to day variation
  - Slow changes
  - Regular changes (breathing)
  - Fast changes
  - Trending
- Different spatial scales
  - Dimensions (1, 2, 3?)
  - mm, cm
  - Translation, rotation, deformation



Time also applies to what we do with images: Corrective strategies



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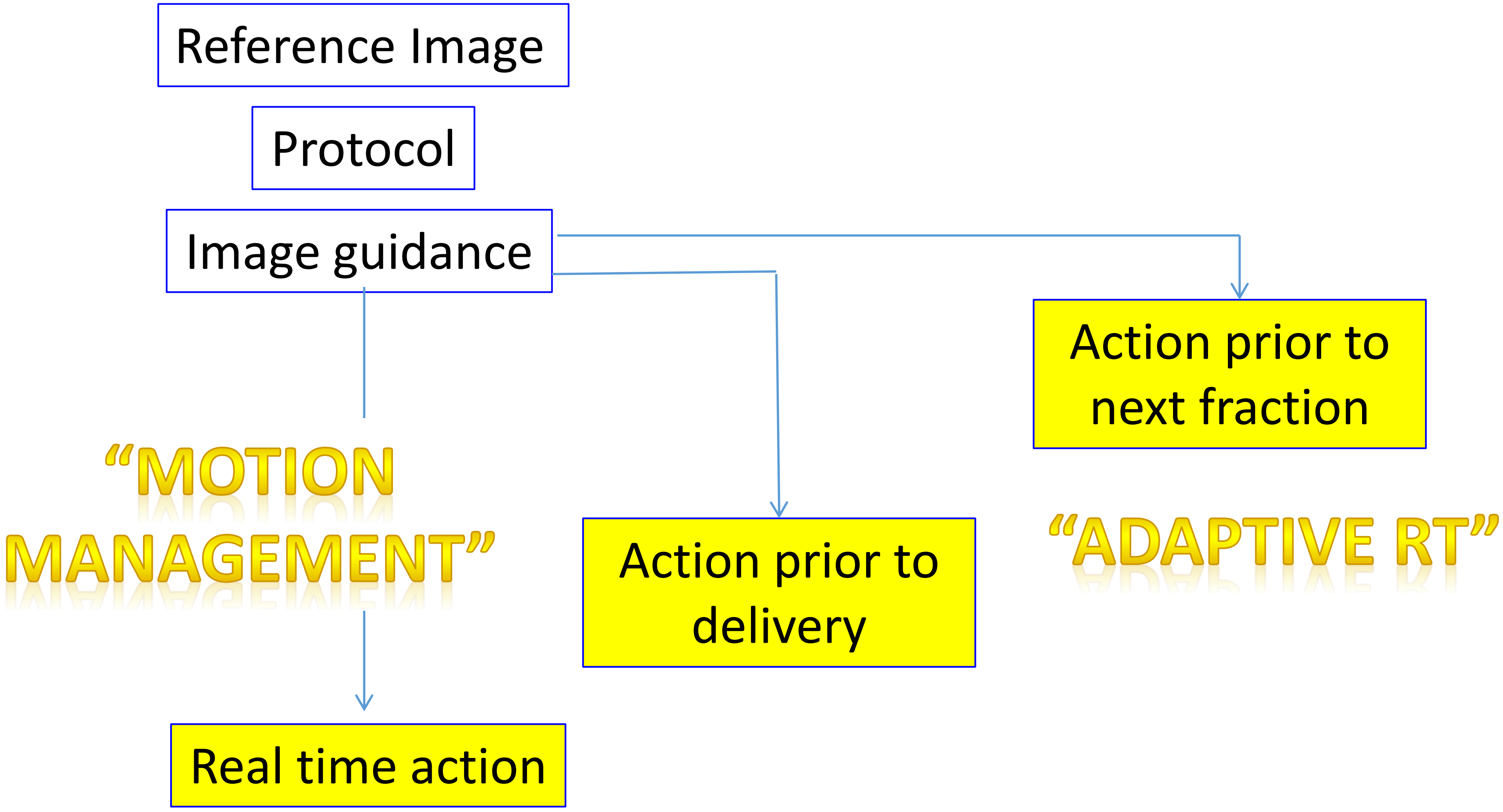

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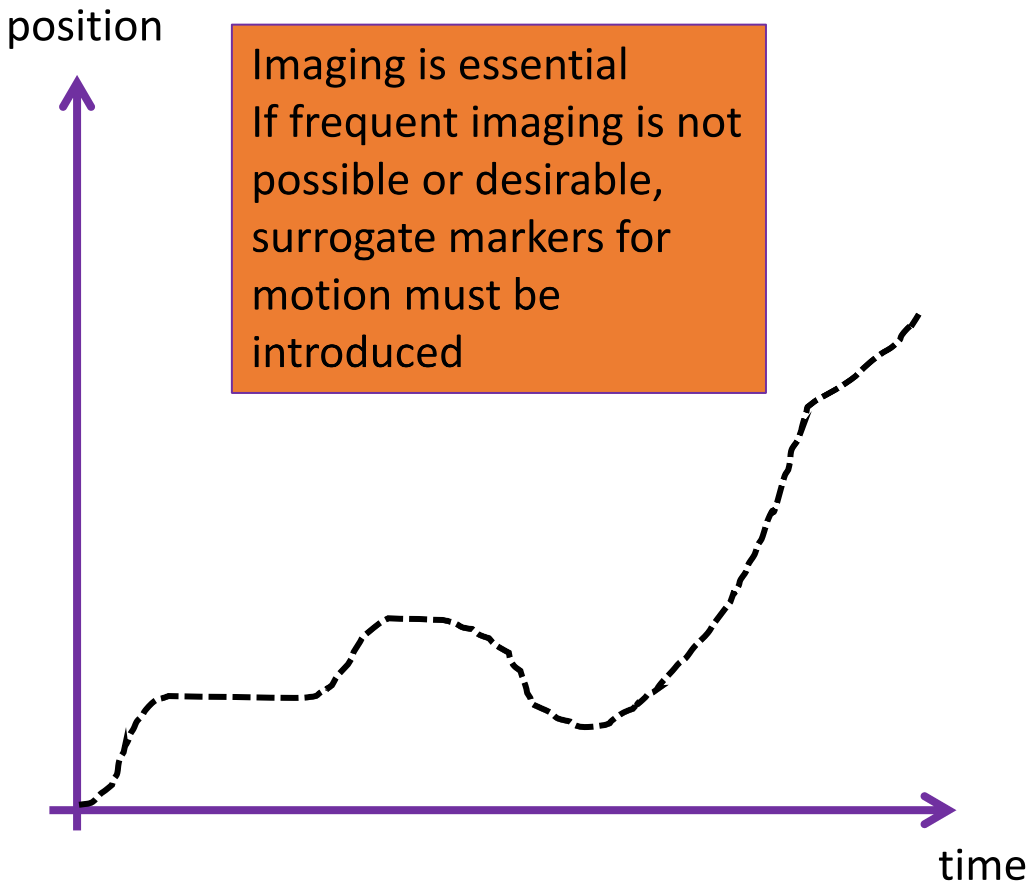


A modern radiotherapy treatment unit (imaging equipment highlighted)

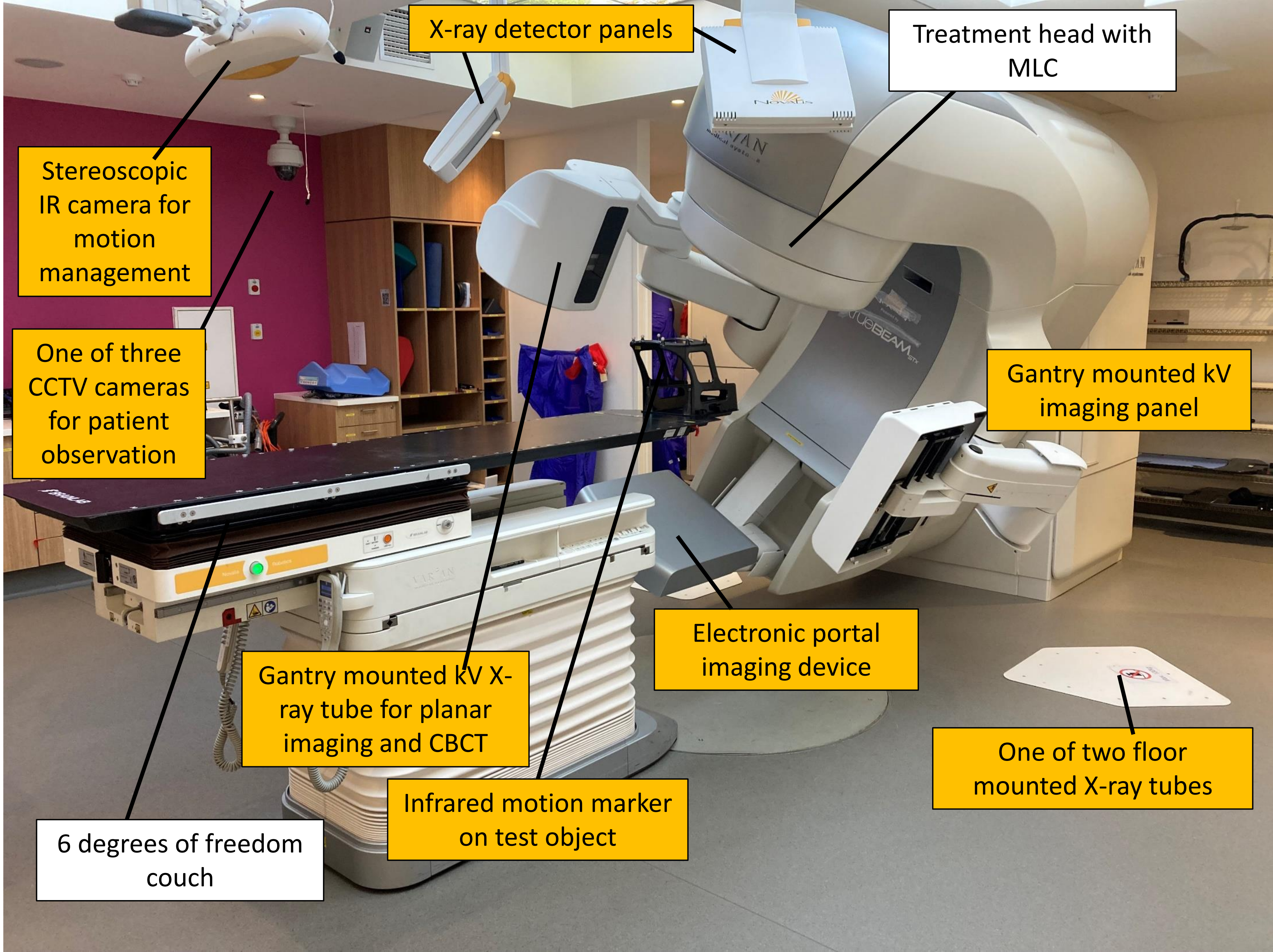
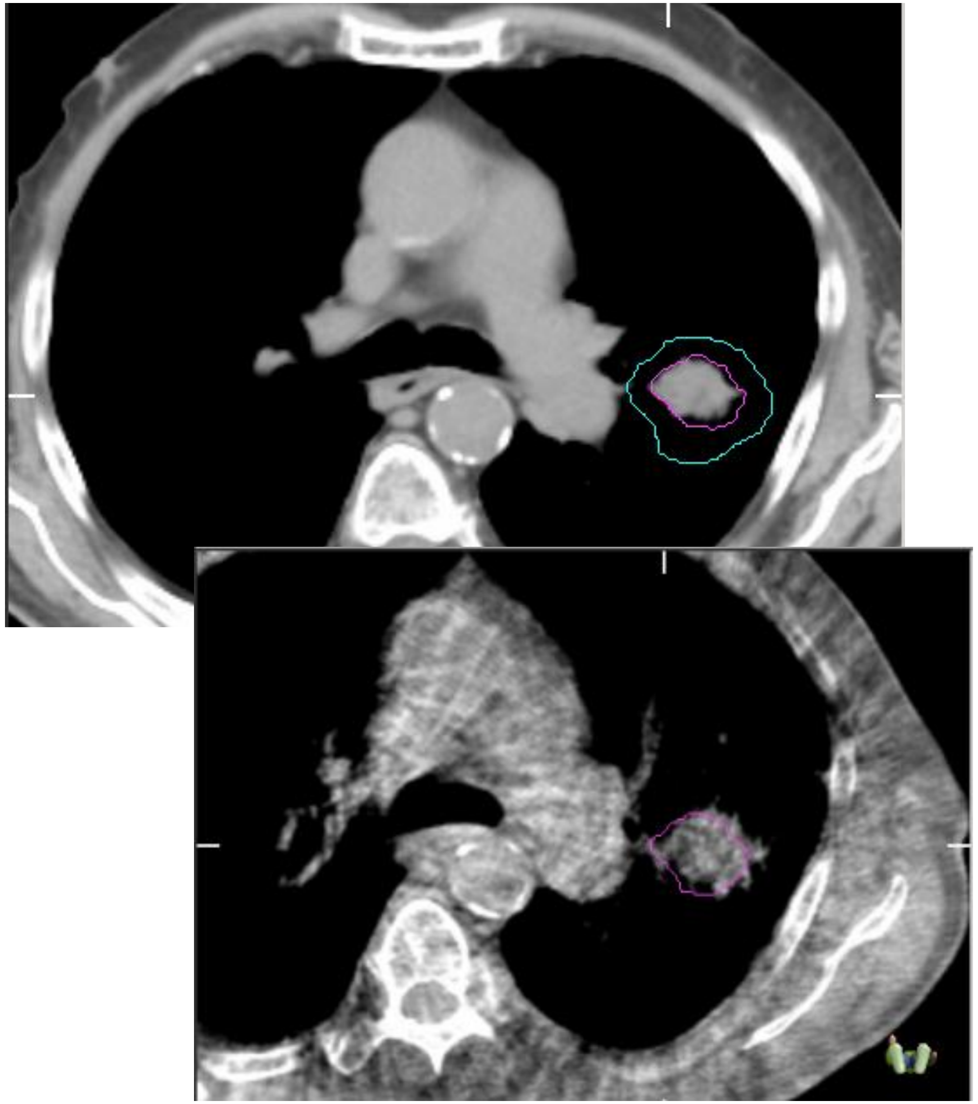


Image guidance

- Essential
- Many options
- Must verify target position
- Must take motion into consideration
- Must justify the GTV → PTV margins



The effect of irregular breathing patterns on internal target volume in four-dimensional CT and cone-beam CT images in the context of stereotactic lung radiotherapy

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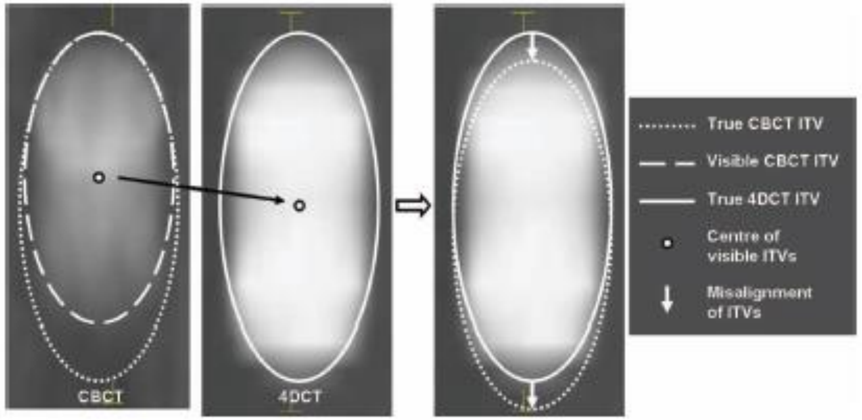


Compare 4DCT derived volumes with CBCT

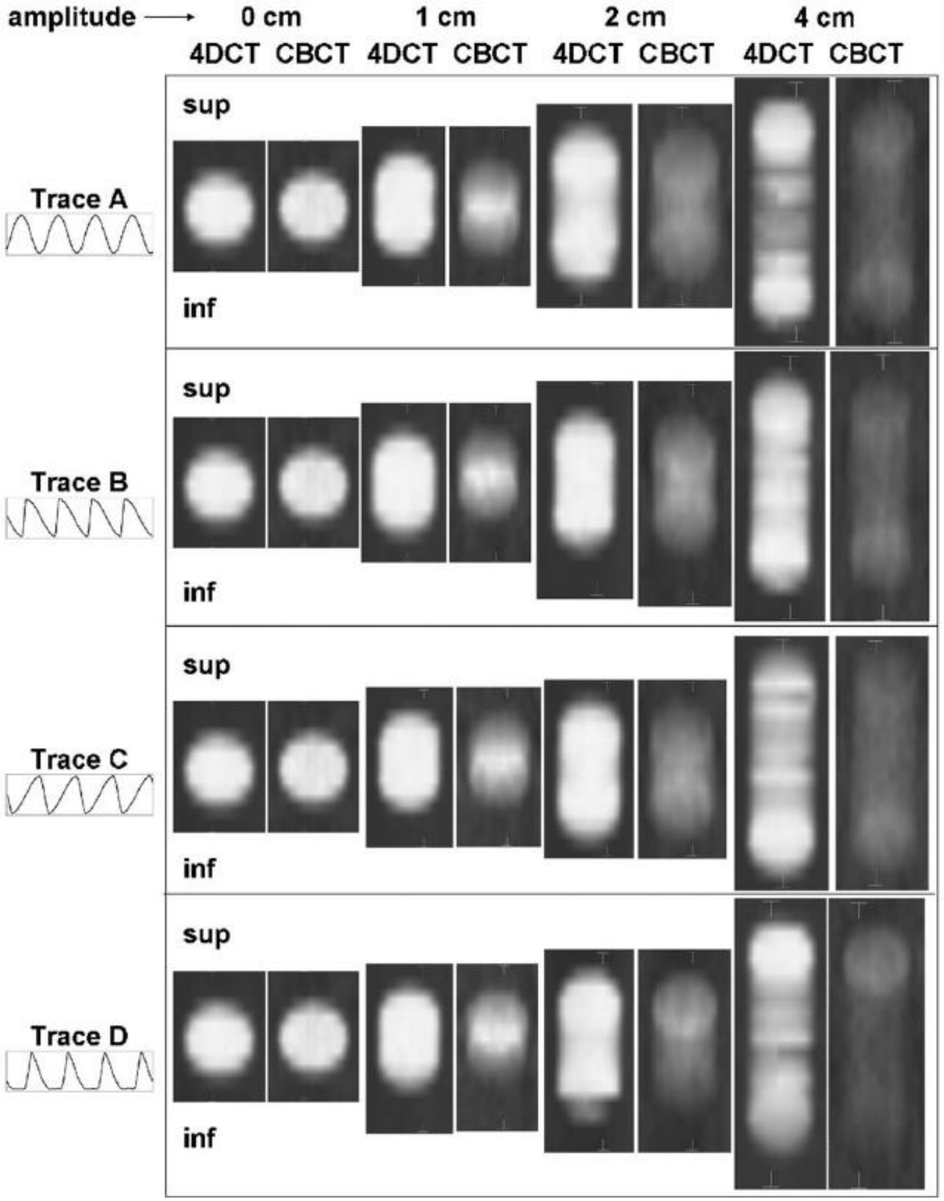
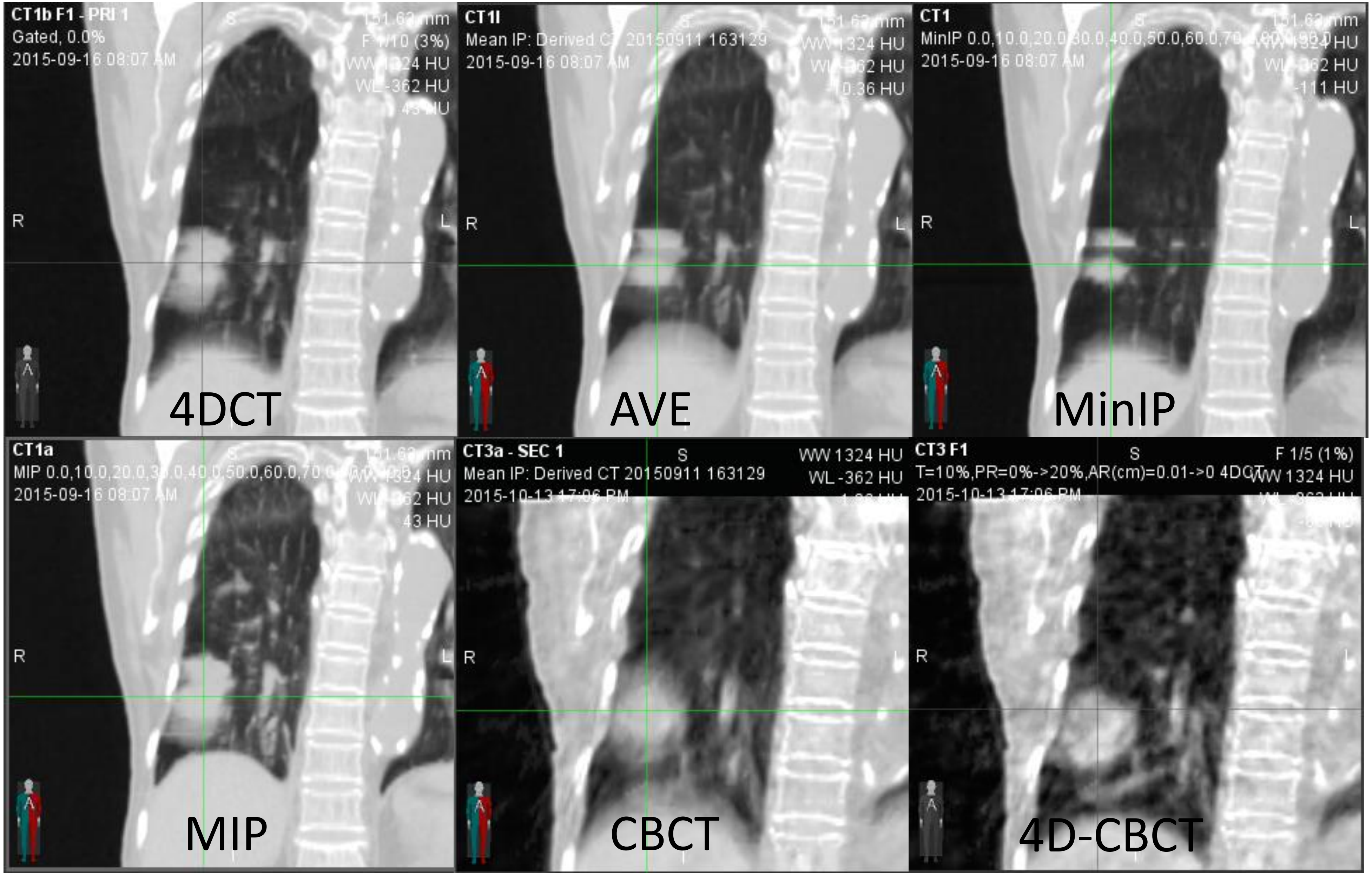


FIG. 3. The qualitative effect of amplitude on 4DCT MIP and CBCT ITVs for the small lesion moving with computer-generated breathing patterns Traces A–D.

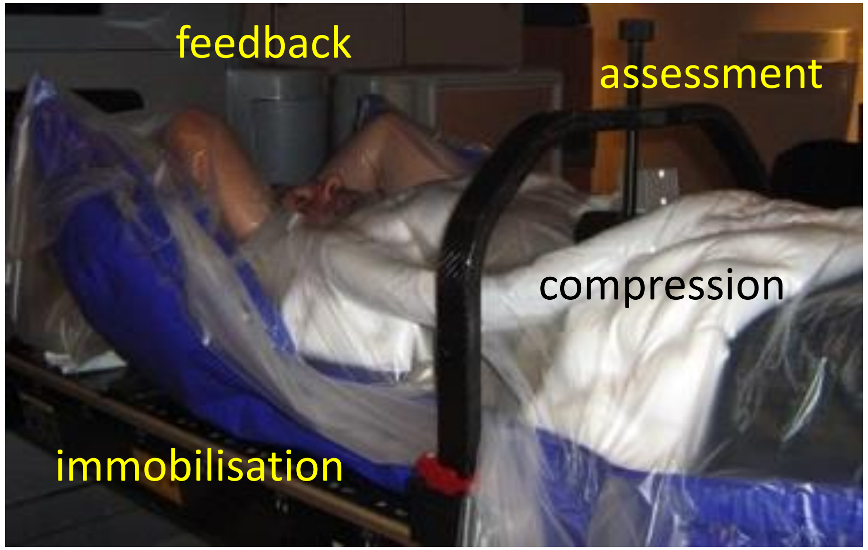
4DCT and its derivatives



Why is CT the sweet heart of radiotherapy?

- CT is 3D
- CT is fast (contrast, breath hold) and relatively cheap
- CT shows anatomy
- CT is distortion free – 1 cm seen is 1cm in reality
- CT allows dose calculation
- CBCT replicates CT at the time of treatment providing a perfect opportunity to compare verification and reference images

Motion management in practice



- **Treatment options**
  - Breath hold
  - Compression
  - Motion adaptive treatment
  - Gating
  - Internal target volume

Motion management in practice

- **Planning tasks**
  - Assessment of motion
  - Control of motion
  - Reference (images + motion)

- **Treatment options**
  - Breath hold
  - Compression
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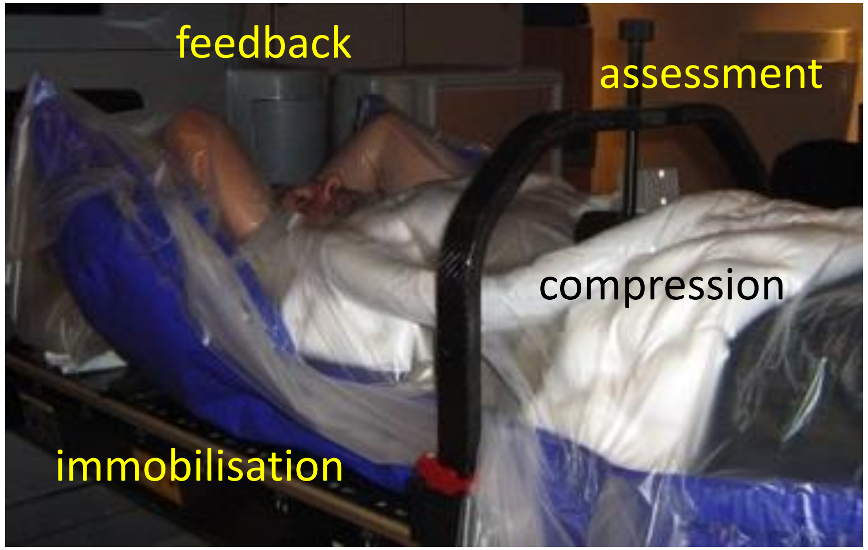
  - Internal target volume

Increasing demands on patients



Respiratory Motion Management

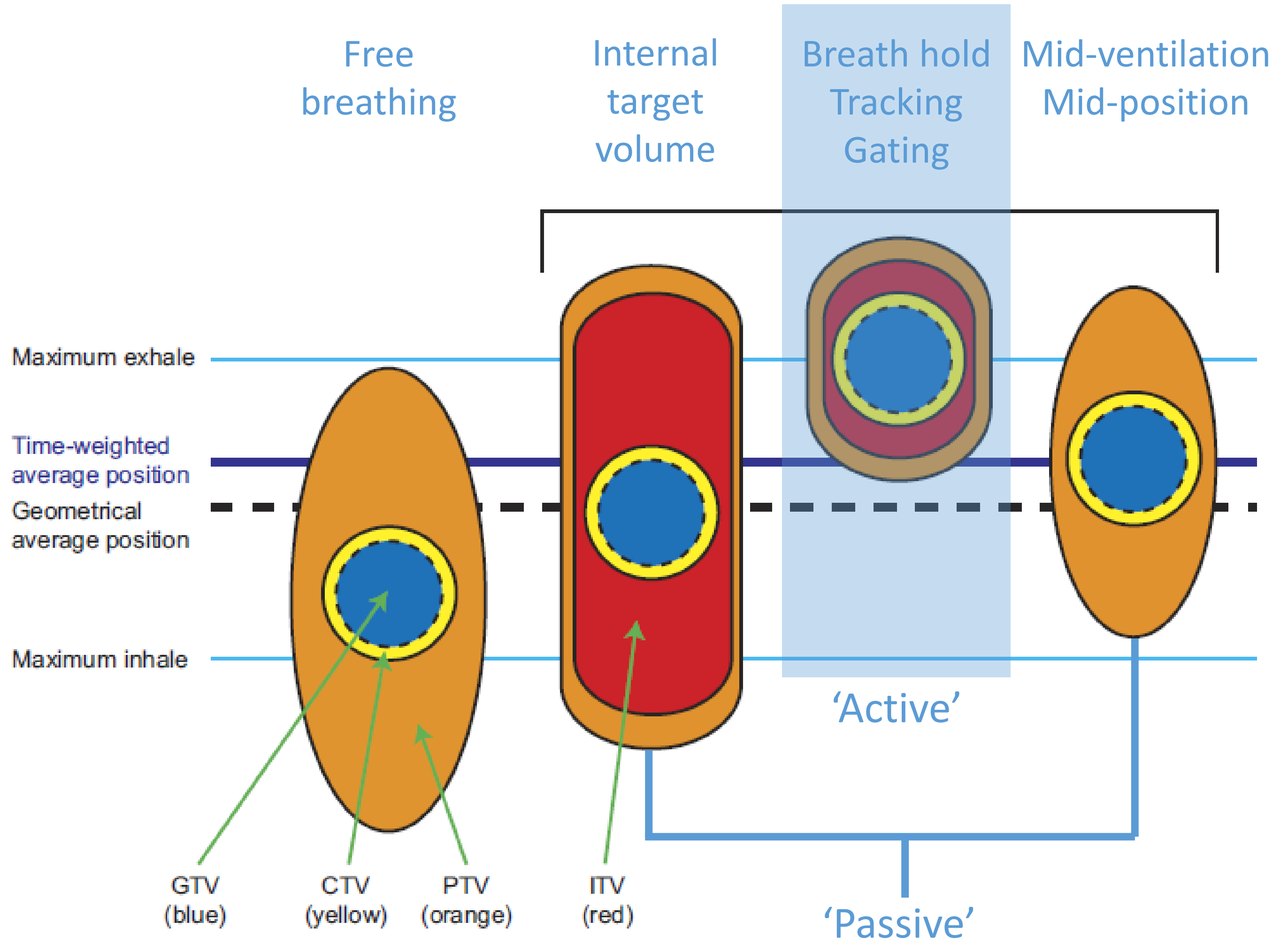


Fig. 1. Schematic overview of different treatment-planning concepts: conventional free-breathing, internal target volume (ITV), gating (at exhale), and mid-position. GTV = gross tumor volume; CTV = clinical target volume; PTV = planning target volume.

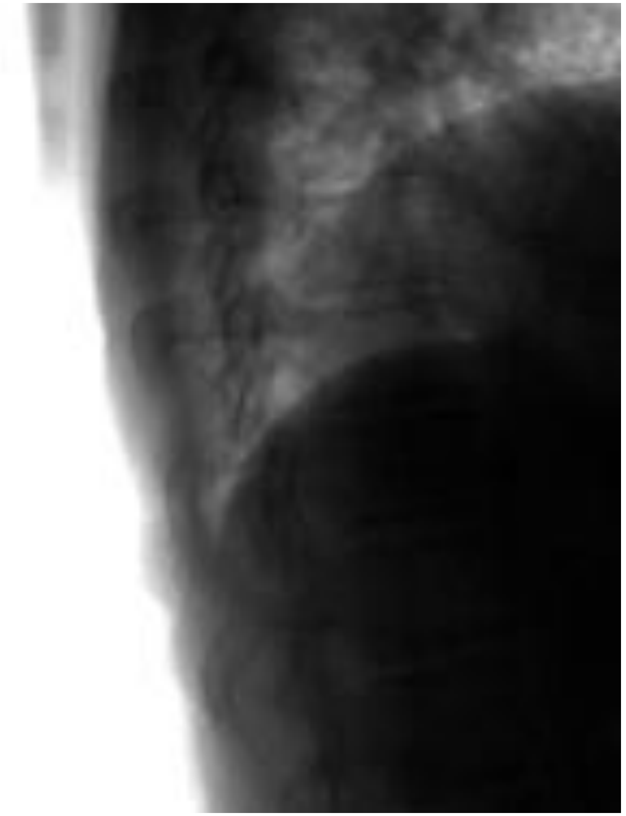
Wolthaus et. al. IJROBP 70 (4) 2008

So many choices – how can we decide

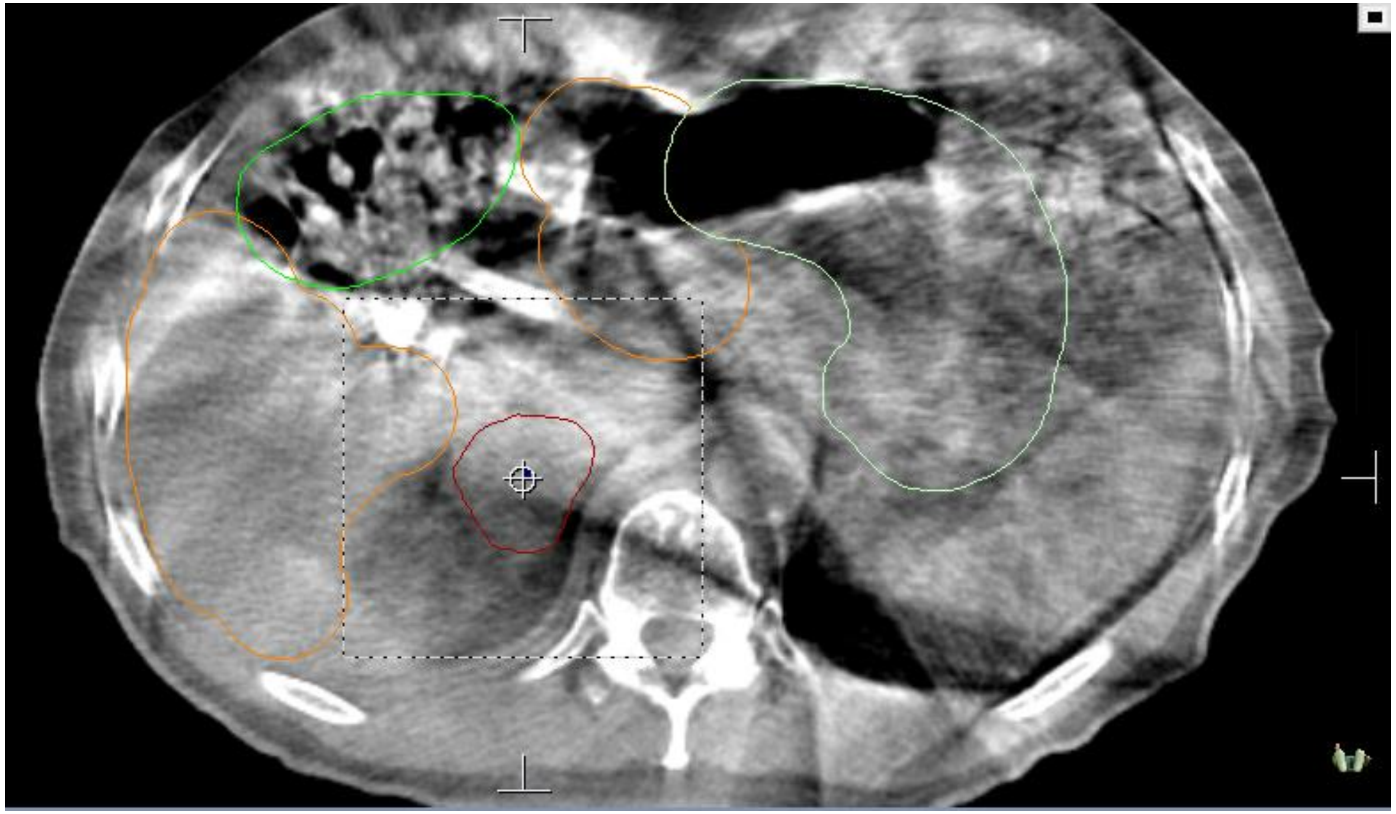
1. Image quality needed
    - 3D, frequency, contrast
2. Dose
3. Time allowed
    - Patient on the couch
    - Changes due to delay
    - Automation (GPU calculation, AI segmentation)
4. Training, experience, documentation

1. Image quality – bowel/stomach gas

CBCT projections



Reconstructed CBCT (FDK)



2. Dose from CBCT

Jun Deng 09

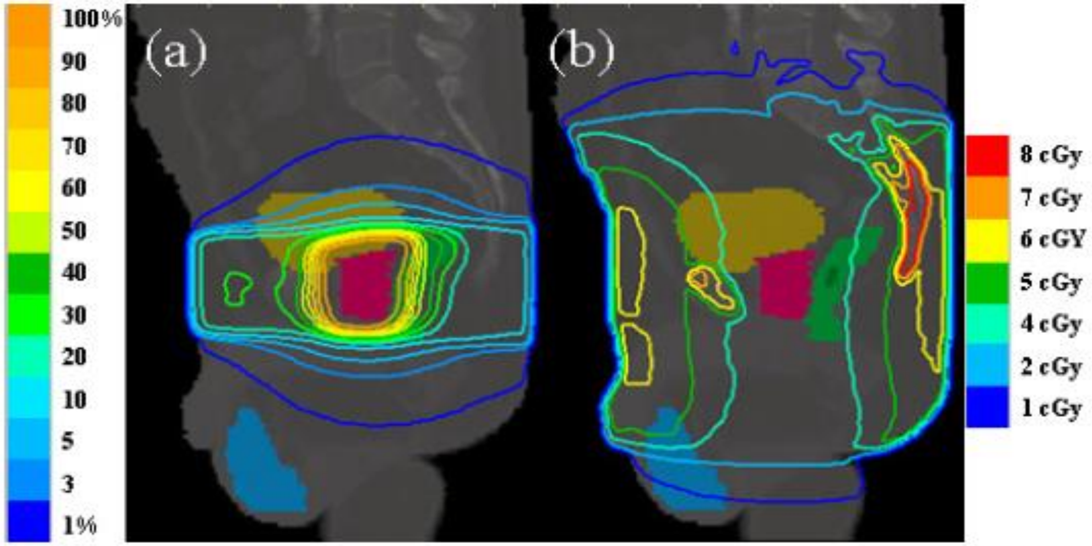
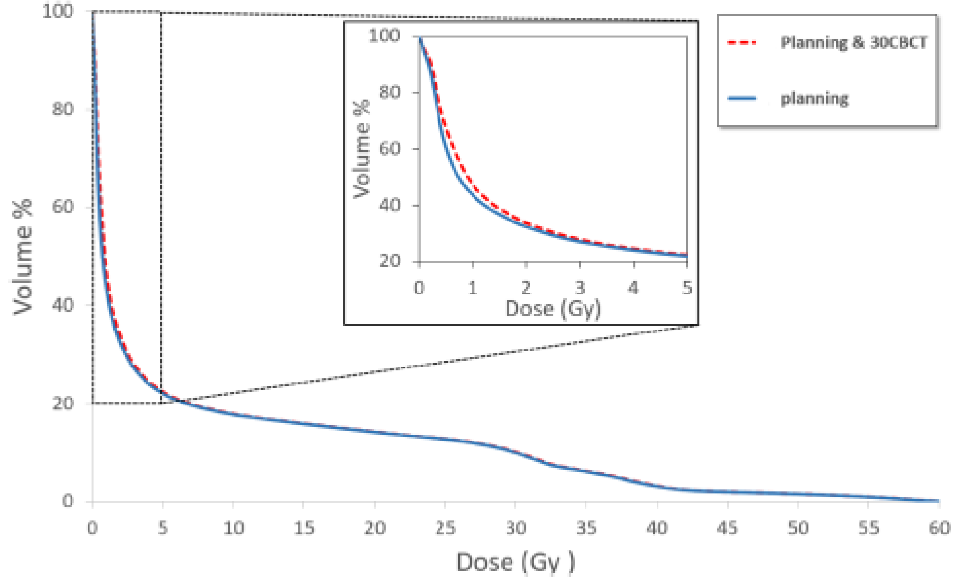


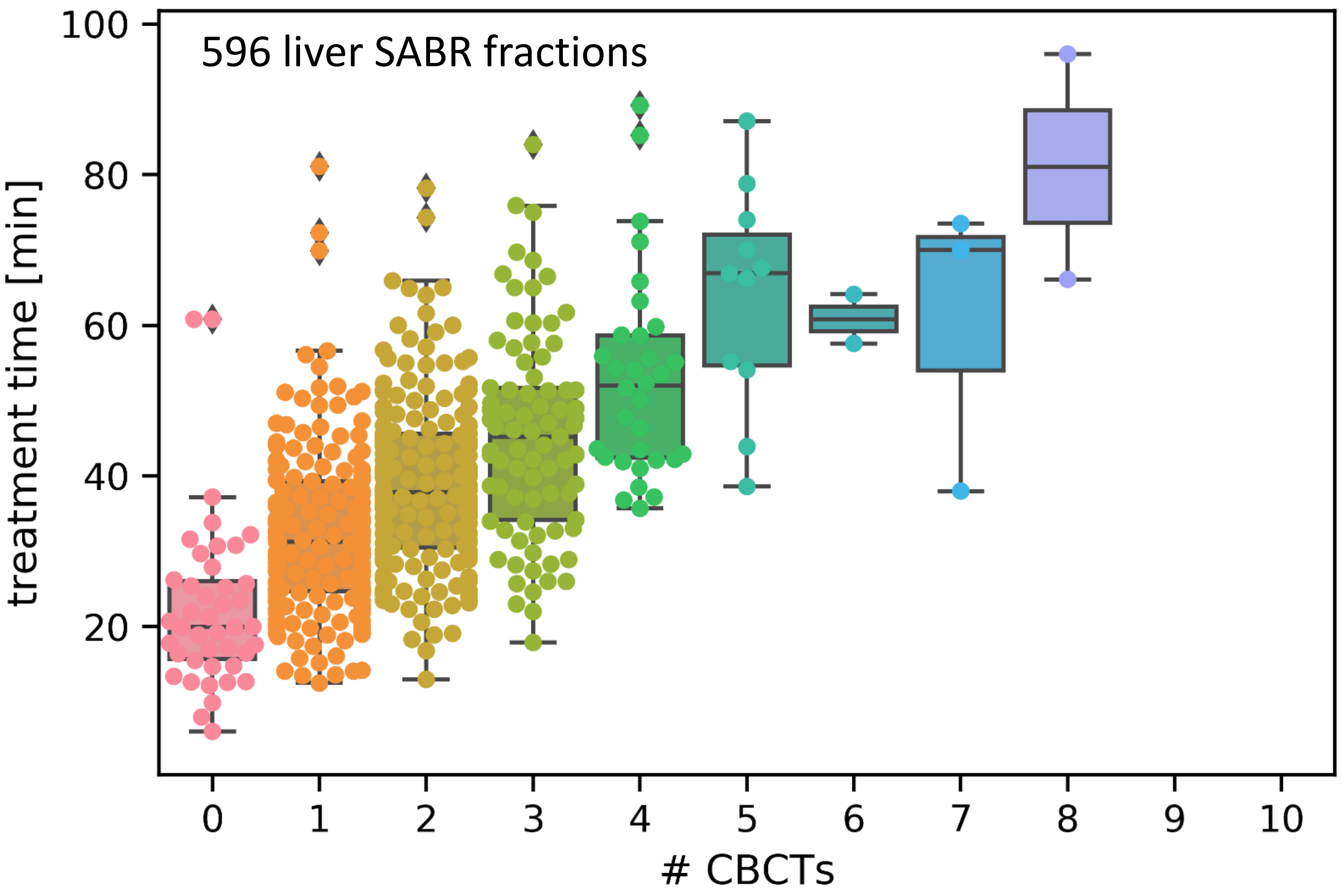
Figure 5: Comparison of Monte Carlo calculated dose distributions in sagittal views for (a) a 10 MV 5-field IMRT plan, and (b) a 125 kV CBCT scan in half-fan mode with half-bowtie filter. The field span in superior-inferior direction is 23.6 cm by default.

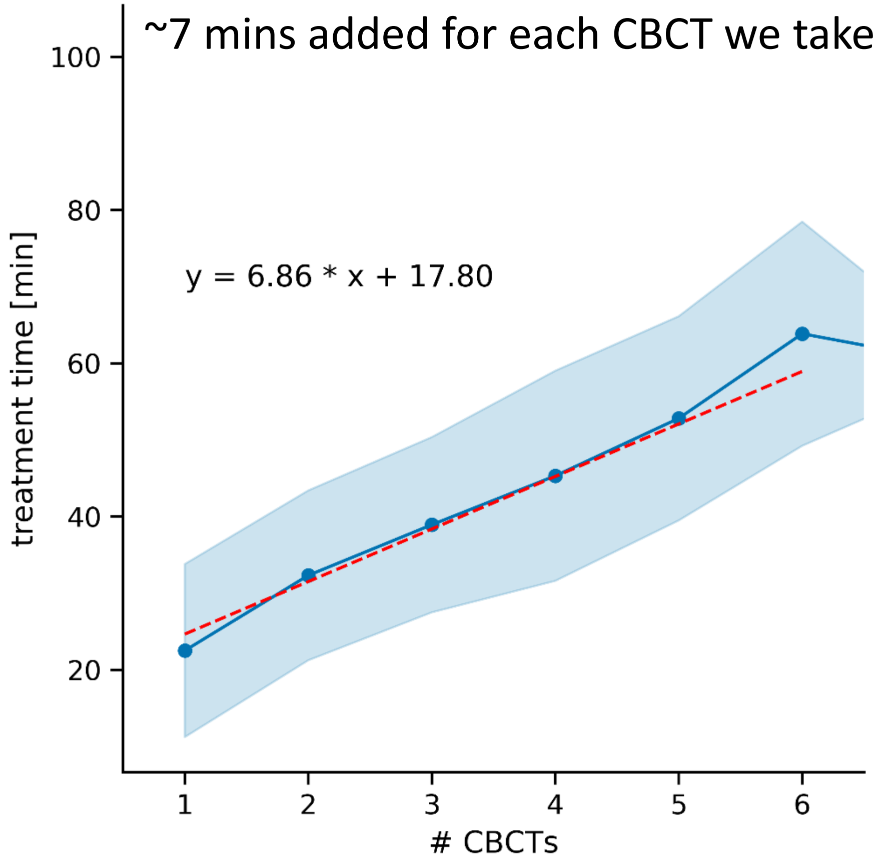
- Scatter is very significant (>50% of dose)
- Field size reduction reduces dose
- Dose higher in outer part of the patient
- Dose higher in full fan and small objects…
- Dose cannot be accounted for in planning

Alkarabatii et al 22



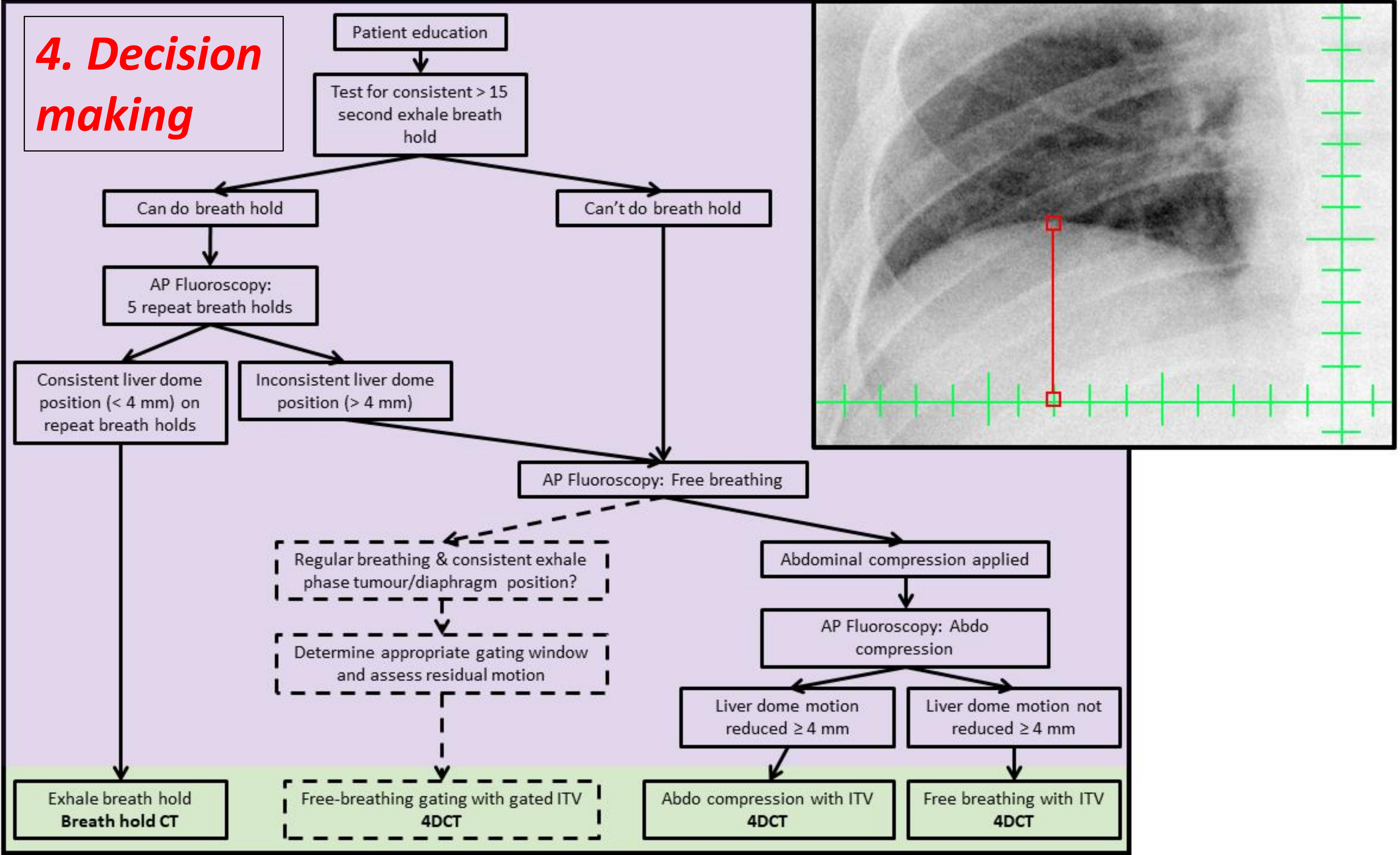
3. Time



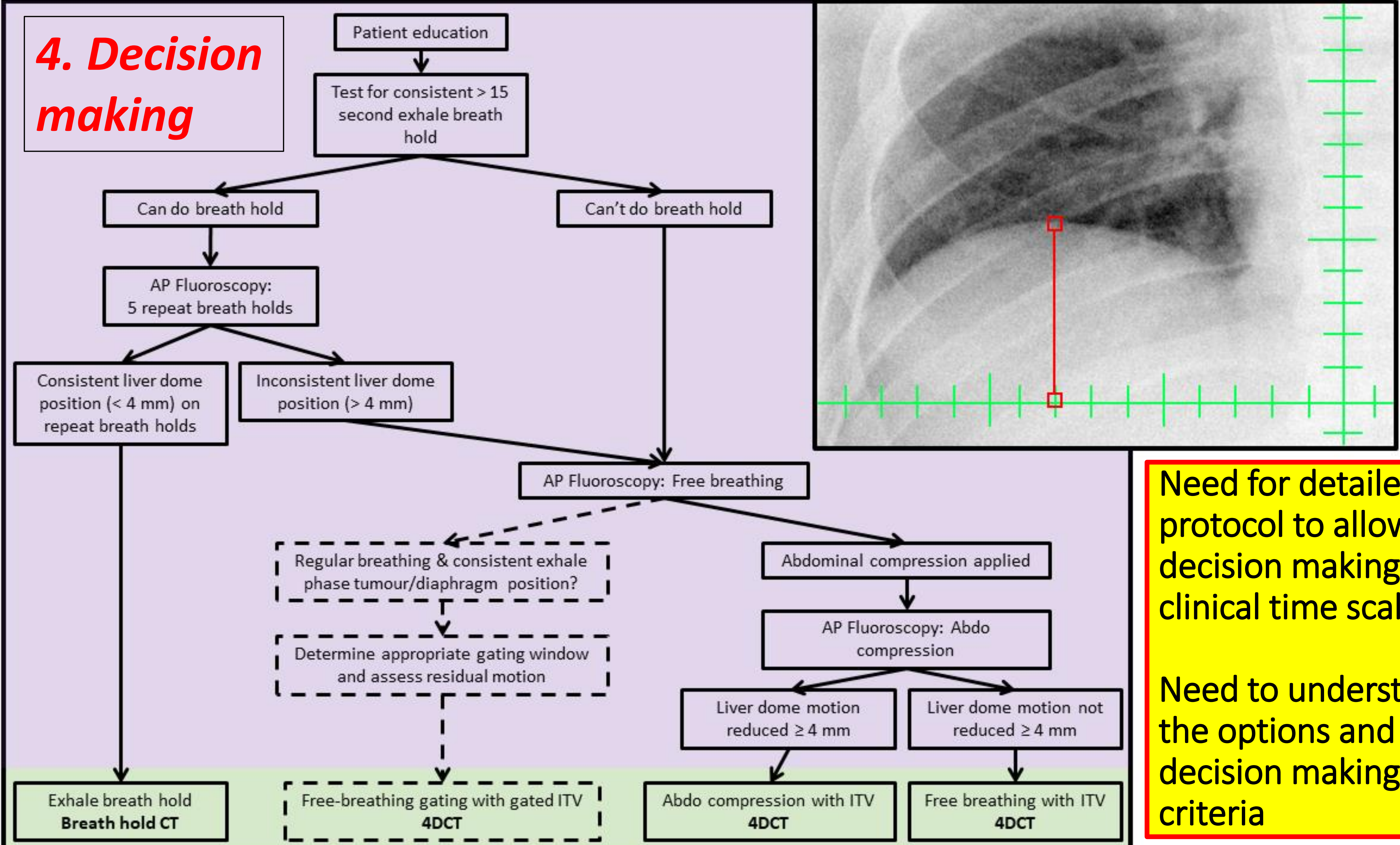


Triggered imaging can reduce treatment time, if we don't need to take CBCTs?

4. Decision making



4. Decision making

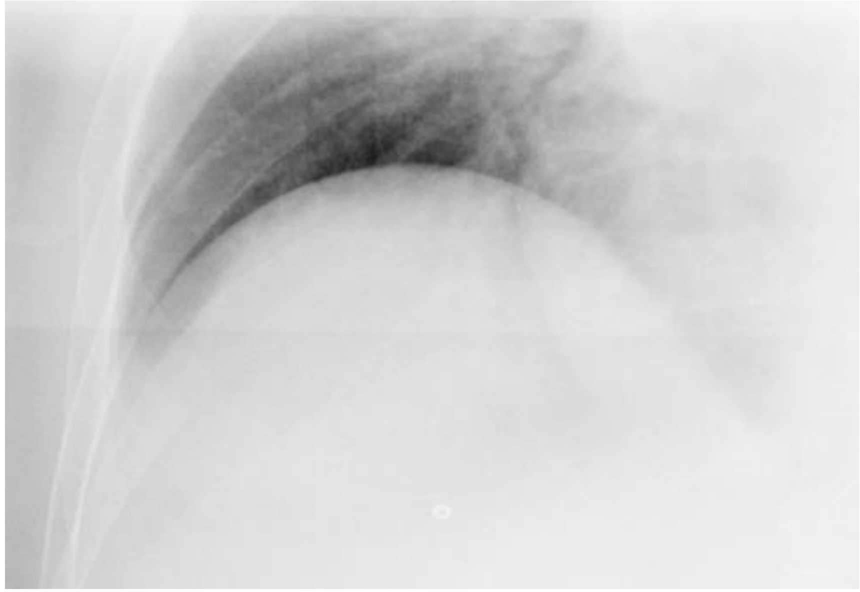


Need for detailed protocol to allow for decision making on a clinical time scale

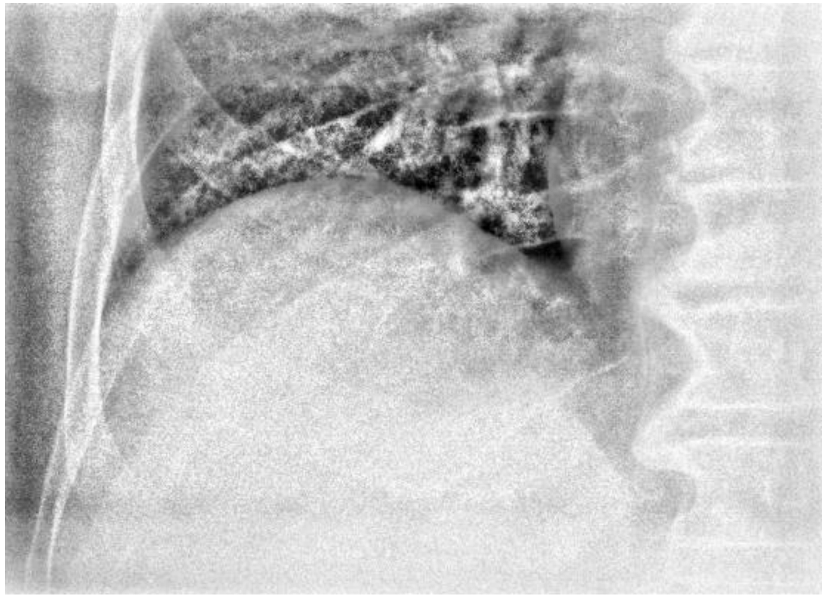
Need to understand the options and decision making criteria

Lets look at a few examples: Exhale breath hold

Reproducible (0.7 mm variation)

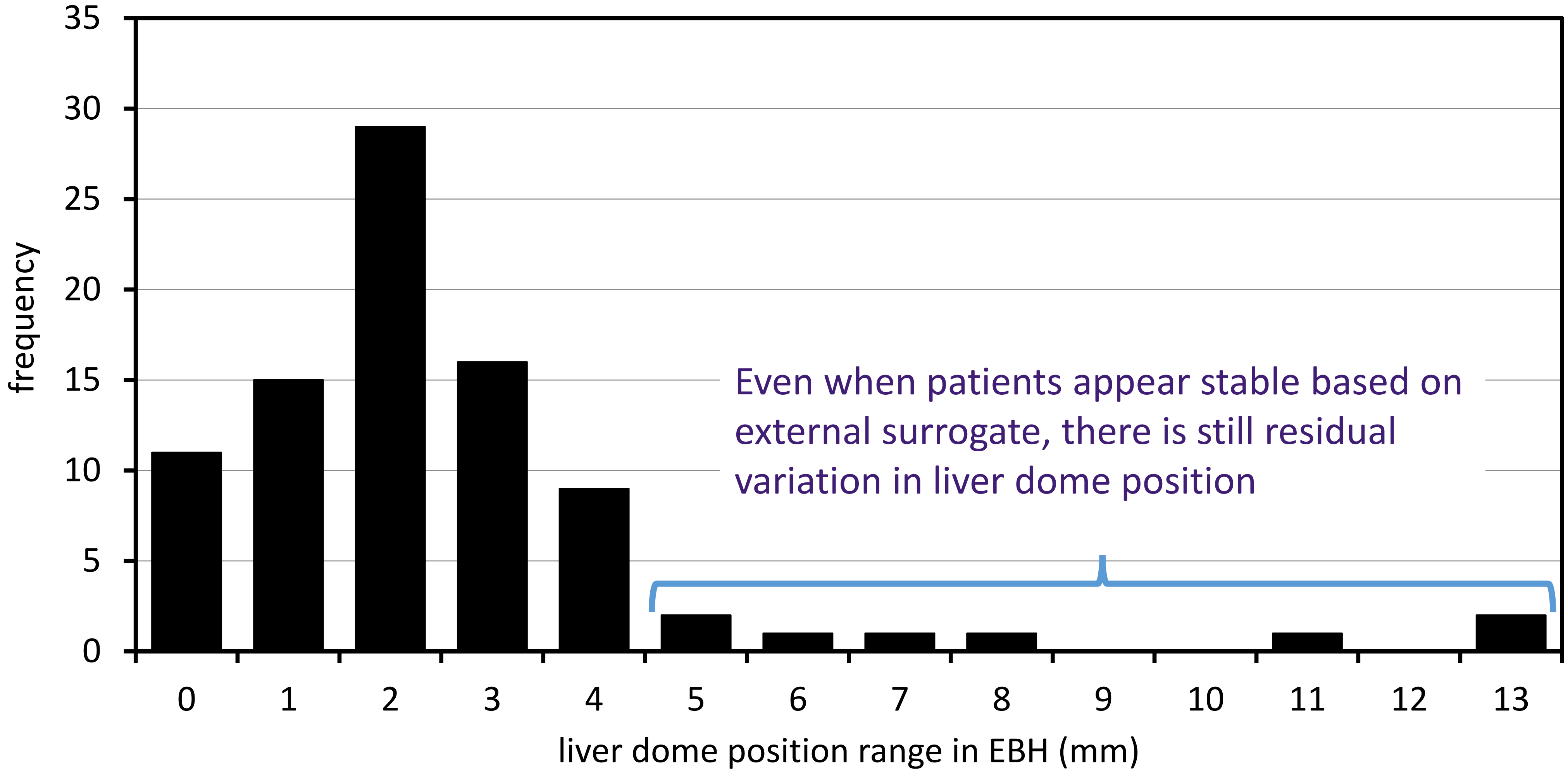


Not reproducible (5.5 mm variation)

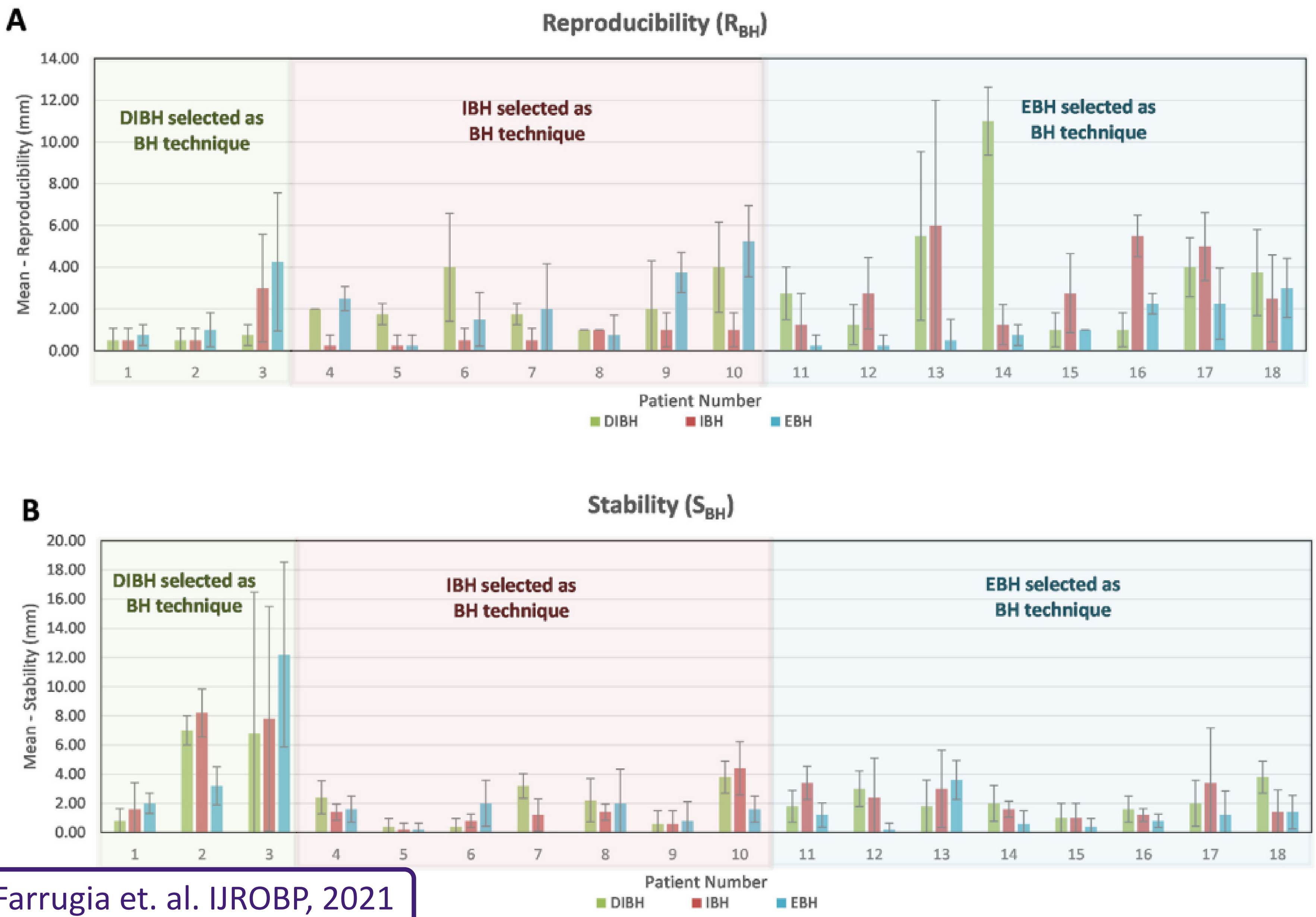


(80 kV, 5 mAs, 7 fps)

How consistent is the liver dome between repeat breath holds?



Inhale or exhale breath hold?



What are you trying to achieve with breath hold?

- Stable anatomy?
- Increased lung volume?
- Reduced treated volume?

What is best for the patient?

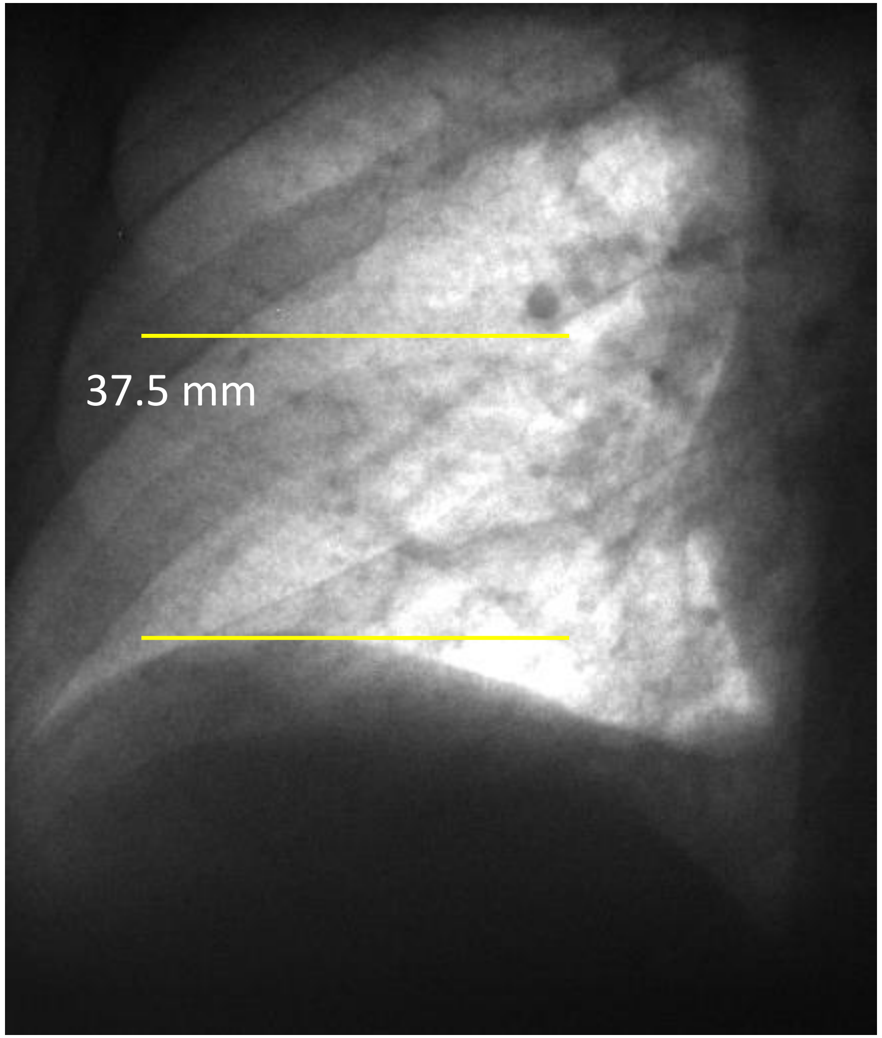
Farrugia et. al. IJROBP, 2021

Abdominal Compression

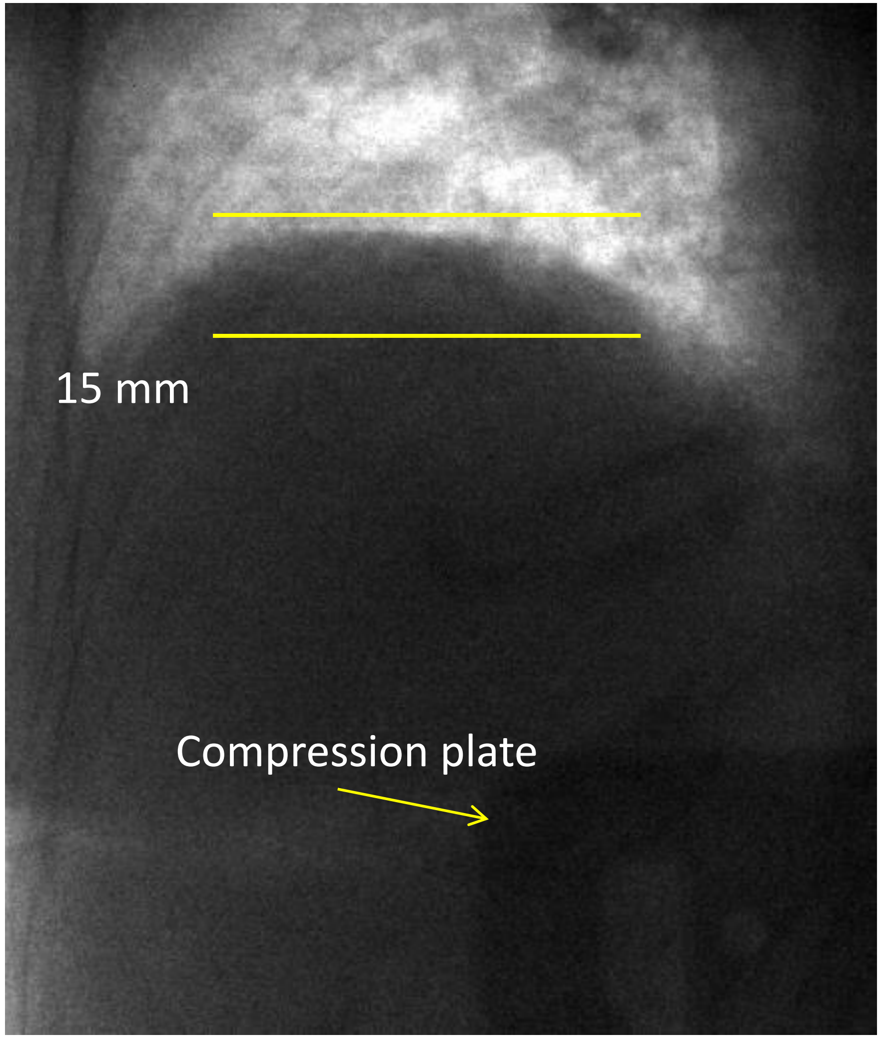
- Abdominal compression of the upper abdomen to physically limit diaphragm motion
- Typically a compression plate or band
- Contraindications are patient comfort, stoma bag
- May limit beam angles
- Reduces, not eliminates motion

Examples: Abdominal Compression

Free breathing

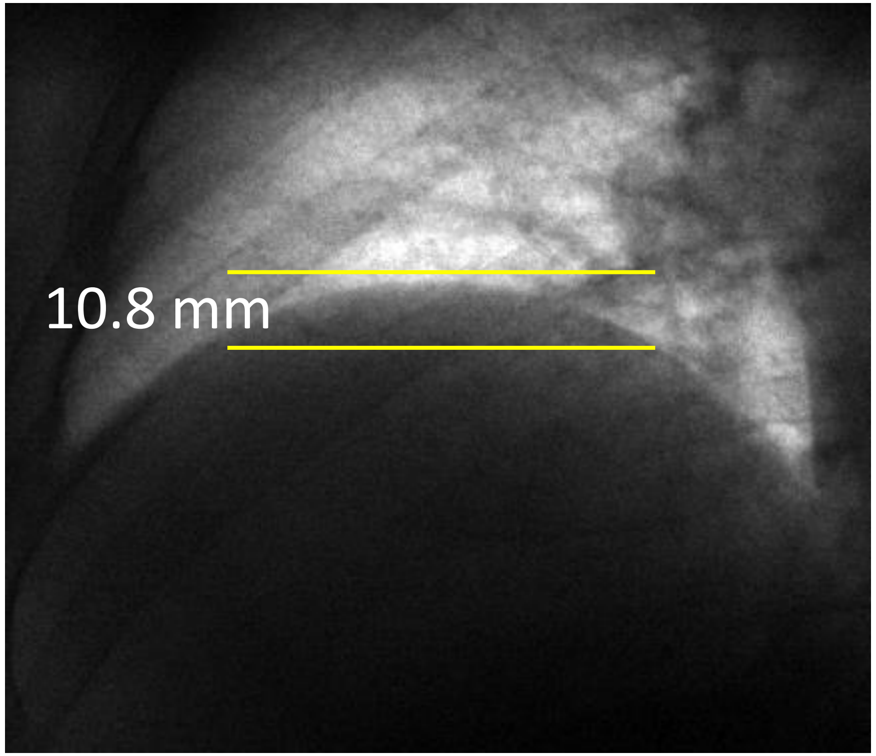


Abdominal compression

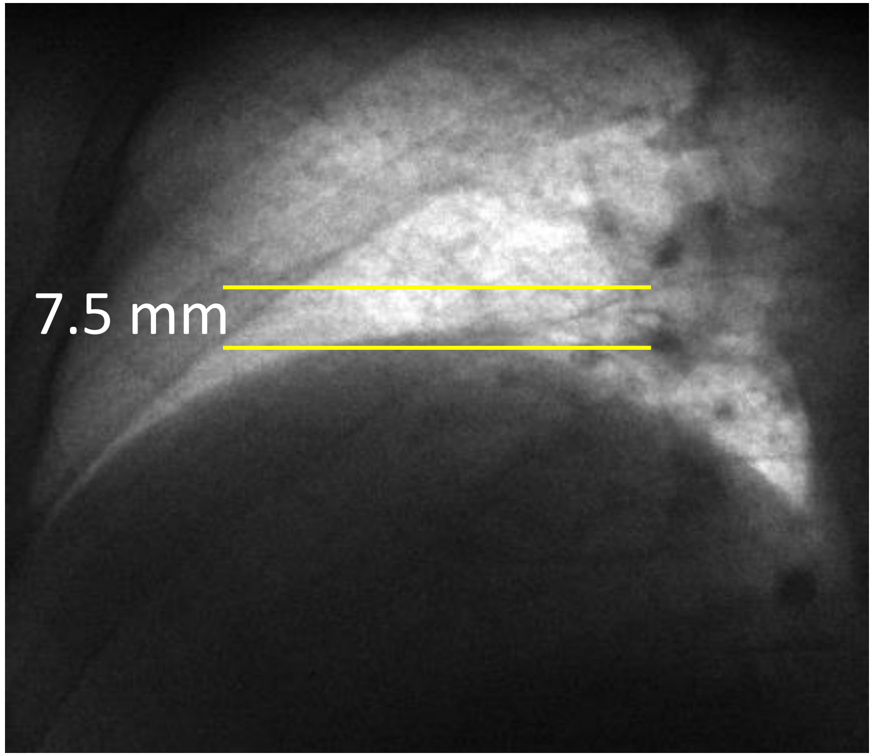


Examples: Abdominal compression

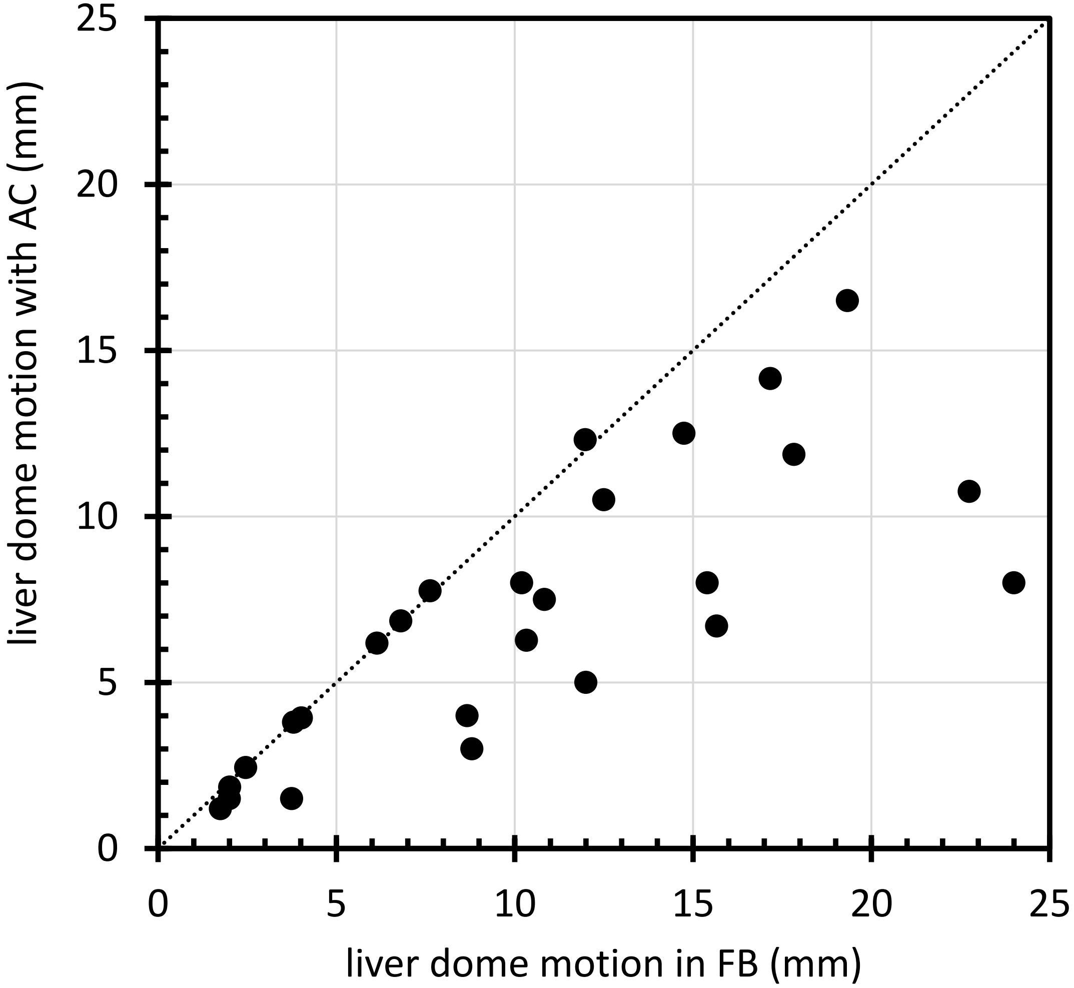
Free breathing



Abdominal compression



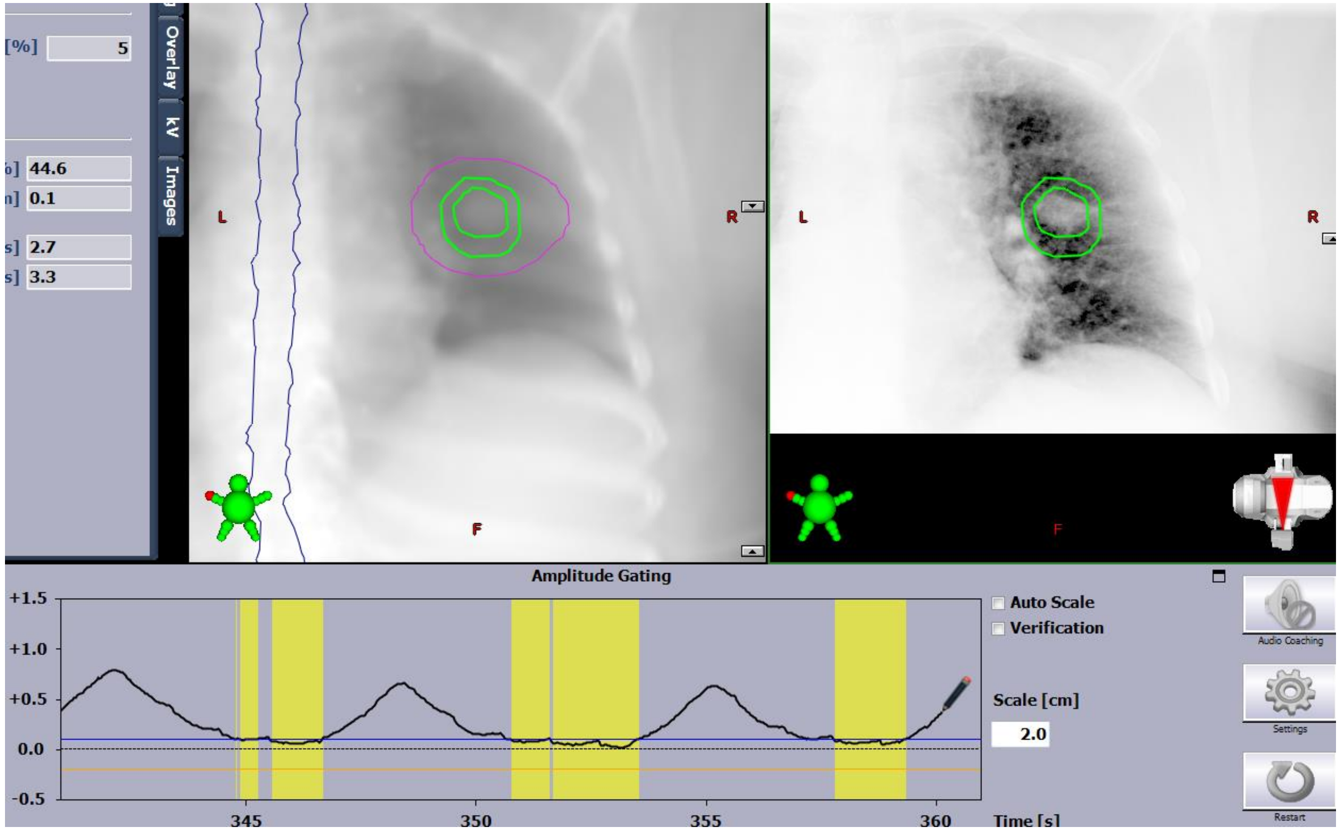
How consistently does abdominal compression work?

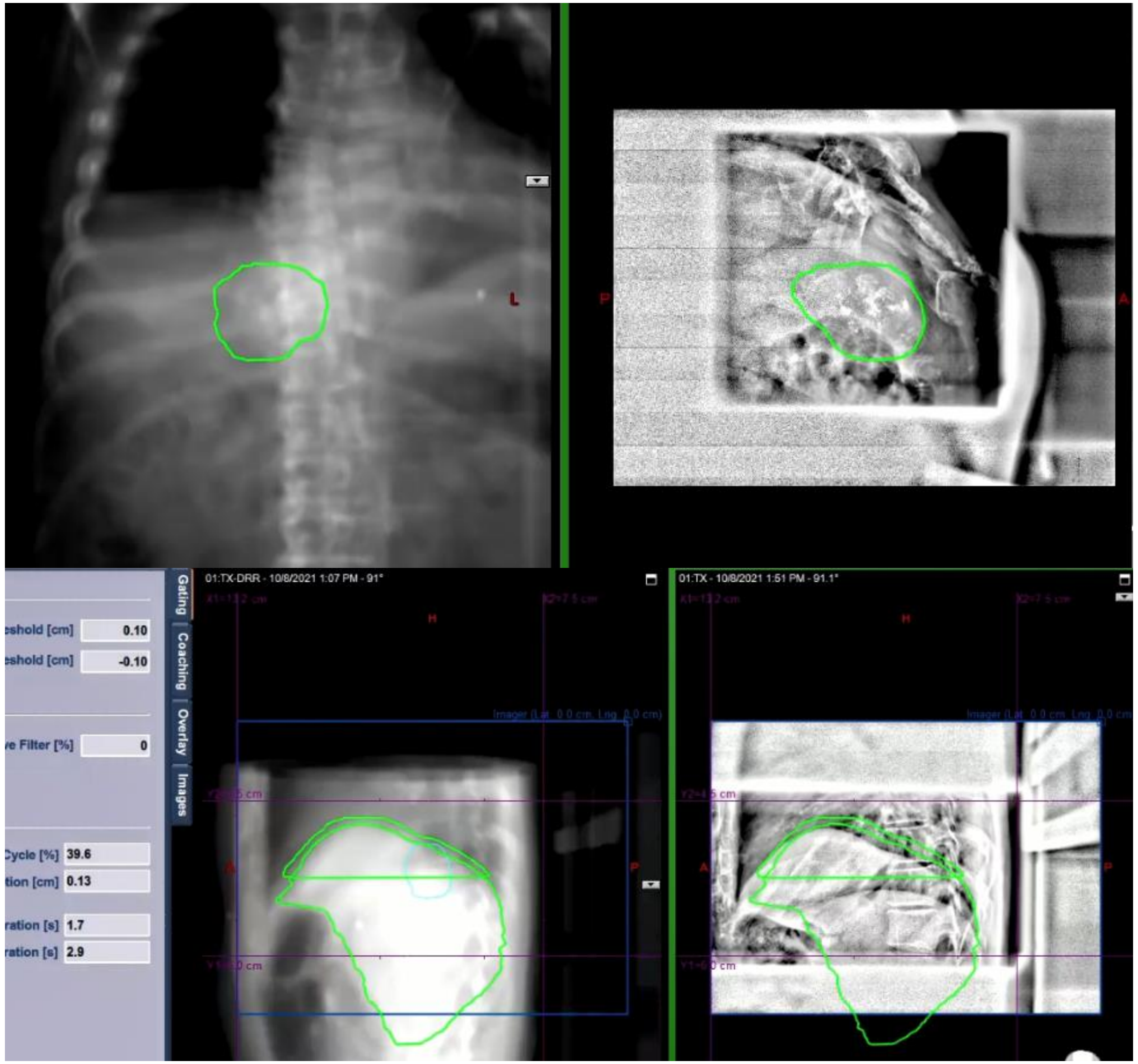


This shows abdominal compression band has limited benefit in a number of patients

-> we need to assess gain with abdominal compression on a per-patient basis

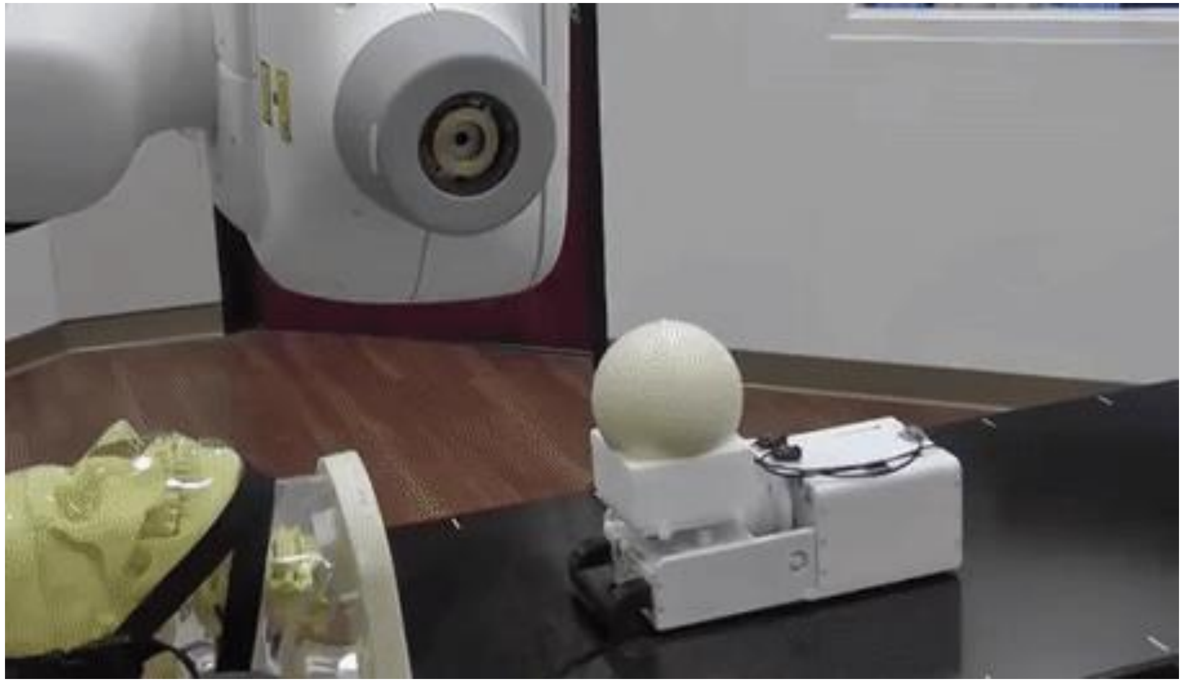
Intrafraction imaging





Planar kV images acquired during beam on, triggered by monitor units, respiratory gating, time, gantry angle

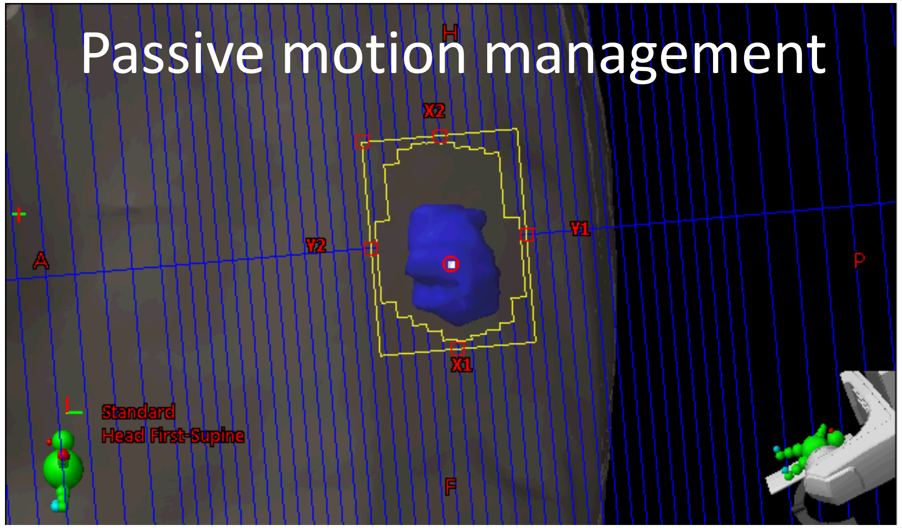
Real-time tracking

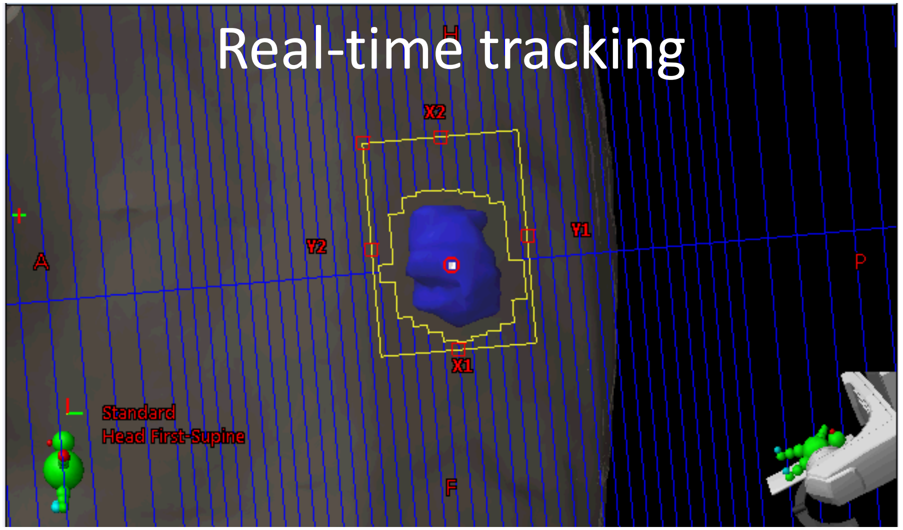


https://www.accuray.com

Real-time tracking

- Patient breathes 'normally', beam is always on and tracks the tumour as it moves
- Requires some signal of where the tumour is in real time, as well as a prediction algorithm
    - Prediction algorithm does better with more reproducible breathing
- Minimal patient preparation required (apart from surrogate e.g. fiducials)
- Effectively removes motion (similar to breath hold), mixed impact on OARs





Received: 2 June 2019 | Revised: 8 December 2019 | Accepted: 26 December 2019
DOI: 10.1002/acm2.12825

RADIATION ONCOLOGY PHYSICS

WILEY

QA?

Independent review of 4DCT scans used for SABR treatment planning

Rachitha Antony[1] | Peta Lonski[1] | Elena Ungureanu[1] | Nicholas Hardcastle[1,2] | Adam Yeo[1] | Shankar Siva[3,4] | Tomas Kron[1,4]

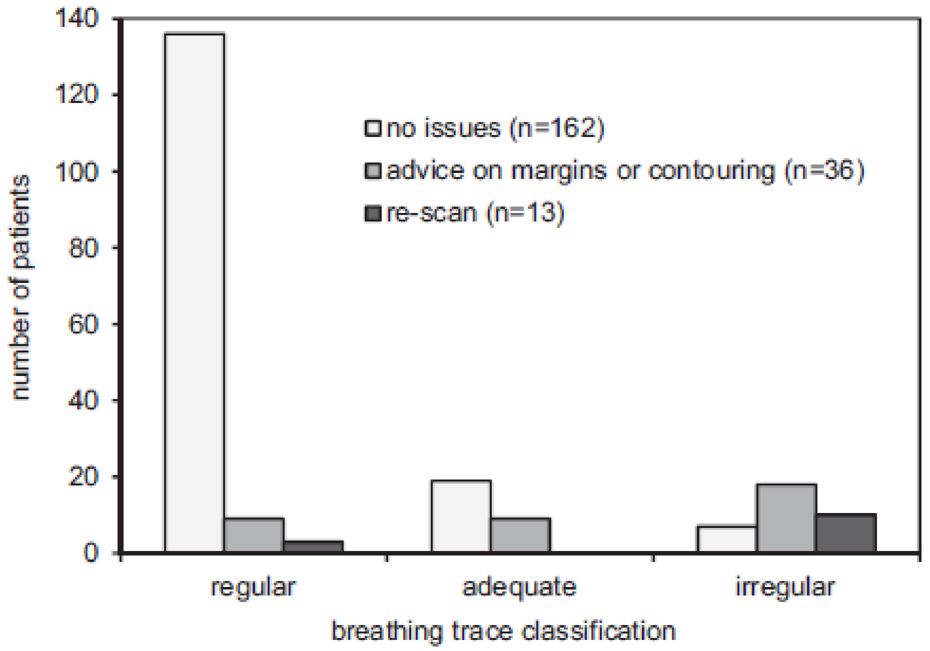
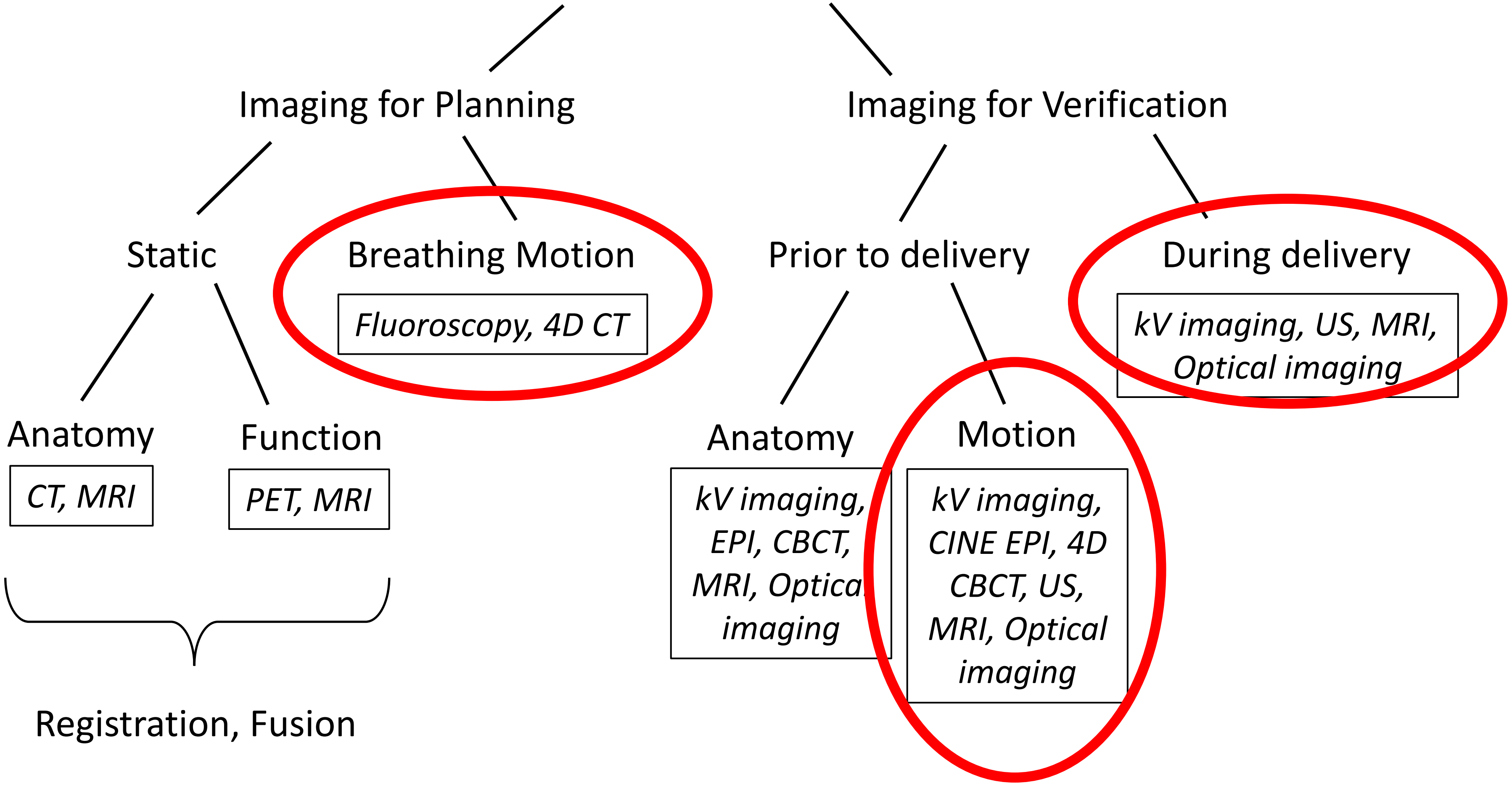


FIG. 2. Distribution of patient breathing traces according to respiratory cycle regularity for 211 SABR patients. Change in patient management as a result of 4DCT review is indicated by the shaded bars. A total of 49 cases (23%) required change in patient management. Of those, 25 (51%) were classified as 'adequate' or 'irregular' breathing

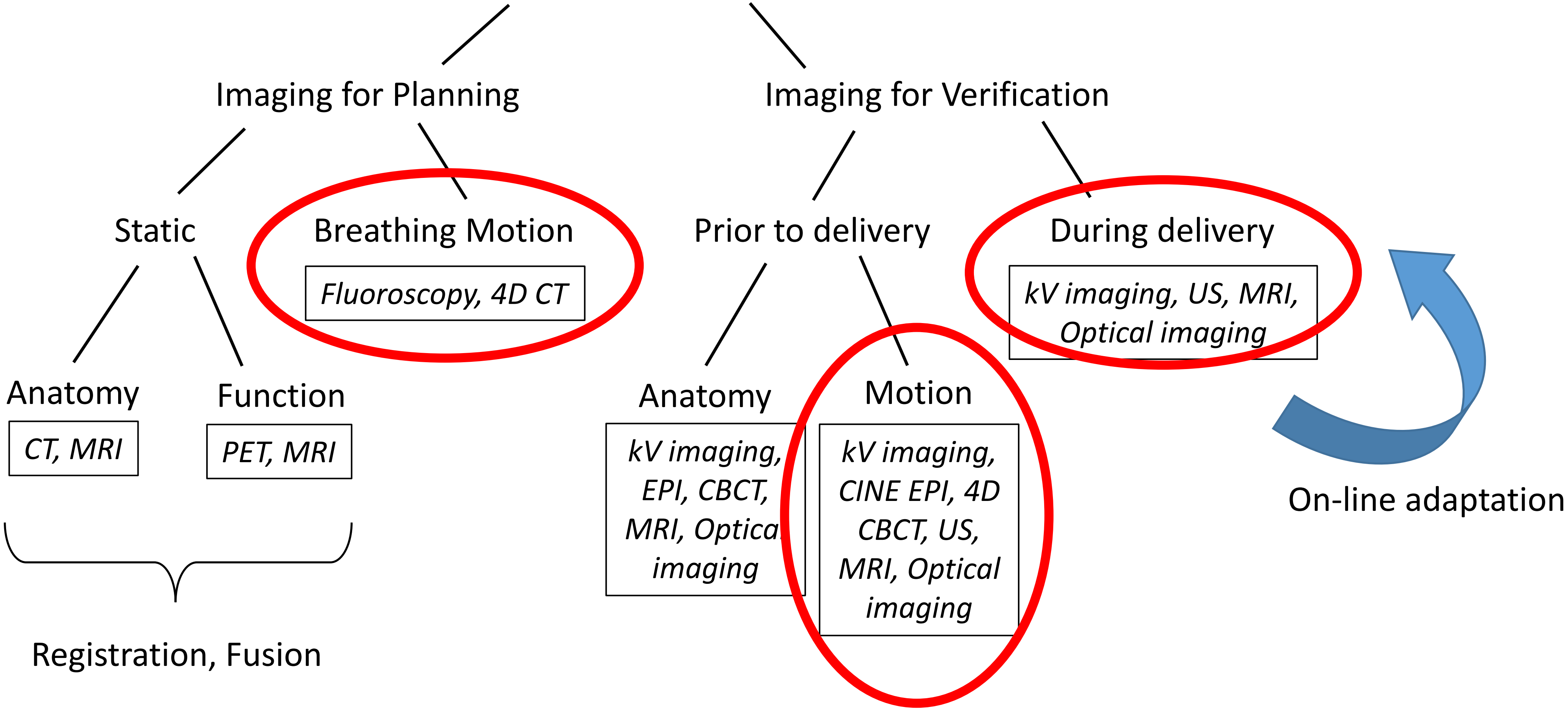
	No issues		Re-scan or advice	
Hysteresis	n	%	n	%
Yes/Slight	41	25	23	48
No	122	75	25	52

Summary: Imaging and Motion in Radiotherapy



Lots of imaging → Radiotherapy Physics needs Imaging Physics

Summary: Imaging and Motion in Radiotherapy



Lots of imaging → Radiotherapy Physics needs Imaging Physics

So many choices – how can we decide

1. Image quality needed
    - 3D, frequency, contrast
2. Dose
3. Time allowed
    - Patient on the couch
    - Changes due to delay
    - Automation (GPU calculation, AI segmentation)
4. Training, experience, documentation
5. **Does it make a difference?**

Motion management – Lung gating

ORIGINAL ARTICLE

Respiratory Gating Techniques for Optimization of Lung Cancer Radiotherapy

Philippe Giraud, MD, PhD,† Esra Morvan, PhD,† Line Claude, MD,‡ Françoise Mornex, MD, PhD,§ Cécile Le Pechoux, MD,‖ Jean-Marc Bachaud, MD,¶ Pierre Boisselier, MD,# Véronique Beckendorf, MD,** Magali Morelle, MD,†† Marie-Odile Carrère, MD, PhD,†† and The STIC Study Centers*

Purpose: The primary objective of the STIC 2003 project was to compare the clinical and economic aspects of respiratory-gated conformal radiotherapy (RGRT), an innovative technique proposed to limit the impact of respiratory movements during irradiation, versus conventional conformal radiotherapy, the reference radiation therapy for lung cancer.

Methods and Materials: A comparative, nonrandomized, multi-center, and prospective cost toxicity analysis was performed in the context of this project between April 2004 and June 2008 in 20 French centers. Only the results of the clinical study are presented here, as the results of the economic assessment have been published previously.

Results: The final results based on 401 evaluable patients confirm the feasibility and good reproducibility of the various RGRT systems. The results of this study demonstrated a marked reduction of dosimetric parameters predictive of pulmonary, cardiac and esophageal toxicity as a result of the various respiratory gating techniques. These dosimetric benefits were mainly observed with deep inspiration breath-hold (DIBH) techniques (ABC and SDX systems), which markedly increased the total lung volume compared with the inspiration-synchronized system based on tidal volume (Real-time Position Management). These theoretical dosimetric benefits were correlated clinically with a significant reduction of pulmonary acute toxicity, and the pulmonary, cardiac, and esophageal late toxicities, especially with DIBH techniques. Pulmonary function parameters, although more heterogeneous, especially DLCO, showed a tendency to reduction of pulmonary toxicity in the RGRT group.

Conclusions: RGRT seems to be essential to reduce toxicities, especially the pulmonary, cardiac, and esophageal late toxicities with the DIBH methods.

Key Words: Non-small cell lung cancer, Respiratory gating, Breath-hold techniques, Toxicities.

(*J Thorac Oncol.* 2011;6: 2058–2068)

Adapting radiotherapy to respiratory movements has always been a major concern in chest radiotherapy. The importance of this aspect has been further accentuated with the development of conformal radiotherapy (CRT), with and without intensity modulation, using reduced irradiation fields, and especially the growing interest in stereotactic hypofractionated radiotherapy.[1] These new techniques were developed very rapidly in the 1990s as a result of progress in information technology, but the various uncertainties of treatment, especially related to respiratory movements, were not studied in detail. Radiotherapists rapidly had to make a number of choices. In the absence of precise data, they incorporated empirical safety margins of 1.5 to 2 cm derived from con-

- Some evidence for reduction in acute pulmonary toxicity when using DIBH techniques in conventional lung
- No high level data demonstrating active motion management reduces toxicity in lung SABR

- We only typically use for select patients
  - Lots of motion (> 20 mm)
  - Multiple lesions
  - Re-irradiation
  - Central (proximity to heart, bronchial tree, oesophagus)
- Mix of free-breathing gating or deep-inspiration breath hold

Giraud P, Journal of Thoracic Oncology, 2011

Motion management - Liver

Andratschke *et al. BMC Cancer* (2018) 18:283
https://doi.org/10.1186/s12885-018-4191-2

BMC Cancer

RESEARCH ARTICLE Open Access

The SBRT database initiative of the German Society for Radiation Oncology (DEGRO): patterns of care and outcome analysis of stereotactic body radiotherapy (SBRT) for liver oligometastases in 474 patients with 623 metastases

N. Andratschke[1*], H. Alheid[2], M. Allgäuer[3], G. Becker[4], O. Blanck[5], J. Boda-Heggemann[6], T. Brunner[7], M. Duma[8], S. Gerum[9], M. Guckenberger[1], G. Hildebrandt[10], R. J. Klement[11], V. Lewitzki[12], C. Ostheimer[13], A. Papachristofilou[14], C. Petersen[15], T. Schneider[16], R. Semrau[17], S. Wachter[18] and D. Habermehl[19]

"Local control for metastases treated with advanced motion management methods defined as either gating (active breathing control; free breathing gating) or tracking (fiducial based) was significantly higher compared to methods relying on target localization during free breathing, including CBCT based strategies"

- Liver SABR follows an isotoxic prescription
  - More motion = larger target volume = more liver dose = lower tumour dose
- If we remove motion, we reduce our treated volume:

'active' motion management in all liver cases

Key take home messages

- Motion management requires imaging
- Effective motion management starts in treatment planning
- Radiotherapy is a 4D problem and CT is a good starting point
- Patient involvement is essential for most motion management strategies (comfort, breath hold, regular breathing, …)
- Medical physicists have the skills and competence required to support and lead motion management in radiotherapy

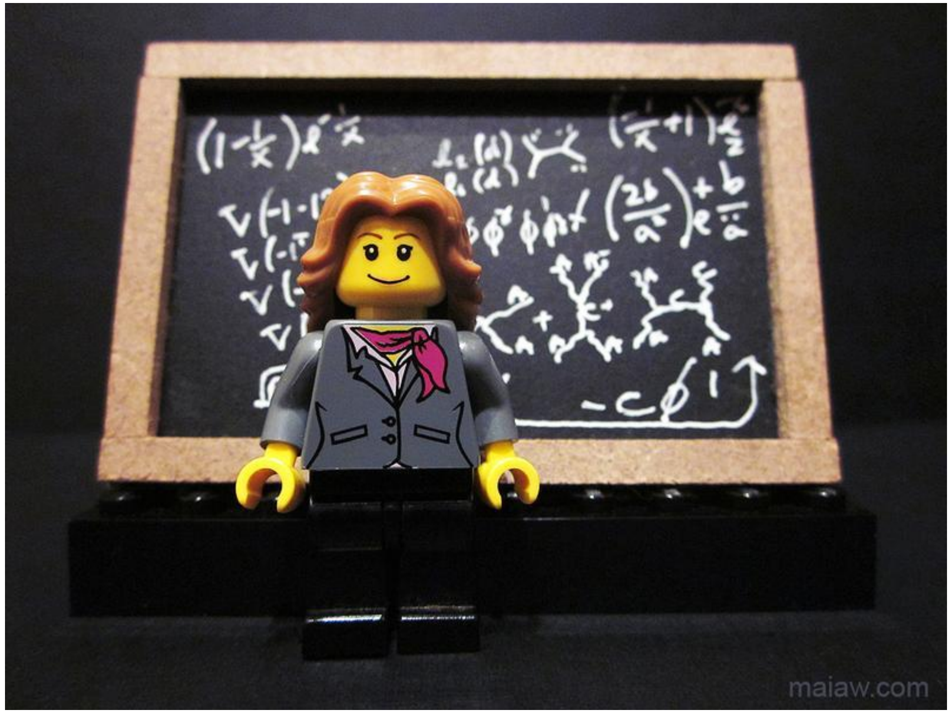
Modern Radiotherapy – the effort is worth it and physicists are an integral part of it

1960s	Fixed SSD RT		Hand planning
1970s	Isocentric RT	better set-up	Computer planning
1980s	Conformal RT	better targeting	3D planning
1990s	Stereotactic RT	more beams	inverse planning
2000s	IMRT, VMAT	better sparing	4D planning
2010s	IGRT, Motion management	better and more frequent personalization	Fast computer assisted (AI) based adaptive re-planning
2020s	Adaptive RT		

Complexity, quality, need for QA

Need for computers and physics input

Thank you – happy to answer questions



… and thanks to many colleagues from all disciplines in radiation oncology and medical imaging

What is the goal of motion management?

- Ensure target is irradiated as it moves during respiration
- Reduction of respiratory motion to reduce treated volume
- Reduction of respiratory motion to avoid adjacent critical organs
- Movement of the target away from adjacent critical organs or previously treated regions
- Improved visualisation of the tumour at time of treatment