Treatment Planning

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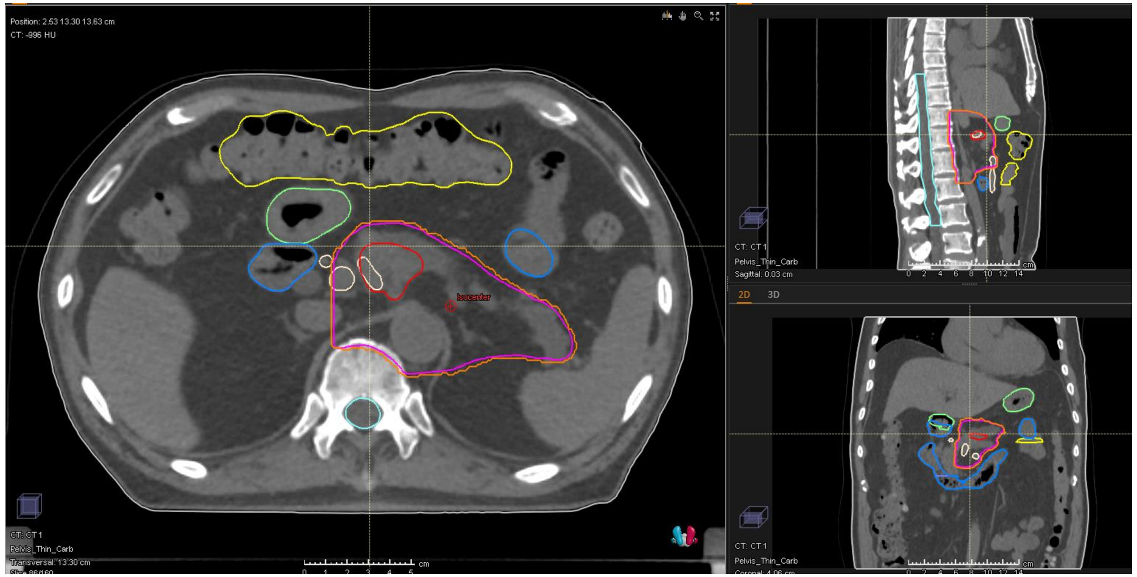
Fondazione CNAO – Medical Physics Unit

Anatomical module

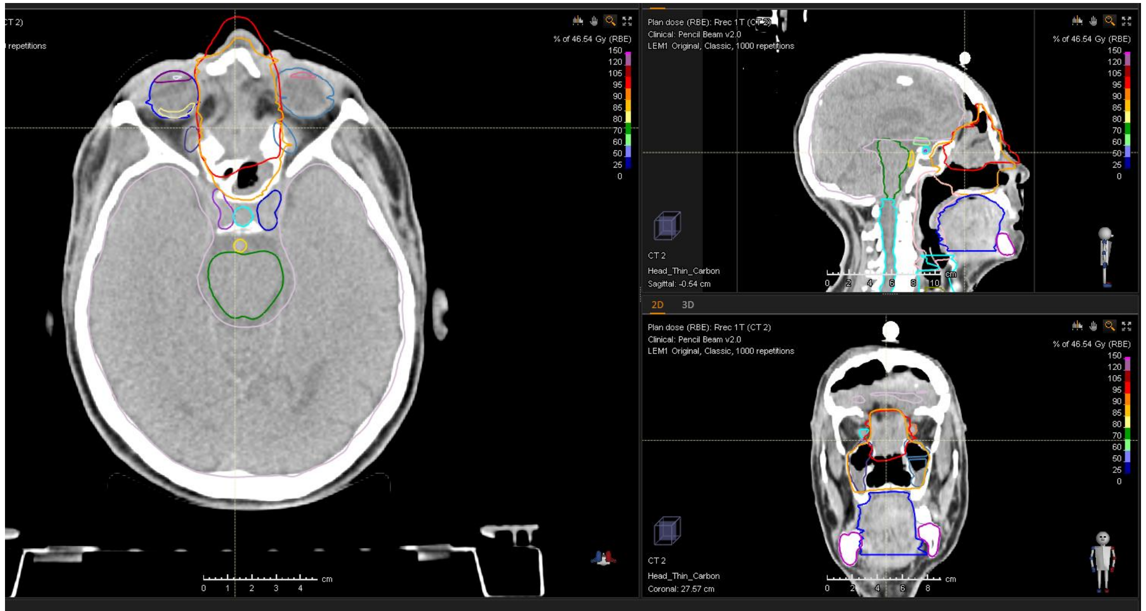


3D model of the patient

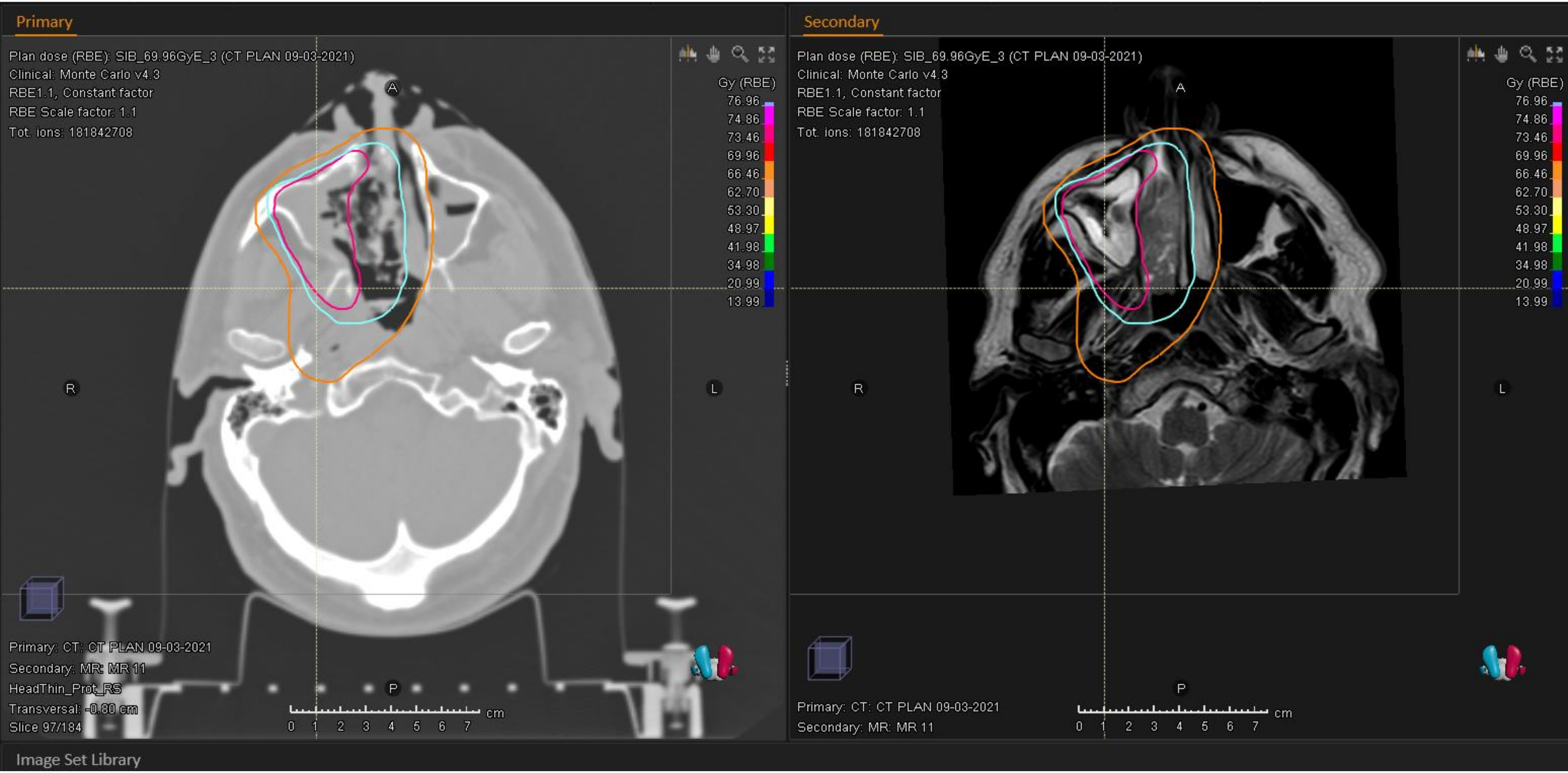
Target and OARs contouring

Pancreas

H&N



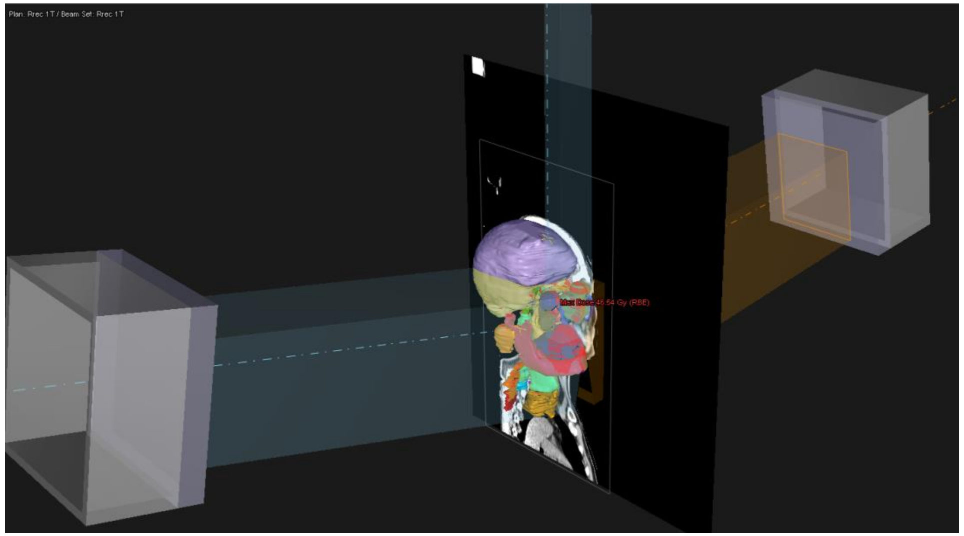
Multi – imaging (CT – MR – PET-CT)

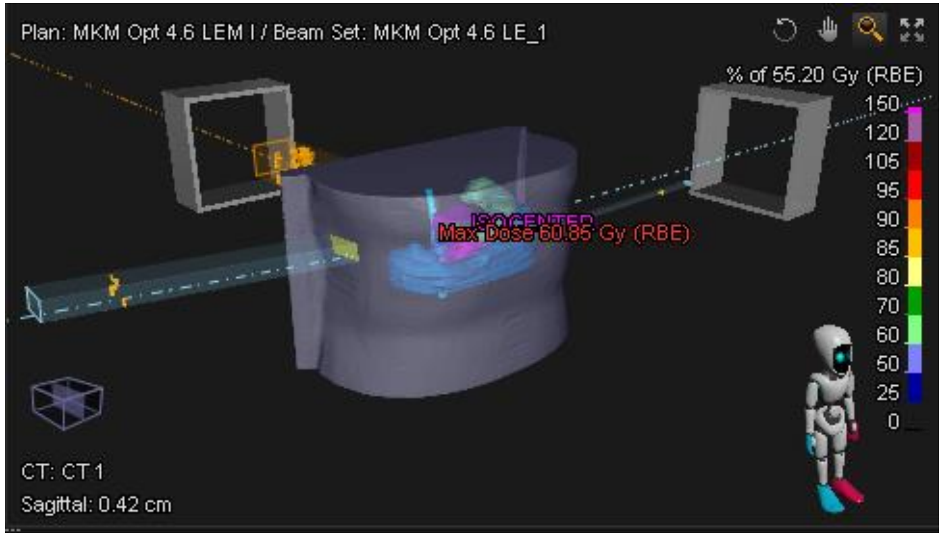


Plan geometry

3D Model of the beam ➔

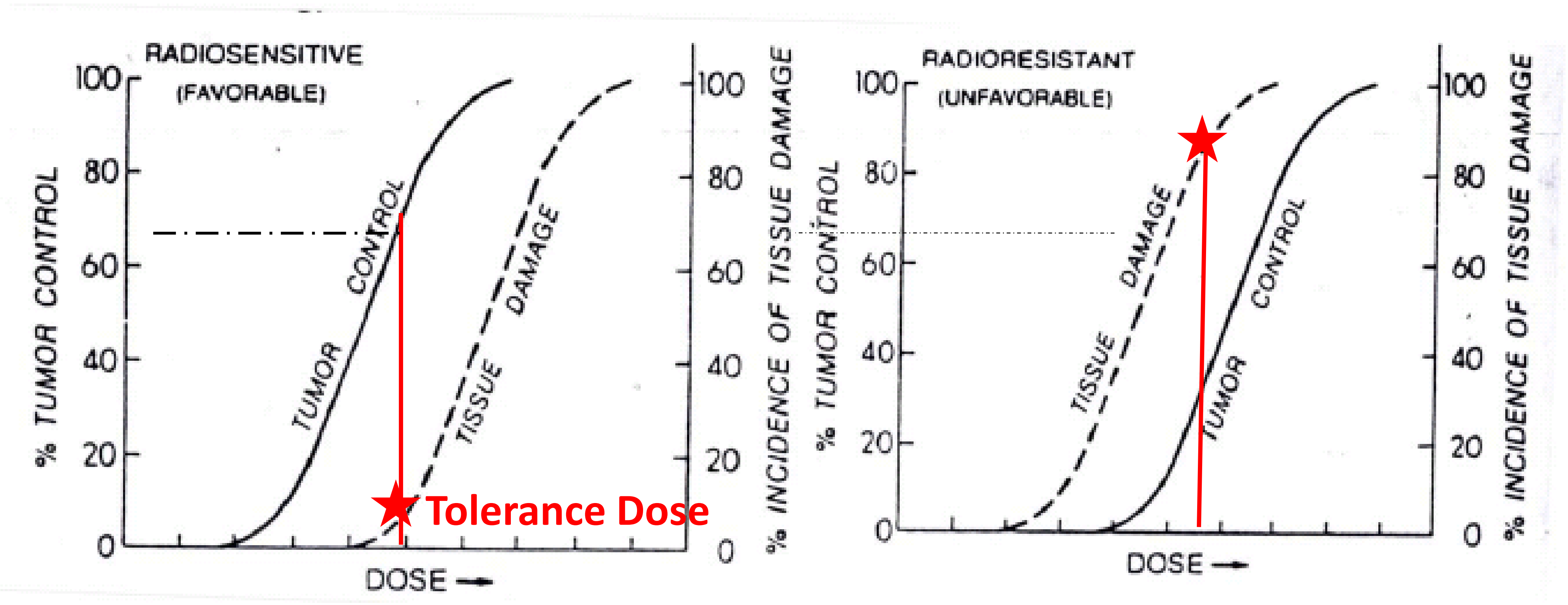
- Isocenter position
- Beams geometry
- Gantry angle
- Couch angle
- Passive systems





No.		Name	Isocenter [cm] Name	R-L	I-S	P-A	Snout Nam	Position [cr	Gap [cm]	Gantry [deg]	Couch [deg]	Range shifter	Range modulator	Spot Tune ID	Number of energy layers	10^6 NP/fx	Spot weight [10^6 NP/fx] Min	Max
1		B1	MKM O	0.72	11.49	-3.27	Dumr	65.80	54.29	180.0	0.0	(None)	RF4mmRoom3	4	47	1557.3062	0.0087	0.2200
2		B2	MKM O	0.72	11.49	-3.27	Dumr	70.30	49.09	90.0	0.0	(None)	RF4mmRoom3	4	50	1088.0736	0.0085	0.1490
3		B3	MKM O	0.72	11.49	-3.27	Dumr	70.30	46.79	90.0	185.0	(None)	RF4mmRoom3	4	52	1267.5614	0.0085	0.1408

Dose (calculation) - Optimization



→ maximize the therapeutic ratio → max tumor control with an acceptable probability of treatment complication

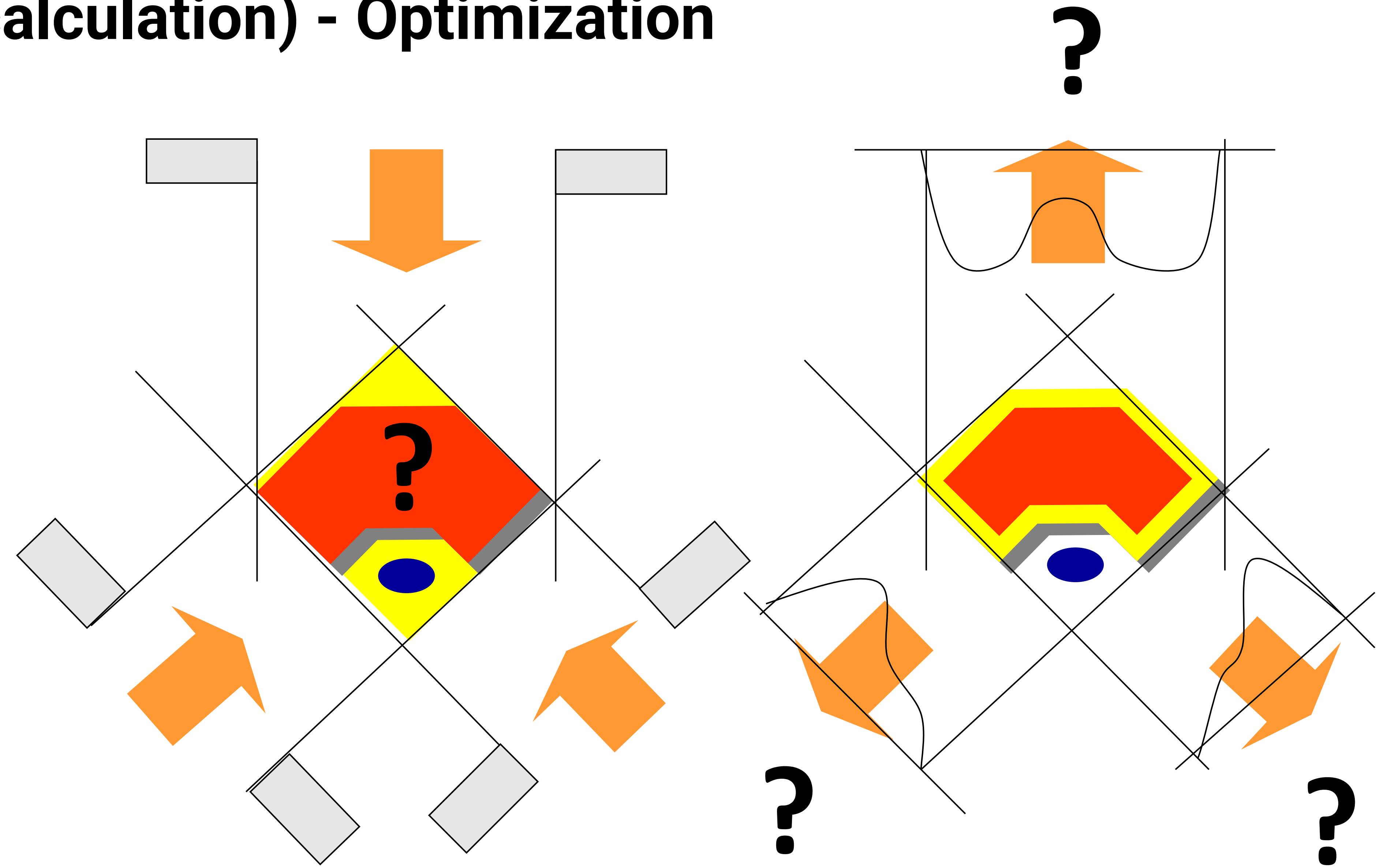
Parameters to be optimized

- Intensity maps, MLC fluence
  gantry speed – dose rate ➡ IMRT, VMAT, TomoTherapy

- Beam number and orientation ➡ SBRT

- Number of particles/spot
  Beam energy and Scan path ➡ Hadrontherapy

Dose (calculation) - Optimization



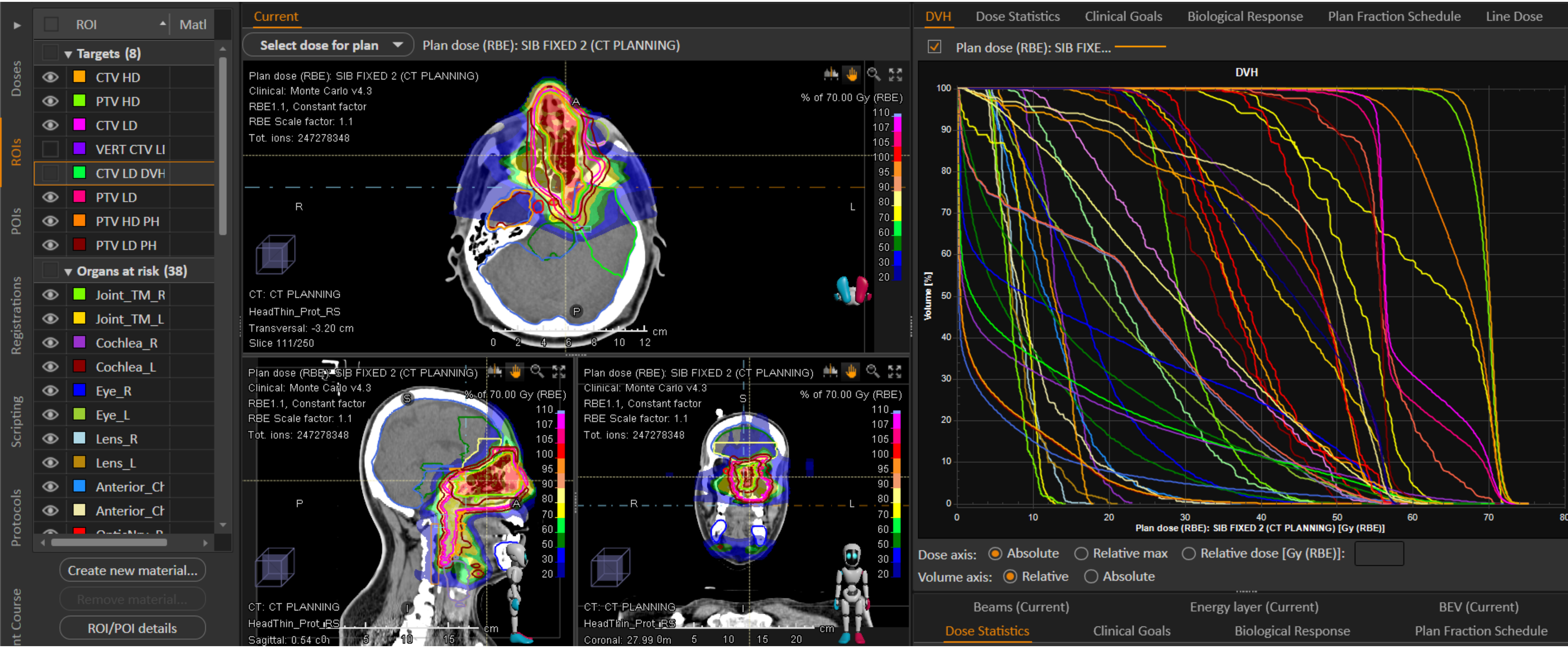
Forward planning

Inverse planning

Plan optimization - inverse planning

The process of generating an optimal plan following desired objectives. The planner specifies objectives (optimization criteria) including constraints (limits that should not be violated) and goals for both the target and normal structures. Internally, the planning system represents these objectives in a cost function (<u>mathematical expression of desirable properties and clinical goals</u>), which must be maximized or minimized by an optimization algorithm.

It could get quite complex …



Objectives/Constraints | Beams | Energy Layers | Beam Computation Settings | Beam Weighting | Beam Dose Specification Points

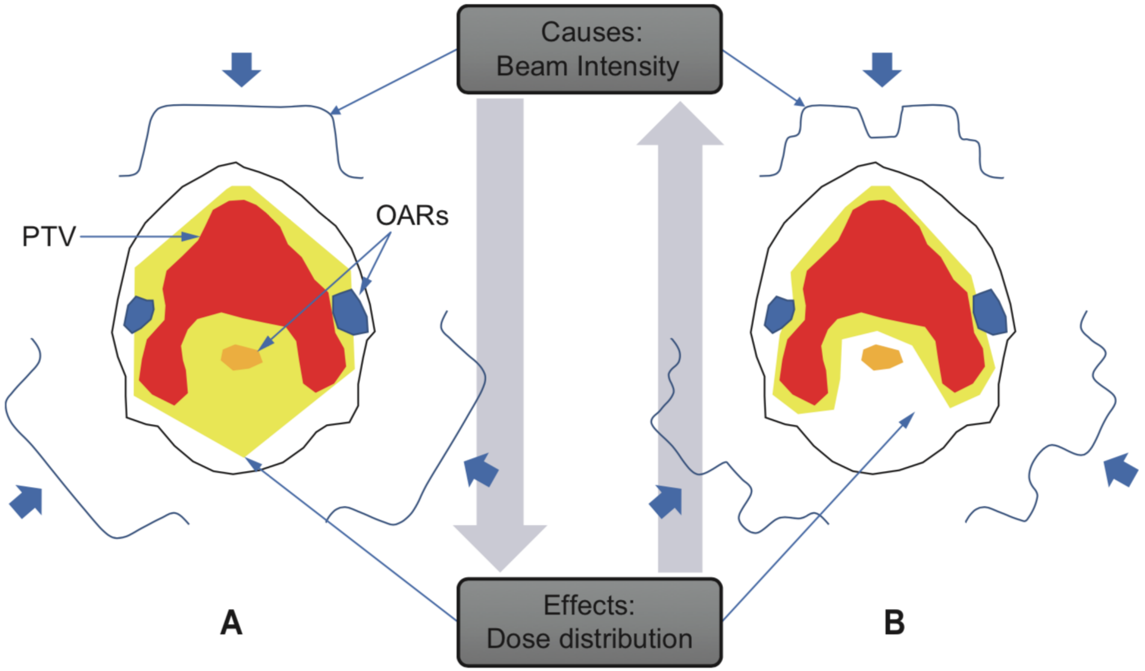
Add physical... | Add biological... | Edit... | Delete | Load template... | Create template... | Add MCO function

Function	Constraint	Dose	ROI	Description
Max Dose		Plan (RBE)	Anterior_Chmb_L	Max Dose 65.00 Gy (RBE)
Max EUD		Plan (RBE)	Retina_L	Max EUD 30.00 Gy (RBE), Parameter A 1
Max Dose		Plan (RBE)	SpinalCord	Max Dose 15.00 Gy (RBE)
Max DVH		Plan (RBE)	OpticNrv_R	Max DVH 48.00 Gy (RBE) to 10.5% volume
Max DVH		Plan (RBE)	OpticChiasm	Max DVH 50.00 Gy (RBE) to 10% volume
Max Dose		Plan (RBE)	CTV HD	Max Dose 73.00 Gy (RBE)
Uniform Dose		Plan (RBE)	CTV LD DVH	Uniform Dose 56.00 Gy (RBE)
Max Dose		Plan (RBE)	Ring	Max Dose 66.50 Gy (RBE)
Dose Fall-Off		Plan (RBE)	CTV LD DVH	Dose Fall-Off [H]71.50 Gy (RBE) [L]56.00 Gy (RBE), Low dose distan
Max DVH		Plan (RBE)	Avoid	Max DVH 13.00 Gy (RBE) to 1% volume
Uniform Dose		Beam Set (RBE)	VERT CTV LD	Uniform Dose 56.00 Gy (RBE), Beam 'B3'
Max DVH		Plan (RBE)	Lobe_Temp_R_subCTVLD	Max DVH 65.00 Gy (RBE) to 1% volume
Max DVH		Plan (RBE)	Lobe_Temp_L_subCTVLD	Max DVH 65.00 Gy (RBE) to 1% volume
Max DVH		Plan (RBE)	Lobe_Frontal_subCTVLD	Max DVH 65.00 Gy (RBE) to 1% volume
Uniform Dose		Plan (RBE)	PTV HD	Uniform Dose 70.00 Gy (RBE)
Min DVH		Plan (RBE)	CTV HD	Min DVH 69.00 Gy (RBE) to 92.5% volume
Max Dose		Plan (RBE)	OpticChiasm	Max Dose 60.00 Gy (RBE)
Min DVH		Plan (RBE)	CTV HD	Min DVH 70.00 Gy (RBE) to 70% volume
Max DVH		Plan (RBE)	Glnd_Lacrimal_R	Max DVH 18.00 Gy (RBE) to 5% volume
Max EUD		Plan (RBE)	Pharynx	Max EUD 45.00 Gy (RBE), Parameter A 1
Max EUD		Plan (RBE)	Larynx	Max EUD 40.00 Gy (RBE), Parameter A 1
Max DVH		Plan (RBE)	Larynx	Max DVH 40.00 Gy (RBE) to 15% volume

DV-based

IMRT

- *IMRT or* Intensity-Modulated Radiation Therapy is a technique that allows confinement of the high dose region to that of the target volume.



Cho et al. Radiat Oncol J 36, 2018

Multileaf collimator (MLC)

IMRT delivery methods: MLC-based

A multileaf collimator (MLC) is a device made up of typical 80 to 120 individual "leaves" of a high atomic numbered material, usually Tungsten, that can move independently in and out of the path of a radiation beam in order to block it.

- Leaf height (thickness): 6-11 cm
- Material: mostly a Tungsten alloy (hard, reasibly inexpensive, easy to machine, low coefficient of thermal expansion)
- Density: (Tungsten) 17-18.5 g/cm^3
- Primary X-ray transmission:
  - <2% through leaves
  - <3% interleaf transmission
- Different designs: single and double focus, single and double layer
- Position accuracy < 0.5 mm

IMRT – Dose conformation

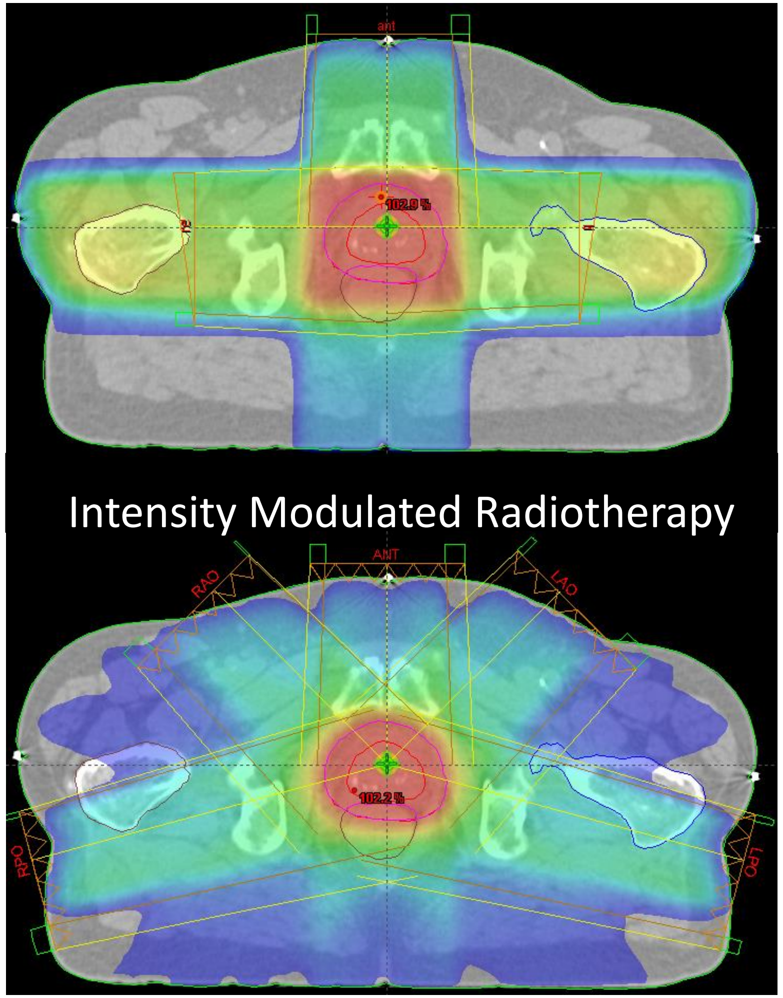
- "Conformity index" is a measure of how well the dose is confined to the target volume:

$$CI=\mathbf{V}_{target}/\mathbf{V}_{treated}$$

- Conventional RT gives a low CI whereas the CI of IMRT approached unity.

→Increased conformity keeps high dose levels away from OAR

Conventional Radiotherapy

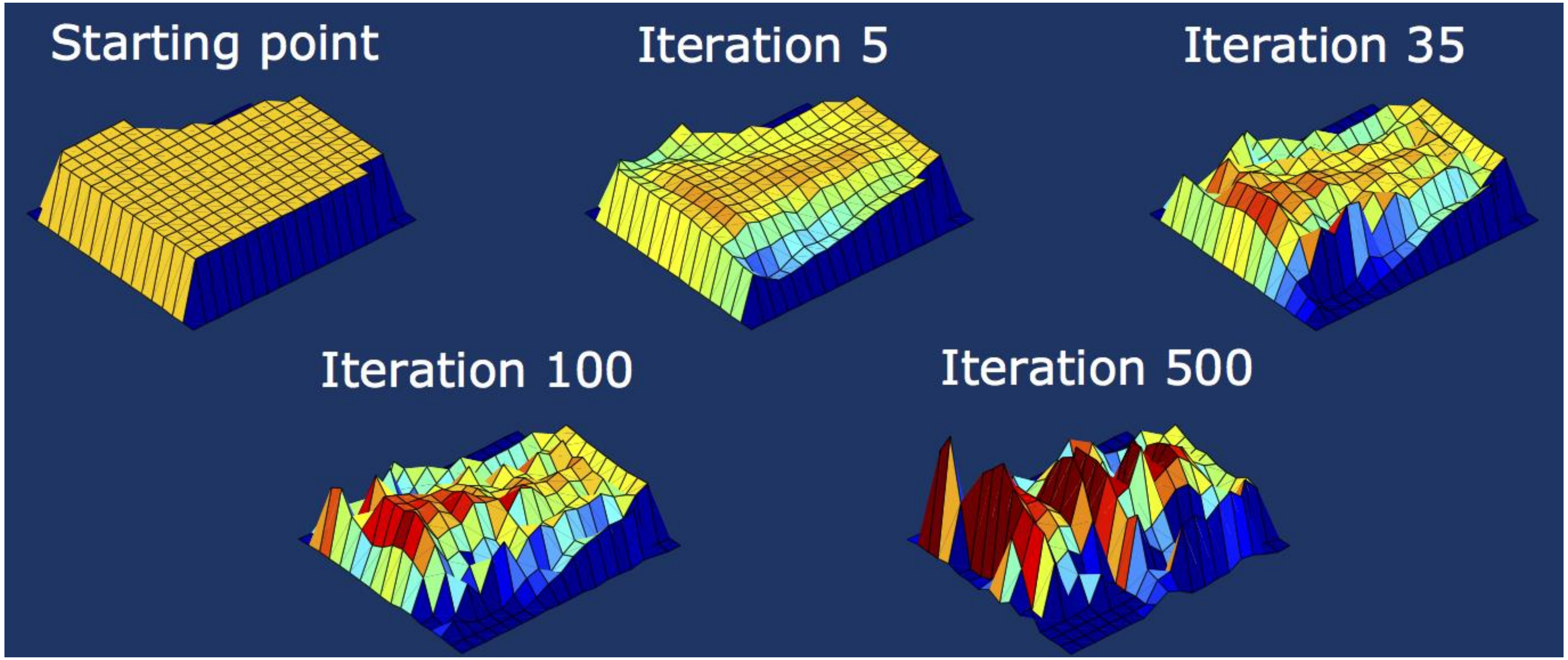


Knoos T, Kristensen I, Nilsson P: **Volumetric and dosimetric evaluation of radiation treatment plans: radiation conformity index.**
Int J Radiat Oncol Biol Phys 1998, 42(5):1169-1176

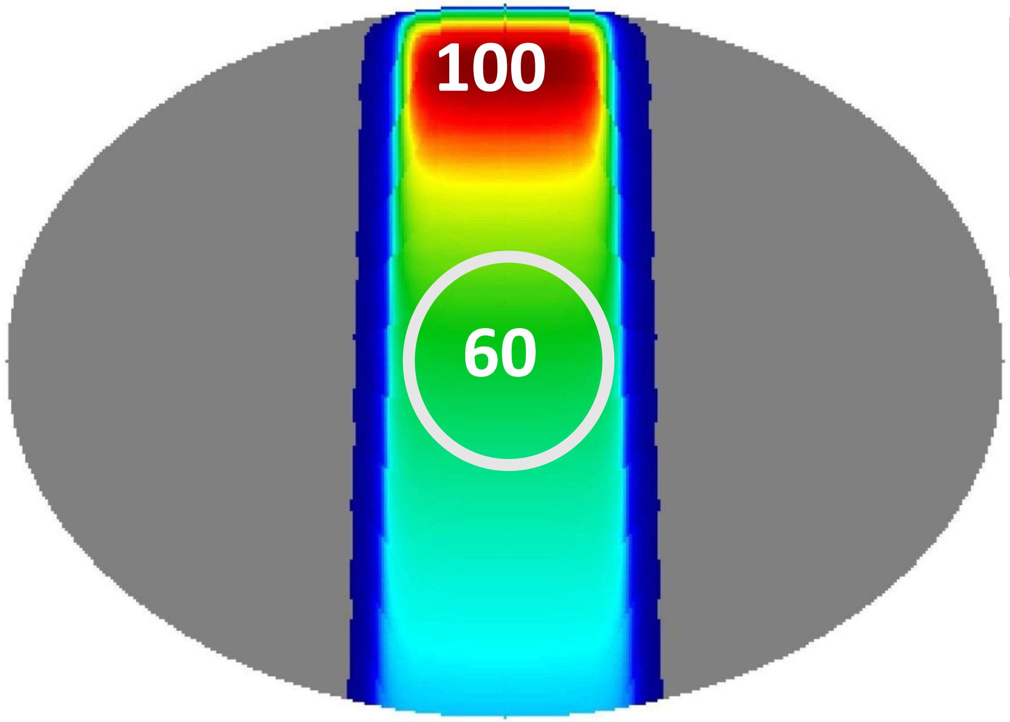
IMRT optimization

Independent variables:
Beamlet intensities, segment weights

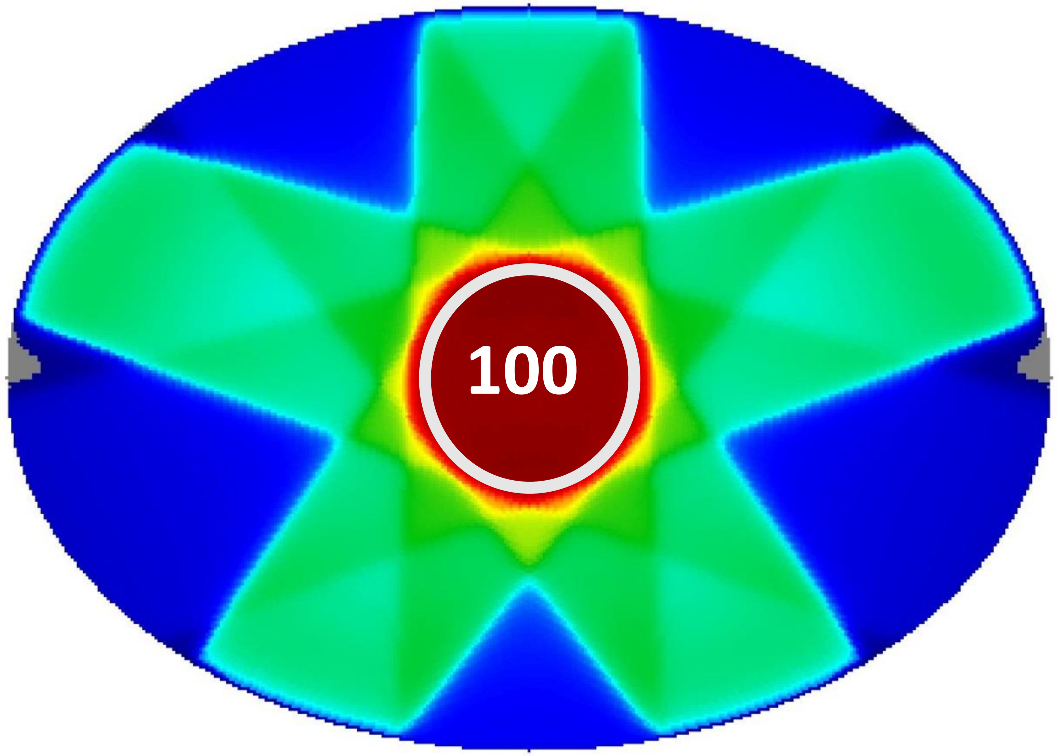
Intensity maps gradually evolve to a solution …



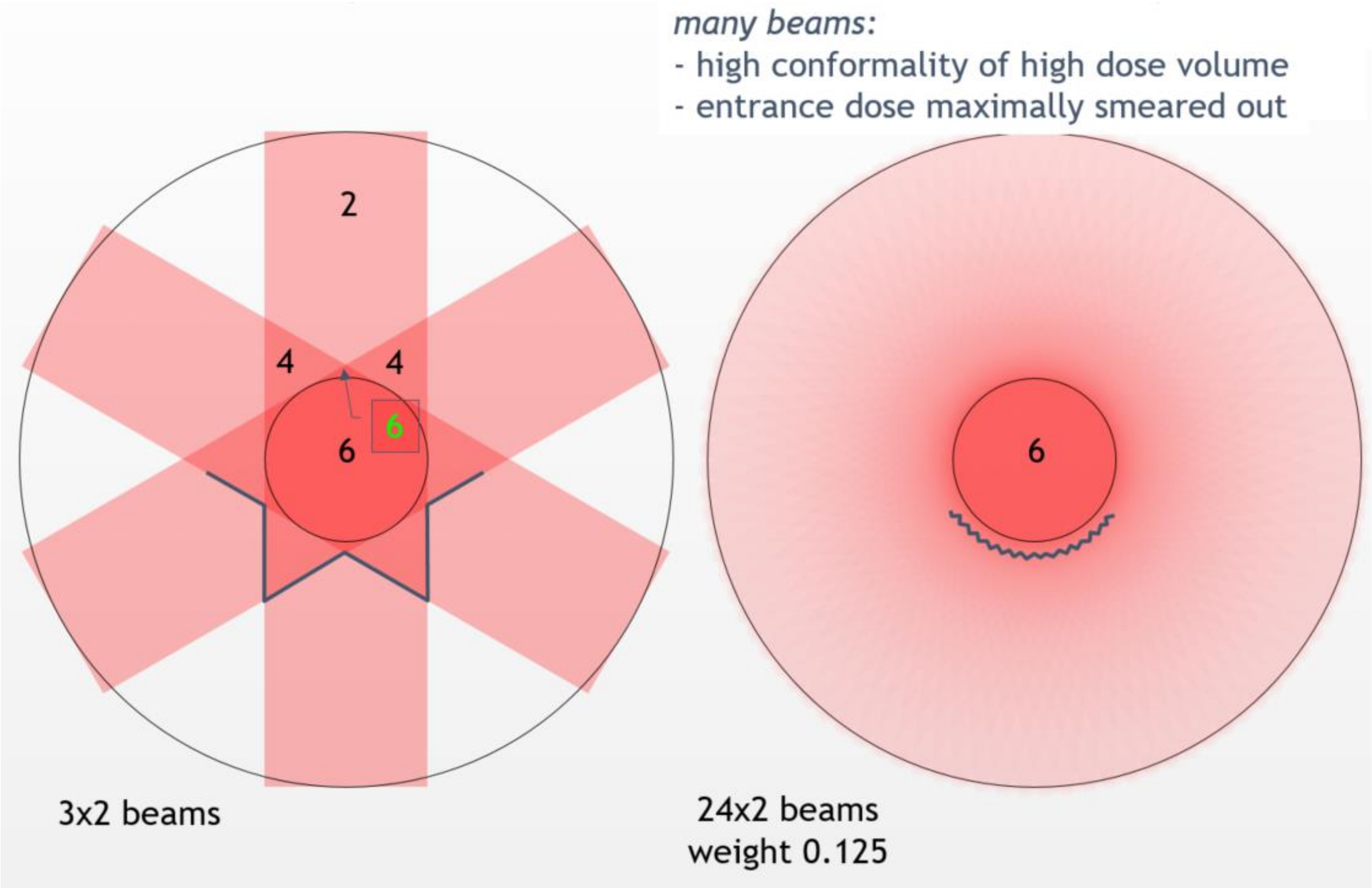
Reason 1) many beams to spread out entrance dose



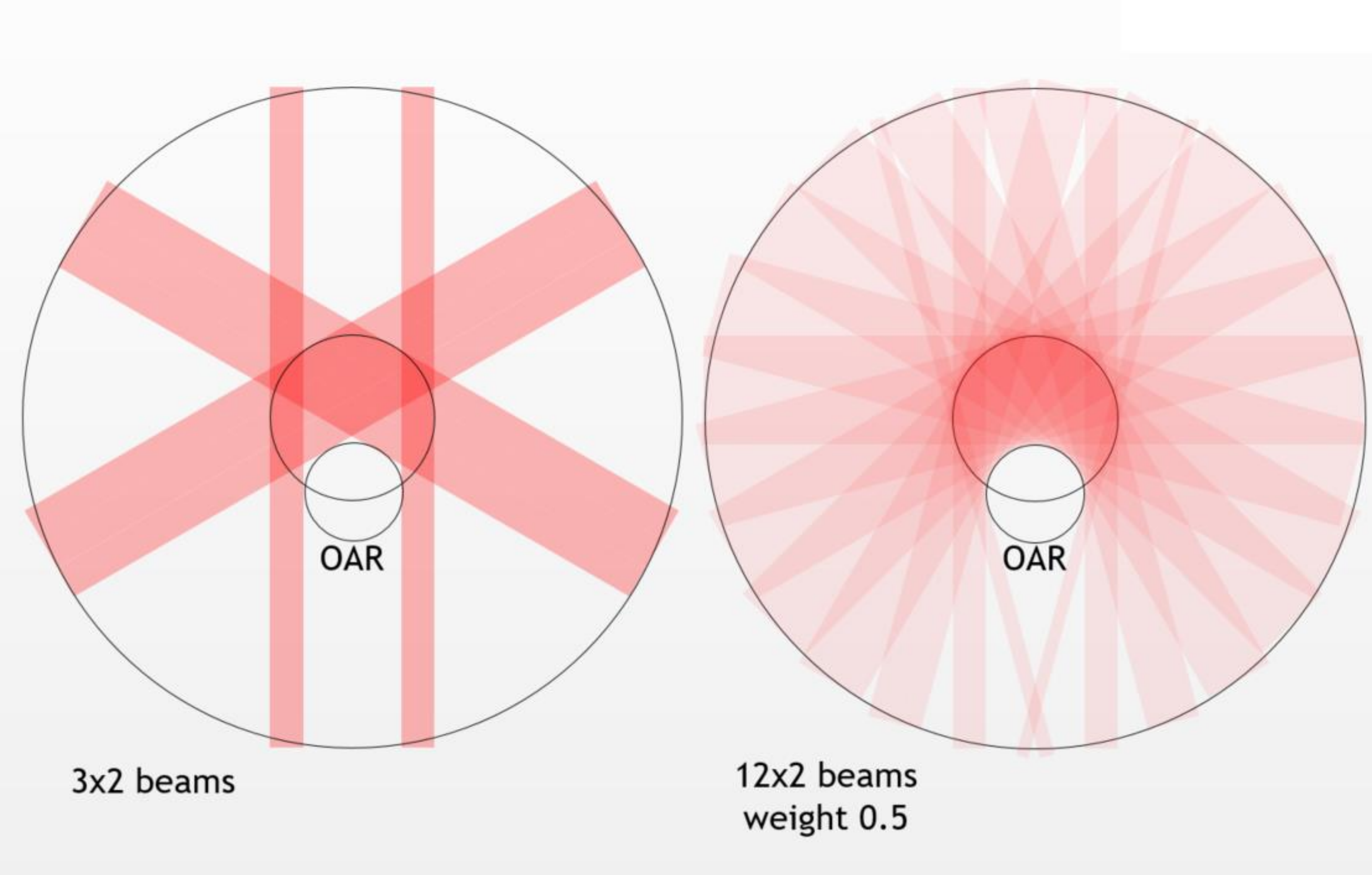
Problem in external beam RT: single beam → low dose in deep seated tumors



Reason 2) many beams to increase dose conformality



Reason 3) many beams to increase dose homogeneity



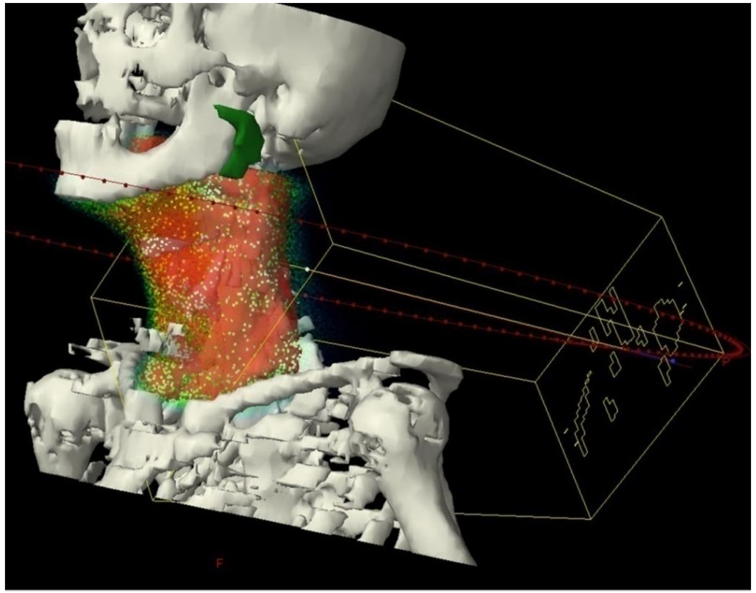
Volumetric Modulated Arc Therapy

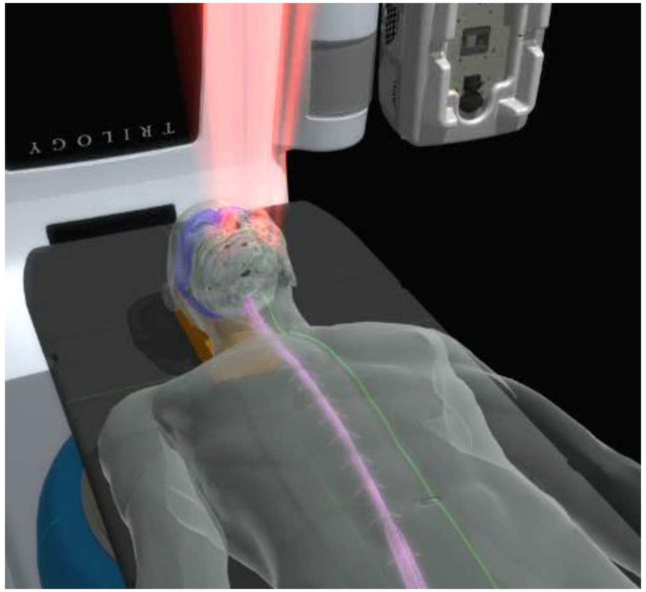
- Techniques that delivers IMRT through rotational delivery using regular linacs (and MLC), with optimized field shapes for all angles, each irradiating part of the tumor (not conformal)

- **Volumetric** irradiation → cone beam - long fields

- While rotating, continuous dynamic variation of:

field size/shape (MLC) - dose rate - gantry speed





Helical Thomotherapy - Hi-Art Tomotherapy Inc (Accuray)

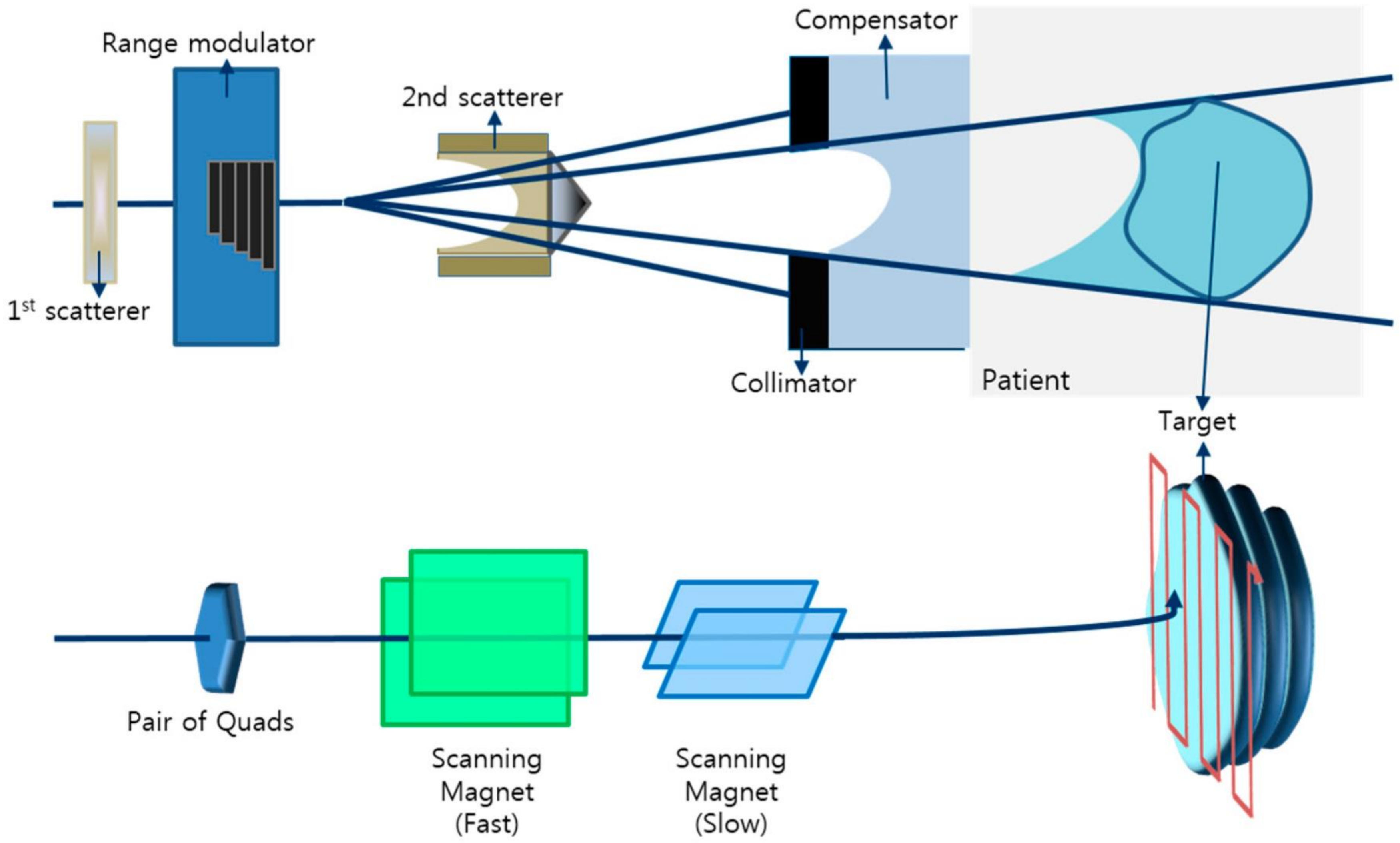
T.R. Mackie, T.W. Holmes, S. Swerdloff, P. Reckwerdt, J.O. Deasy, J. Yang, B. Paliwal, T. Kinsella.
Tomotherapy: A New Concept for the Delivery of Conformal Radiotherapy
Med. Phys. 20, 1709-1719 (1993).

- Literally tomotherapy means 'slice therapy': use of fan beam
- Helical: effectively there is a spiral delivery
- The dose is delivered by translating the patient in a continuously rotating fan beam which is modulated by a binary MLC for a maximum of 51 different configurations during every rotation.

DOSE DELIVERY

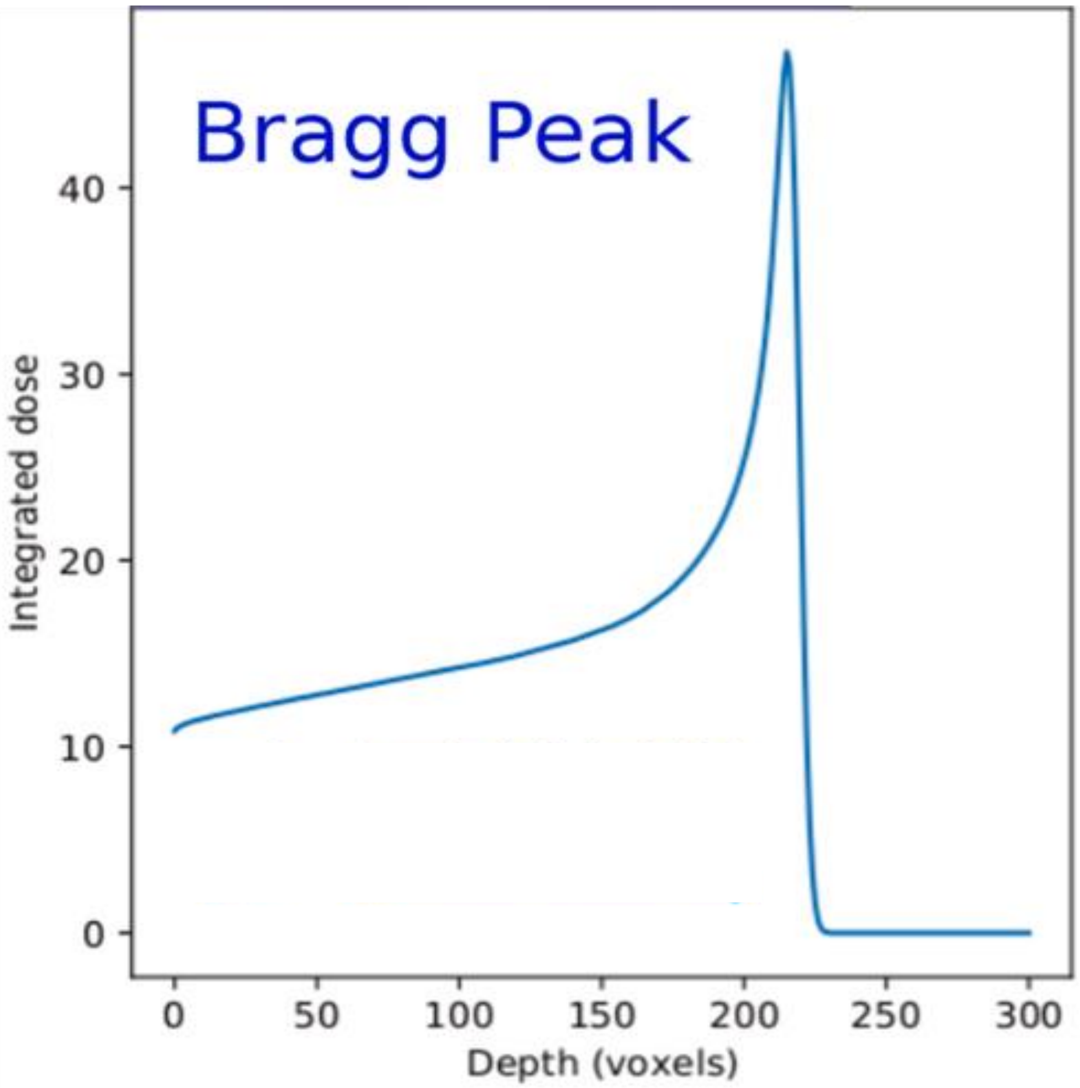
Passive scattering

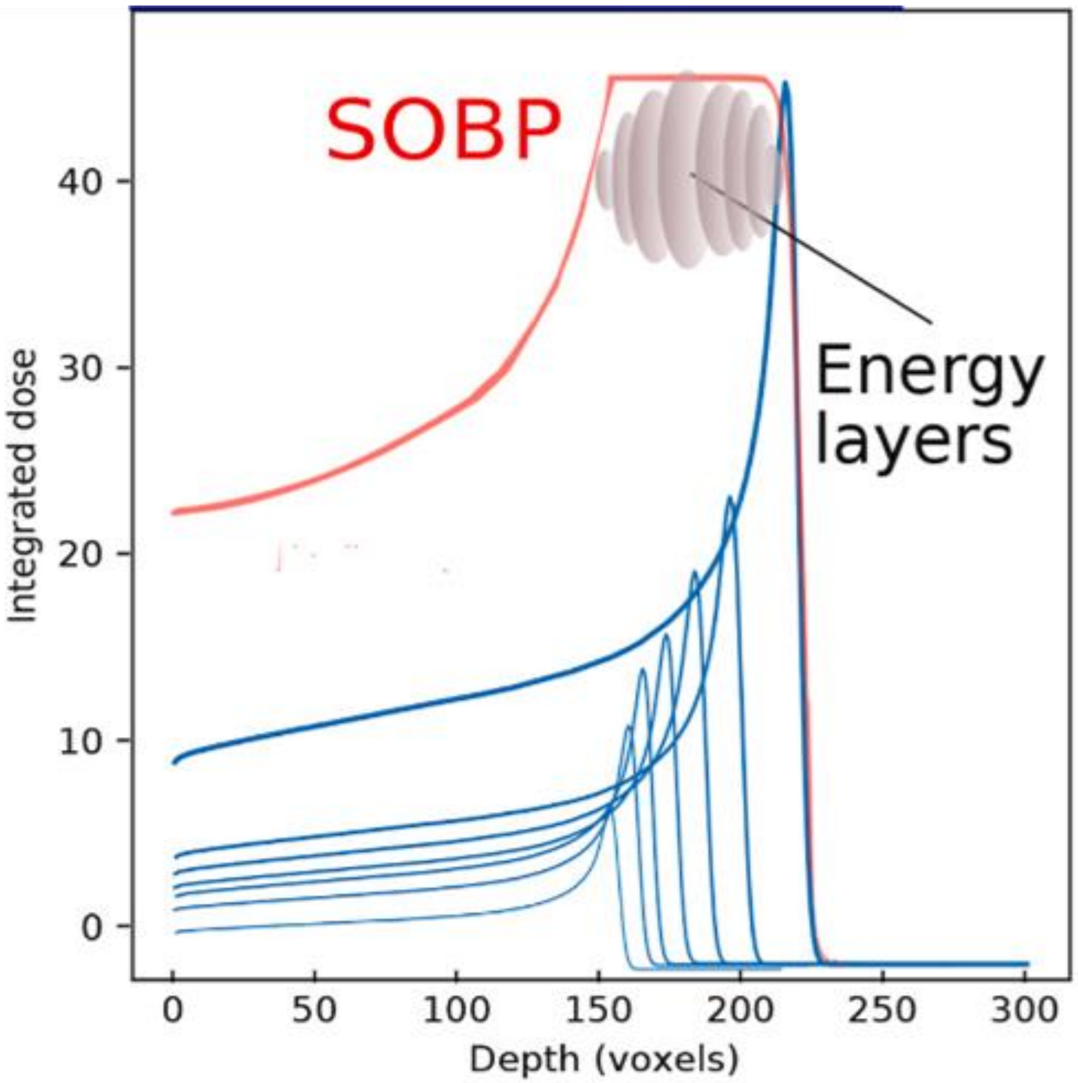
Pencil beam scanning



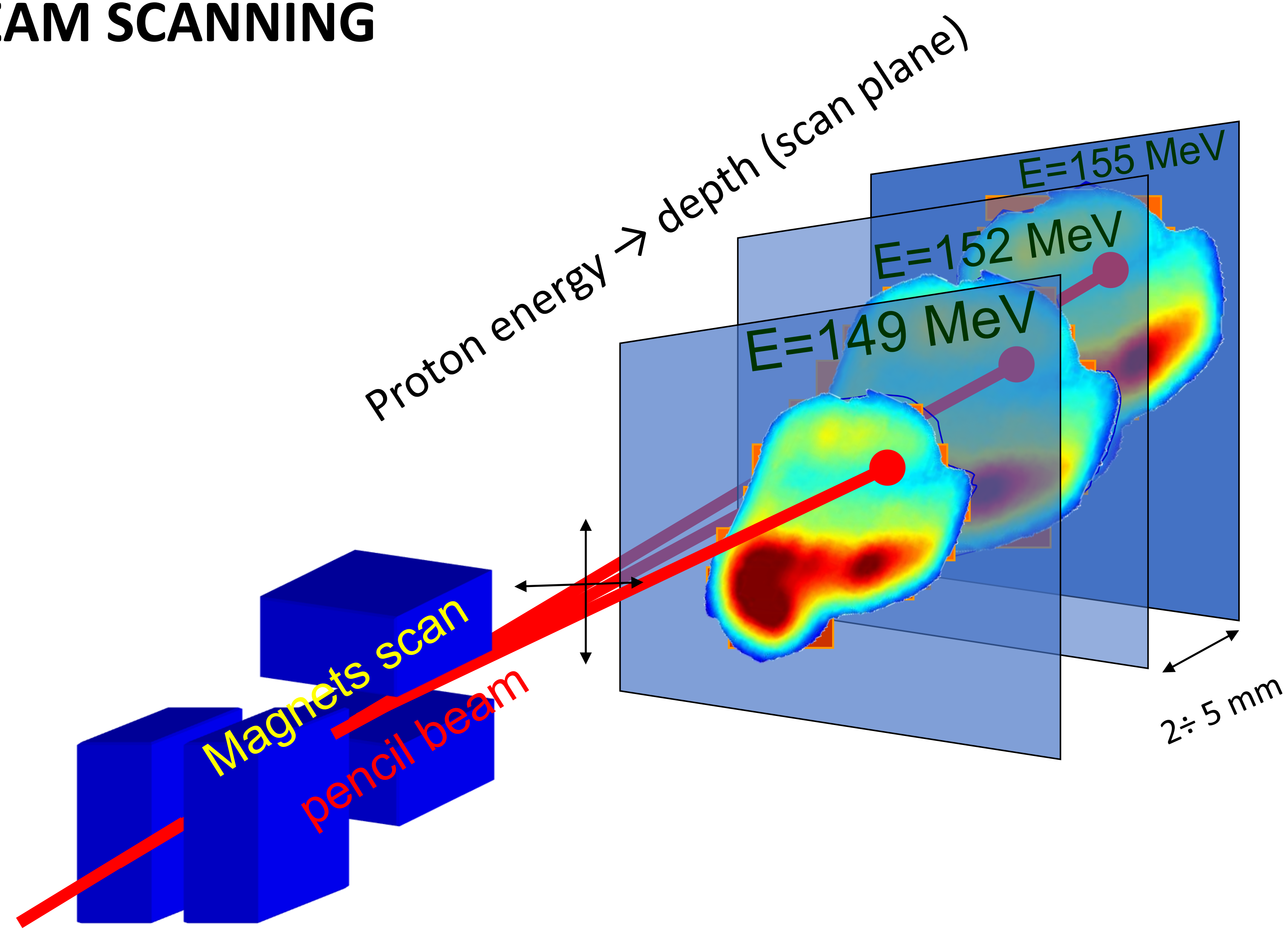
we need to spread the dose laterally and along the beam direction to cover a 3D target volume

SPREAD OUT BRAGG PEAK





PENCIL BEAM SCANNING



→ The target volume is irradiated sequentially

PBS - Optimization

SFUD (Single field uniform dose optimization)

IMPT (Intensity-modulated particle therapy)

+ Flexibility of arbitrarily setting non uniform intensities of pencil beams of a sequence of energies of multiple beams incident from different directions

- Intensities of spots (and dose distribution) per beam can be highly inhomogeneous -> Higher **sensitivity** to range, set-up and treatment delivery uncertainties

Physics problem in RT

Improved dose focusing

3DCRT → IMRT
Passive → PBS
SFUD → IMPT

More sensitive to **errors**

Higher precision in target localization (in space and time)	Uncertainties management Robustness analysis	Advanced QA

Matching between imaging, planning and delivery is a key factor

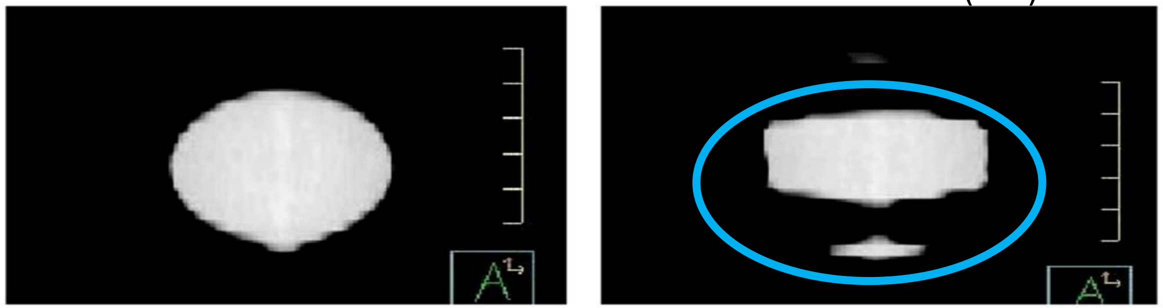
Motion effect on Imaging - CT Artefacts (Lung)

Image blurring
contours overlapping and organ smearing

Figure 3. Examples of breathing induced image artifacts in coronal 3DCT images: overlapping contours and smearing of the right diaphragmatic dome (left). Overlapping structures and smearing of the caudal part of the tumor in the right lung (middle). Duplicate structures are seen in the tumor in the right lung (right). (Reprinted with permission from Persson (2011).)

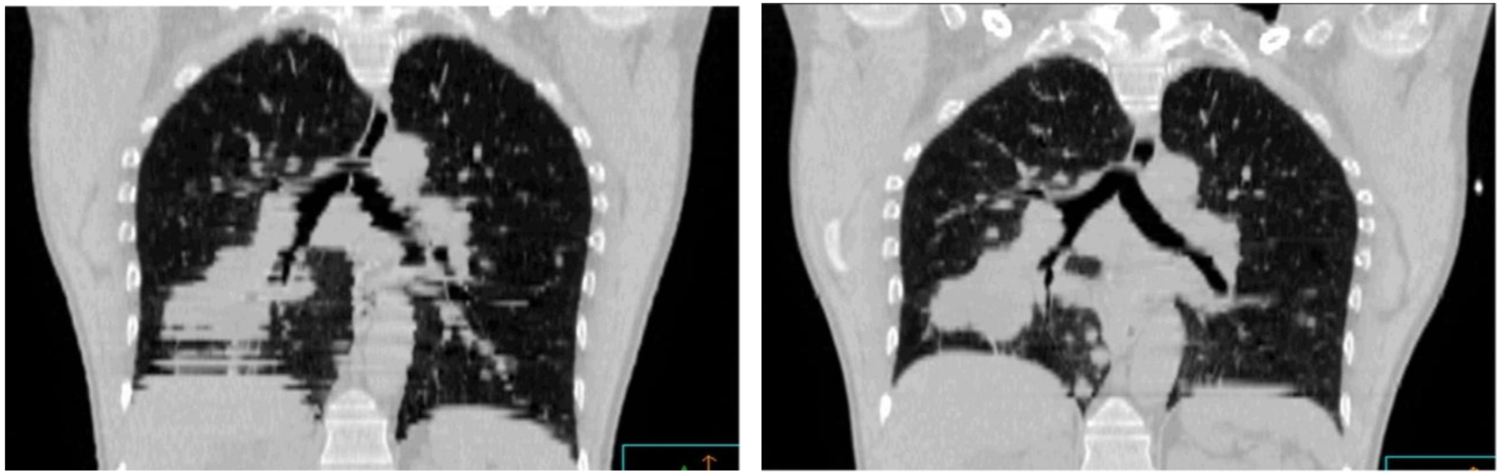
Korreman S PMB (57) 2012

Partial projection effect
→ interference between moving structure and patient movement in the scanner
→ adjacent slices in the scan show non-adjacent parts of the moving structure



- 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).
- Vedam et al. PMB (48) 2003

Motion effect on Imaging – 4DCT



Coronal views of CT scans of the same patient taken during free breathing (FB) (a)
and with respiratory-gated scanning at exhale (b)
Keall et al. Australas Phys Eng Sci Med 25 (1), 2002.

CT acquisition synchronized with respiration

→ Very high quality

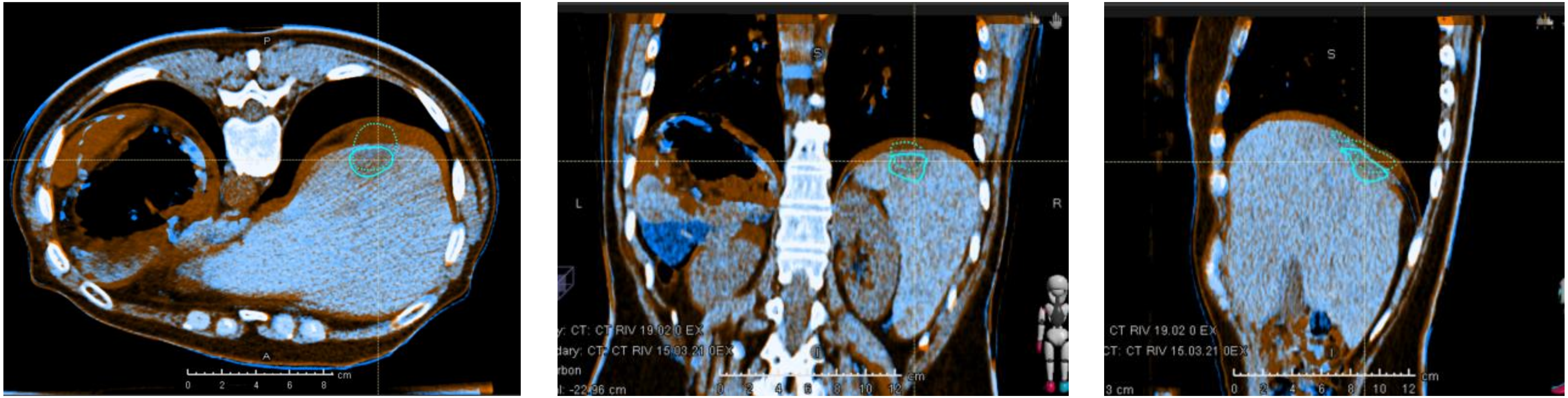
→ Still non zero, but few artefacts

NB: it's a movie snapshot of the motion during few cycles

→ **Irregularities in breathing cycles cannot be seen**

GATING – 4D INTER-FRACTION

… And then you need to check it again (on-line or at least every week)



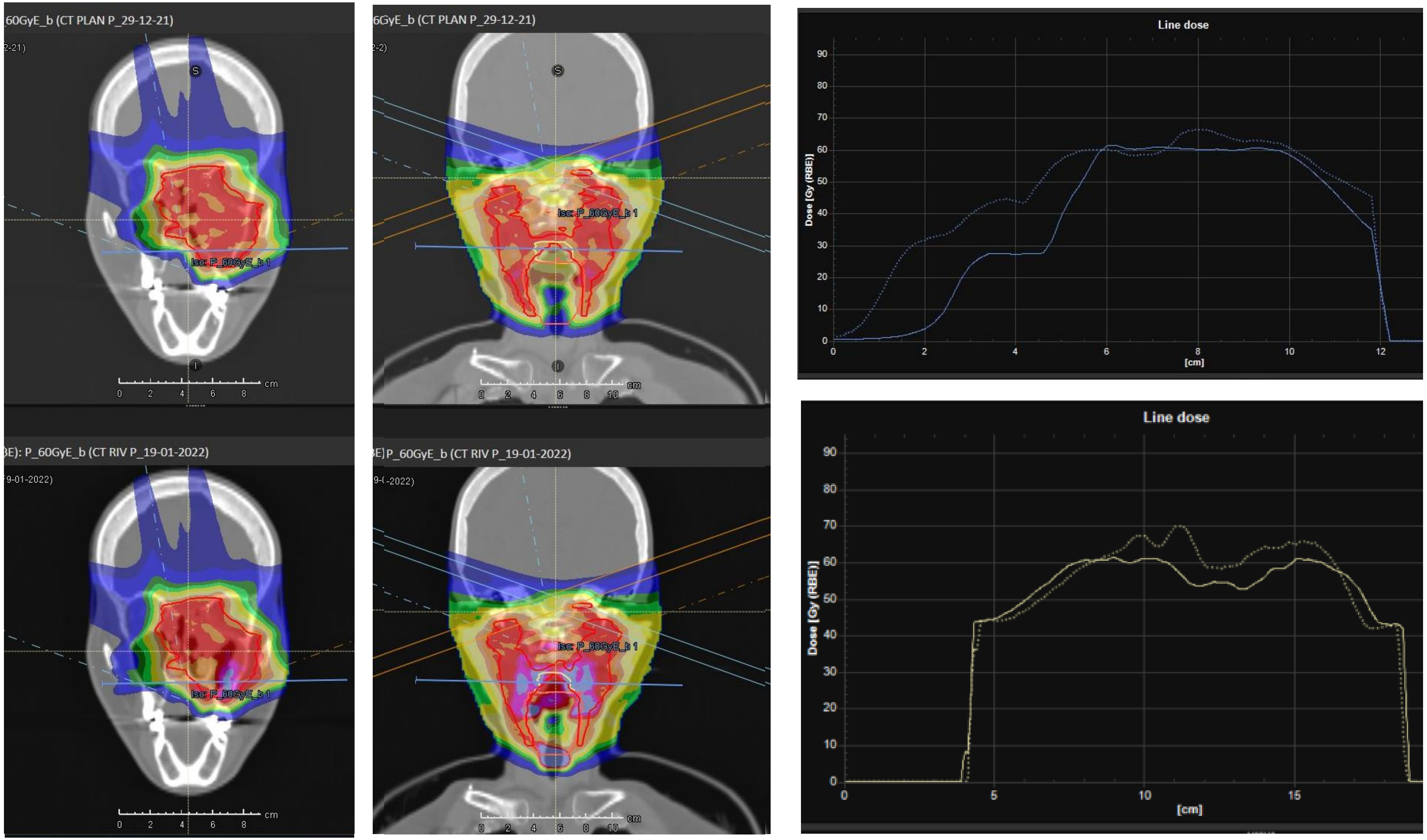
15 March → 19 March

PARTICLE RANGE VARIATION

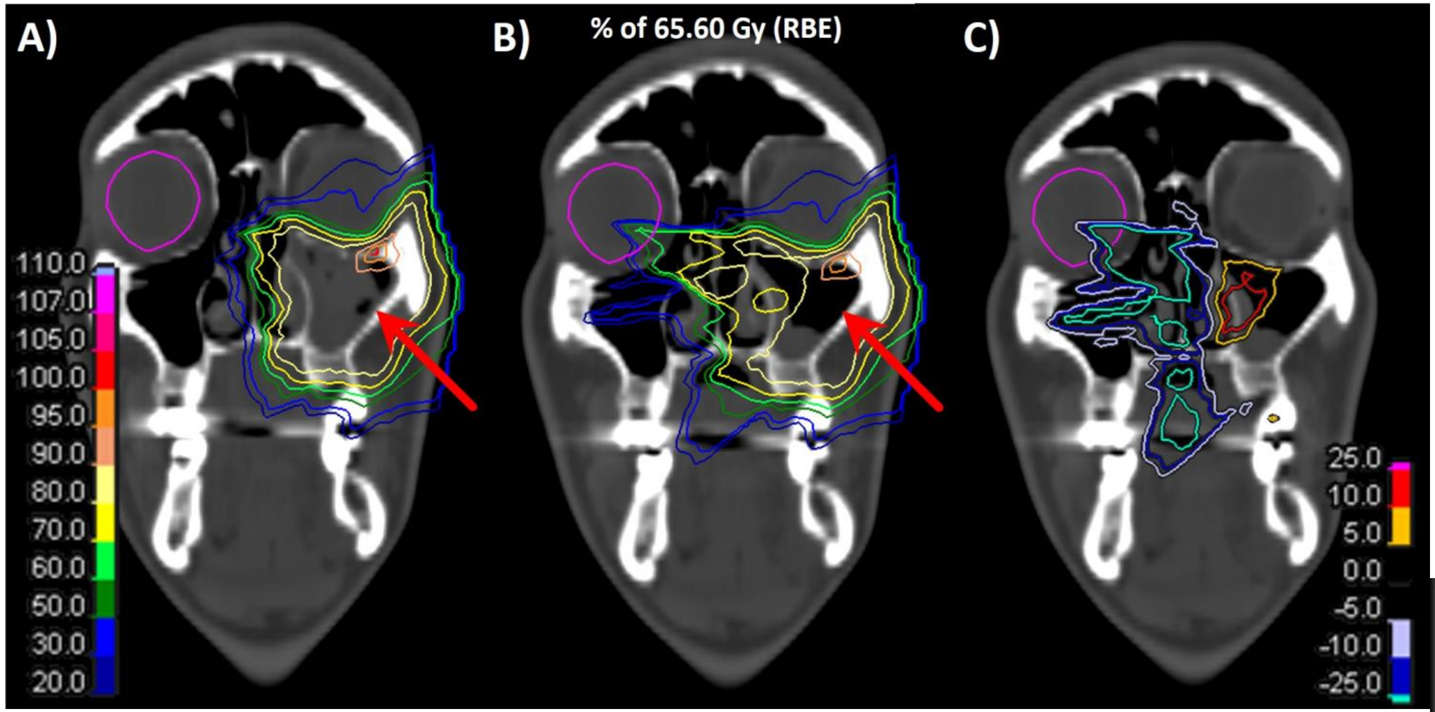
→ Particle dose is not only shifted, but distorted and deformed inside and ouside the target volume

Planned

Re-evaluation

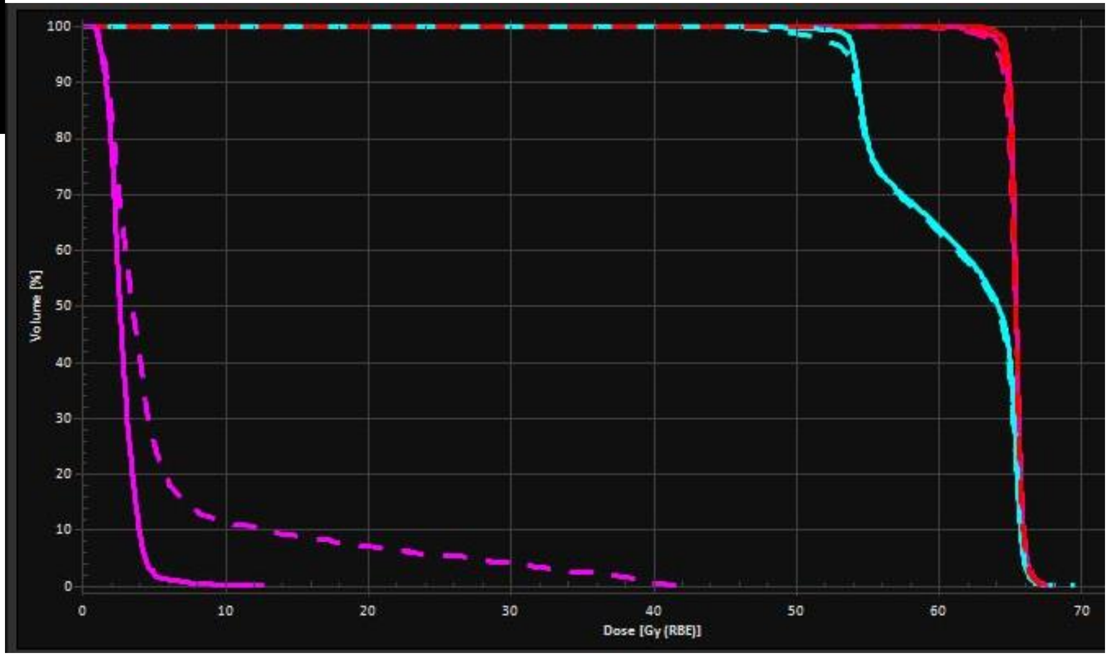


PARTICLE RANGE VARIATION



Mucosal filling of the sinuses

OAR – DISTAL POSITION



Molinelli S et al HEAL 2024

Interplay - Dynamic techniques

Problem: planning for IMRT, dynamic arc treatment or pencil beam scanning particle therapy on a moving target.

→ the motion of the target may **interfere constructively or destructively** with the motion of the MLC leaves, the beam opening, the gantry rotation, the beam scan path and/or other dynamic parameters during treatment delivery.

→ **Interferences are not modeled** in the treatment planning system!

Interplay - Dynamic IMRT

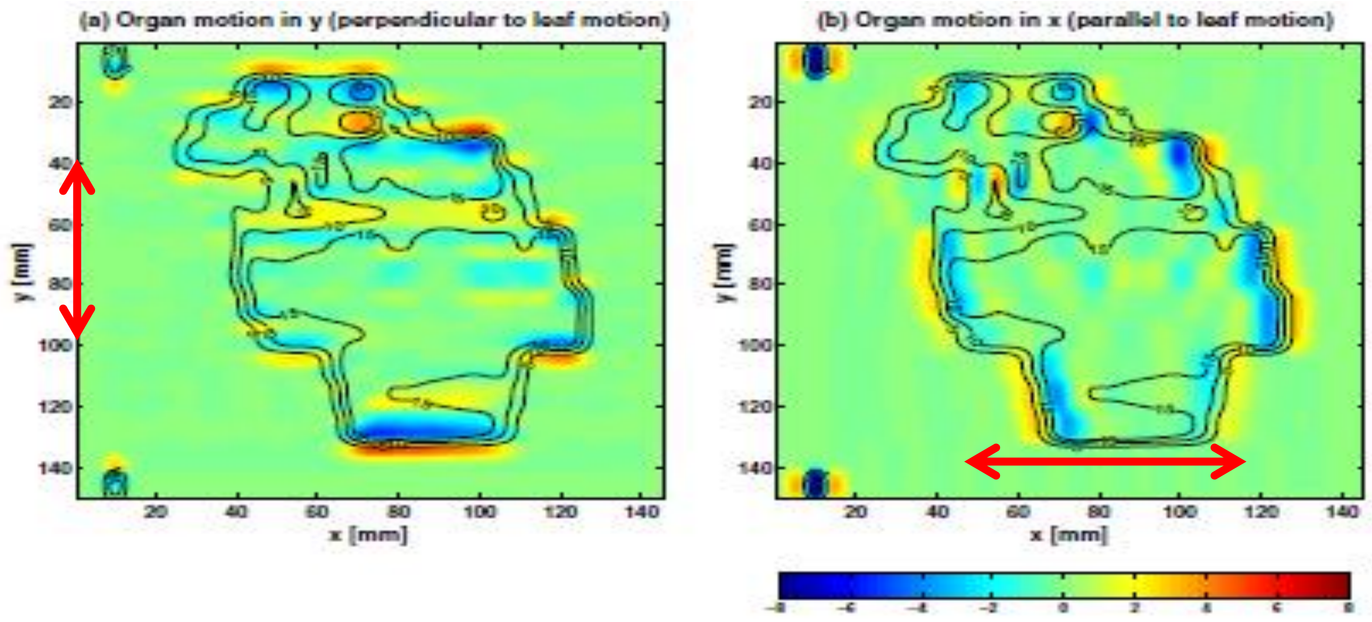
→ If motion mitigation is not applied during IMRT to a moving target

CTV under/over-dosage

- Fractionation 1fx → 20% dose variation
  30fx → <2% dose variation

Bortfeld PMB (47) 2002 - Jiang PMB (48) 2003 - …

- Multiple fields → statistical averaging over the beam reduces the overall dose error



Bortfeld PMB (47) 2002

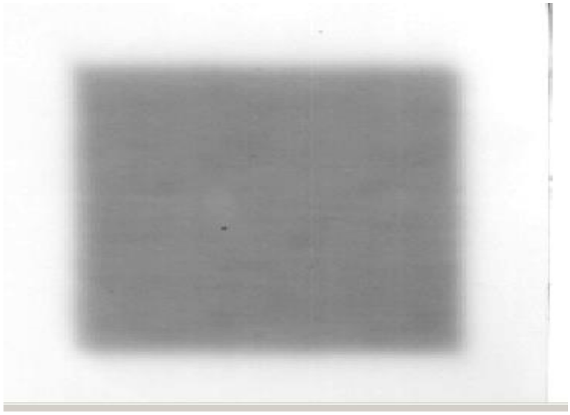
- Avoid low MU segments (few s delivery) Seco et al. Med Phys(34) 2007

→ Delivery time comparable to breathing period

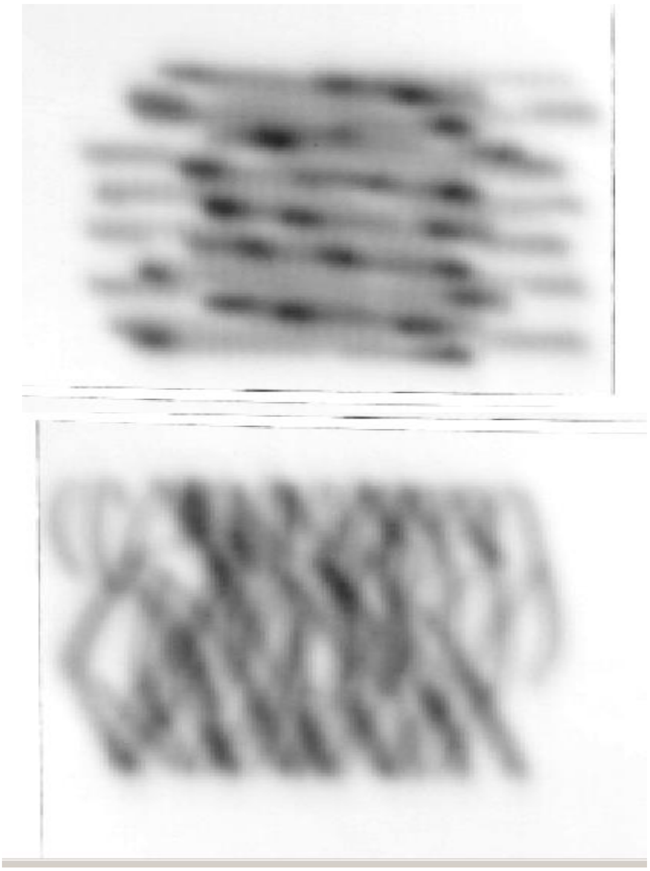
→ Segment size comparable to breathing amplitude

Interplay – Particle therapy - PBS

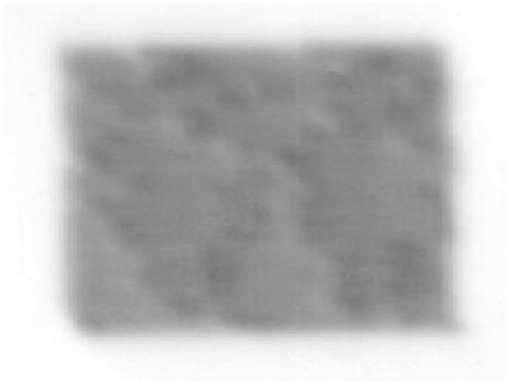
Static field



Motion - scan direction

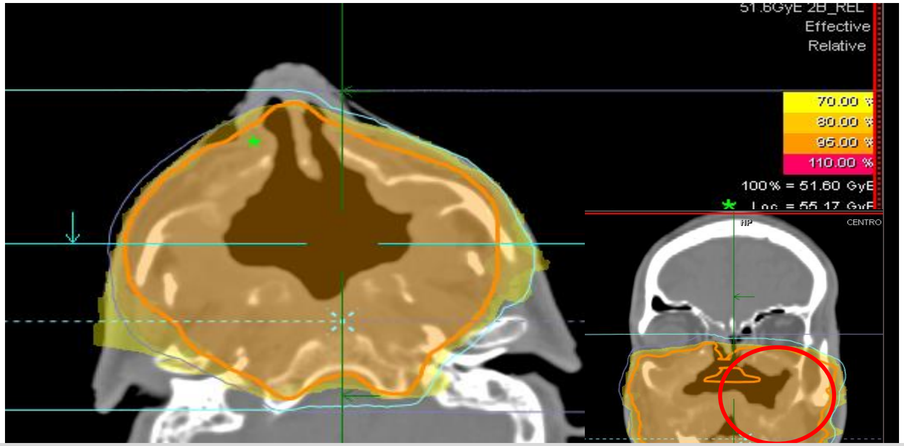


Gated field

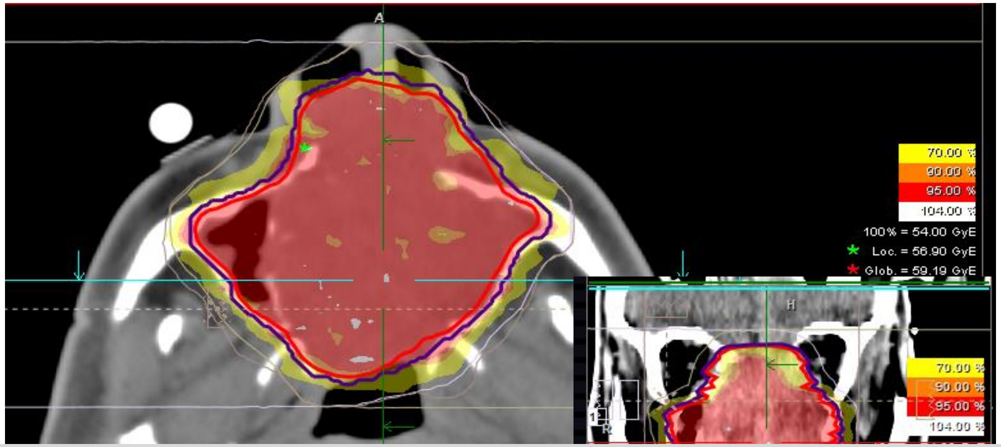


Inter-fraction – Tumor volume variation

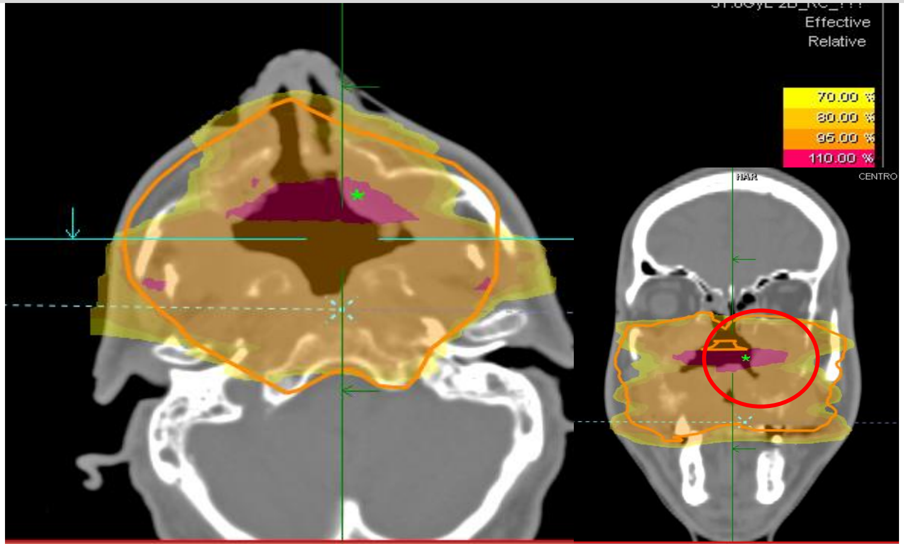
Tumor growth

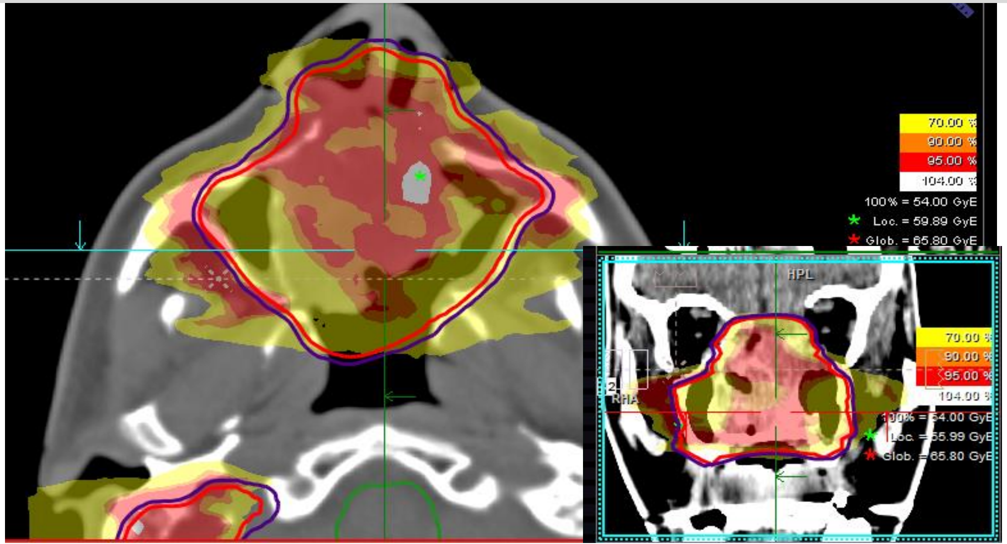


Tumor shrinkage



You need to replan!





Adaptive radiation planning

Abstract. Adaptive radiation therapy is a closed-loop radiation treatment process where the treatment plan can be modified using a systematic feedback of measurements. Adaptive radiation therapy intends to improve radiation treatment by systematically monitoring treatment variations and incorporating them to re-optimize the treatment plan early on during the course of treatment. In this process, field margin and treatment dose can be routinely customized to each individual patient to achieve a safe dose escalation.

Yan D, Vicini F, Wong J, Martinez A: Adaptive radiation therapy. Phys Med Biol 1997, 42(1):123-132.

OFF-LINE PLAN ADAPTATION

CNAO - 221 patients (6 months – no eye)

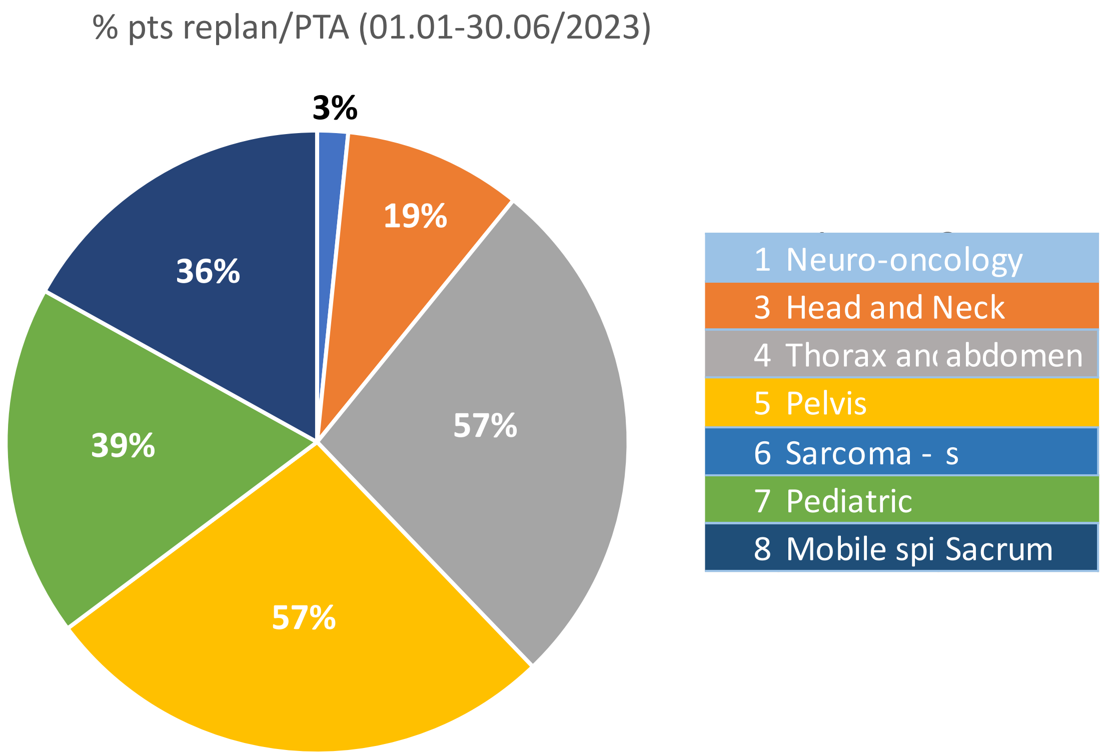
→ 154 (70%) RE-CT (at 22 days on average)

→ 57 1 RP

→ 25 >1 RP

37% (p≈C)

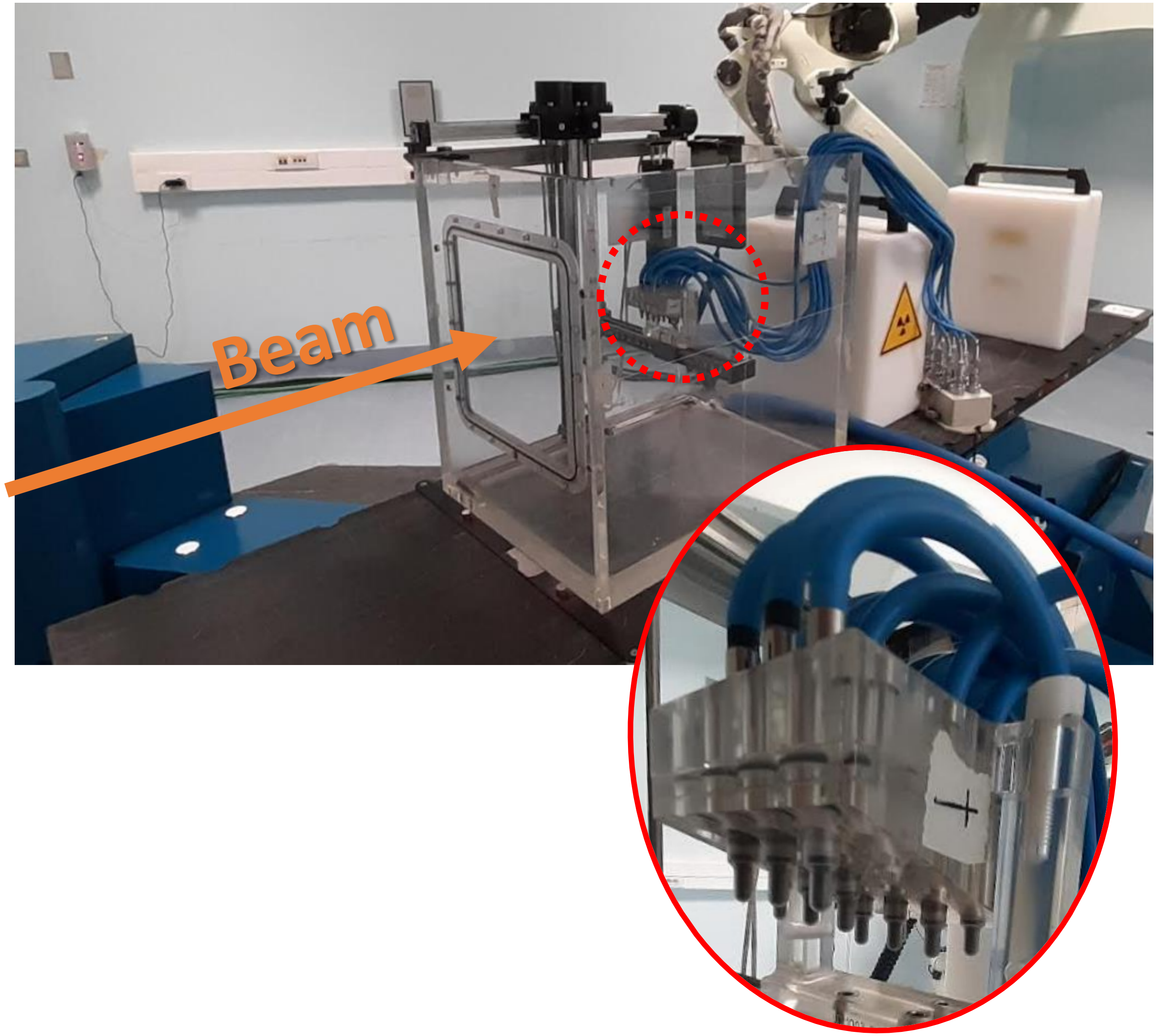
→ 78% Target coverage

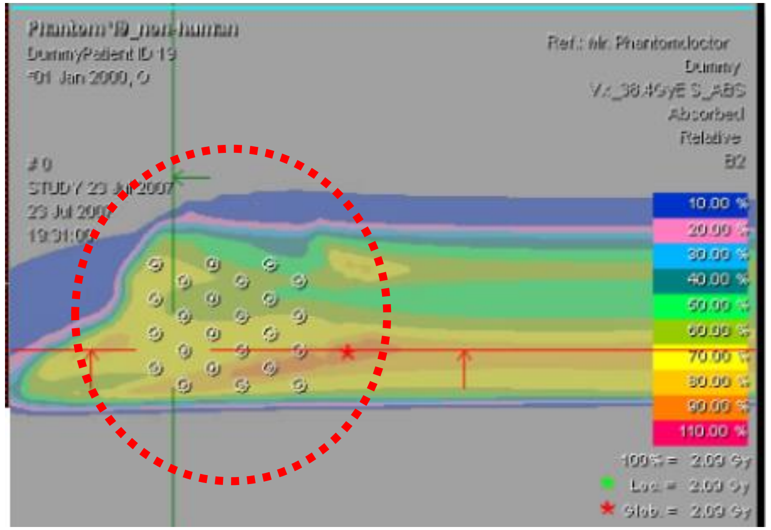


Courtesy of A. Vai

PATIENT-SPECIFIC QA

Measurement





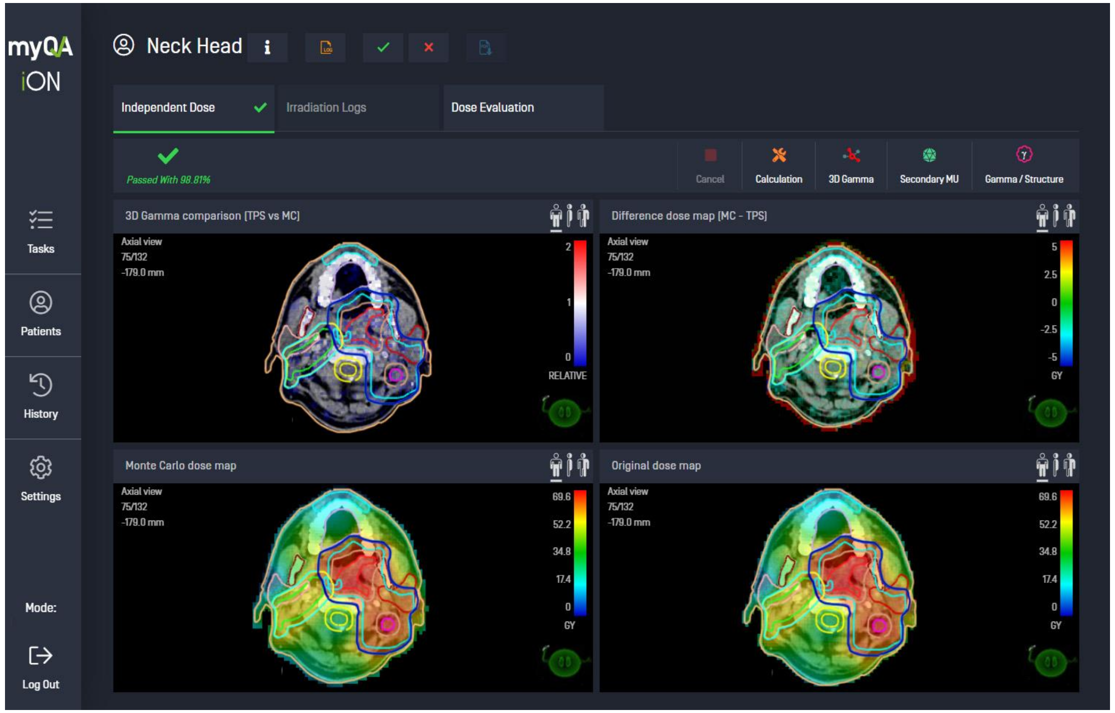
$$\sum_{i}^{N} \frac{1}{N} \frac{(d\text{meas}_i - d\text{calc}_i)}{d\max} \%.$$

- Limited number of dose points
- Homogeneous dose regions
- Low-dose gradients
- Poor sensitivity to range variations
- Not sensitive to delivery failures far from the measured points
- Time consuming

PATIENT-SPECIFIC QA

LOG-files based QA

- 3D dose comparison
- Inhomogeneities and HD gradients
- Highly sensitive to range variations and delivery failures
- Extremely fast



IBA CE-marked PSQA workflow

Received: 10 October 2023 | Revised: 31 January 2024 | Accepted: 7 February 2024

DOI: 10.1002/acm2.14328

JOURNAL OF APPLIED CLINICAL MEDICAL PHYSICS

RADIATION ONCOLOGY PHYSICS

Commissioning and clinical implementation of an independent dose calculation system for scanned proton beams

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Beam modeling and beam model commissioning for Monte Carlo dose calculation-based radiation therapy treatment planning: Report of AAPM Task Group 157

Med. Phys. 47 (1), January 2020

TABLE III. Acceptance tests for a Monte Carlo (MC) beam model. The dose tolerances should be used for low dose gradient regions and distance-to-agreement (DTA) tolerances should be used for high dose gradient regions for MC-calculated dose distributions.

Category	Test	Tolerance
Dose calculation tests	Perform dose calculations for a standard photon beam dataset. Tests should include various open fields, different SSDs, blocked fields, MLC-shaped fields, inhomogeneity test cases, multibeam plans, asymmetric jaw fields, wedged fields, and others.	<2%/2 mm[a]
	Perform a set of dose calculations for a standard electron beam dataset. Tests should include various open fields, different SSDs, shaped fields, inhomogeneity test cases, surface irregularity test cases, and others.	<2%/2 mm[a]
Speed Benchmarks	Check the time to compute dose for each beam energy to a preset statistical precision, for a specified field size, voxel size, phantom volume, and SSD, and compare with vendor's benchmark time on the same or comparable computer hardware	Within $\pm$ 10% of vendor's benchmark time for the specified configuration
Statistical tests	Verify whether code allows dose calculation at different preset statistical uncertainties (e.g., 2%, 1%, 0.5%, or smaller)	Consistent with documentation
	Verify statistical uncertainty for each preset statistical uncertainty in uniform dose regions both inside and outside typical fields for each beam energy, x ray and electron	Agrees within 30% of independently calculated statistical uncertainties (if available), or within 30% of observed statistical uncertainties, which can be estimated using the dose values in a uniform dose region, or at the same location but calculated with different random number seeds
	Verify that the uncertainty quoted by the system follows a $1/\sqrt{N}$ behavior. Note that the history number N is generally proportional to the CPU time T for the same calculation	The $1/\sqrt{N}$ behavior is followed to within 10 %
	Verify the fidelity of the denoising option, if present, in uniform dose regions both inside and outside typical fields for different voxel sizes (e.g., 1–2 mm voxels for stereotactic radiosurgery or radiotherapy)	The denoising option does not cause a difference of more than 3σ from the unsmoothed distribution

TABLE IV. Subset of commissioning tests from TG53 and TG244 with tolerances specific for Monte Carlo (MC)–based treatment planning system (TPS). Note that the dose difference is the difference between the calculated and measured dose. The dose tolerances should be used for low dose gradient regions and distance-to-agreement (DTA) tolerances should be used for high dose gradient regions for MC calculated dose distributions. TG53 and TG244 tests not listed in this table should be performed with the tolerances listed in those reports.

Category	Test	Tolerance
Dose distributions	Absolute dose for the reference condition (e.g., the central-axis dose at a depth of 10 cm in water for a 10 cm × 10 cm field defined at 100 cm SSD). Note that this should be the normalization point for MC calculated dose distributions and the dose differences do not include all the uncertainties associated with determining the absolute dose under standard calibration conditions	0.5%[a]
	Relative dose distribution in water for each energy and all field sizes available (typically 2 cm × 2 cm–40 cm × 40 cm for linacs, 1 cm × 1 cm if needed, for example, for SBRT)	2%/2 mm[b]
Output factors	For photon beams, open fields with different field sizes (2 cm × 2 cm–40 cm × 40 cm), off-axis open fields (asymmetric jaws), and blocked fields including trays and wedges (physical and dynamic) for different SSDs (80 cm–120 cm)	2%[b]
	For electron beams, all applicator sizes available and arbitrarily-shaped cutouts used clinically	2%[b]
Beam modifier implementation	Dose distribution for a single field in water for each energy and all beam modifiers available clinically such as MLC, blocks, wedges, compensators, cutouts, bolus	2%/2 mm[b]
Patient dose calculation	Point dose measurements for composite dose distribution in homogeneous or heterogeneous phantoms (relative to the prescription dose)	2%[b]
	Planar/volumetric dose array for composite dose distribution in treatment plan QA phantoms	2%/2 mm[b], no pass rate tolerance, but areas that do not pass need to be investigated[108]

ESTRO-EPTN radiation dosimetry guidelines for the acquisition of proton pencil beam modelling data

Carles Gomà [a,b,c,2,*], Katrin Henkner [d,1], Oliver Jäkel [d,e,1,3], Stefano Lorentini [f,1,4], Giuseppe Magro [g,1,5], Alfredo Mirandola [g,1,6], Lorenzo Placidi [h,1,7], Michele Togno [i,1,8], Marie Vidal [j,1,9], Gloria Vilches-Freixas [k,1], Jörg Wulff [l,m,1,10], Sairos Safai [i,11]

Physics and Imaging in Radiation Oncology 31 (2024) 100621

- Integrated depth-dose curves (IDDs)
- Lateral spot profiles in air at minimum 3 different z-positions
- Reference dosimetry (IAEA TRS-398 Rev 1)

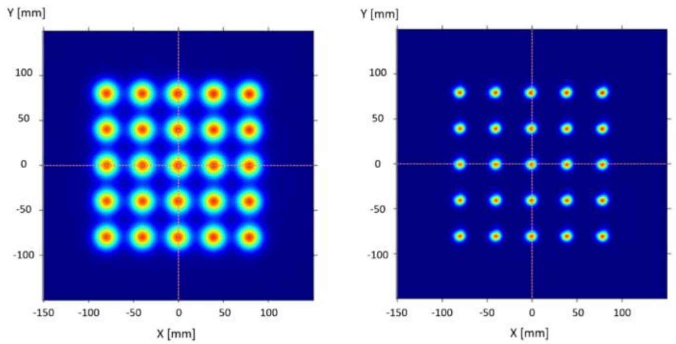


Fig. 3. Spot maps in air at isocentre for two different energies (154 and 227 MeV) in a Mevion 250i HYPERSCAN delivery system.

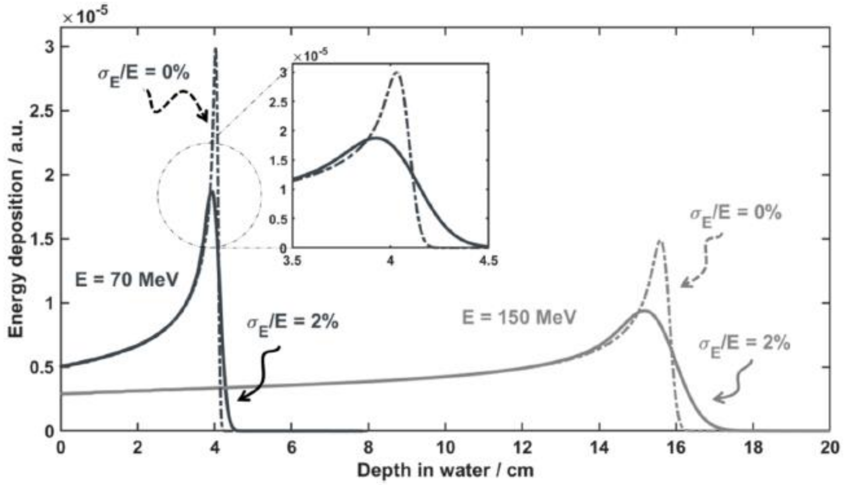
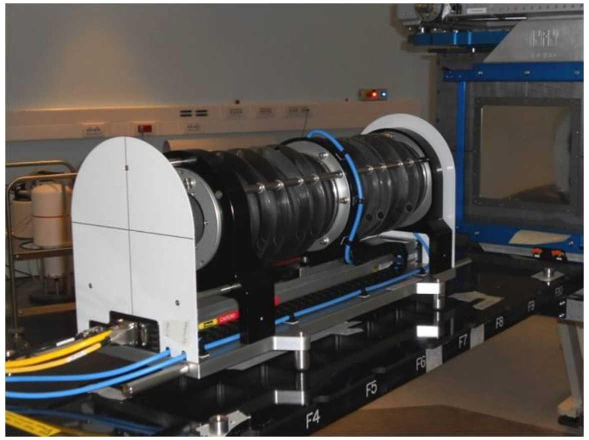


Fig. 1. Integrated depth-dose curves of proton pencil beams of different initial mean energy (70 and 150 MeV) and relative energy spread of 0 % (dashed lines) and 2 % (solid lines).



Clinical commissioning of intensity-modulated proton therapy systems: Report of AAPM Task Group 185

Med Phys 48 (1), January 2021

11. RADIOTHERAPY PLANNING SYSTEM COMMISSIONING

11.A. Dose modeling for treatment planning

11.A.1. Analytical dose model representation

11.A.2. Modeling low-dose halo

11.A.3. Accuracy and limitations of analytical dose algorithms

11.A.4. Monte Carlo as a dose model for treatment planning

11.B. Apertures and energy absorbers

11.C. Dose normalization to absolute dose

11.D. Dose model data acquisition

11.D.1. Integral depth-dose measurement, scaling, and corrections

11.D.2. Spot profiles

11.D.3. Virtual source–to-axis distance

11.D.4. Energy absorbers

11.D.5. Ripple filters

11.D.6. Apertures

11.E. Monitor unit determination

11.F. Beam model verification

11.G. Role of Monte Carlo in data modeling

TABLE IV. Typical dose model measurements and methods for intensity-modulated proton therapy commissioning.

Type	Modeling (M) calibration (C), or verification (V)	IMPT method and materials
Integral depth dose (IDD) with and without range shifter(s)	M	A large-diameter parallel-plate chamber scanned along a single central beamlet in a water phantom. Monte Carlo corrections are usually required for all current methods.[188] Although MLICs are useful for quality assurance, they are not recommended for IDD acquisition for the TPS modeling need
SOBP depth dose in water	C, V	Parallel-plate ionization chamber in a scanning water phantom. Change the setup geometry to each different SOBP center
Spot profiles X/Y with and without energy absorber(s)	M	Film or a scintillation detector. Measure across the energy band in multiple planes transverse to the central beamlet axis at, proximal to, and distal to the isocenter. The film and scintillation detector need to be validated for use in the scanning beam, avoiding saturation or quenching
Virtual source-to-axis distance [X] in air	M	Scanned proton-field film measurements. Defined as the physical magnet center. Verify with back-projection of in-air 50–50%radiation field widths along the central axis
Virtual source-to-axis distance [Y] in air	M	Same as above; VSAD(X) $\neq$ VSAD(Y)
Dose halo	M	Superposition measurements of an individual beamlet or peripheral scans around a central measurement point in air
Proton dose per MU density [Gy mm^2/MU] calibration per energy	C	A single monoenergetic fixed beamlet or scanned beamlets delivered to a large-diameter parallel-plate chamber or small-volume ionization chamber, respectively, fixed at a depth of 1–2 cm in a water phantom
Lateral dose profiles at depth	V	Scan at multiple depths Small-volume cylindrical ionization chamber in a scanning water phantom for integrated point measurements, or film, or scintillating detector. Change setup geometry to each different SOBP center. Measure at multiple depths

12. END-TO-END VERIFICATION

Due to the complexity of IMPT systems and their internal interactions and dependencies, it is recommended that end-to-end verification must be performed before the onset of patient treatments. It is also recommended that the end-to-end verification should be performed for the typical clinical treatment sites representing the intended practice.

IROC Imaging and Radiation Oncology Core — Global Leaders in Clinical Trial Quality Assurance

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Remote End-to-End Dosimetry Auditing Service

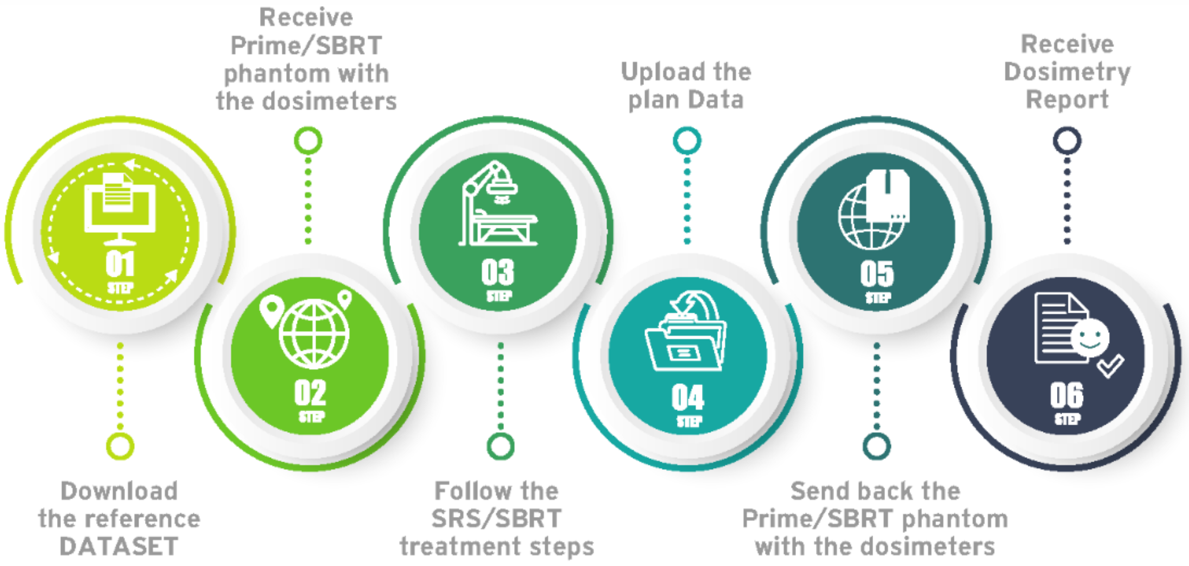
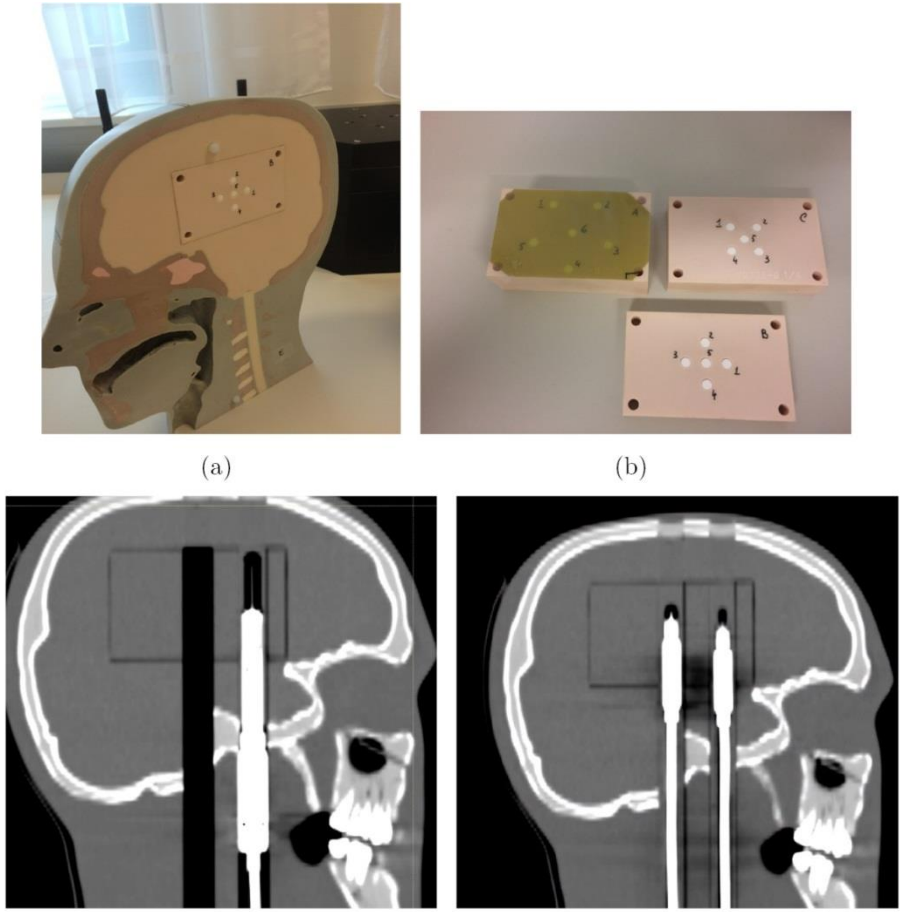


Figure 1: The RTsafe Prime phantom used in the audit, along with the specially designed inserts to accommodate Gafchromic EBT film, OSL and polymer gel dosimeters.



(a) (b)

(c) (d)

Physics in Medicine & Biology

IPEM Institute of Physics and Engineering in Medicine

PAPER

End-to-end tests using alanine dosimetry in scanned proton beams

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Università degli Studi di Palermo

End-to-end tests with alanine dosimetry for lung treatments with photon, proton and carbon ion beams

CNAO The National Center for Oncological Hadrontherapy

INFN

A. de Farias Soares[1,2,*], M.C. D'Oca[1,2,3], M. Romeo[1,2,4], M. Ciocca[5], L. Mantovani[6], R. Di Liberto[6], A. Mirandola[5], E. Rossi[5], L.M.C. Gomez[6], M. Marrale[1,2,3].

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Detectors allocation

A total of 8 pellets for irradiation cycle was used. The pellets were allocated within the **Dynamic Thorax Phantom.**

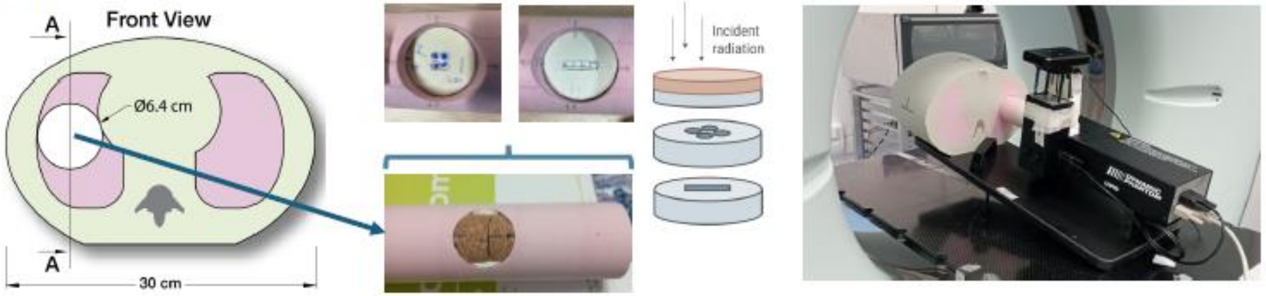

Fig. 3. Scheme showing the pellets allocation.