WP 4: Ion therapy for intra-fractional moving targets

WP convener: Dietmar Georg, Christoph Bert

David Sarrut, Guido Baroni, Flavio Marchetto, and **MANY** others

Objectives

- Establish 4D imaging, deformable image registration, and motion modelling with a precision that is sufficient for particle therapy treatment planning and delivery.
- Develop a motion monitoring system that can provide precise target position information on a timescale of milliseconds.
- Develop a tracking system prototype for CNAO.
- Implement rescanning functionality at UKL-HD/HIT.
- Develop workflow concepts including radiation protection aspects for 4D ion radiotherapy.

Structure of WP4

• WP4.1: 4D imaging: acquisition, analysis, and modelling of image data	David Sarrut
• WP4.2: Motion monitoring	Guido Baroni
• WP4.3: Organ motion compensation for the CNAO dose delivery	Flavio Marchetto
• WP4.4: Implementation of rescanning at UKL-HD/HIT	Christoph Bert
• WP4.5: Quality assurance aspects of 4D ion beam therapy	Dietmar Georg

Review of Deliverables

Months 18 – February 2011

- 4.1: 4D deformation model for generation of reference data (DS)
- 4.2: Prototype of optical tracking system based on external markers and surface detection (GB)
- 4.3: Lateral compensation strategy based on motion monitoring signal (FM)
- 4.4: Rescanning component of UKL-HD treatment control system (CB)

Months 24 – August 2011

- 4.5 Motion model demonstrating internal-external correlation (DS)
- 4.6: Strategies demonstrating the integration of optical tracking (GB) with in-room 2D, 3D, 4D imaging and 4D dose delivery
- 4.7: Lateral and longitudinal compensation based on monitoring signal (FM) → M36
- 4.8: Overview and comparison of existing workflow concepts for 4D radiotherapy (DG)

Review of Deliverables

September 2011 – Mid Term review in Marburg

Months 36 – August 2012

- 4.9: 4D deformation model with adaptation to daily data (DS)
- 4.10: Combined internal/external motion monitoring (GB)

Months 48 – August 2013

- 4.11: Guideline document on QA and workflow aspects (DG)
  (incl. radiation protection) for 4D ion beam therapy U
- 4.12: Rescanning prototype validation (CB)

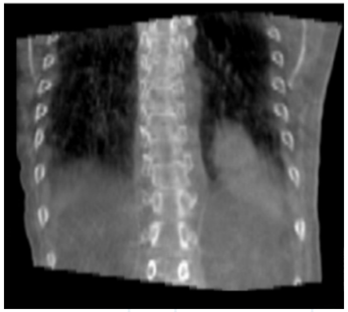
Meetings / Visits

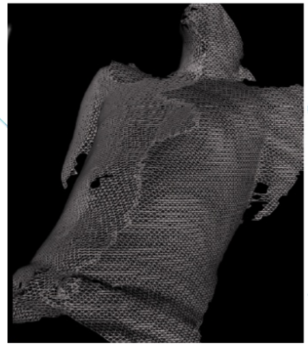
- F2F meetings
  - → April 2012: Vienna
  - → April 2011: Milano
  - → April 2010: Darmstadt
- Regular phone meetings
- Visits/exchange of researcher within the framework of collaborations
  - → subWP 4.2 - 4.1 / subWP4.2 - 4.4 / subWP4.2 – 4.3 / …

WP4.1 – 4D imaging

- Goal :
  → Establish 4D deformable image registration and motion models with a precision that is sufficient for particle therapy treatment planning and delivery
- Joint activities with WP4.2:
  → Develop a motion monitoring system that can provide precise target position information on a timescale of milliseconds .

WP4.1 – 4D imaging



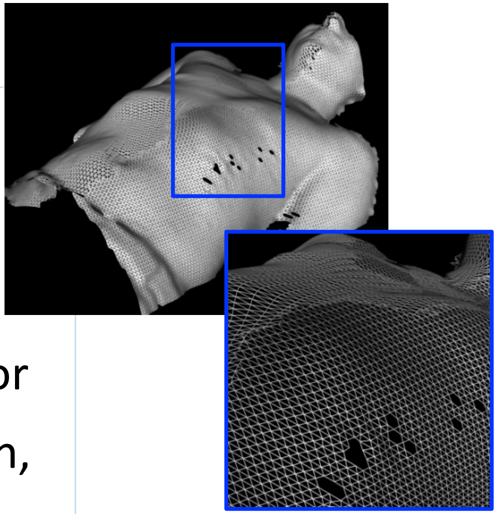


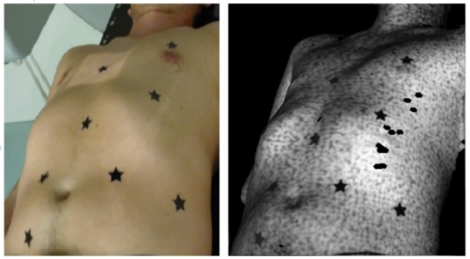
Basic Task - establish database

- Hypo-fractionated, Stage I NSCLC
- 16 patients, 75 sessions
- Acquired at CLB, Lyon
- During planning : 4D CT
- At each treatment session (between 3-6) :
  - ➔ 1 or 2 CBCT
  - ➔ 1 or 2 Vision RT during patient setup
  - ➔ Synchronized with CBCT !
  - ➔ 2 or 3 VisionRT during treatment
- Available to Ulice members

WP4.1: Deformable surface registration

- Challenge: Successive frames from surface (VisionRT) not consistent - not possible to obtain point trajectories during breathing.
- Solution: non-rigid ICP algorithm inspired from [Amberg et al., 2011]
  - ➔ Results. Tested on surfaces acquired on volunteers. Error < 1.20 mm. Good performances along Ant-Post direction, still difficulties along Sup-Inf.
  - ➔ For details see: J. Schaerer, A. Fassi, M. Riboldi, P. Cerveri, G. Baroni, D. Sarrut "Multi-dimensional respiratory motion tracking from markerless optical surface imaging based on deformable mesh registration" PMB 57 (2012), . 357-373.

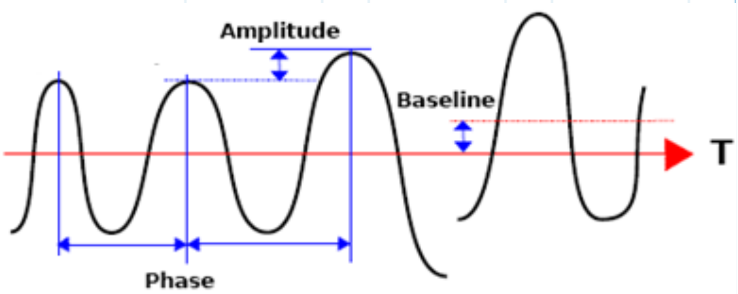




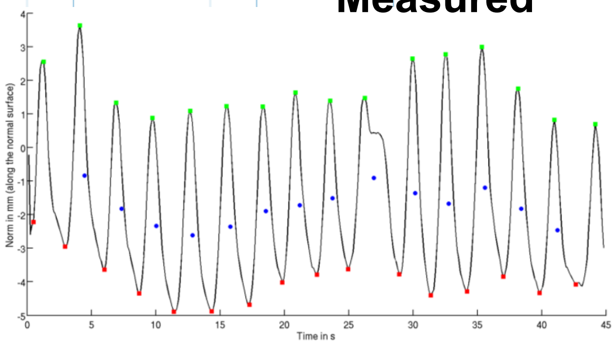
WP4.1: Statistical surface analysis

- Goal: To investigate the patient specific variability of thoraco-abdominal surface motion
- Method: Deformable surface registration, segmentation in cycle, computation of respiratory parameters

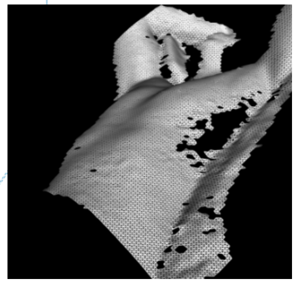
Model



Measured



- Tested on the patient DB, strategy to obtain intra- and inter variability maps for each patient.
  - ➔ Publication in progress.



WP4.1: current status

- ✓ Internal-external database acquisition (at Centre Léon Bérard, Lyon)
- ✓ Internal patient-specific breathing motion modeling [Vandemeulebroucke et al., Med. Phys. 2011]
- ✓ External deformable surface registration / Collaboration Milano – Lyon
- Internal image contrast enhancement (CBCT) Collaboration Milano – Lyon, Presented at ESTRO 2011, Article in progress
- External statistical surface analysis and Internal-external correlation fitting Collaboration Milano – Lyon In progress

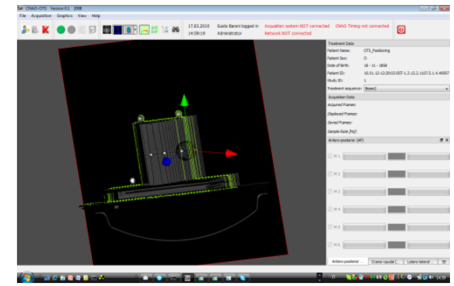
WP 4.2 – OTS Technology development

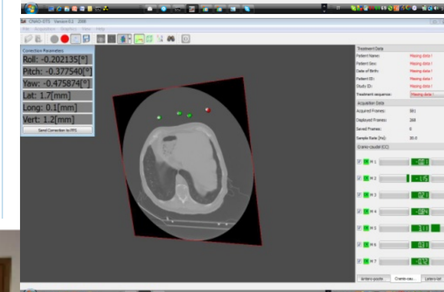
fondazione CNAO

Hybrid motion tracking:

- based on commercial general purpose motion analysis and on off-the-shelf general purpose motion capture system
- **automatic recognition and 3-D reconstruction of :**
  - **co-operative passive markers (1 cm diameter)**
  - **laser spots projected on patient skin**
  - **programmable laser pattern projector synchronized with TVC acquisition (optimal sync for maximal spot number per frame is ongoing work)**
- automatic point-based, surface-based and constrained **iterative registration featuring 6 dof with correction vector computation**
- **breathing detection capabilities** based subset of markers

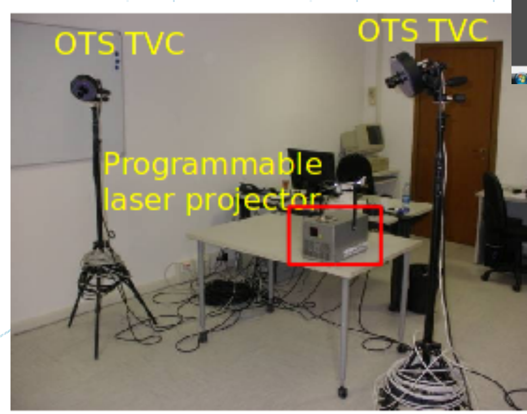
Motion tracking TVC set-up @ CNAO (byunker 1)





Motion tracking application snapshot

Delivered at M18…



Laboratory set-up for hybrid surface surrogates acquisition and registration

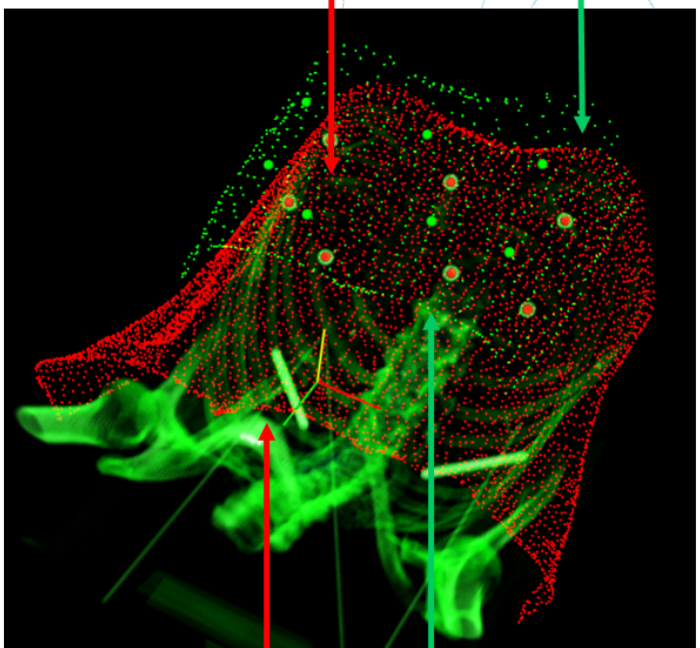
WP4.2 - Hybrid registration algorithm

fondazione CNAO

marker

Marker localized in CT image

Marker localized in treatment room



Patient surface from CT image

Surface acquired in the treatment room

surface

Marker model	Cloud model	Marker data	Cloud data	Iterations limit	**Constraints**

Initial weights → points cloud= 1, marker = 0.5

Corresponding points localization

Optimization procedure → R , T

Constraints verification and marker reweight

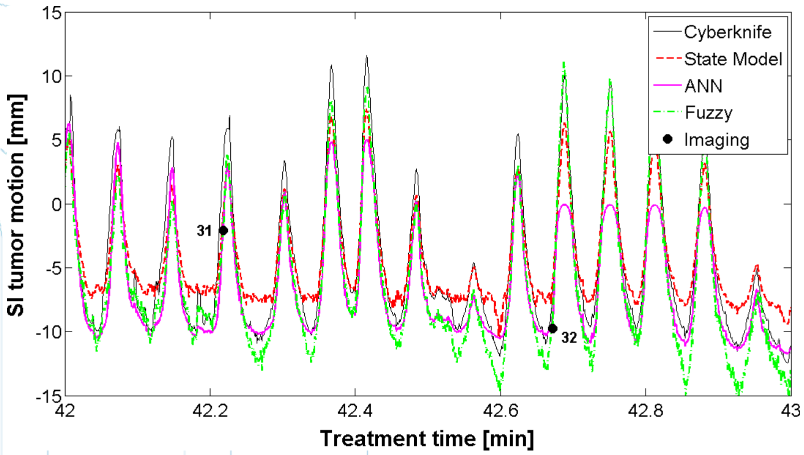
Convergence check

R, T

Delivered at M18…

WP 4.1/4.2 Combined internal-external motion monitoring

- Internal-external correlation on simulated and clinical data
- Respiratory parameters extraction from optically tracked markers and surfaces (4.1 – 4.2 joint activities)

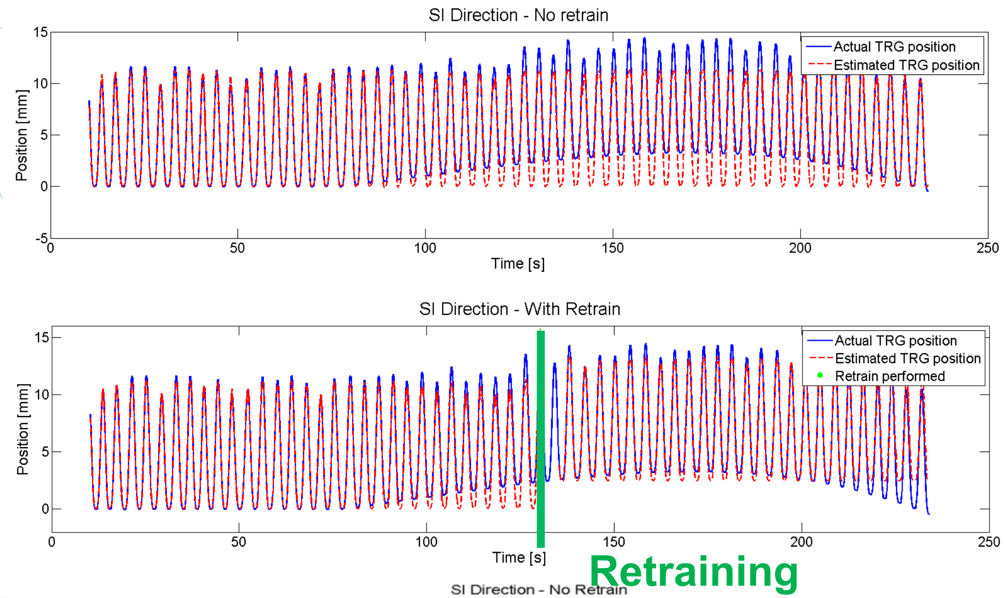


- Interfacing optical tracker with GSI OMC (4.4 – 4.2 joint activities)
- Interfacing optical tracker with CNAO DD (4.3 – 4.2 joint activities)

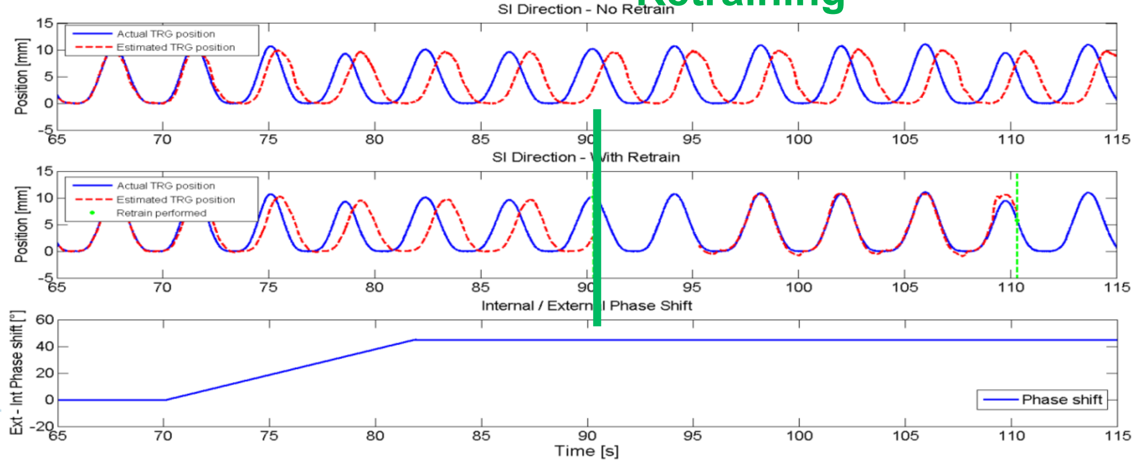
Delivered in in August 2012…

WP4.2 ANN performance w/wo retraining on simulated data

Baseline drift



Phase shift

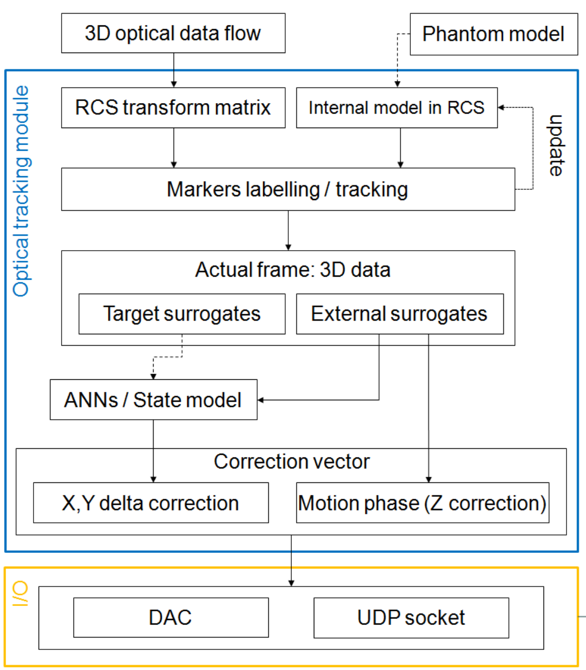


Seregni et al., PMB, in press

WP 4.1/4.2/4.4 – "Integration work"

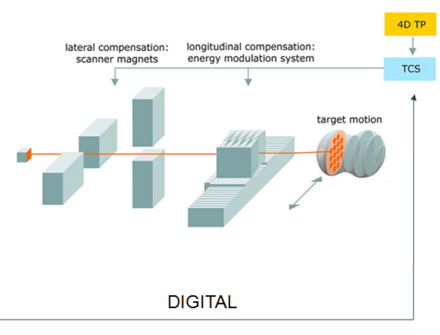
- Strategies demonstrating the integration of optical tracking with in-room 2D, 3D, and 4D dose delivery
  - ➔ Algorithm comparative assessment
  - ➔ ANN real-time lesion tracking from external surrogates
  - ➔ Breathing phantom activities / measurements

Detailed description: beam correction 100 Hz cycle



TECHNICAL SPECIFICATION

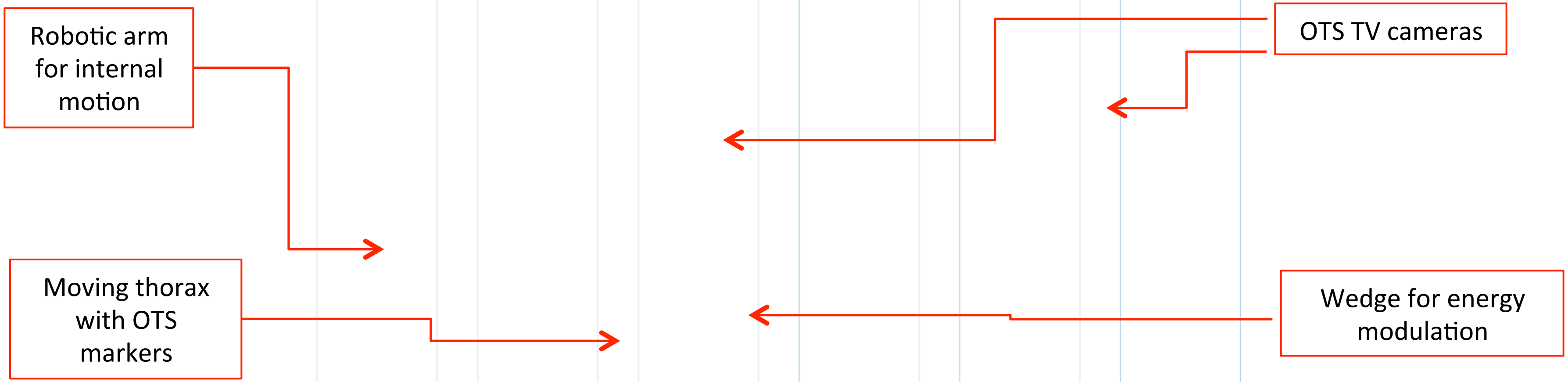
- Sub-millimetric setup geometry verification
- Milliseconds time scale
- Target position prediction:
  - ANNs
  - State Model
- Amplitude based motion phase detection
- Communication:
  - IN: digital (TTL signals)
  - OUT: digital (UDP socket)



WP 4.1/4.2/4.4 – “Integration work”

Set-up

- ✓ Breathing phantom: GSI *BruceLee*
- ✓ Optical tracking system: CNAO-PoliMI *OTS* (2 TVC configuration)
- ✓ Digital interfacing: UDP with prediction to overcome 30 msec delay
- ✓ Measurement tools: 18 pin-point chambers
- ✓ Tests: feedback to GSI beam steering system (planar compensation and energy modulation via wedge motion) by direct target tracking (1 test)



Experimental set-up in GSI cave with *BruceLee* phantom (moving thorax with markers and robotic arm moving internal target) and moving wedge for beam energy modulation

WP4.2 and “partners” – research outcome

Papers

- Seregni M, Pella A, Riboldi M, Orecchia R, Cerveri P, Baroni G.(2011) Real-time tumor tracking with an artificial neural networks-based method: A feasibility study. Phys Med. Dec 29. [Epub ahead of print].
- Seregni M, Pella A, Riboldi M, Baroni G. (2011) Development and validation of a prototypal neural networks-based tumor tracking method. Conf Proc IEEE Eng Med Biol Soc. Aug;2011:2780-3
- Schaerer J, Fassi A, Riboldi M, Cerveri P, Baroni G, Sarrut D. (2012) Multi-dimensional respiratory motion tracking from markerless optical surface imaging based on deformable mesh registration. Phys Med Biol 21;57(2):357-73.

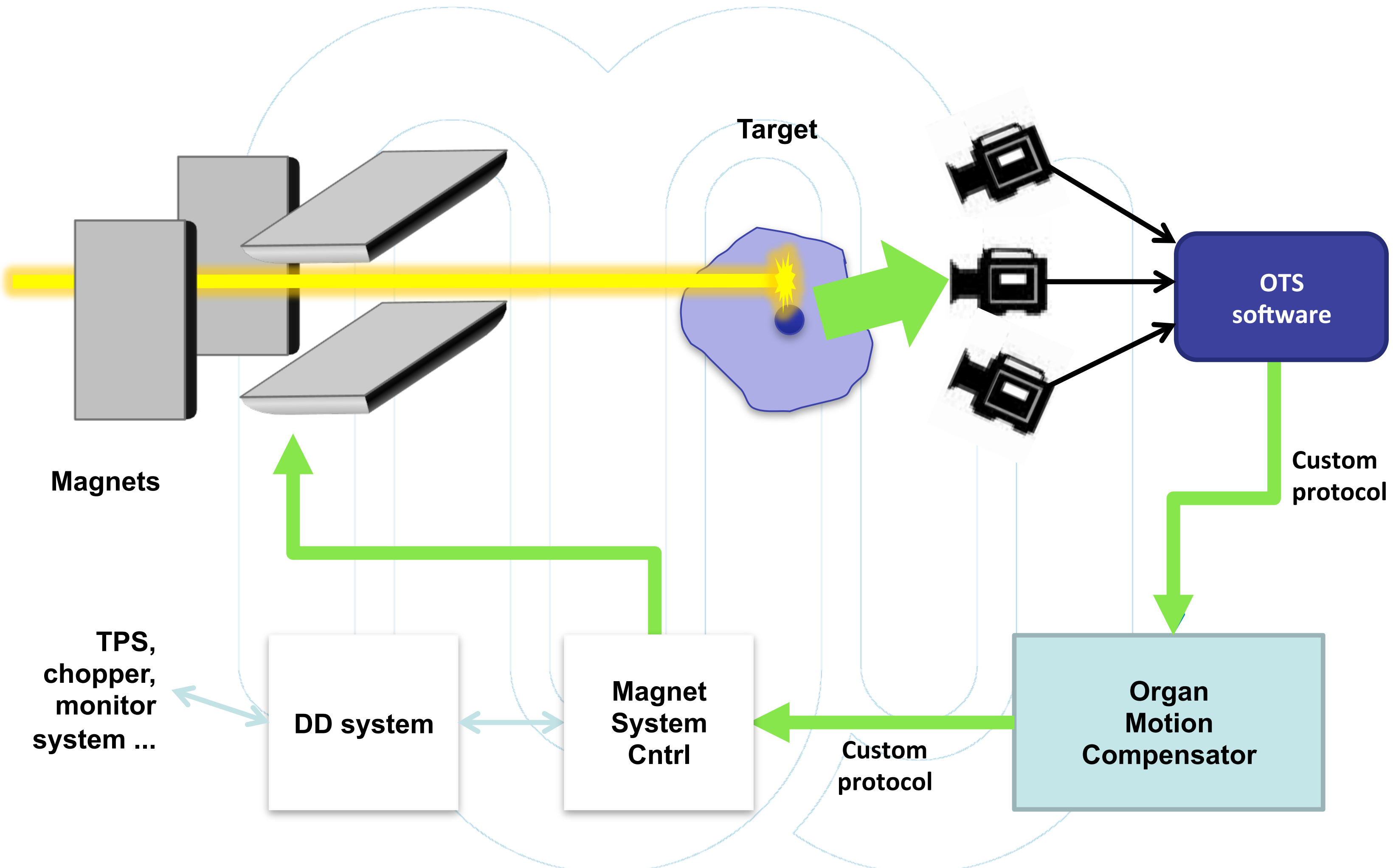
Book chapters

- M. Riboldi, M. Seregni, A. Pella, A.E. Torshabi, R. Orecchia, G. Baroni (2011) Real-time tumor targeting in external beam radiotherapy, in Brain cancer, Tumor Targeting and Cervical Cancer, Nova Science Publisher, ISBN: 978-1-61122-738-3
- A.E. Torshabi, M. Riboldi, A.Pella, A. Negarestani, M. Rahnema and G.Baroni (2012) A Clinical Application of Fuzzy Logic. In Emerging Technologies and Applications, ISBN 978-953-51-0337-0, edited by Elmer P. Dadios.

Conferences

- A. Fassi, J. Schaerer, M. Riboldi, D. Sarrut, G. Baroni. “A novel CT-based contrast enhancement technique for markerless lung tumor tracking in X-ray projection images”. ESTRO Conference Proceedings 2011.
- Fattori G., Saito N., Pella A., Kaderka R., Seregni M., Costantinescu A., Cerveri P., Steidl P., Riboldi R., Baroni G., Bert C. “Integration of optical tracking for organ motion compensation in scanned ion therapy”. AAPM 2012.
- Capasso L., Donetti M., Fattori G., Riboldi M., Baroni G., Cirio R., Garella MA, Giordanengo S., Hosseini A., Marchetto F., Peroni C., Sacchi R. “An Organ Motion Compensator for the CNAO Center of Oncological Hadrontherapy”. AAMP (Trieste) 2012.

WP4.3 – Organ motion strategy for CNAO

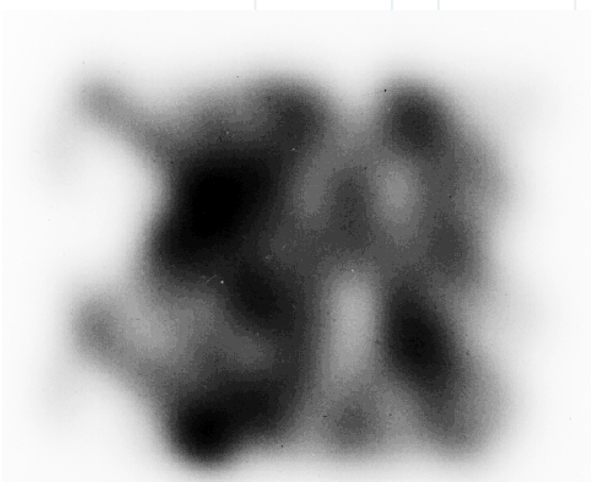


WP4.3: OMC (first version) for CNAO

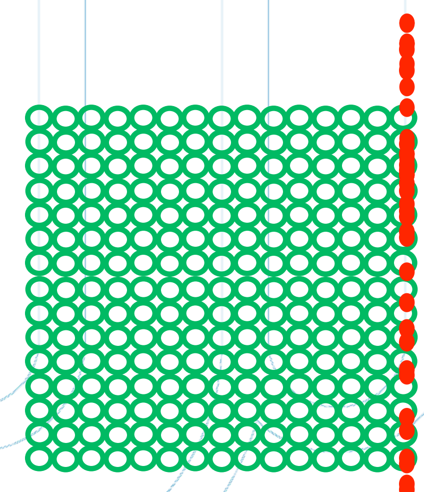
- Performed inside an FPGA board (NI PXI-7831R), housed into a PXI crate;
- It receives the target measured position and the respiratory phase from the OTS
- OMC task:
  - → to compensate for planar motion along the X-Y plane (in this version the Z correction and the respiratory phase are not used);
  - → to adapt data coming from different reference systems (of OTS and OMC);
  - → to convert the X and Y units (mm/100) into units used by the Magnet System Controller;
  - → to write a log file, stored into the memory of the PXI controller.

WP4.3: Experimental Test

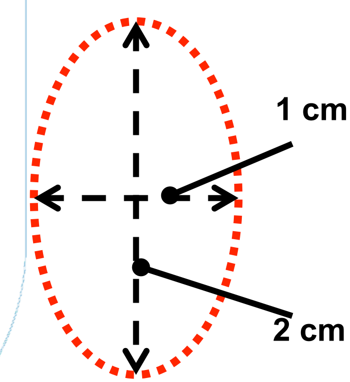
- OMC was tested by adding (sinusoidal) shifts to a full square field, painted on a static film by the Dose Delivery system;
- 1) only the shifts on X – 2) then only on Y - and 3) finally combination of the two effects (with different amplitudes);
  - ➔ raster scanning of the beam starts from the top right corner…..



test pattern with articifical



Modifications ON THE Y DIRECTION

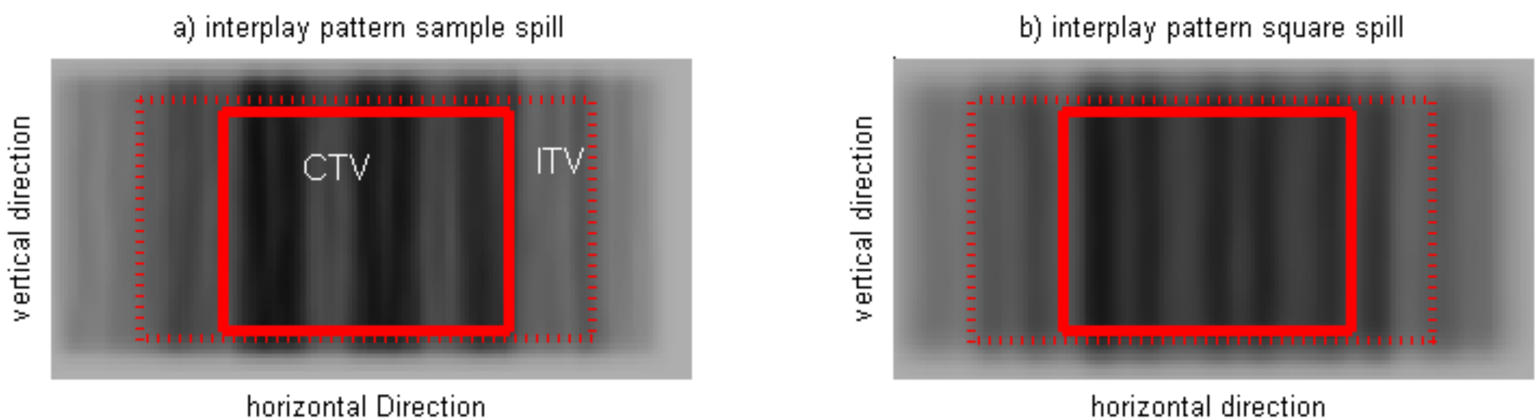


TRAJECTORY OF THEIR COMBINATION

WP4.3: Next test

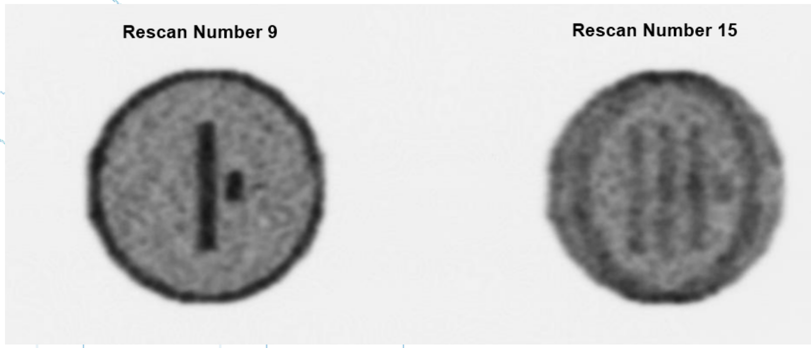
- Film placed upon a moving phantom: the OMC will be “instructed” to follow the movements of the phantom
  - → simulate different respiratory patterns, respiration periods, amplitudes, etc .
  - → Measurements planned for October / November 2012

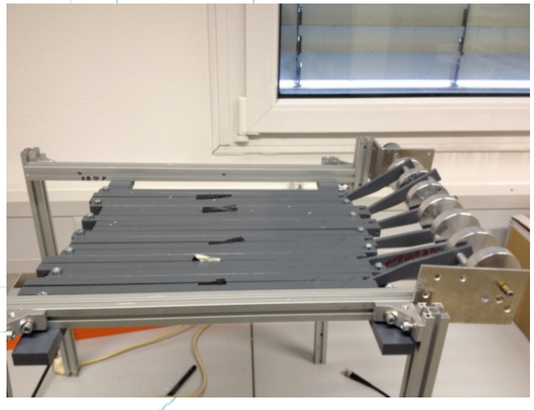
Courtesy C Bert / GSI



WP4.4 – Rescanning: current focus

- Experimental work at HIT/GSI
  - ➔ implementation of rescanning at HIT
  - ➔ technical test of implementation
  - ➔ research on rescanning modes using the implementation
- Effects of number of rescans, spill length, phase and amplitude dependence, period dependence, particle intensity dependence, …

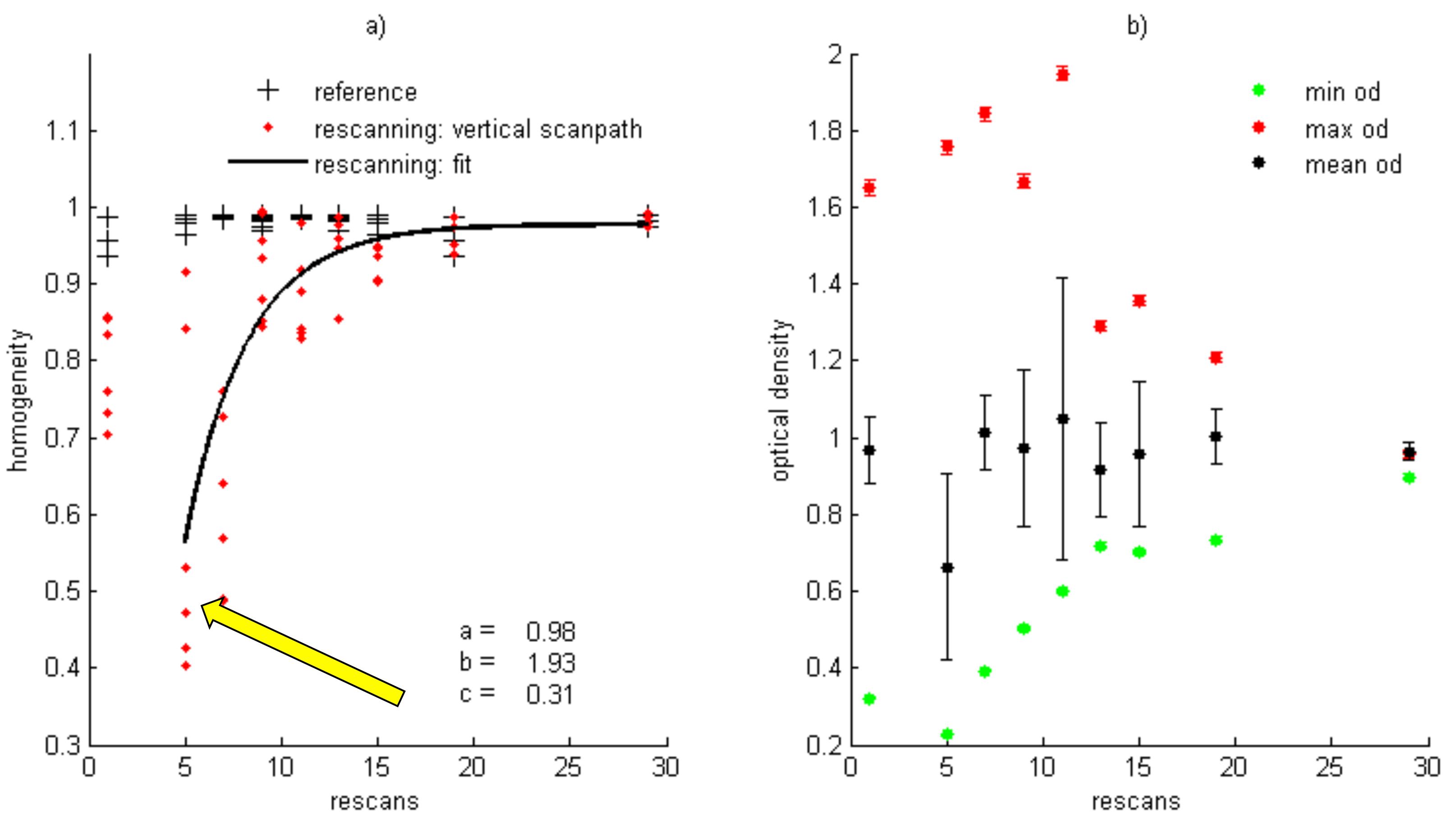




WP4.4 – Rescanning: current focus

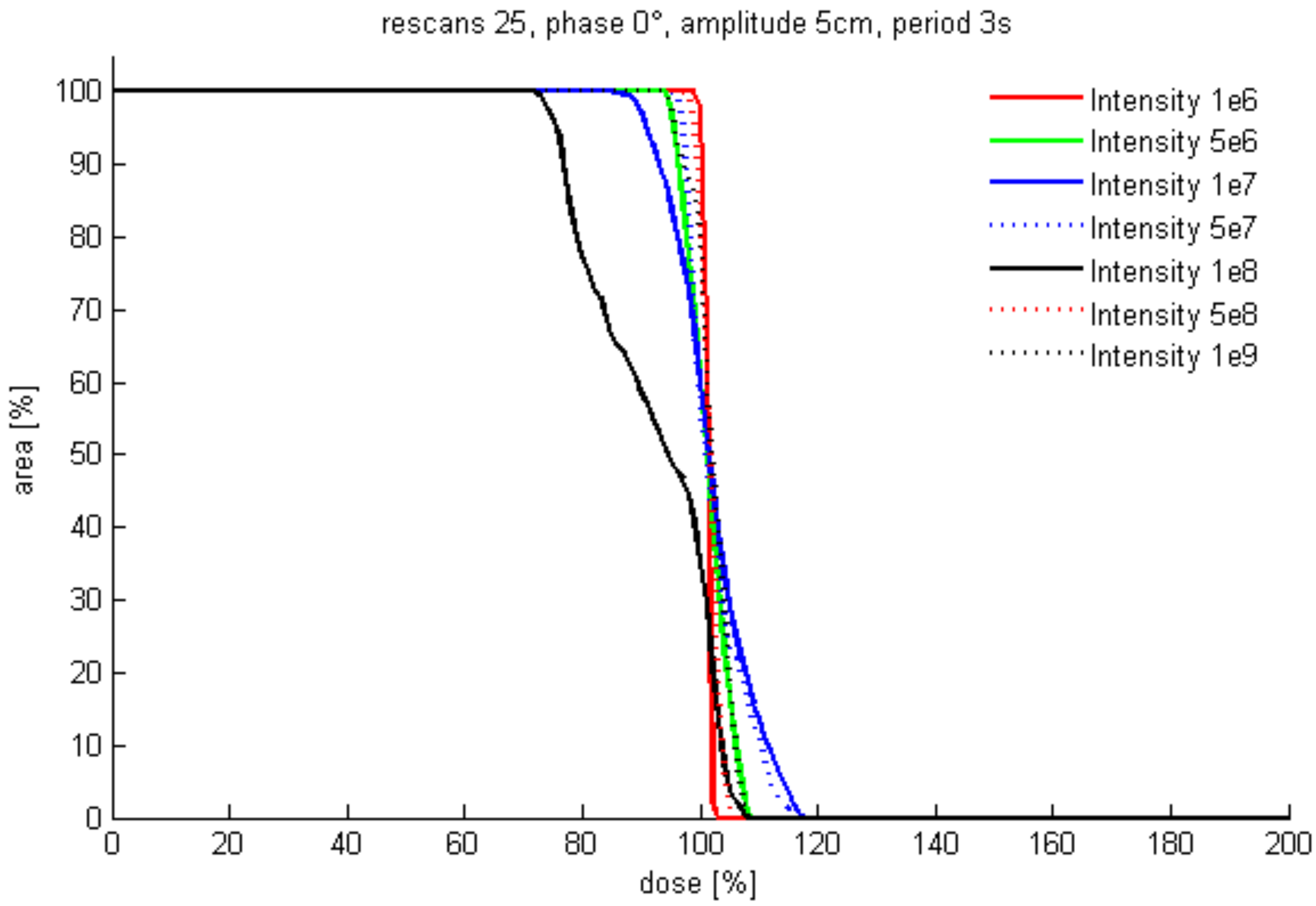
- 4D treatment planning studies using GSI TPS TRiP4D
  - ➔ based on patient data (4DCT, deformation maps, ...)
  - ➔ assess rescanning modes based on clinical data

WP4.4 – Interplay Experiments @ HIT



- **5 cm horizontal amplitude, period 4s**

WP4.4 : Simulation - Intensity Dependence

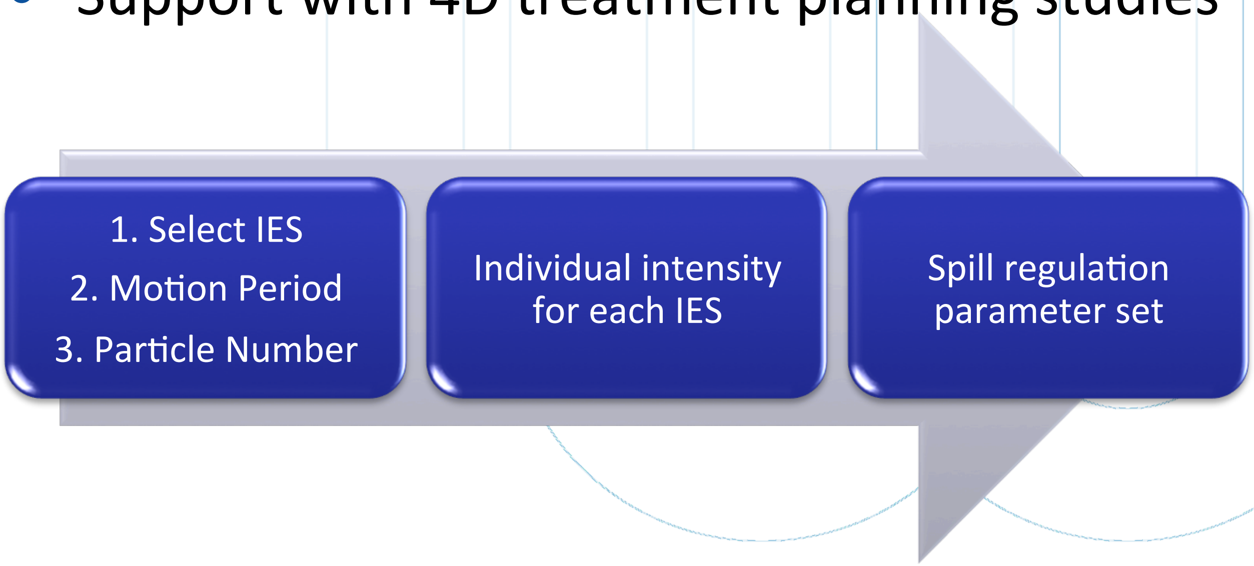


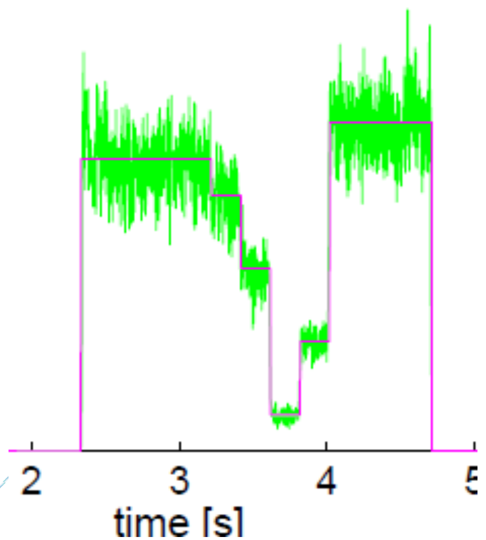
→ **Interplay maximum for 10^8 particles per spill**

→ **"Very low" intensities converge to x-ray irradiation**

WP4.4: Goal Breath Sampled rescanning

- **Matching of rescanning length and breathing period improves dose homogeneity [Seco et al, Furukawa et al.]**
- Use spill regulation to achieve matching (incl. feedback loop)
  - ➔ Test at QA cave of HIT
- Support with 4D treatment planning studies





[Schömers et al., HIT]

WP4.5 – QA aspects of 4D ion beam therapy

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- Imaging dose for IGRT in lung
  - ➔ Evaluate imaging dose for different imaging protocols
    - Compare conventional scheme vs. extensive IGRT
  - ➔ Is there an impact on current imaging protocols?
  - ➔ Is there an impact on adaptive protocols?
  - ➔ Is there an impact on planning constraints?

- Design end to end test for 4D ion beam therapy in cooperation with WP4.3 and 4.4
- Risk and workflow assessment

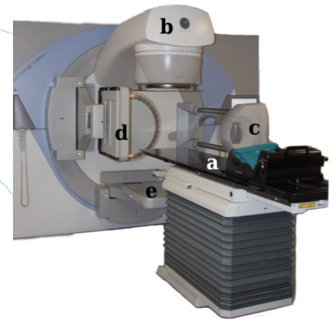
} **2013**

WP4.5 – Imaging dose for IGRT in lung

- kV Imaging Devices
  - ➔ CBCT at the Elekta Linac
  - ➔ CBCT at the Simulator
  - ➔ Siemens MultiSlice-CT
  - ➔ ExacTrac x-ray
  - ➔ Planar Imaging on Linac
- MV Imaging Devices
  - ➔ Portal Imaging

3D

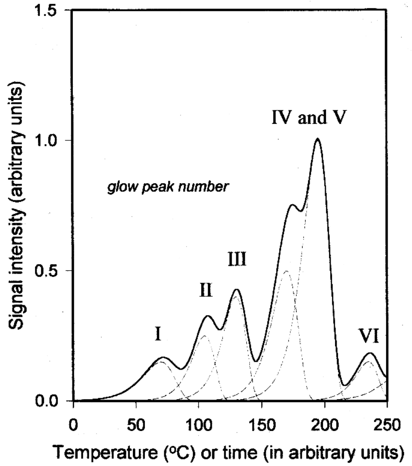
2D

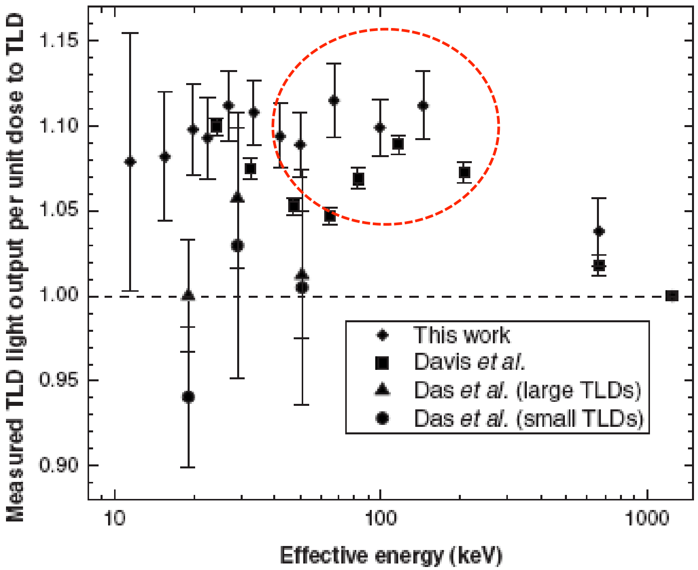


- Currently: measurements at CNAO
- Other Ion beam centers : WIP

WP4.5 – Imaging dose for IGRT in lung

- TLD-100, 3 x 3 x 1 mm^3
- TLD rel. sensitivity within ± 3%
- Several points of interest evaluated in Alderson phantom
- 3 TLDs for each point
- LiF has different photon interaction cross section compared to water
  - ➔ Energy correction for MV and kV range





Nunn et al MP 35 (2008)

WP4.5 – Imaging dose

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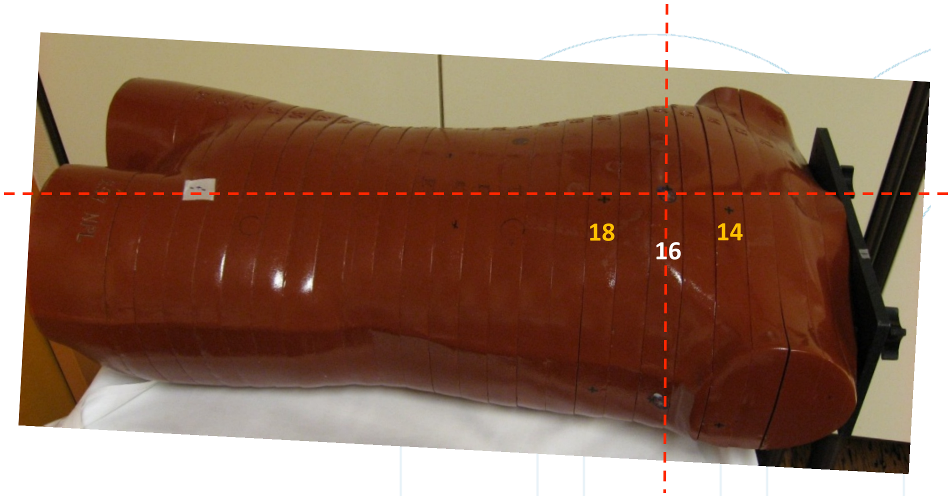
Phantom slabs 10-34+297

TLD placement :

Slab	Organ	„Measurement position“
13	Chestwall	a
	Lung contralat	b
	Lung ipsilat	c
	Spine	d
	Esophagus	e
14	Bronchus	f
15	Heart	g
	Vertebrae	h
16	Chestwall	i
	Lung contralat	j
	Lung ipsilat	k (iso)
	Spine	l
	Esophagus	m

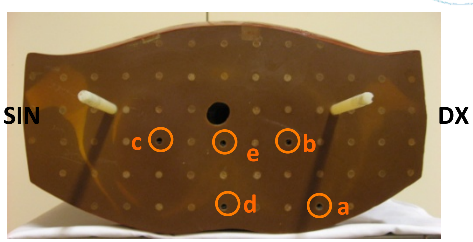


- - - - - - - Iso

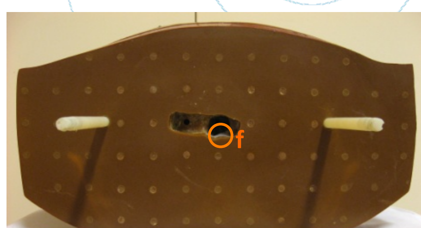
Icocenter in left lung, ~5.5. cm from midline, slab 16.

Measurements for **skin dose** on the surface of slabs 14, 16, and 18.

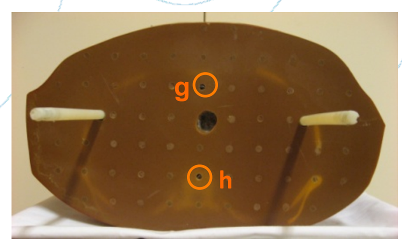
Slab 13: Chestwall, Lung contralat/ ipsilat, Esophagus, Spine



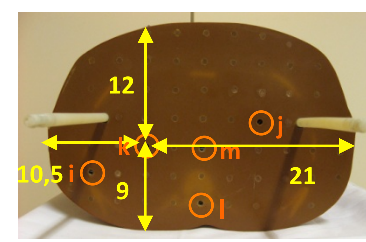
Slab 14: Bronchus



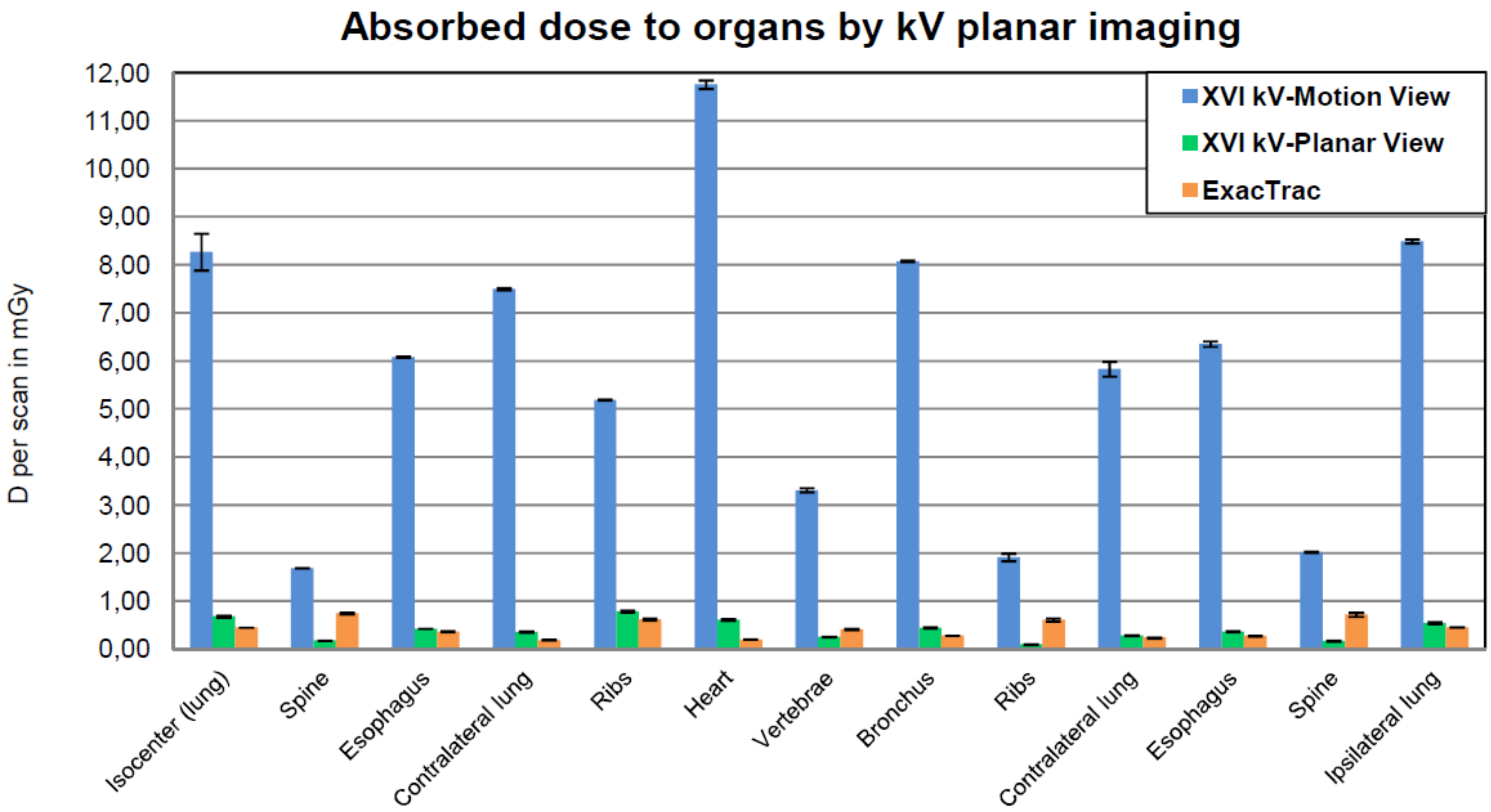
Slab 15: Heart, Vertebrae



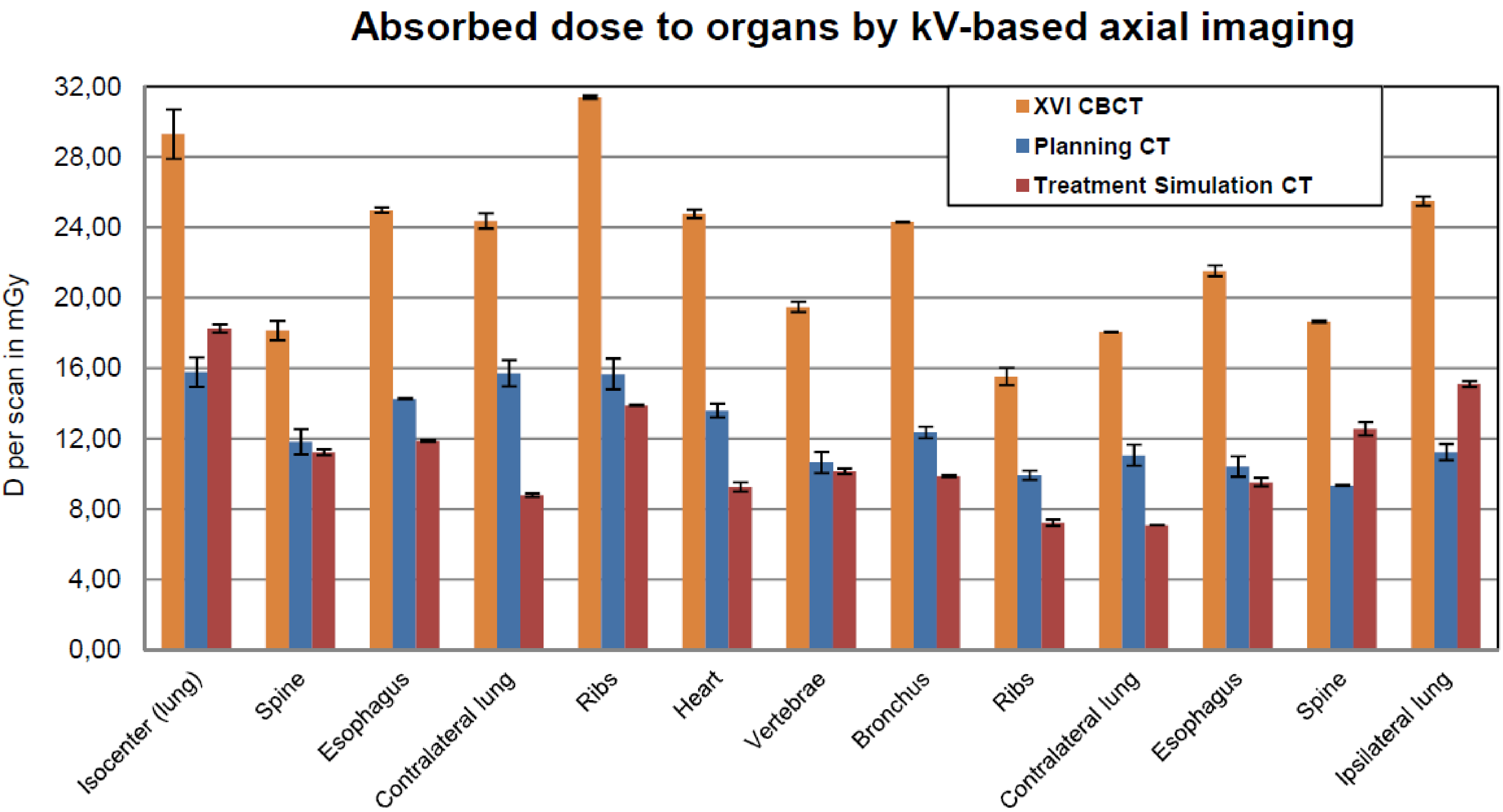
Slab 16: Chestwall, Lung contralat/ipsilat, Esophagus, Spine



WP4.5 – Imaging dose for IGRT in lung



WP4.5 – Imaging dose for IGRT in lung



WP4.5 – Imaging dose for IGRT in lung

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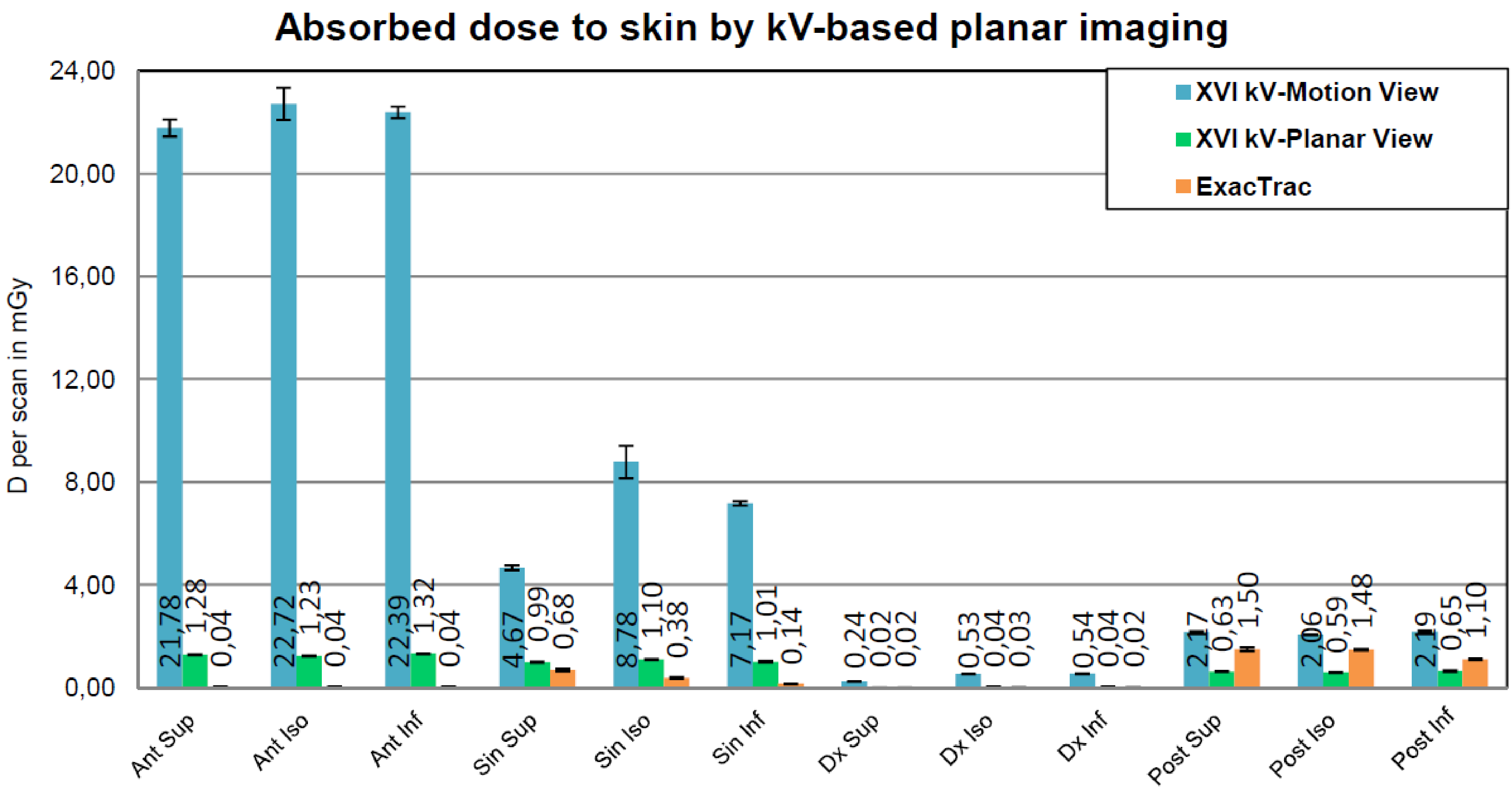
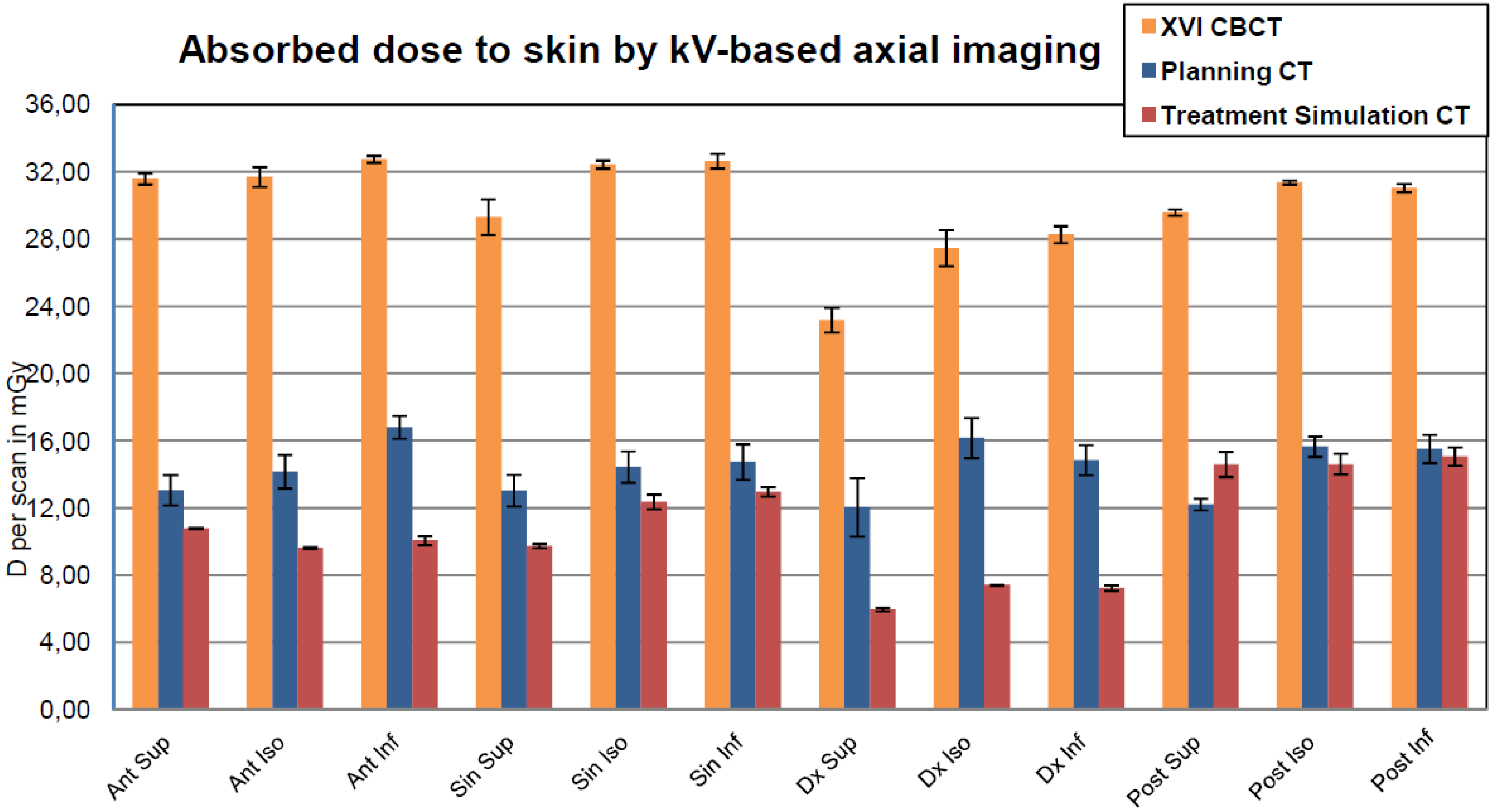


WP4.5 – Imaging dose for IGRT in lung



WP4.5 – Imaging dose for IGRT in lung

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- Planned to perform additional dose study on IGRT devices in particle therapy centres
  - → CNAO
  - → "IBA" centre
  - → Various 4D-CTs to simulate sliding CT option
  - → HIT?
  - → PSI?
  - → ....

Outlook

- **Final Deliverables can & will be completed in 2013**
  - ➔ Deliverable 4.7 completed end September

- Next phone conference: End September / Early October 2012
- Next F2F meeting: Proposal April in Lyon 2013

- **Acknowledgements:** All co-workers and members of WP4 working at several institutions!