ORGAN MOTION MANAGEMENT

CARLO CAVEDON
MEDICAL PHYSICS UNIT
VERONA UNIVERSITY HOSPITAL - ITALY

SCHOOL ON MEDICAL PHYSICS FOR RADIATION THERAPY
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The Abdus Salam
**International Centre
for Theoretical Physics**

IAEA
International Atomic Energy Agency

United Nations
Educational, Scientific and
Cultural Organization

ORGAN MOTION IN RADIATION ONCOLOGY

- **respiratory motion**
    - *pseudo-regular motion – predictable in a short interval (50-500 ms)*

- **skeletal-muscular motion**
    - *irregular motion – can be controlled*

- **cardiac motion**
    - *(pseudo-)regular motion – generally not explicitly accounted for in RT*

- **gastrointestinal motion**
    - *unpredictable – can be partly limited*

- **genitourinary system – e.g. bladder filling**
    - *large displacements - can be partly limited*

RESPIRATORY MOTION IN RADIATION ONCOLOGY

The Management of Respiratory Motion in Radiation Oncology

Report of AAPM Task Group 76

July 2006

RESPIRATORY MOTION – organs that move with respiration

SHALLOW BREATHING RANGE OF MOTION

- **lung**   up to 50 mm
- **esophagus**
- **liver**   up to 40 mm
- **pancreas**   up to 35 mm
- **breast**
- **prostate (!)**
- **kidneys**   up to 40 mm
- **...**

RESPIRATORY MOTION IN RADIATION ONCOLOGY

Table 2. Lung tumor–motion data. The mean range of motion and the (minimum–maximum) ranges in millimeters for each cohort of subjects. The motion is in three dimensions (SI, AP, LR).

Observer	Direction		
	SI	**AP**	**LR**
Barnes[85]: Lower lobe	18.5 (9–32)	--	--
Middle, upper lobe	7.5 (2–11)	--	--
Chen et al.[84]	(0–50)	--	--
Ekberg et al.[26]	3.9 (0–12)	2.4 (0–5)	2.4 (0–5)
Engelsman et al.[28]:			
Middle/upper lobe	(2–6)	--	--
Lower lobe	(2–9)	--	--
Erridge et al.[101]	12.5 (6–34)	9.4 (5–22)	7.3 (3–12)
Ross[76]: Upper lobe	--	1 (0–5)	1 (0–3)
Middle lobe	--	0	9 (0–16)
Lower lobe	--	1 (0–4)	10.5 (0–13)
Grills et al.[91]	(2–30)	(0–10)	(0–6)
Hanley et al.[77]	12 (1–20)	5 (0–13)	1 (0–1)
Murphy et al.[87]	7 (2–15)	--	--
Plathow[220]: Lower lobe	9.5 (4.5–16.4)	6.1 (2.5–9.8)	6.0 (2.9–9.8)
Middle lobe	7.2 (4.3–10.2)	4.3 (1.9–7.5)	4.3 (1.5–7.1)
Upper lobe	4.3 (2.6–7.1)	2.8 (1.2–5.1)	3.4 (1.3–5.3)
Seppenwoolde et al.[67]	5.8 (0–25)	2.5 (0–8)	1.5 (0–3)
Shimizu et al.[52]	--	6.4 (2–24)	--
Sixel et al.[92]	(0–13)	(0–5)	(0–4)
Stevens et al.[66]	4.5 (0–22)	--	--

AP: anterior–posterior; LR: left–right; SI: superior–inferior.

RESPIRATORY MOTION IN RADIATION ONCOLOGY

Table 3. Abdominal motion data. The mean range of motion and the (minimum–maximum) ranges in millimeters for each site and each cohort of subjects. The motion is in the superior–inferior (SI) direction.

Site	Observer	Breathing mode	
		Shallow	**Deep**
Pancreas	Suramo et al.[74]	20 (10–30)	43 (20–80)
	Bryan et al.[75]	20 (0–35)	--
Liver	Weiss et al.[89]	13 +/– 5	--
	Harauz et al.[90]	14	--
	Suramo et al.[74]	25 (10–40)	55 (30–80)
	Davies et al.[68]	10 (5–17)	37 (21–57)
Kidney	Suramo et al.[74]	19 (10–40)	40 (20–70)
	Davies et al.[68]	11 (5–16)	--
Diaphragm	Wade[80]	17	101
	Korin et al.[79]	13	39
	Davies et al.[68]	12 (7–28)	43 (25–57)
	Weiss et al.[89]	13 +/– 5	--
	Giraud et al.[78]	--	35 (3–95)
	Ford et al.[86]	20 (13–31)	--

SOURCES OF INFORMATION – RESPIRATORY MOTION

- **radiography** (e.g. double exposure or cine)

- **fluroscopy** (with or without fiducial markers)

- **ultrasound**

- **CT** and **4D-CT** (amplitude- or phase-based / prospective or retrospective / ...)

- **MR** and **4D-MR**

- **PET** and **4D-PET**

MITIGATION OF MOTION AND MOTION IRREGULARITY

- patient **training**
- audiovisual **feedback**
- oxygen administration?
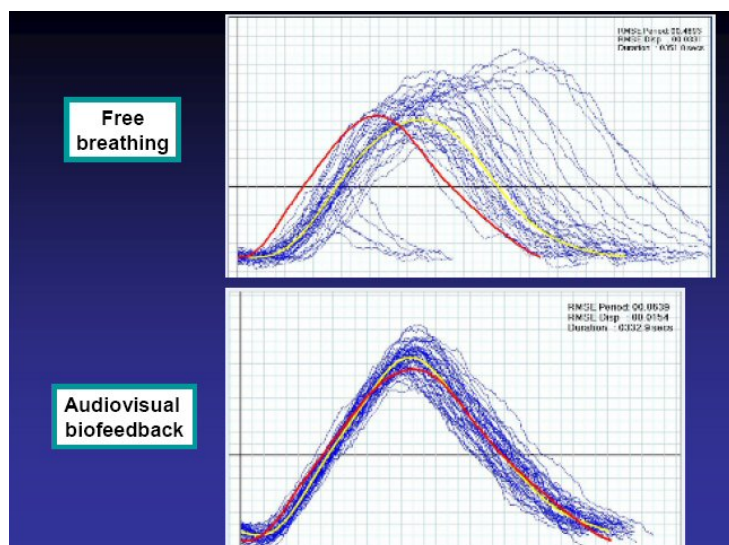
	Air	O_2
Breath Hold time (sec)	20 (11-40)	100 (85-230)
% O_2 Pre BH	95% (90-97)	100%
%O_2 After BH	94%(90-97)	100%

M Romano, C Cavedon, A Porcaro, M Palazzi, M Gabbani, N Marciai, A D'Amico, S Dall'Oglio, F Pioli, MG Giri, A Grandinetti, "Does pre-radiation oxygen breathing prolong deep inspiration breath hold?" ASTRO meeting 2013

R George et al., "Audio-visual biofeedback for respiratory-gated radiotherapy: Impact of audio instruction and audio-visual biofeedback on respiratory-gated radiotherapy", Int J Rad Onc Biol Phys 65, 924-933 (2006)

RESPIRATORY MOTION – 5 MAJOR STRATEGIES FOR MANAGEMENT

- **motion encompassing** techniques

- **respiratory-gating** techniques

- **breath-hold** techniques

- **forced shallow-breathing** techniques

- **respiration-synchronized** techniques (**tracking**)

RESPIRATORY MOTION - IMPLICIT MANAGEMENT

- **motion encompassing** techniques
  - *concept: treat the whole volume defined by the envelope of positions during respiration*

- **ITV = internal target volume** (ICRU 62) = CTV+IM
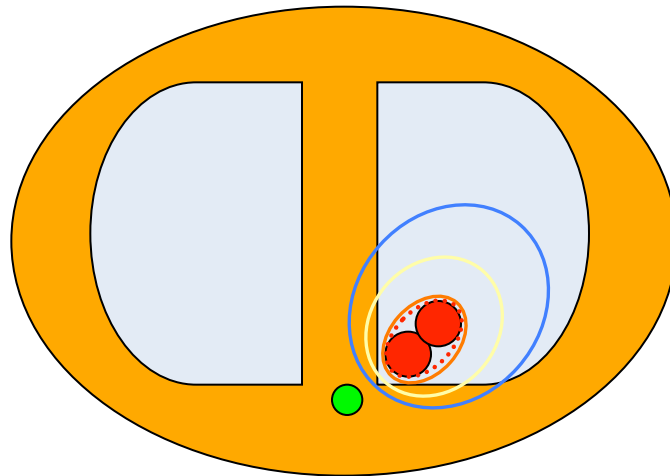
MOTION ENCOMPASSING – EXAMPLE - expiration
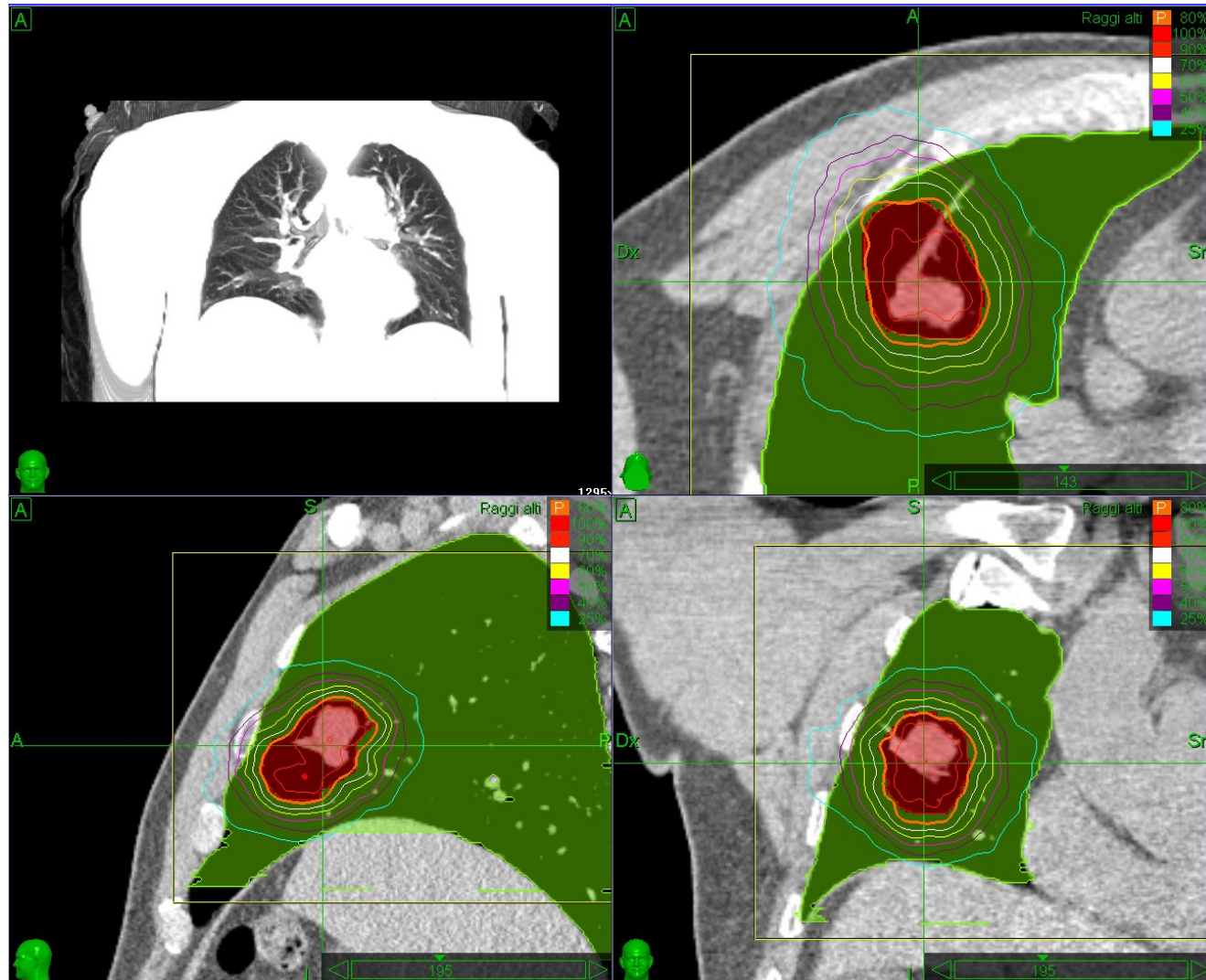
MOTION ENCOMPASSING – EXAMPLE - inspiration
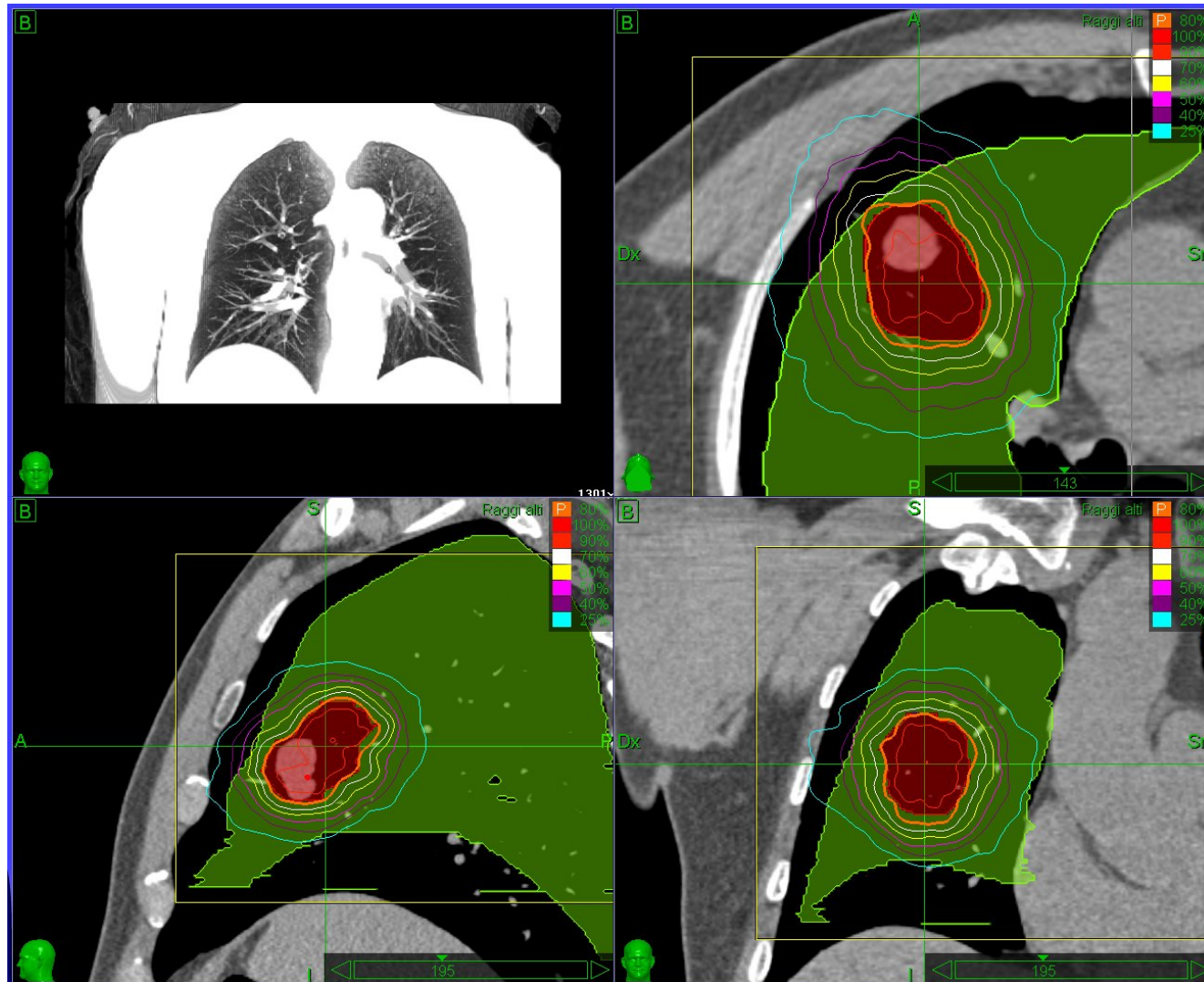
RESPIRATORY MOTION – EXPLICIT MANAGEMENT

- **respiratory gating** techniques
  - *concept: treat only when the target is within the "gating window"*
  - *volume / normal tissue preservation*
  - *long treatment times*
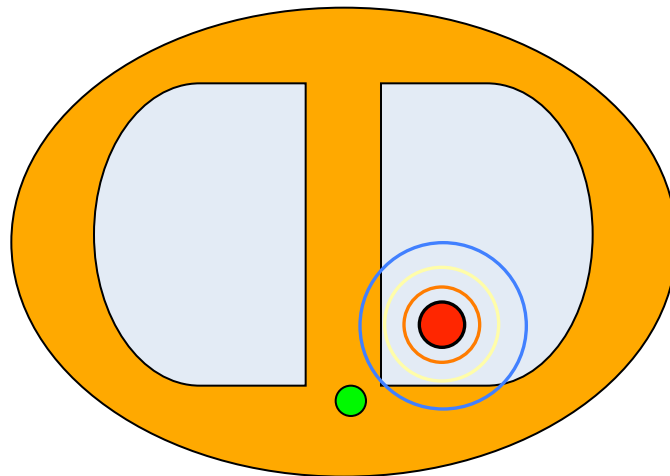
RESPIRATORY GATING – EXAMPLE
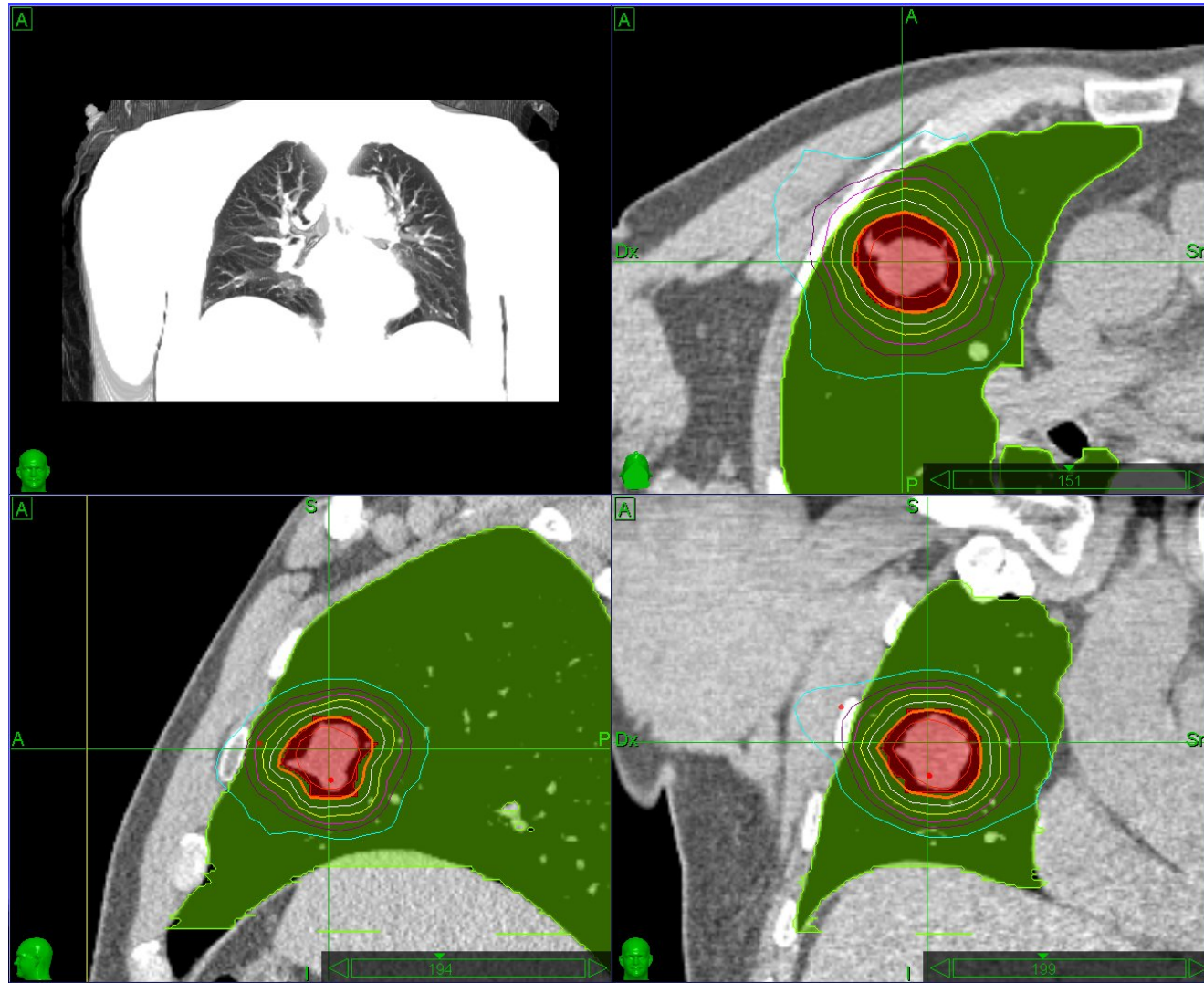
RESPIRATORY GATING

- surrogate signal needed to describe motion in real time

camera

Marker block

Photos courtesy of P Keall
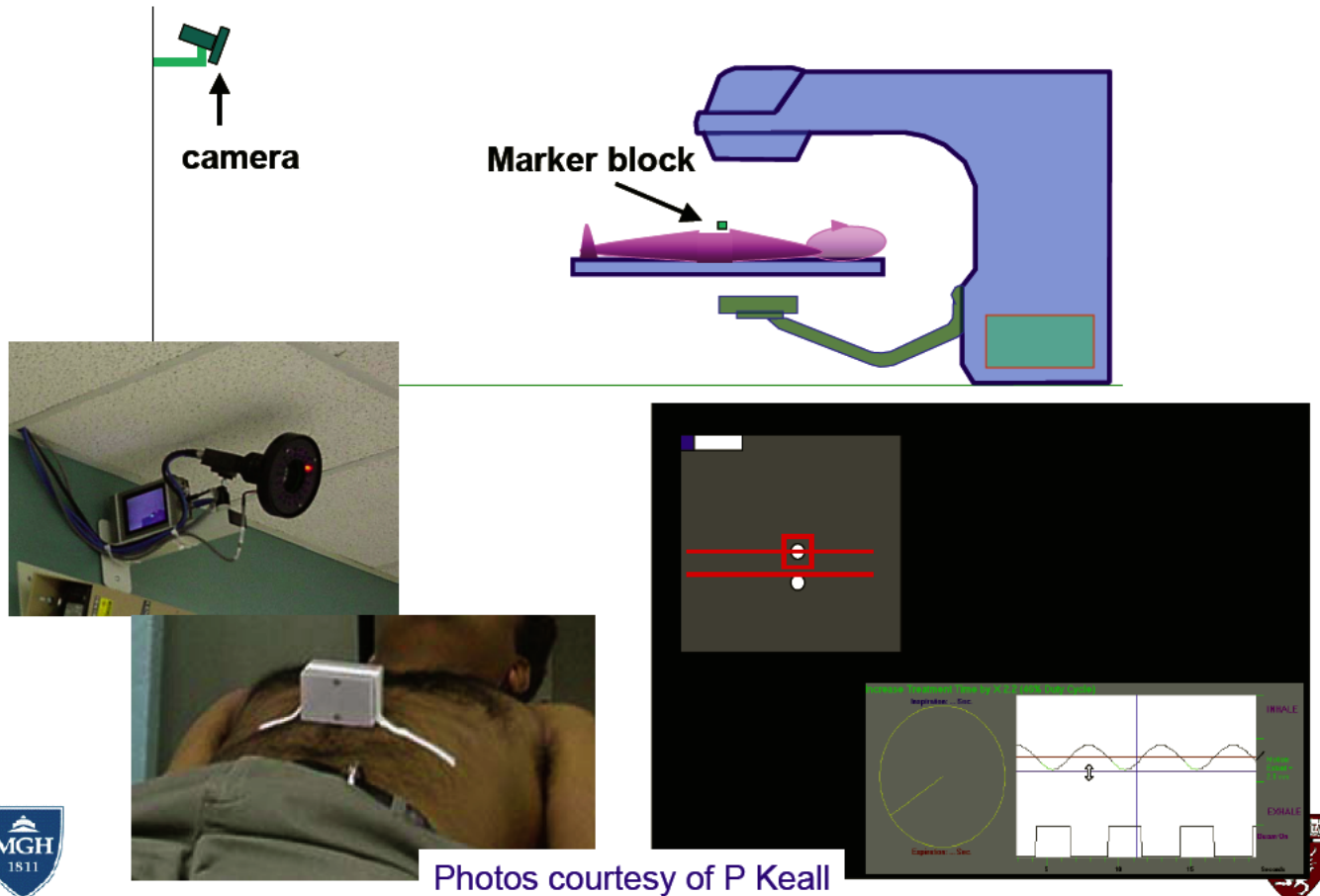
RESPIRATORY GATING – need for surrogate signal

- possible inaccuracy from the relation between tumor motion and surrogate signal
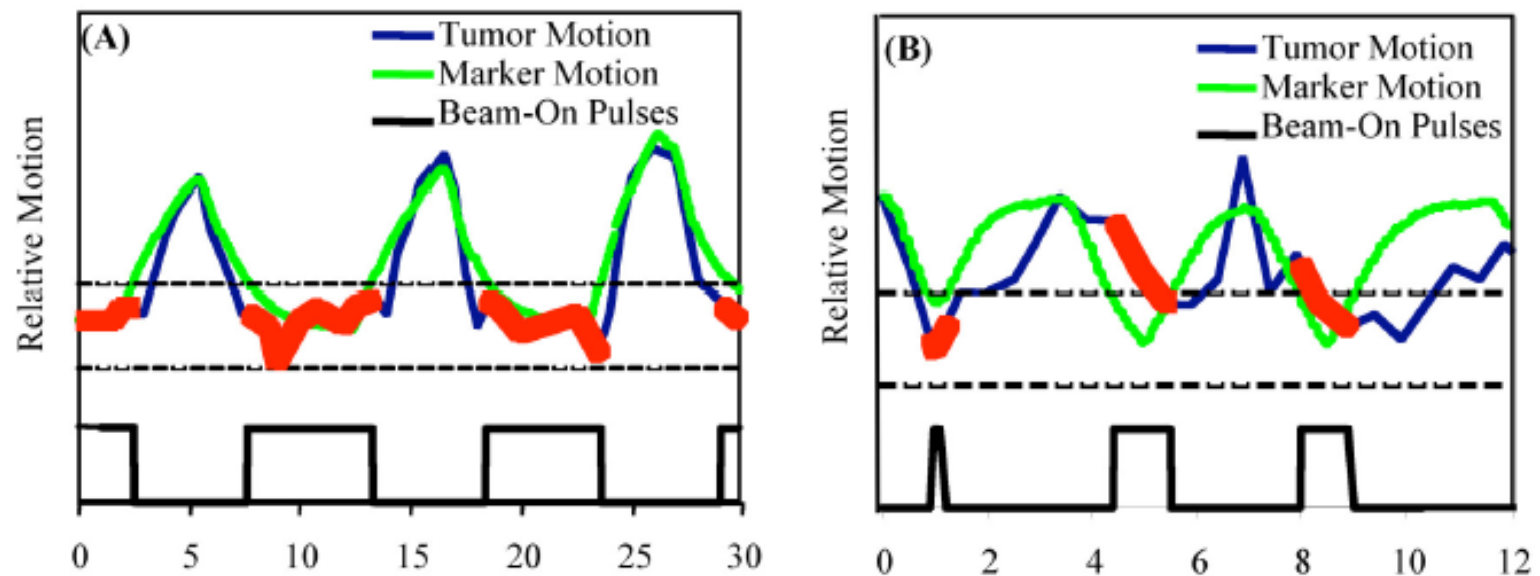
Figure 7. Comparison of external marker block motion with internal motion of the clinical target volume (CTV) for a patient with (a) no phase shift and (b) a patient with significant phase shift. The respiratory gating thresholds are set using the external marker block motion. The beam-on pulses are highlighted in red over the internal CTV position. [Reproduced from reference 227: *Int J Radiat Oncol Biol Phys*, vol 48, "Clinical experience with a commercial respiratory gating system." C. R. Ramsey, D. D. Scaperoth, and D. C. Arwood, pp. P164-165. © 2000, with permission from Elsevier.]

RESPIRATORY MOTION – EXPLICIT MANAGEMENT

- **respiratory tracking (synchronized)** techniques
  - *concept: redirect beam to the target position in real time*
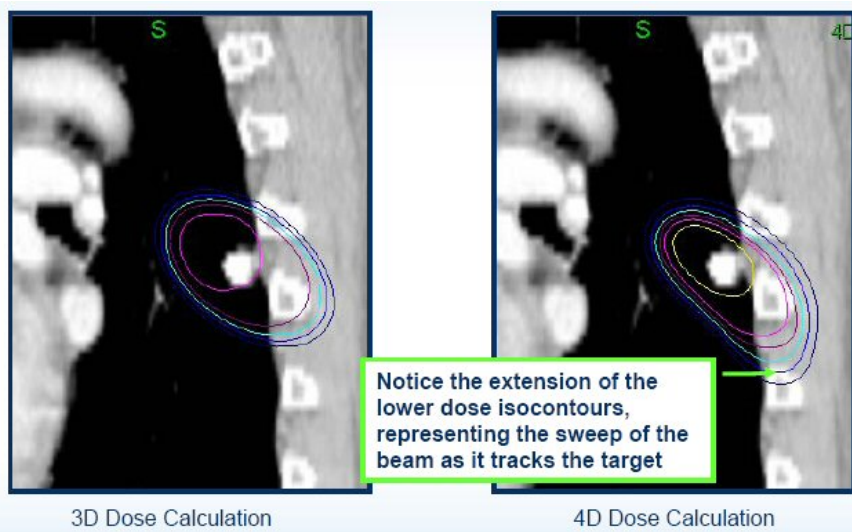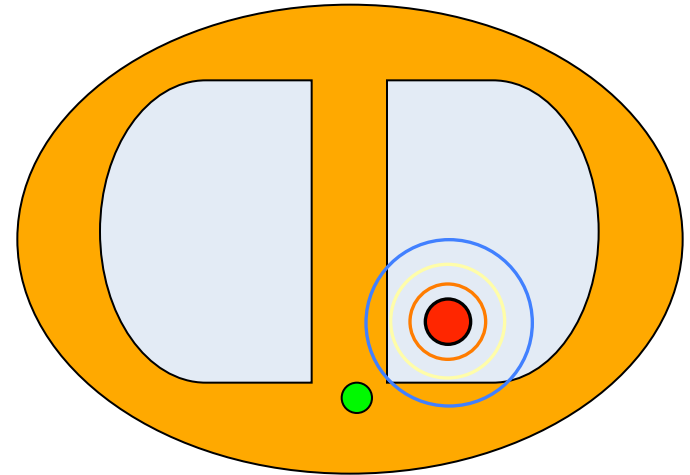 - *volume / normal tissue AND treatment time preservation*
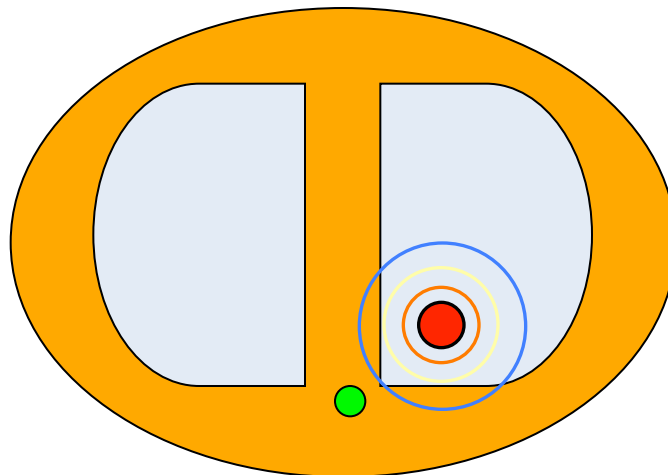
RESPIRATORY MOTION – EXPLICIT MANAGEMENT

- **respiratory tracking (synchronized)** techniques
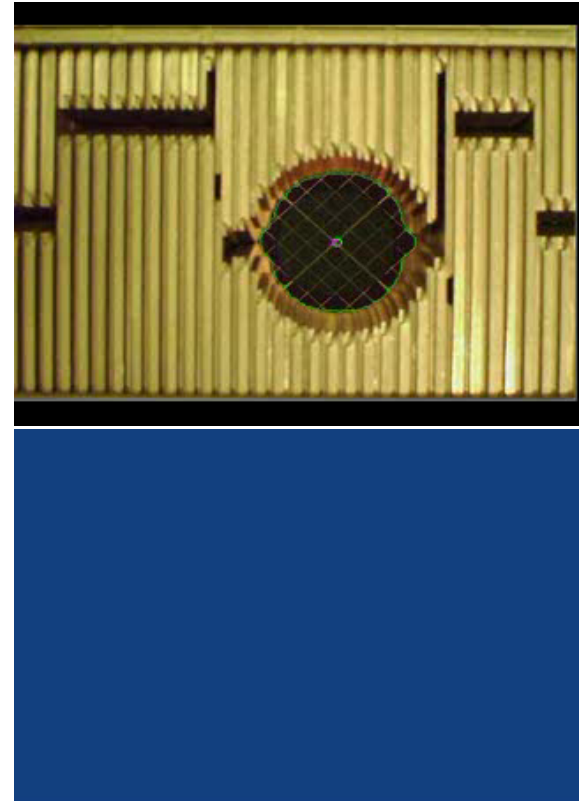
RESPIRATORY TRACKING

- **need for 4D PLANNING**

- planning on one phase does not guarantee dosimetric accuracy on nearby tissues

Notice the extension of the lower dose isocontours, representing the sweep of the beam as it tracks the target

3D Dose Calculation   4D Dose Calculation

- 4D planning requires a complete description of the respiratory phase (e.g. 4DCT – see below)

MOTION CONTROL IN IMAGING FOR TREATMENT PLANNING AND TREATMENT VERIFICATION

- need for **temporal coherence** between **imaging** for treatment planning and **treatment** administration

- imaging shall **describe the treatment condition**

- **quantitative imaging** (e.g. BTV based on SUV map) shall account for motion in order to avoid **quantification errors**

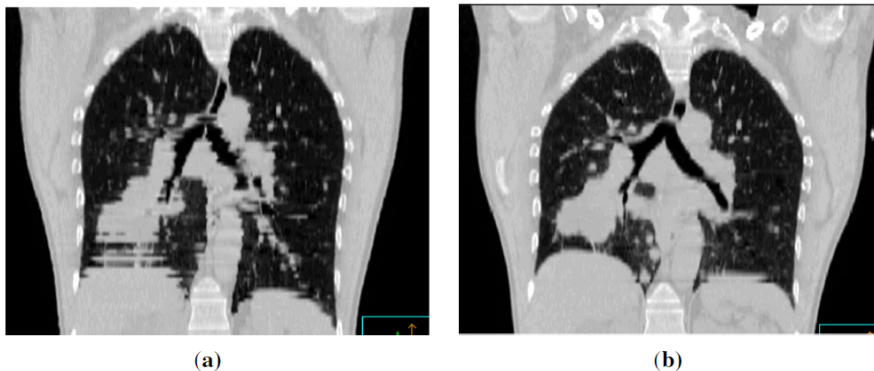# MOTION CONTROL IN IMAGING FOR TREATMENT PLANNING AND TREATMENT VERIFICATION

Figure 1. Coronal views of CT scans of the same patient taken during free breathing (FB) (a) and with respiratory-gated scanning at exhale (b). [Reproduced from reference 53: P. J. Keall, V. R. Kini, S. S. Vedam, and R. Mohan, "Potential radiotherapy improvements with respiratory gating," *Australas Phys Eng Sci Med* 25(1):1–6, Figure 1. © 2002, with permission from APESM.]

Figure 2. Coronal views of CT scans of a static sphere (a) and a sinusoidally moving sphere (b) (2-cm range of motion and a 4-second period). [Reproduced from reference 56: S. S. Vedam, P. J. Keall, V. R. Kini, H. Mostafavi, H. P. Shukla, and R. Mohan, "Acquiring a four-dimensional computed tomography dataset using an external respiratory signal," *Phys Med Biol* 48(1):45–62, Figure 1. © 2003, with permission from IOP Publishing Limited.]

- effect of motion on a free-breathing patient (CT left) and at exhale (right)

- static sphere seen at CT (left) and effect of sinusoidal motion (right)

4D-CT: principle

4D CT Scanning

4D-CT: modes of operation

- **prospective** acquisition
    - *x-ray on* only in the phase chosen for acquisition (e.g. full exhale)
    - dose sparing – limited information
   - useful e.g. in breath-hold treatment

- **retrospective** sorting
    - *redundant acquisition – "a posteriori" sorting*
    - higher dose –full information
   - necessary e.g. for 4D planning and to estimate the full envelope of positions – tumor trajectory

4D-CT: how to use the information

- information from 4D-CT used for planning shall be **coherent with the delivery technique**, e.g.:

- *free-breathing treatment => MIP or other method to estimate envelope of positions*

- *gating and breath-hold: use the phase(s) that will be used to treat*
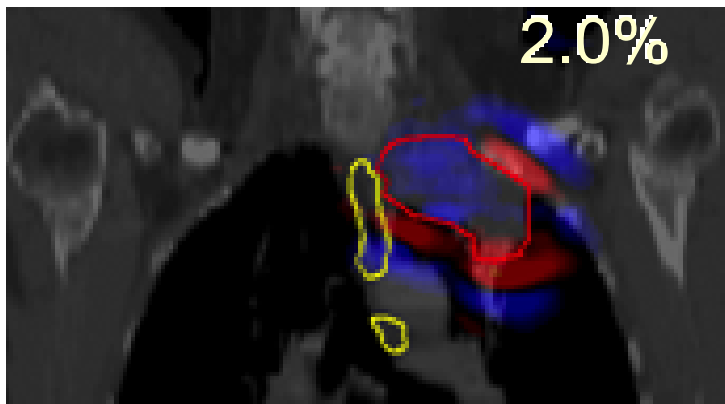
- *tracking: use all information for 4D planning*
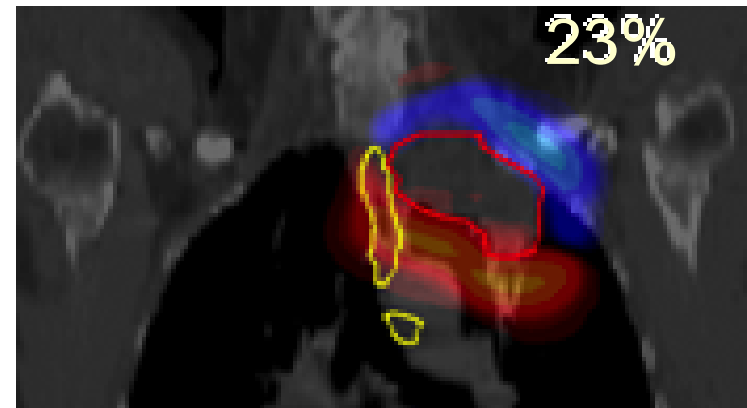
4D-CT: how many phases?
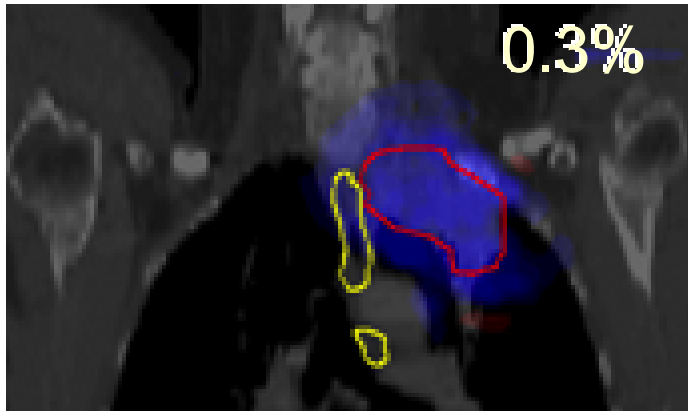
11 Phases – 6 Phases
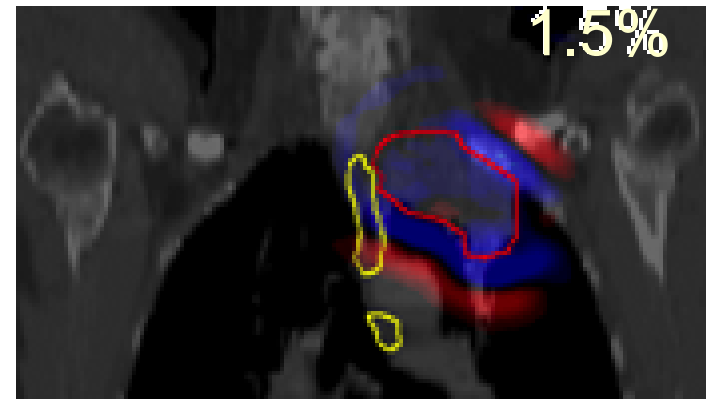
11 Phases – 2 Phases

11 Phases – AVE Phase

11 Phases - Exhale

Courtesy Mihaela Rosu, Virginia Commonwealth Univ.

4D-MR: methods

- **4D-MR** is less frequently used for RT treatment planning than 4D-CT

- **Breath-hold**
    - long acquisition times
    - poor reproducibility
    - dynamic behaviour might be poorly described in breath-hold

- **Cine-MR / Echo Planar Imaging (SSh, EPI, …)**
    - poor spatial resolution
    - artifacts at tissue interfaces

- **4D-MR - sorting**
    - external surrogate: volume, strain-gauge, IR markers …
    - internal surrogate: pencil-beam excitation, 2D slice-stacking
    - generally available as phase-based (limited TR => limited T2 weighting)

4D-MR: methods

- "navigator" sagittal slice
- sorting based on diaphragm position and vascular details
- axial slice acquisition at 2.8 Hz
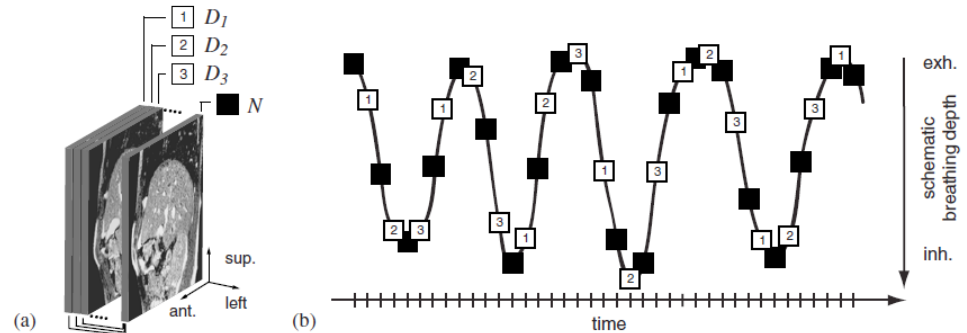- acquisition time ~ 1h (200 frames/slice)

Figure 1. (a) Sagittal slices covering the volume of interest. One dedicated slice N is used as navigator slice for image sorting. (b) Interleaved acquisition of data and navigator frames.
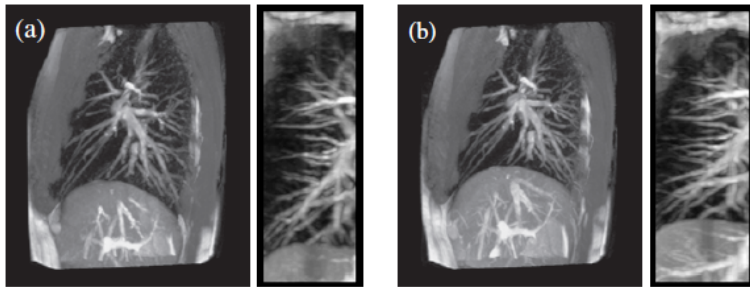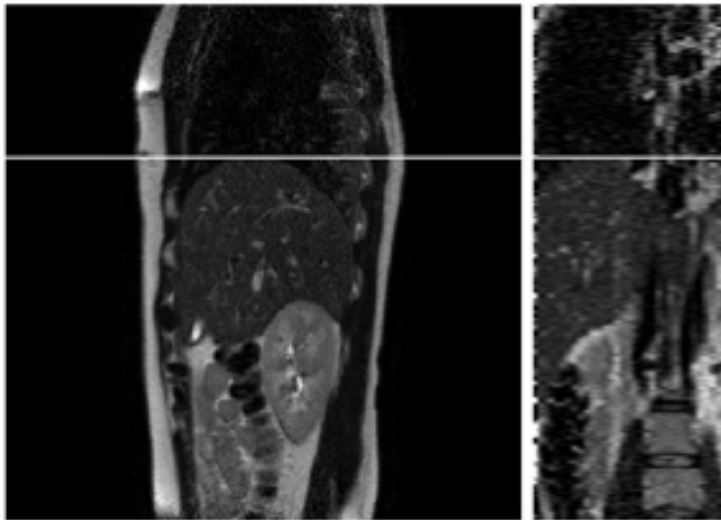

Figure 6. Sagittal and coronal maximum intensity projections after 3D interpolation showing the right part of the lung at (a) inhalation and (b) exhalation.
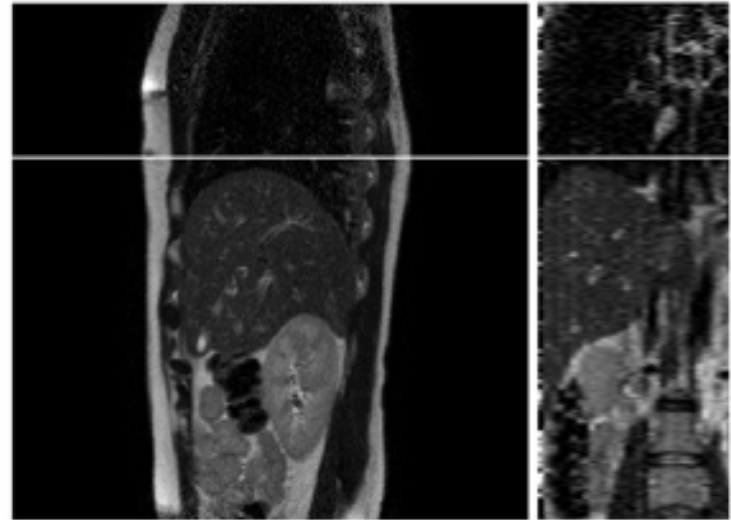
- very good temporal resolution
- generates deformation maps that can be used in CT etc.
- potentially useful for *dose tracking* in treatment adaptation
- sensitive to breathing irregularities
- not clinically available yet with full functionality

M von Siebenthal et al., ""4D MR imaging of respiratory organ motion and its variability", Phys. Med. Biol. 52, 1547-1564 (2007)

4D-MR: methods

- 4D-MRI in RT is constantly growing
- generally phase-based triggering => T1-weighting only (limited TR – comparable to breathing cycle => non applicable to new quantitative techniques)
- recent studies on amplitude-based triggering (strain gauge) => T2 weighting


max expiration   max inspiration

Y Hu, SD Caruthers, DA Low, PJ Parikh, S Mutic, "Respiratory Amplitude Guided 4-Dimensional Magnetic Resonance Imaging", Int J Radiation Oncol Biol Phys, Vol. 86, No. 1, pp. 198e204 (2013)

PET-CT: quantitative imaging

- reference volumes based on SUV (^{18}F-FDG)
- imaging of hypoxia (^{18}F-MISO, ^{64}Cu-ATSM, …)
- cell proliferation (^{18}F-FLT)
- transport of amino acids – synthesis of proteins (^{18}F-FET)
- neo-angiogenesis
- …

=> dose-painting by numbers?
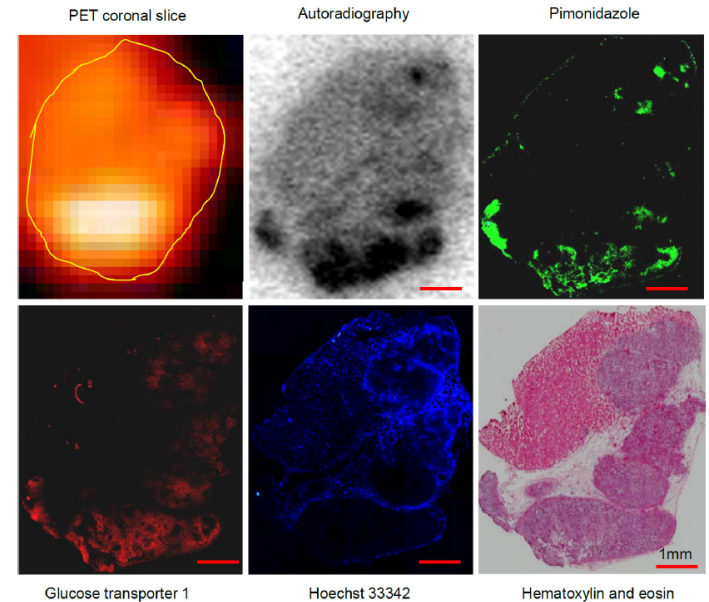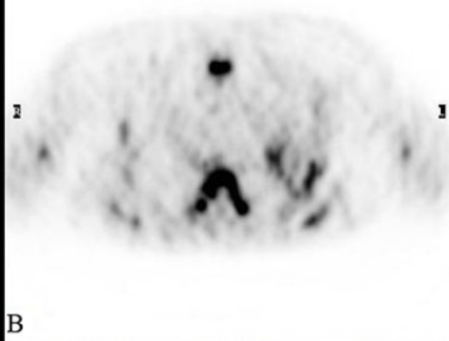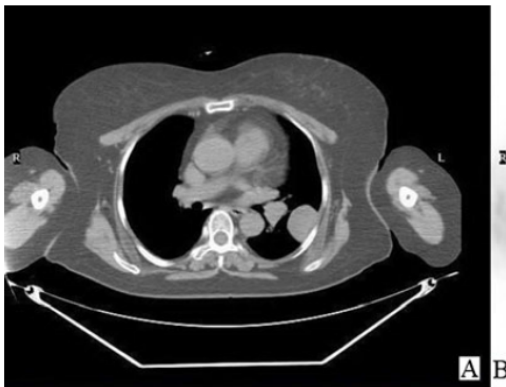
example of ^{18}F-MISO PET-CT – accumulation in hypoxic areas (NSCLC – animal model)

T Huang et al., "^{18}F-misonidazole PET imaging of hypoxia in micrometastases and macroscopic xenografts of human non-small cell lung cancer: a correlation with autoradiography and histological findings", Am J Nucl Med Mol Imaging 2013;3(2): 142-153

example of ^{18}F-FLT PET-CT – evidence of cell proliferation areas

W Yang et al., "Imaging proliferation of ^{18}F-FLT PET/CT correlated with the expression of microvessel density of tumour tissue in non-small-cell lung cancer", Am J Nucl Med Mol Imaging 2013;3(2):142-153

4D-PET-CT – INSTRUMENTS *(gating)*
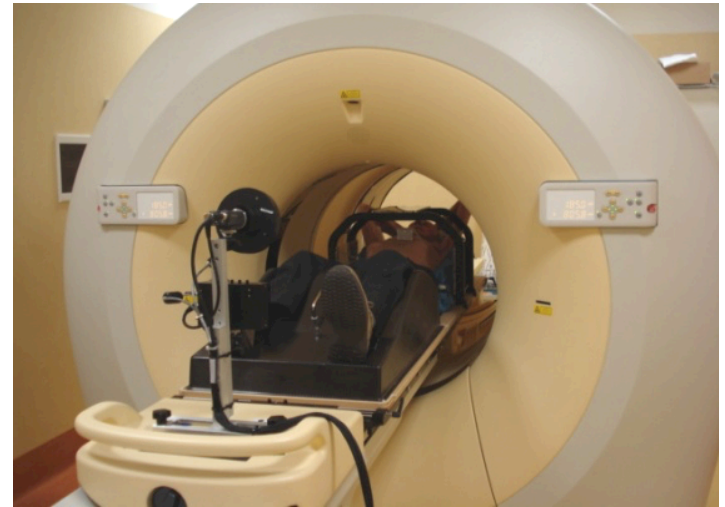

-**gating** – 4D PET-CT

-surrogate signal:

- *optical*
- *"strain-gauge" belt*
- *"tidal volume" measurement*
- *thermometry*
- *...*
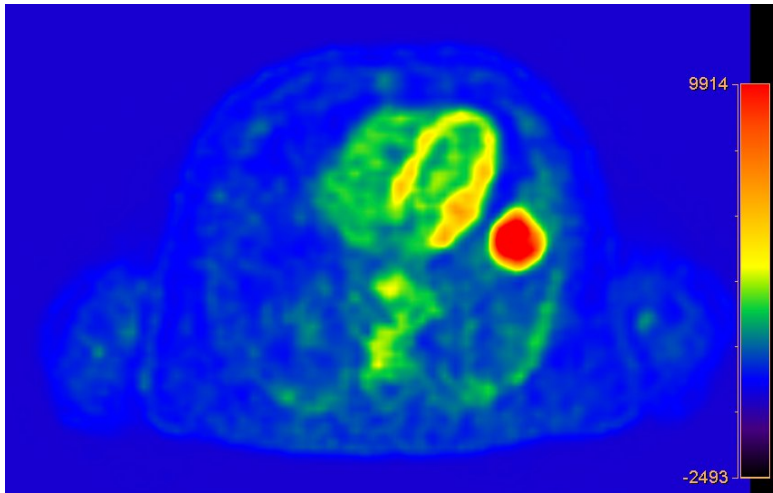
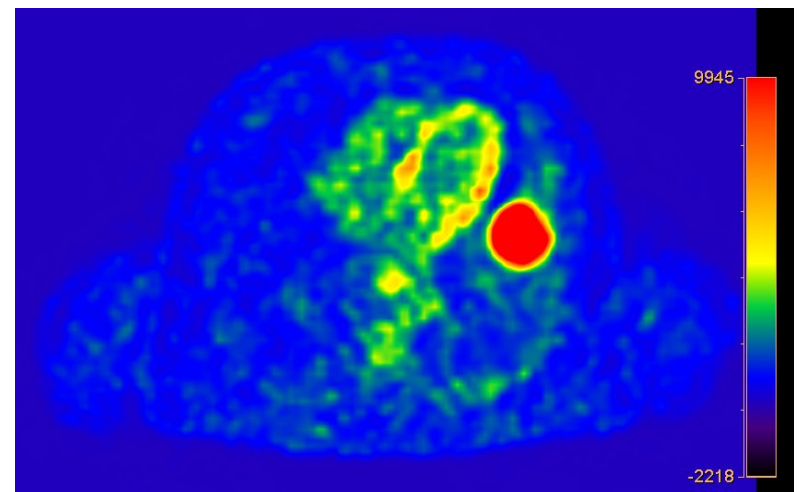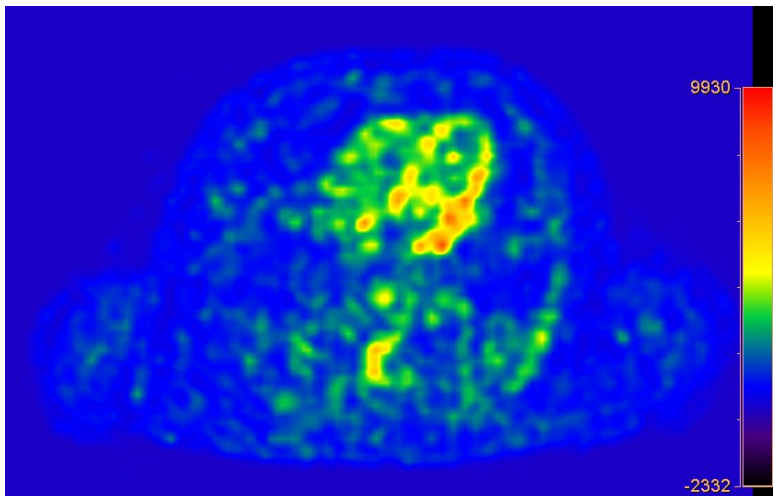-phase-based gating

-prospective or retrospective CT

-**loss of SNR** compared to uncontrolled acquisition
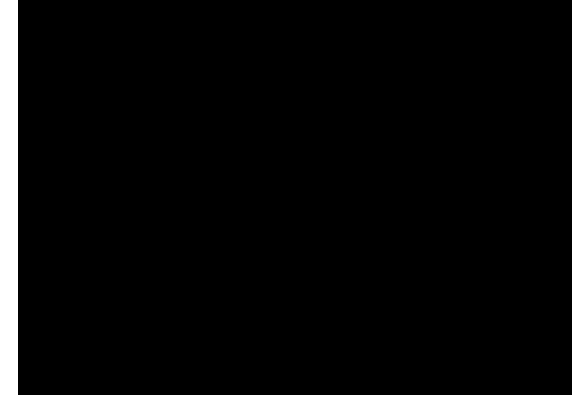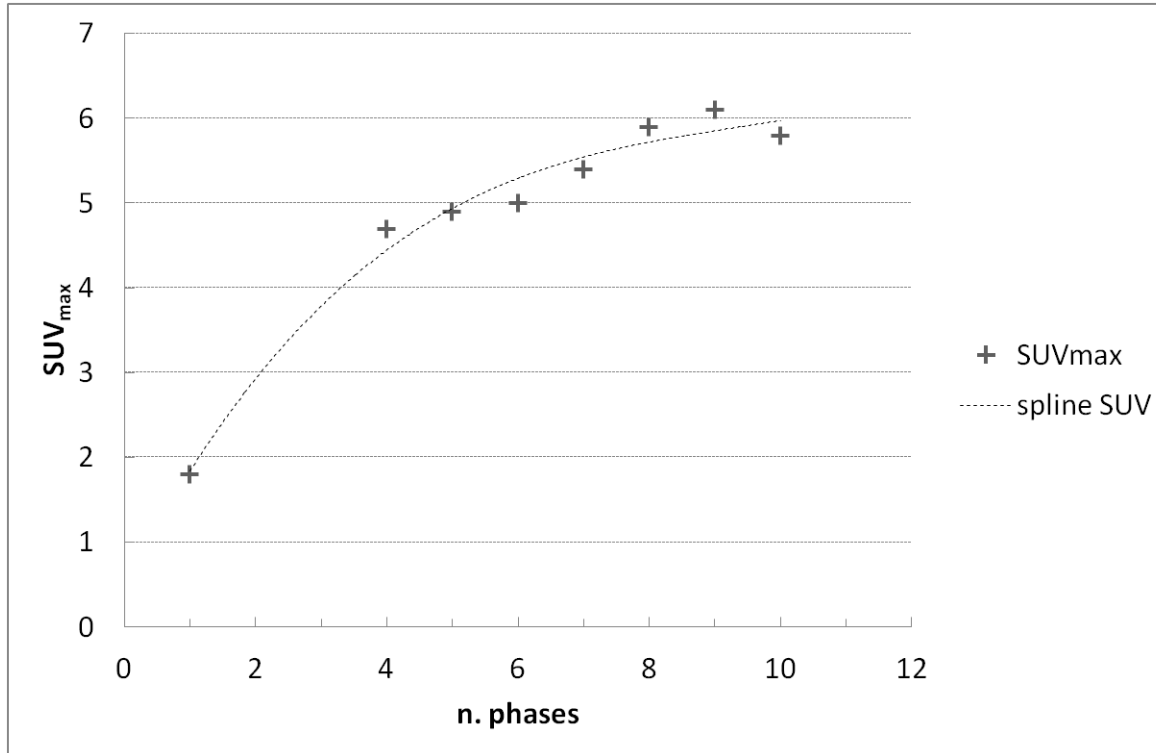
4D-PET-CT – INSTRUMENTS *(gating)*

- above: free-breathing uncontrolled acquisition

- lower left: "gated" acquisition - **max inspiration**

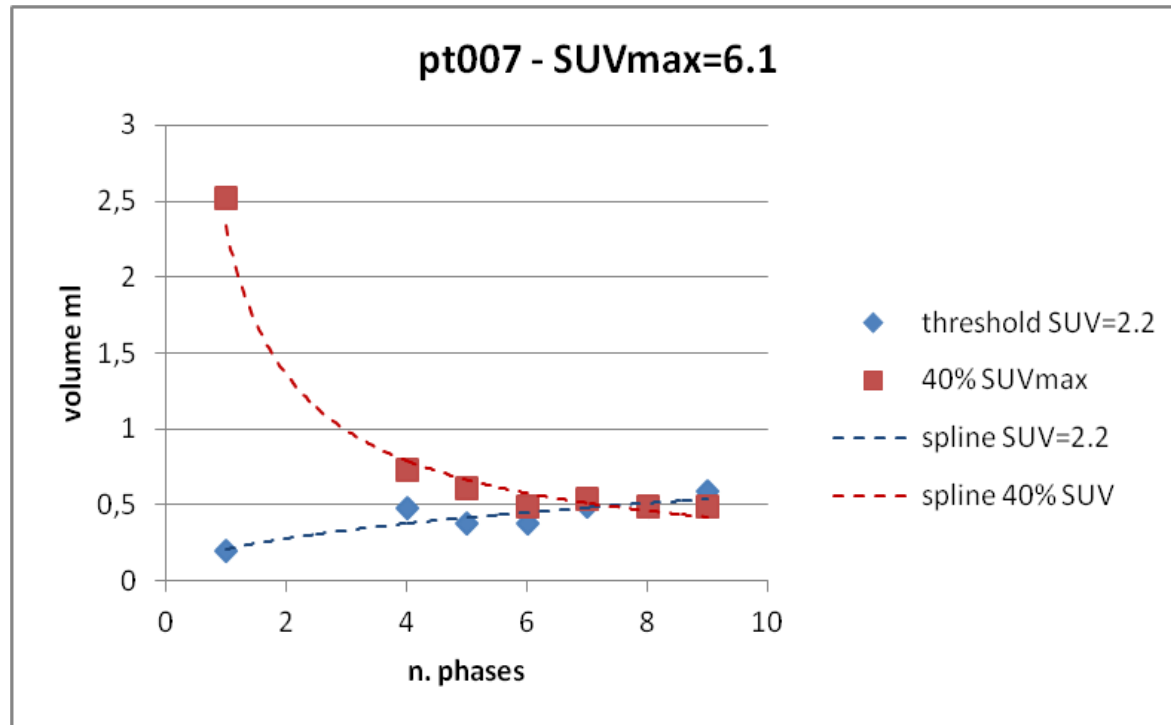- lower right: "gated" acquisition **max expiration**

THE EFFECT OF MOTION ON SUV VALUES

- excursion 19 mm

- SUV_{max}=1.8 non-gated

- SUV_{max} =6.1 @9ph

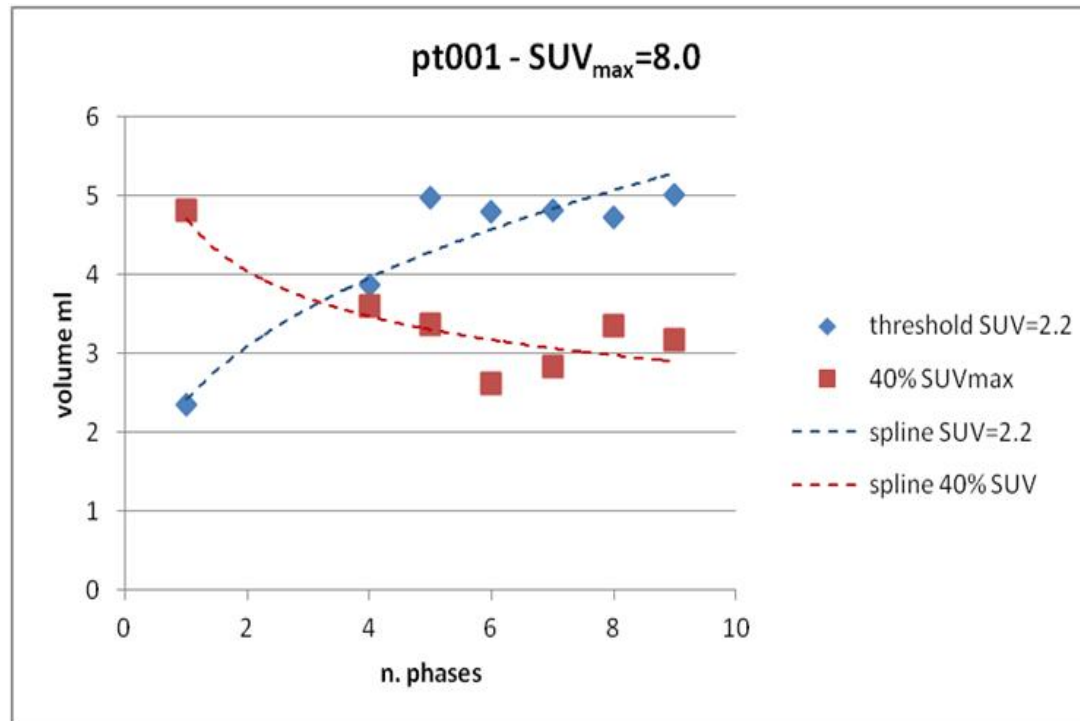- SUV_{max} in expiration as a function of the number of phase-bins

THE EFFECT OF MOTION ON SUV-BASED VOLUMES

pt007 - SUVmax=6.1

CASE 1
- threshold-based algorithms => underestimation of volume
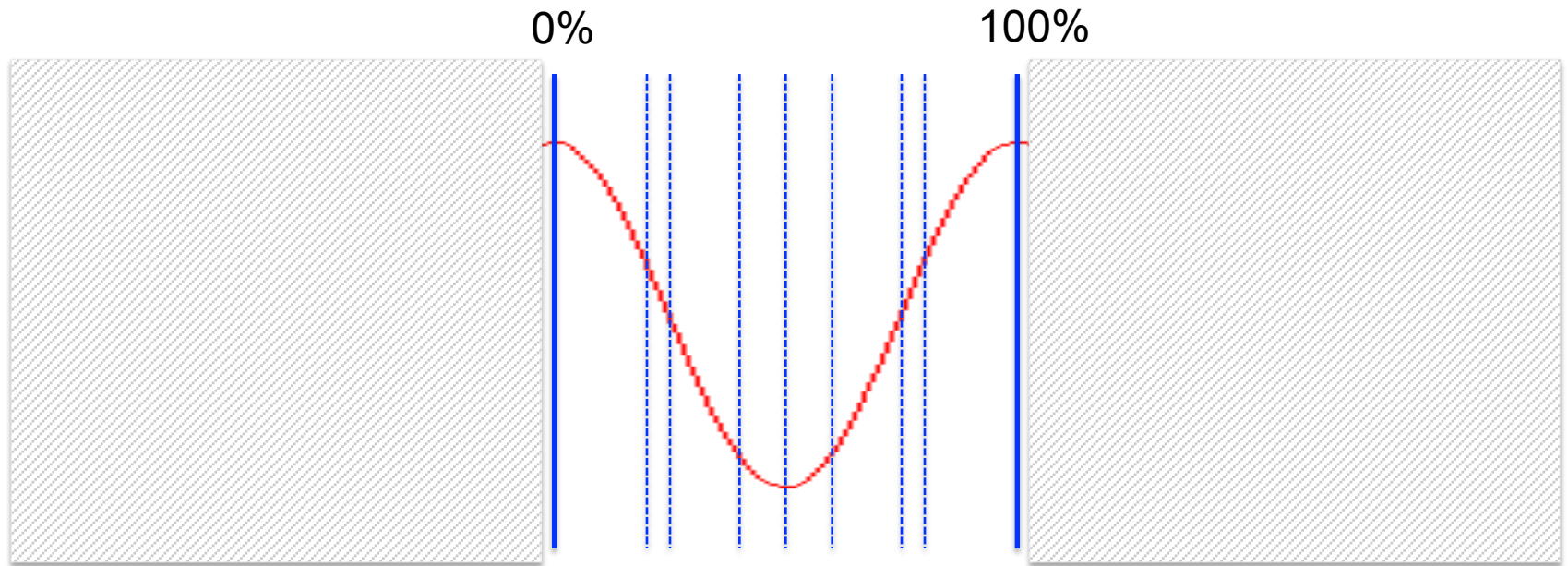- %SUVmax algorithms => overestimation of volume

THE EFFECT OF MOTION ON SUV-BASED VOLUMES

pt001 - SUV_{max}=8.0

volume ml vs n. phases

- threshold SUV=2.2
- 40% SUVmax
- - - spline SUV=2.2
- - - spline 40% SUV

CASE 2
- threshold-based algorithms => ?
- %SUVmax algorithms => ?
- more complex algorithms needed for accuracy

GATING in PET-CT – how many phases?

**If** 0% and 100% correspond to max inhale **and** the breathing pattern is symmetrical, than it is convenient to use an **odd number of phases (5-7)**

EXPERIMENTAL VALIDATION – VERIFICATION

- use of programmable **motion phantoms** (recommended - AAPM TG76)

- capable of simulating **realistic motion patterns** (ideally, real-patient motion)

- capable of reproducing both **tumor motion and surrogate motion**
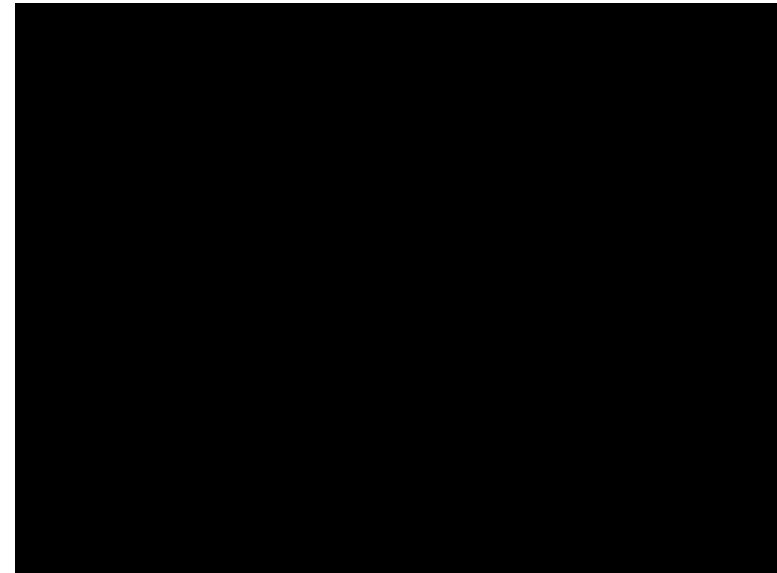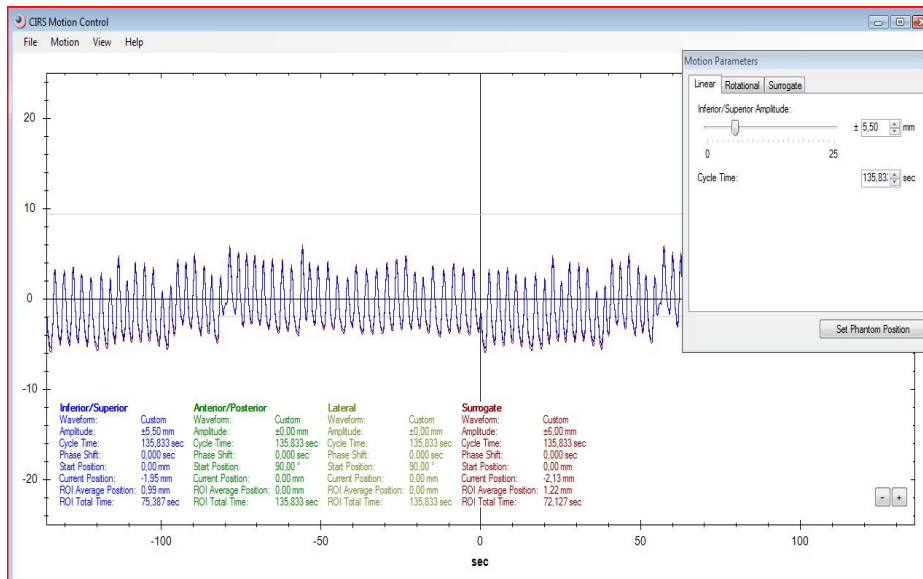
EXPERIMENTAL VALIDATION – VERIFICATION
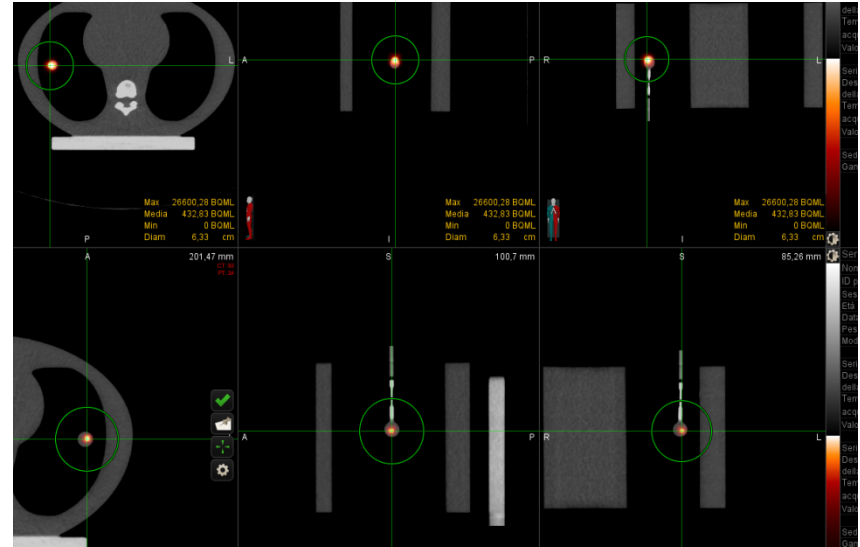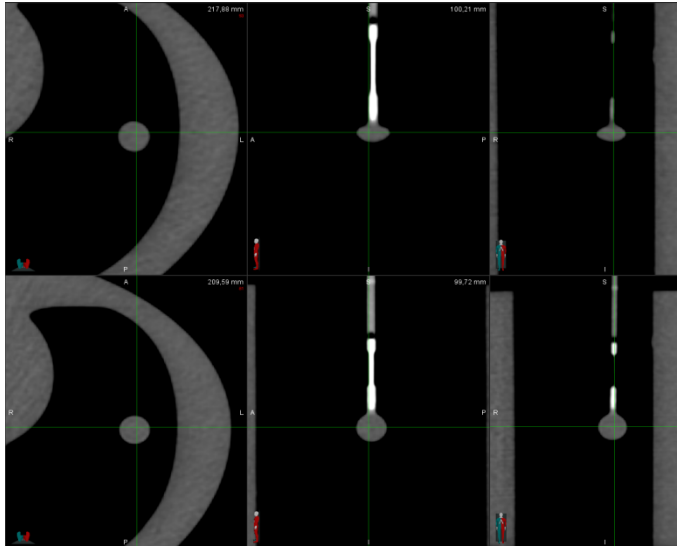
- available for **4D-CT**

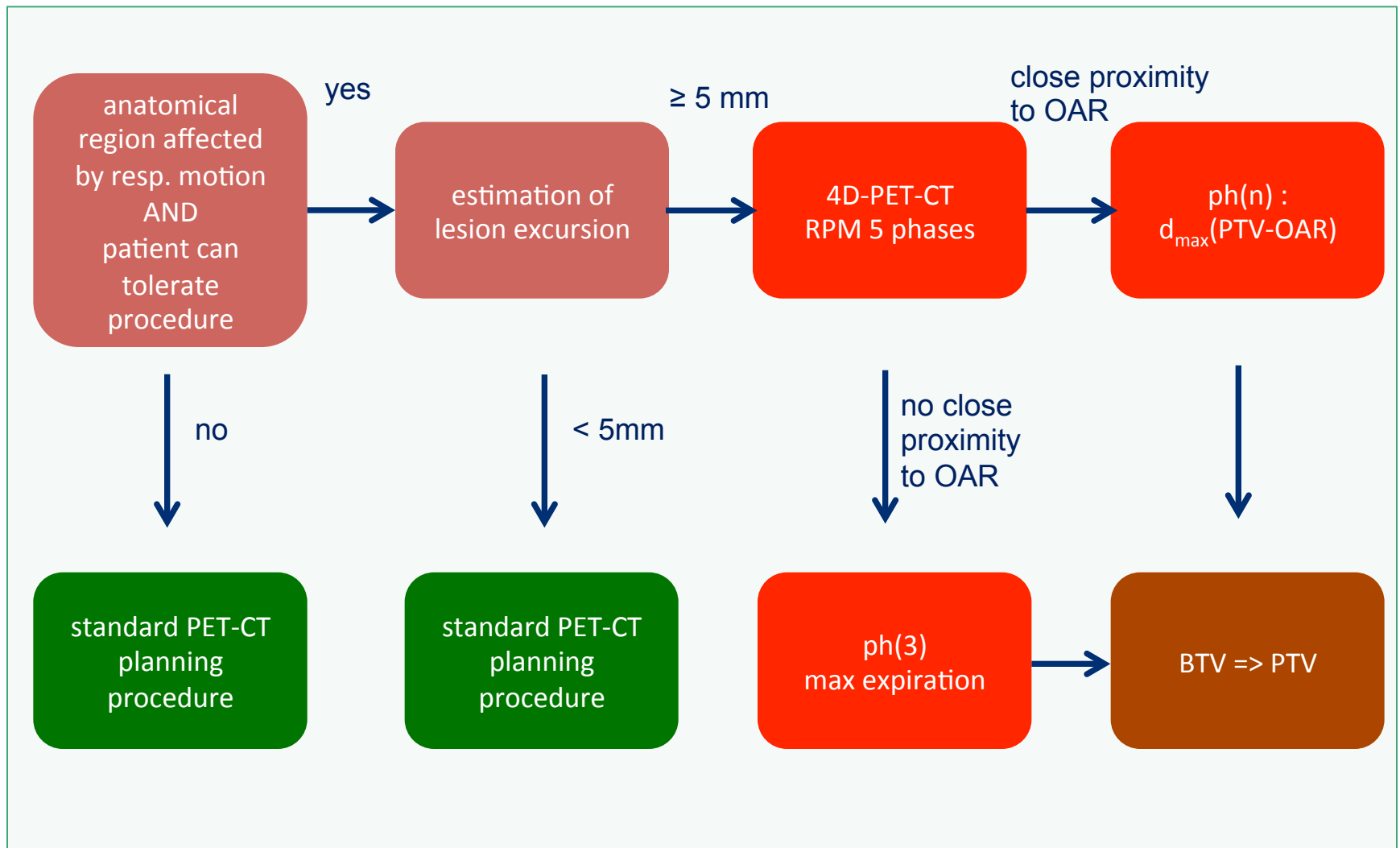- inserts and accessories for **PET-CT** easily found (or custom-made)

- **3D motion** difficult to reproduce in full detail

- **MR-compatible** instruments not easily found

EXPERIMENTAL VALIDATION – VERIFICATION

- analisys and tests on **system logfiles**

- **consistency checks** (e.g. volume preservation of solid tumors in different respiratory phases)

- **expert judgment** definitely required

Example of decision-tree - 4D-PET-CT for RT planning

anatomical region affected by resp. motion AND patient can tolerate procedure

yes →

estimation of lesion excursion

≥ 5 mm →

4D-PET-CT RPM 5 phases

close proximity to OAR →

ph(n) : d_{max}(PTV-OAR)

no ↓

standard PET-CT planning procedure

< 5mm ↓

standard PET-CT planning procedure

no close proximity to OAR ↓

ph(3) max expiration →

BTV => PTV

TAKE HOME MESSAGES

1. **tumor/organ motion** shall always be considered and accounted for, but an explicit management is not always necessary

2. **explicit methods** of motion management might prolong treatment time and/or introduce significant uncertainties (e.g. of dose to OARs)

3. **temporal coherence** is necessary between imaging used for planning and treatment administration technique

4. **validation – experimental verification** is necessary when implementing a motion-management program (including easily-performed consistency tests)

5. **balance** between accuracy and **clinical applicability** must be considered

EXERCISE

1. Login to TPS (groups of 3-4 people)

2. Open patient "exercise 4DCT"

3. Build an ITV based on GTV contours on each phase (already delineated)

4. Make considerations on a plausible expansion to account for residual uncertainties (anisotropic?)