Imaging in Radiotherapy and Particle Therapy

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Imaging in Radiotherapy

Stage 1: PRE-Treatment
Stage 2: DURING Treatment
Stage 3: POST-Treatment

Acta Oncologica, 2015; 54: 1254–1258

Taylor & Francis
Taylor & Francis Group

COMMENTARY

Imaging in particle therapy: State of the art and future perspective

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- PRE-Treatment Imaging:
  - Most Important!
  - Tumor Staging: PET/CT or PET/MRI or CT
  - Stopping Power Estimation: Dual-Energy CT
  - Tumor Motion Characterization: Respiratory/Breathing Monitoring Systems
- DURING-Treatment Imaging:
  - 2nd Most Important.
  - Tumor Motion Monitoring and Adaptation: In-Room MRI or X-ray Fluoroscopy
  - Daily Treatment Setup and Alignment: CT or Cone-Beam CT or In-Room MRI
  - Beam Range Real-Time Tracking: Prompt Gamma Imaging
- POST-Treatment Imaging:
  - Treatment Response Follow-up: PET/CT or PET/MRI or CT

PRE-Treatment Imaging

PRE-Treatment Imaging

Tumor Staging: PET/MRI or CT (Responsibility of the Clinician)

Cancer is often staged twice.

- The first rating is done before treatment and is called the clinical stage (with **PET/MRI/CT**/Biopsy).
- The second rating is done after treatment, such as surgery, and is called the pathologic stage.

TNM (Tumor, Node, Metastasis) staging system

The TNM staging system is most often used by doctors to stage cancer.

Responsibility of the Clinician

Acquisition Methods for medical images

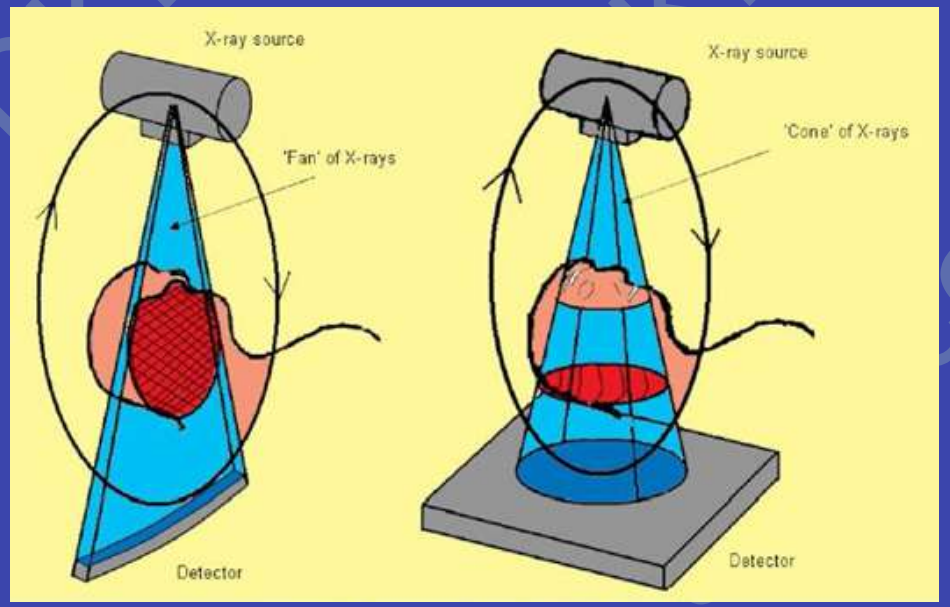
1. X-Rays
2. Computer Tomography (CT or CAT)
3. MRI (or NMR)
4. PET / SPECT (Positron Emission Tomography, Single Photon Emission Computerized Tomography
5. Ultrasound

X-ray Images

- bones contain heavy atoms -> with many electrons, which act as an absorber of x-rays
- commonly used to image gross bone structure and lungs
- excellent for detecting foreign metal objects
- main disadvantage -> lack of anatomical structure
- all other tissue has very similar absorption coefficient for x-rays

Computerized Tomographic (CT) Imaging

- measures the attenuation of X-rays from many different angles
- a computer reconstructs the organ under study in a series of cross sections or planes
- combine X-ray pictures from various angles to reconstruct 3D structures



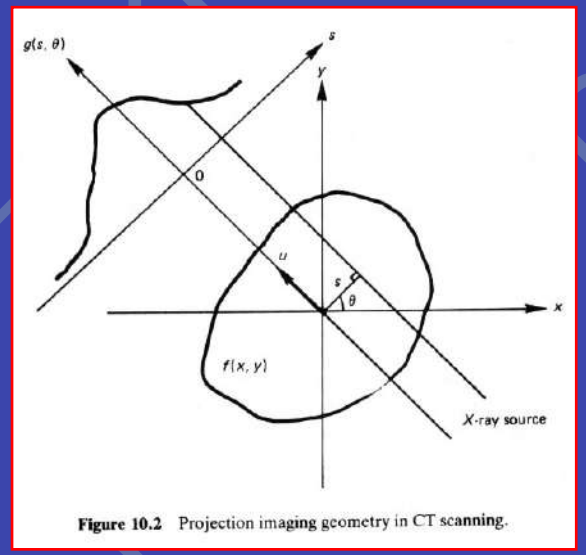
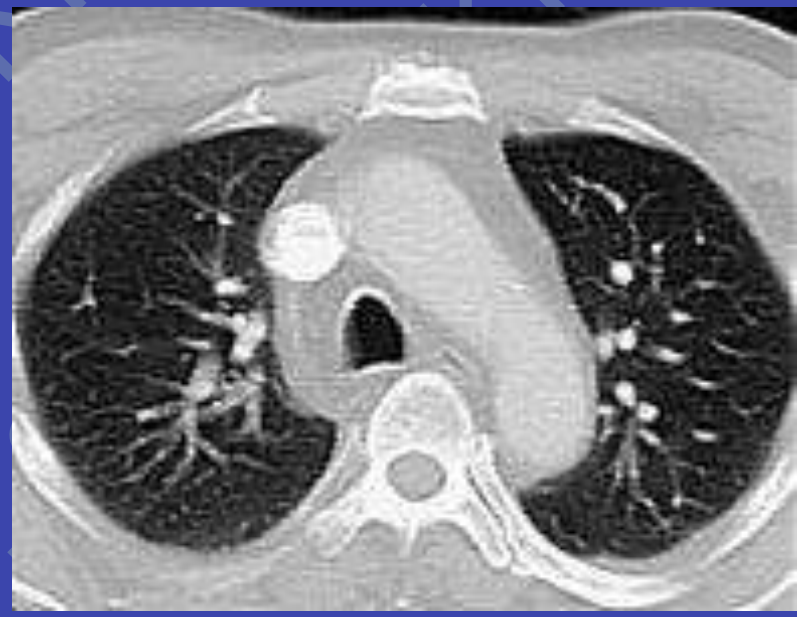


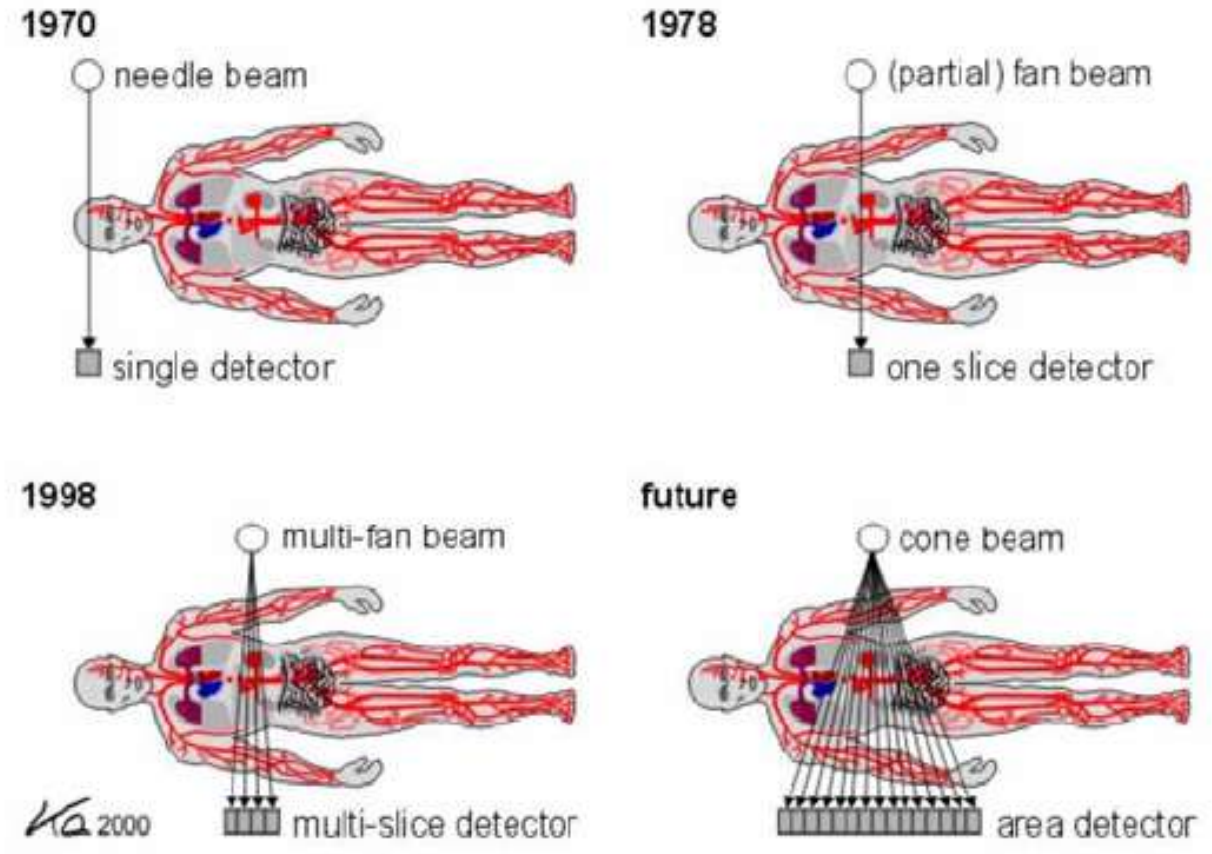
Figure 10.2 Projection imaging geometry in CT scanning.

Radon Transform



Evolution of CT technology

Multi-slice CT - Dates



http://www.multislice-ct.com/www/media/introduction/technology_2003_03_05.pdf

Nuclear Magnetic Resonance (NMR)

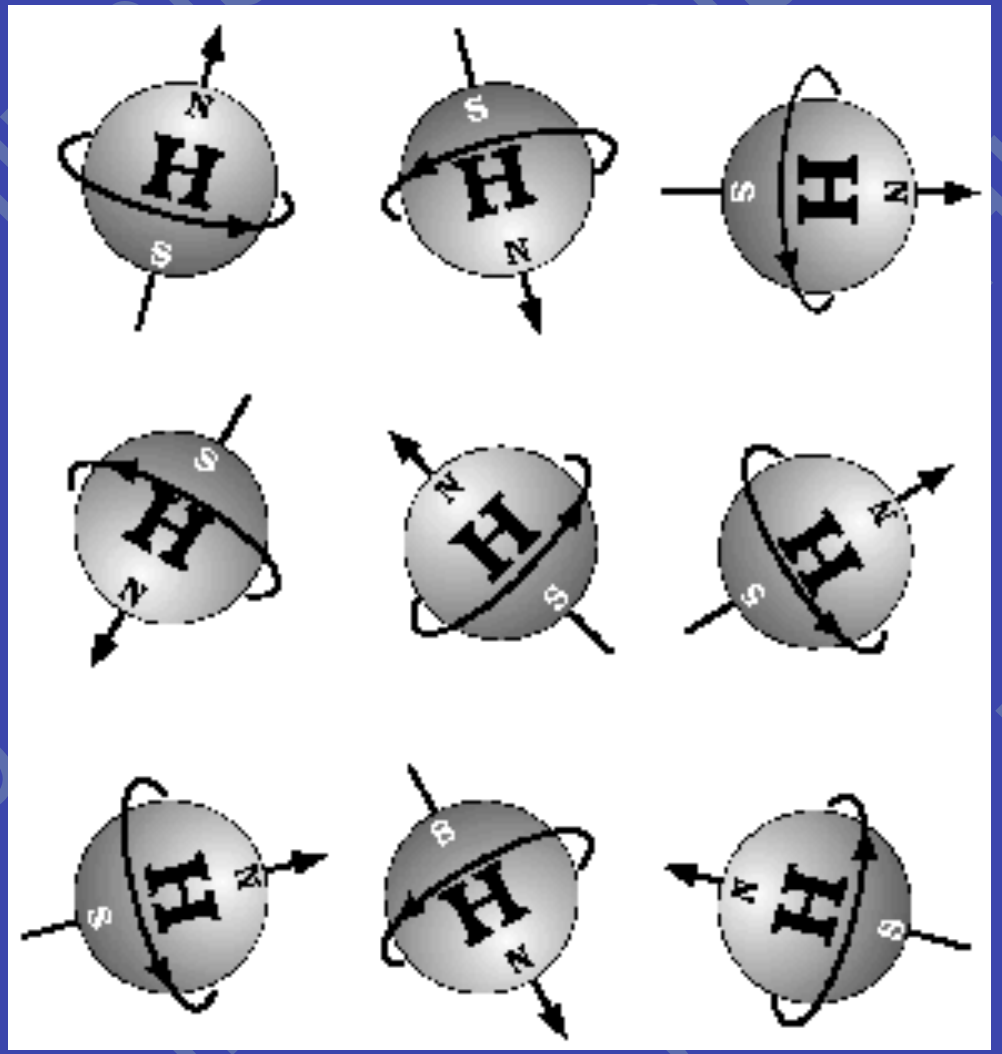
Magnetic Resonance Imaging (MRI)

MRI

- Nuclear Magnetic Resonance (NMR) (or Magnetic Resonance Imaging - MRI)
- most detailed anatomical information
- high-energy radiation *is not* used, i.e. this is "safe method"
- based on the principle of nuclear resonance
- (medicine) uses resonance properties of protons

MRI

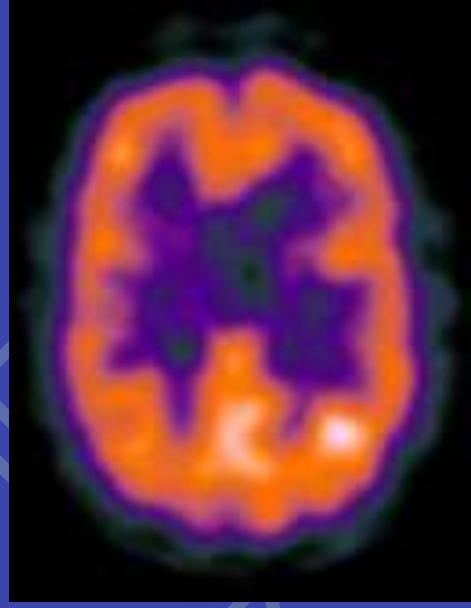
- all atoms (core) with an odd number of protons have a ‘spin’, which leads to a magnetic behavior
- Hydrogen (H) - very common in human body + very well magnetizing
- Stimulate to form a macroscopically measurable magnetic field



MRI

- proton density pictures - measures H
  MRI is good for tissues, but not for bone
- signal recorded in Frequency domain!!
- Noise - the more protons per volume unit, the more accurate the measurements - better signal to noise ratio (SNR) through decreased resolution

PET/SPECT



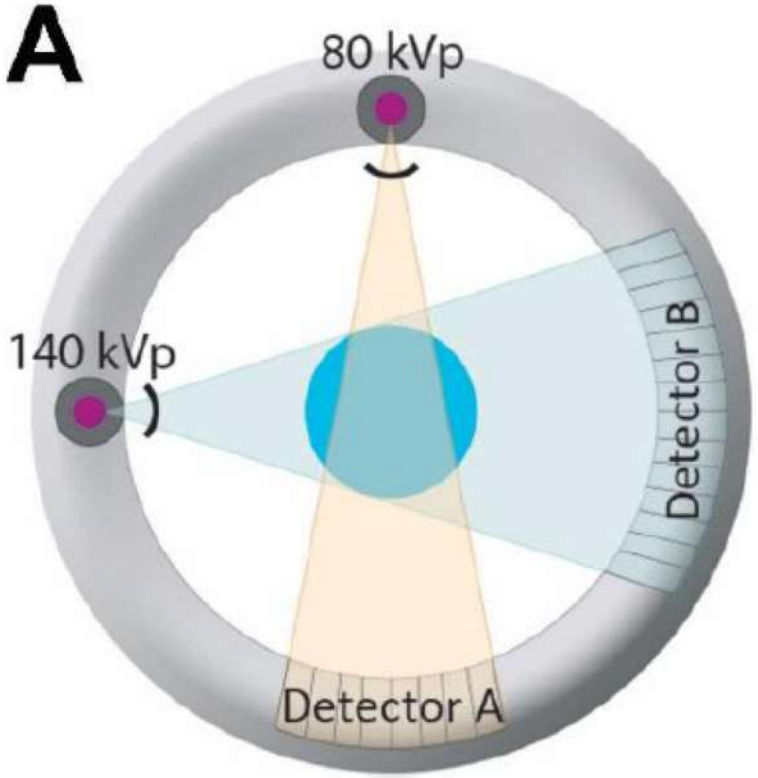
- **Positron Emission Tomography**
  Single Photon Emission CT
  - recent technique
- involves the emission of particles of antimatter by compounds injected into the body being scanned
- follow the movements of the injected compound and its metabolism
- reconstruction techniques similar to CT - Filter Back Projection & iterative schemes

PRE-Treatment Imaging

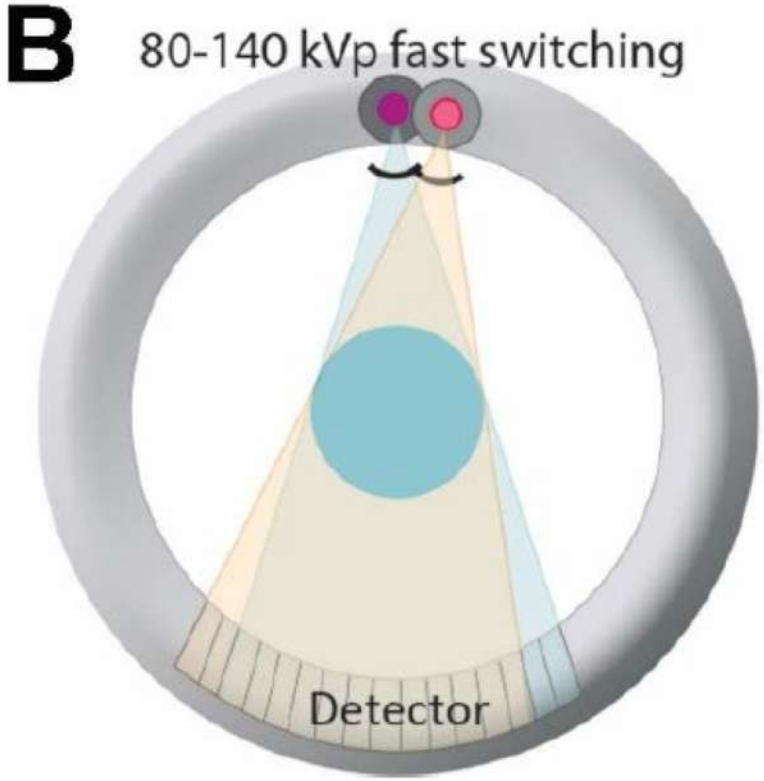
❖ Stopping Power Estimation: Dual-Energy CT

Dual-Energy CT Scanners

SIEMENS



GE Healthcare



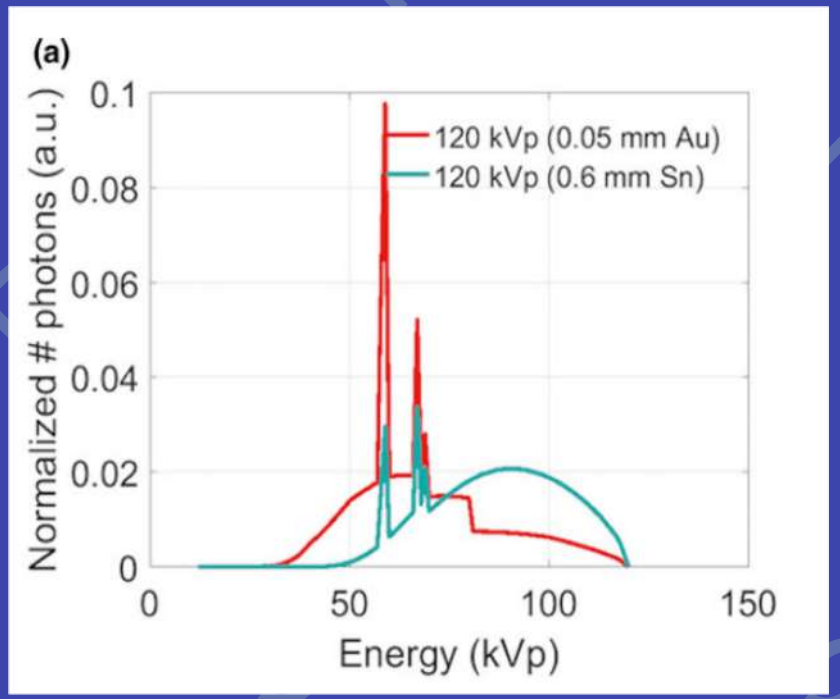
PHILIPS

PRE-Treatment Imaging

❖ Stopping Power Estimation: Dual-Energy CT

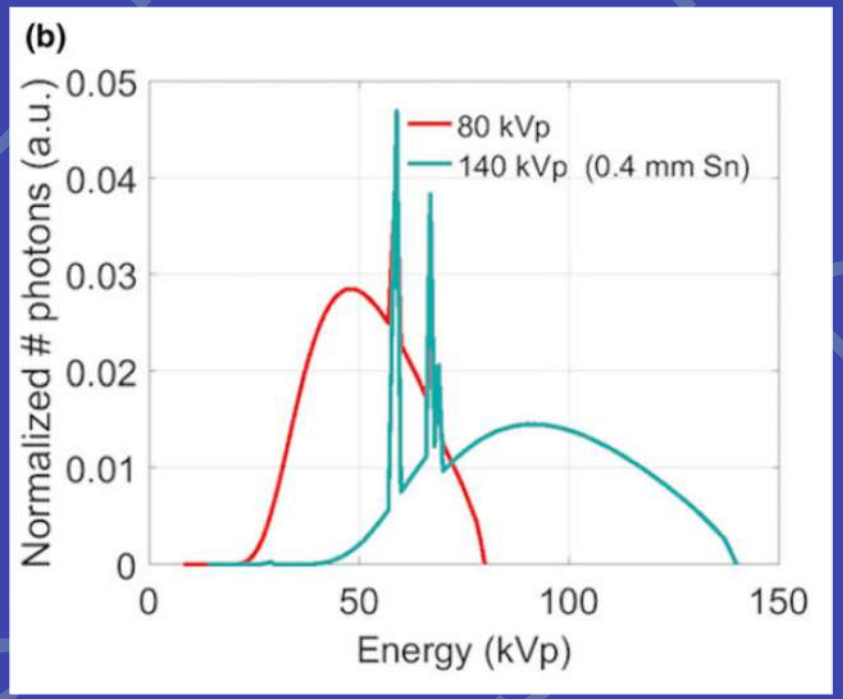
SIEMENS DECT Scanners: X-ray Spectrum

EDGE



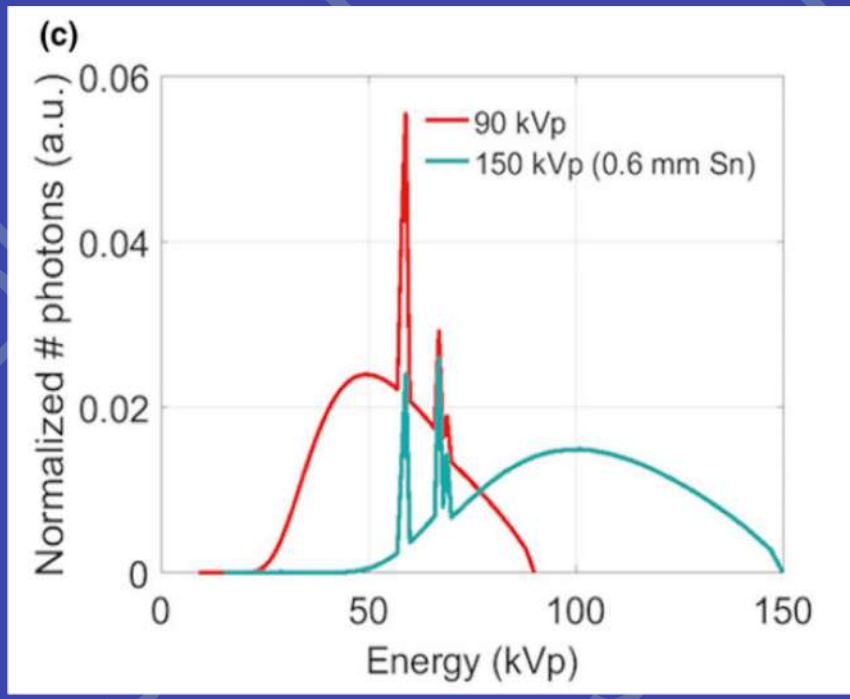
3rd Generation Twin-Beam scanner

FLASH



3rd Generation Dual-Source scanner

FORCE



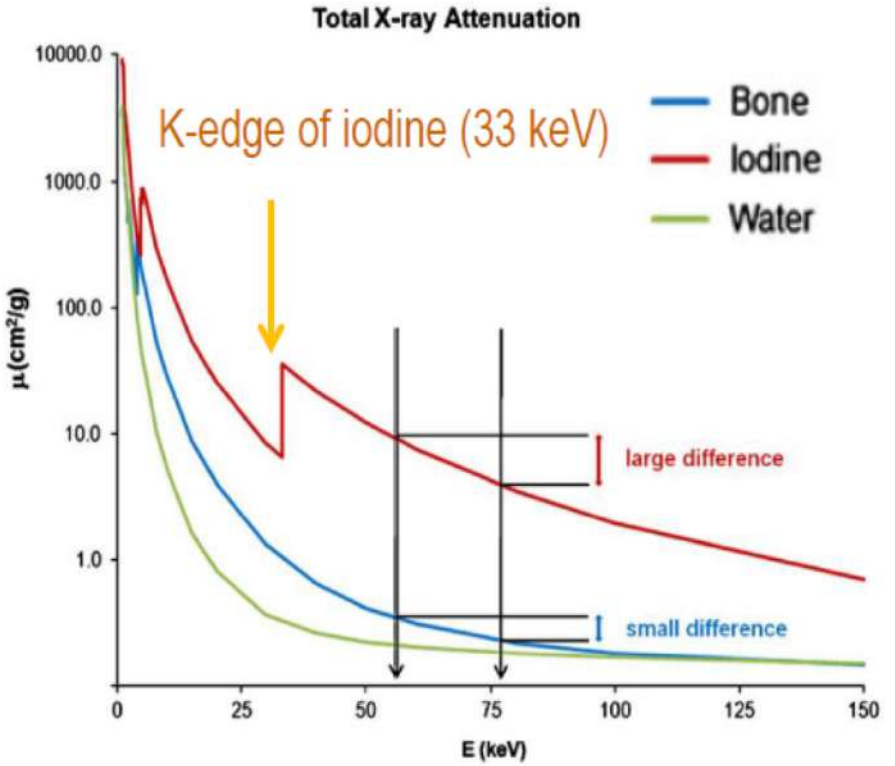
2nd Generation Dual-Source scanner

PRE-Treatment Imaging

❖ **Stopping Power Estimation**: Dual-Energy CT

Generally 2 types of Parameterization of Attenuation Coefficient (μ_{eff}) in DECT

- *Electron density (ρ_e) and effective atomic number (Z_{eff})*



PRE-Treatment Imaging

❖ **Stopping Power Estimation**: Dual-Energy CT

Bethe-Bloch formula

$$SPR = \frac{\varrho_{e,medium}}{\varrho_{e,water}} \cdot \frac{\ln\left(\frac{2m_e c^2 \beta^2}{(I_{medium}/eV)(1-\beta^2)}\right) - \beta^2}{\ln\left(\frac{2m_e c^2 \beta^2}{(I_{water}/eV)(1-\beta^2)}\right) - \beta^2}$$

Relative Electron Density

Mean Excitation Energy (I_{medium})

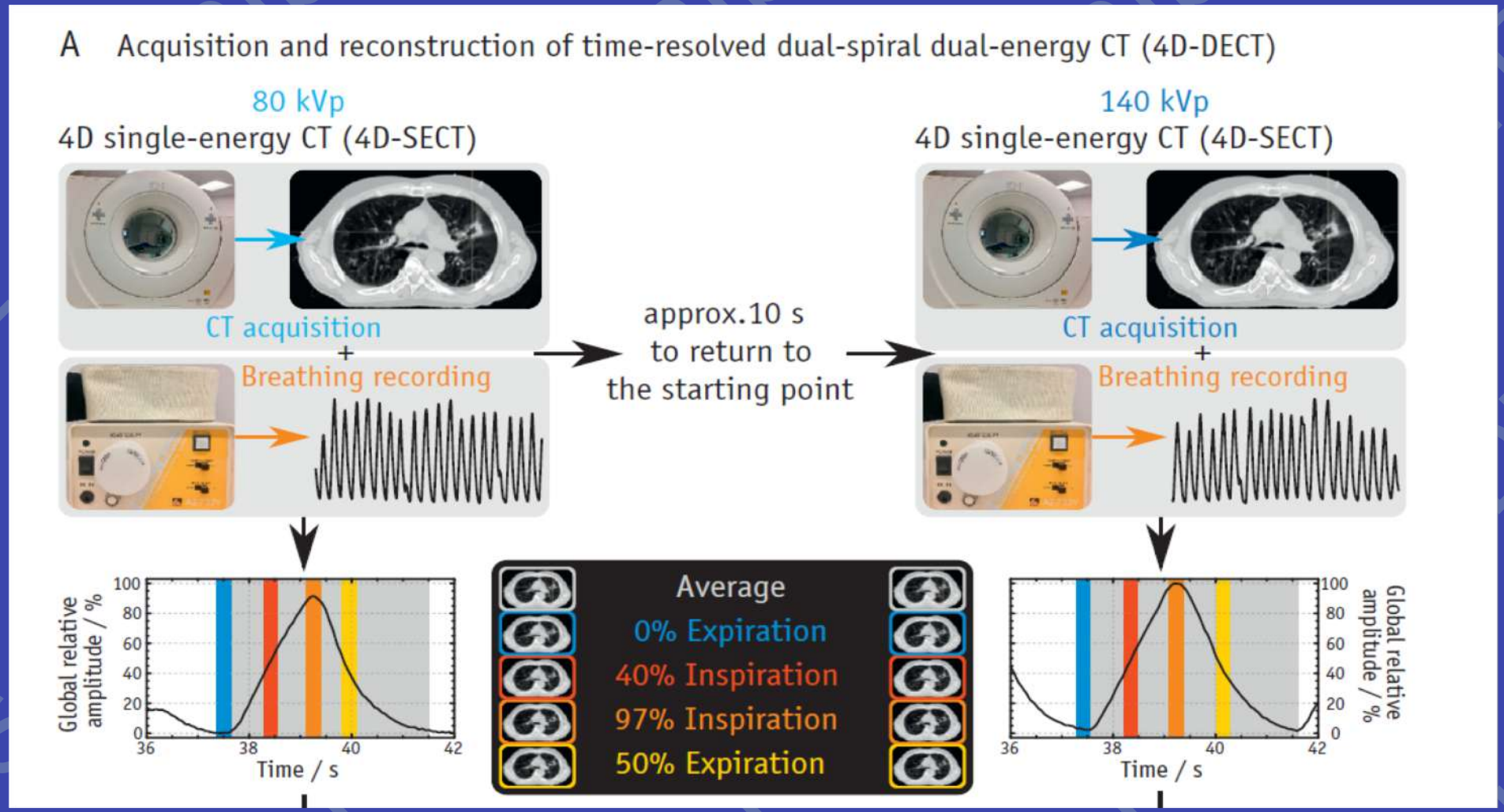
Yang et al

Effective Atomic Number (Zeff)

Dual Energy CT scan

PRE-Treatment Imaging

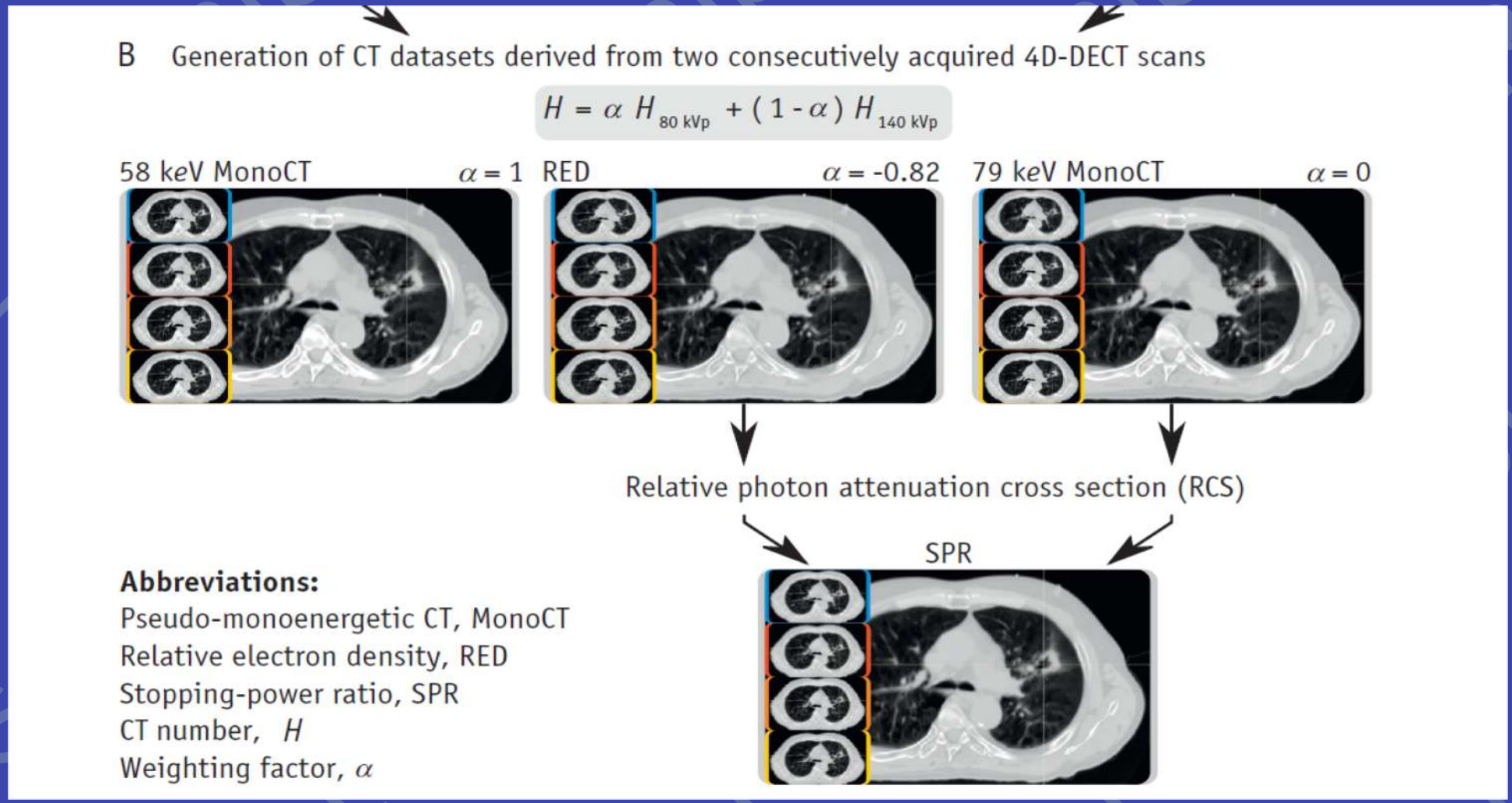
❖ **Stopping Power Estimation**: **4D Dual-Energy CT**



Wohlfahrt et al (2018) Clinical feasibility of single-source dual-spiral 4D DECT for proton..” IJROBP

PRE-Treatment Imaging

❖ **Stopping Power Estimation**: **4D Dual-Energy CT**

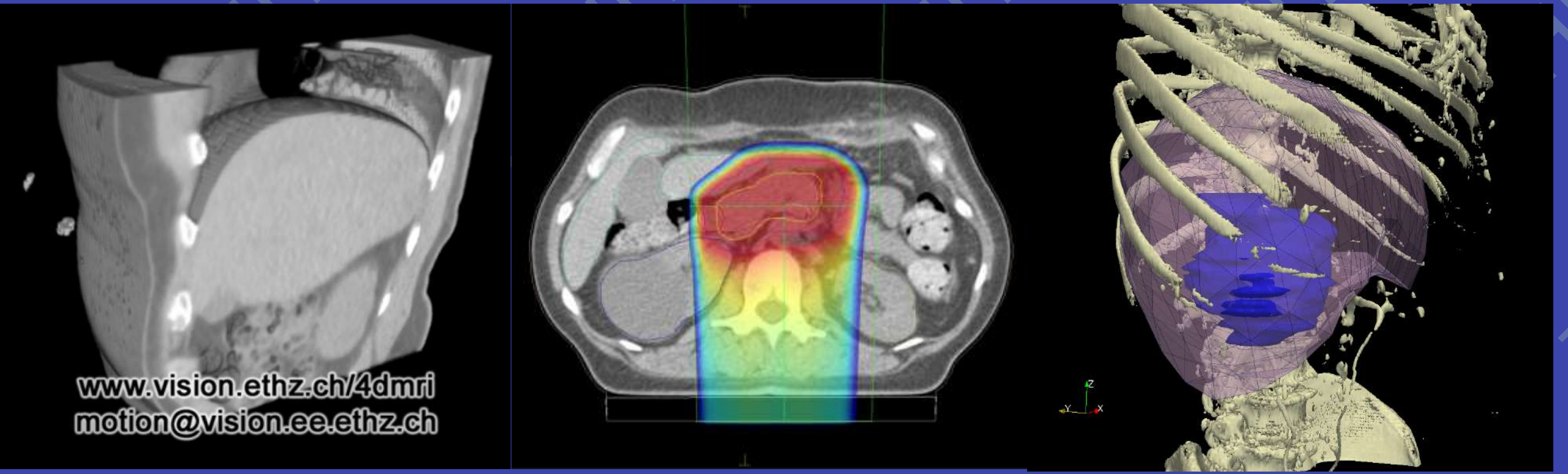


Wohlfahrt et al (2018) Clinical feasibility of single-source dual-spiral 4D DECT for proton..” IJROBP

PRE-Treatment Imaging

❖ **Tumor Motion Characterization: Respiratory/Breathing Monitoring Systems**

image plan **Breathing motion.**



For several tumor sites we cannot assume the patient geometry is static during the delivery of a treatment fraction.

Tumor Motion Characterization

- Currently:
  - Not many proton facilities treat moving targets.
  - Experience is often based on passively scattered protons, while new centers are scanning facilities.
  - Simulation studies are often not conclusive as results are patient and facility specific.

facility characteristics

scanning / passively scattered delivery

spot size
140MeV beam in air: 6-25mm

scanning speed
2Gy to a 10x10x10cm cube: 25-300s

patient characteristics

tumor position

motion
amplitude: 0-30mm

respiration frequency

tumor size

Tumor Motion Characterization

Intra-fractional changes happen due to:

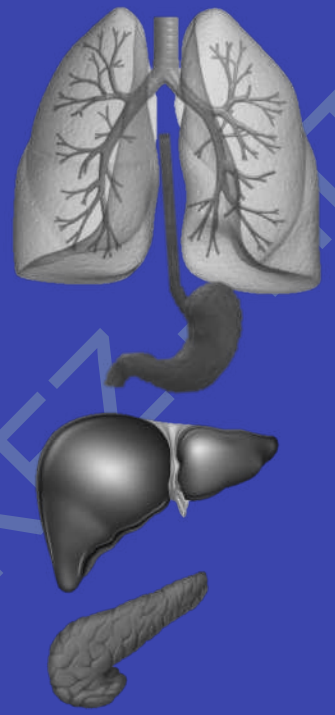
→respiration
periodic motion
12-15 cycles per min

→ heartbeat
periodic motion
60-90 beats per min

→ relaxation
drift motion
settling after 5-10 min

Motion effects cannot be resolved completely by fixation devices.
Targets in the whole thorax have to be considered mobile.

Tumor Motion Characterization



Lung

Liver

→ **Whithout motion mitigation, a limited number of patients shows motion <5mm.**

→ **Motion variations are difficult to predict.**

Pancreas

Esophagus

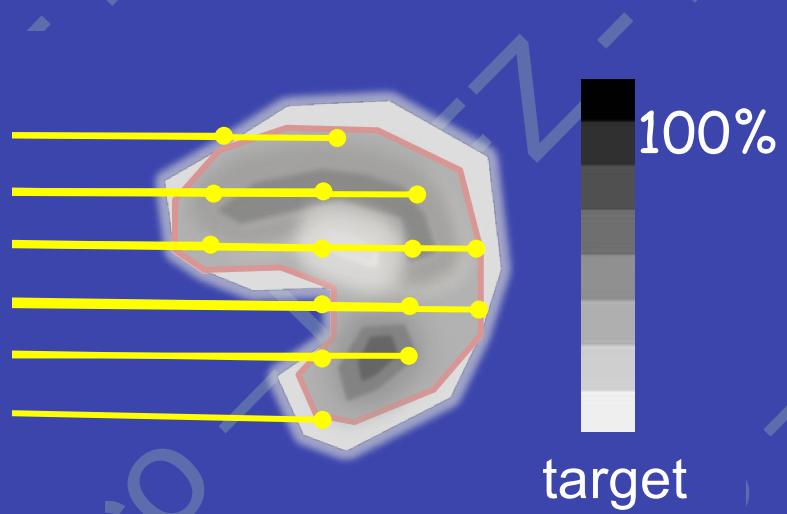
→ Almost all patients show motion >5mm.

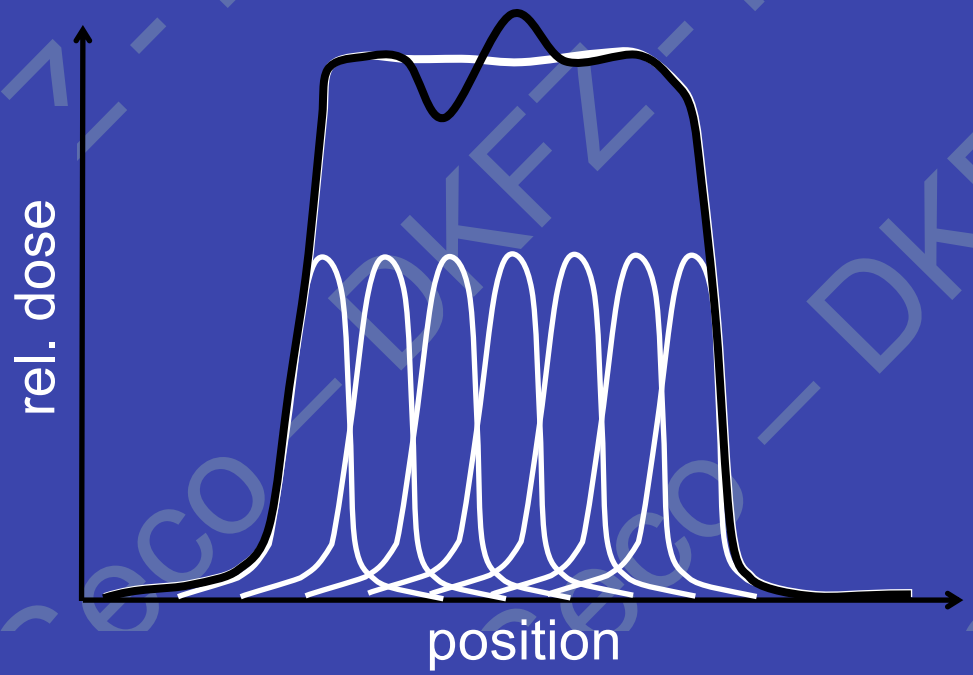
→ Main motion direction superior-inferior (S-I).

If we want to treat all patients with targets in the thorax and abdomen with proton therapy we need specific solutions!

Tumor Motion Characterization

Motion effects include target miss, dose blurring and the interplay effect.

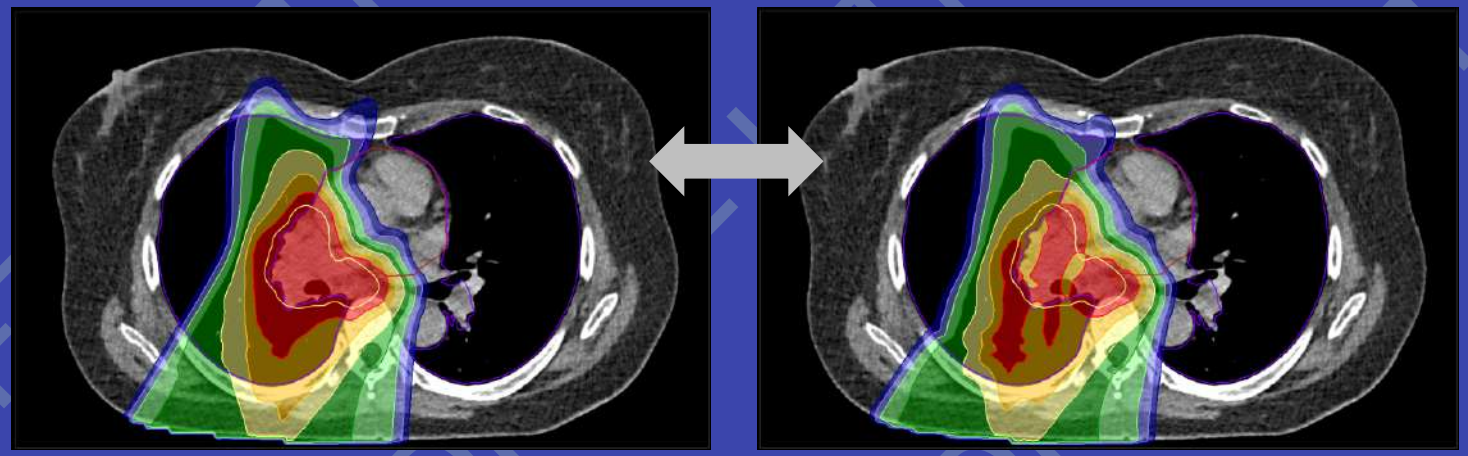




Due to the interplay-effect, margins won't solve the motion problem for protons treatments!

DURING-Treatment Imaging

Motion Monitoring / Adaptation
(DURING-treatment Imaging)



planned dose

delivered dose

Are the differences significant?

↓

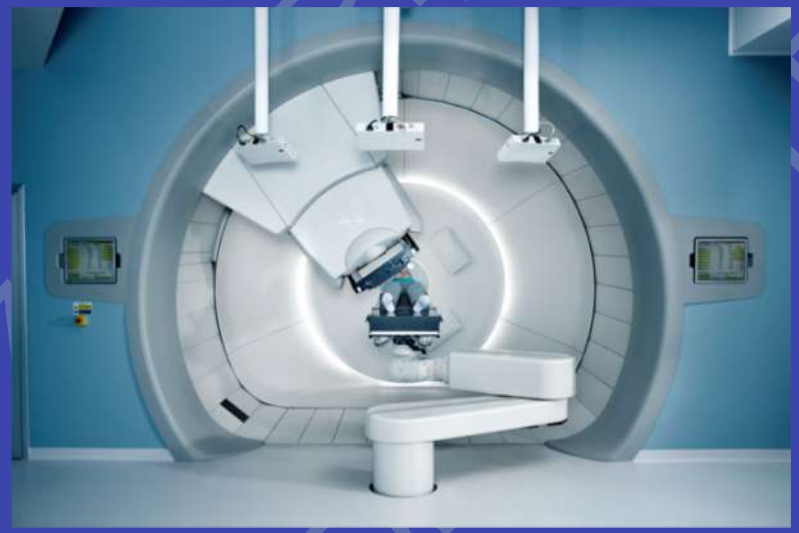
Adaptation!

→ day-specific anatomy
→ day-specific motion
→ day-specific delivery characteristics

→ Motion mitigation aims to minimize motion effects on a daily basis.

Motion Monitoring / Adaptation

(DURING-treatment Imaging – Clinical Reality TODAY)



Motion Record

ANZAI belt

Mechanical Ventilator

VisionRT

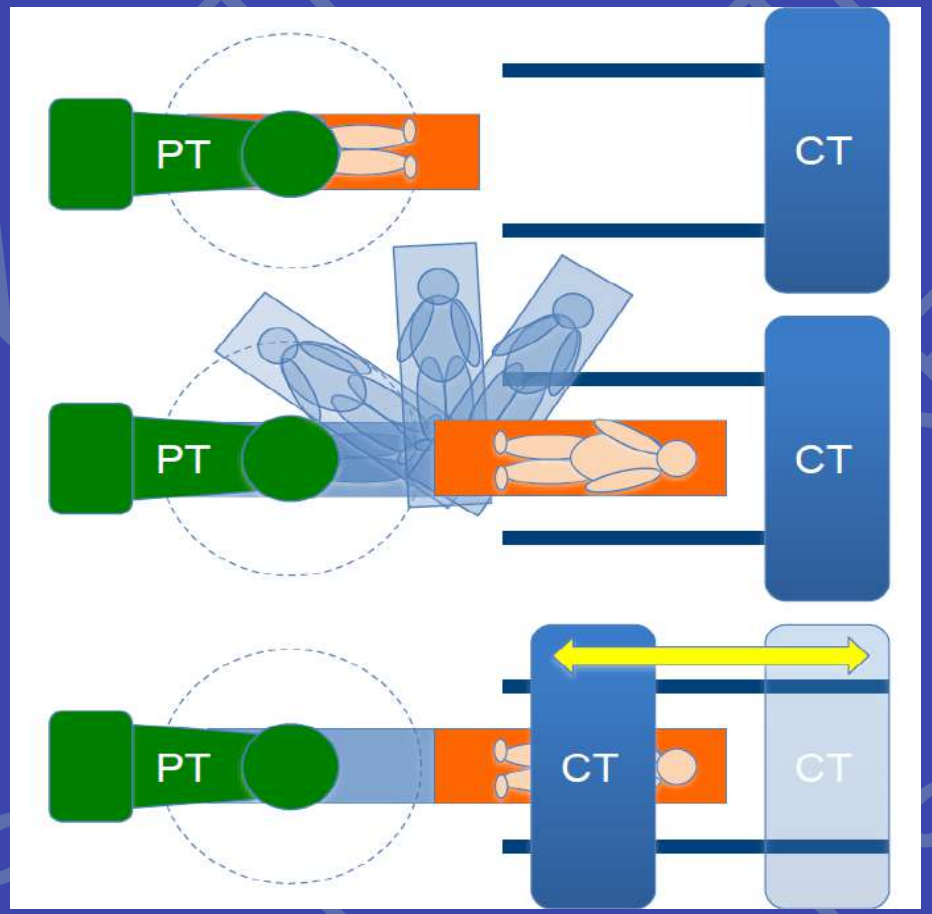
Hokkaido Proton Center

Kanehira et al. 2017 International Journal of Radiation Oncology*Biology*Physics 100(1) 173-181

DURING-Treatment Imaging

- **Daily Treatment Setup and Alignment: CT or Cone-Beam CT or In-Room MRI**

In-room CT-on-rails in proton therapy



In-Room CT on Rails. Patient is rotated from treatment position to CT

DURING-Treatment Imaging

- **Daily Treatment Setup and Alignment: CT or Cone-Beam CT or In-Room MRI**

1999: 1st CBCT integrated with X-ray Linac

2016: 1st Proton-Gantry mounted CBCT

Texas Center for Proton Therapy treats first patient with CBCT and PBS

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iba

Texas Center for Proton Therapy treats first patient with isocentric Cone Beam CT and Pencil Beam Scanning

Dallas area facility represents the leading edge of precision proton therapy treatment.

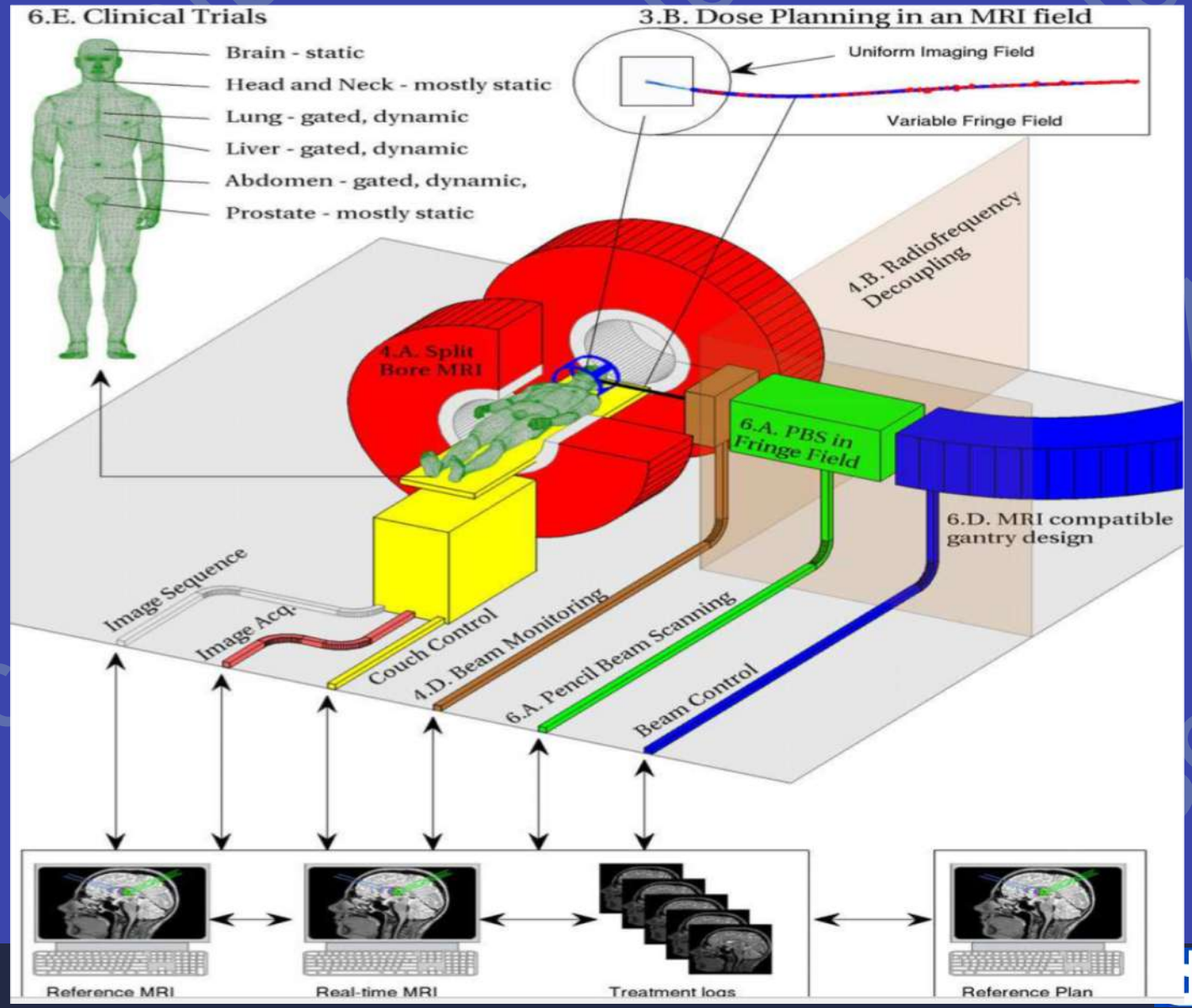
DURING-Treatment Imaging

- **Daily Treatment Setup and Alignment: CT or Cone-Beam CT or In-Room MRI**

Addressing in-room Movement

with PROTON MRI

FUTURE of PROTON THERAPY (?)



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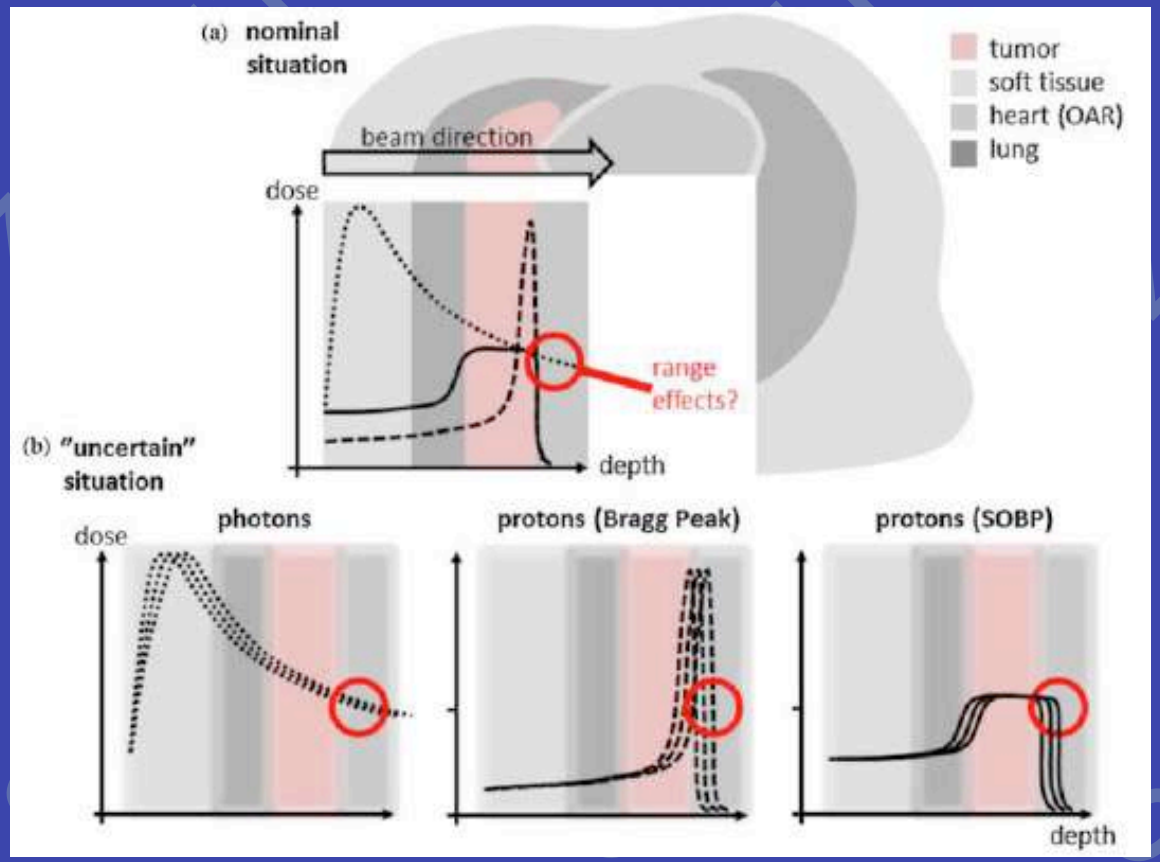
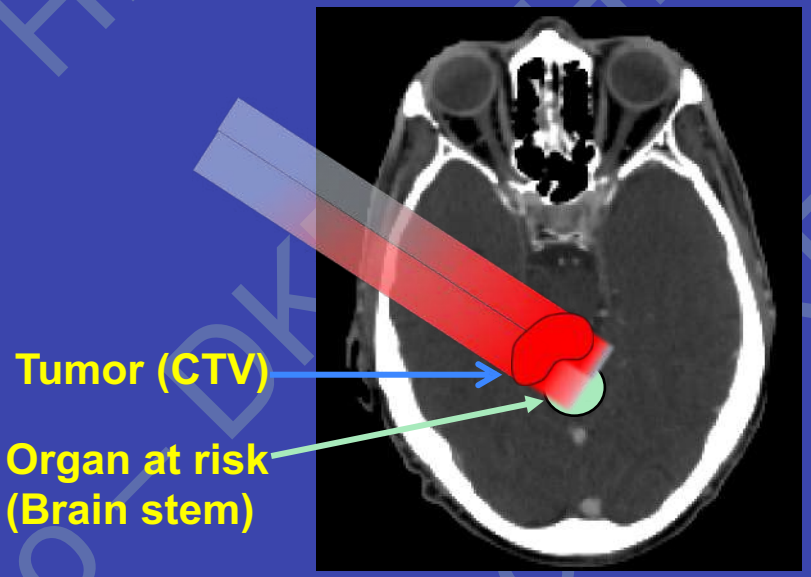
DURING-Treatment Imaging

- **Beam Range Real-Time Tracking**: Prompt Gamma Imaging

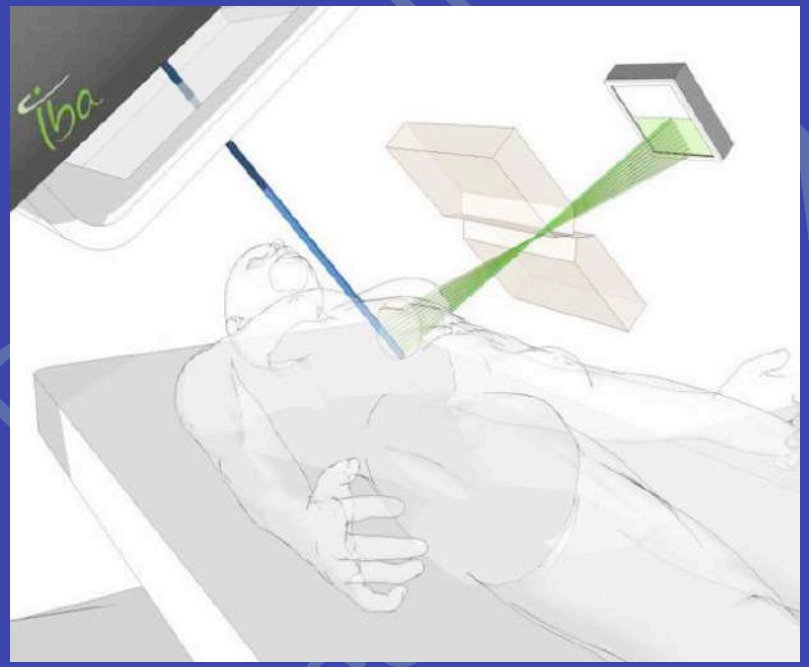
Range Uncertainties in Particle Therapy

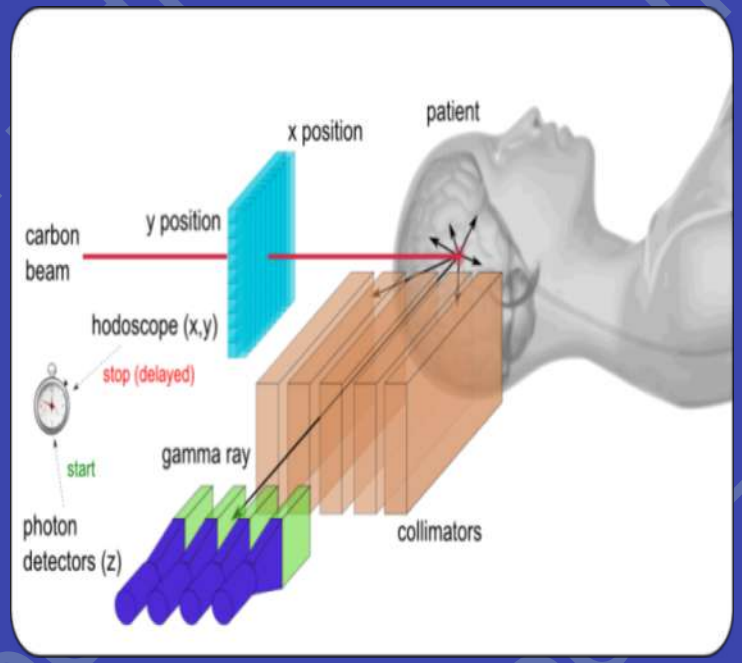


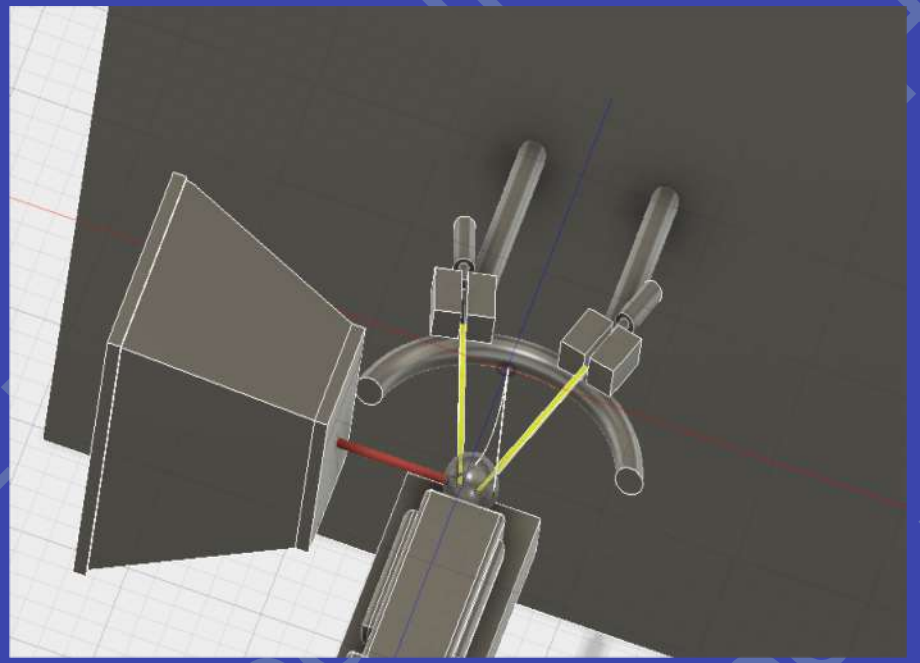


DURING-Treatment Imaging

- **Beam Range Real-Time Tracking: Prompt Gamma Imaging**







Slit-Camera design

Smeets J et al. Prompt gamma imaging with a slit camera for real-time range control in proton therapy. Phys. Med. Biol 57.11 (2012),

Prompt Gamma Spectroscopy

Verburg JM and Seco J. Proton range verification through prompt gamma-ray spectroscopy. Phys. Med. Biol 59.23 (2014)

POST-Treatment Imaging

POST-Treatment Imaging

- Treatment Response Follow-up: PET/CT or PET/MRI or CT

Followup Imaging "Watching for recurrence"

One goal of follow-up care is checking for a recurrence. Recurrent cancer is cancer that has come back after treatment. Cancer recurs because small areas of cancer cells may remain undetected in the body. Followup focuses on the detection of local, regional, or distant recurrence

Followup Imaging "Watching for Side Effects"

Long-term side effects may occur as a result of any part of management of the cancer. The type and severity of these side effects vary according, in part, to the type of therapy that have been given.

Current Clinical Practice Follow-up Imaging involves the use of PET/CT or CT or MRI

Future Clinical Practice will include the use of PET/MRI

Conclusions

- Imaging plays a major role in particle therapy.
- There are 3 stages in which imaging can be adopted in particle therapy
  - ❖ Stage 1: PRE-Treatment
  - ❖ Stage 2: DURING-Treatment
  - ❖ Stage 3: POST-Treatment

- The PRE-Treatment Stage is the most important since it involves all the needed preparation for treatment, from the dose calculation to tumor staging and involving the organ contouring.

- The DURING-Treatment Stage is the 2nd most important and involves all the daily imaging performed during treatment

- The POST-Treatment Stage involves the treatment response assessment and plays a vital role in understanding the success or not of the therapy.

Thank You for Your Attention ☺

Thank You for Your Attention ☺

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Relaxing!