FMH resident physics training course in RO PSI, 30/9/2024

Imaging in Radio-Oncology

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Instruction for participating to the quiz

1. Download the **PointSolutions app** on your smartphone or tablet

Or access to the web page

https://student.turningtechnologies.eu/#/

2. Connect to the session: fmhro2024

- Enter as guest

- You don’t need to enter personal data

Table of contents

1. Current imaging in RO
2. Reference anatomical imaging
   - CT, MRI
3. Immersion into 3D
   - DRR
4. Reference functional imaging in RO
   - PET, SPECT, MRS
5. Guidance imaging
   - CBCT, MVCT, Stereo, MR-linac
6. Image fusion
7. 4D imaging
8. Take home message


Current
Imaging

Medical imaging

Definition:

Set of technologies for creating an intelligible visual representation of medical information

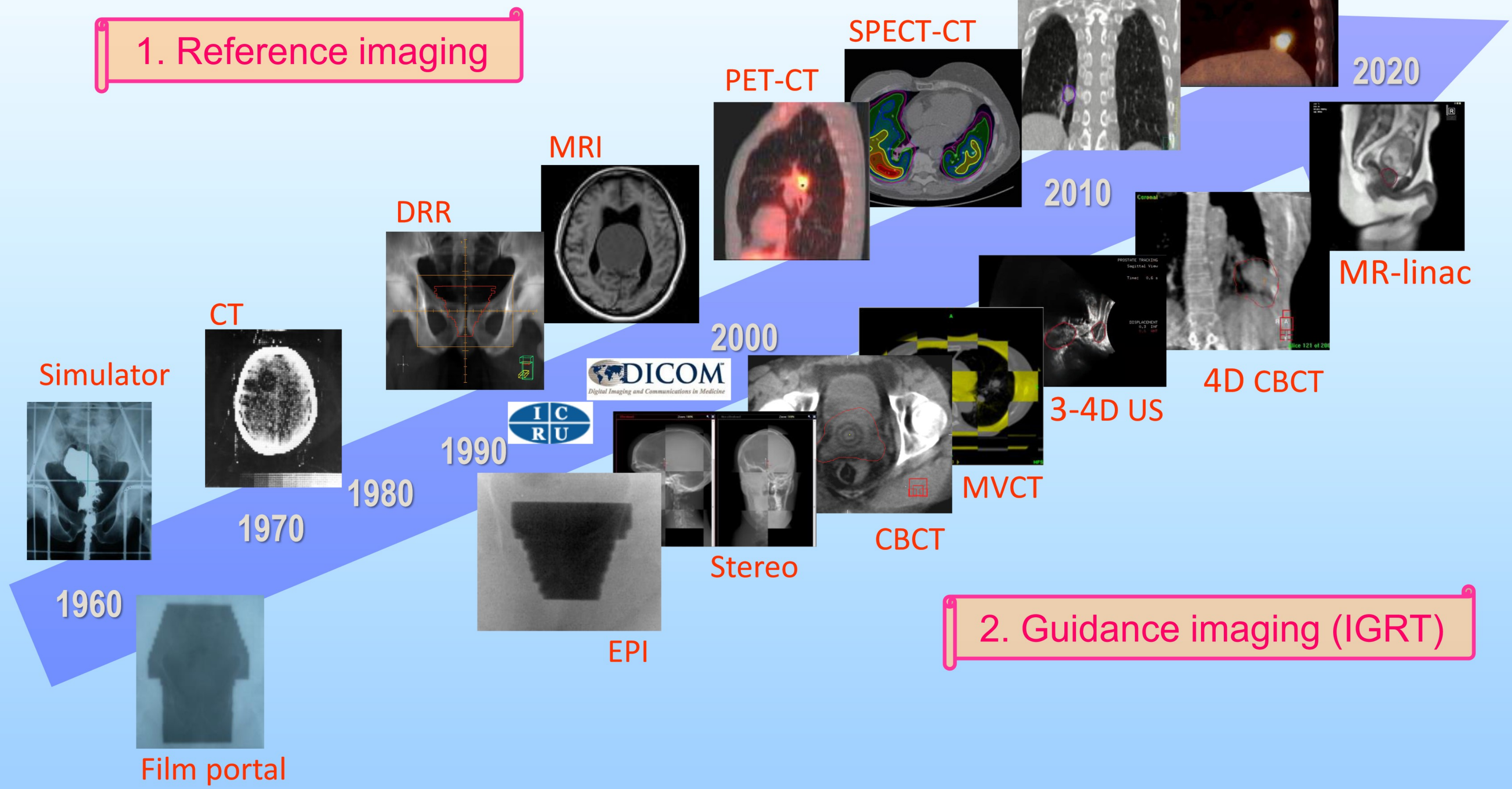
Medical imaging

Definition:

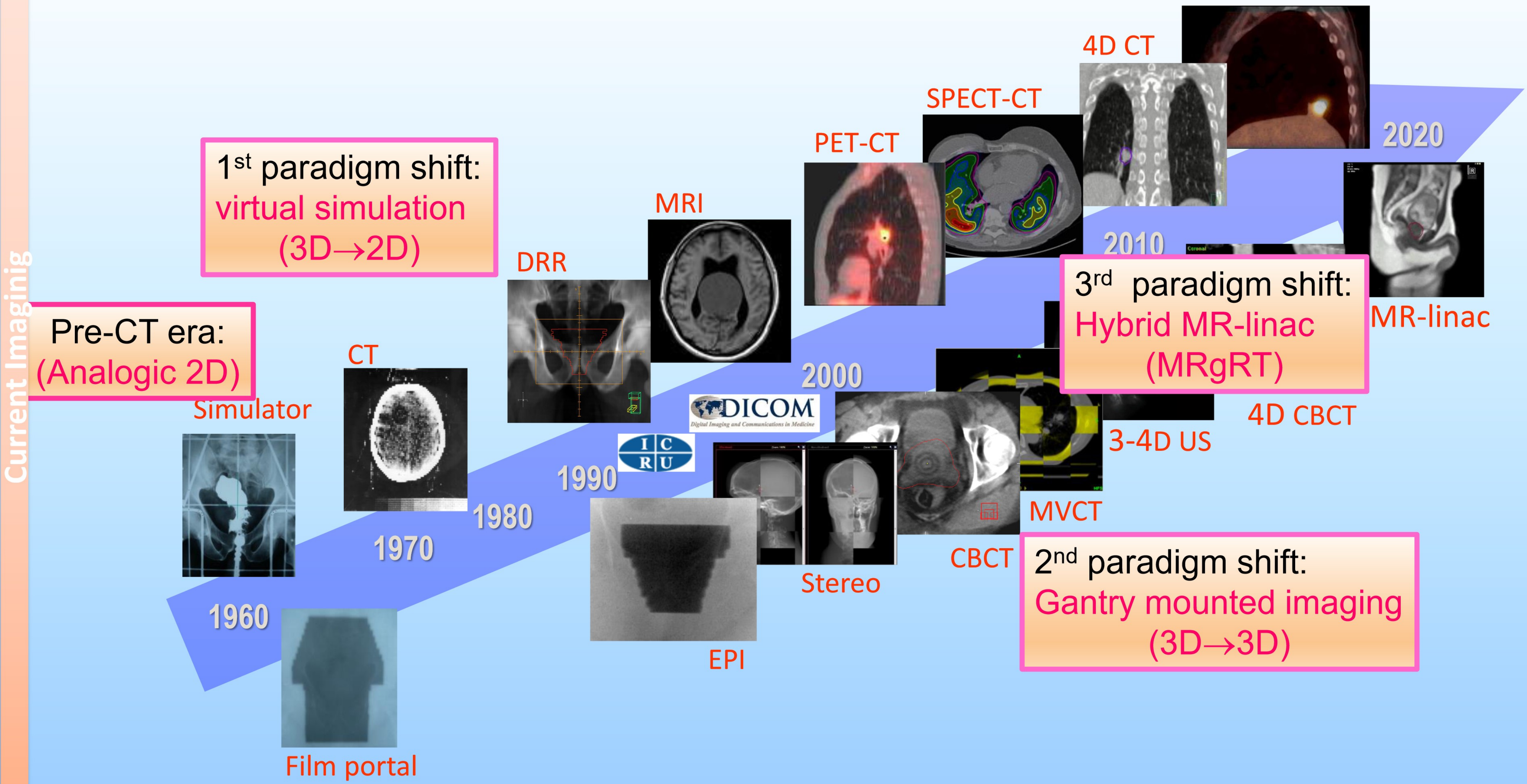
Set of technologies for creating an intelligible visual representation of medical information

- Radiation therapy uses **specific information**: Position, geometry and components of organs, density of tissues, internal motion,…
- Radiation therapy make use of a large number of **different modalities** which has increased with time due to technology advances.

Image data in RO can be classified in 2 categories



Paradigm shifts in RT guidance



Current imaging paradigm in RO

Imaging is pervasive in RO :

❖ RO is image-based in three aspects:

1. For the **definition of volumes** during planning ☞localization
2. For the **simulation of treatment** ☞virtual simulation
3. For the **correction** of the ballistic during treatment ☞guidance

❖ Images for RO are multimodal (CT,MRI, PET, SPECT, …, CBCT, MVCT, US, MR-linac…).

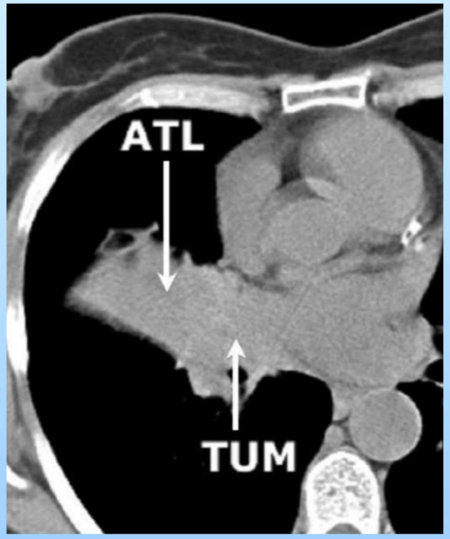
DICOM Images for RO are compliant with the DICOM standard (*Digital Imaging and COmmunications in Medicine)* for display, storage, transfer and links.

Hierarchical key questions for your use of imaging in RO

1. *Does the imaging modality allow you to differentiate the target volume from its environment?*

Problematic of delineating lung tumor adjacent to ateleclectasy:

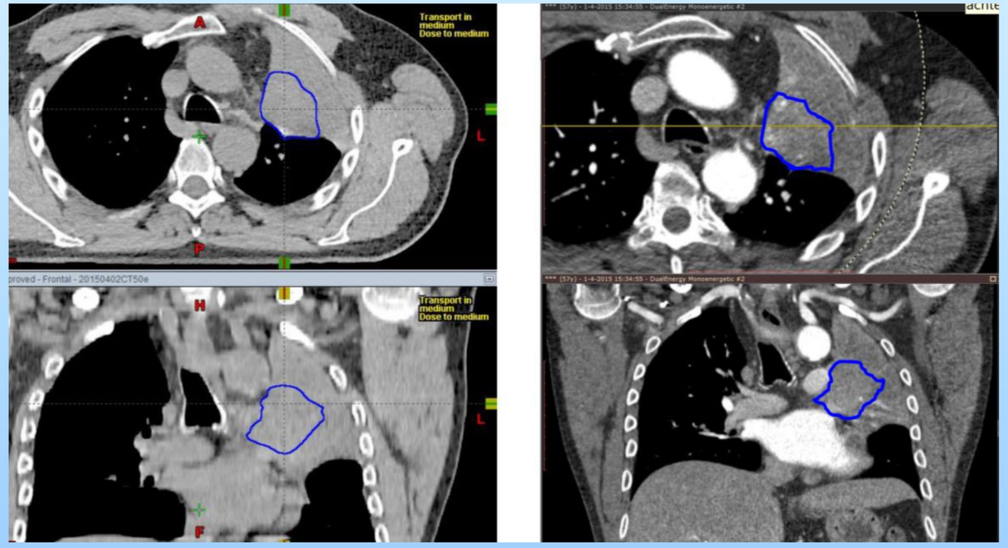
Example of quasi impossible delineation



Kovalev et al 2007, ISBN 1 901725 33 2

Workaround: dual CT for contrast enhancement (combination of 2 RX energies)

Standard CT



Dual energy CT

Wouter van Elmpt 2016, MAESTRO

Hierarchical key questions for your use of imaging in RO

1. *Does the imaging modality allow you to differentiate the target volume from its environment?*
2. *Does the imaging modality reflect the true anatomy?*
   - *Artefacts*
   - *Partial volume effect*

Artefacts $_{1/2}$

Definition:

An artefact is any visible structure which does not reflect the reality of the patient anatomy (wrong CT numbers)

Artefacts may be patient related:

a. Metallic objects inside the body (prothesis, clip, dental filling,…)

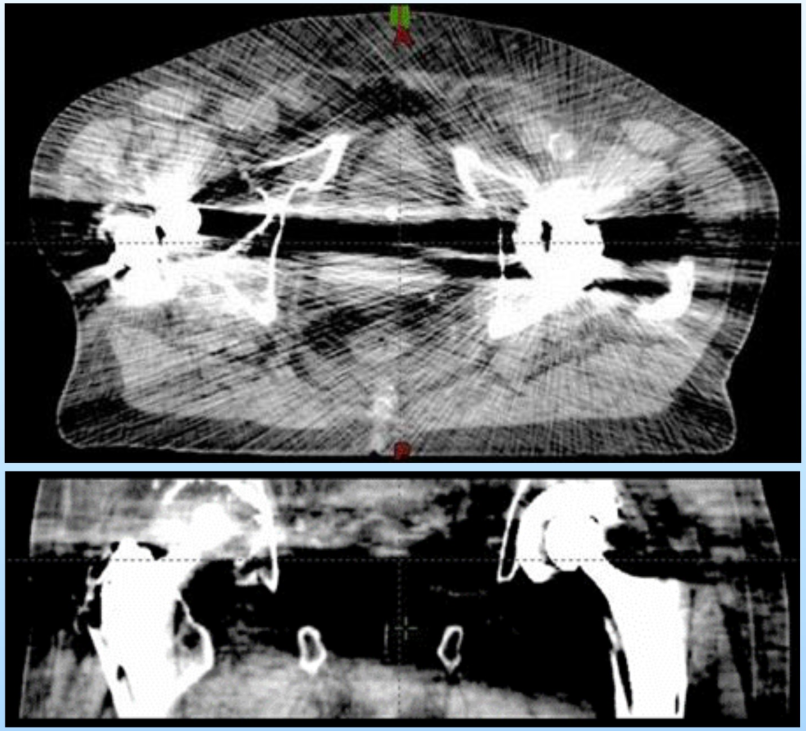
b. Patient voluntary or involuntary motions (blurring)

c. Field of view smaller than patient size (obese patients)

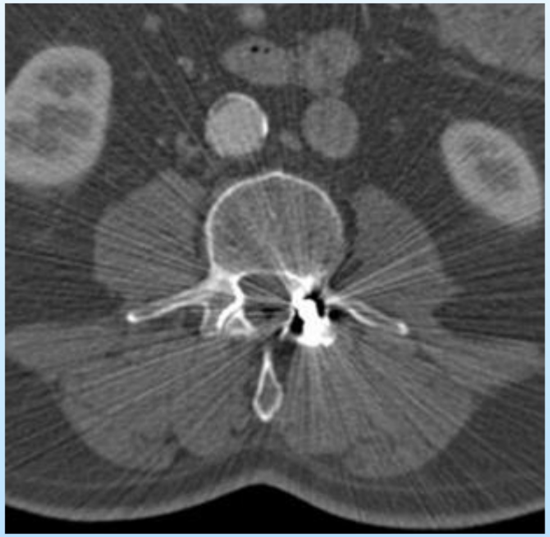
Metalic CT artefacts $_{2/2}$

Examples of streaks due to metal inside the patient:

Double hip prothesis



Brilliance Big Bore, Courtesy of Triemli

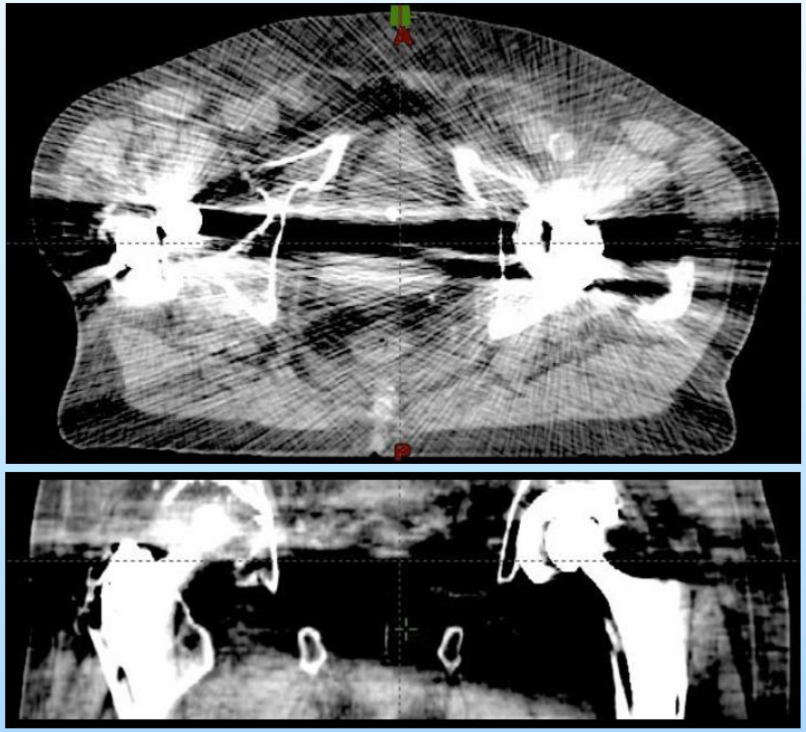


Disk prothesis

Metalic CT artefacts $_{2/2}$

Examples of streaks due to metal inside the patient:

Double hip prothesis



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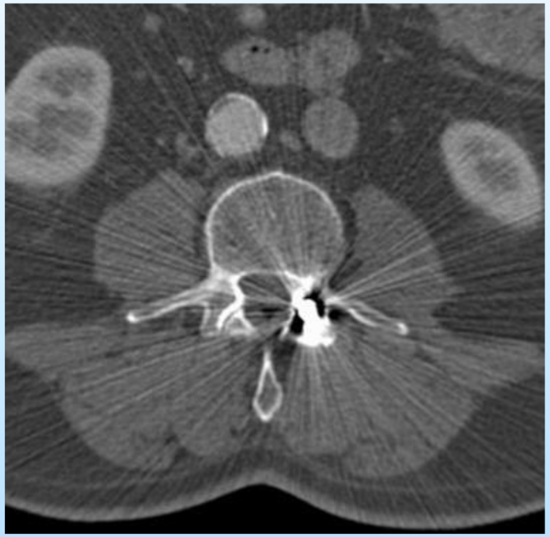
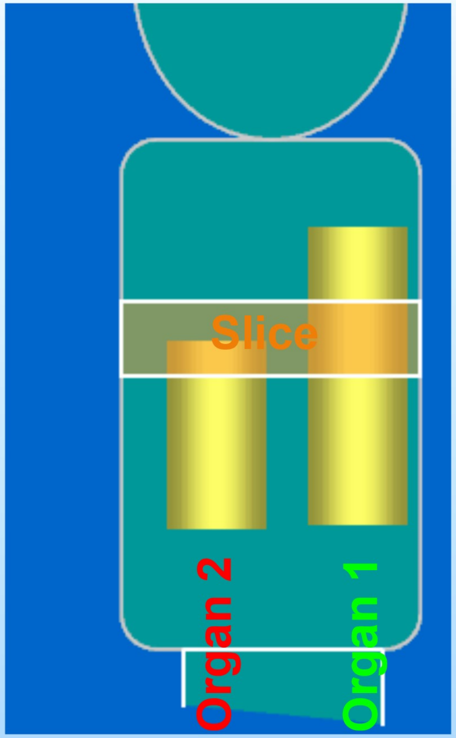


Disk prothesis

Workaround: use special protocols (example Philips O-MAR) or MV imaging or reduce pitch

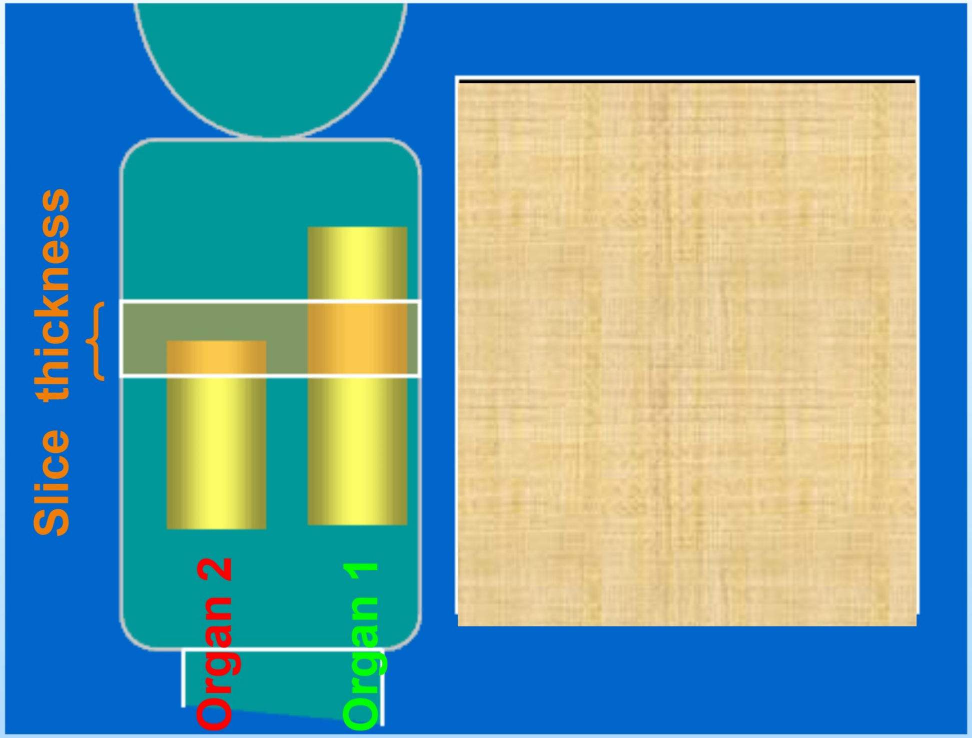
Partial volume effect 1/2

Examples of 2 organs with the same electronic density



Partial volume effect 1/2

Examples of 2 organs with the same electronic density



Definition:

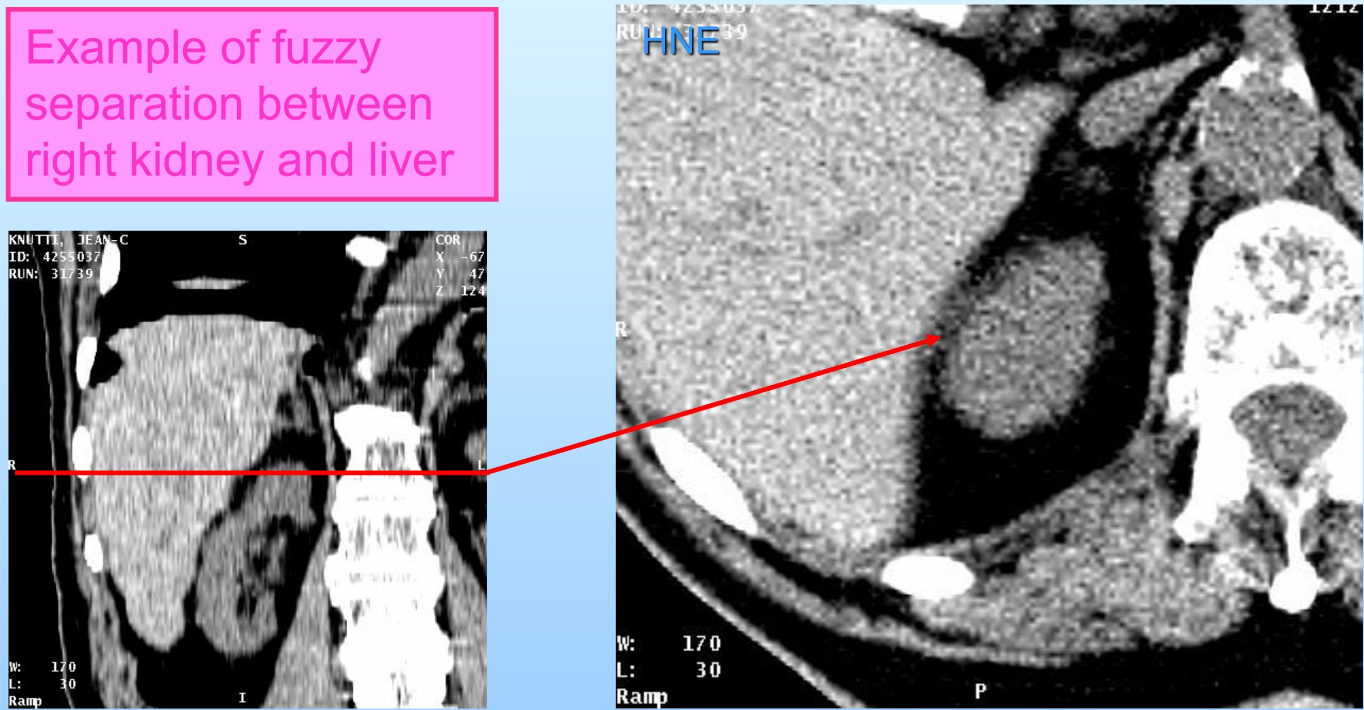
The partial volume effect is the part of an organ which has a reduced contrast due to finite extension in the cranio-caudal direction

Partial volume effect $_{2/2}$

Negative consequences:

- Organ longitudinal extension is seen smaller than reality (⚠ GTV)
- Small objects like lymph nodes are showing low contrast
- Partial volume effect is worsen if organ is moving
- Adjacent organ borders can be blurred

Example of fuzzy separation between right kidney and liver

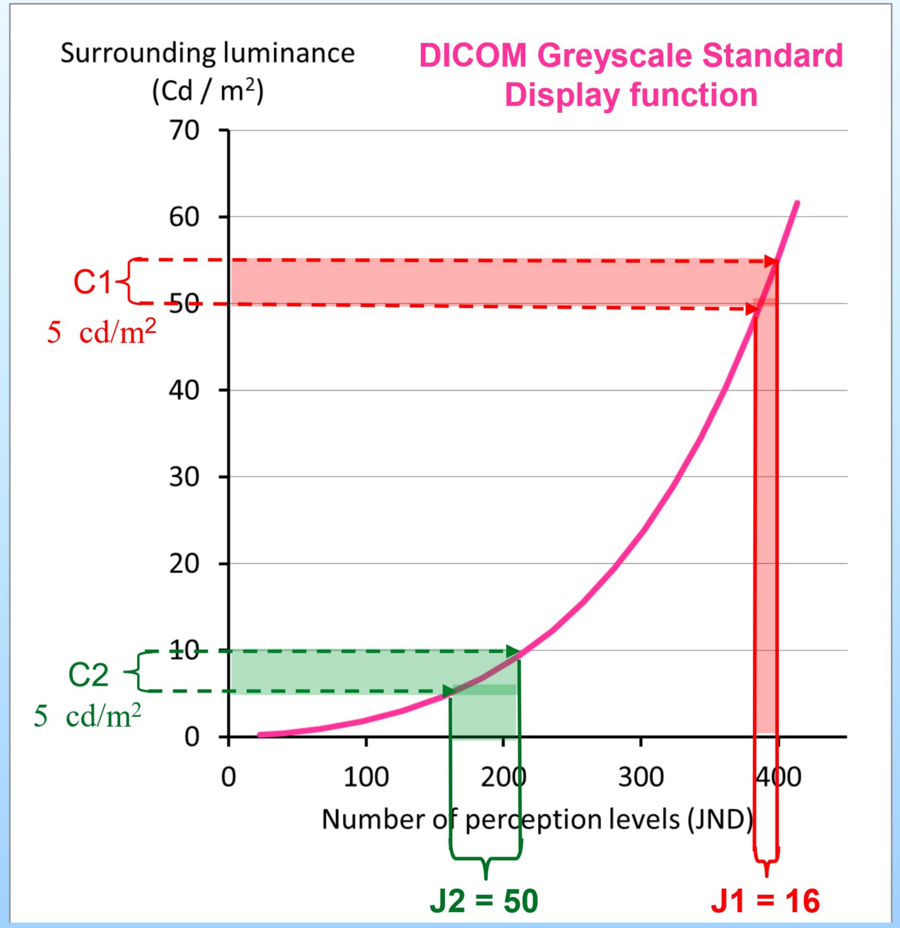


Hierarchical key questions for your use of imaging in RO

1. *Does the imaging modality allow you to differentiate the target volume from its environment?*
2. *Does the imaging modality reflect the true anatomy?*
3. *Does the image display allows the observer to visually perceive the target volume?*
   a. Sensitivity of human eye (example: edge perception)
   b. Image filtering
   c. Contrast adaptation
   d. Visual windowing

a. Sensitivity of the human eye

Barten's model of visual perception:



- Human eye is more sensitive in the low luminance range (Weber-Fechner law of psycho-physics)
- A change in lighting leads to a more discernible gray levels at low luminance:

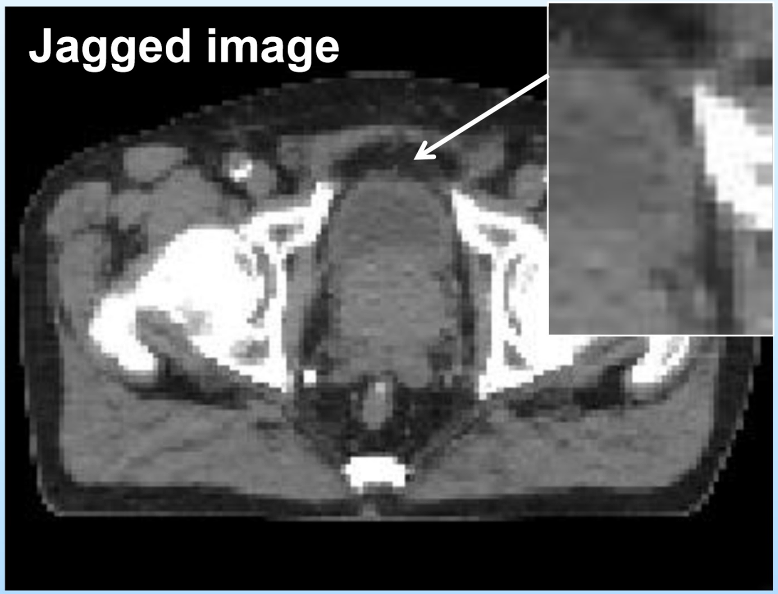
  C1= C2 → J1 << J2

- **Delineate in rooms with reduced ambient light (15- 60 lux)**

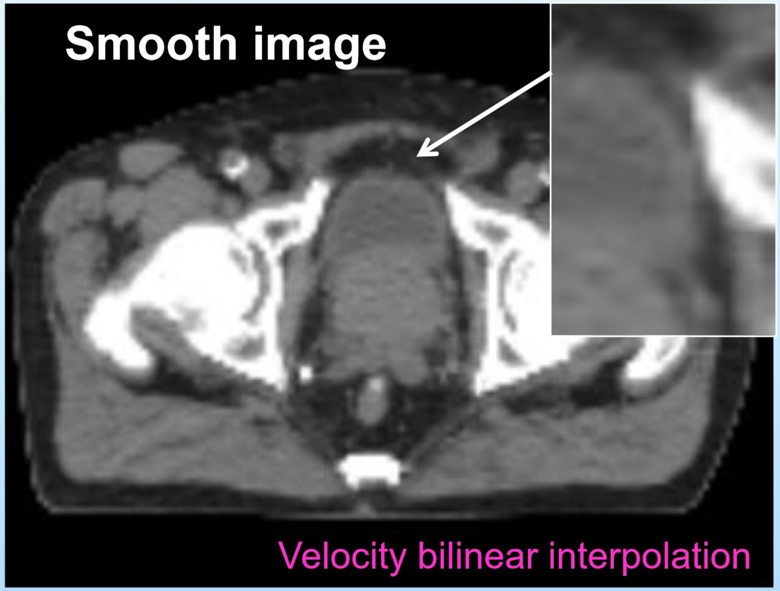
b. Image filtering

Images are displayed using interpolation techniques

Raw 256x256 pixels data as stored in TPS

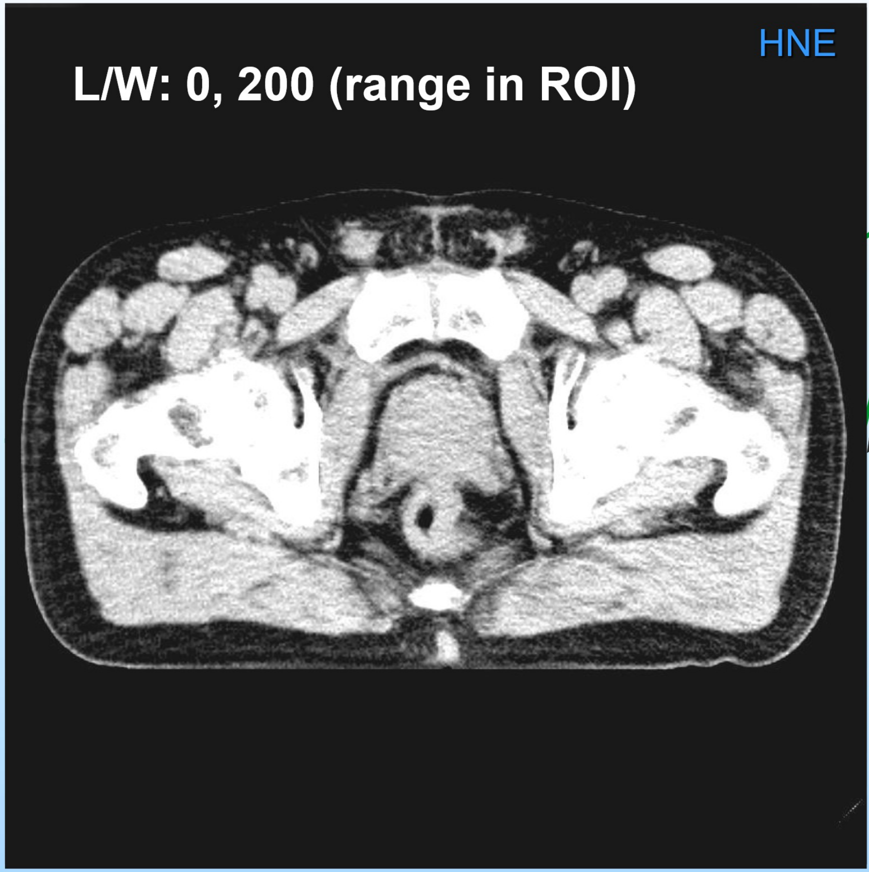


Interpolated images for display (bilinear, bicubic, …)

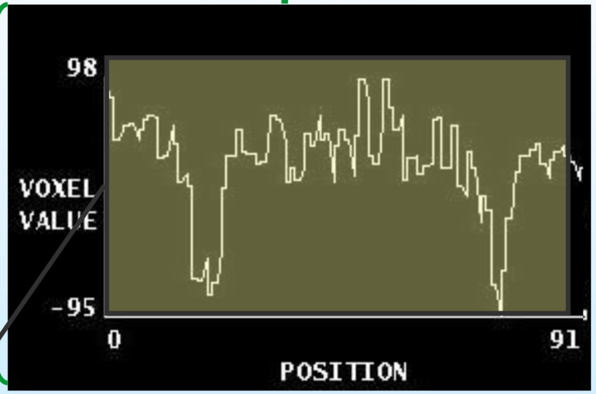


⚠ Automatic contouring methods (thresholding) could be using raw data, leading to jagged contours which unless smoothed by postprocessing

c. Visual contrast adaptation



HN profile

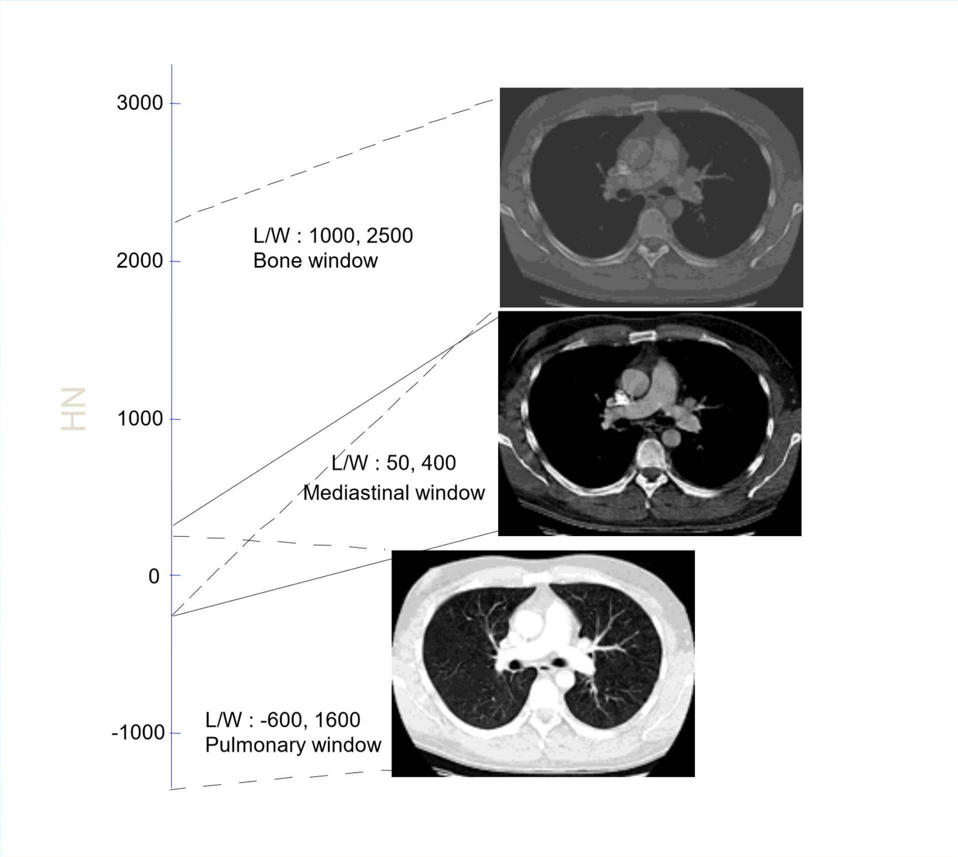


1. Dispay a full profile
2. Zoom in on VOI
3. Set L/W to average, range of VOI HN's

Automatic protocols are nowadays implemented in imaging software in function of localisation

d. Visual windowing

- Display of only a subset of the whole Hounsfield scale
- Choice of the level (L) and the window (W) from definite protocols
- Anatomy with HN>L+W/2 is shown as white, with HN<L-W/2 as black

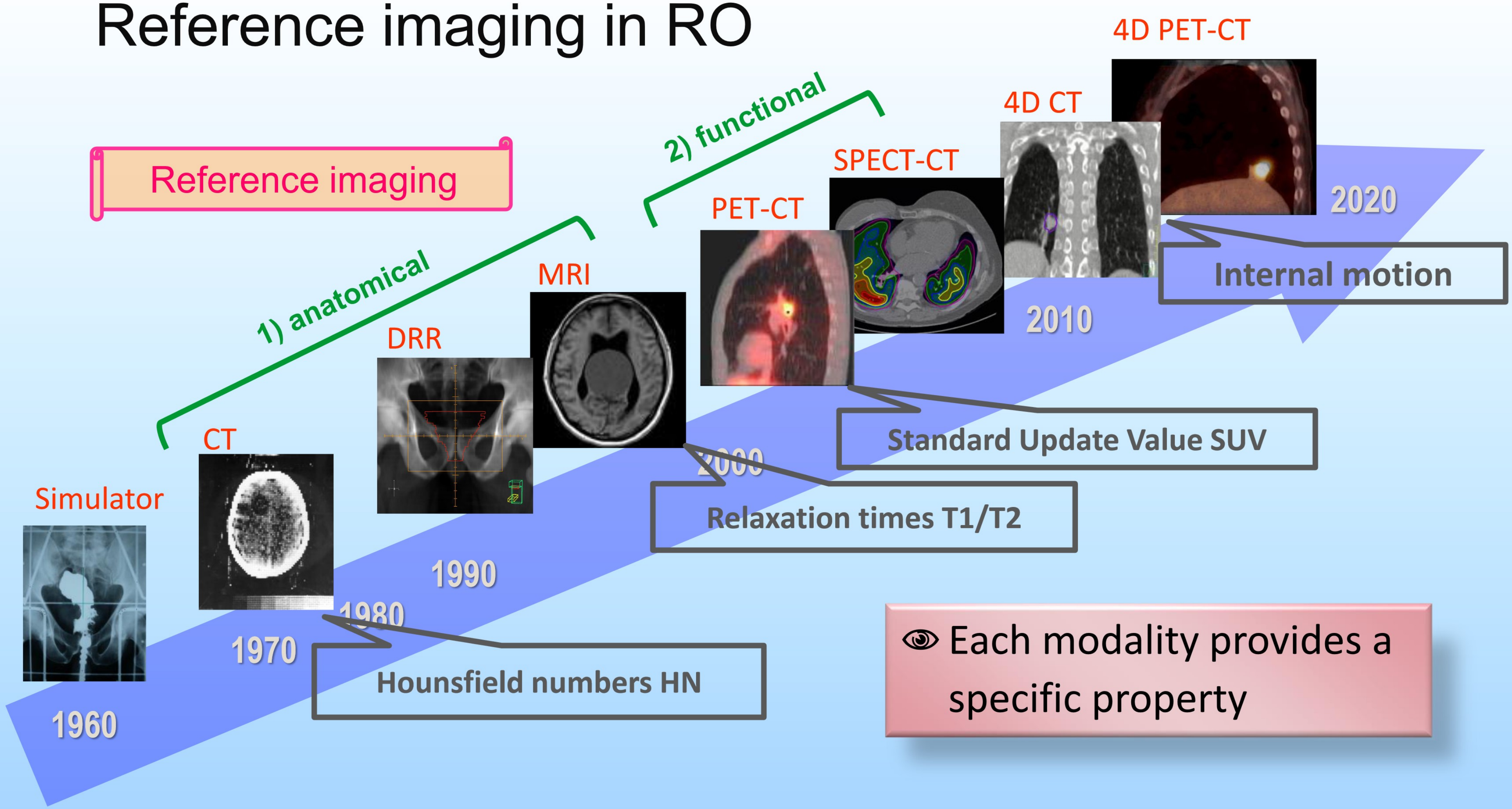


The choice of the window can influence the delineation of organs

→ Use always a window setup from the same protocols


Reference
imaging

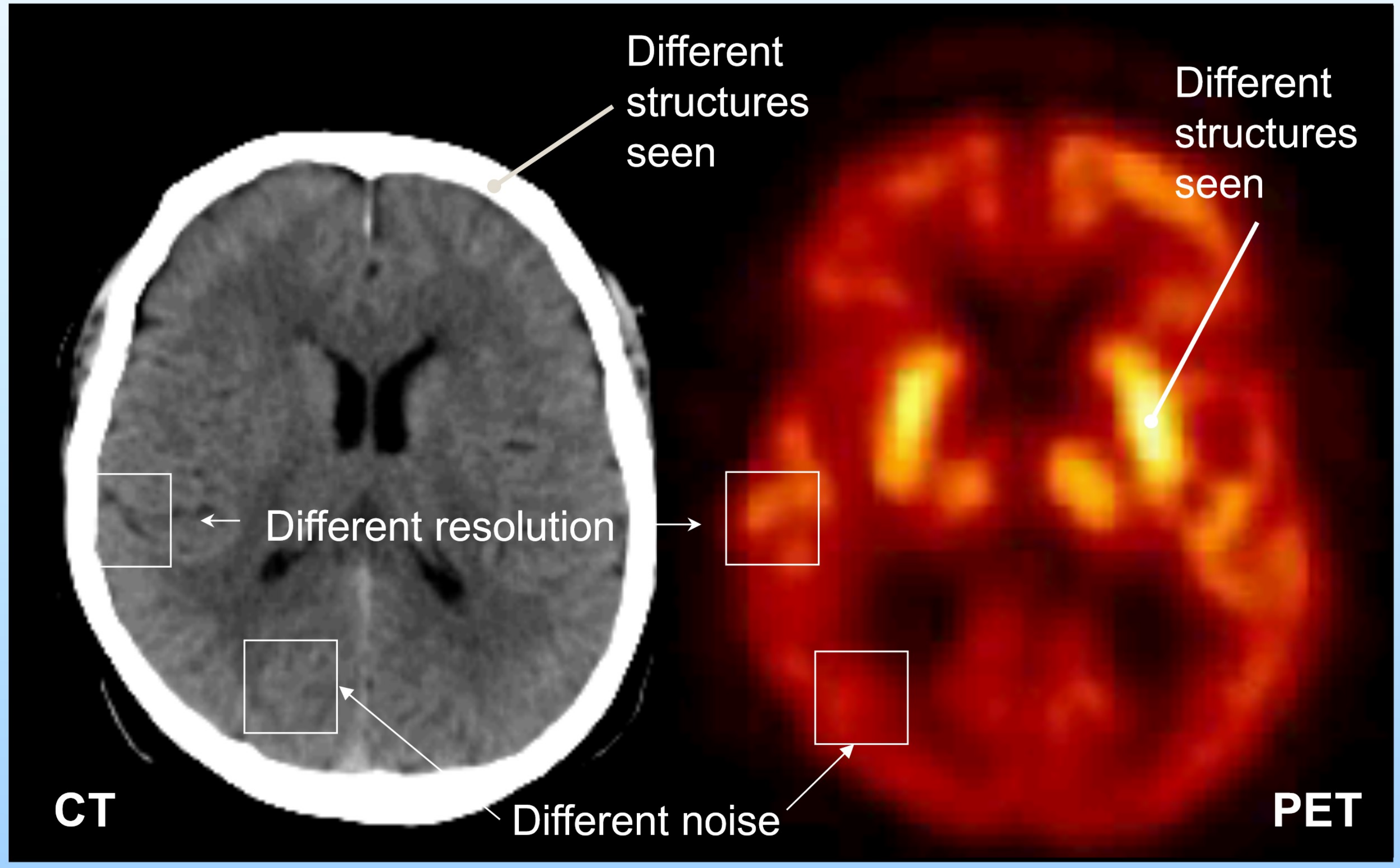
Reference imaging in RO



👁 Each modality provides a specific property

Example of different modalities characteristics

structural against functional



From_F. Schoenahl , Cours CFPFTRM, 2005

Current imaging paradigm in RO 3/5

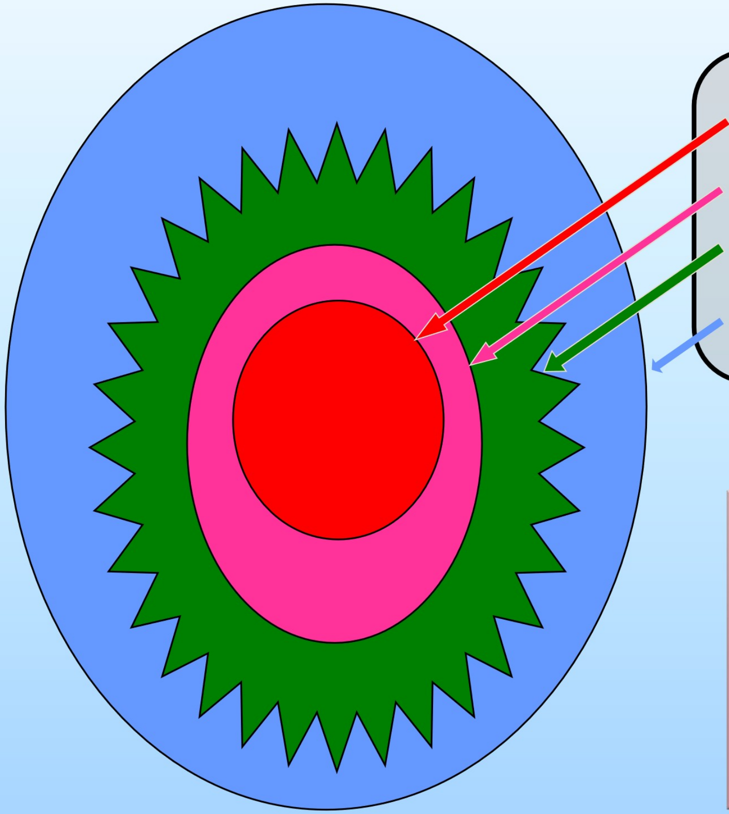
Main characteristics for various reference modalities:

Technique	Clinical resolution	Temporal resolution	Sensitivity / Specificity	Tumour discrimination
Radiography	5mm	excellent	good / poor	poor
CT	0.5 mm	good	good / poor	good
MRI	0.5 mm	poor/good	good / good	excellent
PET/SPECT	5 mm	poor	good / good	good
MRS	6 mm	poor	good / excellent	excellent

From Smith A. and K.S. Clifford Chao, Radiation Research, 2005

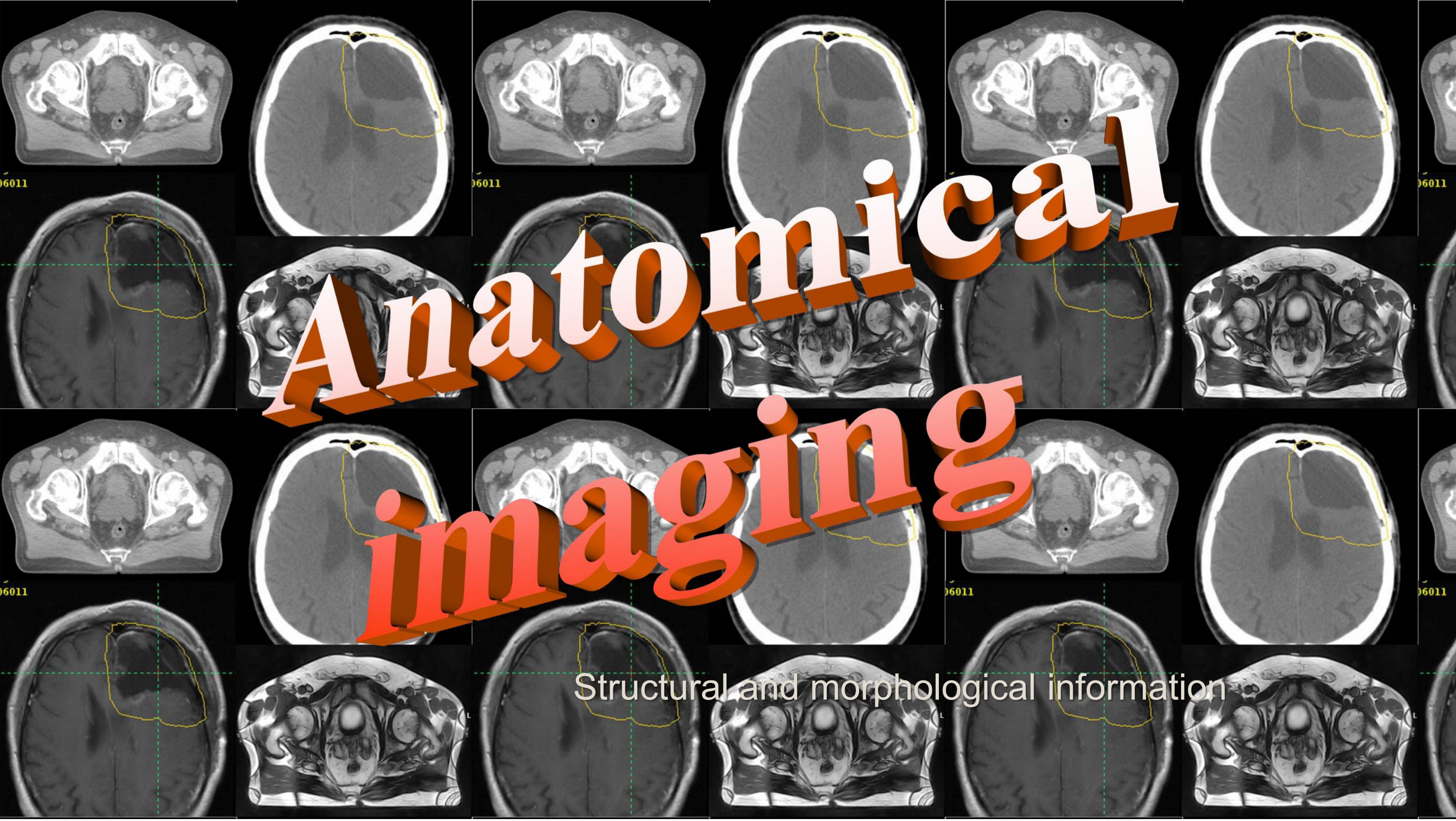
Reference anatomical definition

Normative definition of volumes: **ICRU 50, 62 & 83**



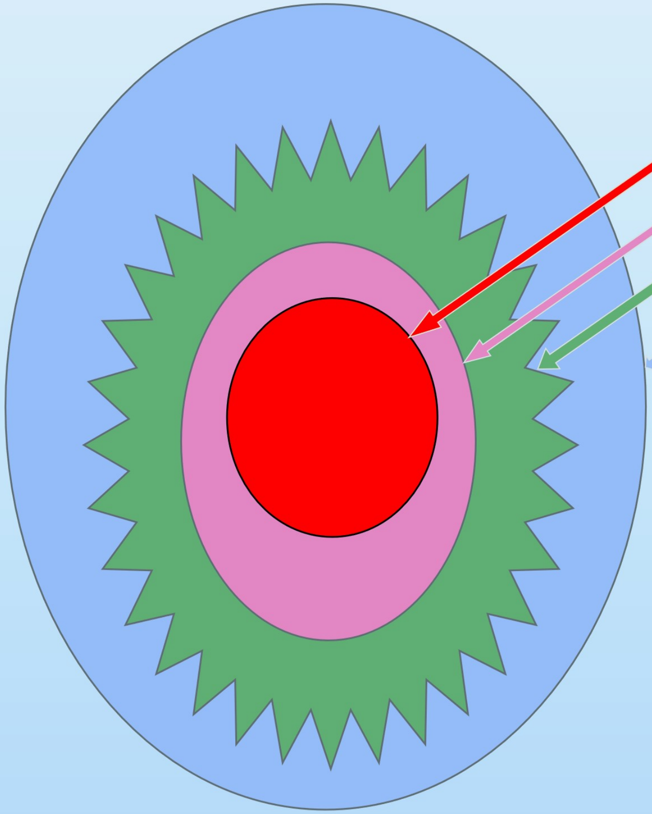
GTV :	Gross Tumor Volume
CTV:	+ subclinical involvement
ITV:	+ Internal margin
PTV:	+ Setup margin

Imaging techniques in RO aim to provide the necessary tools for delineating or checking these ICRU volumes


Anatomical imaging
Structural and morphological information
06011

Paradigm of target volumes delineation

Normative definition of volumes: **ICRU 50, 62 & 83**



GTV : Gross Tumor Volume
CTV: + subclinical involvement
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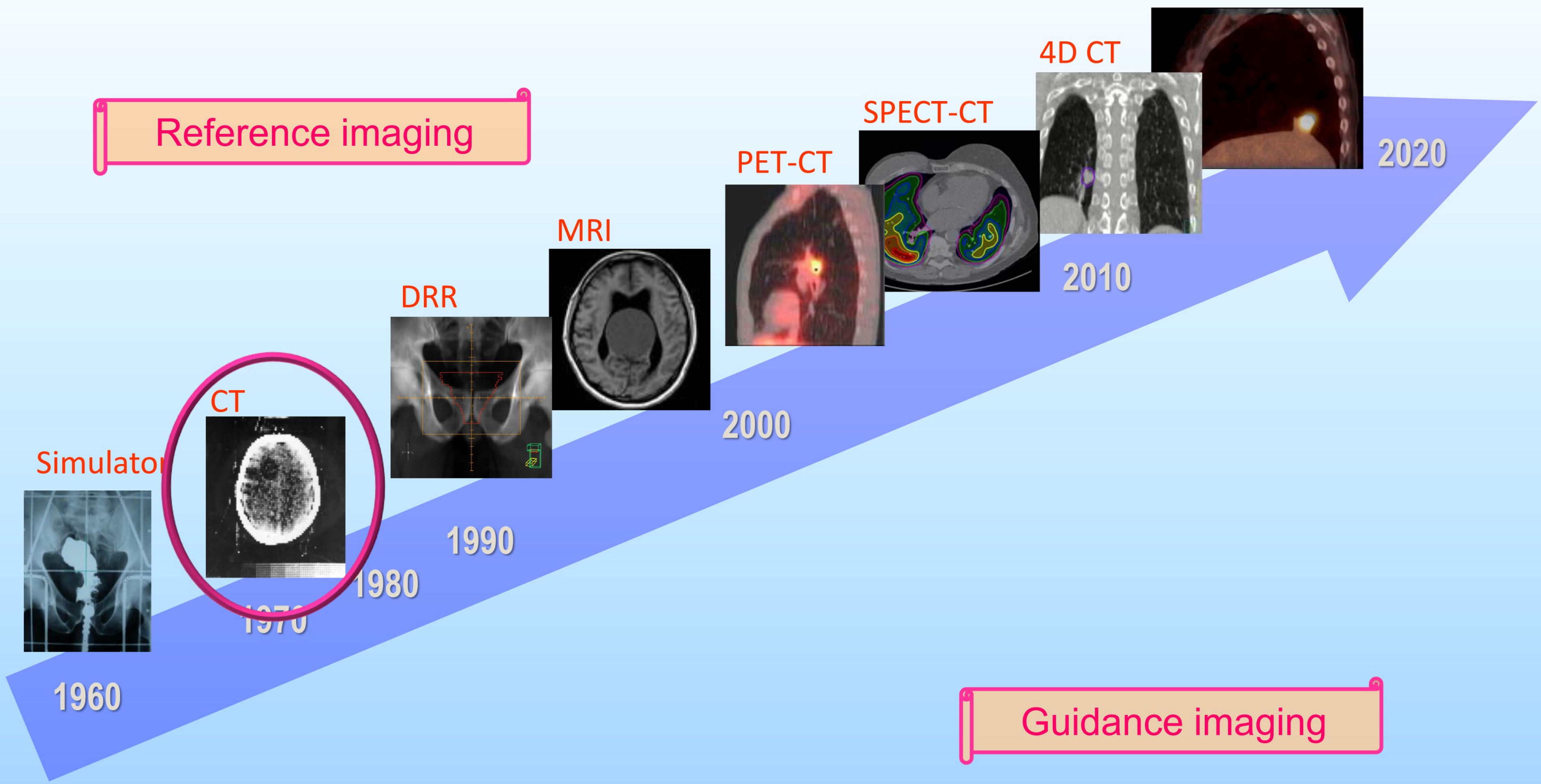
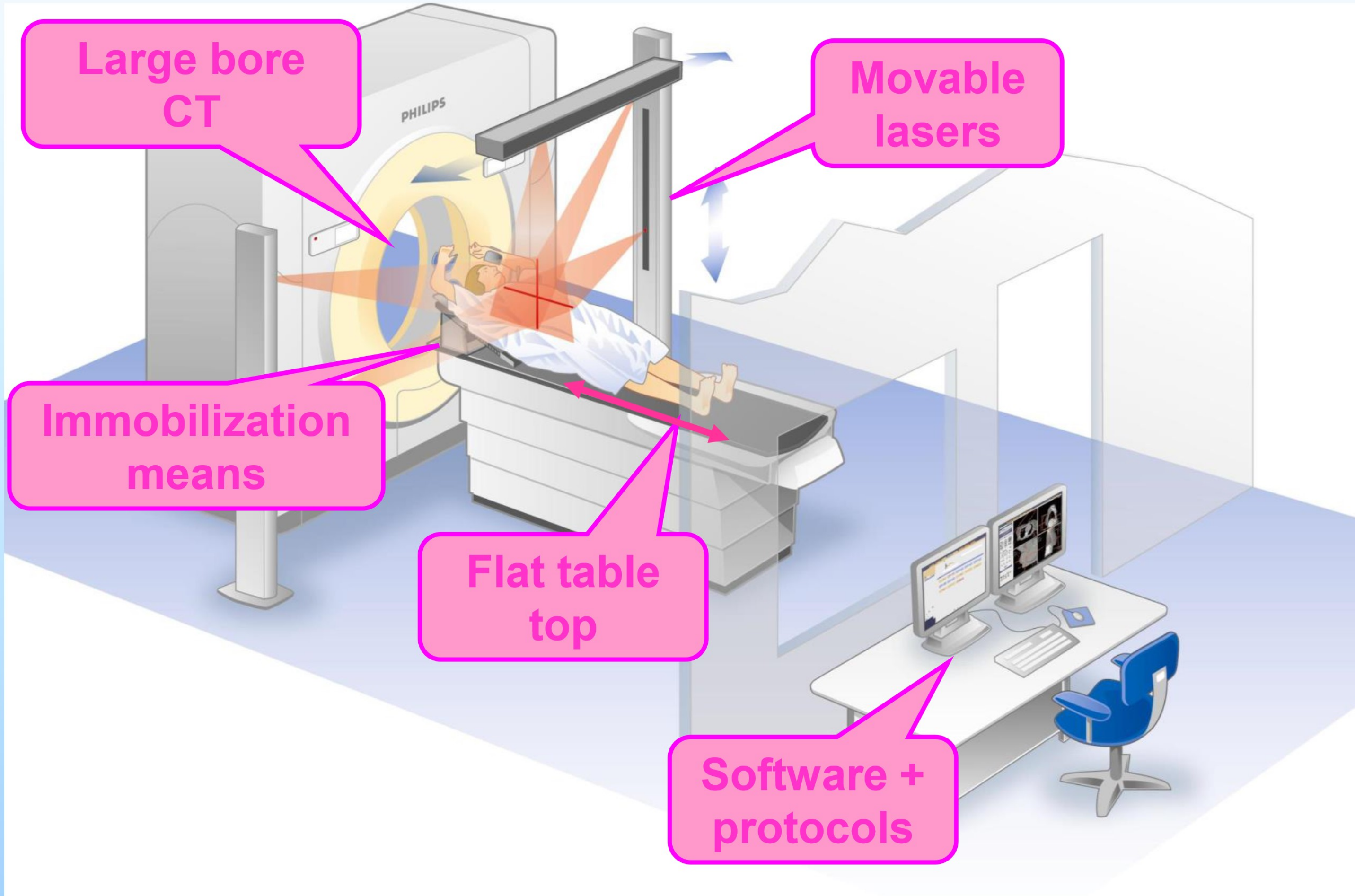
PTV: + Setup margin

Anatomical imaging in RO is the primary choice for delineating the GTV

Image data in RO



Computer Tomography equipment for RO



Artist view, courtesy of Philips Medical Systems

Images are calibrated using Hounsfield scale

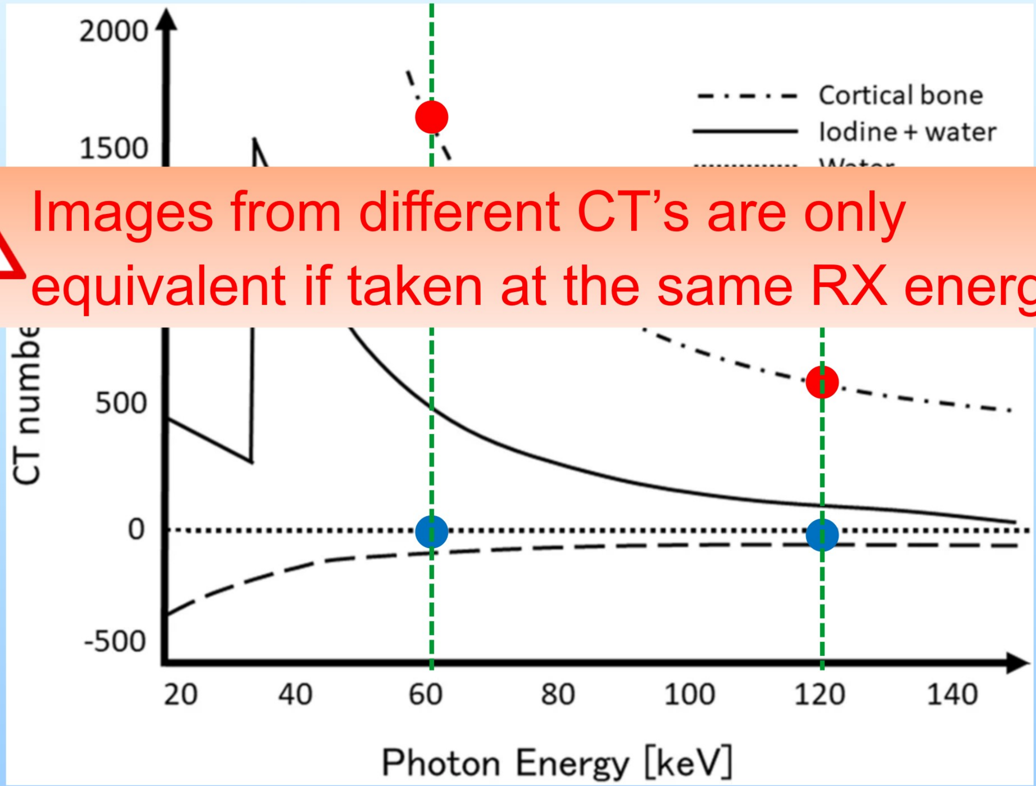
- Hounsfield numbers (HN) = Tissue absorption coefficients μ compared to water
- $HN = 1000 * \left(\frac{\mu_{Tissue} - \mu_{Water}}{\mu_{Water}} \right)$ => Normalized scale

Common used abbreviations:

- HN (Hounsfield number)
- HU (Hounsfield unit)
- CT number

Dependence of HN on RX energy

- Hounsfield numbers (HN) = Tissue absorption coefficients μ compared to water
- $HN = 1000 * \left(\frac{\mu_{Tissue} - \mu_{Water}}{\mu_{Water}} \right)$ => Normalized scale



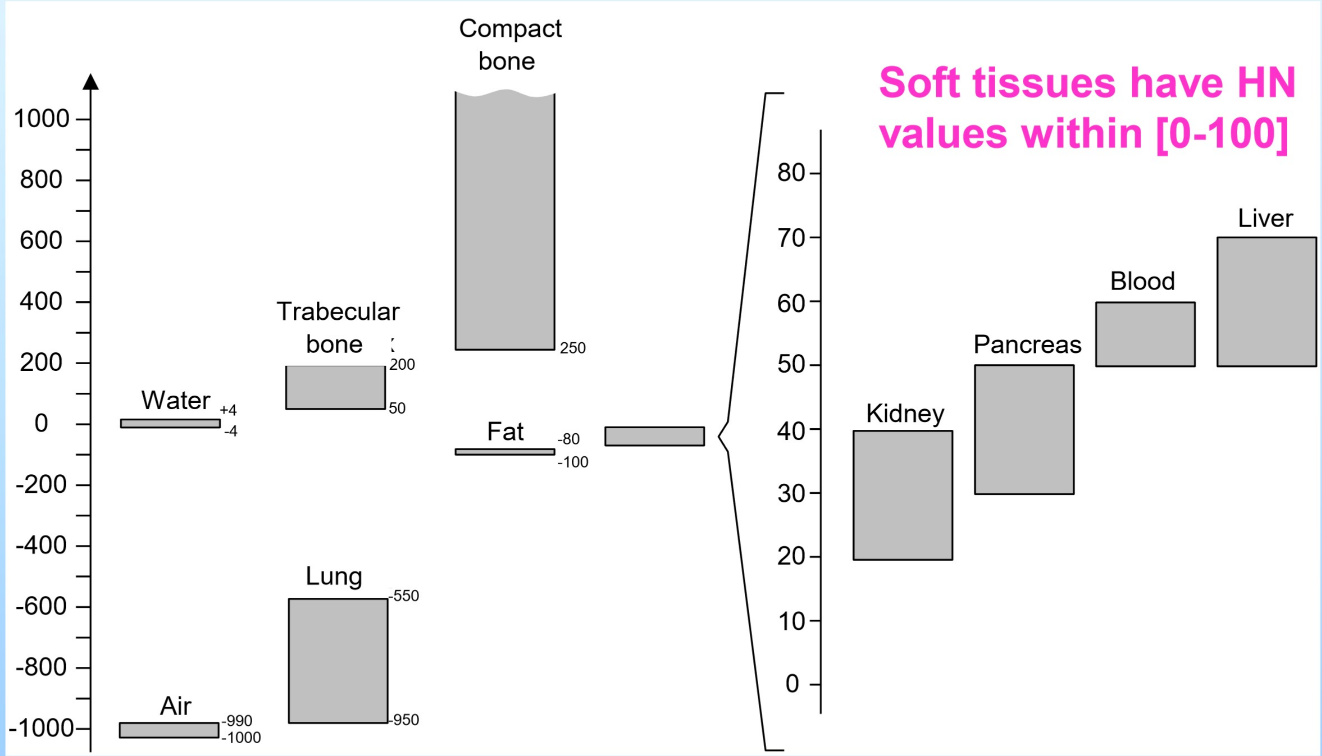
Tatsugami, et al. Japanese Journal of Radiology (2022)

⚠ Images from different CT's are only equivalent if taken at the same RX energy

- By definition, HN of water is energy independent
- HN of cortical bone is energy dependent due to the photoelectric effect (also for iodine)
- This principle of material decomposition is used in dual CT imaging

Standard HN values for typical organs

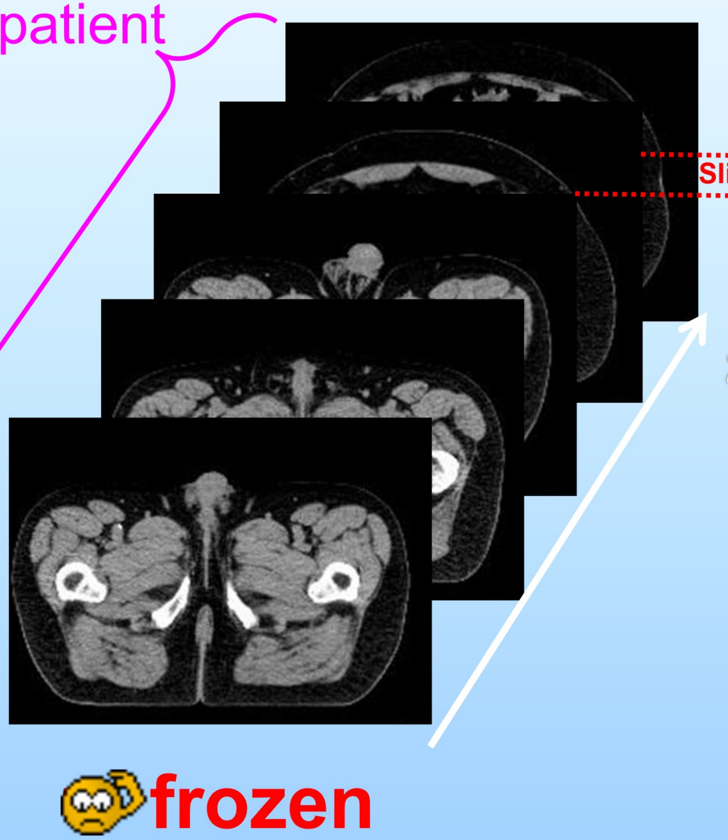
- Hounsfield numbers (HN) = Tissue absorption coefficients μ compared to water
- $HN = 1000 * \left(\frac{\mu_{Tissue} - \mu_{Water}}{\mu_{Water}} \right)$ => Normalized scale




Immersion
into 3D
Volumetric information
Patient Name
ID: 505064
RUN: 6989
PLAN: Prost+vessem
3-D
W: 500
L: 40
Ramp

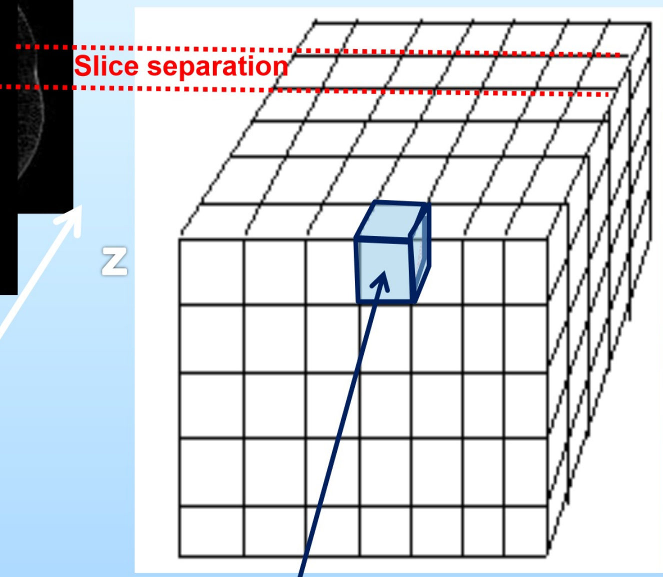
3D model of images

Transverse images are stacked into a 3D virtual patient



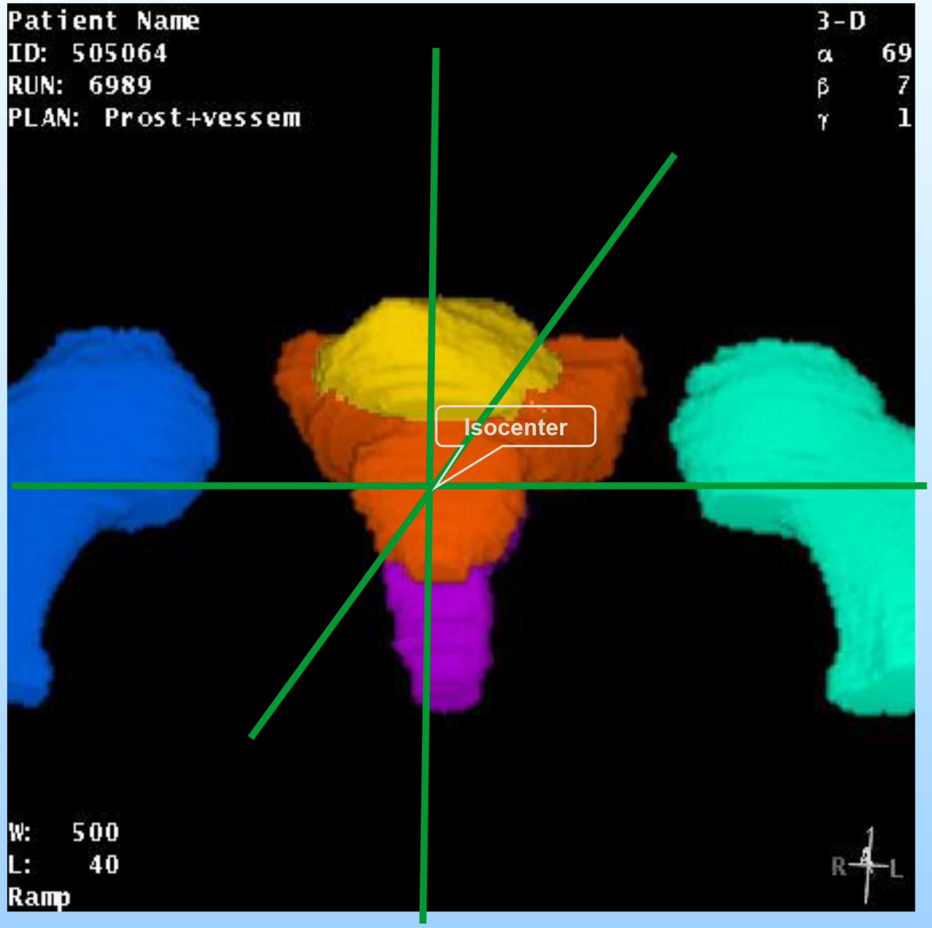
Multidimensional values attributed to each voxel:

HN, SUV, T1, T2, …



Voxel definition

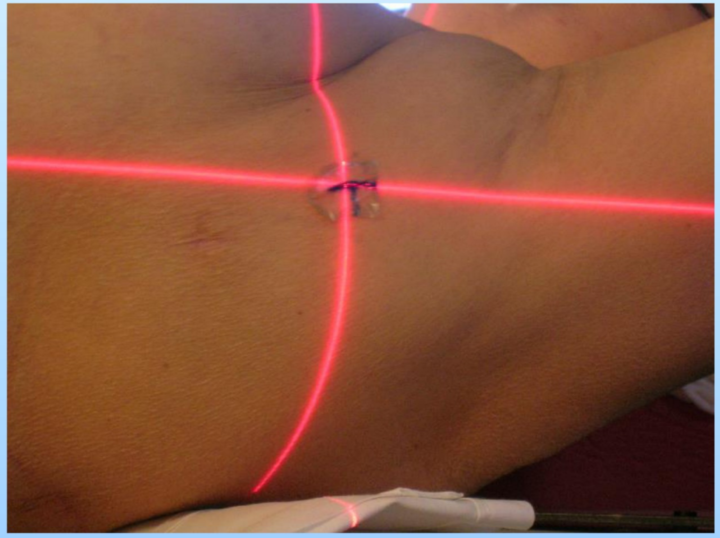
3D model of contours



- The contoured organs are becoming geometrical 3D objets
- The isocenter (barycenter) of the target volume (GTV) is defining the position of the objects system
- The isocenter is spotted by an orthogonal system of coordinates

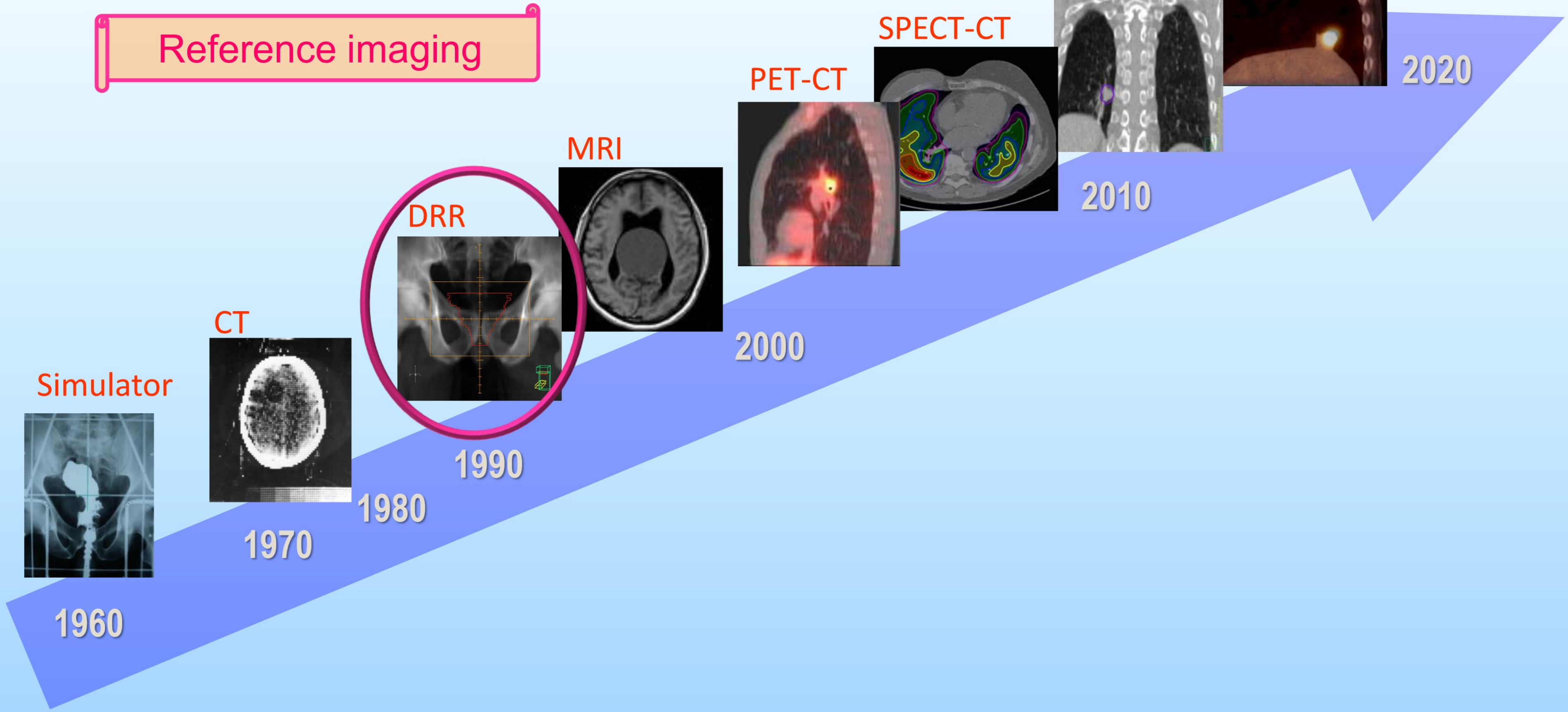
Patient marking

- The lasers system mimics the orthogonal system of coordinates



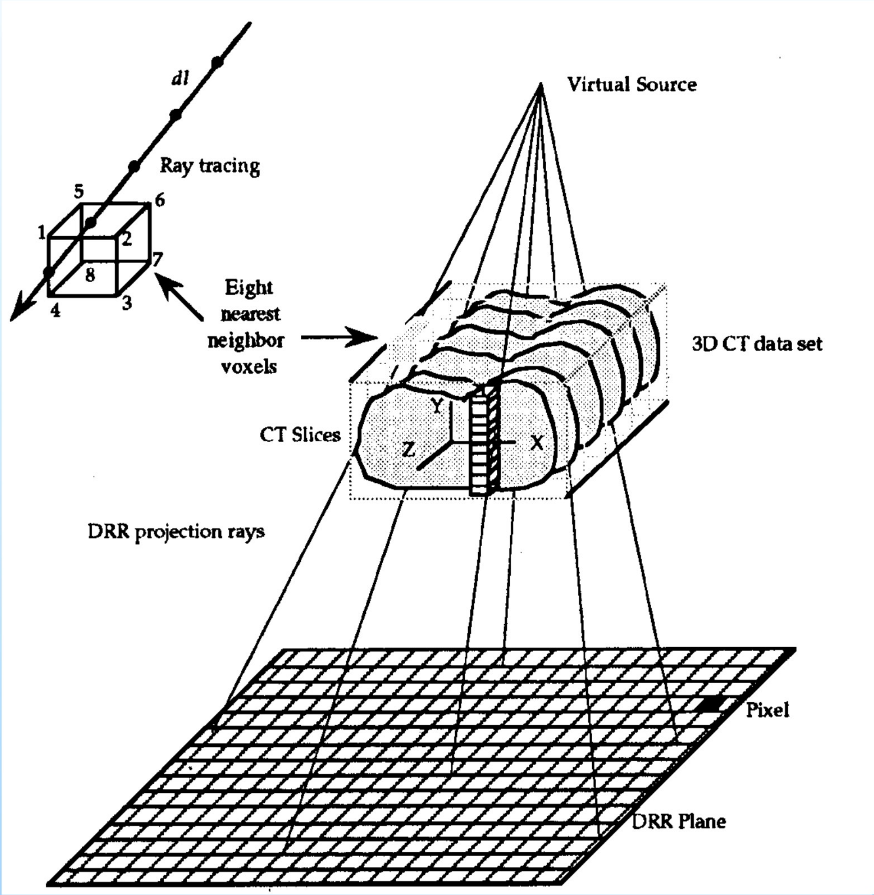
- The patient is usually tattoed at the lasers intersections with the skin

Image data in RO



Techniques of DRR's reconstruction

DRR = Digitally Reconstructed Radiograph



Reconstruction algorithm:
Abrams et Goitein, 1983

Ray tracing : Siddon's method

↓

Interpolation : Trilinear or cubic

↓

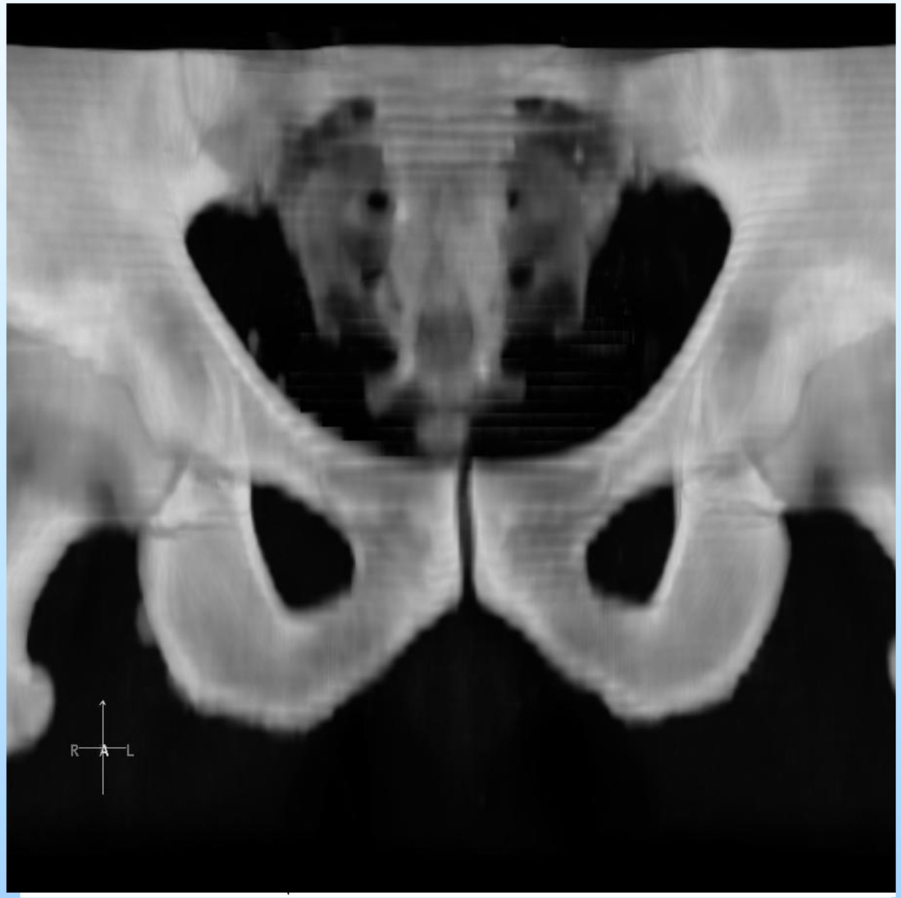
Absorption : Curved integration

↓

Windowing : Remapping LUT table

Techniques of DRR's reconstruction

DRR = Digitally Reconstructed Radiograph



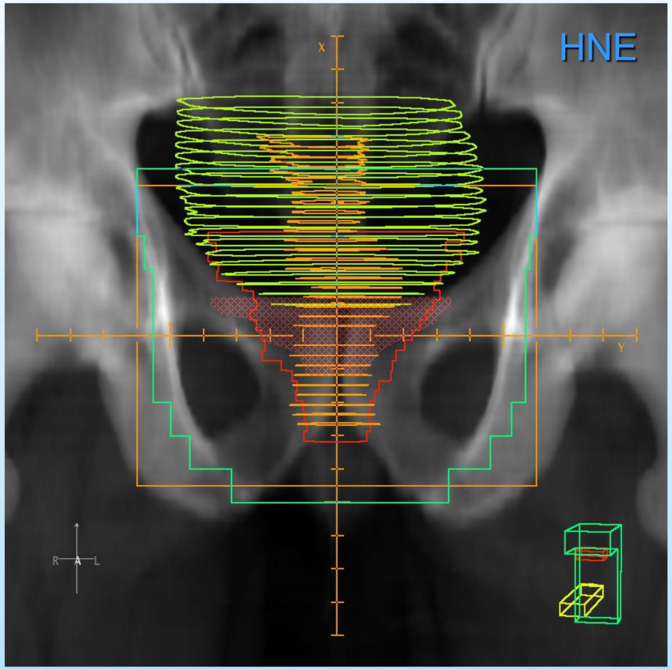
Reconstruction algorithm:
Abrams et Goitein, 1983

Ray tracing : Siddon's method
→ Interpolation : Trilinear or cubic
→ Absorption : Curved integration
→ Windowing : Remapping LUT table

⚠ ⚠ **Projective image from reconstructed images**

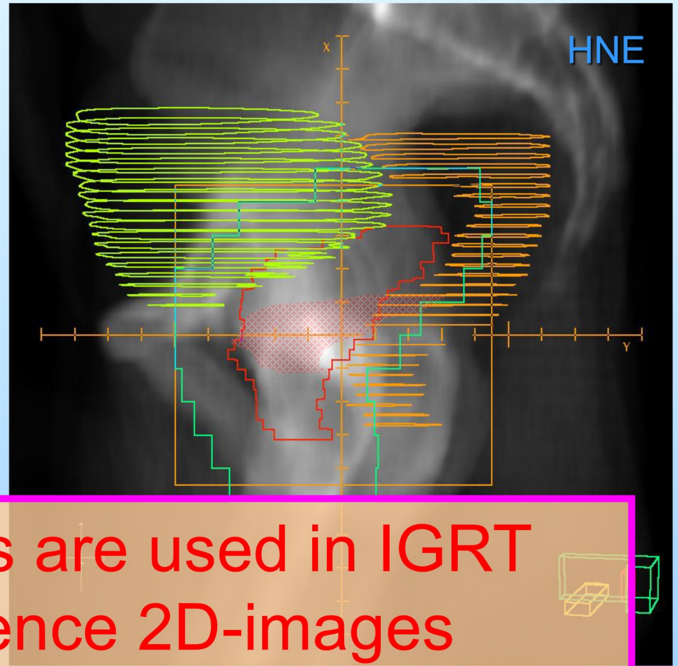
Use of DRR in Beam Eye View

Example of MLC conformation for a 4-fields prostate treatment :



Anterio-Posterior beam

Overlay of structures on top of DRR's (augmented reality)



L-R Lateral beam

☺ DRR's are used in IGRT as reference 2D-images (Portal, Stereo, …)

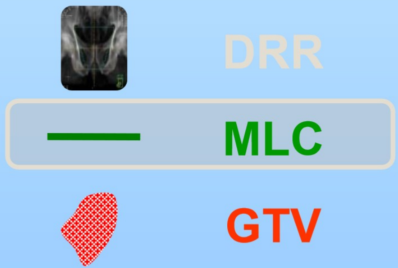
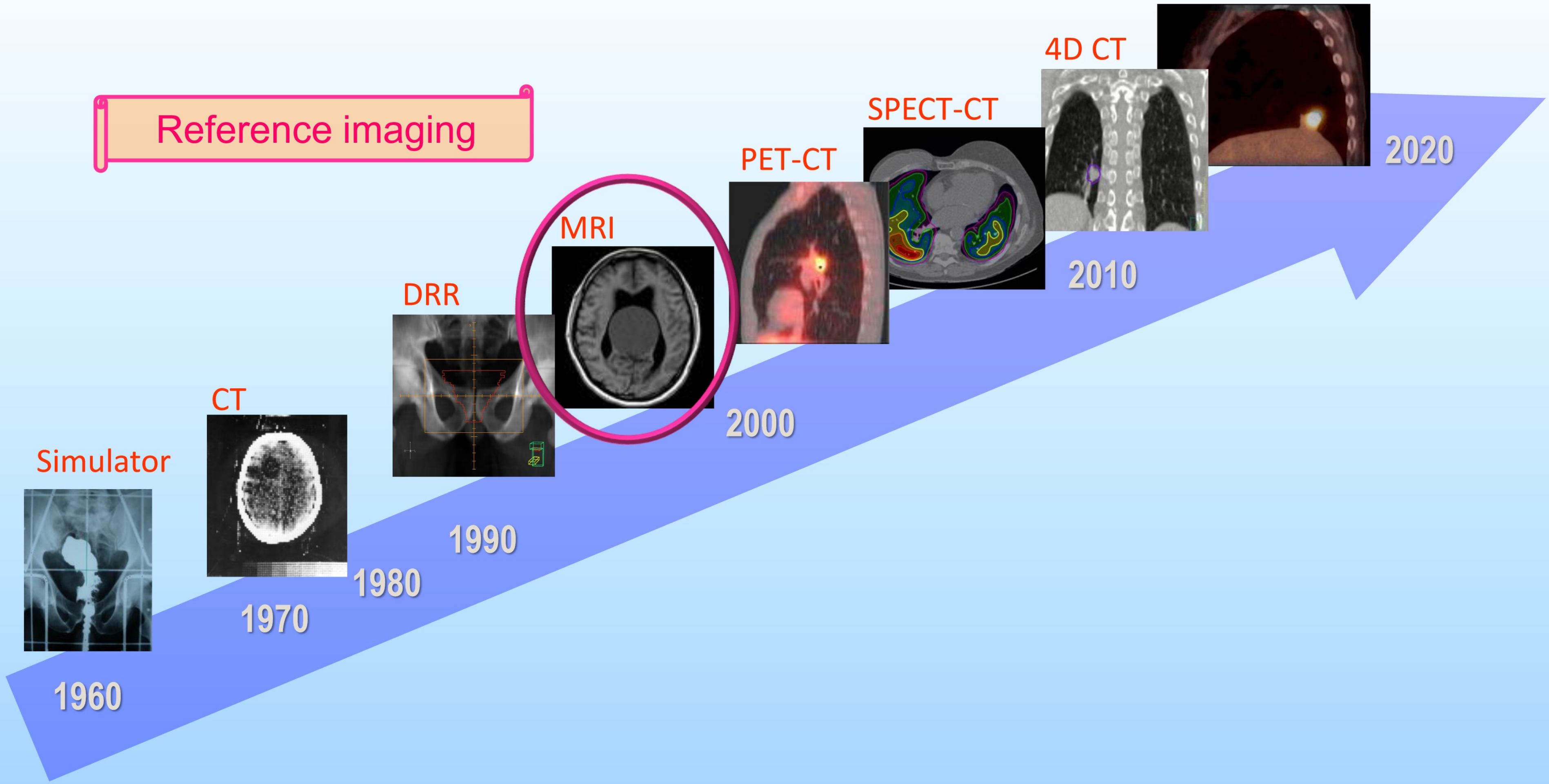
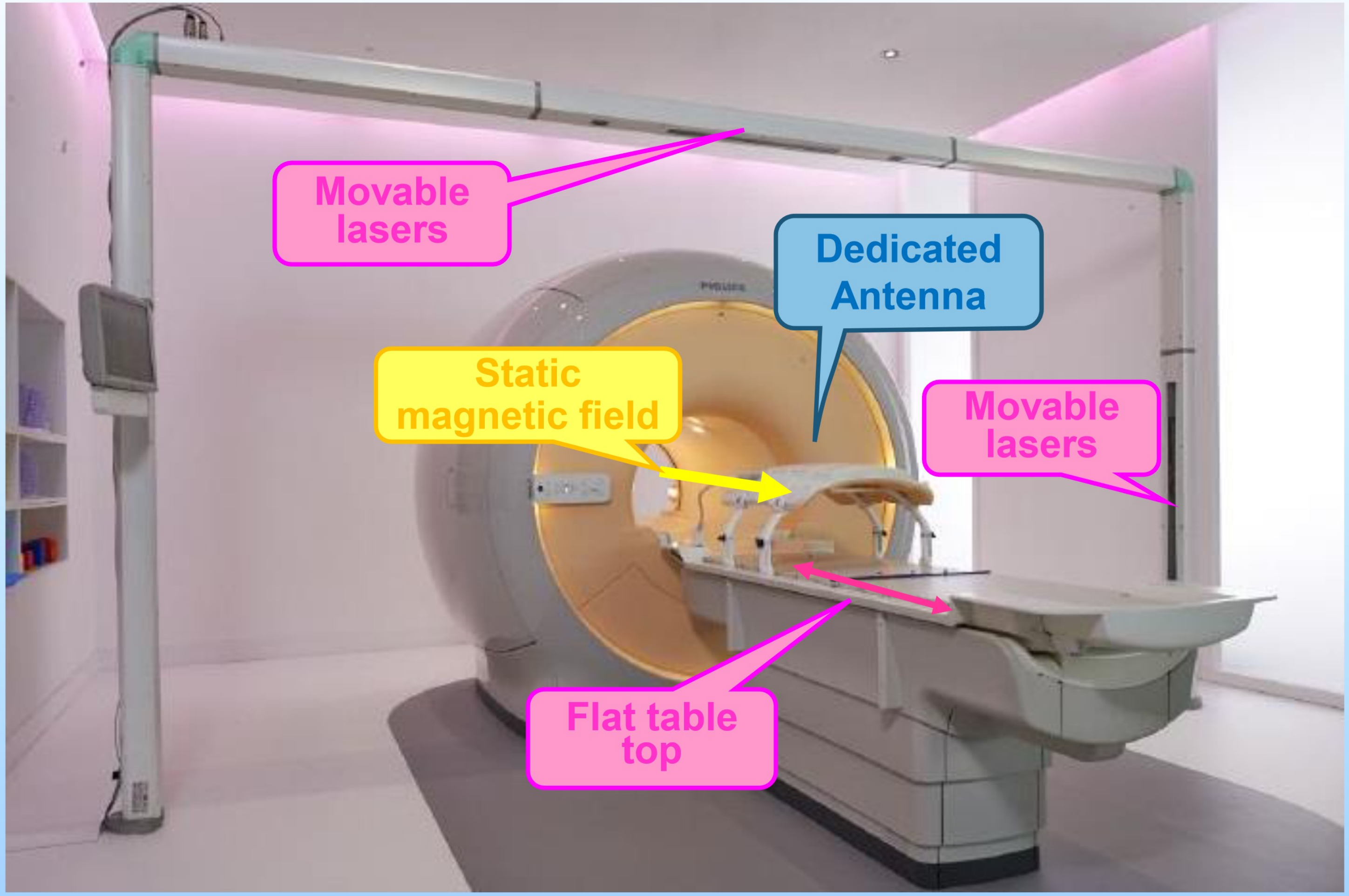


Image data in radiotherapy

Reference imaging



Magnetic Resonance Imaging equipment for RO



Ingenia MR-RT - Philips Medical Systems

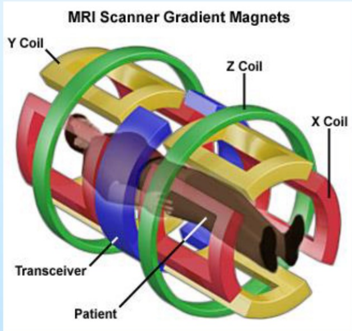
Basic process of MRI

Process in 3 steps:

Magnetisation

The proton spins are aligned by the constant magnetic field

Spin rotation



The rotated proton spins generate electromagnetic wave

Signal detection

The electromagnetic wave is picked up by receiving antenna

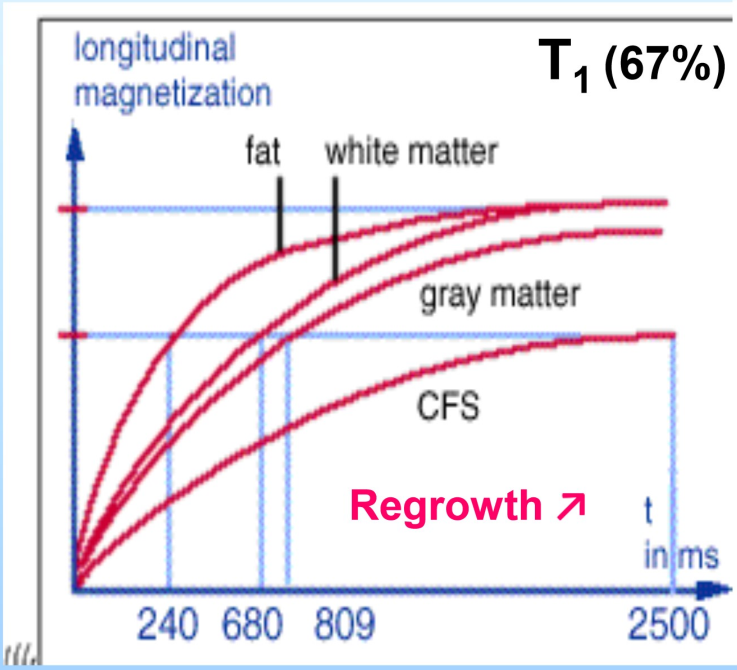
This process provides the time evolution of the spin relaxation

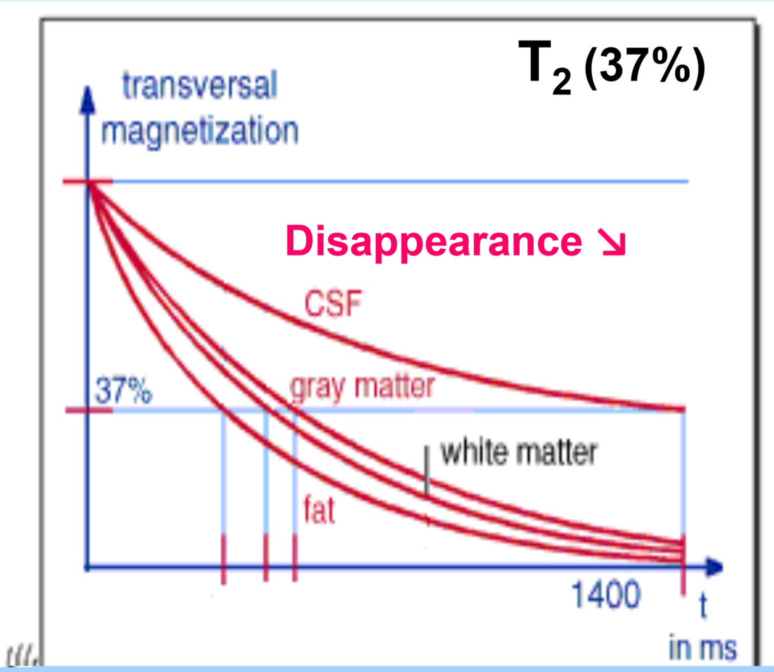
The contrast is obtained by T-weighting

Spin relaxation times measured by special (spin-echo) sequences

- T1: Longitudinal = spin-lattice
- T2: Transverse = spin-spin

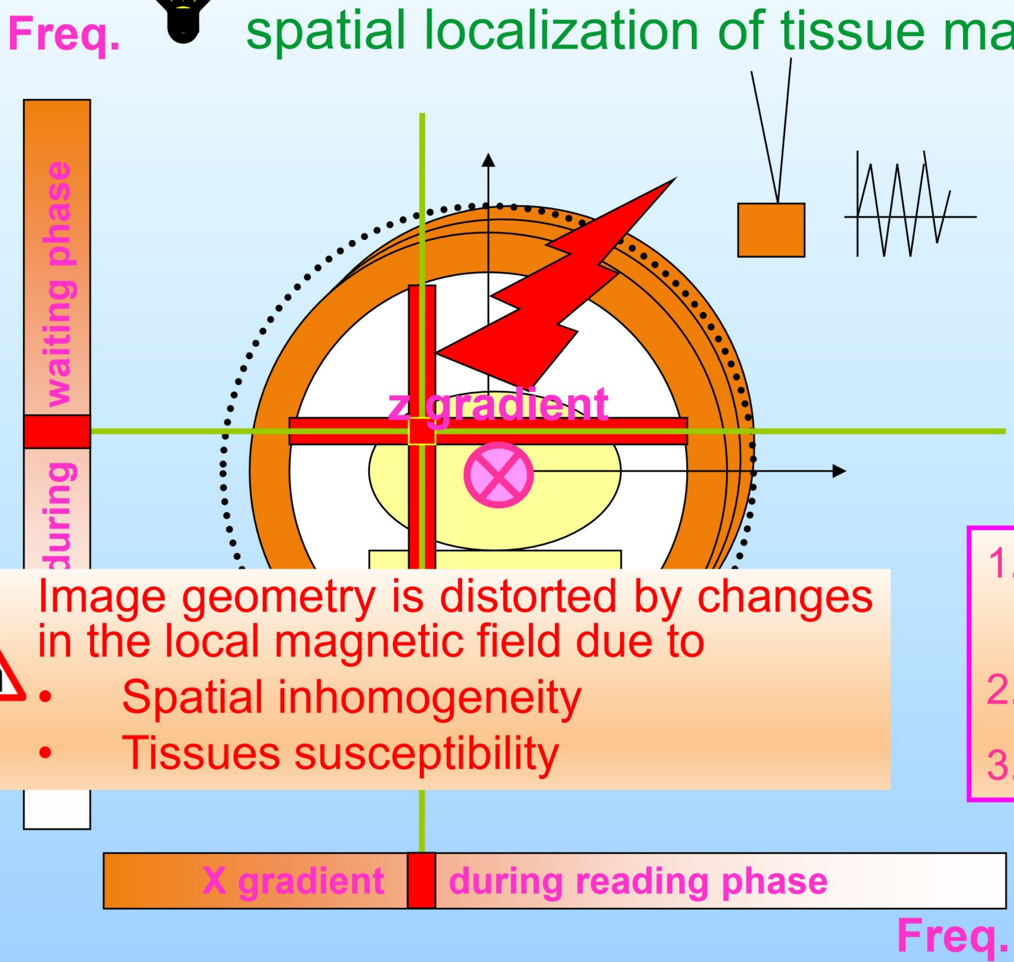
} Specific of tissue types





MRI techniques of spatial acquisition

Special time sequences of EM fields must be used for spatial localization of tissue magnetization



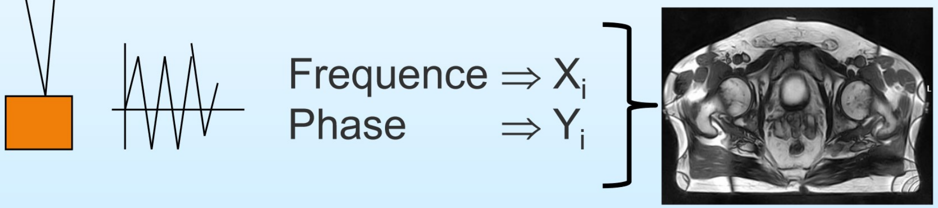


Image geometry is distorted by changes in the local magnetic field due to

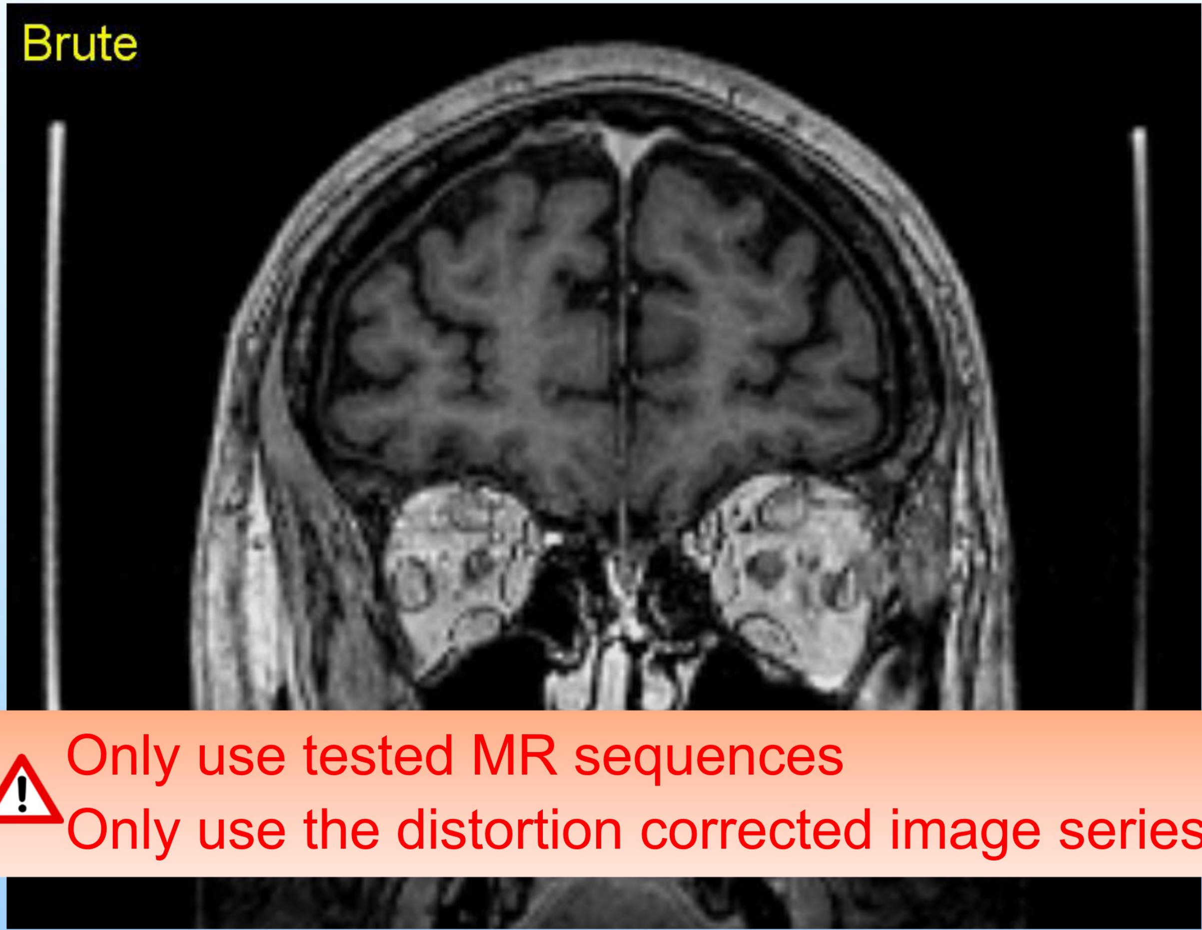
- Spatial inhomogeneity
- Tissues susceptibility

1. Excite one plane (ask transverse)
2. Select one raw
3. Select one column

time

Example of system MRI artefacts

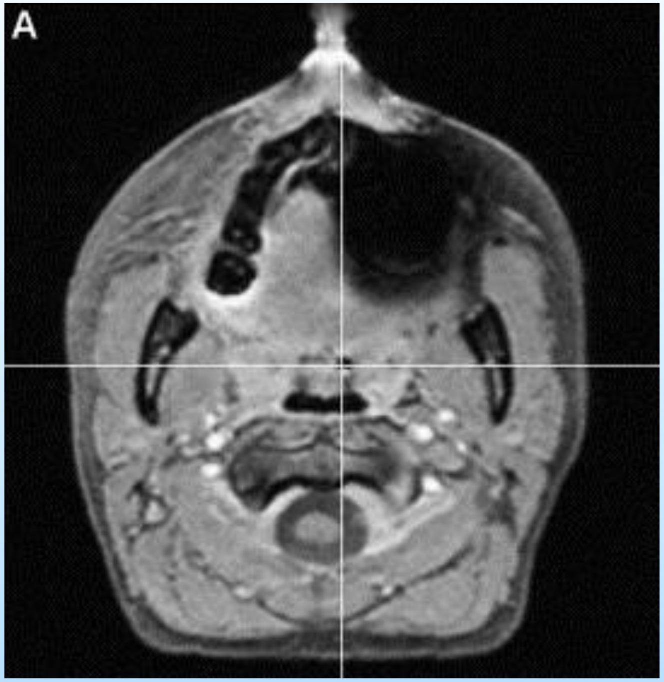
Beware of possible image distortion



⚠ Only use tested MR sequences
Only use the distortion corrected image series

Example at CHUV 2013

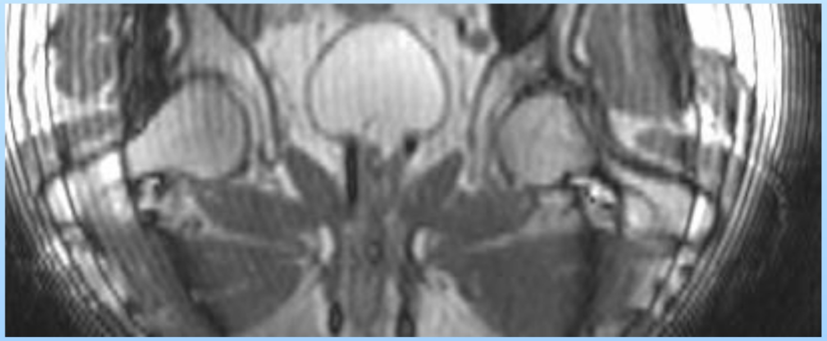
Examples of patient related MRI artefacts



Courtesy of HUG

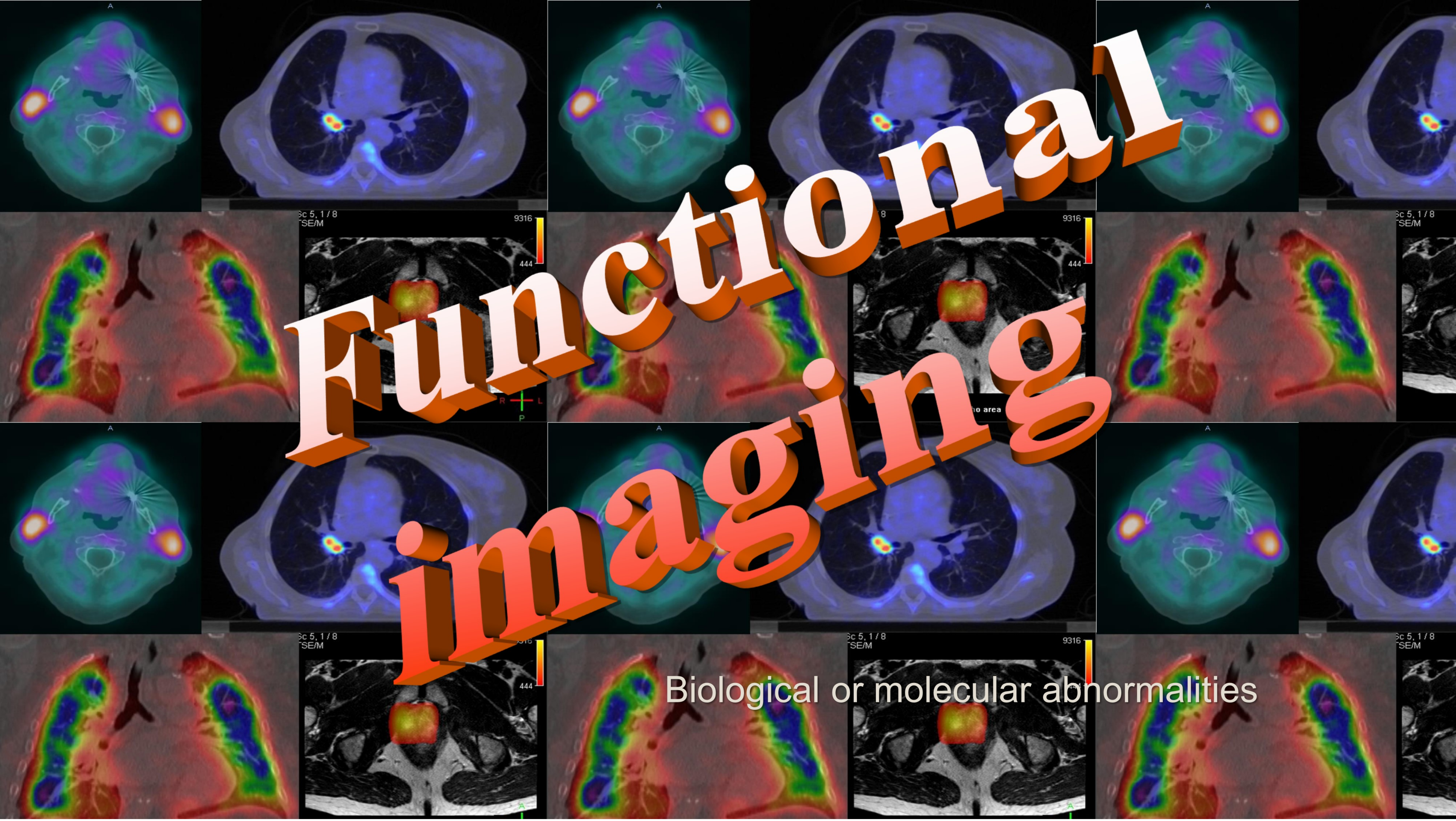
- Black hole in dental amalgam

- Distortion at field edges



Courtesy of HUG

For a complete list of artefacts, see
http://www.mritutor.org/mritutor/artifact.htm

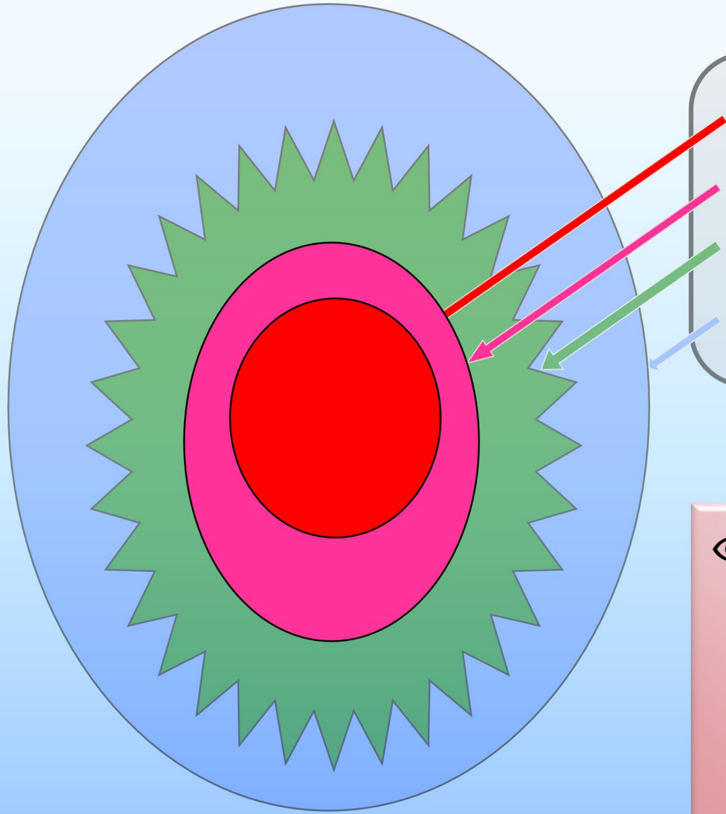


Functional imaging

Biological or molecular abnormalities

Paradigm of target volumes delineation

Normative definition of volumes: **ICRU 50, 62 & 83**



GTV :	Gross Tumor Volume
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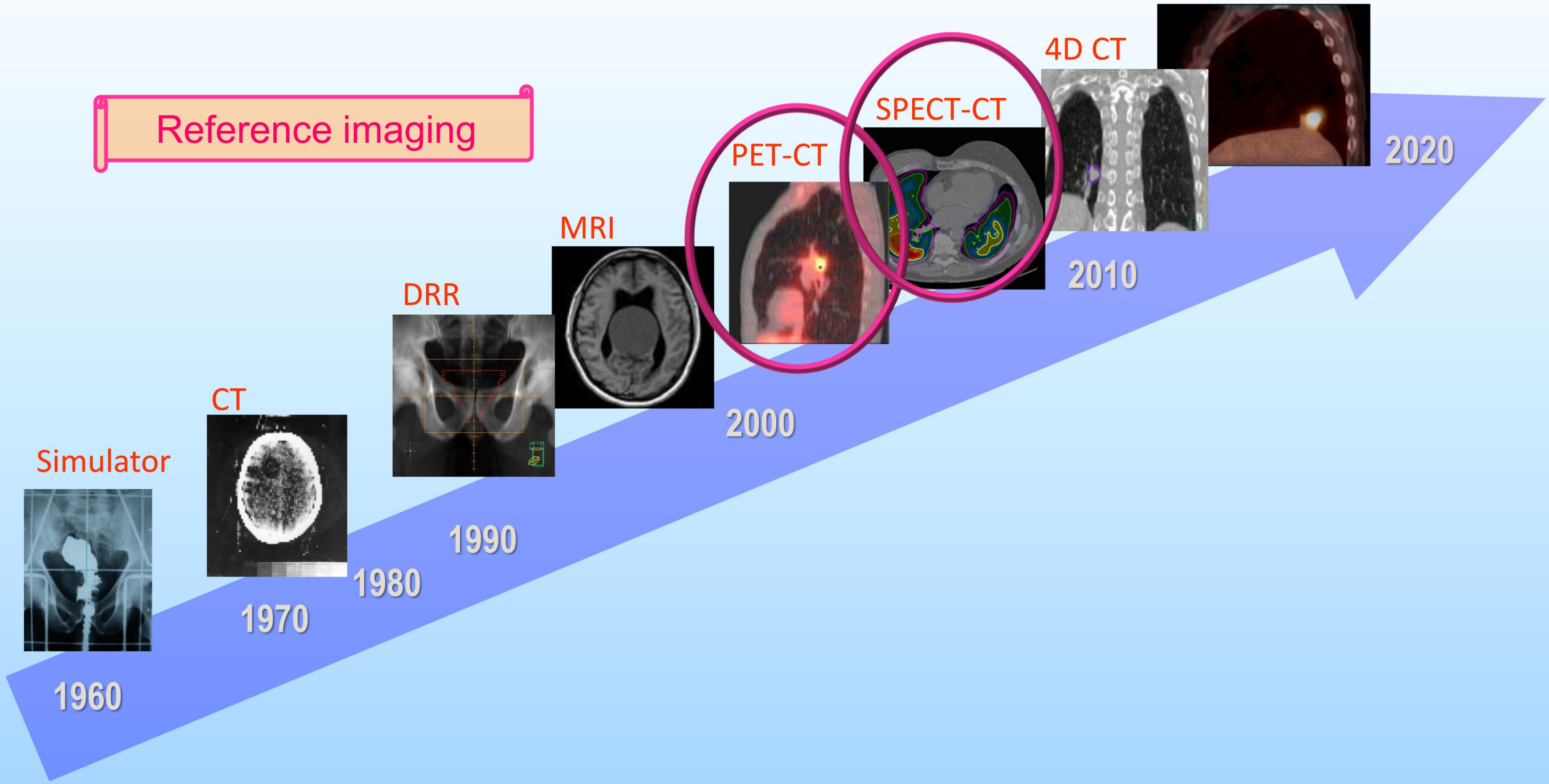
ITV:	+ Internal margin
PTV:	+ Setup margin

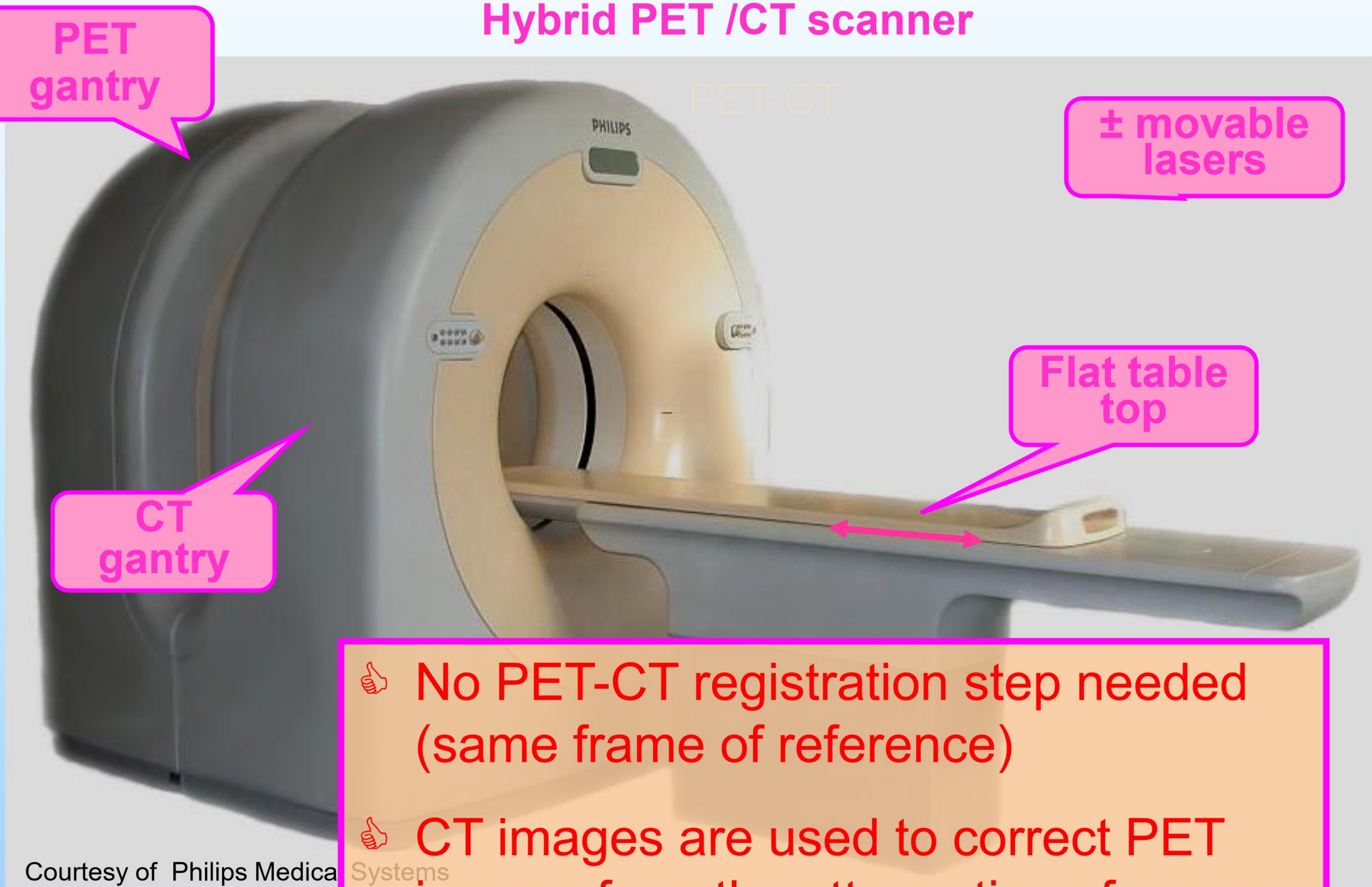
- Molecular imaging in RO can be used for delineating the functional GTV and functionality of organs at risk

Image data in RO



Positron Emission Tomography equipment

Hybrid PET /CT scanner

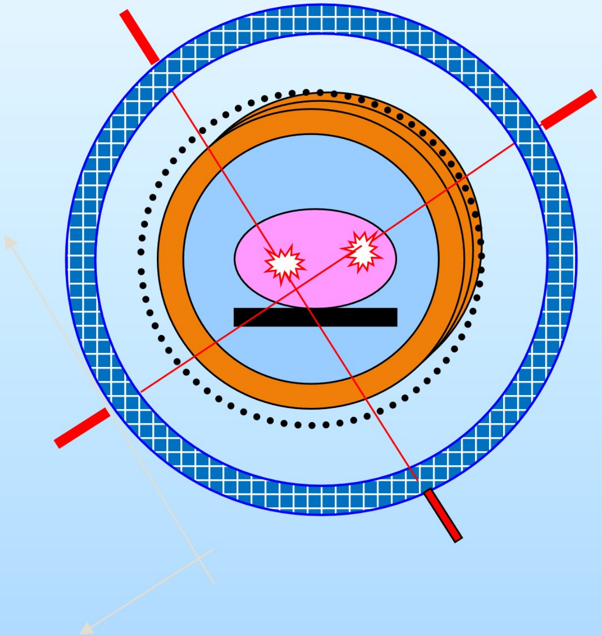


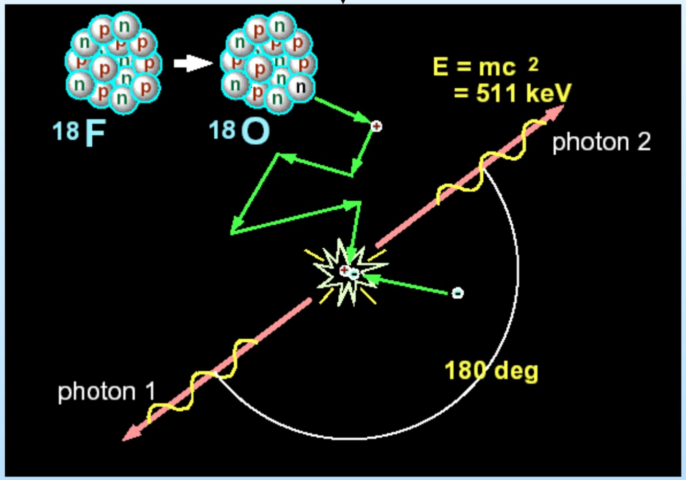
Courtesy of Philips Medical Systems

- No PET-CT registration step needed (same frame of reference)
- CT images are used to correct PET images from the attenuation of γ rays

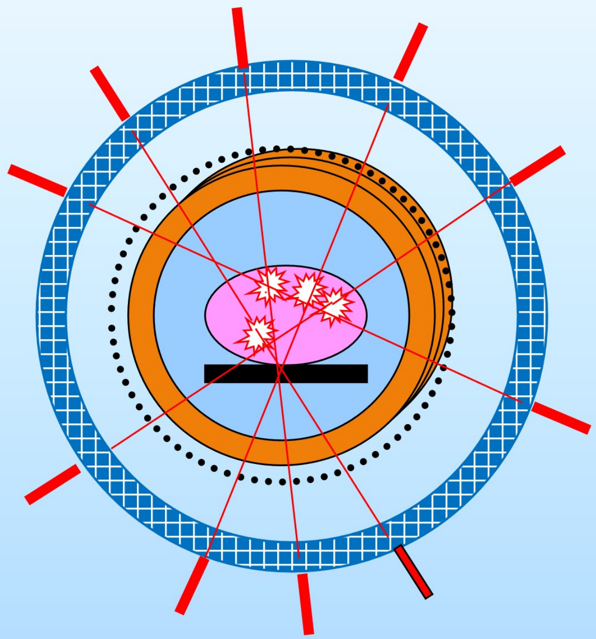
PET data acquisition 1/2

Injected radiotracer = β^+



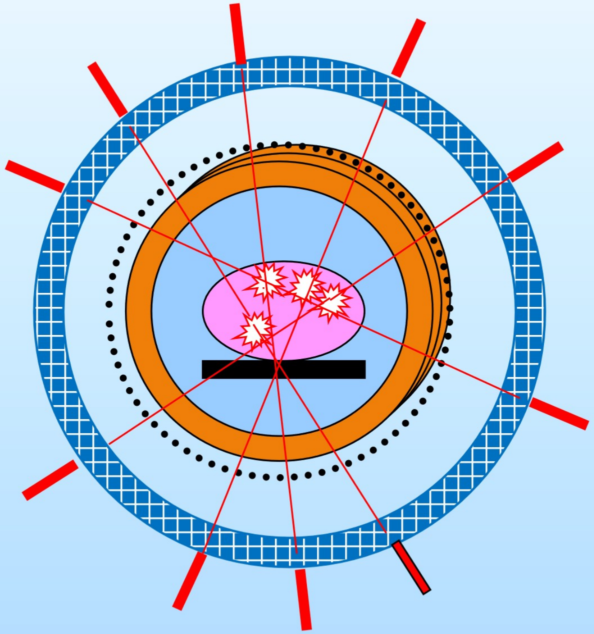


PET data acquisition 2/2

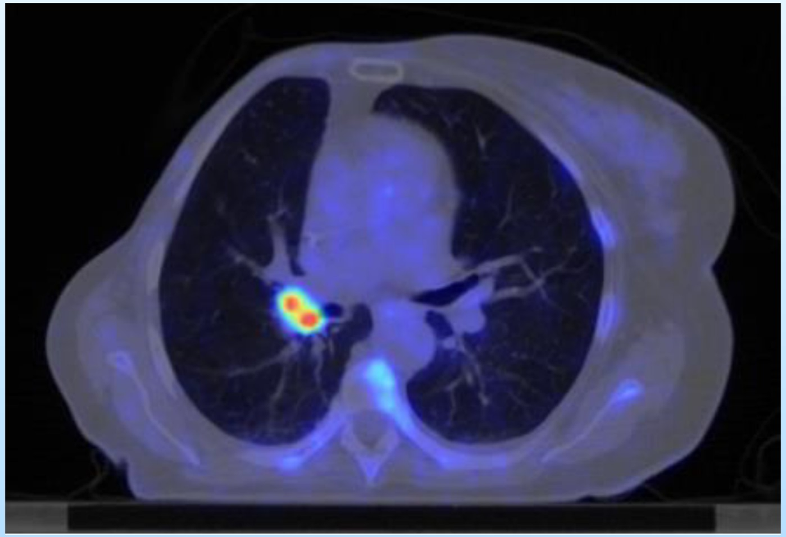


- 2 opposed γ from e^+e^- annihilation detected in coincidence (5 – 20 ns)
- The intersections of the lines of response (LOR) define the positions of the annihilations
- Obtention of an emission sinogram

PET image reconstruction



- Same backprojection technics of images reconstruction as for CT (after correction of attenuation)

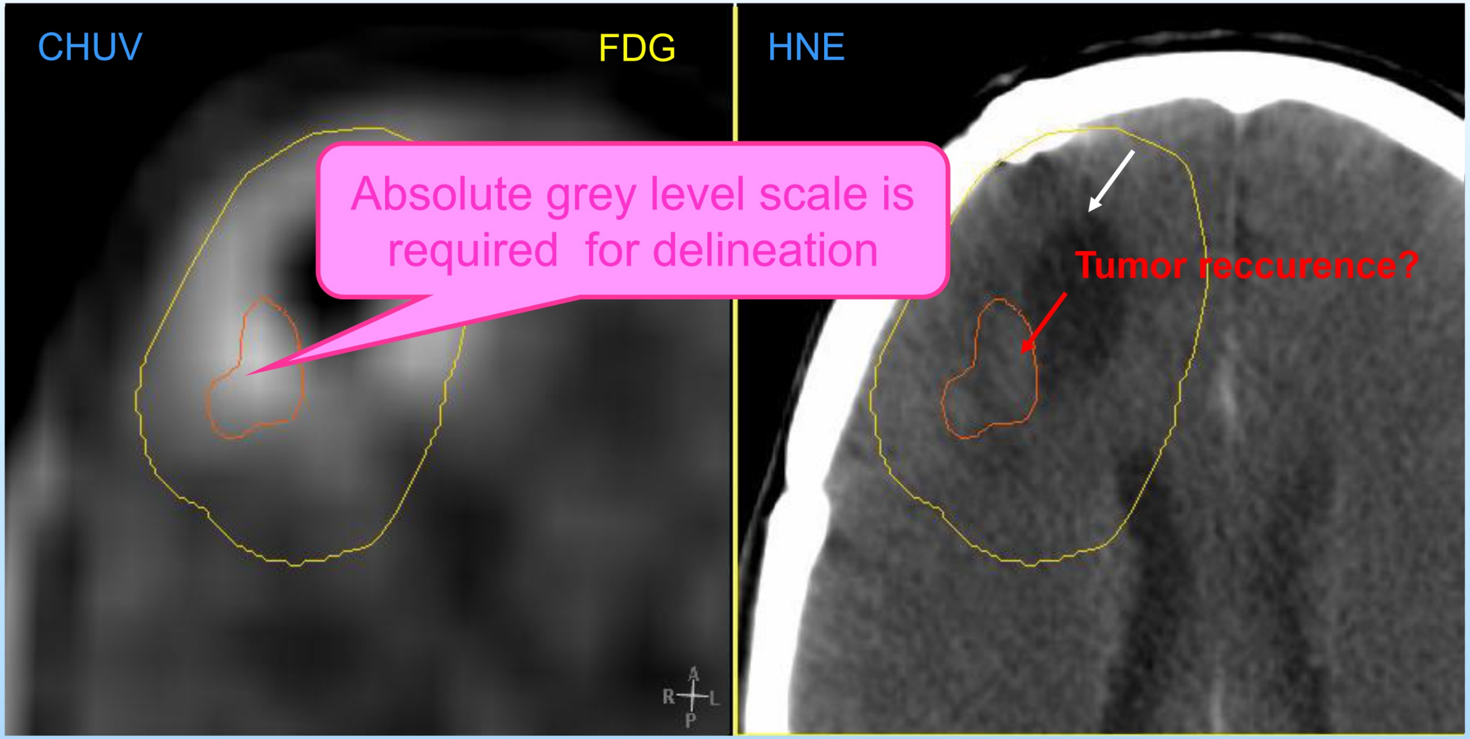


GE Discovery 690 PET-CT – CHUV 2014

Topography are difficult to localize on pure PET images but much easier to read on PET- CT fused imagesof structures

Problematic of organs delineation on PET – CT

Example of glioma (after resection):



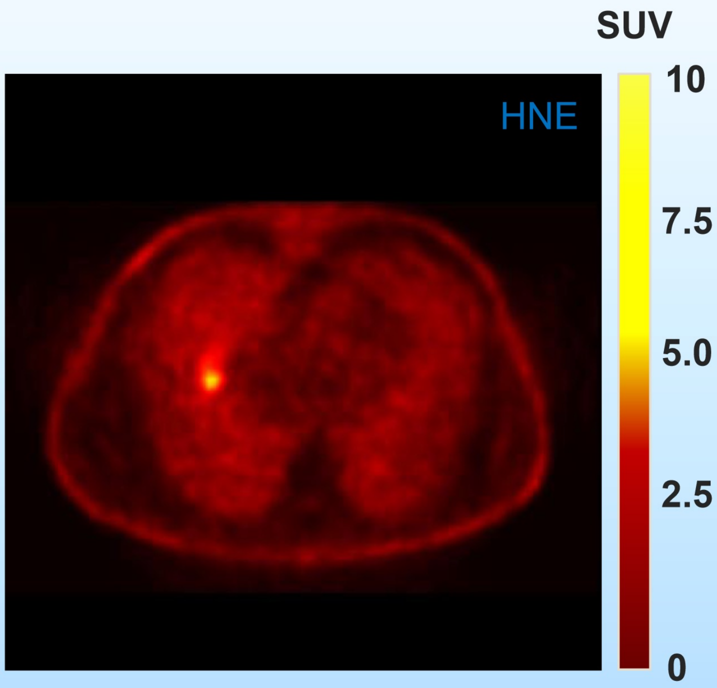
- ✓ Cavity correctly mapped between PET and CT
- ✓ GTV delineated on CT correspond to FDG fixation
- FDG fixation volume looks much larger, is it true?

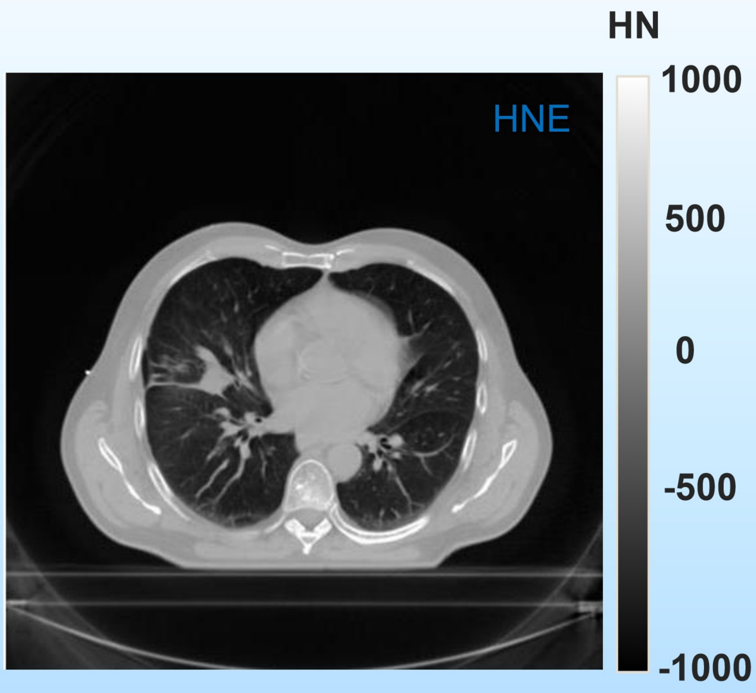
Standard Uptake Value (SUV)

Semiquantitative index based on ROI values

- Formula: $SUV = \frac{(\text{Activity in ROI / Volume of ROI})}{(\text{Injected activity / patient weight})}$
- Calculation of SUV requires corrections for:
  - Photons attenuation and scatter ⚠ Use the right reconstructed serie
- Values of SUV are affected by:
  - Partial volume effect (👎 5mm voxel size)
  - Organ motion (👎 long acquisition time)
- SUV = 1 if radiotracer would be uniformly distributed within the organism
- Present recommendations for GTV delineation are
  - $SUV > 2.5$ 👎 But sites and techniques dependent
  - $SUV >$ 40% of maximum SUV

Comparison between PET and CT scales





PET :

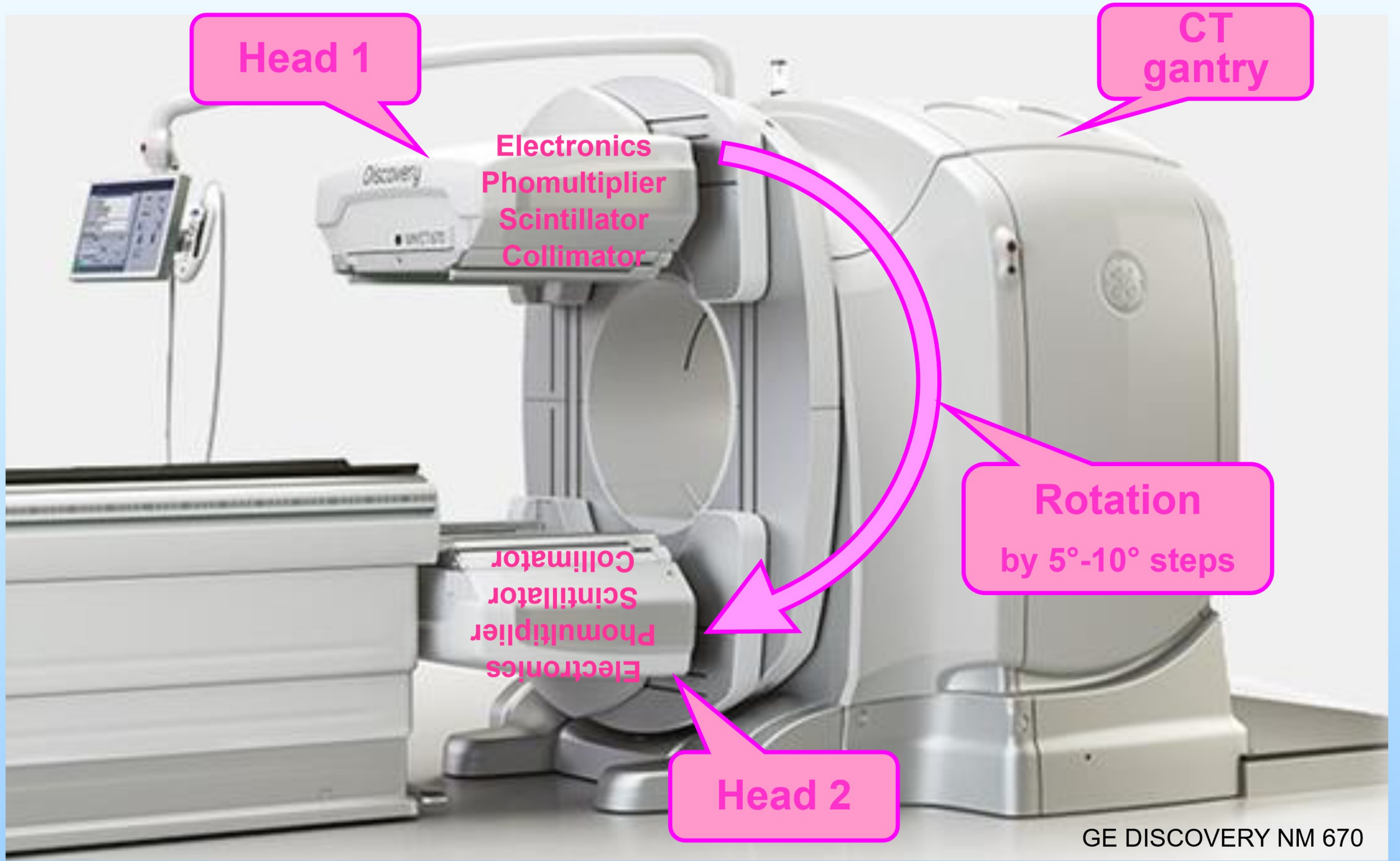
- Standard Uptake Value SUV
- Concentration of radiotracer
- Scale: 0 to ~ 14

CT :

- Houndsfield numbers HN
- Tissue absorption coefficients
- Scale: -1000 to + ~ 1000

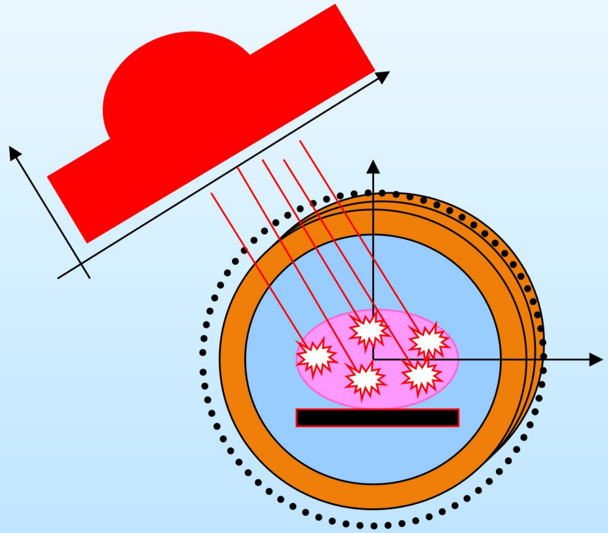
Single Photon Emission CT equipment

Hybrid SPECT /CT scanner



SPECT data acquisition

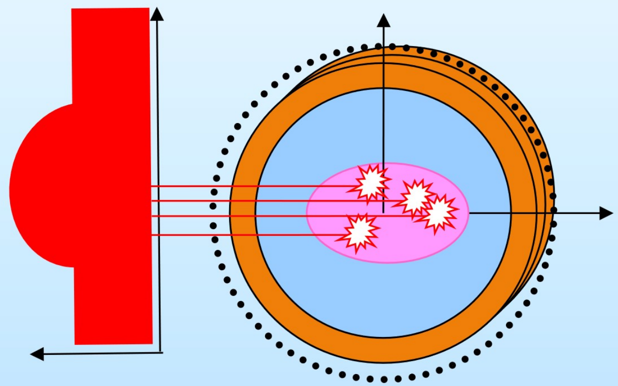
Detection of γ rays emitted by injected γ radiotracers



1. Acquisition of an emission profile at fixed gantry angle

SPECT data acquisition

Detection of γ rays emitted after injection of γ radiotracers
typically Tc-99m

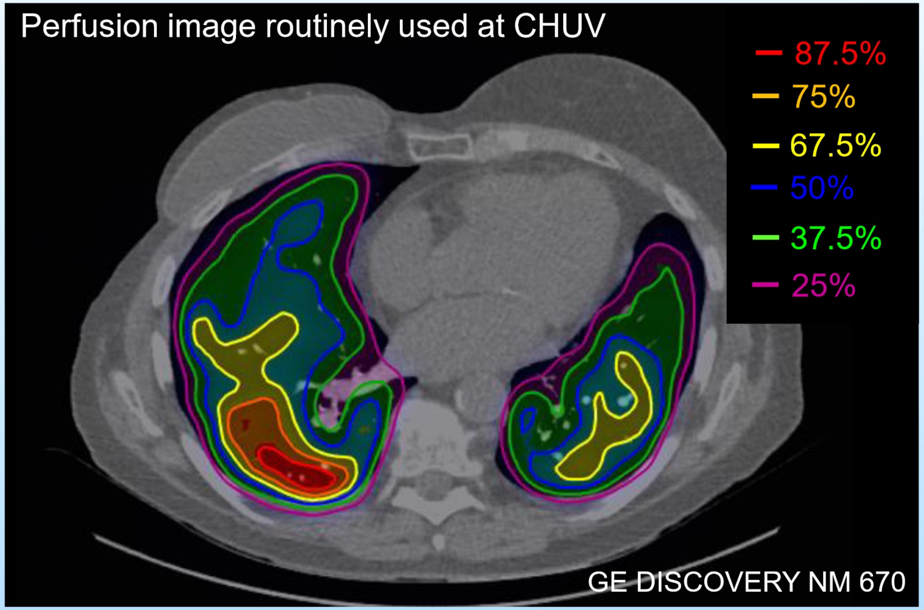


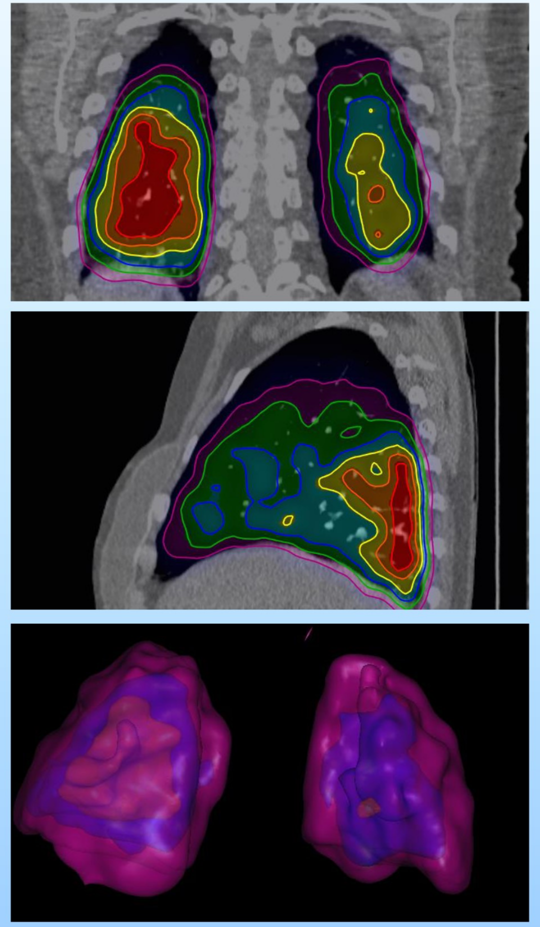
1. Acquisition of an emission profile at fixed gantry angle
2. Acquisition of a second emission profile at a different fixed gantry
3. Repeat step 2 in acquiring profiles for an uniform set of angles
4. Use the same technics of images reconstruction as for PET

- Color intensities are usually represented as % of the maximal measured radionuclid activity and not in absolute value.
- But quantitative SPECT-CT (SUV) is becoming available.

Clinical use of SPECT/CT in RO

Example using intraveneous albumin tagged Tc-99m





Legend:

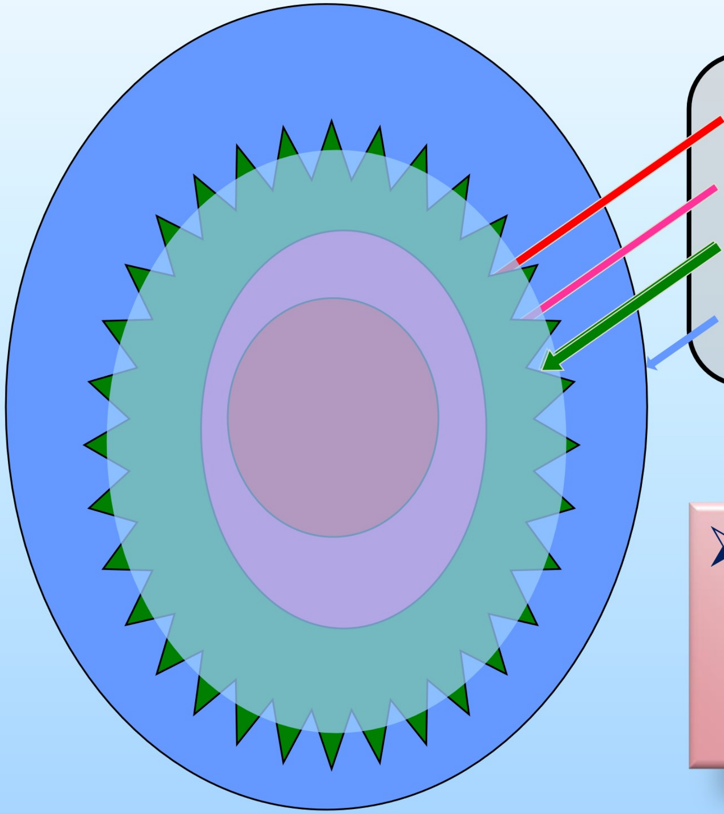
Isocurves defined as % of maximal measured Tc-99m activity

Value of perfusion > 50% = lung zone associated to an organ at risk


Image guidance
IGRT

Current imaging paradigm in RO

Normative definition of volumes: **ICRU 50, 62 & 83**



- GTV : Gross Tumor Volume
- CTV: + subclinical involvement
- ITV: + Internal margin
- PTV: + Setup margin

> ➢ Image guidance in RO can be used for assessing the internal and setup margin

Image data in RO

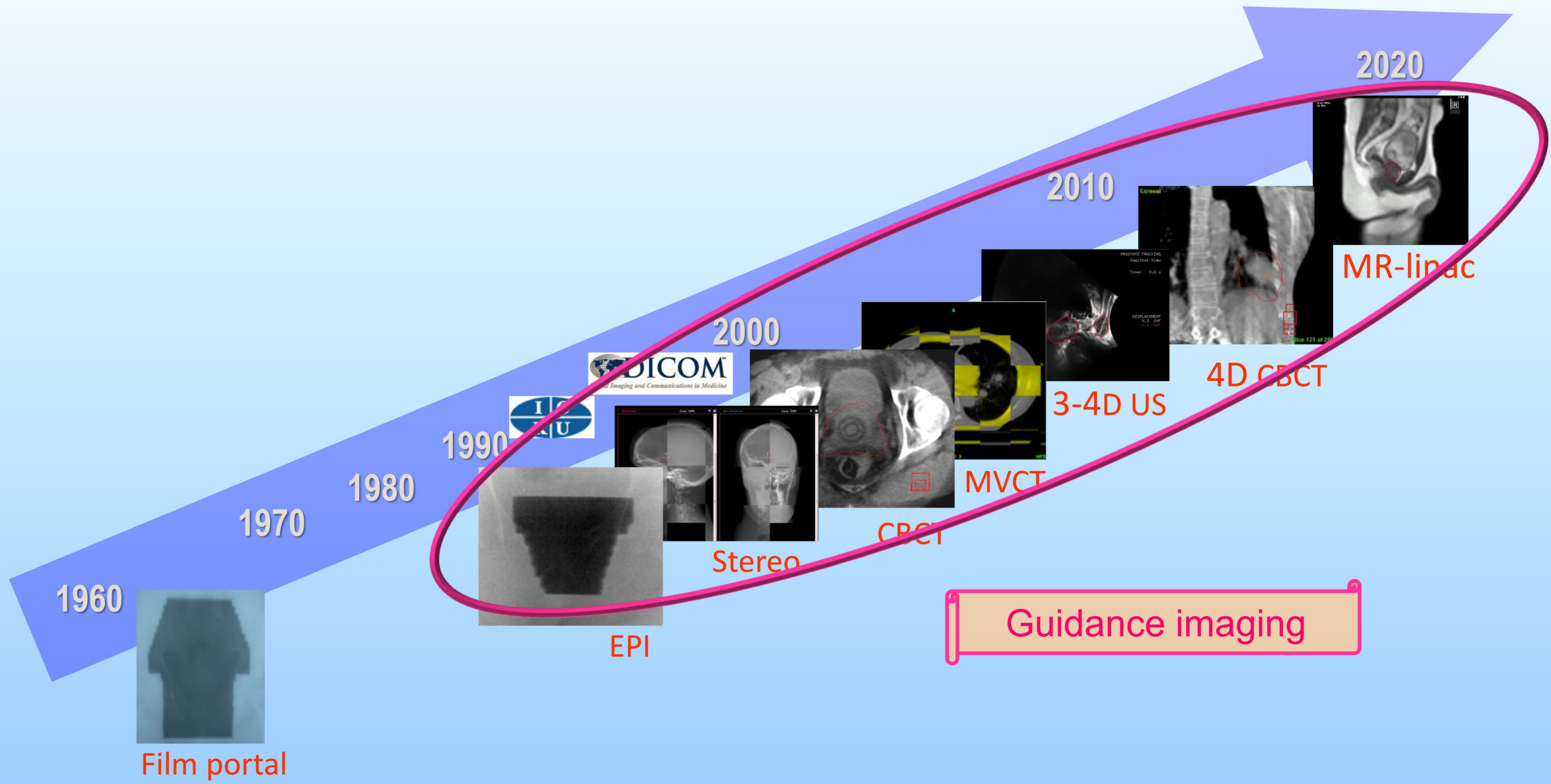
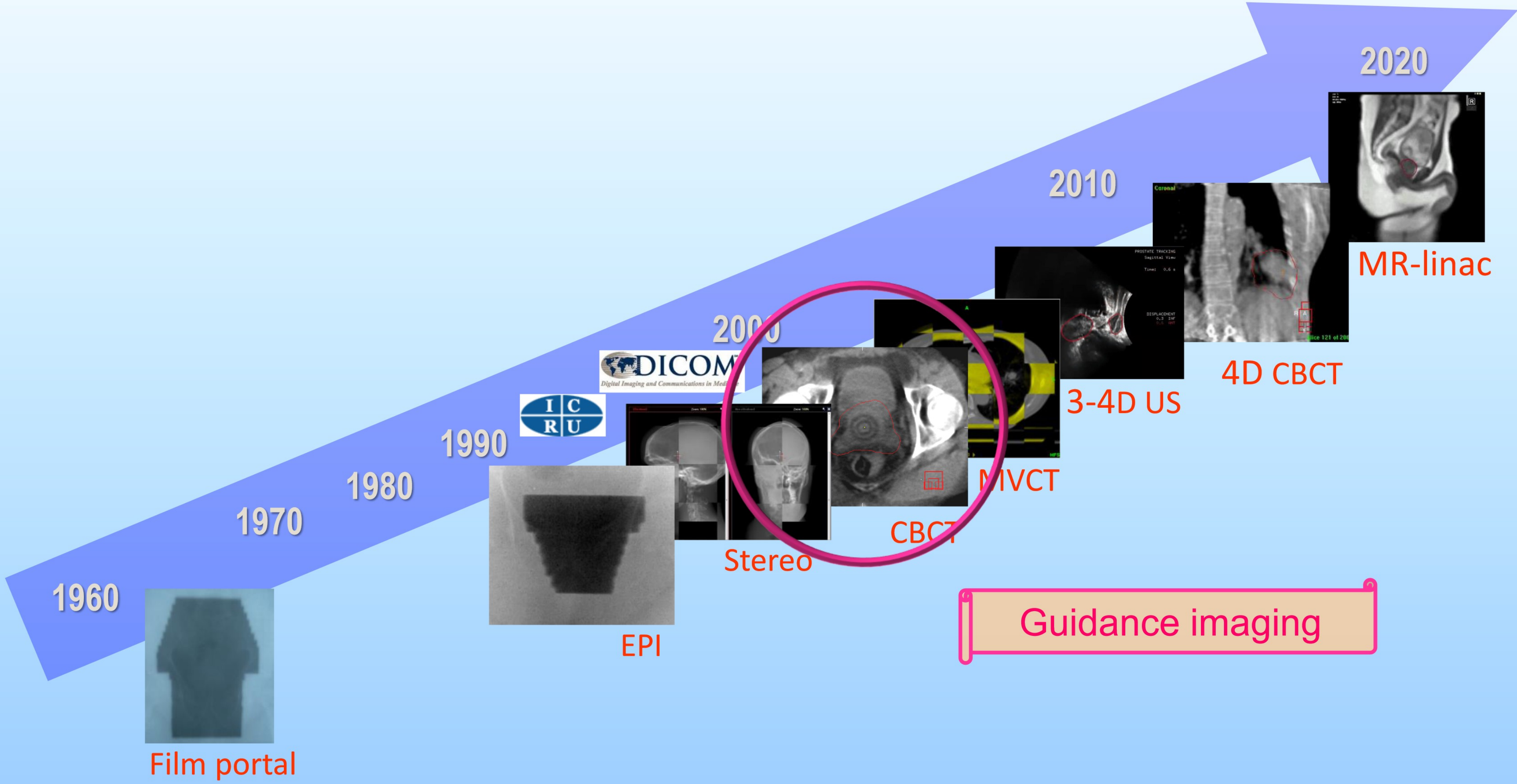


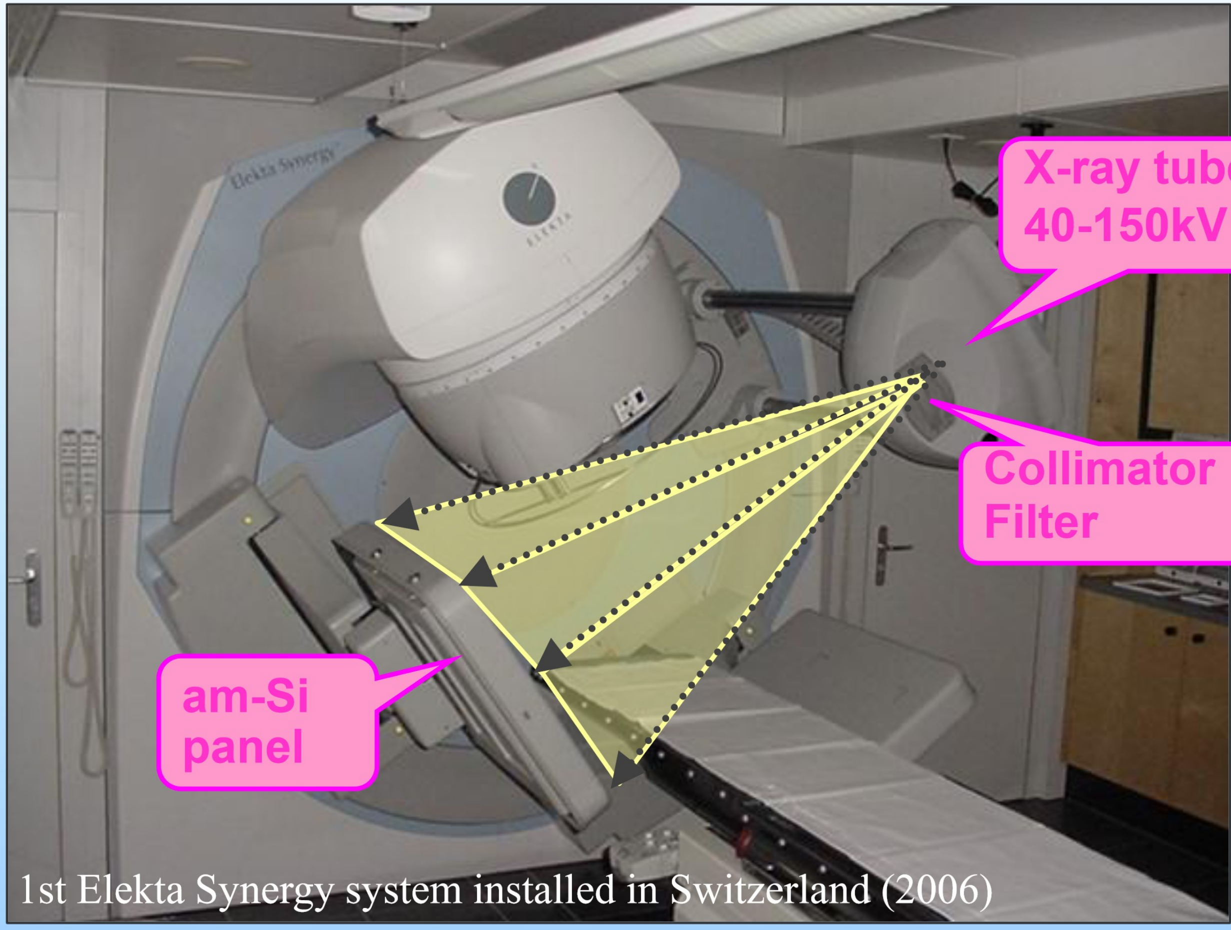
Image data in RO



CBCT
MVCT
Stereo imaging
Mr linac

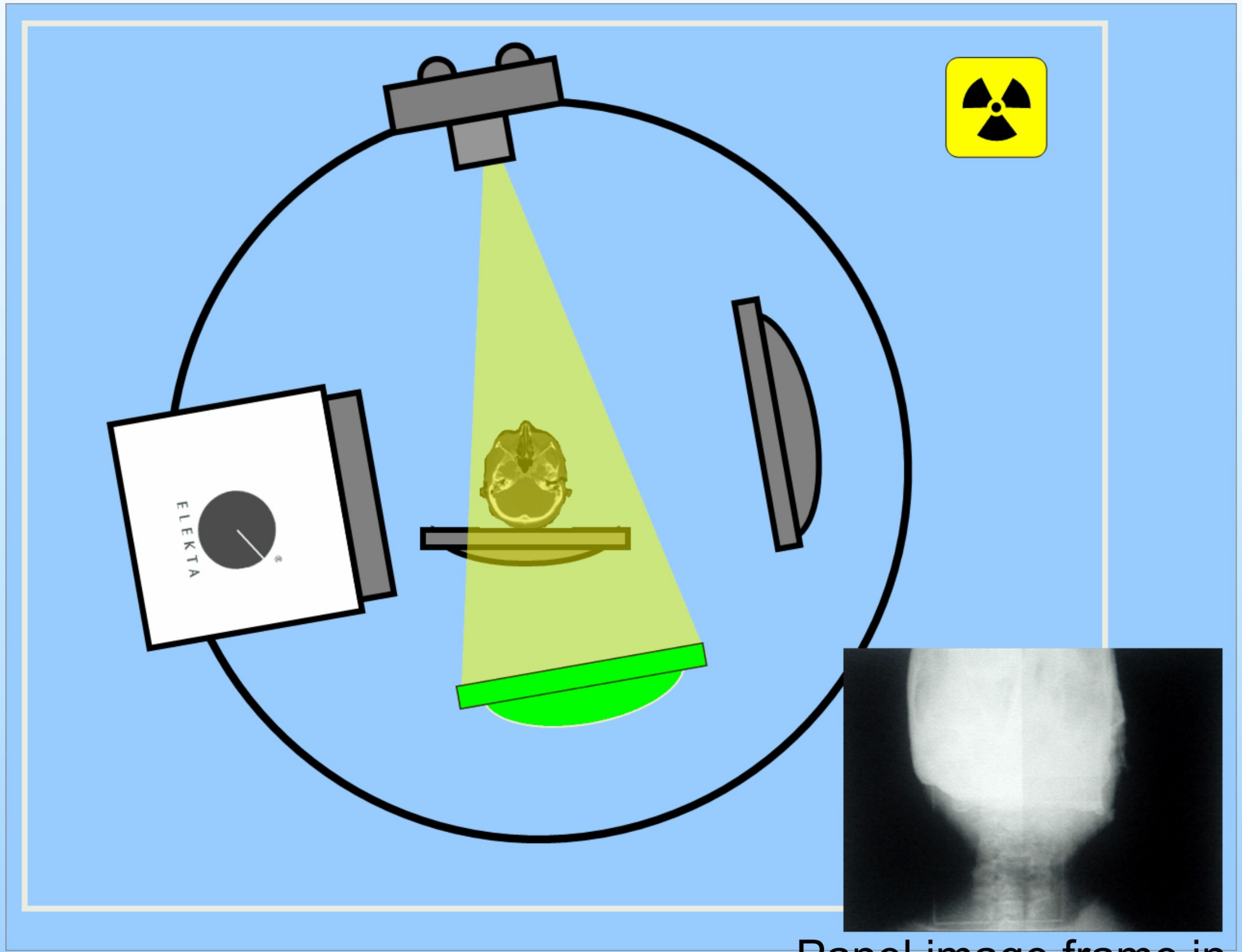
Cone Beam kV-CT equipment

- **Going from a 2D-2D to 3D-3D guidance was a paradigm shift of IGRT**



1st Elekta Synergy system installed in Switzerland (2006)

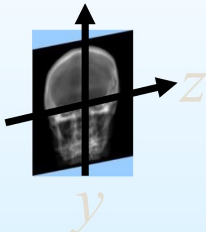
Cone Beam CT frame’s acquisition



Panel image frame in live

CBCT 3D reconstruction

360-630 frames → Frames @ isocenter → Scatter corrections → Filtration → Back-projection



$P_\phi(y - y_{Flex}, z - z_{Flex})$

(y_{Flex}, z_{Flex}) : Correction isocenter

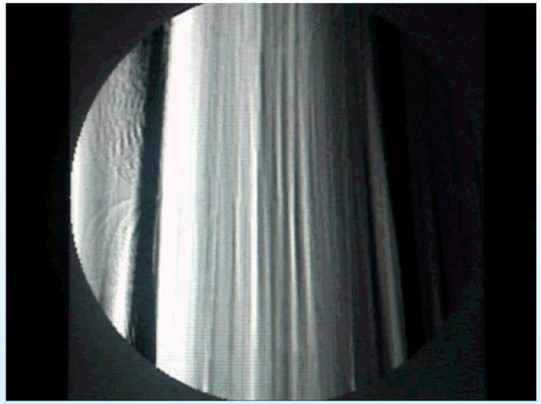
$$P_\phi(y,z) = P_\phi(y,z) - 0.33\langle P_\phi(y,z)\rangle_{Frame}$$

$$p(y,z) = \int dz' \frac{d}{\sqrt{d^2 + y^2 + z'^2}} P_\phi(y,z') h(z-z')$$

d : SAD = 100 cm; $h(z)$: Median filter 5

$$f(\vec{r}) = \frac{1}{4\pi^2}\oint d\phi \frac{d^2}{(d + \vec{r}\cdot\hat{x}')^2} p(y_0, z_0)_{y_0 = \frac{dy}{(d+\vec{r}\cdot\hat{x})}, z_0 = \frac{dr\cdot\hat{z}'}{(d+\vec{r}\cdot\hat{x}')}}$$

$f(\vec{r})$: 3D patient density

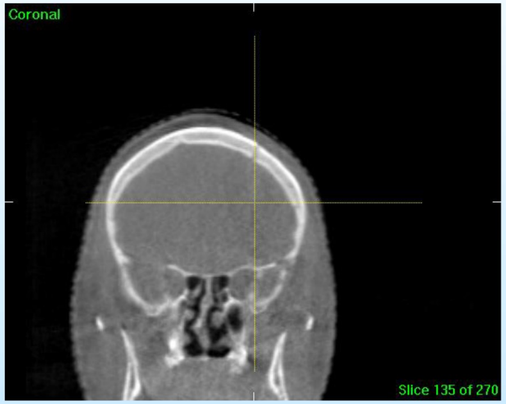


FDK algorithm

- Extension of the backprojection technique used in CT, PET and SPECT
- Nowadays superseded by iterative reconstruction

Examples of CBCT images

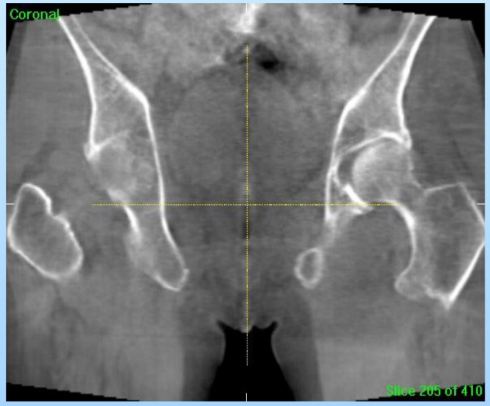
Skull



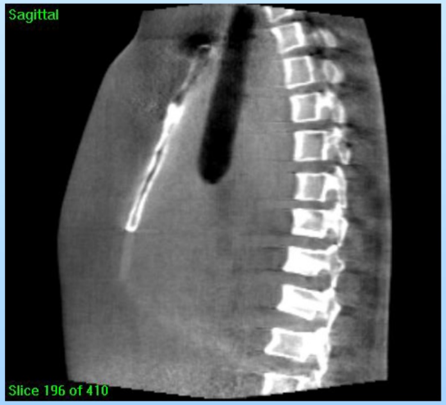
H&N

Lung

Bladder



Verterbras



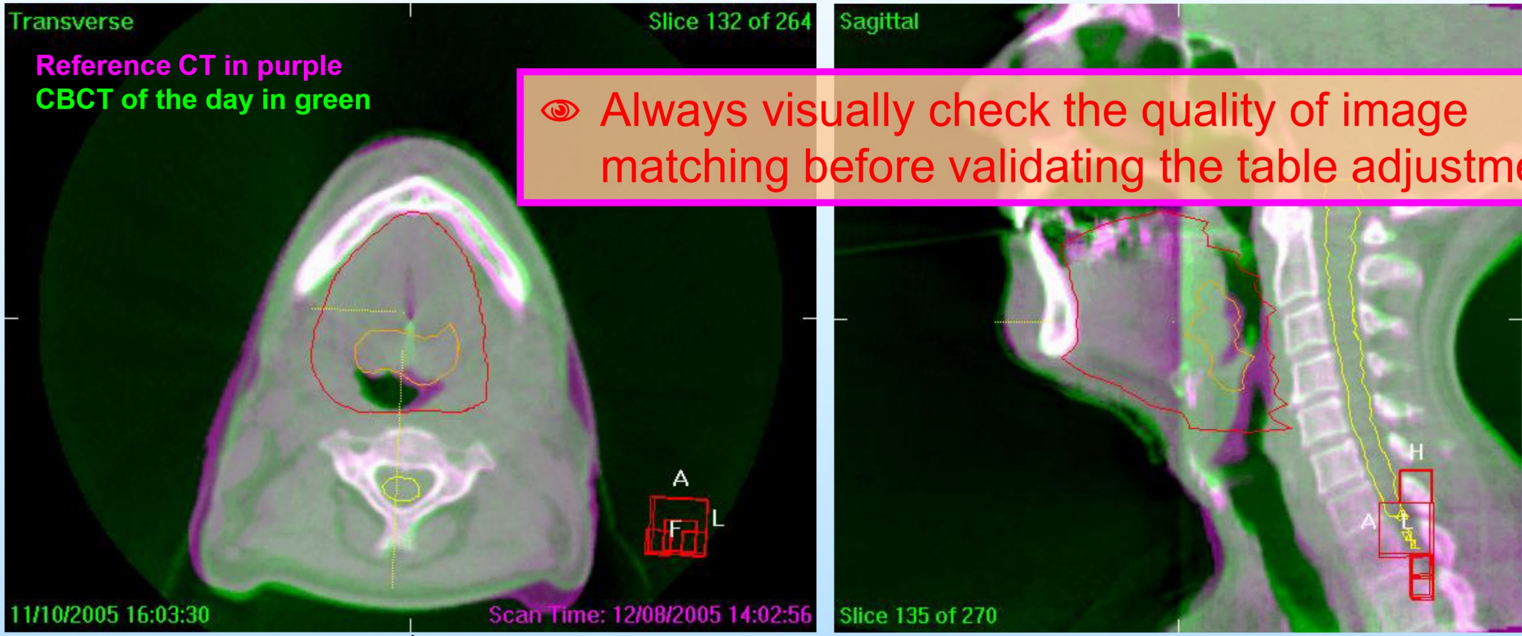
Prostate

Soft tissues are visible

Clinical images from HNE - 2006

Clinical uses of CBCT guidance 1/3

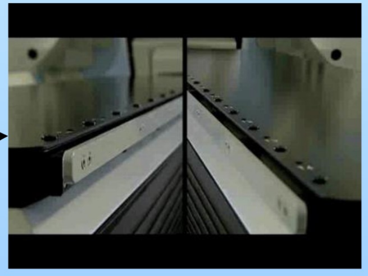
Correction of the base line shift (rigid registration):



Always visually check the quality of image matching before validating the table adjustment

Errors calculated 6D

Position Error Translation (cm)		Rotation (dg)	
X	-0.25	X	360.0
Y	-0.05	Y	2.5
Z	0.24	Z	1.8

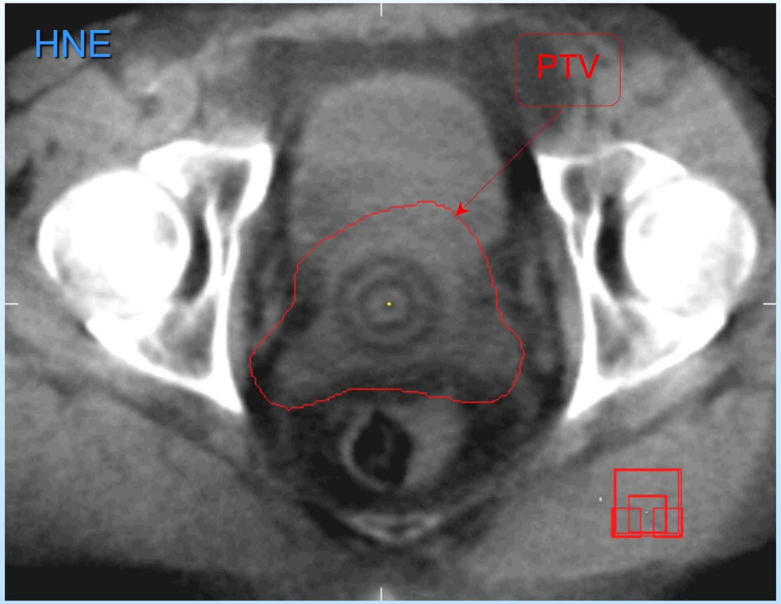


6D Elekta coach

Errors corrected by table adjustment

Clinical uses of CBCT guidance 2/3

Setup margins verification:

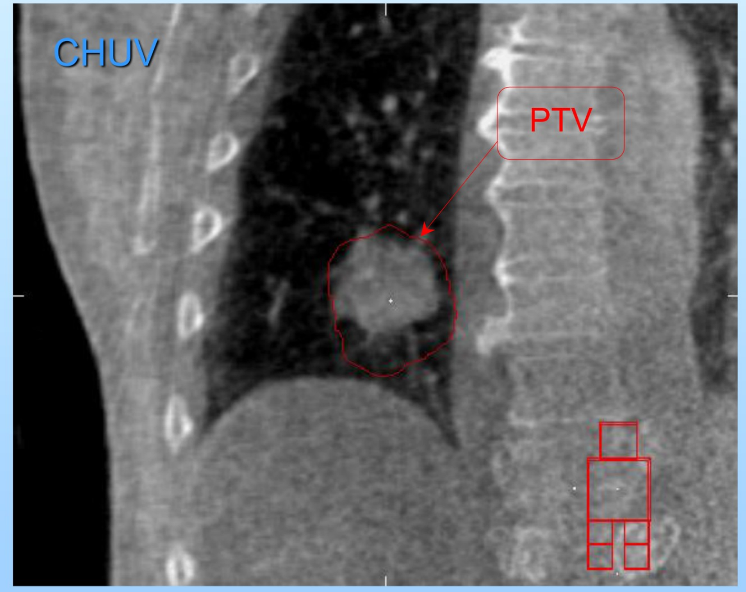


Inter-fractions motion:

- translations
- rotations
- deformations

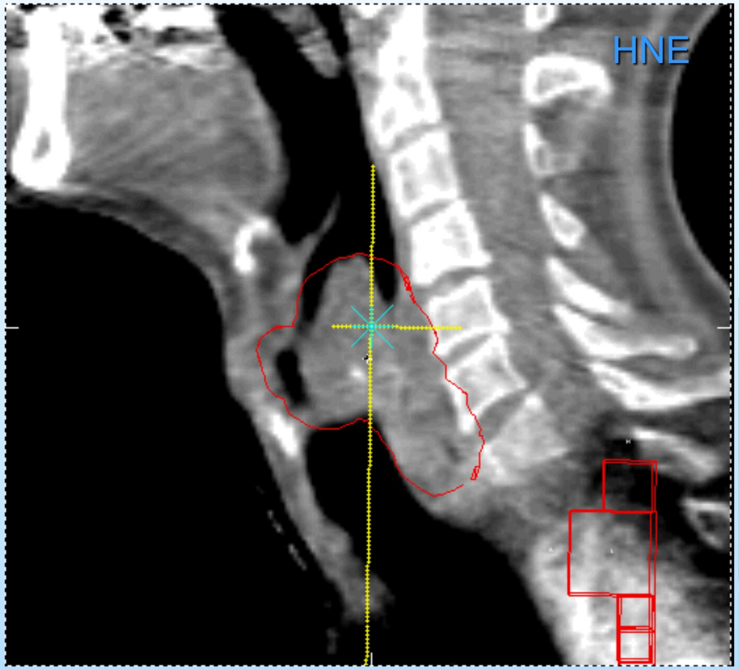
Intra-fraction motion measured by 4D CBCT:

- breathing



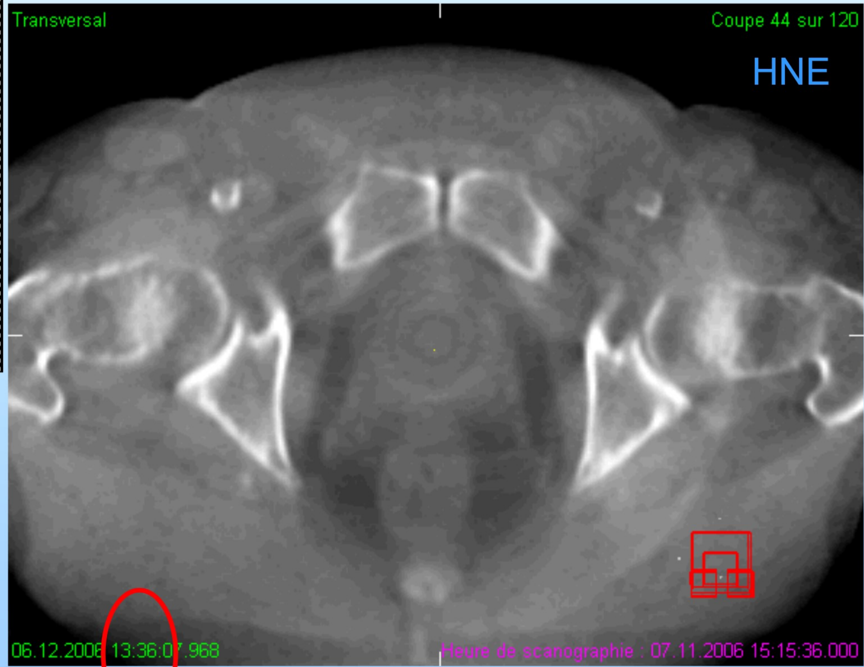
Clinical uses of CBCT guidance 3/3

Morphological changes :



Inter-fractions variations:

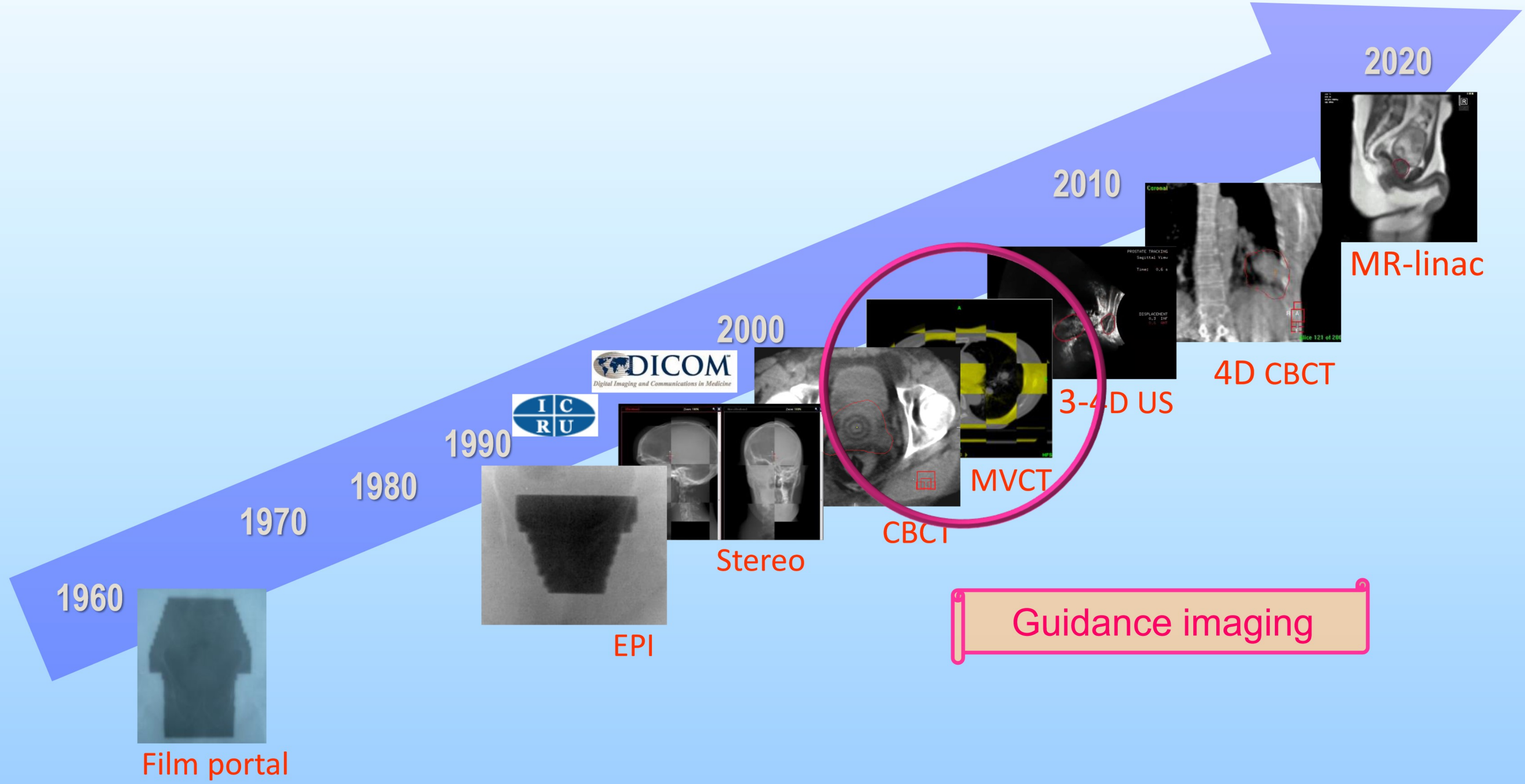
- Tumor response
- Weight loss



Intra-fraction variations

- Peristalsis
- Swallowing

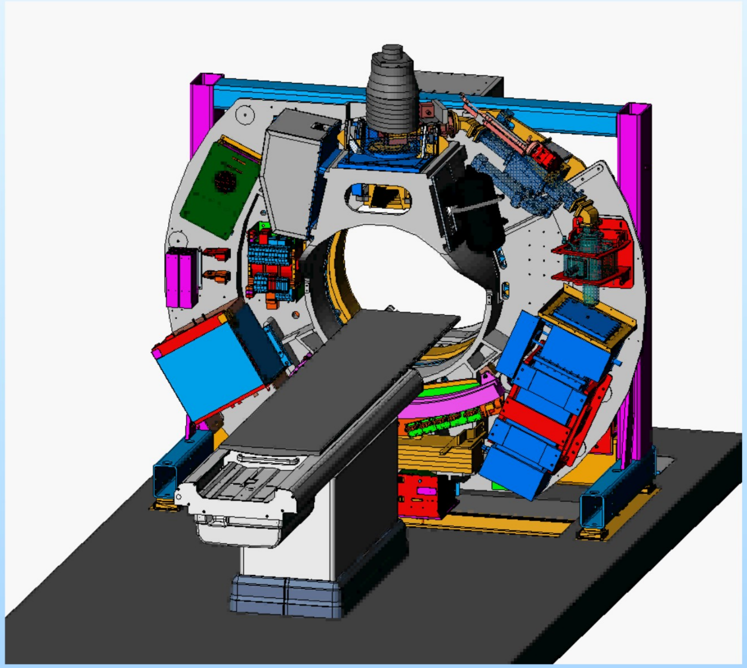
Image data in RO

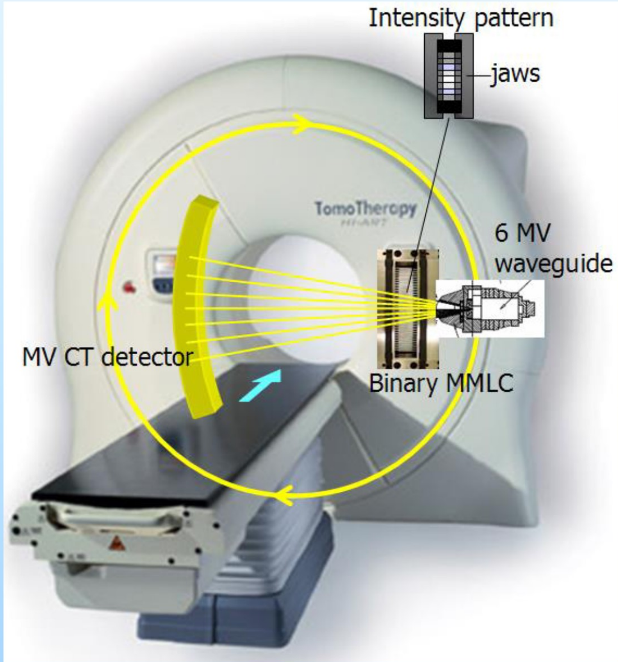


CBCT
MVCT
Stereo imaging
Mr linac

MV-CT equipment

Same principle as helicoidal CT (FBCT), but with the radiation source being a linac

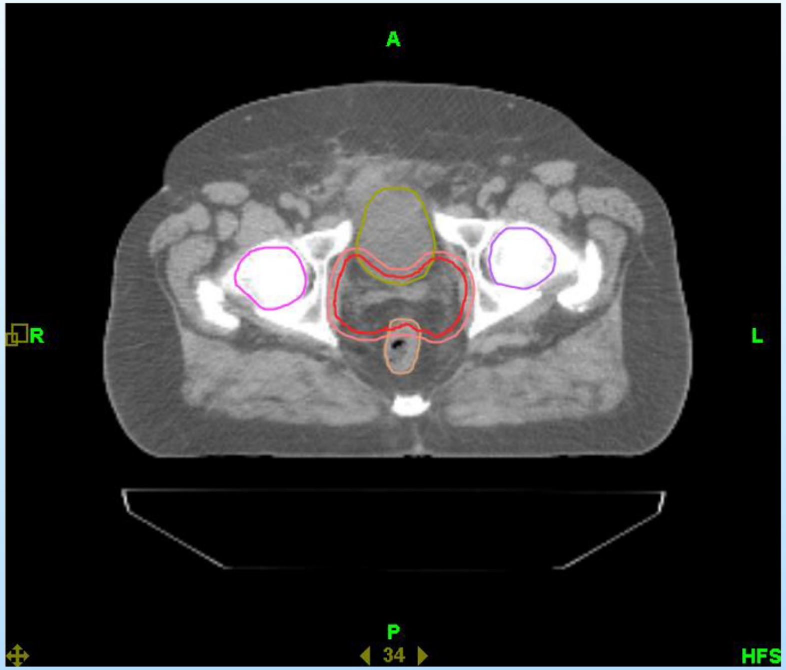




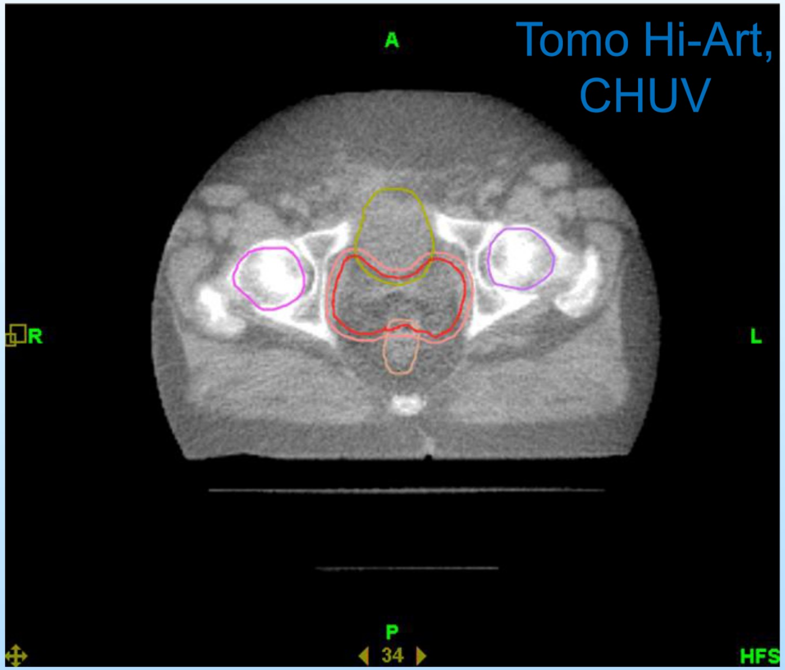
Implemented in the Accuray tomotherapy Hi-Art

Prostate example of MVCT images

Reference CT



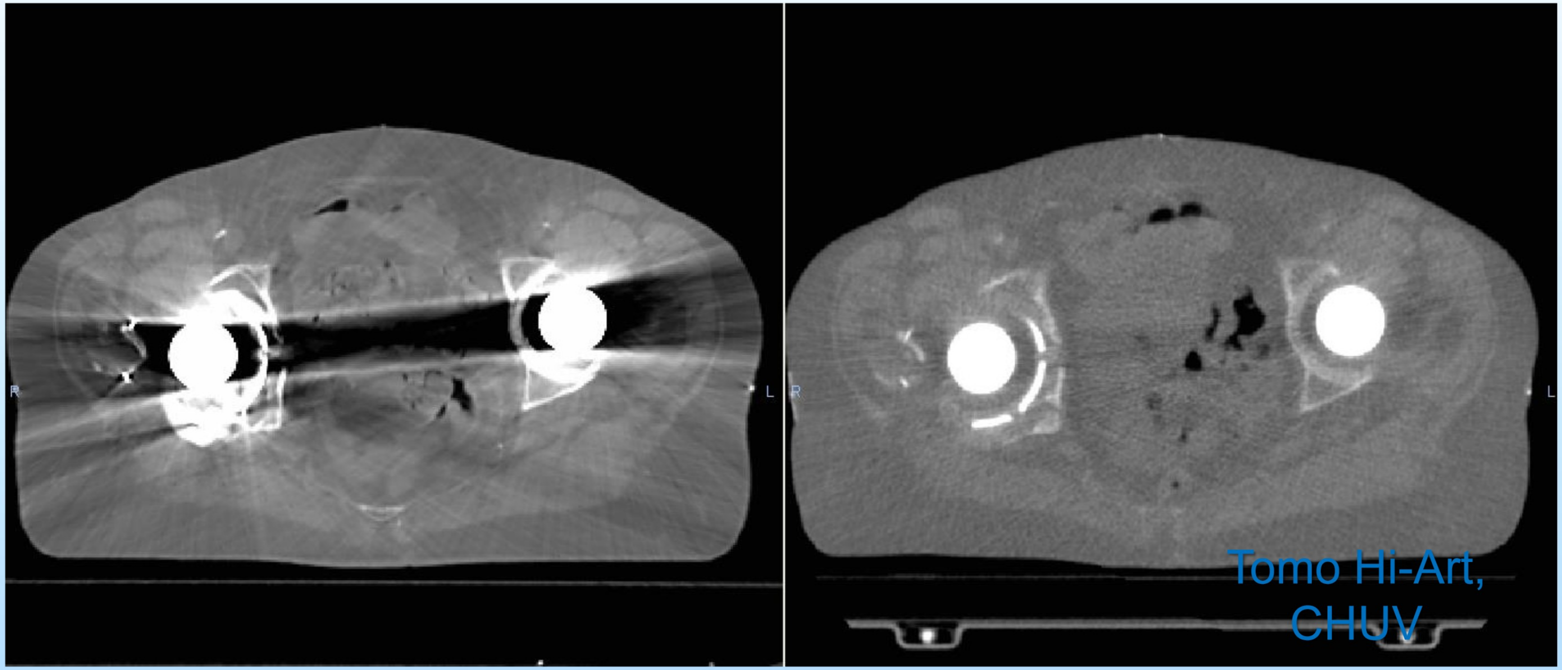
MVCT



- The essential soft tissues (prostate, bladder, rectum) are visible

Clinical uses of MVCT images 2/2

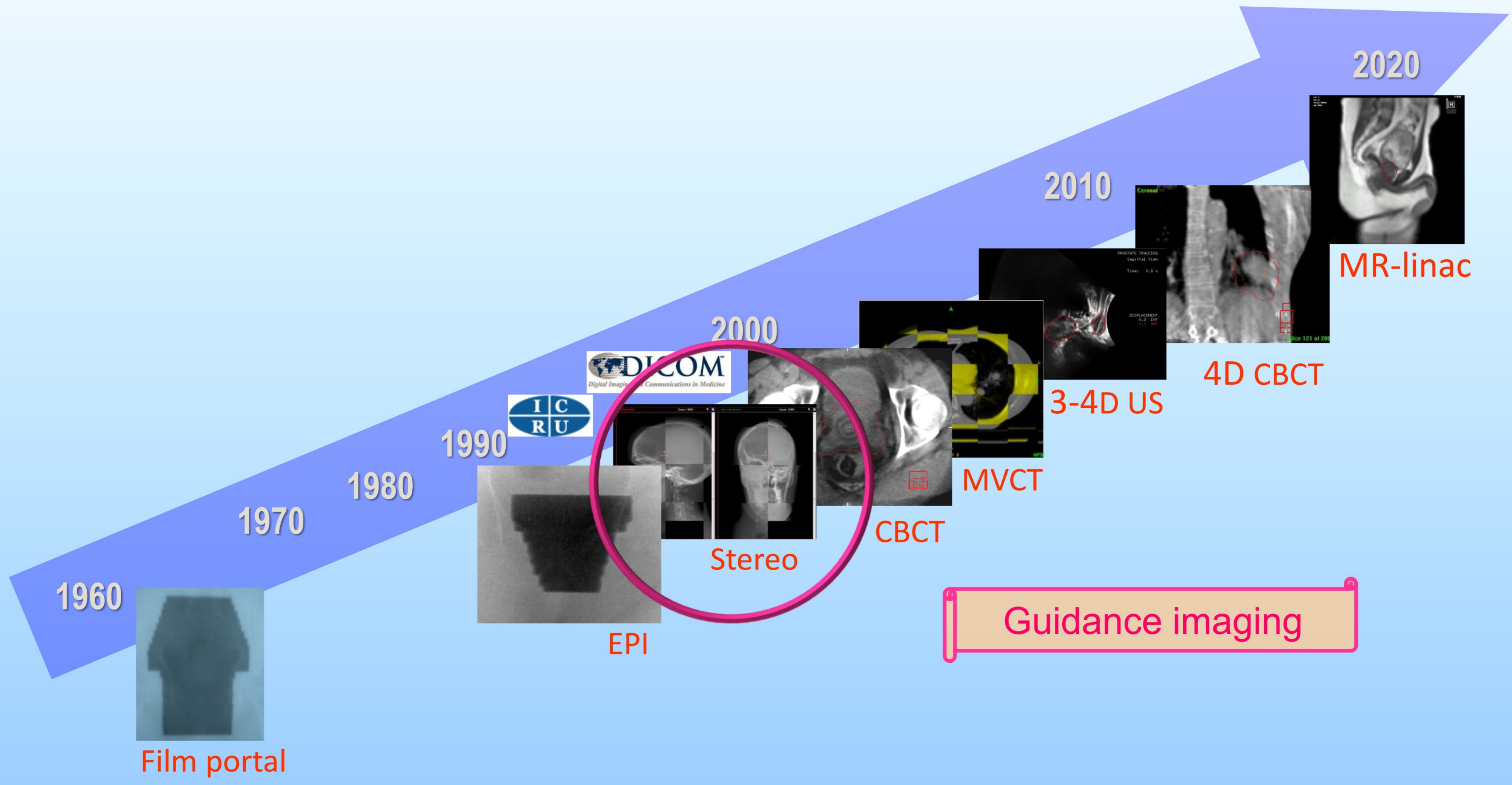
Metal artefacts free images



CT without artefact correction | **MVCT (standard protocol)**

☞ The MVCT images can be used for planning dosimetry without any HU correction

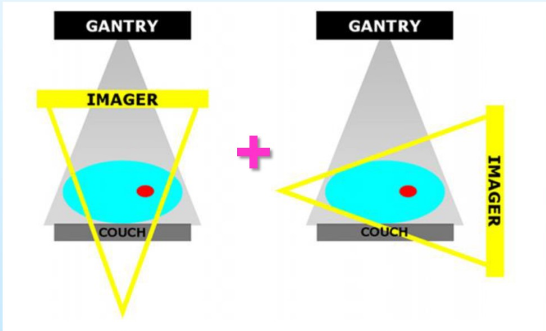
Image data in RO



Stereoscopic kV imaging equipments

❖ Two types of possible mountings:

1. Embarqued (ganty mounted): same equipment as used for CBCT)



👎 **Necessitate a gantry rotation**

2. Fixed (room mounted): 2 sets of orthogonal Rx-tubes + pannels

Brainlab Exactrac

Accuray Cyberknife

👎 **The linac arm can hide 1 or 2 beams**

IGRT stereoscopic procedure

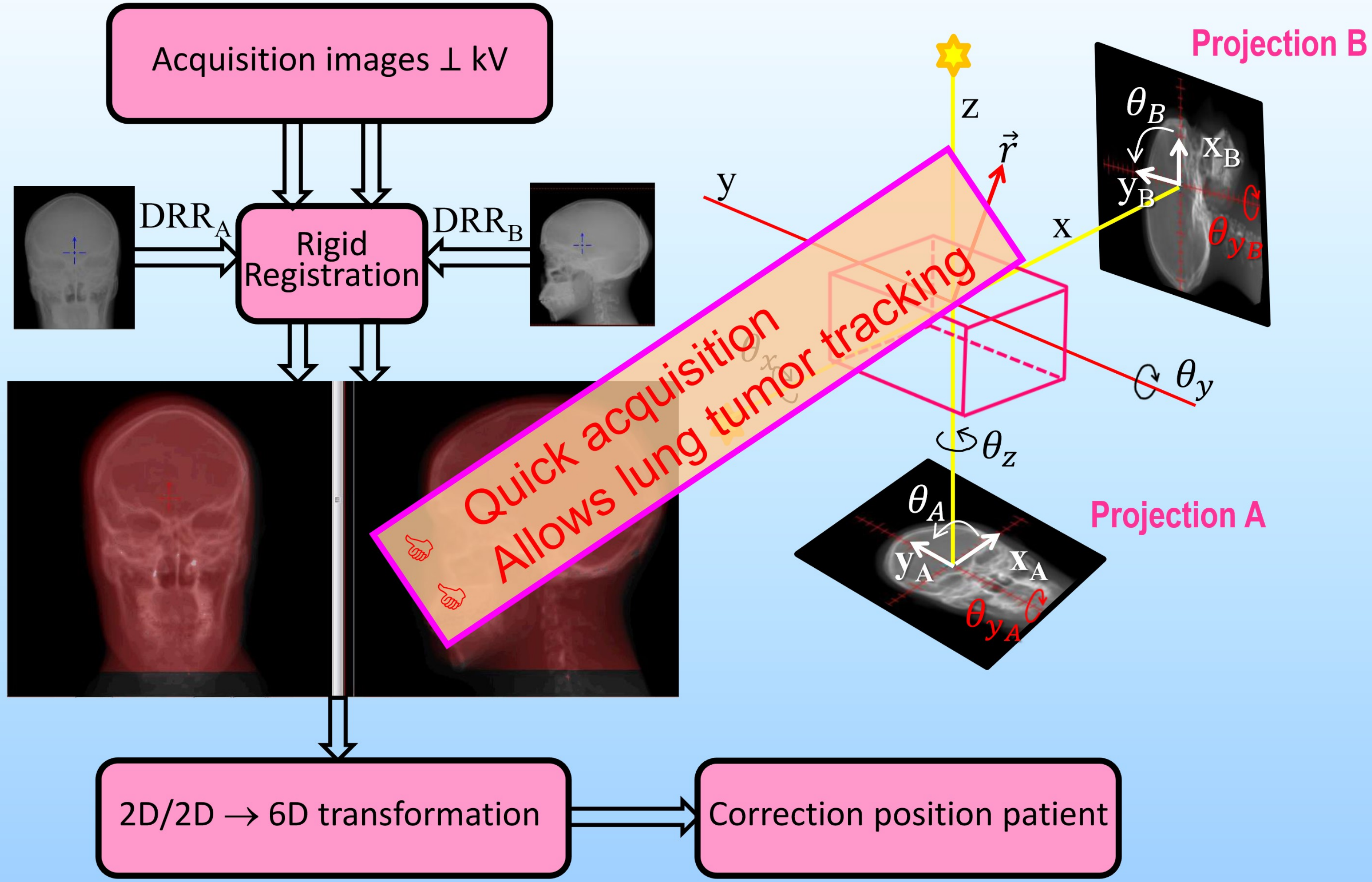
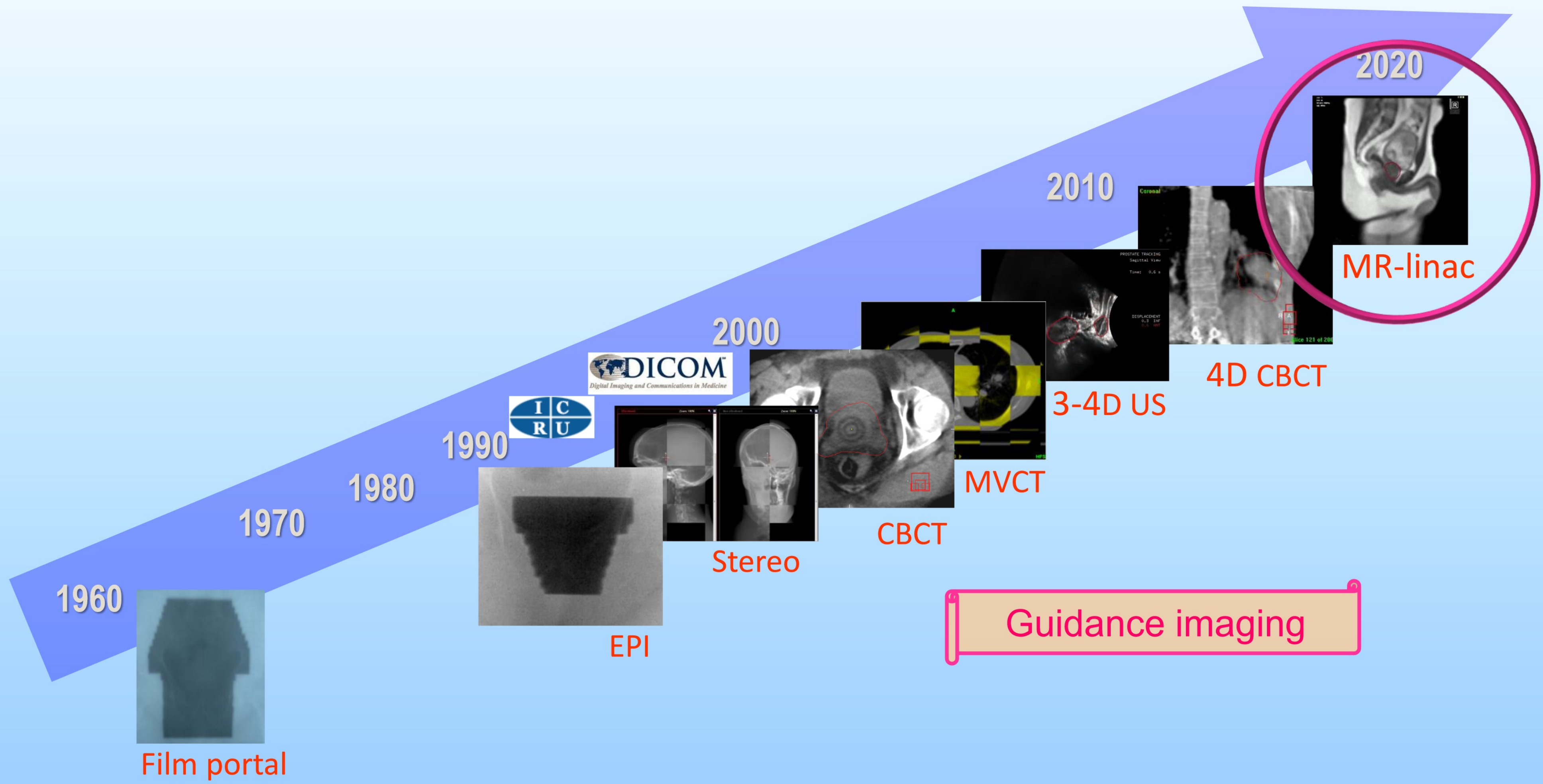


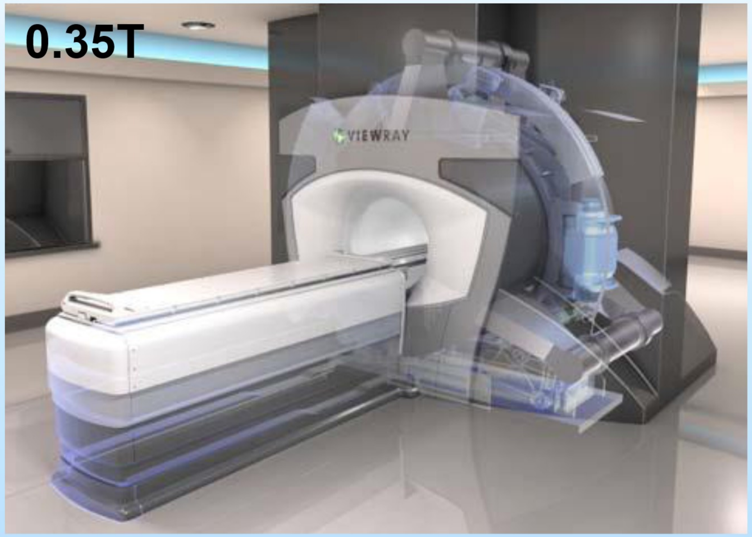
Image data in RO



Hybrid MRI linac equipments

Integrated linac and MRI scanner

Elekta Unity
(1 installed @ Hôpital Riviera-Chablais)

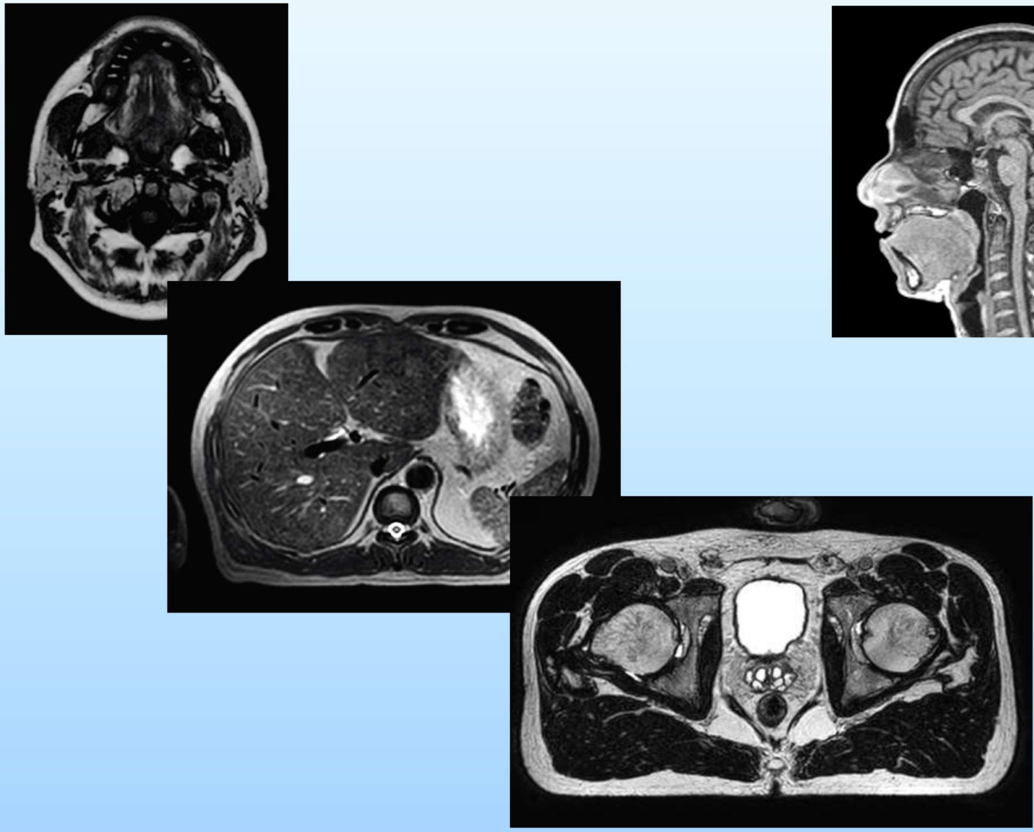


ViewRay MRIdian
(1 installed @ USZ)

Example of images

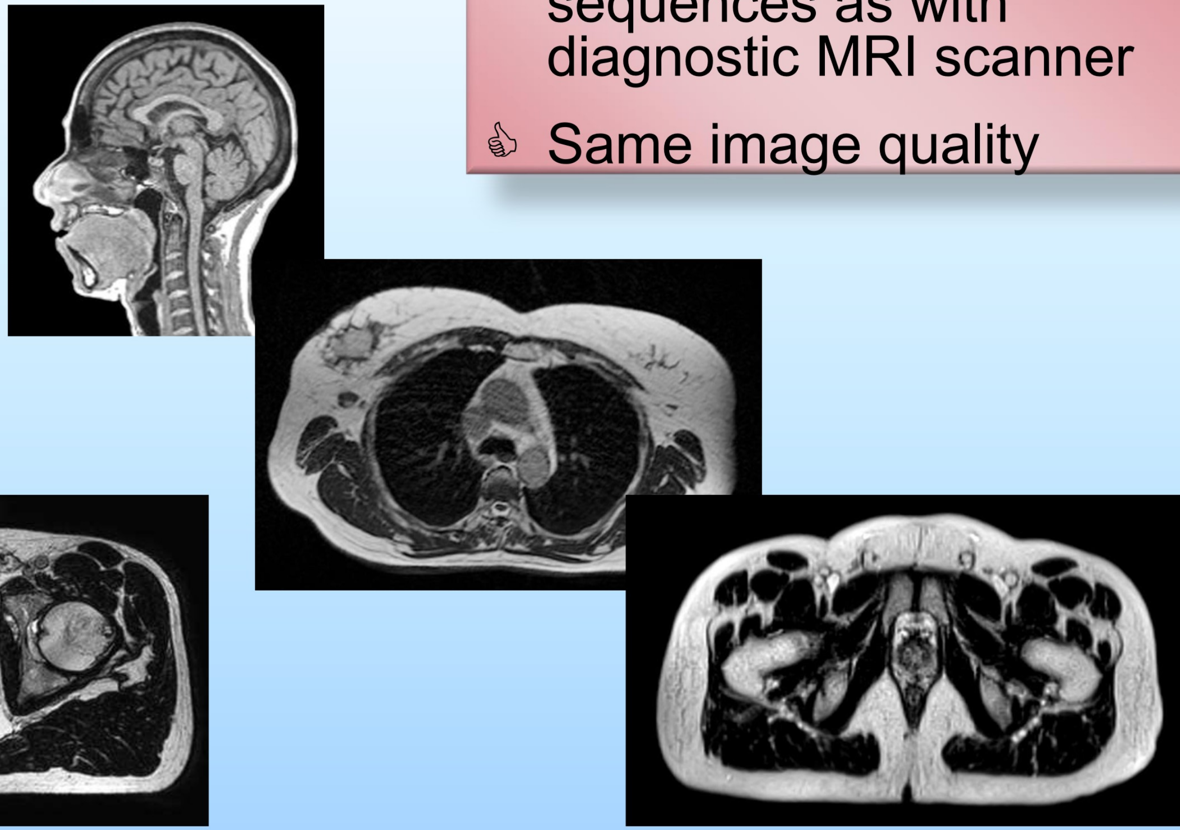
- Same acquisitions sequences as with diagnostic MRI scanner
- Same image quality

Elekta Unity



UMC Utrecht

ViewRay MRIdian



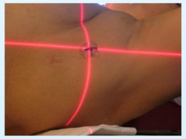
Viewray web site

MR-linac workflow

New IGRT paradigm shift called MRgRT

CBCT guided radiotherapy

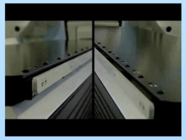
Patient setup on tattooed points



CBCT pre-treatment image

Registration with reference CT

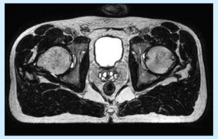
Patient repositioning by table motion



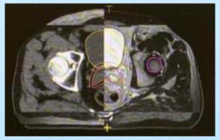
👎 No image during irradiation

MR guided radiotherapy

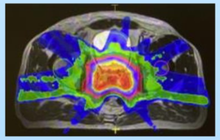
Patient setup on indexed table



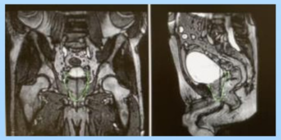
MR pre-treatment image



Registration with the reference CT or MR



Adaptation of the plan of the day

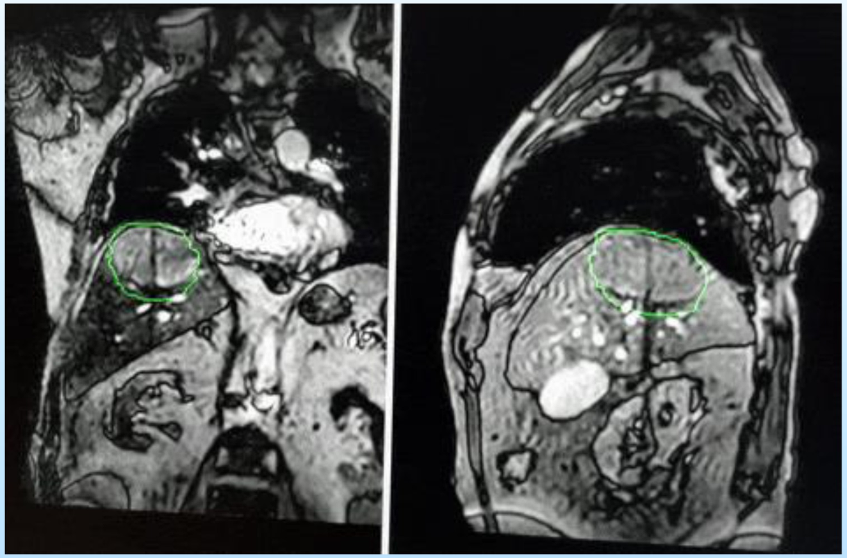


Continuous 2 planes imaging during irradiation

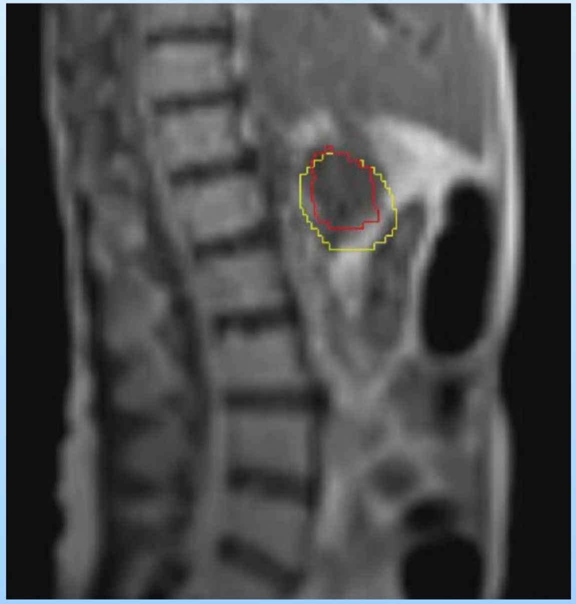
Continuous MR imaging during irradiation

Time resolved 3D dynamic imaging

- Possible control of intra-fraction motion (gating)
- Time resolved 3D dynamic imaging is not possible with 4D-CT/4D-CBCT/4D-PET/CT which are sorted in breathing phases



Example for Elekta Unity, Courtesy of HRC (VD)



Pancreas example for ViewRay MRIdian, Courtesy of USZ

Summary of image guidance modalities characteristics

Modality	Image type	Correction dimensions	Acquisition time	Soft tissues visibility	Intra-fraction motion	Acquisition dose
EPI	Planar / Fluoroscopic	2D	< 1s	Poor	Yes	20-40 mGy
CBCT	Volumetric	6D	40 -120 s	Good	No	1-30 mGy
MVCT	Axial 3D	(3+1)D	80 – 200 s	Good	No	7-30 mGy
Stereo	2 Planar / Fluoroscopic	(3+3)D	< 1s	Poor	Yes	< 1 mGy (except tracking)
MR-linac	Planar/3D MR	6D+time	<1s	Excellent	Yes	No dose

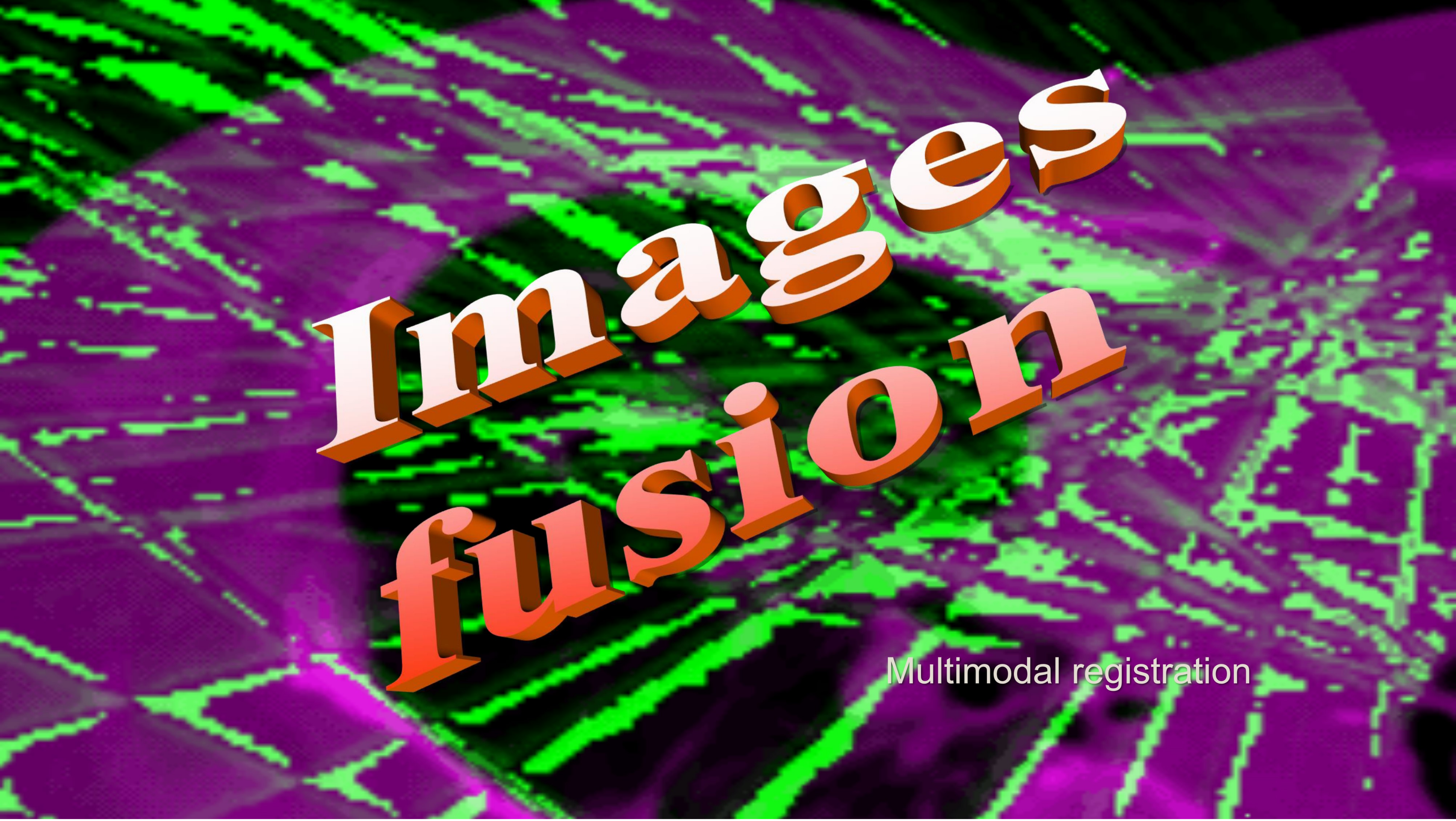
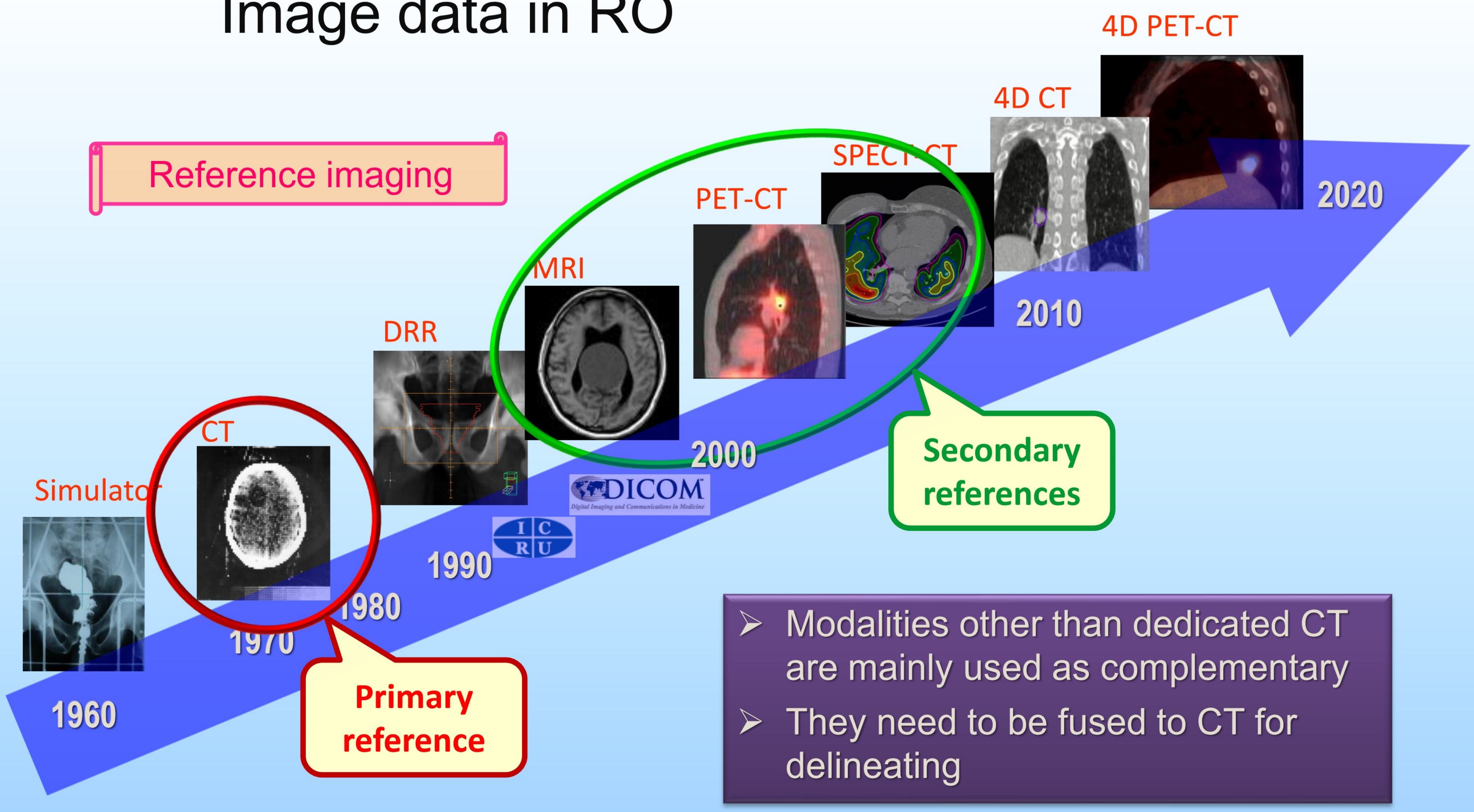

Images
fusion
Multimodal registration

Image data in RO

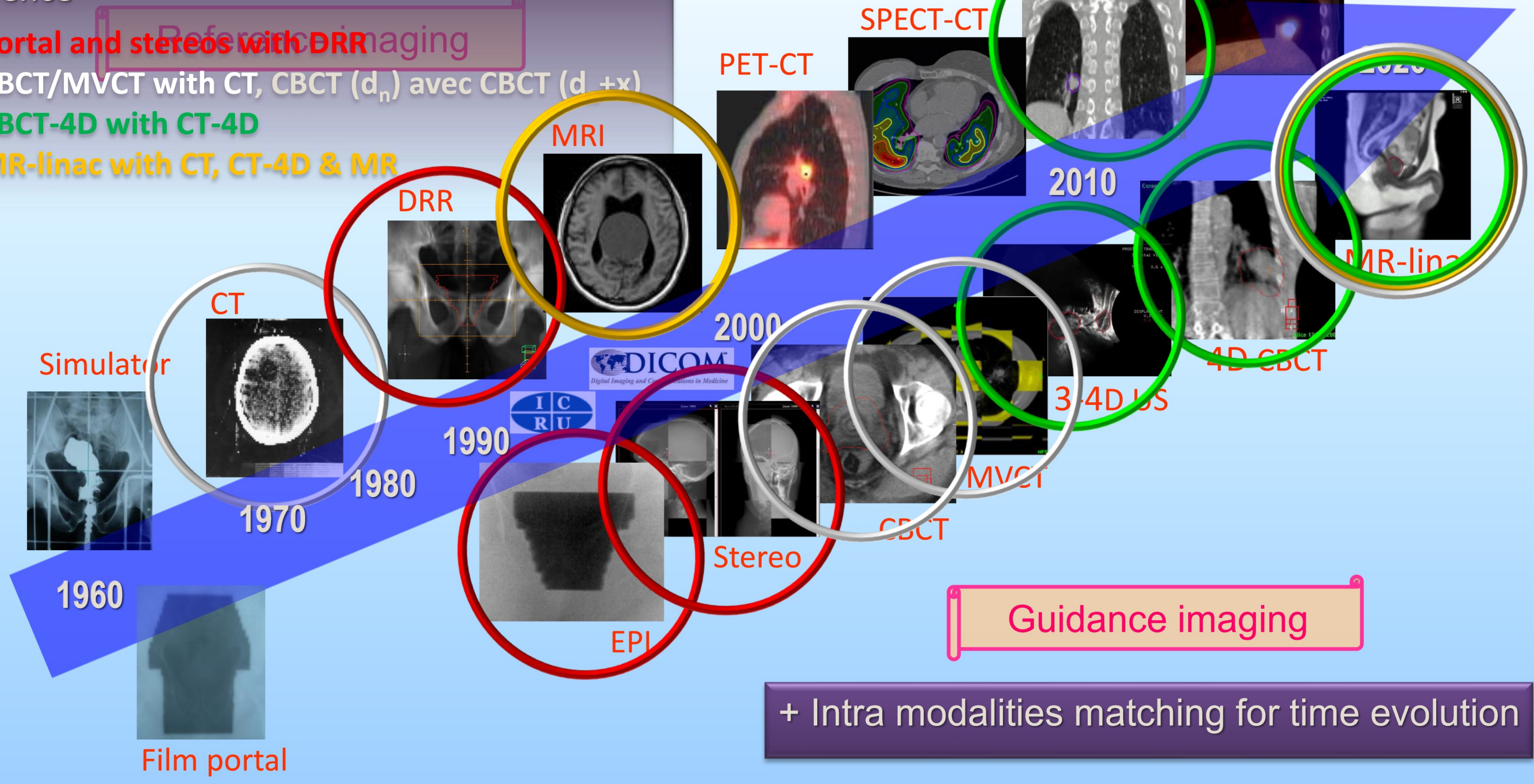


- Modalities other than dedicated CT are mainly used as complementary
- They need to be fused to CT for delineating

Image data in RO

Guidance modalities are matched with their reference

- Portal and stereos with DRR
- CBCT/MVCT with CT, CBCT (d_n) avec CBCT (d_n+x)
- CBCT-4D with CT-4D
- MR-linac with CT, CT-4D & MR



+ Intra modalities matching for time evolution

Processus of image fusion

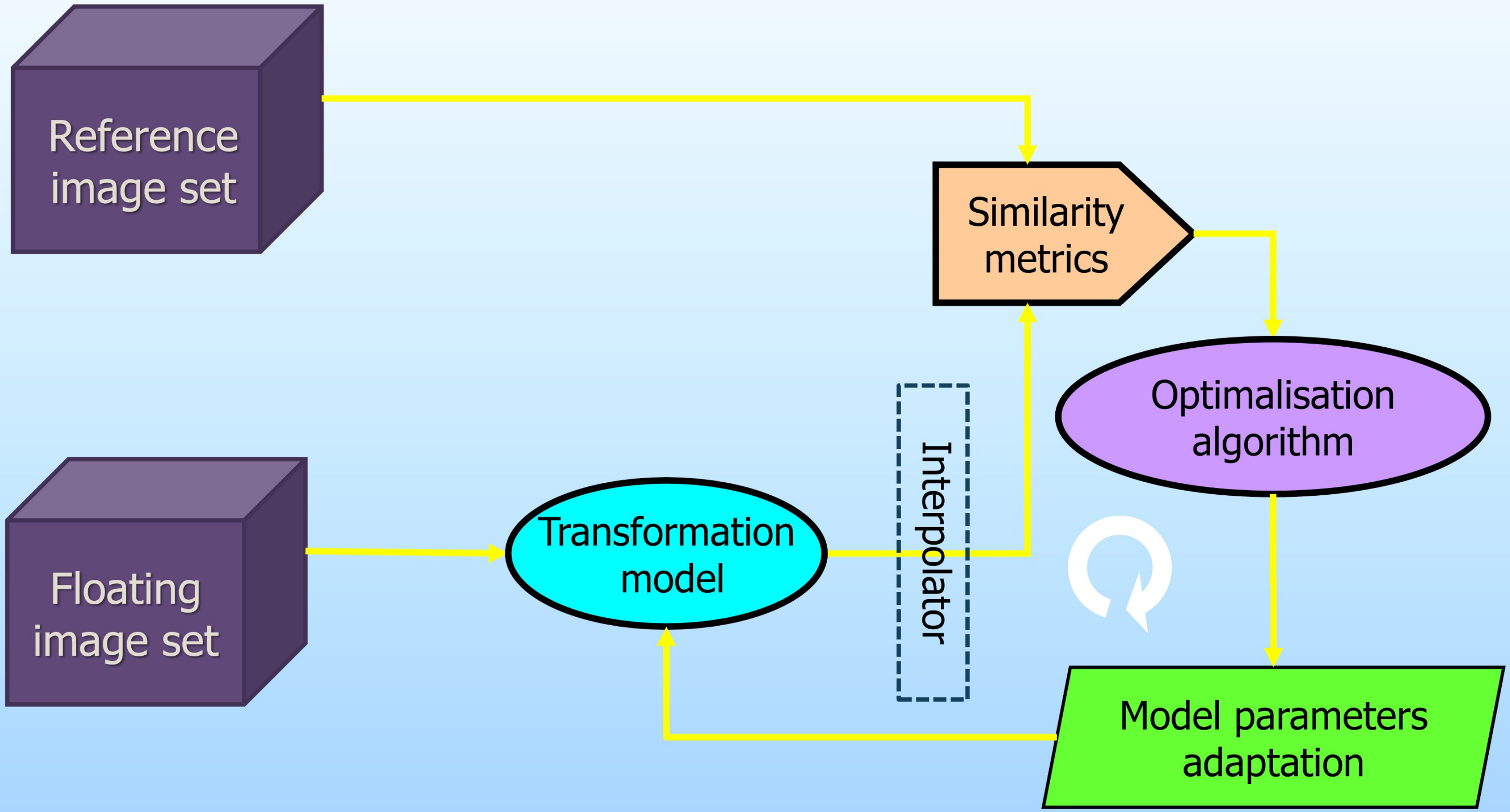
- Image fusion of modalities requires 2 successive operational steps:

1. Registration (spatial matching) of the 2 sets of images :
   a) Rigid method (ex: chamfer matching) ☞
   b) Deformable method (ex: mutual information) ☞

2. Display of the registered images:
   a) Overlay of the 2 sets into one combined data set (fusion) ☞
   b) Display of the 2 sets in 2 synchronized windows

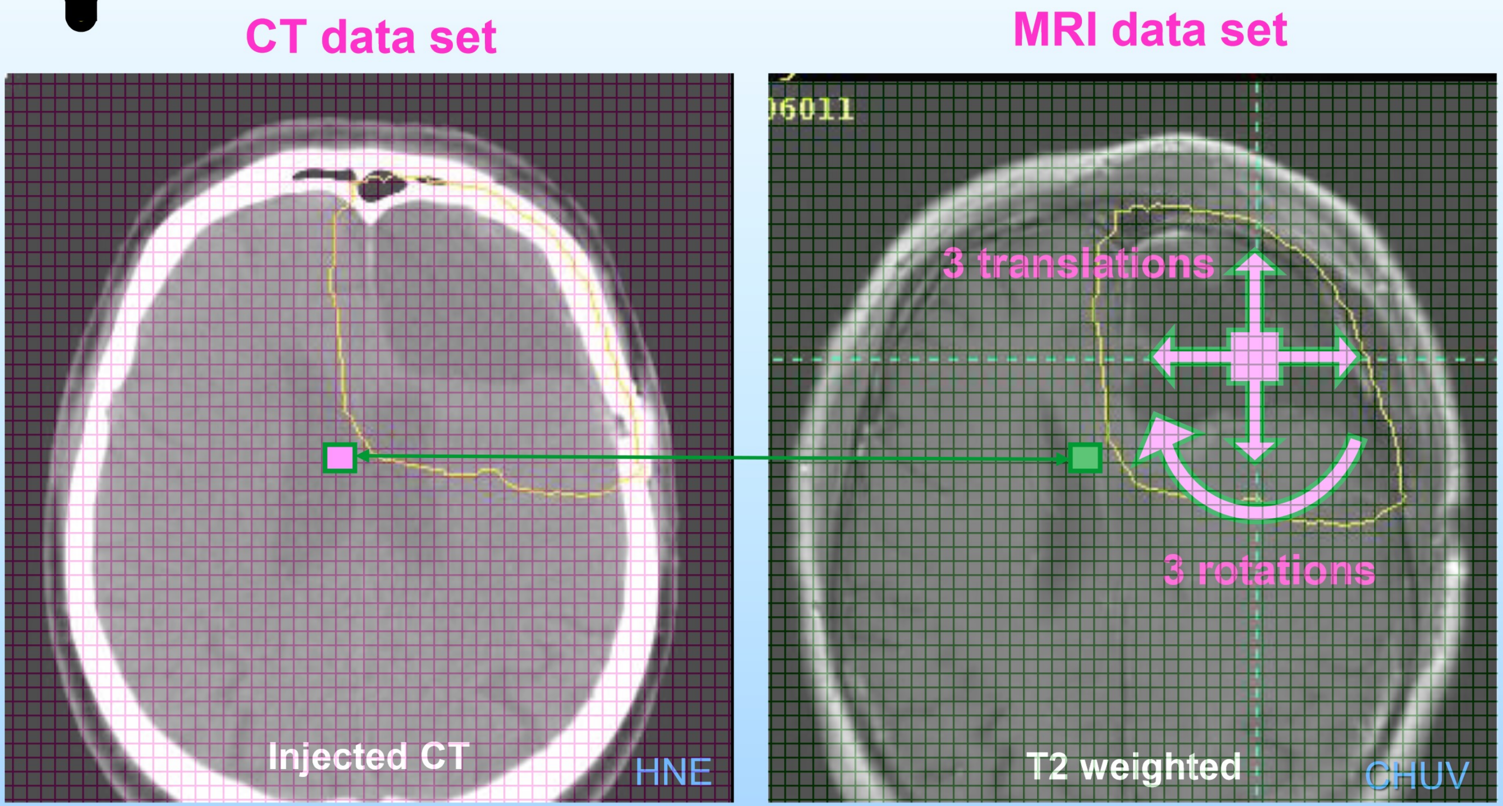
We then should speak of **fusion of registered images** but usually we say simply image fusion

General diagram of automatic registration



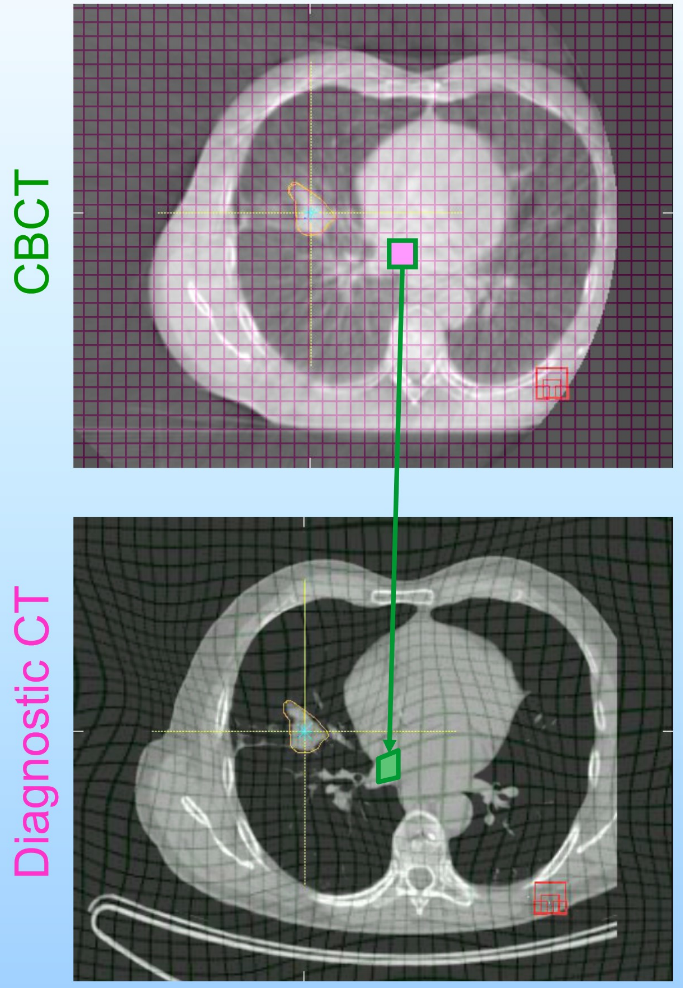
a) Principle of rigid 6D registration

Finds the best rigid transformation between 2 modalities

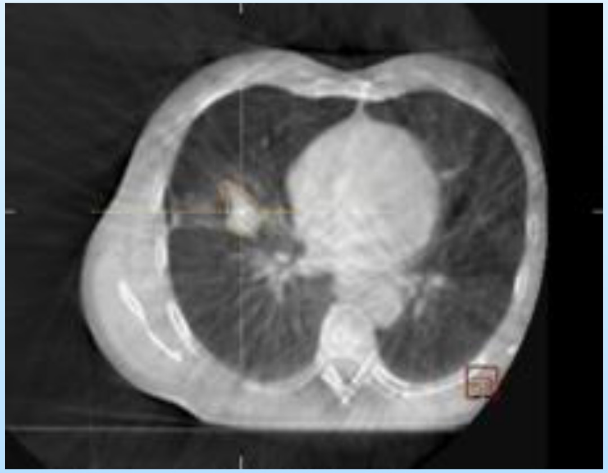


☞ There exist robust automatic algorithms such as chamfer matching technics

b) Principle of deformable 3D registration



Example of different patient positions between diagnostic CT and treatment



Techniques of registration by deformable maps

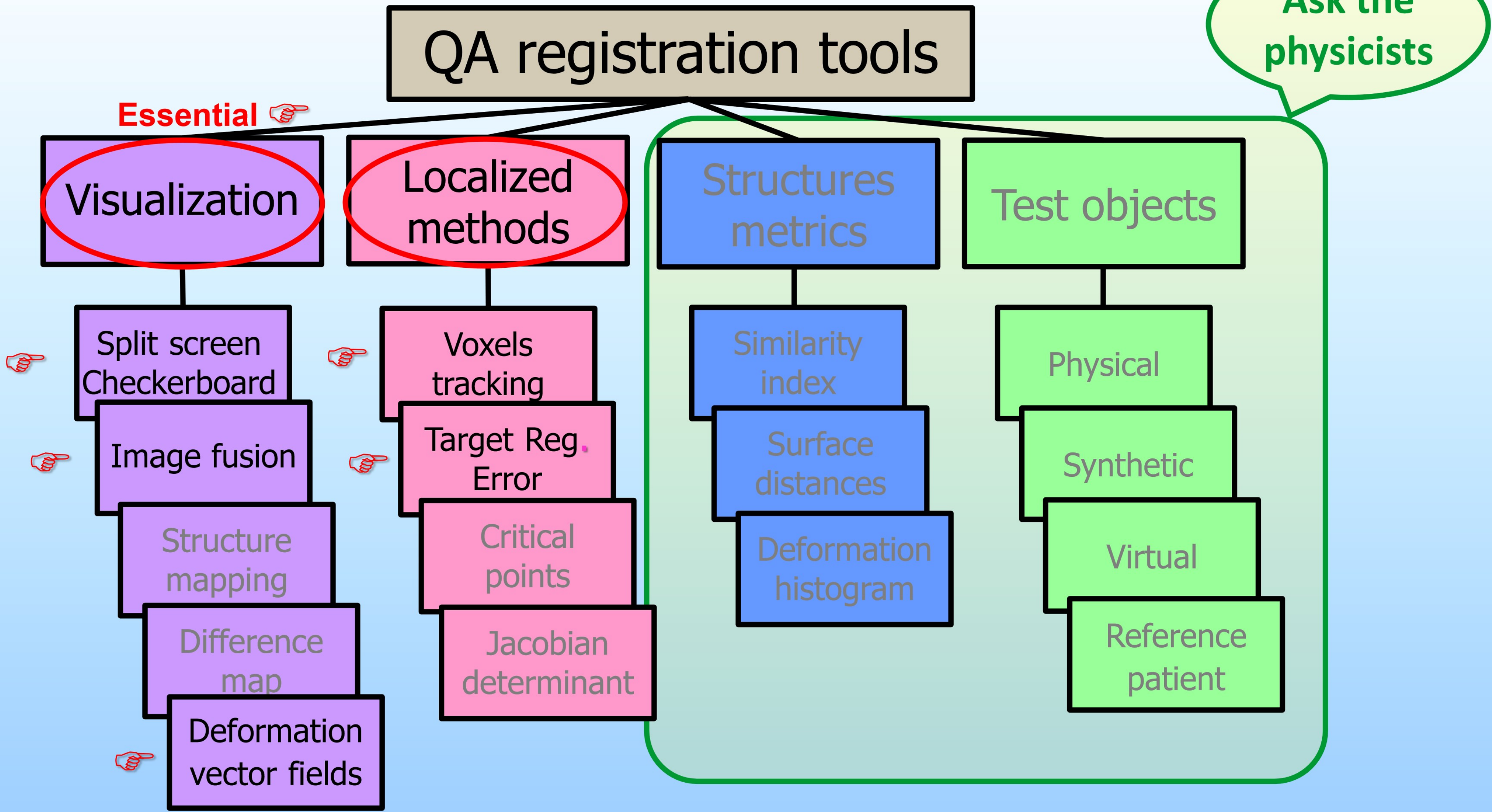
Mathematics of deformable registration (DIR)

- There exists numerous types of transformations:
  - Free forms (B-spline) are used by commercial software
- There exists numerous types of similarity metrics:
  - Mutual information is the most common one
- The transformation must be regularized:
  - Preservation of topology: 2 adjacent points must have adjacent displacements
  - Volume conservation: Incompressibility of some organs (bone)
  - Large deformations are disfavored since torsion or deformation of image consumes energy

⚠ Deformable registration can be far from reality

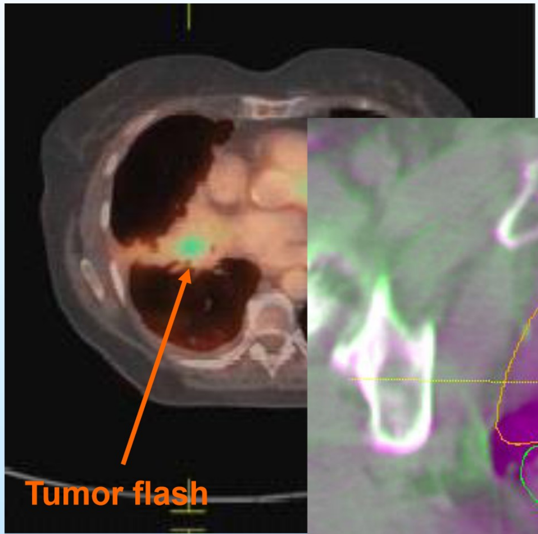
⚠ Registration must be clinically approved

Typology of validation tools for registration



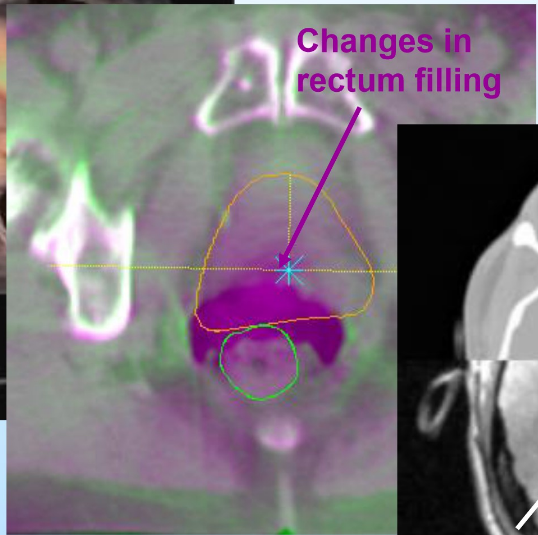
Techniques for image registration validation 1/3

Visualization as fusion of 2 images



Alpha blending BW+1 colour:

CT in grey levels
PET in orange

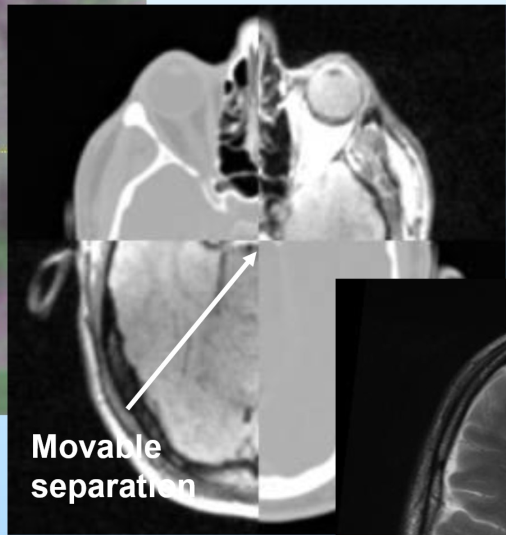


2 colours channels :

Localization CT in purple
CBCT of the day in green

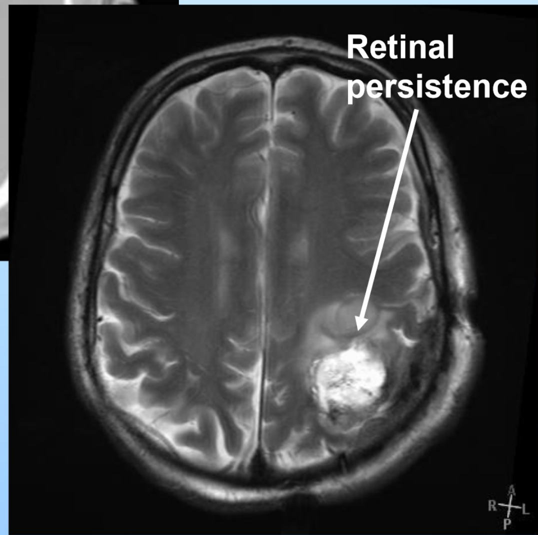
Checkerboard:

CT/MR grey levels in various quadrants



Cine mode:

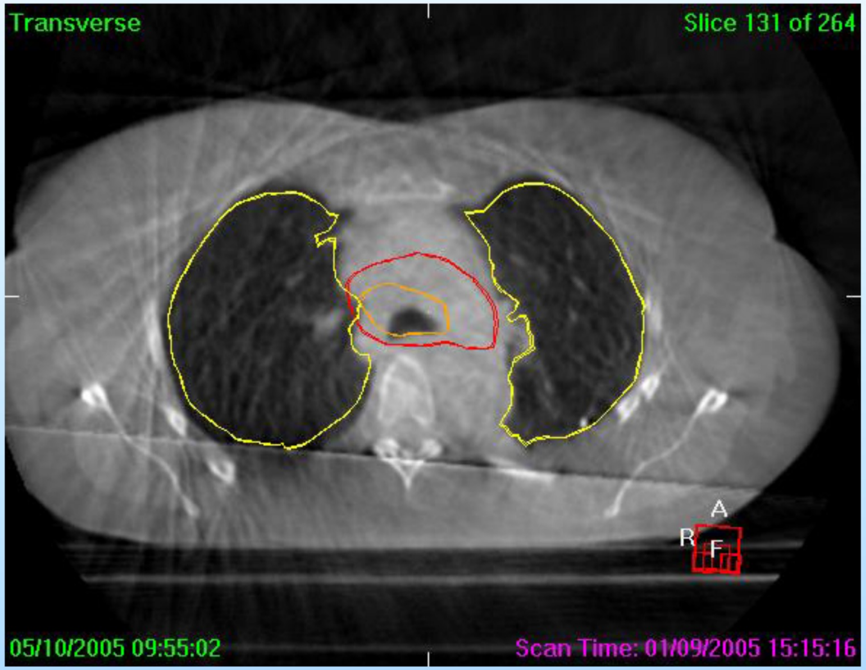
CT/MR grey level in alternance



+ adaptations (split view, side by side, …)

Techniques for image registration validation 2/3

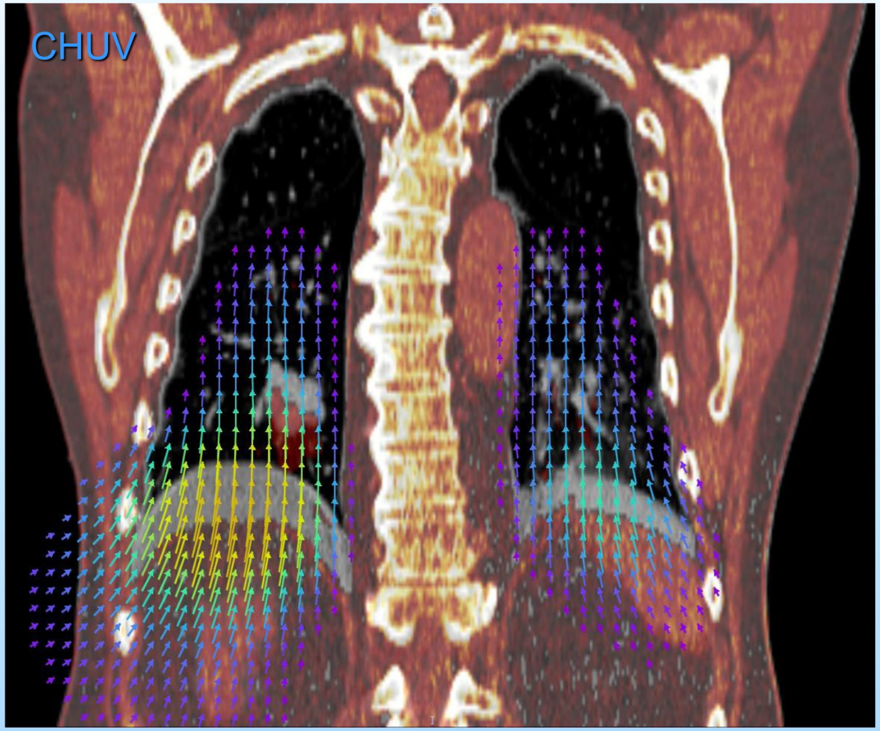
Visualization of contours mapping



- ❖ Anatomical contours drawn on one modality (here CT) are overlaid on a second modality (here CBCT) for validation
- ☝ Useful for spotting organ deformations

Techniques for image registration validation 3/3

Visualization of the warp field



Velocity example for inspirium/expirium

- The arrows show the direction and strength (as colors) of the displacements
- Useful for spotting abnormal deformations
- Right diaphragm have the largest displacement OK

Techniques for image registration validation 1/3

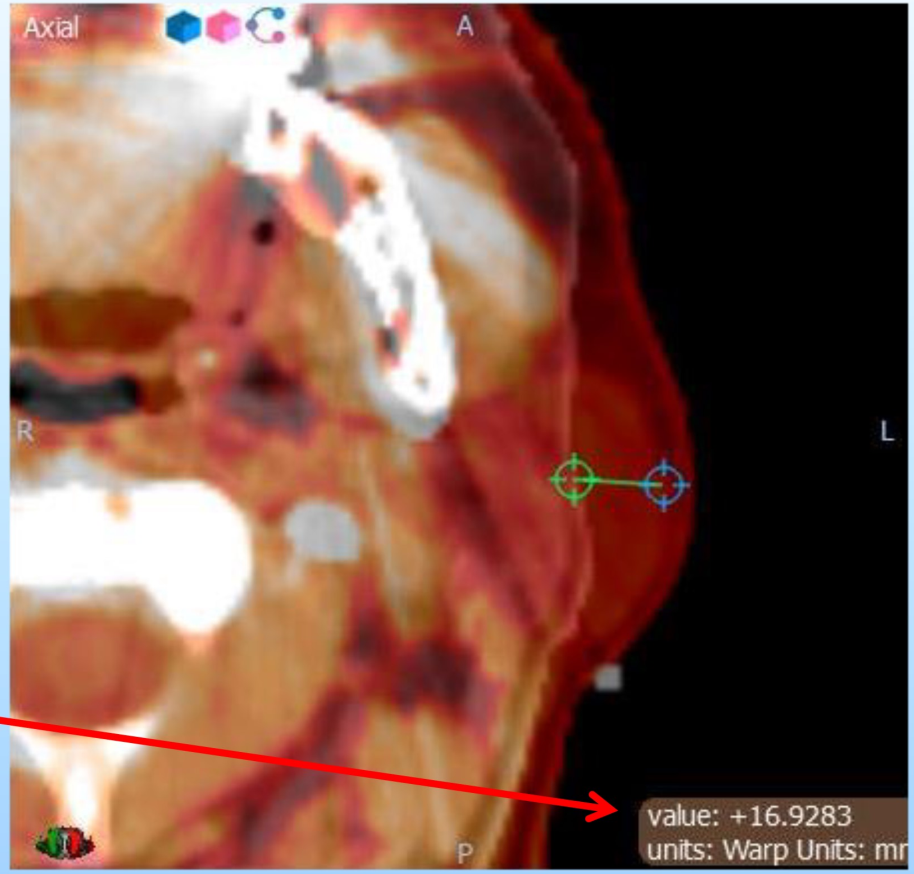
Localisation of points mapping

Exemple of weight loss:

1. The operator click a point in the reference image
2. The software displays this point as mapped on the floating image

☺ Allows to test where voxels are mapped

☺ Quantitative estimation of the displacement

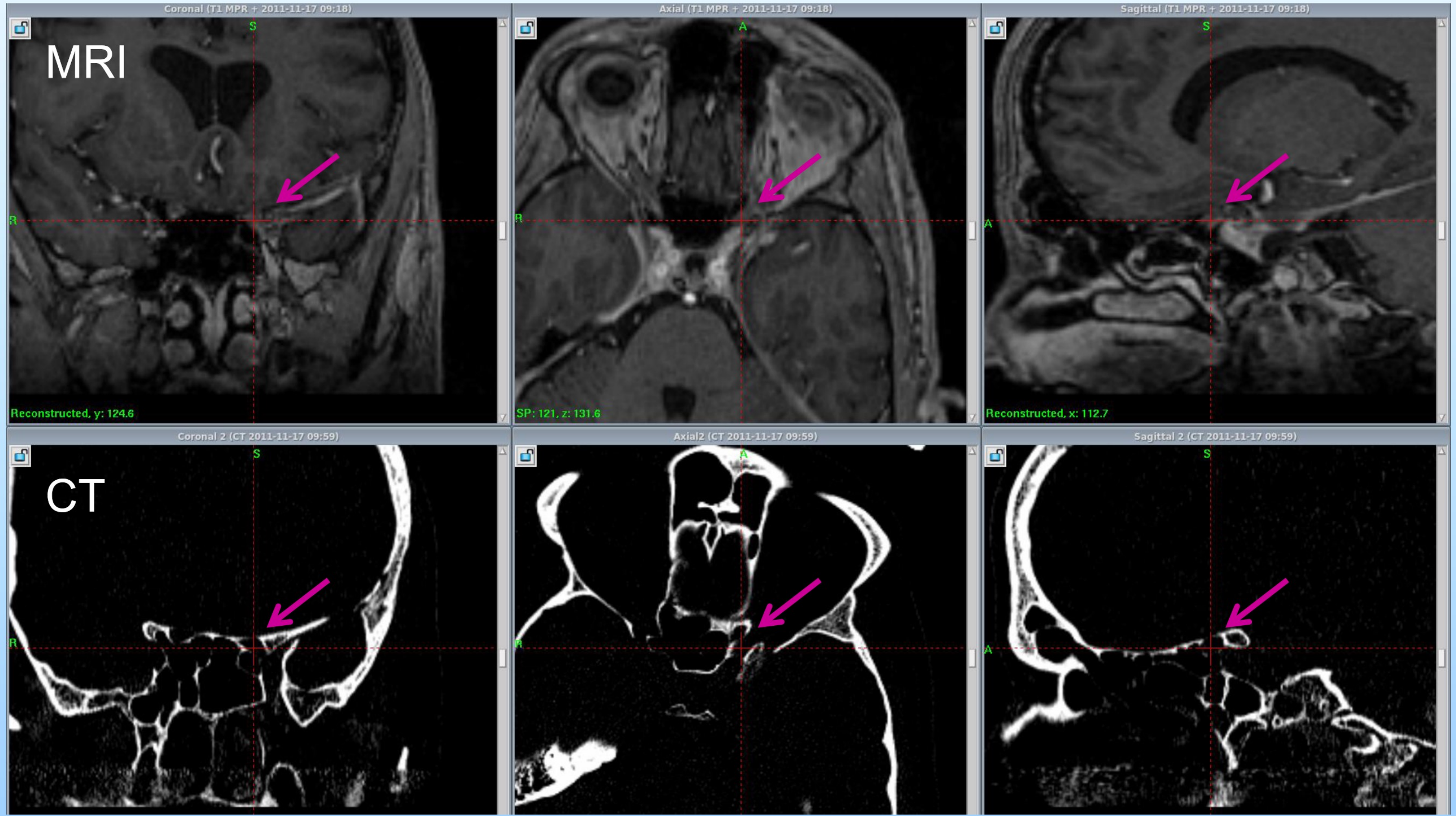


Velocity @ CHUV

Techniques for image registration validation 2/3

Localisation of homologous points: rigid registration

☞ Example for the auditive nerve in radiosurgery (Gammaknife CHUV)



Auditive nerve:

- Seen as mass in MRI
- Seen as canal in CT

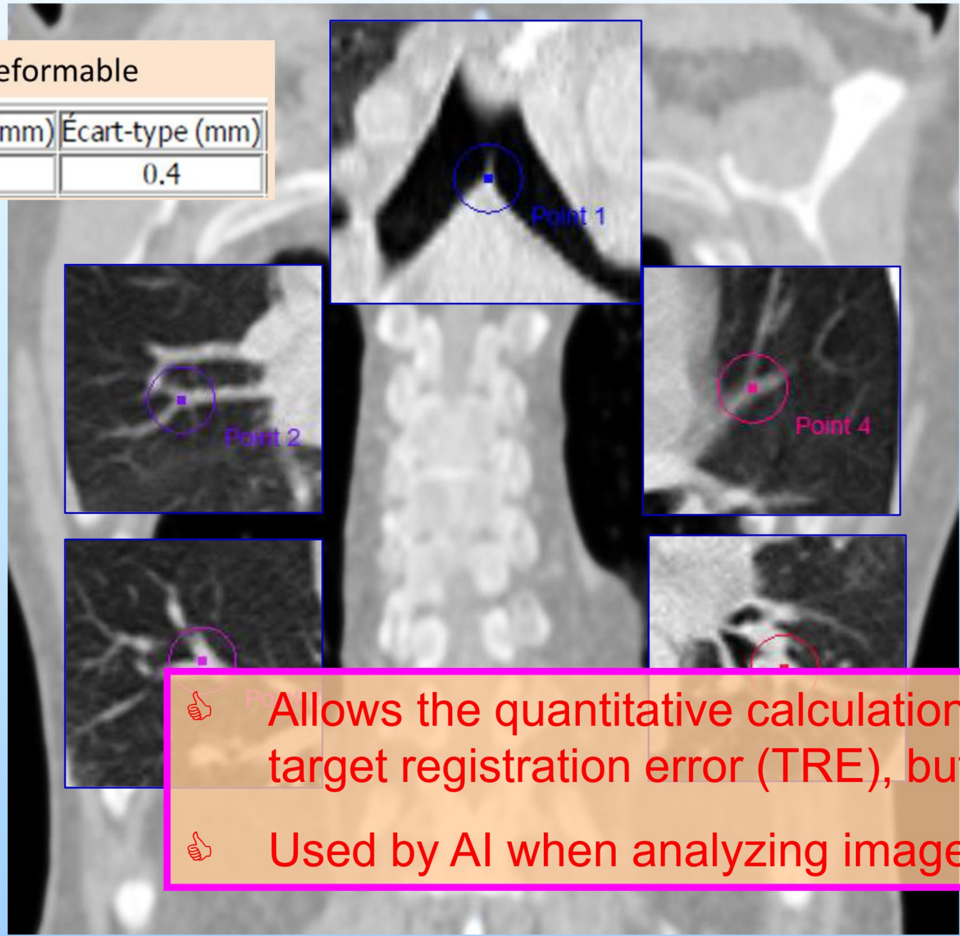
Techniques for image registration validation 3/3

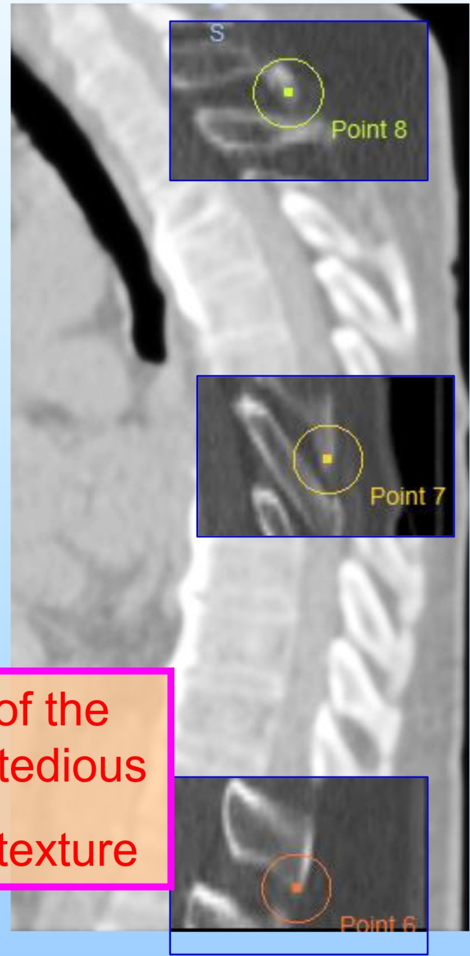
Localisation of homologous points: deformable registration

	Rigid		Deformable	
TRE:	Moyenne (mm)	Écart-type (mm)	Moyenne (mm)	Écart-type (mm)
	4.0	2.9	1.4	0.4

Example of 8 landmarks:

- Carena
- 4 bifurcations
- 3 tips of spinous process

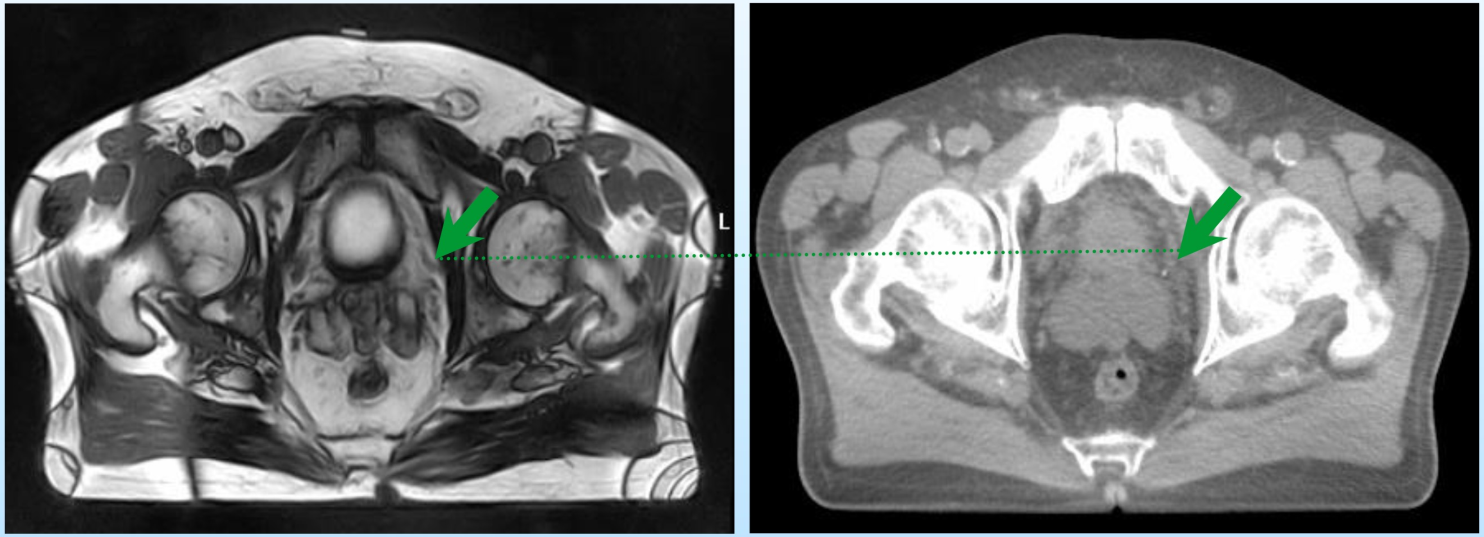




- Allows the quantitative calculation of the target registration error (TRE), but tedious
- Used by AI when analyzing image texture

Techniques for delineating on registered images

Example for MRI –CT :

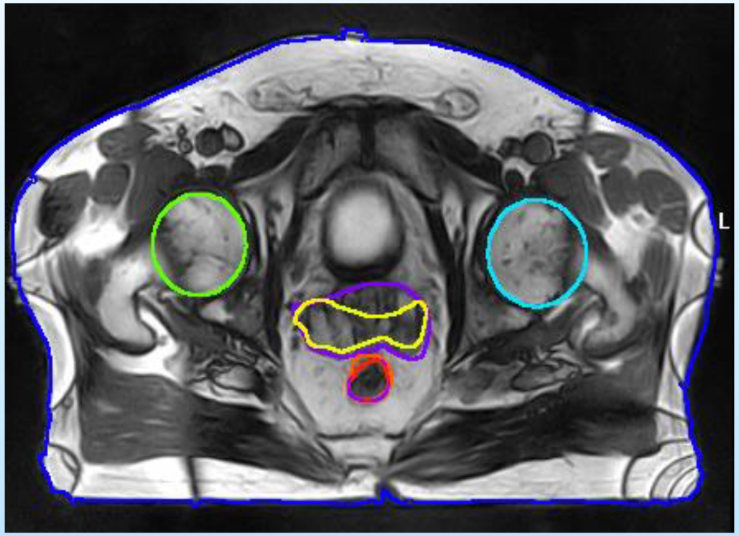


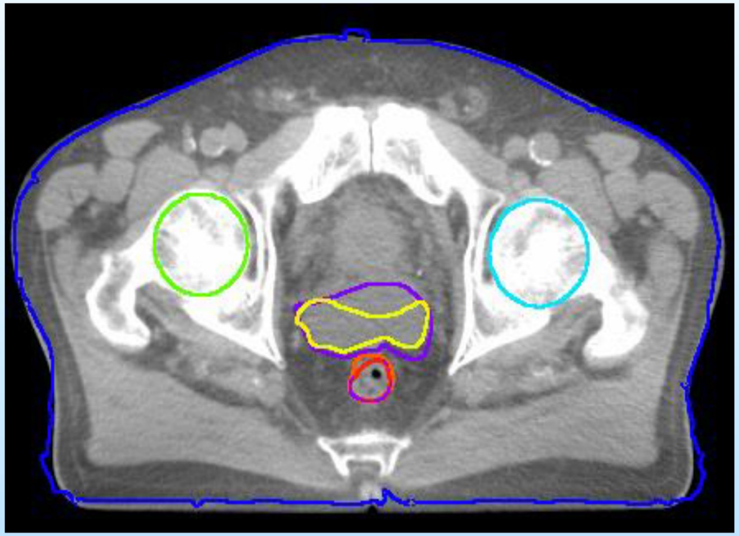
From J. Dipascale et al.,
SASRO meeting,Geneva, 2004

- **Data sets side by side**
- **Synchronized windows**
- **Shared cursor**
- **Simultaneous contours display**

Techniques for delineating on registered images

Example for MRI –CT :



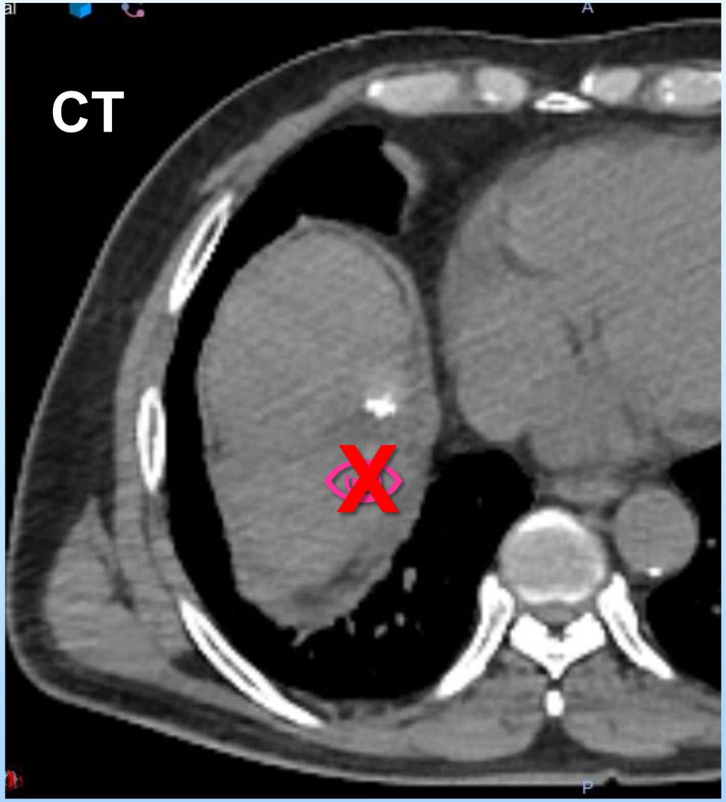


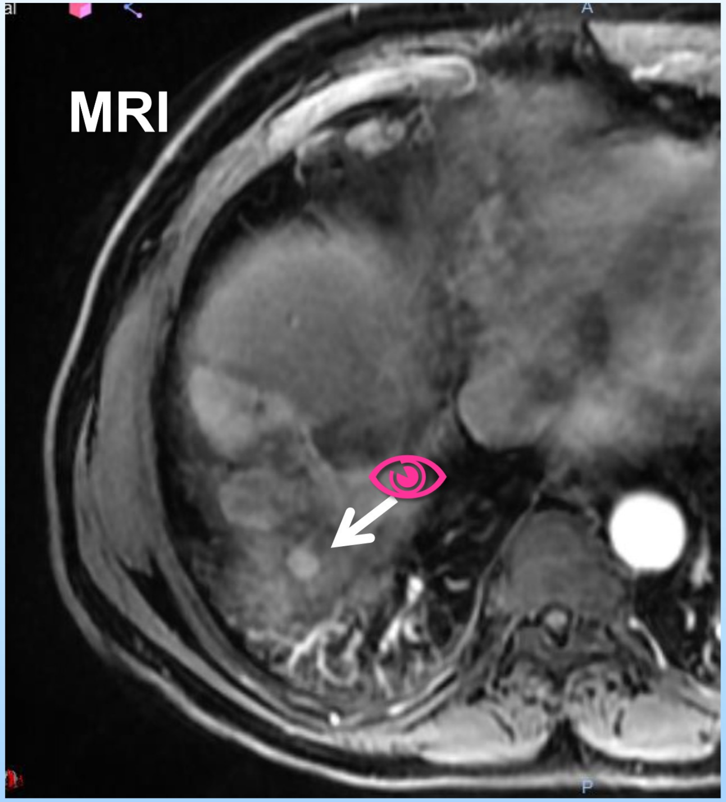
From J. Dipascale et al.,
SASRO meeting,Geneva, 2004

- **Data sets side by side**
- **Synchronized windows**
- **Shared cursor**
- **Simultaneous contours display**

Deleneating GTV observable only in MR $_{1/2}$

Example: Metastasis not seen on CT, but on MRI

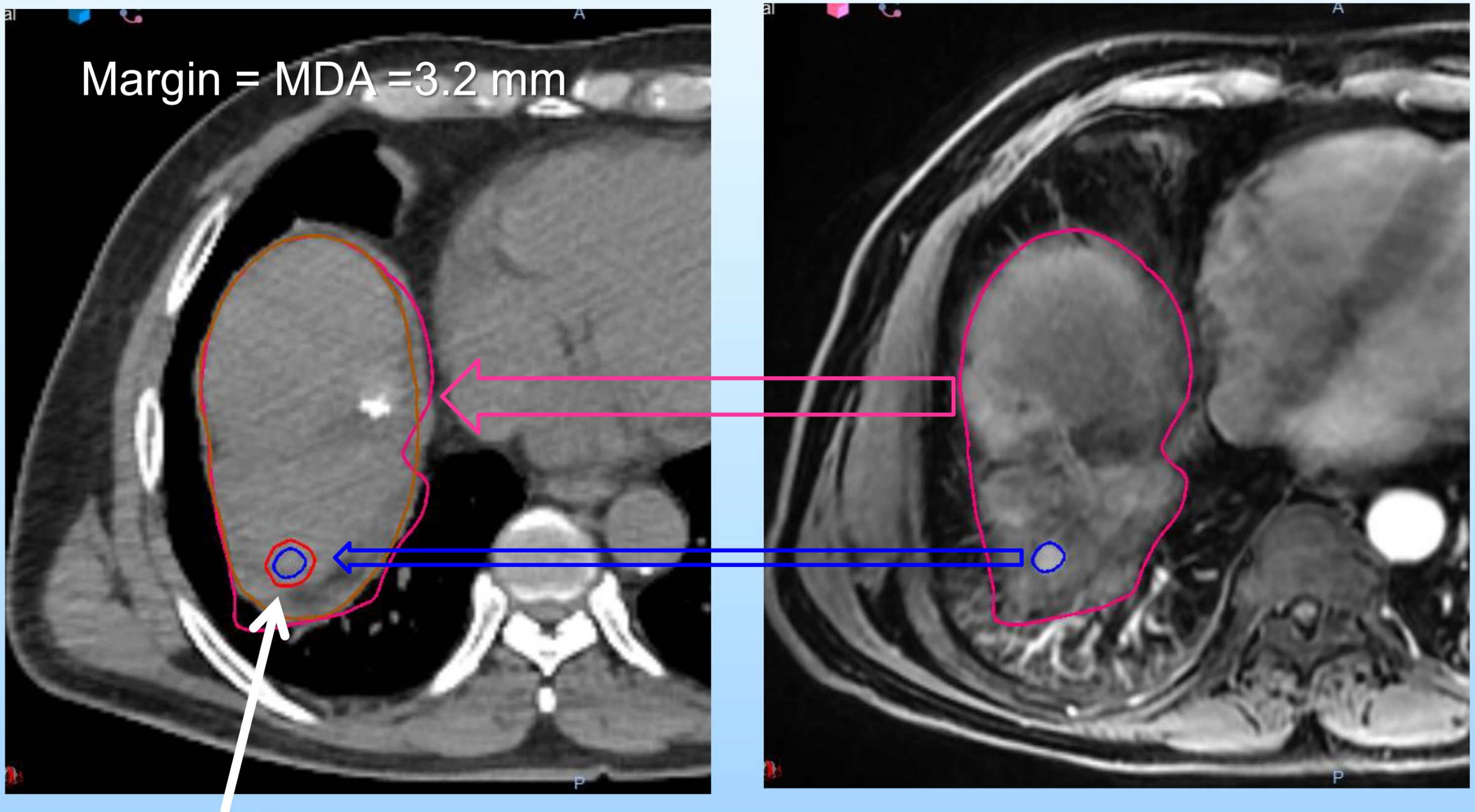




- ❑ How can we check than the metastasis will be mapped correctly?

Deleneating GTV observable only in MR $_{2/2}$

Solution: Use the uncertainties of adjacent visible organs



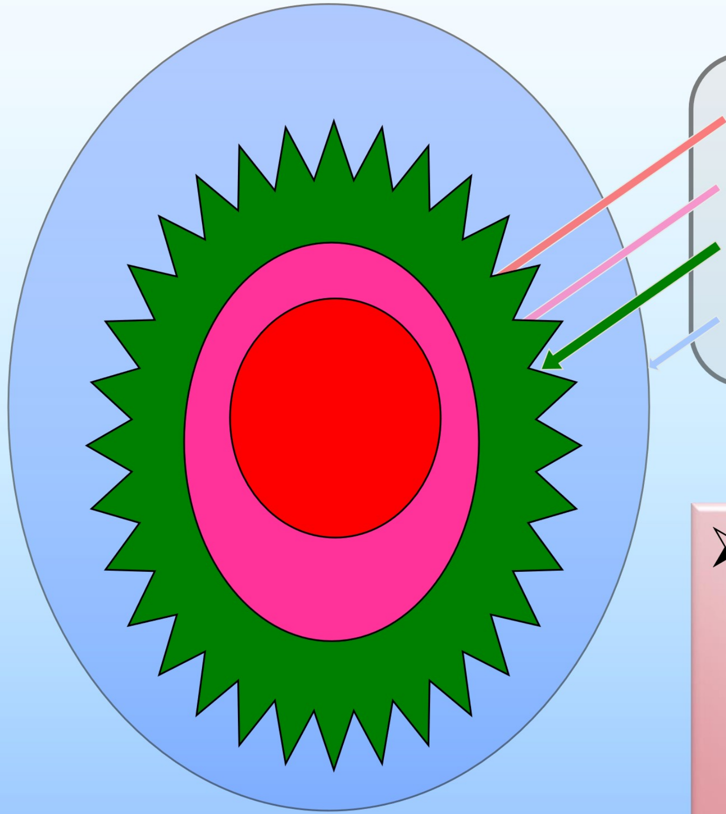
- ❑ Map the metastatsis contour and the liver surface to the CT
- ❑ Add the uncertainty of the liver surface to the metastasis mapped contours

You need to add an extra margin to the mapped GTV


4-D
imaging
Motion management

Current imaging paradigm in RO

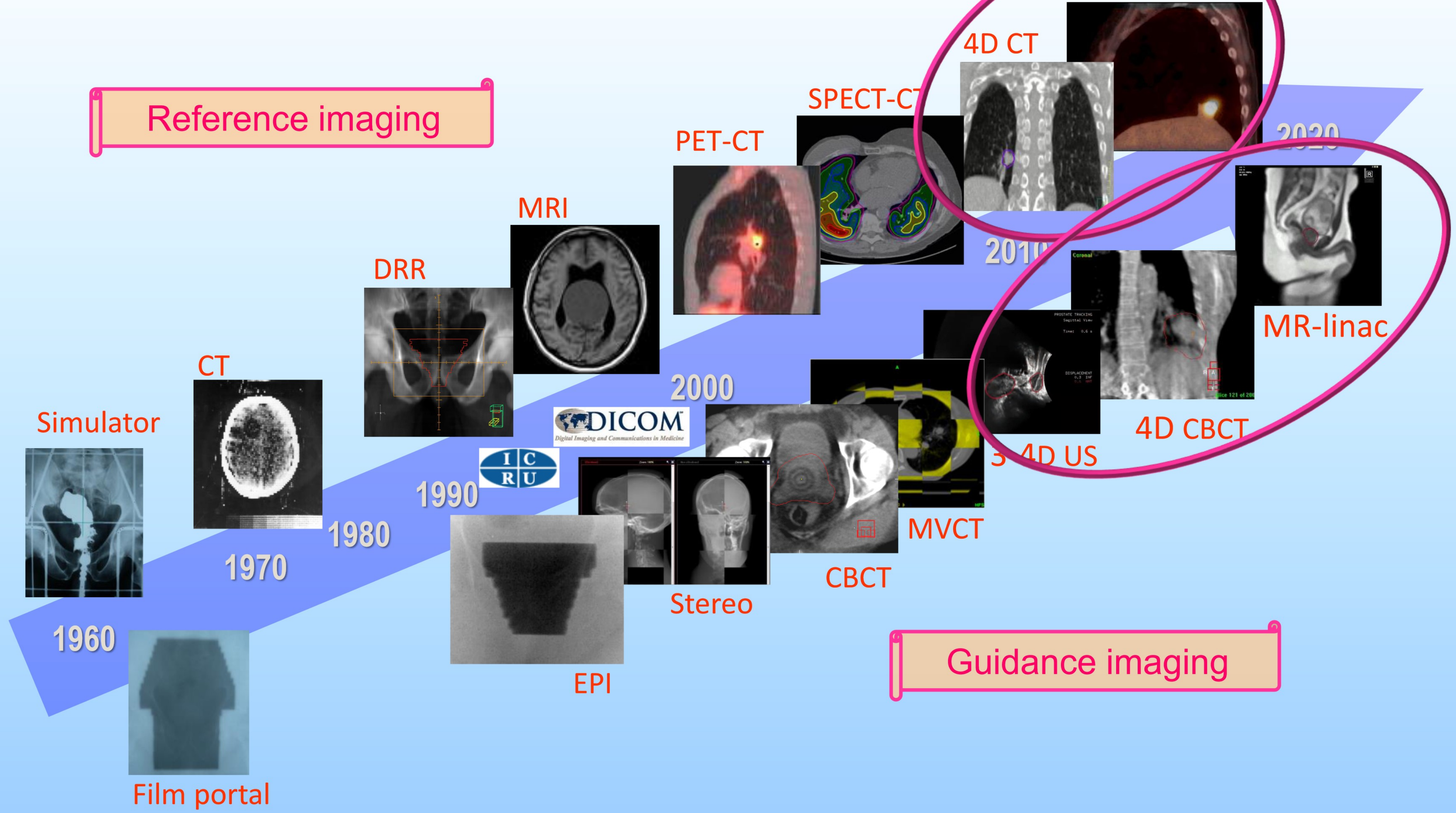
Normative definition of volumes: **ICRU 50, 62 & 83**



GTV : Gross Tumor Volume
CTV: + subclinical involvement
ITV: + Internal margin
PTV: + Setup margin

- 4D imaging in RO can be used for assessing the ITV but for much much more (gating, tracking,…)

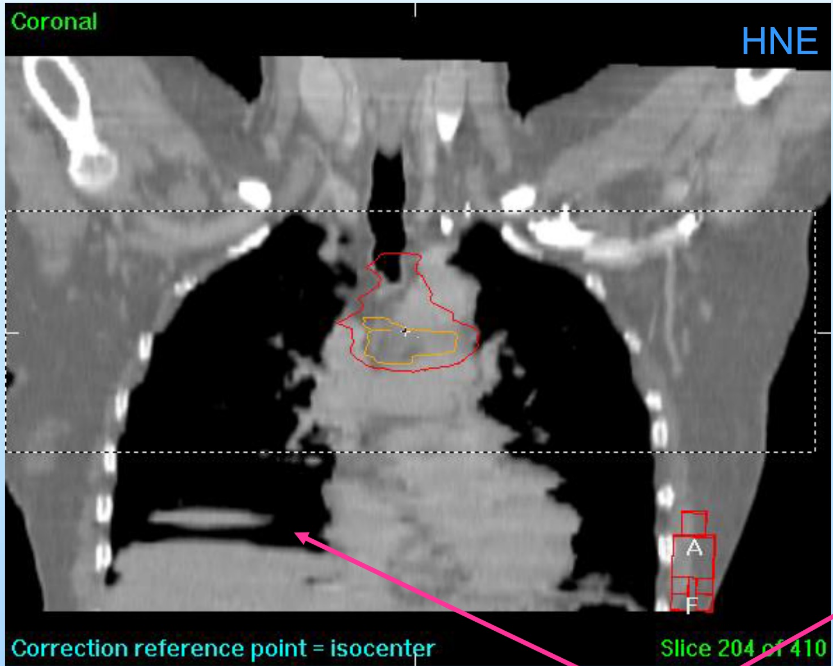
Image data in RO



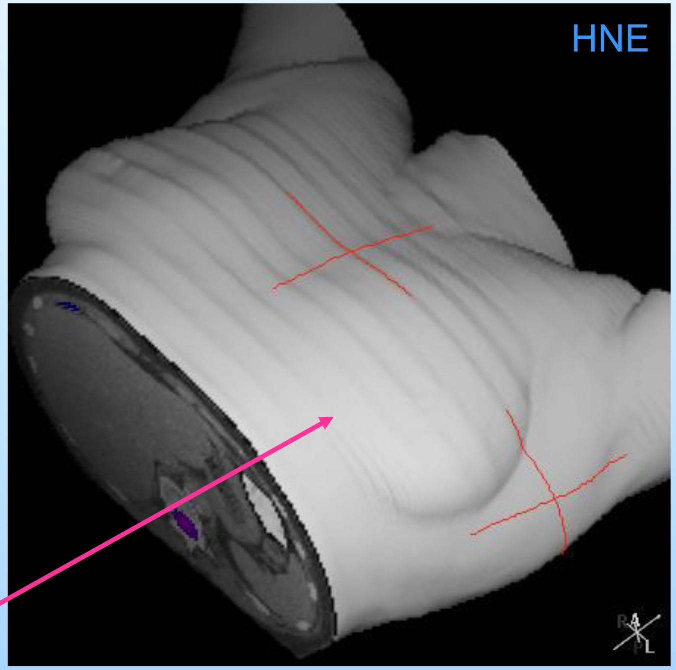
Problems with conventional 3D-CT: motion artefacts

- Axial slices are shuffled
- Tumor shape is modified

2D MPR



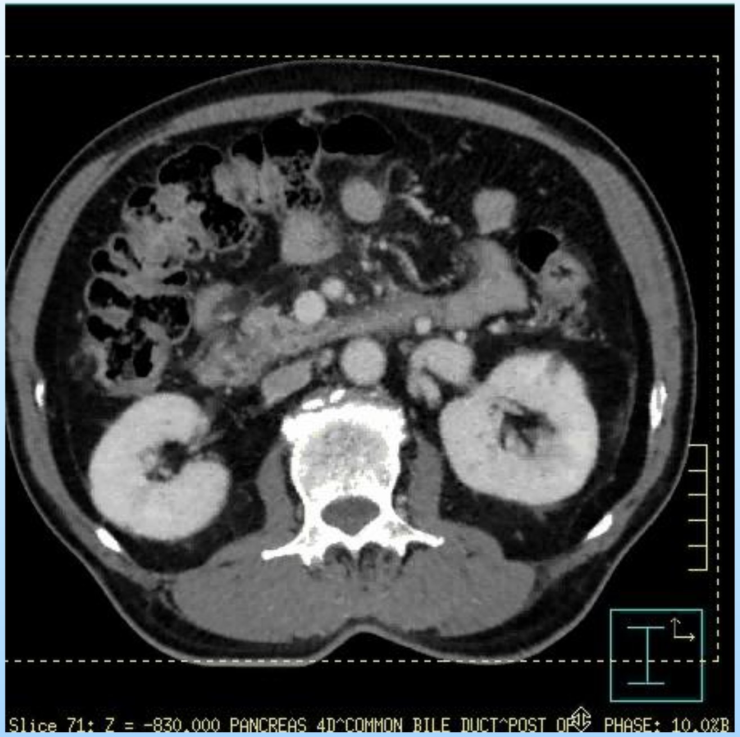
3D rendering

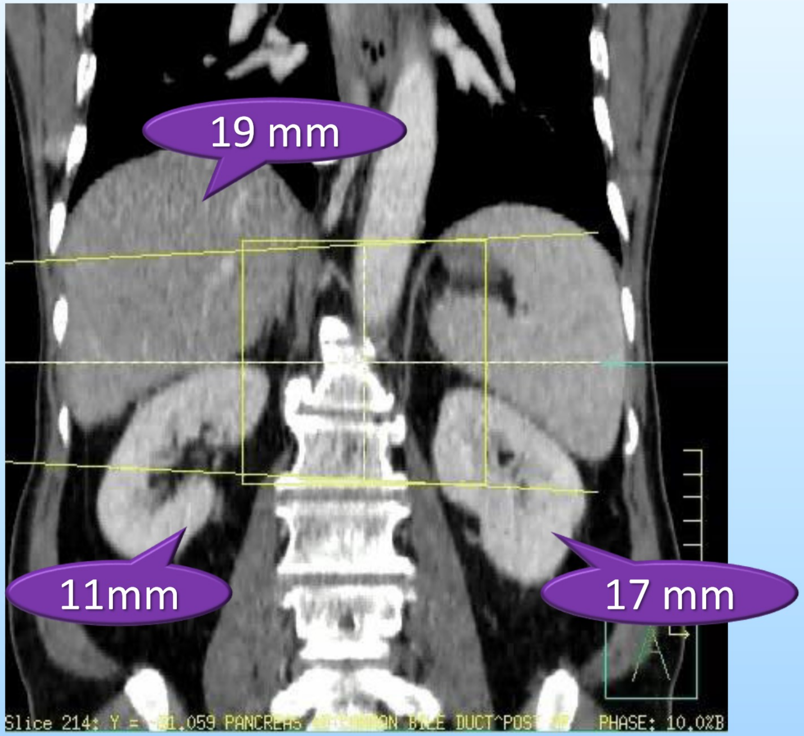


- Helical CT: 1 turn / s
- Frozen virtual patient

Importance of internal organs motion 1/2

⚠ Ventilatory automatism influences organs localization at large distances (liver, kidneys,..):

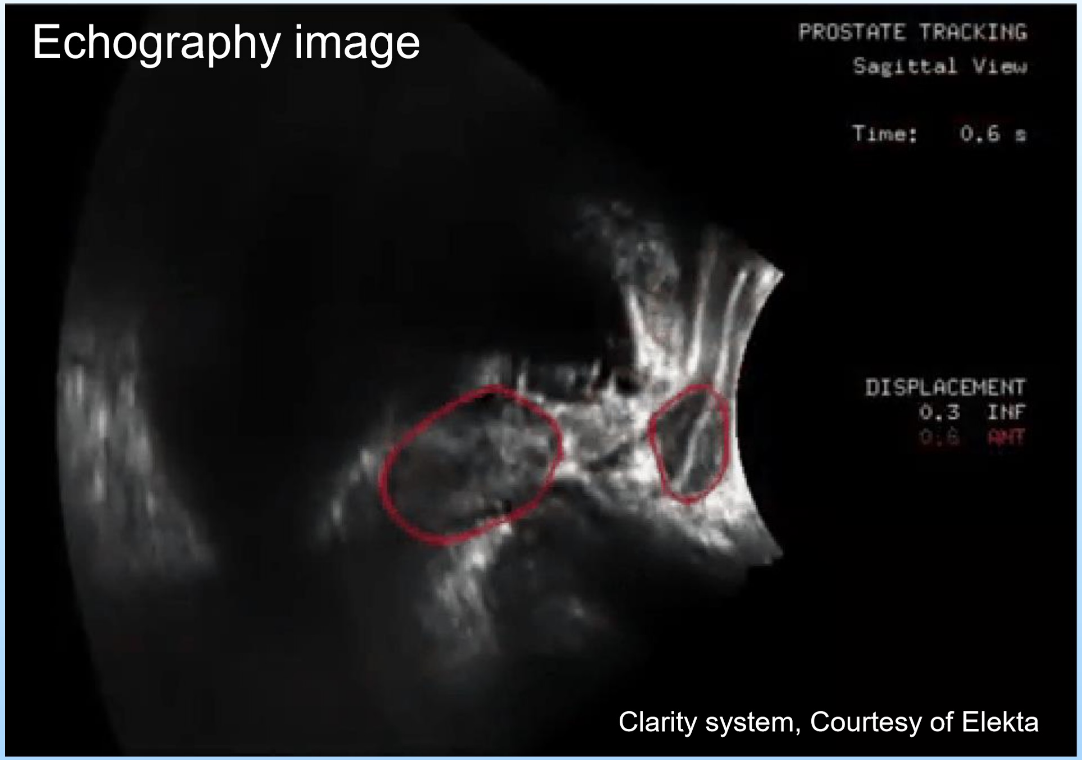




Courtesy of Philips Medical Systems

Importance of internal organs motion 2/2

⚠ Even prostate can exhibit intra-fraction motion:



Motion management by 4D scanning

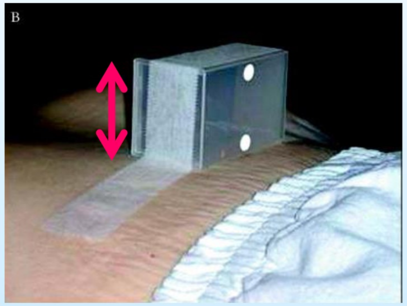
- Available by all manufacturers, but requires
  - Tracking the breathing cycle ☞
    - Camera, belt, deviceless
  - Specific acquisition technics ☞
    - CT: Axial/cine, helicoidal
    - PET: TOF, list mode
  - Adapted type of reconstruction ☞
    - Sinograms sorting, reconstructed images sorting
    - Prospective, retrospective

- Manufacturers are using different combinations of these
- Transposing experience from one system to another one is not straightforward

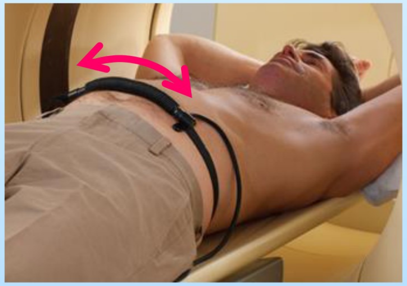
Tracking the respiratory cycle 1/2

Commercially implemented in CT and PET/CT systems

- ✓ RPM Varian (Real-time Position Management):
  - ☞ Tracking of the thorax vertical motion



- ✓ Philips pneumatic belt:
  - ☞ Extension/retraction measurement of the thorax circumference



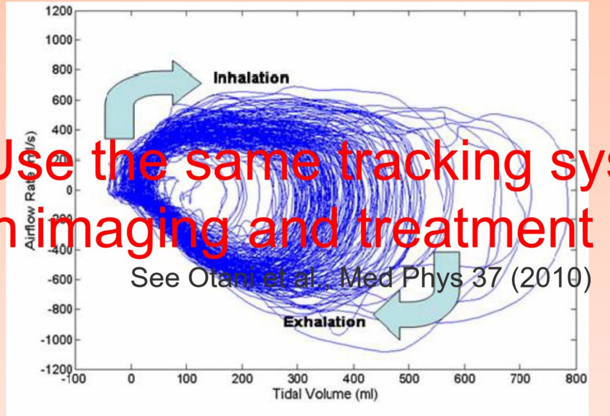
- ✓ Anzai AZ-733V belt:
  - ☞ Measurement of the pressure variations under the belt

Breathing cycle tracking devices mostly used

Tracking the respiratory cycle 1/2

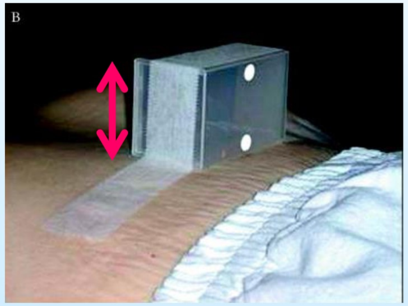
Commercially implemented in CT and PET/CT systems

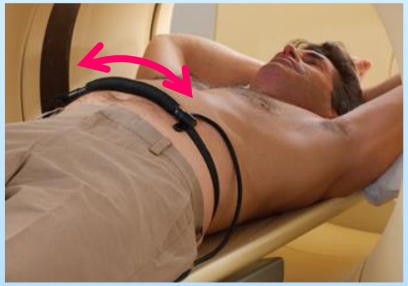
- These signals are different surrogates for the respiratory signal.
- We assume that tumor motion correlates with surrogate signal.
- ☹ Hysteresis influences internal motion of lung tissues (→more than 1 parameter).



Use the same tracking system in imaging and treatment

See Otani et al., Med Phys 37 (2010)

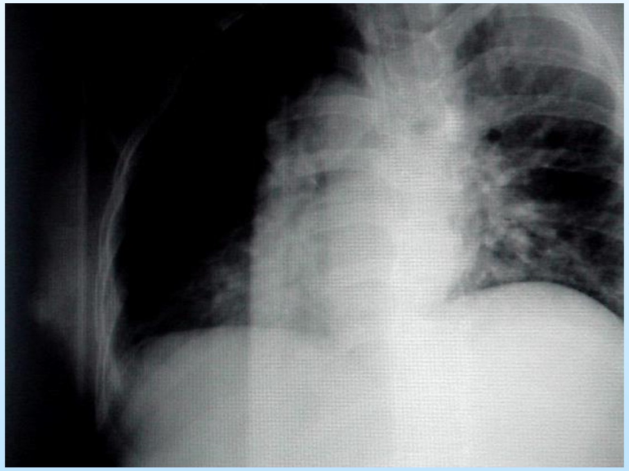




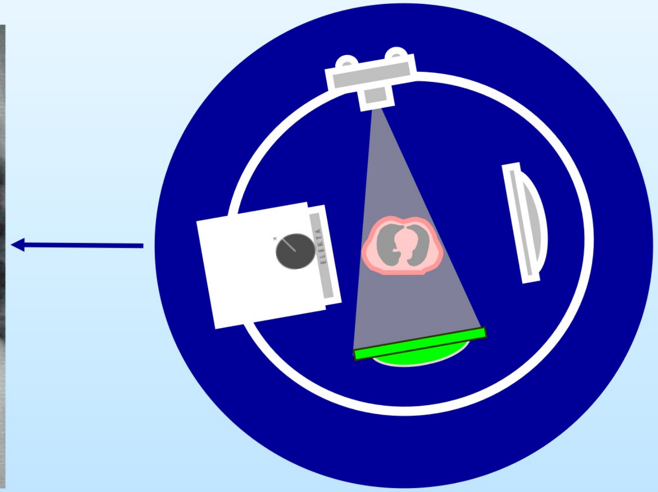
Tracking the respiratory cycle 2/2

Deviceless tracking as implemented in CBCT system

☞ Tracking the diaphragm motion



1250 frames / 4 mn

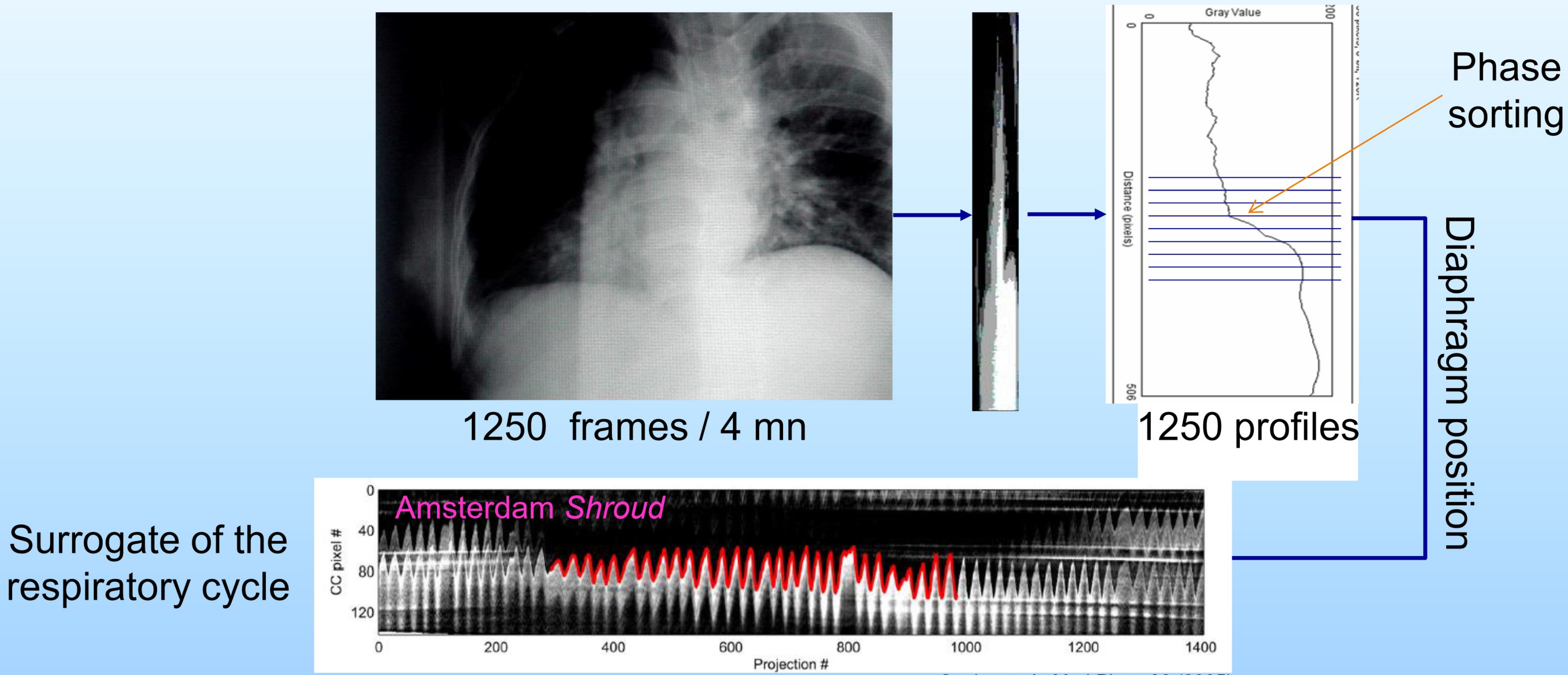


Rotation of 200°

Tracking the respiratory cycle 2/2

Deviceless tracking as implemented in CBCT system

☞ Tracking the diaphragm motion

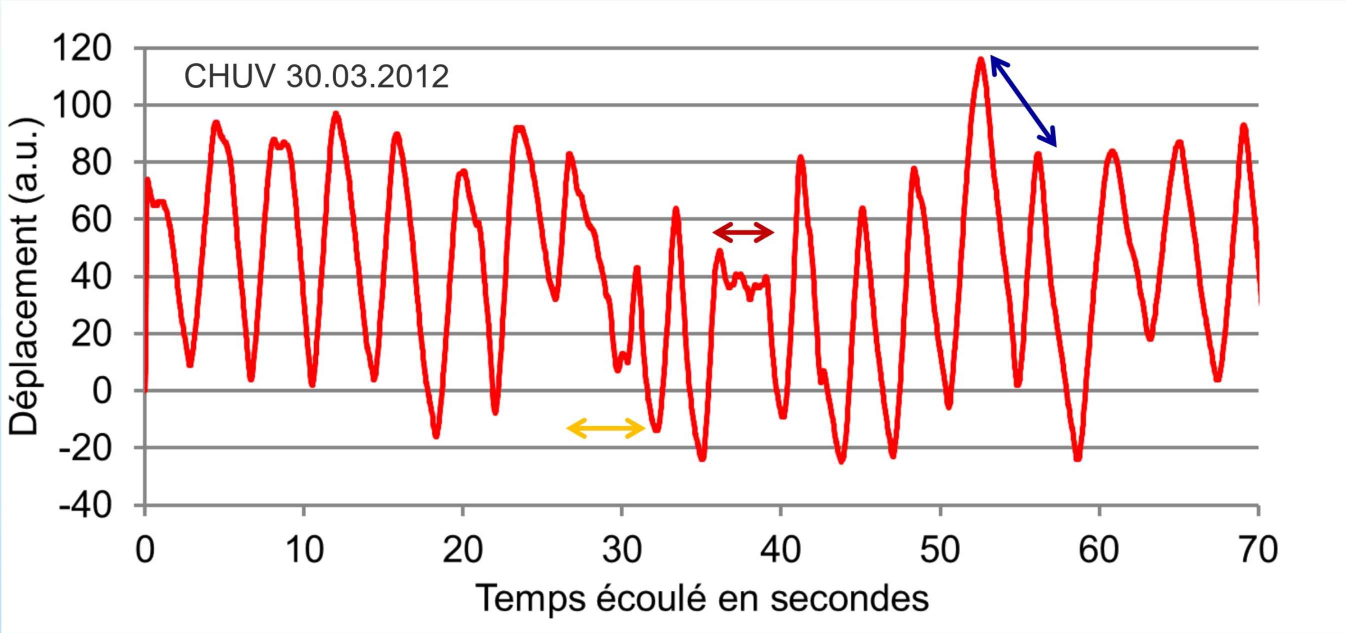


Sonke et al., Med Phys. 32 (2005)

Presently also in development for CT (deviceless 4D)

Actual breathing curve

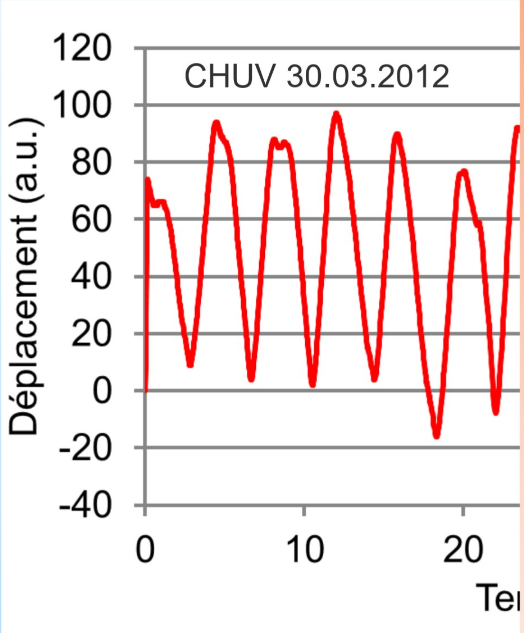
Typical thorax displacement of volunteer (JFG)



- ☞ Variation in amplitude
- ☞ Variation in frequency
- ☞ Chaotic breathing

Actual breathing curve

Typical thorax displacement of volunteer (JFG)



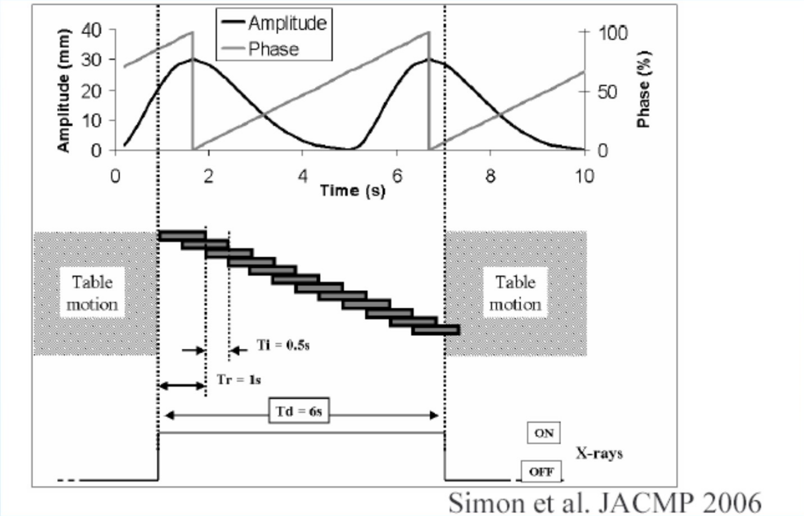
- Breathing pattern fluctuates considerably with time.
- Patient non-compliance is present in 83% of image artefacts:
  - Costal or abdominal breathing
  - Involuntary motions (cough, swallowing,…)
  - Anxiety, discomfort, **relaxation**

Patient compliance should be maximalized

- Variation in amplitude
- Variation in frequency
- Chaotic breathing

4D-CT image acquisition techniques

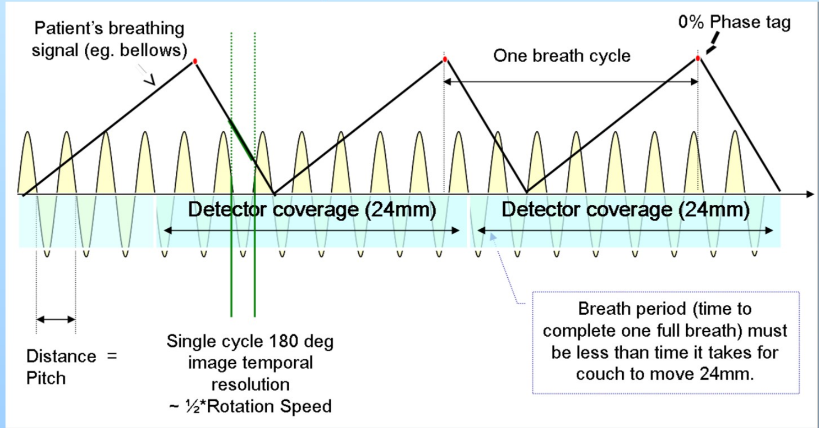
1. Multislices **axial** 4D-CT (cine mode)



Simon et al. JACMP 2006

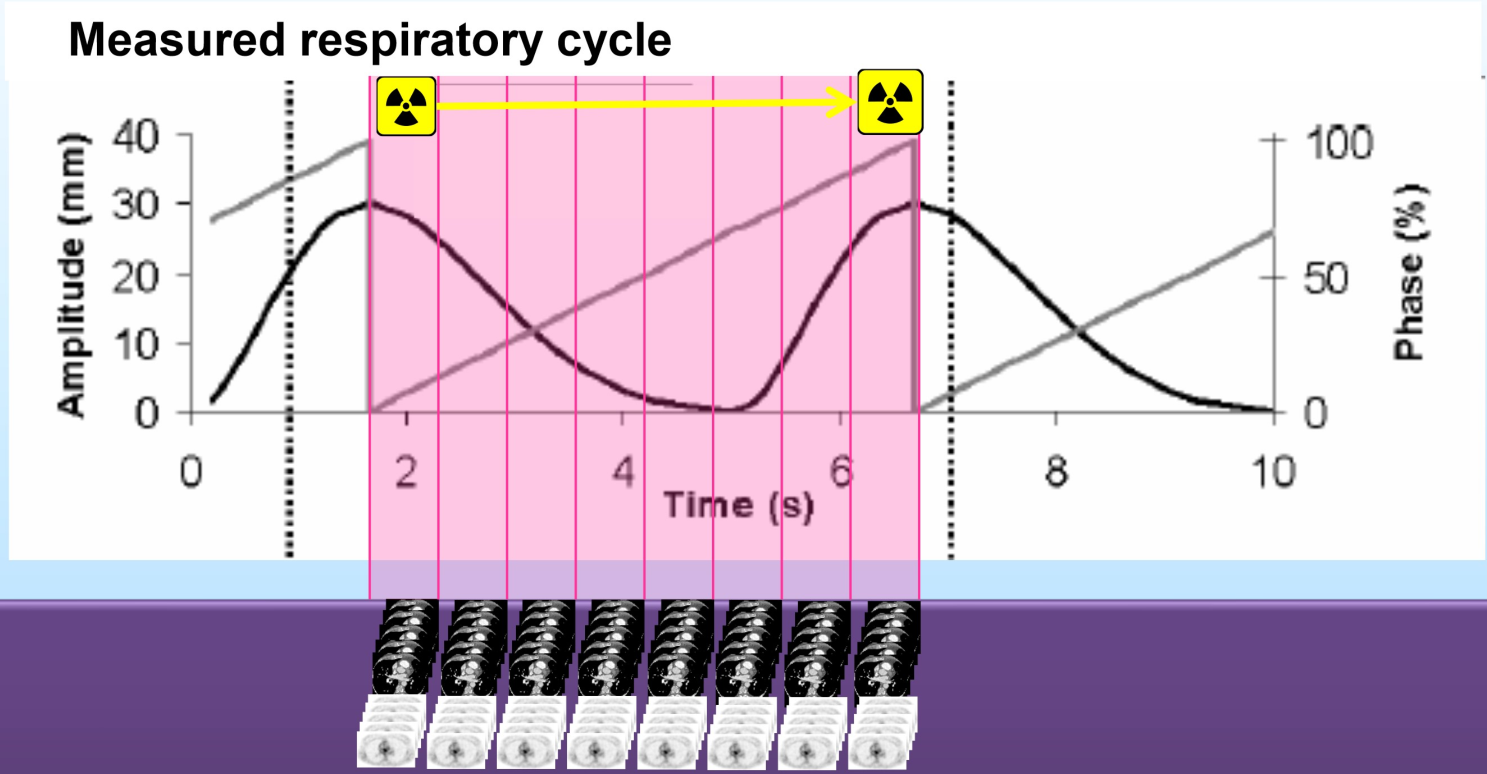
- The coach stays still during a respiratory cycle
- Each slice detector spans all phases consecutively

2. Low pitch **helicoidal** 4D-CT



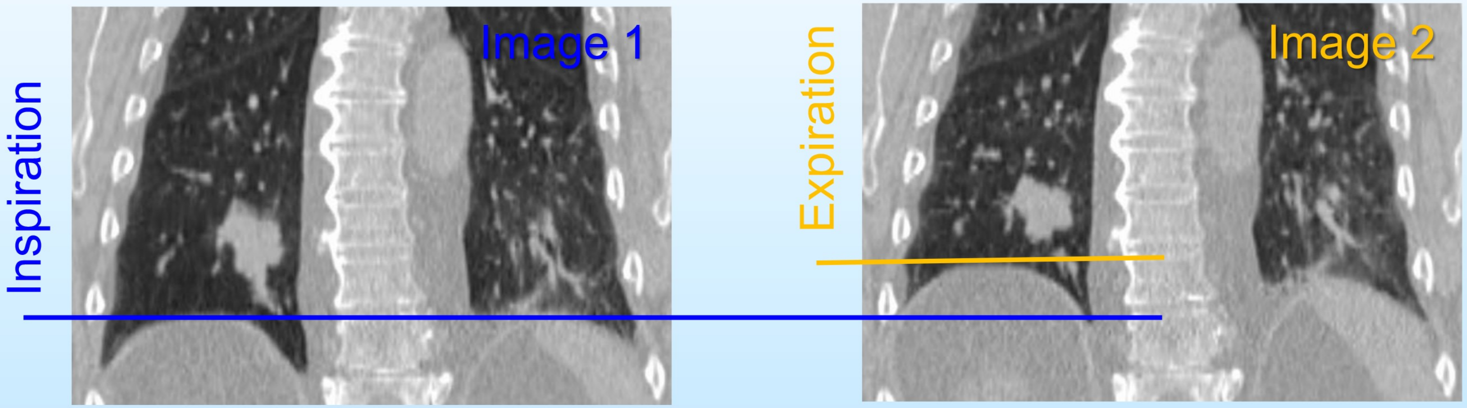
- The table moves much slower than the respiratory cycle (pitch < 0.1)

Respiratory correlated reconstruction



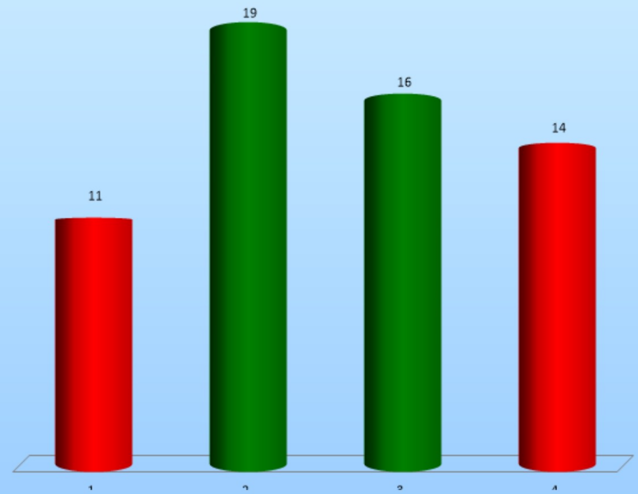
1. The respiratory cycle is divided in bins (8-12 for CT, 5-8 for PET)
2. Raw data (sinograms) are sorted by bins (either phase or amplitude)
3. Separates reconstructions are carried out for each bin

These 2 images belongs to which part of the breathing cycle?



Two solutions are correct

1. Image **1** to expiration
2. Image **2** to expiration
3. Image **1** to inspiration
4. Image **2** to inspiration

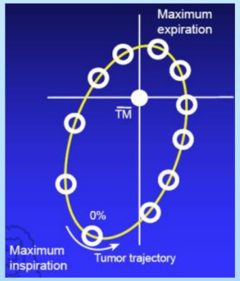


4D-CT image visualization techniques 1/3

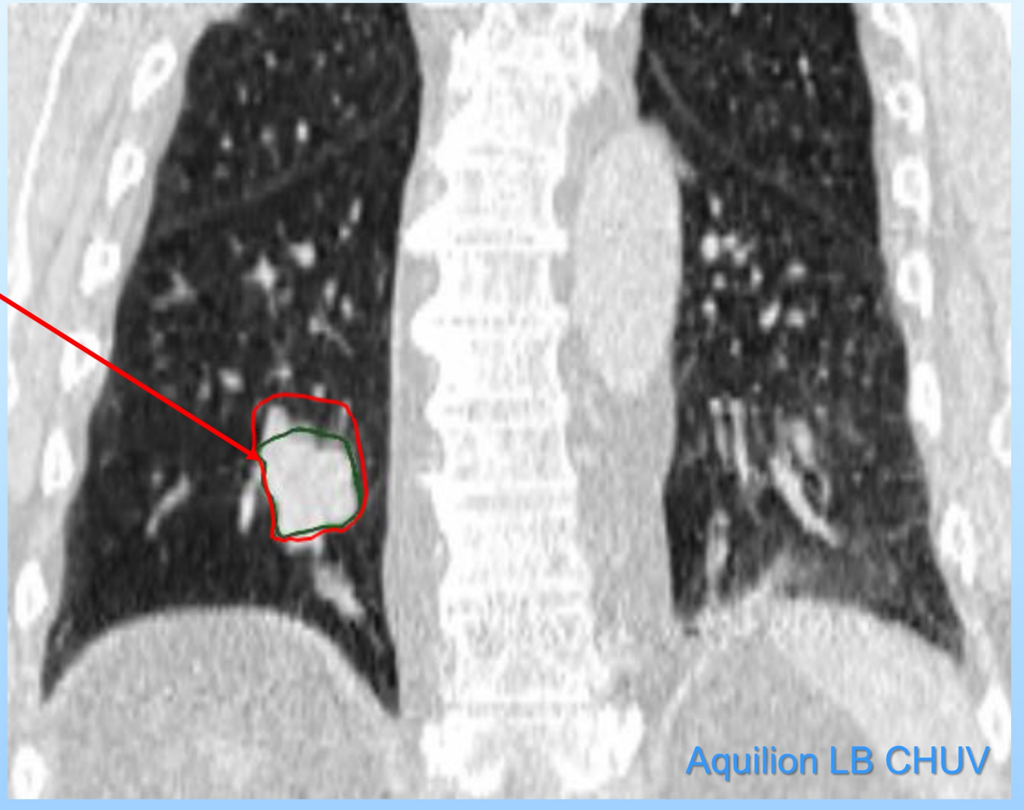
1. Cine Mode

- 4D-CT/CBCT images are only average snapshots of patient motion over a respiratory cycle
- 4D-CT/CBCT images describe the tumor trajectory

The ITV is defined by ICRU as the union of all GTV's



- 1 respiratory phase = 1 frame
- ⚠ 1 GTV per respiratory phase



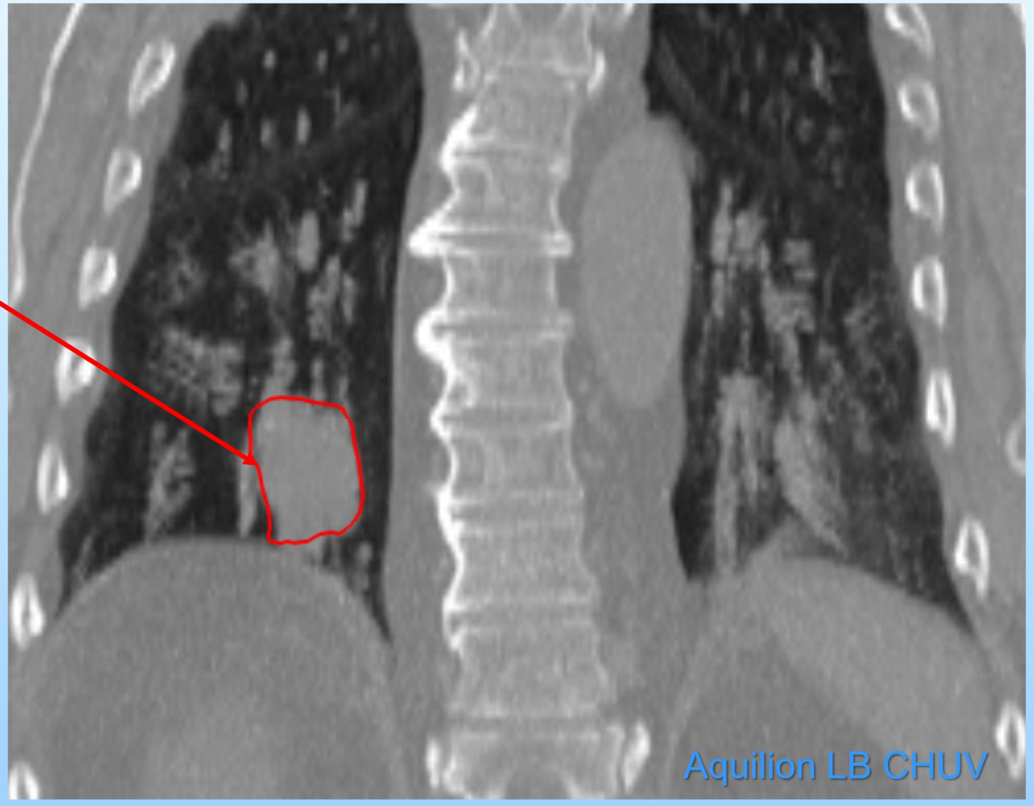
4D-CT image visualization techniques 2/3

2. MIP

- ➢ Multiphasic **M**aximum **I**ntensity **P**rojection
- OK* for drawing ITV, not for dosimetry

The MIP tumor borders match the union of all GTV's

* Ratio = 1.07+ 0.05 measured by Underberg et al. IJROBP 63 (2005)



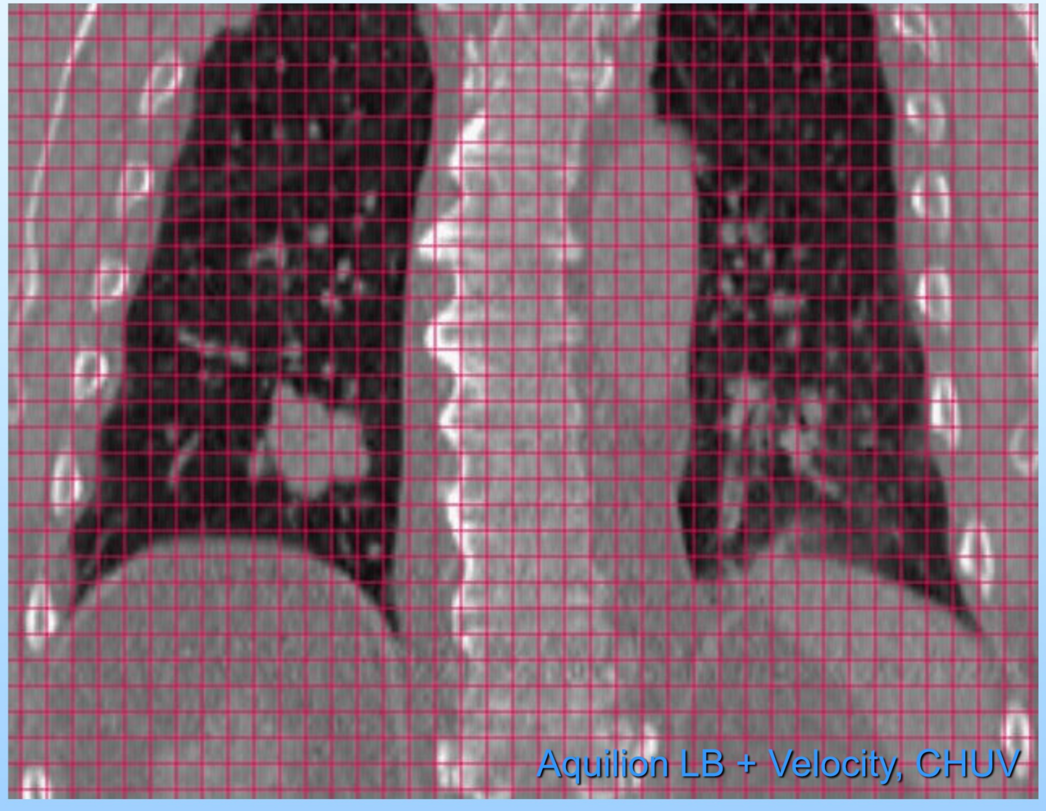
Boundary artefact:

The tumor is wrongly seen touching the diaphragm

4D-CT image visualization techniques 3/3

3. Deformable maps

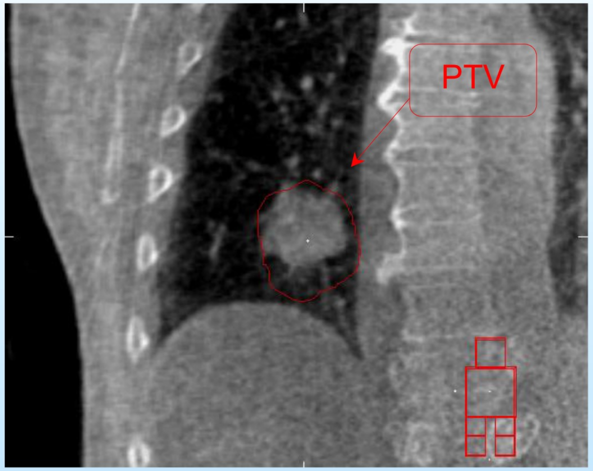
- One grid for each phase
- Spatial details of the kinetics of breathing

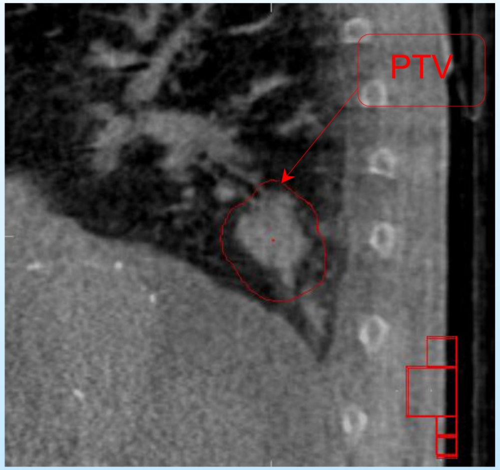


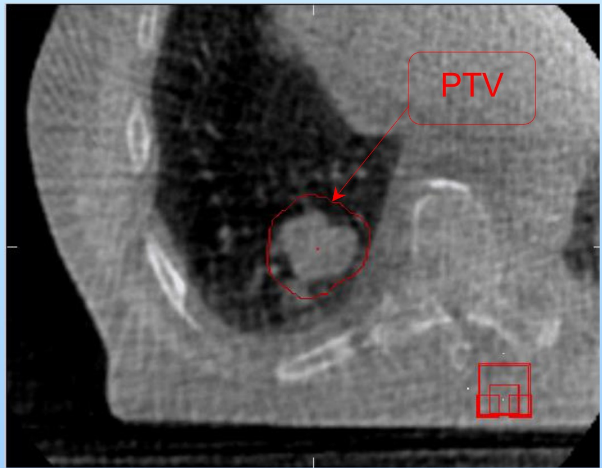
- The diaphragm motion amplitude is larger than the tumor motion
- The tumor is seen to spend more time in expiration phases
- The tumor shape is slightly distorted between phases (motion artefacts)

Application to 4D CBCT$_{1/2}$

Example XVI - CHUV





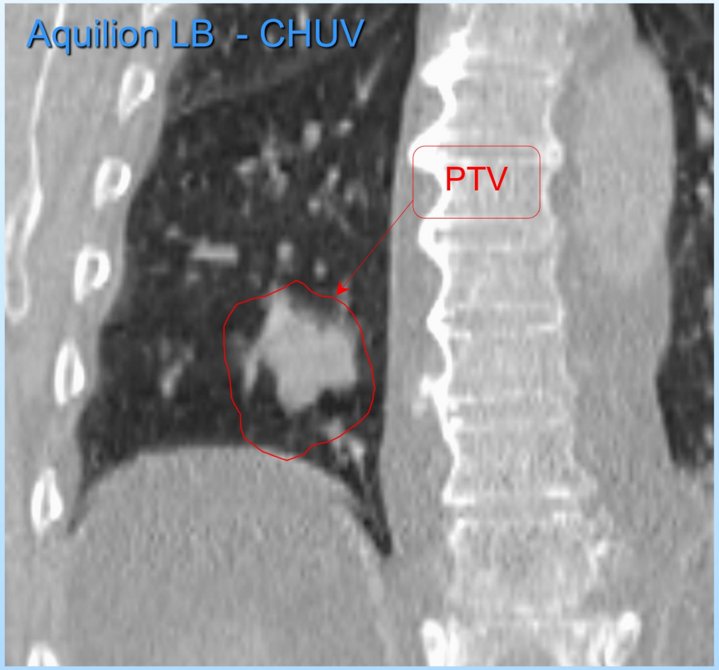


- ☞ For PTV margin validation
- ☞ For checking the performance of breathing control technics

Application to 4D CBCT$_{2/2}$

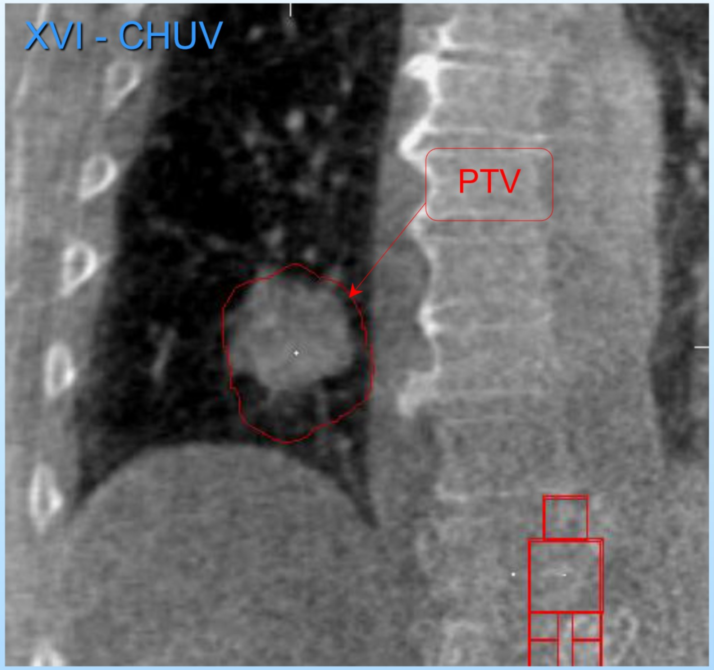
For checking motion agreement with reference images

Planification



CT-4D

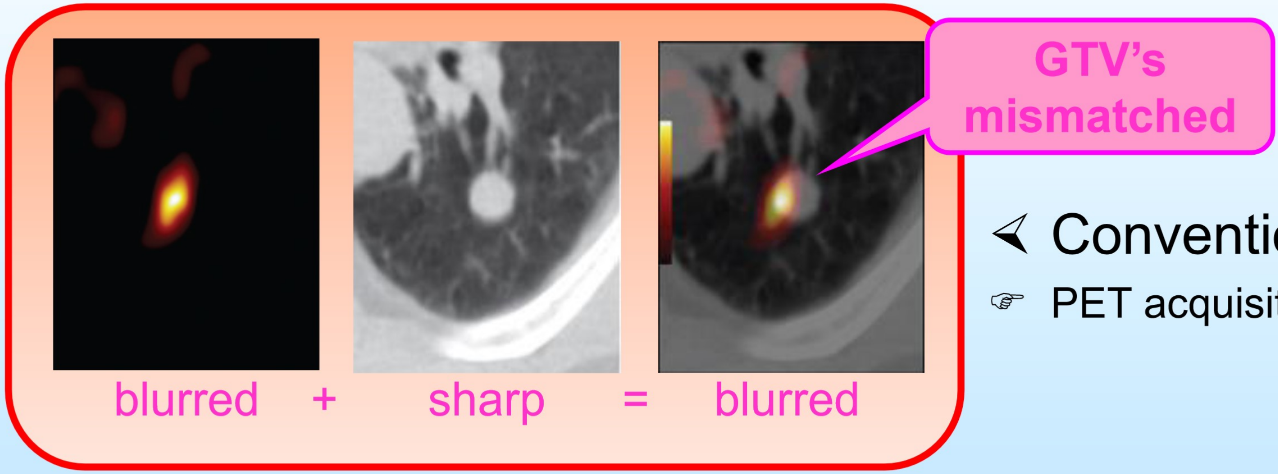
Setup image



CBCT-4D

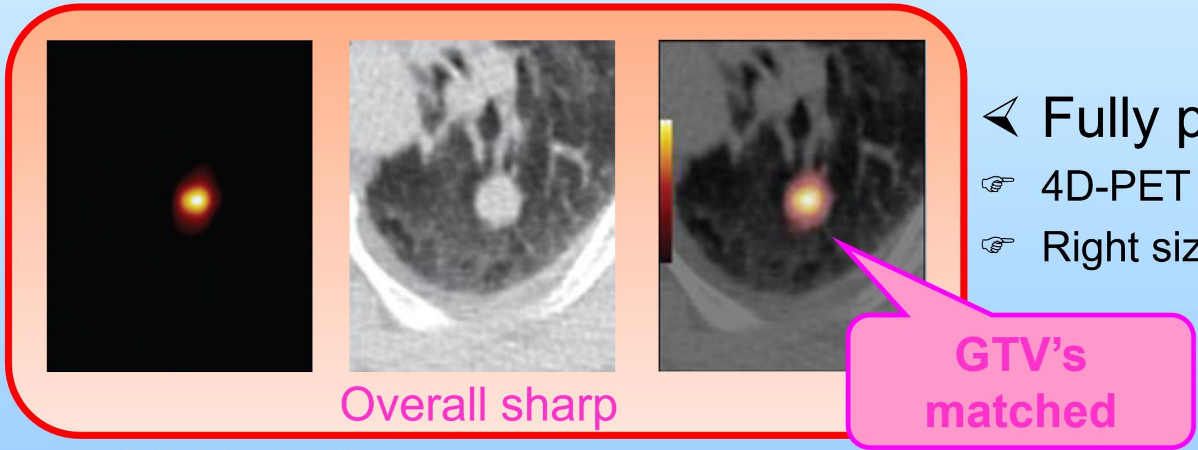
☞ Needs protocols specific to 4D

PET/CT: going from 3D to 4D



- Conventional 3D PET/CT:
  - PET acquisition much longer than CT

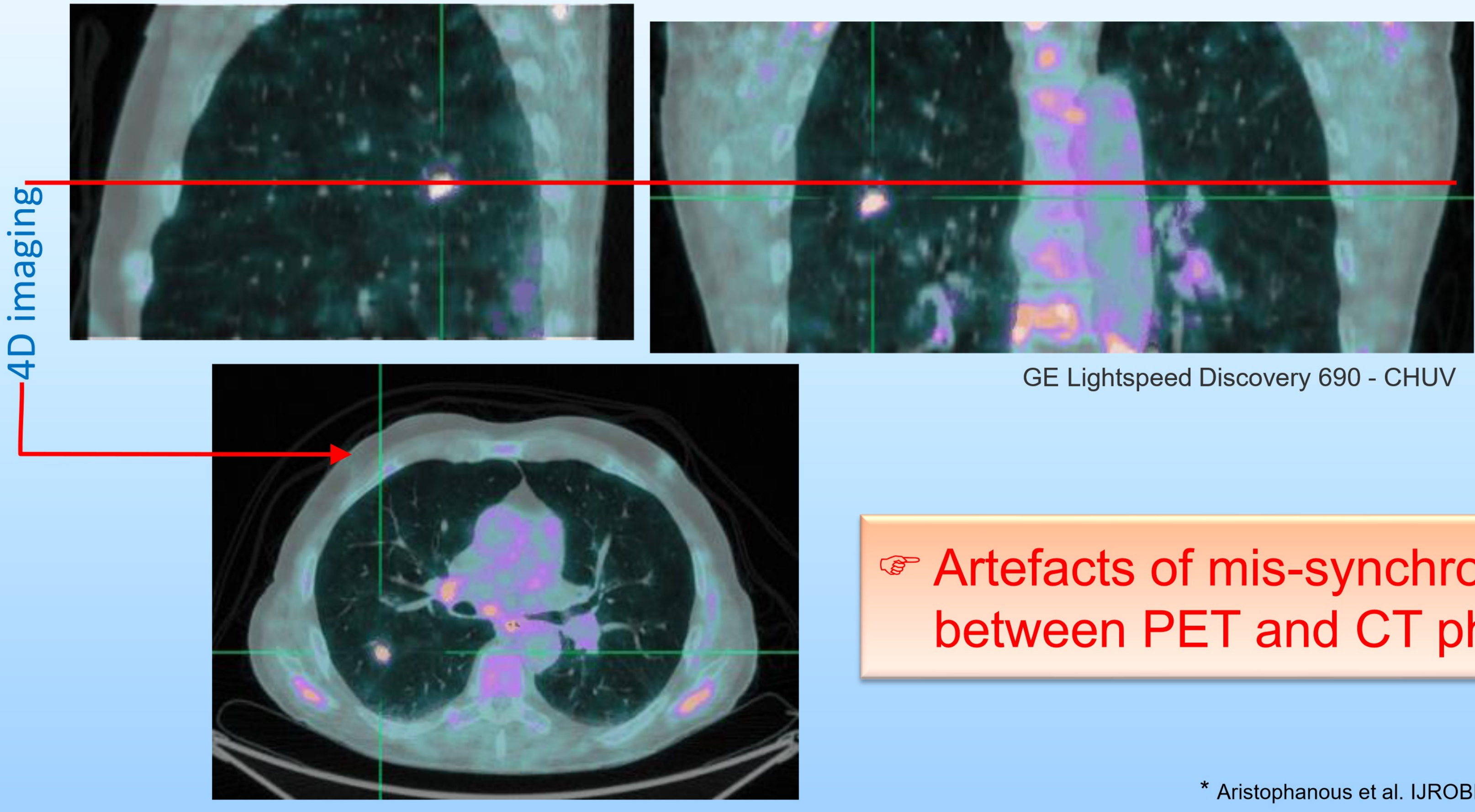
- Fully phase-matched 4D PET/CT:
  - 4D-PET data are corrected using 4D-CT data
  - Right size and more accurate SUV values



San Raffaele hospital, Milan

Viewing 4D- PET/CT images

1 lesion: Cine view of fused MPR images OK



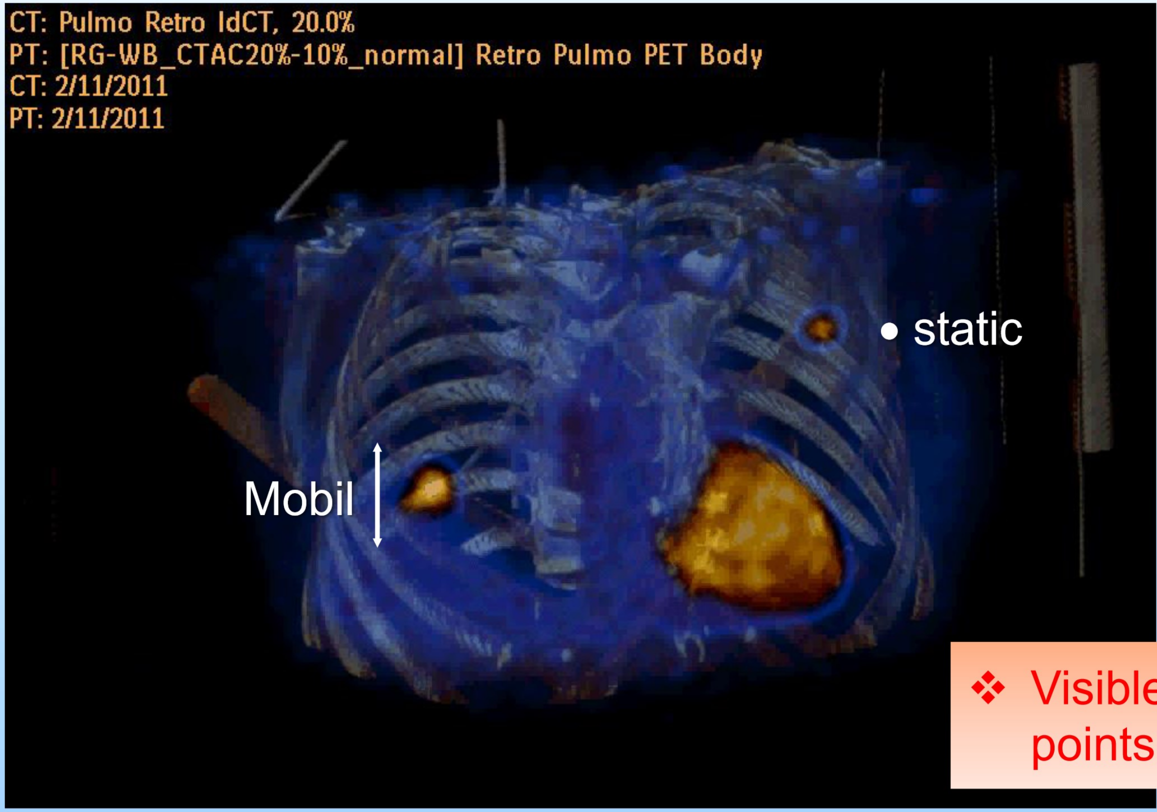
GE Lightspeed Discovery 690 - CHUV

☞ Artefacts of mis-synchronization between PET and CT phases

* Aristophanous et al. IJROBP 49 (2011)

Viewing 4D- PET/CT images

Multiples lesions: Cine view of fused 3D images necessary



Courtesy of Philips Medical Systems

❖ Visible for different points of view


Take home
message

Take home message 1/2

- ❖ Imaging is pervasive in the RO workflow
  - Radio-oncologist cup of tea
- ❖ Anatomical imaging serves as reference for planning as well as for patient setup:
  - Delineation of target volumes by radio-oncologist
  - ICRU as normative framework
  - Beware of the intrinsic limitations of modalities
- ❖ The advanced methods of reference imaging are:
  - Functional imaging
  - 4D imaging
  - Deformable fusion of modalities
- ☞ Delineation in fused set of data always requires specialized tools for clinical validation

Take home message 2/2

- ❖ Imaging during (pre-)treatment (guidance) involves the registration of the image of the day with a localization image used as reference
  - 2D: matching of portal, kV or stereo imaging with DRR's
  - 3D: registration of CBCT/MVCT/MR-linac with CT
  - 3D registration between MRI of the day a reference MRI
- ❖ The advanced methods for guidance are :
  - Fusion of images
  - 4D guidance
  - Tracking of organs
  - MRgRT
- ☞ Patient setup adaptation requires clinical validation of the images


Sometimes imaging
looks like art
Thank you
CHUV 4D CBCT unrealistic registration after two tumors VMAT delivery