THORACIC RADIOTHERAPY: PRINCIPLES, SCOPES, AND CHALLENGES

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Introduction

- Cornerstone in managing chest and lung malignancies.
- It targets and destroys cancer cells through high-energy radiation, either as a curative treatment or for palliative symptom relief.
- It demands **high precision due to critical surrounding structures**.
- Thoracic radiotherapy (RT) is a vital treatment for chest malignancies like **lung cancer and esophageal tumors**.
- The primary scope is **tumor eradication and local control**.
- Main challenges involve **sparing healthy, moving organs** (heart, lungs, and esophagus) and managing severe, dose-limiting toxicities.

The Principles

- Tumor Control: TRT reduces local failure rates, especially in conditions like small cell lung cancer (SCLC) and non-small cell lung cancer (NSCLC) etc.
- Radiobiology: TRT relies on the radiobiological principles of destroying cancerous DNA while allowing healthy tissues to repair.
- Multimodal Integration: Modern TRT is rarely used in isolation. It is typically combined with chemotherapy, targeted therapies, or immunotherapies to achieve maximum efficacy.

Types of Thoracic Tumors Treated

- Lung Cancer
  - Non-Small Cell Lung Cancer (NSCLC)
  - Small Cell Lung Cancer (SCLC)
- Esophageal Cancer
- Mediastinal Tumor
  - Pleural Tumors
- Thymoma and Thymic Carcinoma
- Lymphoma

- Curative Intent
  - Radical Radiotherapy
  - Stereotactic Body Radiotherapy (SBRT)
- Adjuvant Therapy
- Neoadjuvant Therapy
- Palliative Care

Clinical Scope

- Modern technical advancements have expanded the therapeutic scope of thoracic radiotherapy across multiple clinical presentations.
- **Definitive Cure**: Used as primary therapy for locally advanced or inoperable non-small cell lung cancer (NSCLC)
- **Neo-Adjuvant/Adjuvant**: Administered before or after surgery to shrink masses or destroy residual cancer cells
- **Stereotactic Ablation (SABR/SBRT)**: Delivers high-dose focal radiation to early-stage, medically inoperable solid tumors with near-surgical precision.

Clinical Scope

- **Oligometastatic Disease**: Targets limited metastatic spreads to halt progression and delay standard systemic treatments.
- **Palliative Care**: Rapidly relieves distressing local symptoms like severe pain, superior vena cava syndrome, hemoptysis, or profound dyspnea.

- **Definitive Treatment (Non-Surgical Cure)**
  - For patients who cannot undergo surgery due to the location of the tumor or underlying health issues (like severe heart or lung disease), radiation is used as the primary curative option
- **Early-Stage Lung Cancer (Stage I/II)**
  - Stereotactic Body Radiotherapy (SBRT) delivers highly concentrated, pinpoint doses of radiation over 1 to 5 sessions.
  - local tumor control rates of over 90%, comparable to surgery.
- **Locally Advanced Lung Cancer (Stage III)**
  - The clinical standard is **concurrent chemoradiotherapy**.
  - Radiation is delivered in standard daily fractions up to a total dose of **60 Gray (Gy)** while the patient receives chemotherapy, often followed by consolidation immunotherapy

- **Neoadjuvant Therapy (Before Surgery)**
  - In borderline-resectable thoracic tumors, radiation is combined with chemotherapy prior to surgery.
- **Esophageal Cancer**
  - Preoperative chemoradiotherapy (often following the CROSS regimen protocol).
- **Superior Sulcus (Pancoast) Tumors**
  - Radiation shrinks these aggressive lung tumors located at the very top apex of the lungs, pulling the mass away from critical nerves and blood vessels to allow for safe surgical removal.

- **Consolidation chemotherapy**
  - ***Hodgkins***
  - ***NHL***

Adjuvant Therapy (After Surgery)

- Postoperative radiotherapy (PORT) is used selectively to destroy any microscopic cancer cells left behind.
- **Positive Margins**: It is strongly recommended if surgical pathology reveals cancer cells at the edge of the removed tissue (R1 or R2 resections).
- **Thymomas and Mediastinal Tumors**: Used after incomplete surgical removal of thymic malignancies to prevent local recurrence in the chest cavity.

Note: PORT is generally avoided in completely resected (R0), node-negative early-stage lung cancer because it does not provide a survival benefit and poses risks to healthy lung tissue.

Techniques

- 3D Conformal Radiotherapy (3D-CRT)
- Intensity-Modulated Radiotherapy (IMRT) / VMAT
- Image-Guided Radiotherapy (IGRT)
- Proton Therapy
- SBRT

Technological Precision

- Intensity-Modulated Radiation Therapy (IMRT) and Image-Guided Radiation Therapy (IGRT)
  - Escalate tumor doses
  - Conforming to irregular shapes
  - Avoiding adjacent healthy tissues

Major Challenges

- The anatomic configuration of the chest presents unique physical and biological barriers.
  - **Respiratory Motion**: Tumors move constantly during breathing cycles, making precise targeting elusive.
  - **Organ Toxicity (OARs)**: Protecting critical organs at risk like the esophagus and heart remains a priority to prevent radiation-induced esophagitis and radiation induced heart disease
  - **Pulmonary Function Loss**: Many thoracic patients have poor baseline lung capacities from smoking or underlying disease, compounding the risk of radiation pneumonitis.

- ^{68}Gallium V/Q lung PET/CT or Tc – 99m MAA imaging offers a potential to increase the accuracy of lung functional mapping and to better tailor lung radiation therapy plans to the individual's lung function.
- Lung PET/CT imaging may also improve our understanding of radiation induced lung injury compared to the current anatomical based dose–volume constraints.

- **Anatomical Inhomogeneity**: Radiation beams must penetrate complex transitions between air, bone, and soft tissue.
- **Reirradiation Guideline Gaps**: Retreating recurring cancers within previously irradiated margins lacks standardized clinical guidelines and software tools

Motion reasons

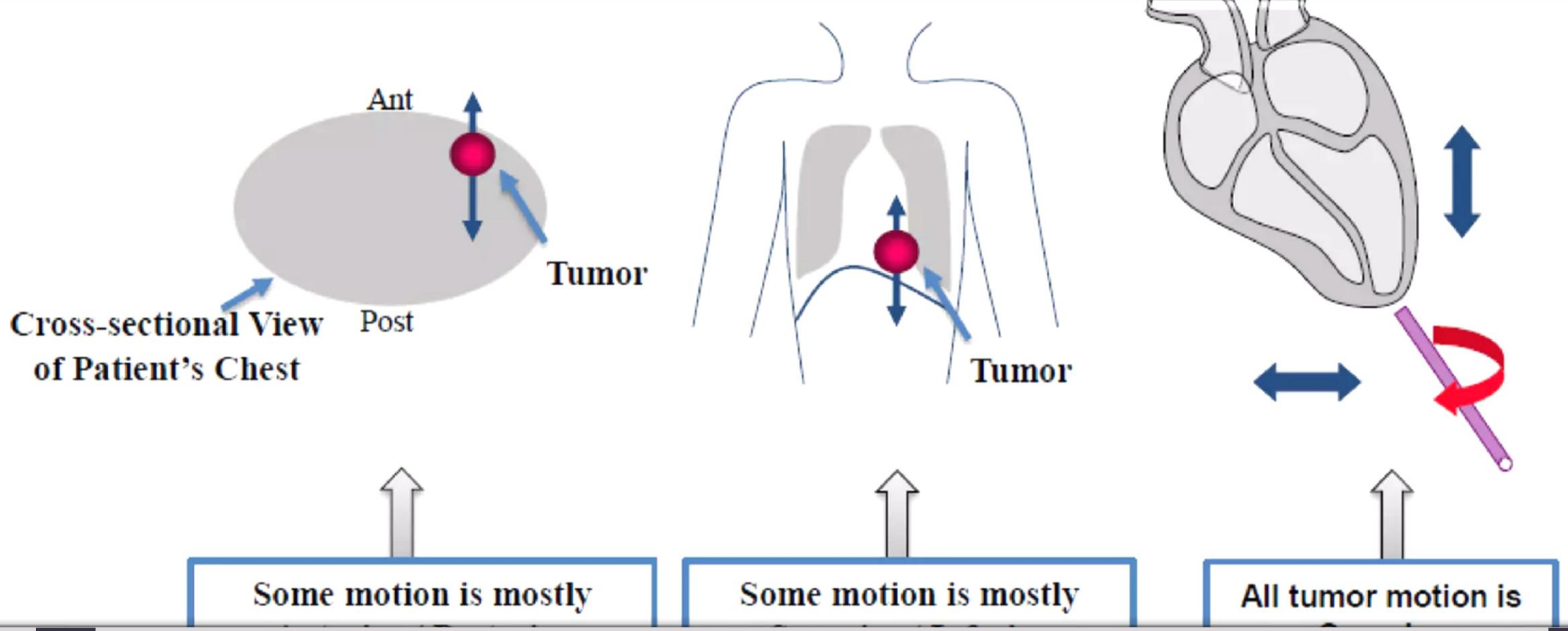
Motion in Radiotherapy

- **Motion:** Anything that may lead to mismatch between the intended and actual location of delivered radiation dose.

- **Intra-fraction motion**
  – during the fraction
  - ✓ Heartbeat
  - ✓ Swallowing
  - ✓ Coughing
  - ✓ Eye movement

- **Inter-fraction motion**
  - in between the fractions
  - ✓ Tumor change
  - ✓ Weight gain/loss
  - ✓ Positioning deviation

- ✓ **Breathing**
  - ✓ Bowel and rectal filling
  - ✓ Bladder filling
  - ✓ Muscle relaxation/tension



TUMOR MOTION DURING RESPIRATION

How much does it move

- The lung is attached to the diaphragm + chest wall. With every breath
  - *Diaphragm moves 1-2 cm*
  - *Chest wall expands*
  - *Tumor + normal lung + OARs all move together*

Location	Typical Motion	Direction
Lower Lobe	1 - 3 cm	Mostly SI
Middle lobe	0.5– 1.5 cm	SI > AP> LR
Upper lobe	0.3 – 0.8 cm	Least motion
Mediastinal nodes	0.2 – 0.5 cm	Very little
Diaphgram	1.5 – 2.5 cm	SI

Problems caused during motion

- Geographical miss : Tumor moves out of beam → underdose → local failure
- OAR overdose : Cord, heart, esophagus move into high-dose region
- Dose blurring: With IMRT/VMAT, moving target smears the dose distribution
- Interplay effect: With VMAT + MLC moving, tumor motion can create hot/cold spots

How we asses motion

- 4D-CT - CT taken over full breathing cycle. Gives 10 phases. ITV is done
- Fluoroscopy - Real-time X-ray to watch tumor motion amplitude
- Fiducials + X-ray Gold seeds in/near tumor - Track on KV imaging
- Surface tracking RPM, AlignRT - camera tracks chest wall motion

Output - ITV = CTV + motion margin. Then add 0.5-0.7cm for setup = PTV

Coughing – add another 1 cm

Motion management

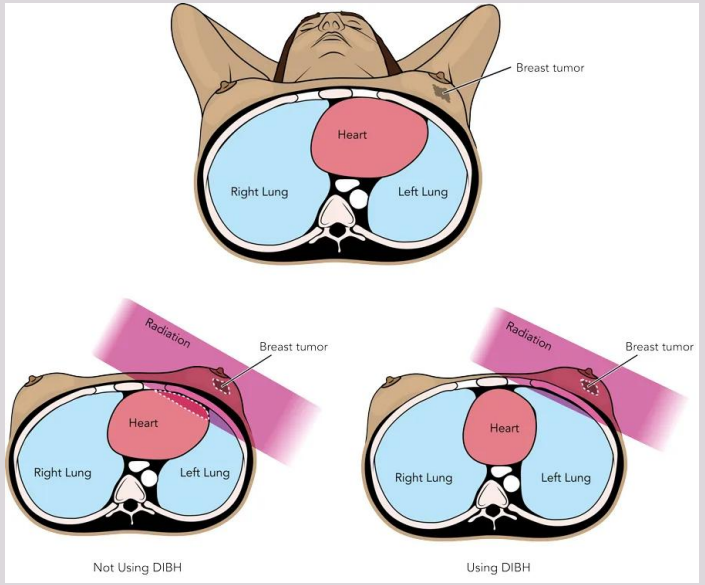
- Why
- Tumor displacement exceeds 5 mm to prevent systematic targeting errors and imaging artifacts

Motion management

- Motion management in thoracic tumors mitigates respiratory movement during radiation therapy.
- Clinicians use 4D-CT imaging to map tumor.
  - *Apply specific strategies*
    - deep-inspiration breath-holds,
    - respiratory gating,
    - tumor tracking,
    - physical compression—to accurately target the tumor while sparing healthy lung and heart tissue

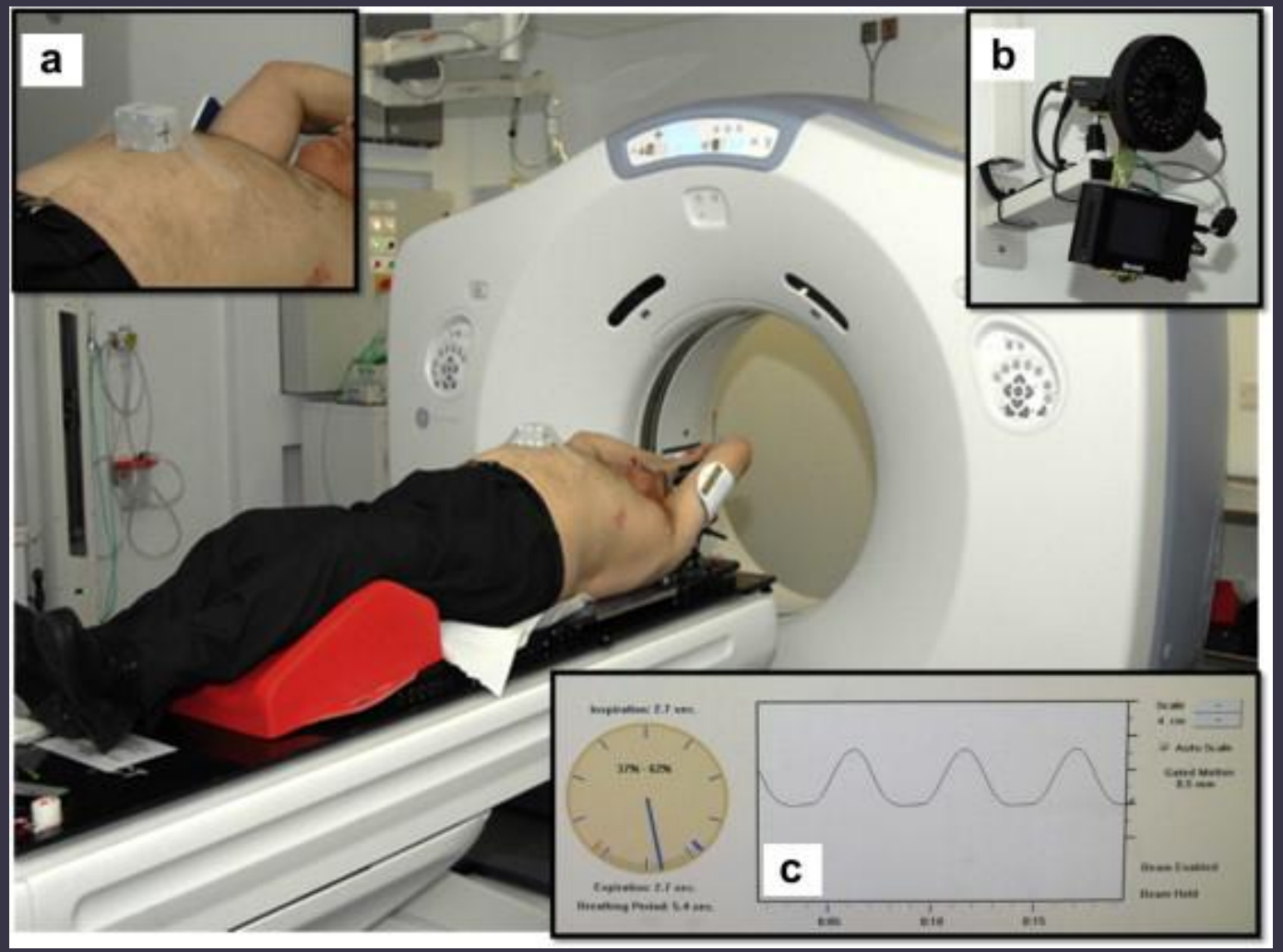
Breath-Hold (BH) Techniques

- **Mechanism:** Patients hold their breath at a reproducible point (usually deep inspiration) while the radiation beam is on.
- **Benefit:** Reduces diaphragmatic motion and immobilizes the tumor, allowing for tighter treatment margins.
- **Application:** Ideal for patients with adequate lung capacity who can consistently follow breath-holding commands.
- Patient holds breath for 20s. Reproducible, also spares heart in left lung/breast



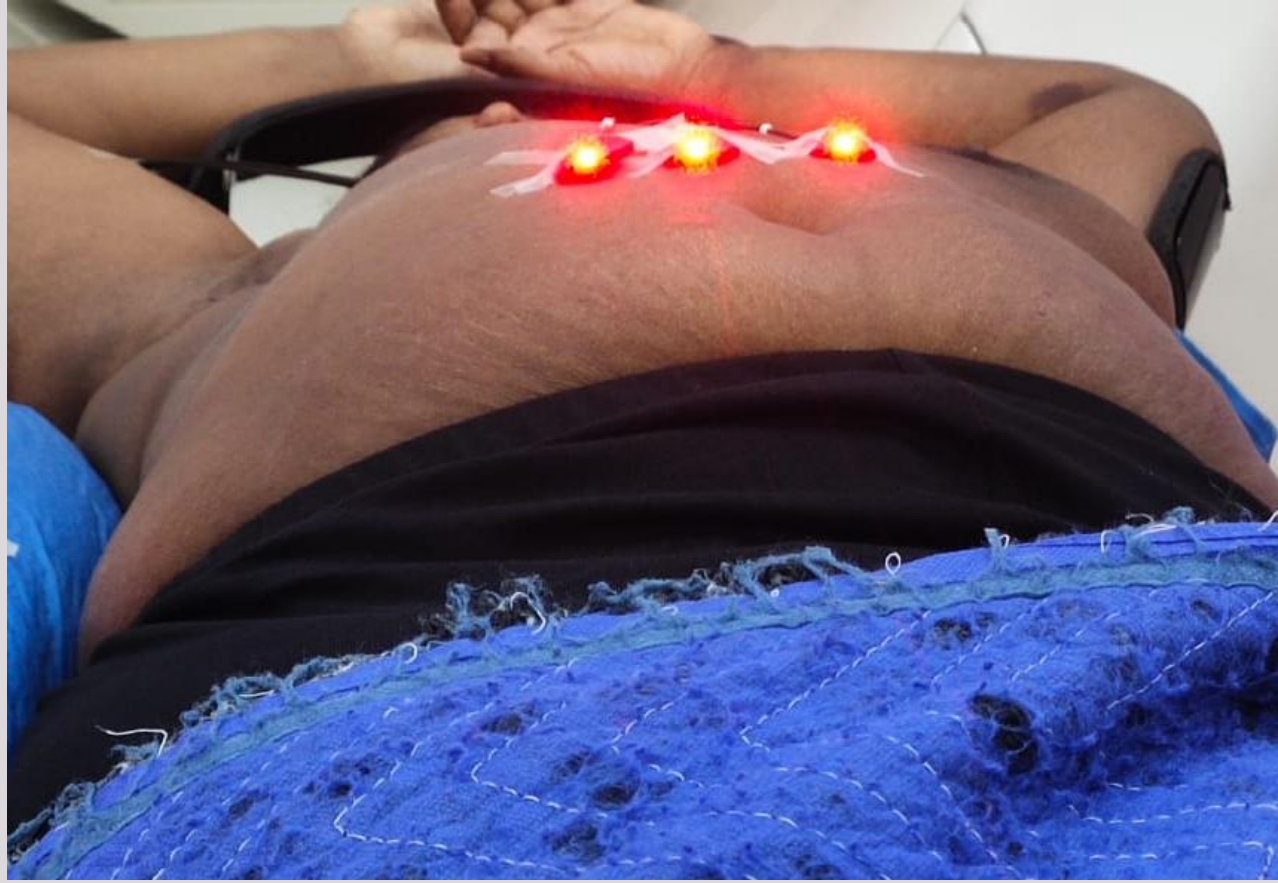
Respiratory Gating

- **Mechanism:** Tracks the patient's breathing cycle using external markers or internal surrogates. The radiation beam only turns on when the tumor is in the targeted "gate" (usually at the end of exhalation).
- **Application:** Suitable for patients with irregular breathing patterns or those unable to comfortably hold their breath for extended periods.
- Respiratory Gating: Beam ON only during 30-50% of breathing cycle, usually end-exhale. Beam OFF when tumor moves out.
- Adds 2-3x to treatment time.

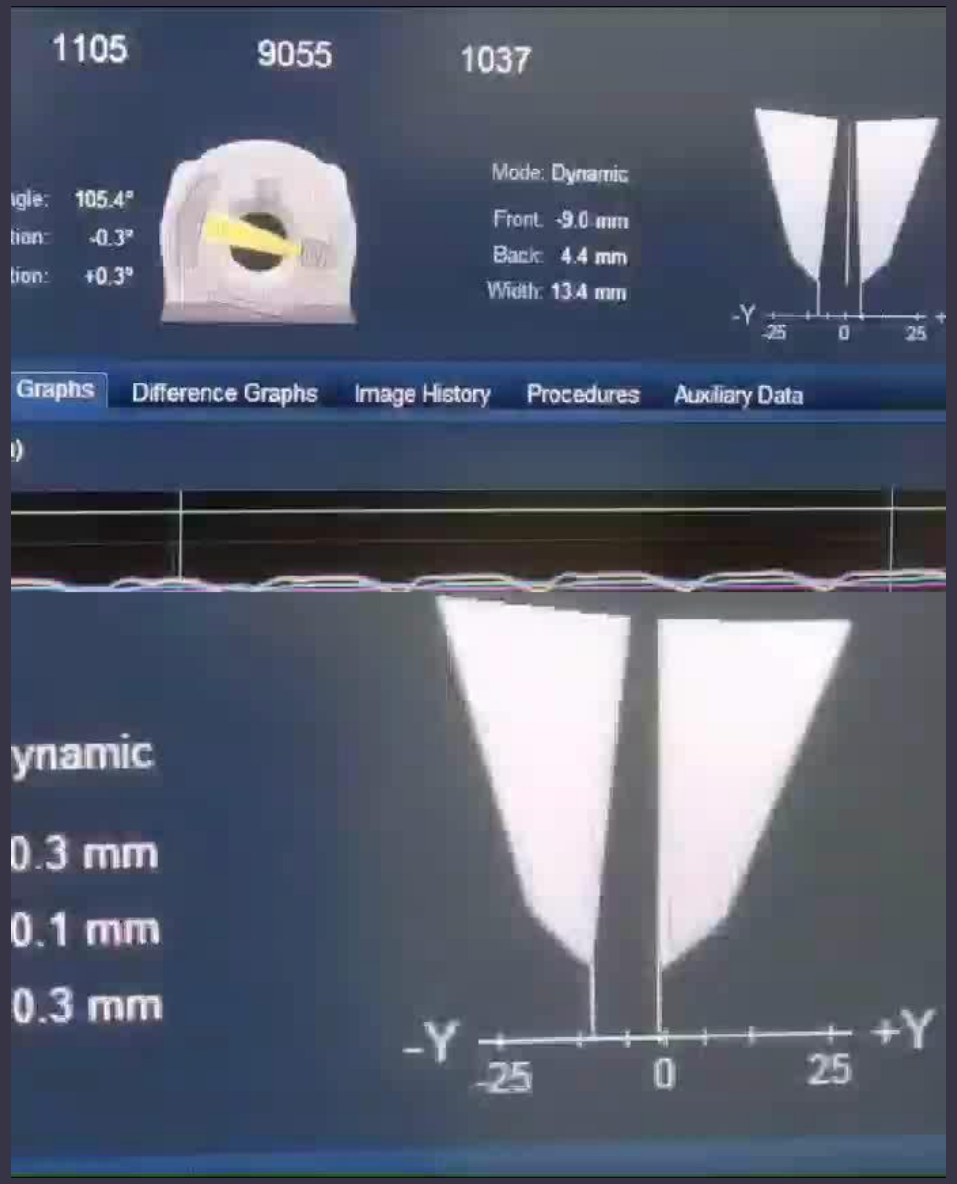


Real-Time Tumor Tracking

- **Mechanism:** Uses advanced Image-Guided Radiation Therapy (IGRT) to continually monitor the tumor's location. The multi-leaf collimator (MLC) dynamically moves to follow the tumor's exact path.
- **Benefit:** Allows for maximum normal tissue preservation without requiring the patient to restrict their natural breathing



LED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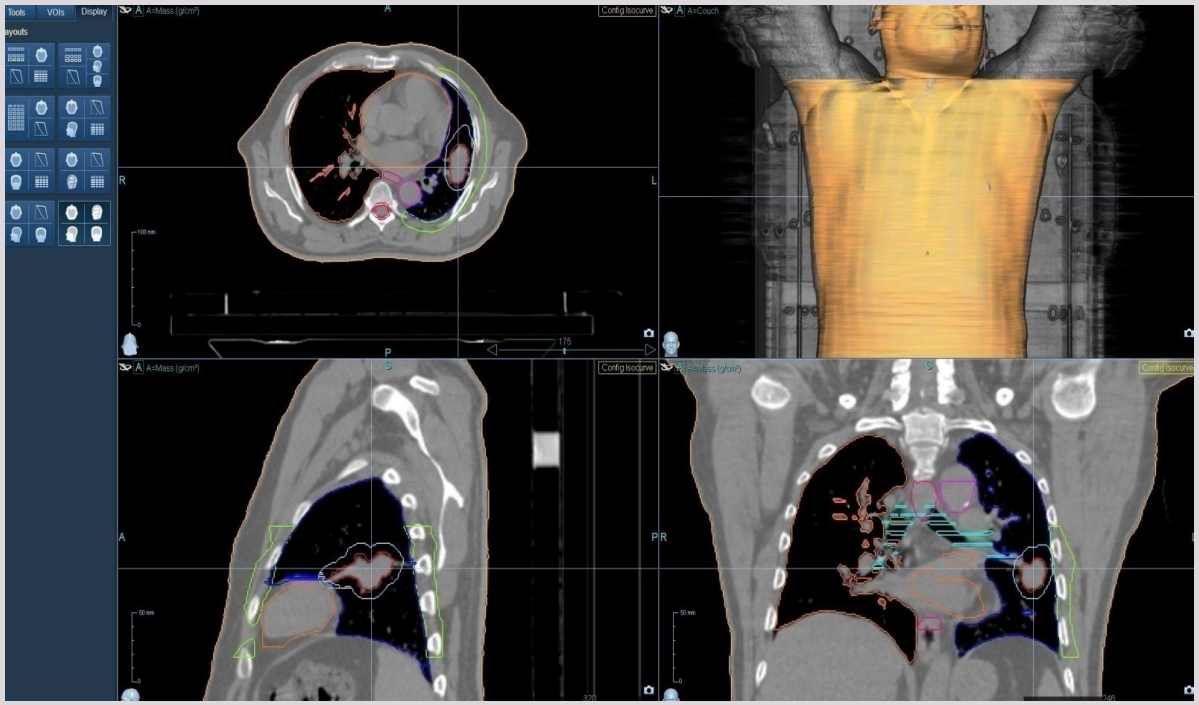
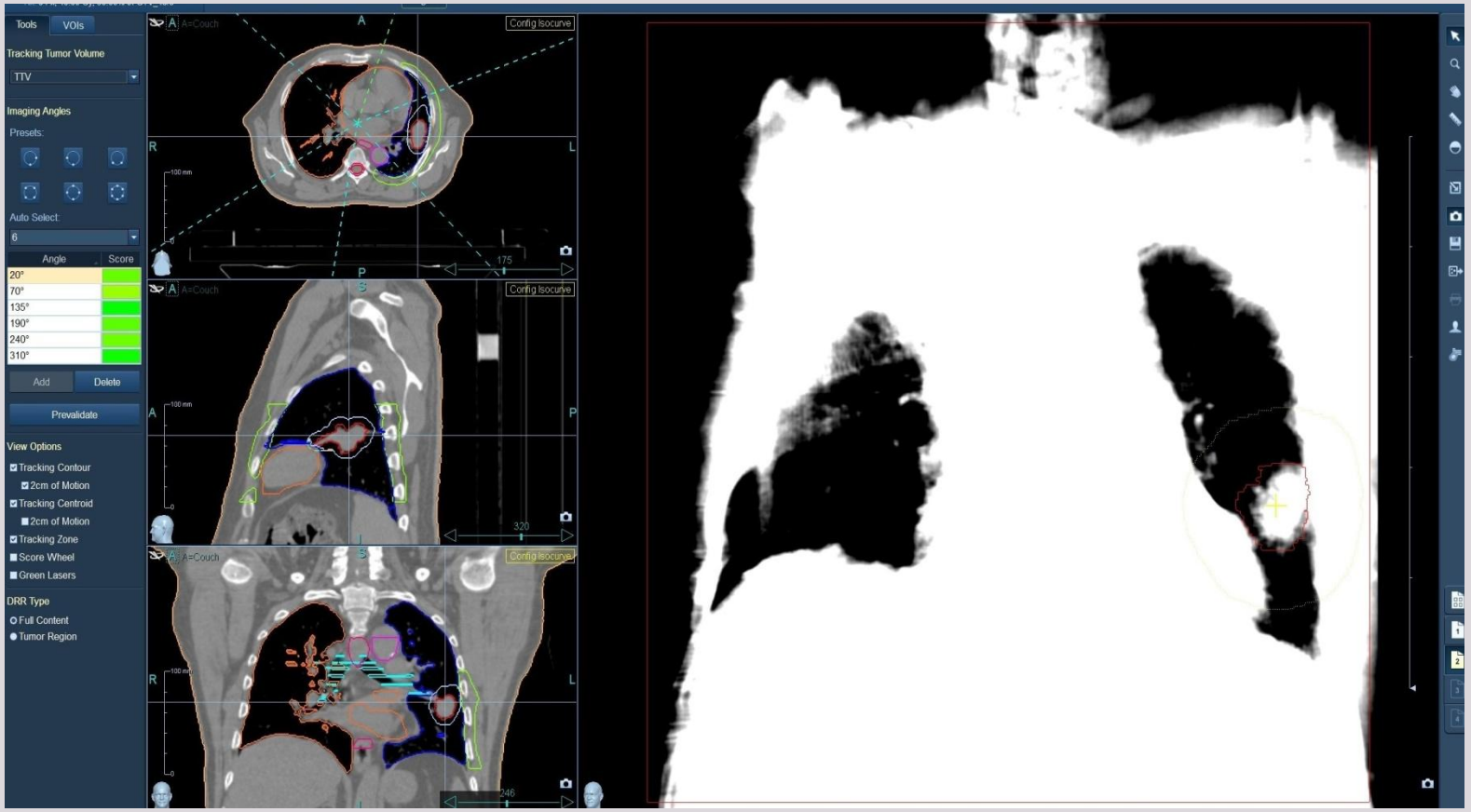
CONSOLE



SYNCHRONY PLANNING LUNG CA


Tools
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Tracking Centroid
2cm of Motion
Tracking Zone
Score Wheel
Green Lasers
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Tumor Region
Config Isocurve
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Abdominal Compression (AC)

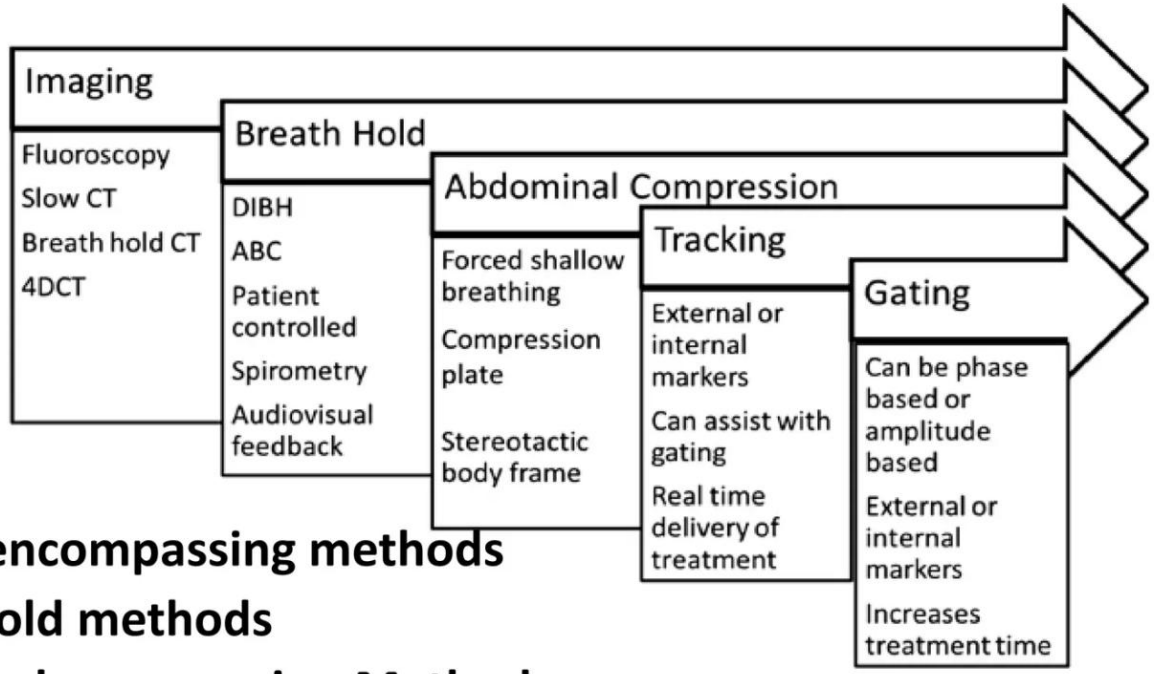
- **Mechanism:** A custom belt or stereotactic body frame exerts gentle, controlled pressure on the abdomen to restrict diaphragmatic movement.
- **Benefit:** Physically dampens the superior-inferior (up and down) respiratory movement of tumors, making them easier to target.
- Belt on abdomen. Cuts SI motion by 50%. Uncomfortable

Motion-Inclusive (Free Breathing)

- **Mechanism:** If motion is minimal (<5 mm), a larger Internal Target Volume (ITV) is mapped to encompass the entire range of tumor motion during normal breathing.
- **Benefit:** No complex patient training or active gating devices are required, though it inherently irradiates a slightly larger margin of healthy tissue.

COMPARISON OF MOTION MANAGEMENT SYSTEM WITH SYNCHRONY

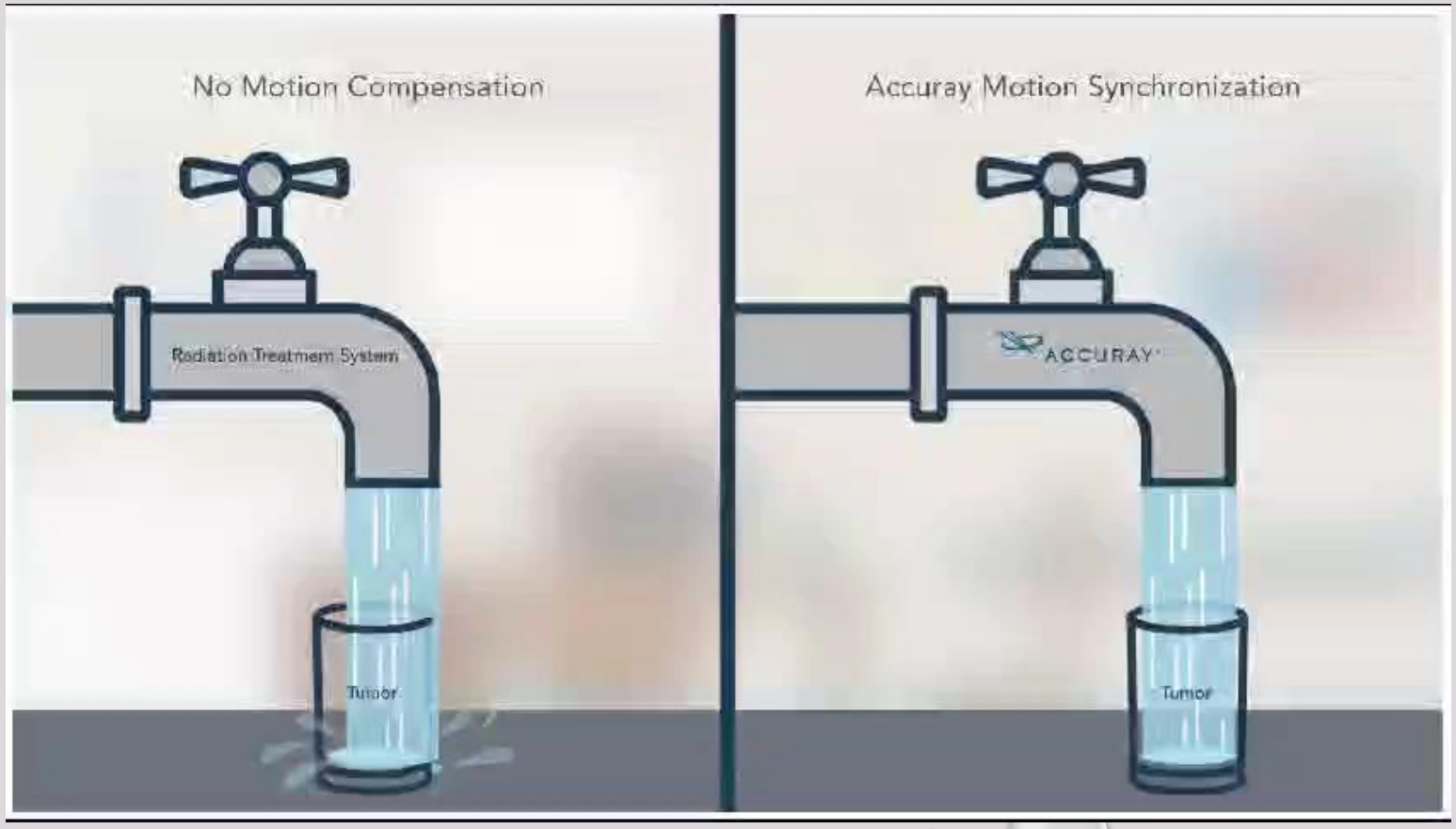
Modern Motion Management Strategies



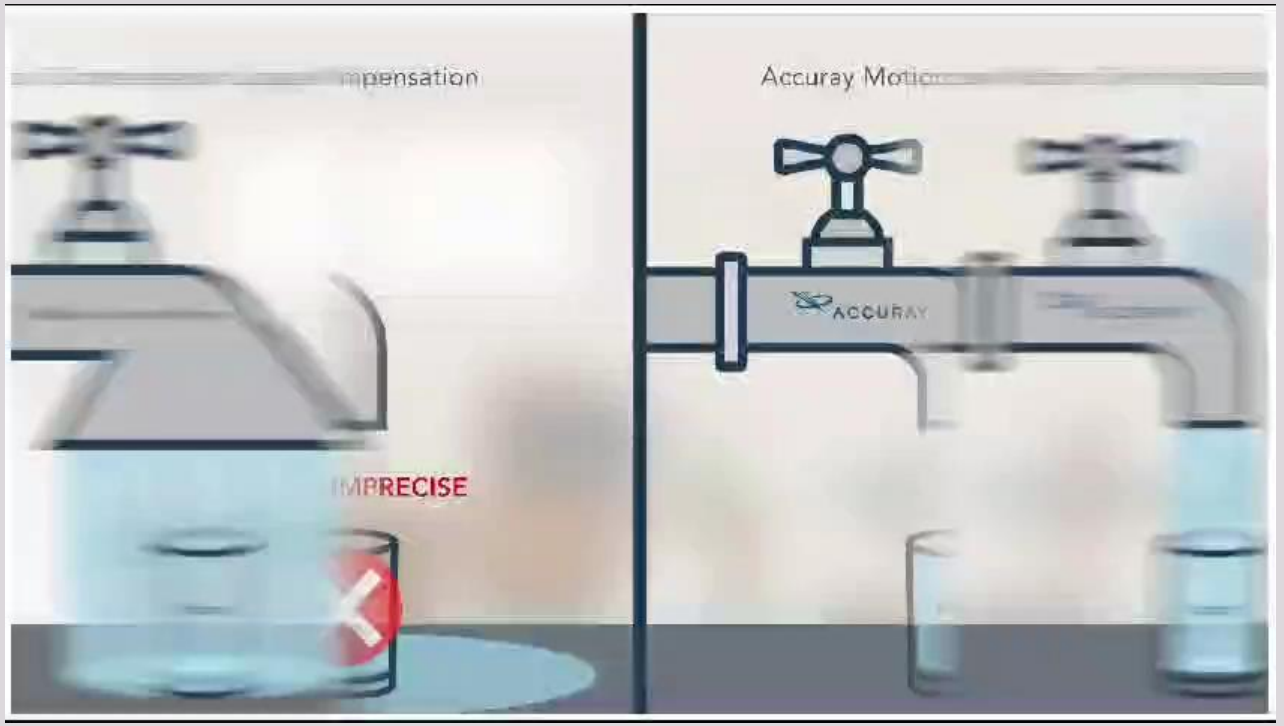
- ✓ **Motion encompassing methods**
- ✓ **Breath hold methods**
- ✓ **Abdominal compression Methods**
- ✓ **Tracking methods**
- ✓ **Respiratory gating methods**

- *AJ COLE/CLINICAL ONCOLOGY/2014*
- *AAPM TG-76*

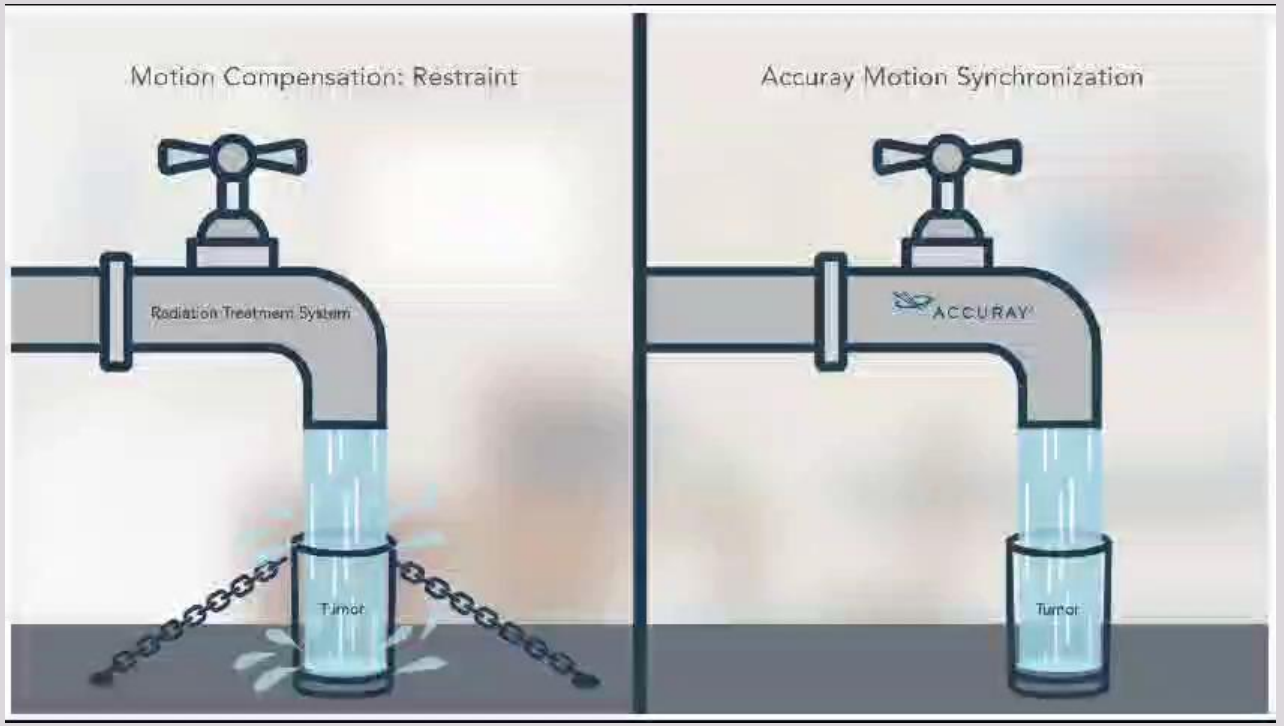
No compensation VS Synchrony



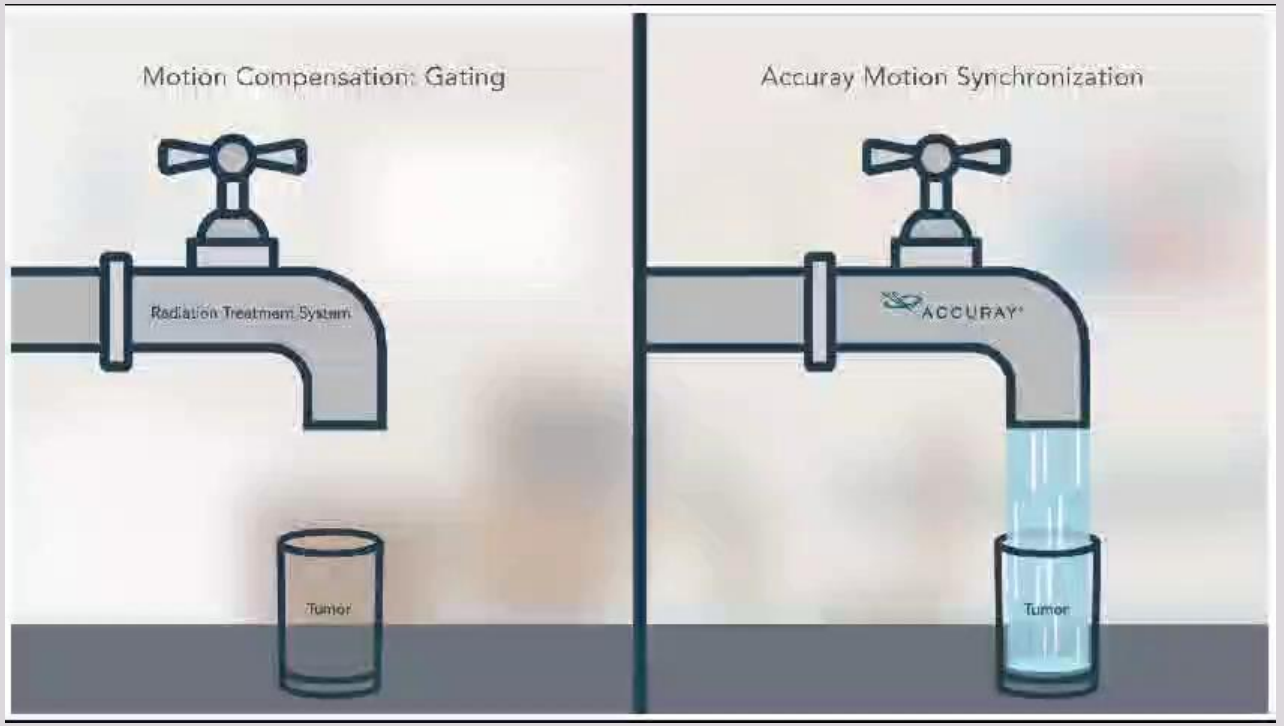
Larger Margin VS Synchrony



Tight Margin Restraint VS Synchrony



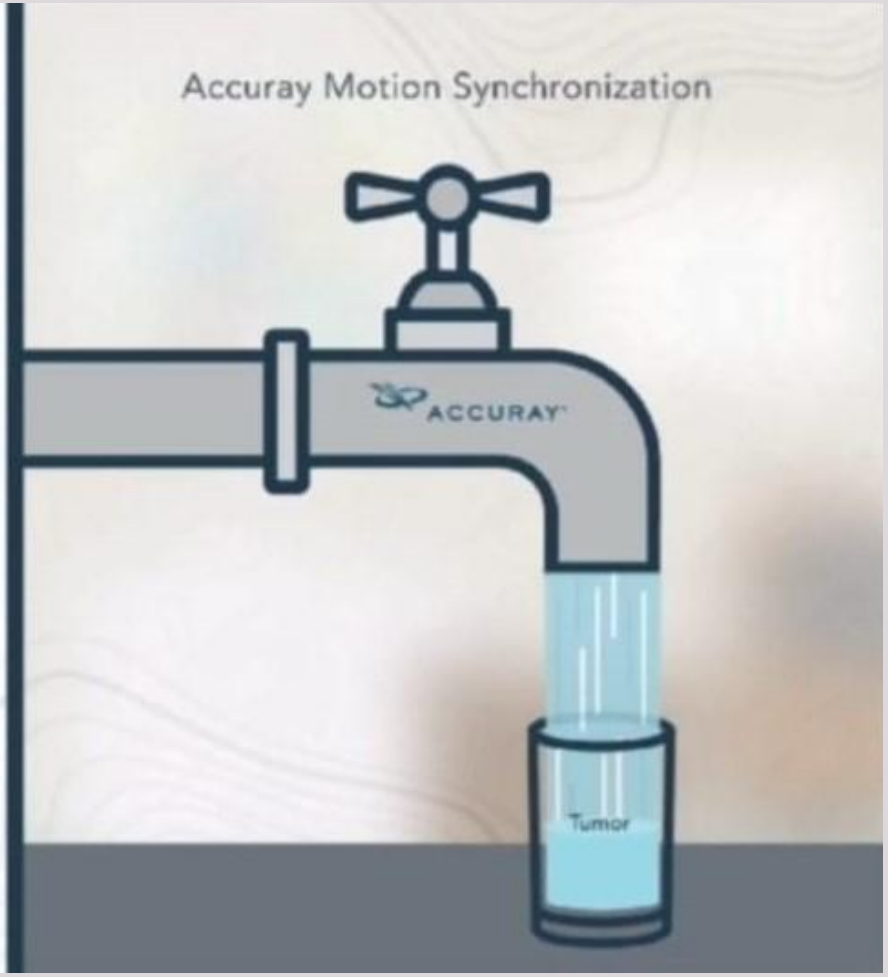
Gating Methods VS Synchrony



Accuray Motion Synchronization is:

ACCURATE
PRECISE
EFFICIENT
COMFORTABLE

Patient, Practice & Physician-first



Clinical workflow summary

- Sim : 4D-CT → measure motion amplitude
- If motion <5mm : Free breathing + ITV margin
- If motion 5-15mm : Gating or DIBH or compression
- If motion >15mm : Consider tracking or replan technique
- Daily : CBCT + check if motion pattern changed. Weight loss/atelectasis changes motion
- Re sim if tumor shrinks > 30% or weight loss >5%

Core Challenges

- **Radiation-Induced Lung Injury (RILI)**
  - The most common toxicity.
  - It can manifest acutely as radiation pneumonitis
  - causing severe coughing and breathlessness, or progress to permanent lung fibrosis.

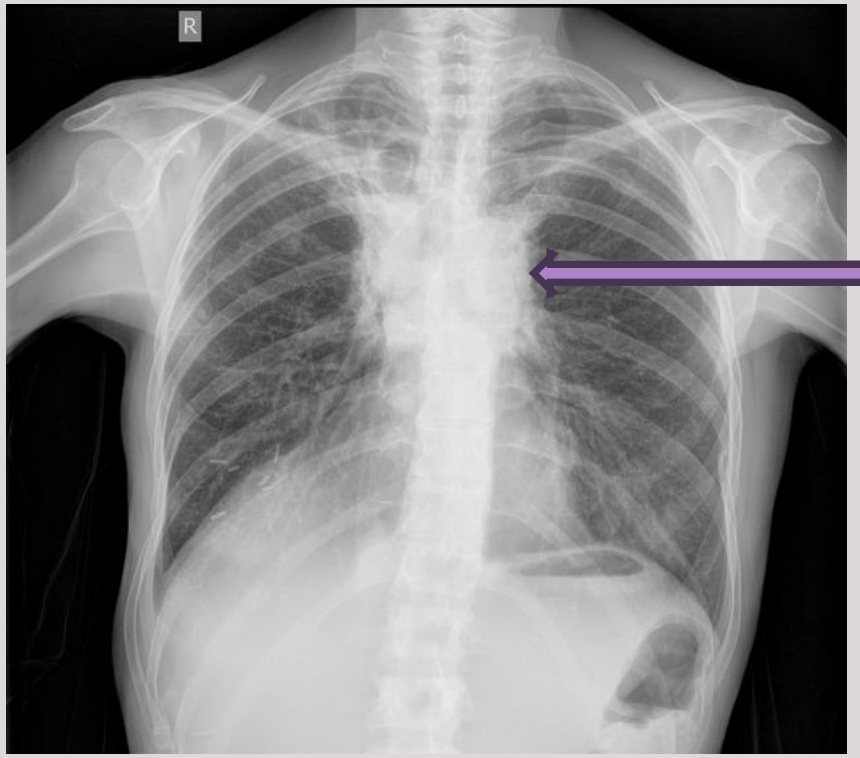
Late Effects of RT

- **Pulmonary Toxicity**
  - Radiation pneumonitis: V20 <30–35%, mean lung dose <15–20 Gy — standard constraints
  - Bleomycin (ABVD): additive pulmonary toxicity; avoid excess lung dose with bleomycin
  - Reduce/omit bleomycin if pulmonary function compromised

- **Acute Radiation Pneumonitis:**
  - **Timing:** Develops within 1 to 3 months after completion of radiation therapy.
  - **Symptoms:** Mild-to-severe shortness of breath (dyspnoea), dry, non productive cough, and occasionally a low-grade fever.
  - **Management:** Usually managed successfully with a course of **corticosteroids** and **supportive care**.
- **Chronic Radiation Fibrosis:**
  - **Timing:** Evolves slowly over 6 to 24 months post-radiation.
  - **Symptoms:** Progressive shortness of breath and chronic pulmonary insufficiency. In severe cases, it can place strain on the heart, leading to pulmonary hypertension and *cor pulmonale*.
  - **Management:** This phase is typically irreversible and managed with supportive care, such as long-term **oxygen therapy** and pulmonary rehabilitation.

- Radiation-induced lung toxicity (primarily **radiation pneumonitis** and **fibrosis**)
- Depends on both total dose and volume exposed.
- Toxicity is rarely seen below **20 Gy** with conventional fractionation, common between **30–40 Gy**, and highly probable above **40 Gy.**

Square pneumonia



Usually seen in Mediastinal irradiation

Late Effects of RT

- **Cardiac Toxicity**
  - Most significant late effect in mediastinal HL — coronary artery disease, pericarditis, valve disease
  - Risk increases with higher doses and older techniques (mantle field)
  - Modern ISRT + IMRT/DIBH reduces mean heart dose to <3 Gy
  - NCCN/ESMO recommend cardiac surveillance — Echo, ECG, lipid profile

- Radiation-induced heart disease (RIHD) risk is directly tied to the mean heart dose (MHD) and the volume of the heart exposed.
- While adverse cardiovascular effects rise significantly at doses **>15–20 Gy**.
- No strict "safe" threshold.
- Damaging effects can occasionally be seen at doses as low as **2 Gy.**

- **Pericarditis:** Acute inflammation or delayed, chronic thickening of the pericardial sac, frequently seen at higher doses (often >40 Gy)
- **Coronary Artery Disease (CAD):** The risk scales linearly. For example, every 1 Gy increase to the mediastinum increases the risk of cardiac mortality by approximately 60%
- **Valvular Dysfunction & Heart Failure:** Thickening, fibrosis, and calcification of the heart valves, or the development of restrictive heart failure over the long term (frequently presenting 10 to 15+ years post-therapy).
- **Arrhythmias:** Disruptions in the heart's electrical system can occur, particularly when combined with previous heart disease or cardiotoxic chemotherapy.

- Modern radiation therapy planning guidelines generally aim for a mean heart dose of **≤ 3 Gy** (using the principle of As Low As Reasonably Achievable, or ALARA).
- Modern techniques
  - Deep inspiration breath-hold (DIBH),
  - 4D-CT,
  - Intensity-modulated radiotherapy (IMRT)
  - Proton beam therapy.

- Risk follows a linear, no-threshold dose-response relationship.
- Dose-dependent, meaning it increases as the radiation dose increases.
- Minimal risk exists even at low doses.
- Clinically significant elevated risks are primarily associated with moderate to high exposures.

Breast cancer

- **Dose Range:** 10 Gy to 40+ Gy
- **Context:** This level of radiation occurs during treatments like mantle/thoracic radiotherapy (e.g., for Hodgkin's lymphoma). The risk of developing secondary breast cancer significantly increases at these levels, particularly for women treated at a younger age (under 30).
- **Details:** The latency period for these cancers is usually 10 to 15 years post-exposure.

Spinal cord

- **Radiation myelopathy -** potential complication of radiation therapy near the spine
- Nervous tissue and its surrounding blood vessels are damaged.
- The severity and timing of symptoms
  - Depends on the total radiation dose, fractionation schedule, and the volume of cord treated.

- **Transient Radiation Myelopathy (TRM)**
  - An early-delayed, benign, and temporary reaction occurring weeks to months after treatment. Symptoms often include **Lhermitte's sign**.
    - Electric shock like sensation that shoots down the spine into the arms and legs.
- **Chronic Progressive Radiation Myelopathy (CPRM)**
  - A rare but severe late effect that usually develops 6 months or longer.
  - It involves irreversible demyelination and damage to white matter, manifesting as sensory changes, progressive motor weakness, pain, and potentially bowel or bladder incontinence

- **Acute Radiation Myelopathy**
  - Occurs during the actual course of treatment and is very rare, presenting with temporary motor or sensory changes.

- **Standard (Conventional) Fractionation**
  - *D*oses of **1.8 to 2.0 Gray (Gy) per fraction**, the spinal cord is quite resilient because it has time to repair cellular damage between treatments.
  - **45 Gy**: Considered the ultra-safe standard clinical limit. **less than 0.03%**.
  - **50 Gy**: The universally accepted **maximum constraint limit** for the full thickness of the spinal cord. Low at **0.2%**.
  - **55–60 Gy**: The risk begins to escalate steeply. At 60 Gy, the probability of myelopathy increases to about **6%**.

Stereotactic Procedure

Number of Fractions	Maximum Tolerated Point Dose
1 Fraction	12.4 -14 Gy
2 Fractions	17 Gy
3 Fractions	20.3 Gy
4 Fractions	23 Gy
5 Fractions	25.3 Gy

Combination with Other Modalities

- Chemotherapy
- Targeted Therapy
- Immunotherapy

To summarise

- Scope of RT is very high
- Challenges are
  - *OAR safety*
  - *Tumor localization*