Questions spéciales de radioprotection (WRPR 3010)

Imaging and proton therapy

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molecular imaging, radiotherapy & oncology

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de Louvain

Objectives of the course

- Basics of radioprotection

- Imaging systems in radiotherapy
  - Description of the systems
  - Dosimetry
  - Advantages and disadvantages of the systems
  - Quality assurance

- Proton therapy
  - Generalities on proton therapy
  - Elements of the physics of nuclear reactions
  - State of the art of neutron dosimetry in patients
  - Considerations on the shielding of proton therapy devices
  - Problem of activation

Course notes

- These slides
- Chapter 10 of IAEA recommendations of QA for imaging systems (only the main principles: what do we need to check? For which reasons?)
- Physics of proton therapy
- For information: papers on proton therapy shielding

Basics of radioprotection

- Radiations do damage

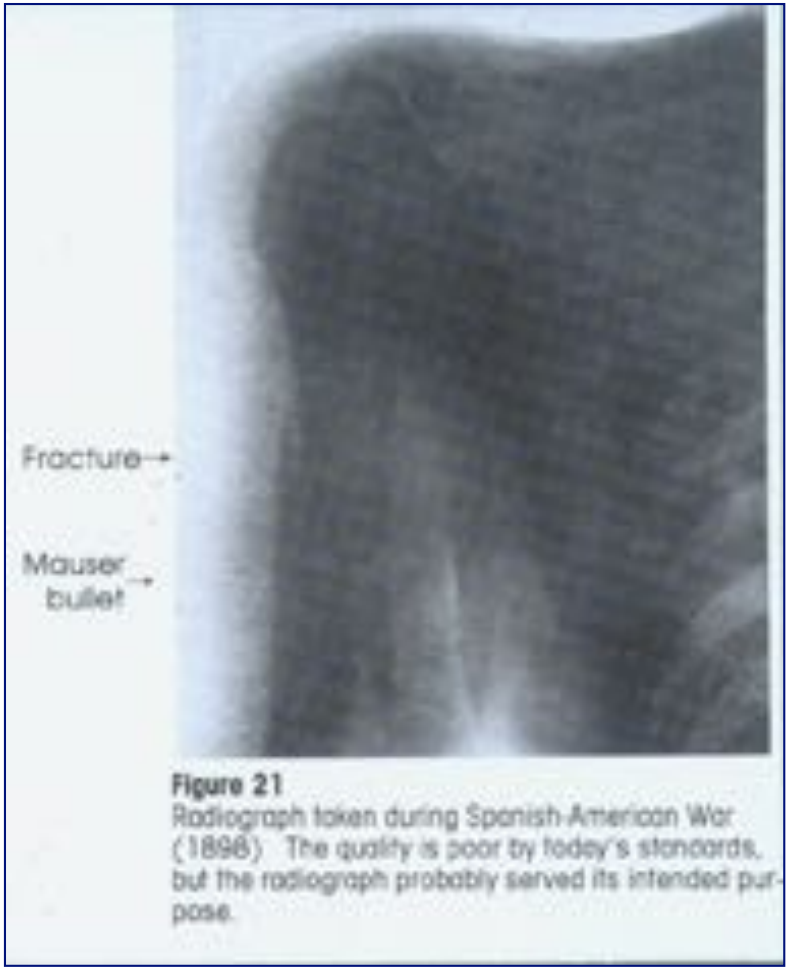


Figure 21
Radiograph taken during Spanish-American War (1898). The quality is poor by today's standards, but the radiograph probably served its intended purpose.

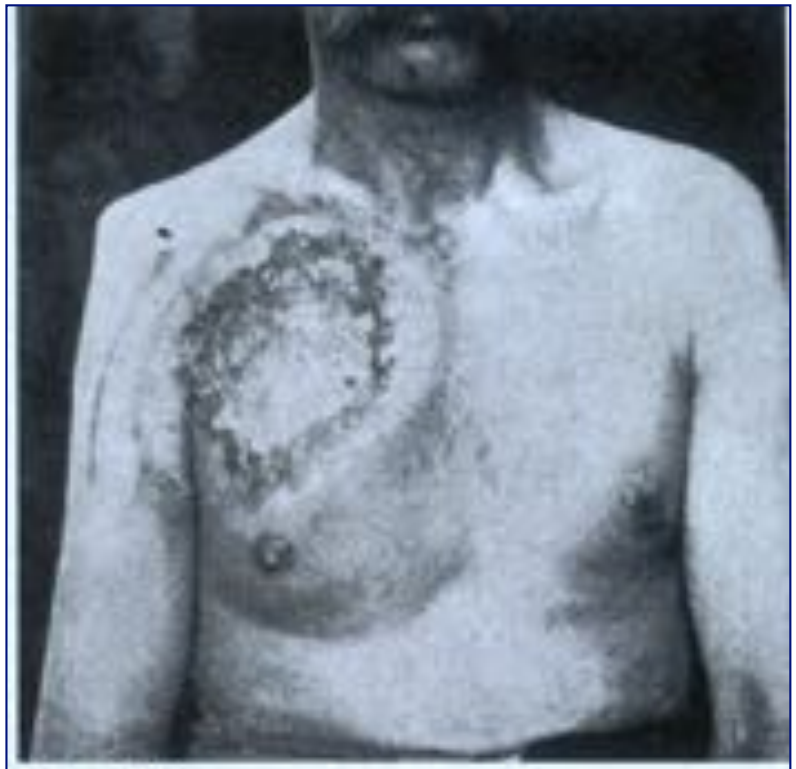
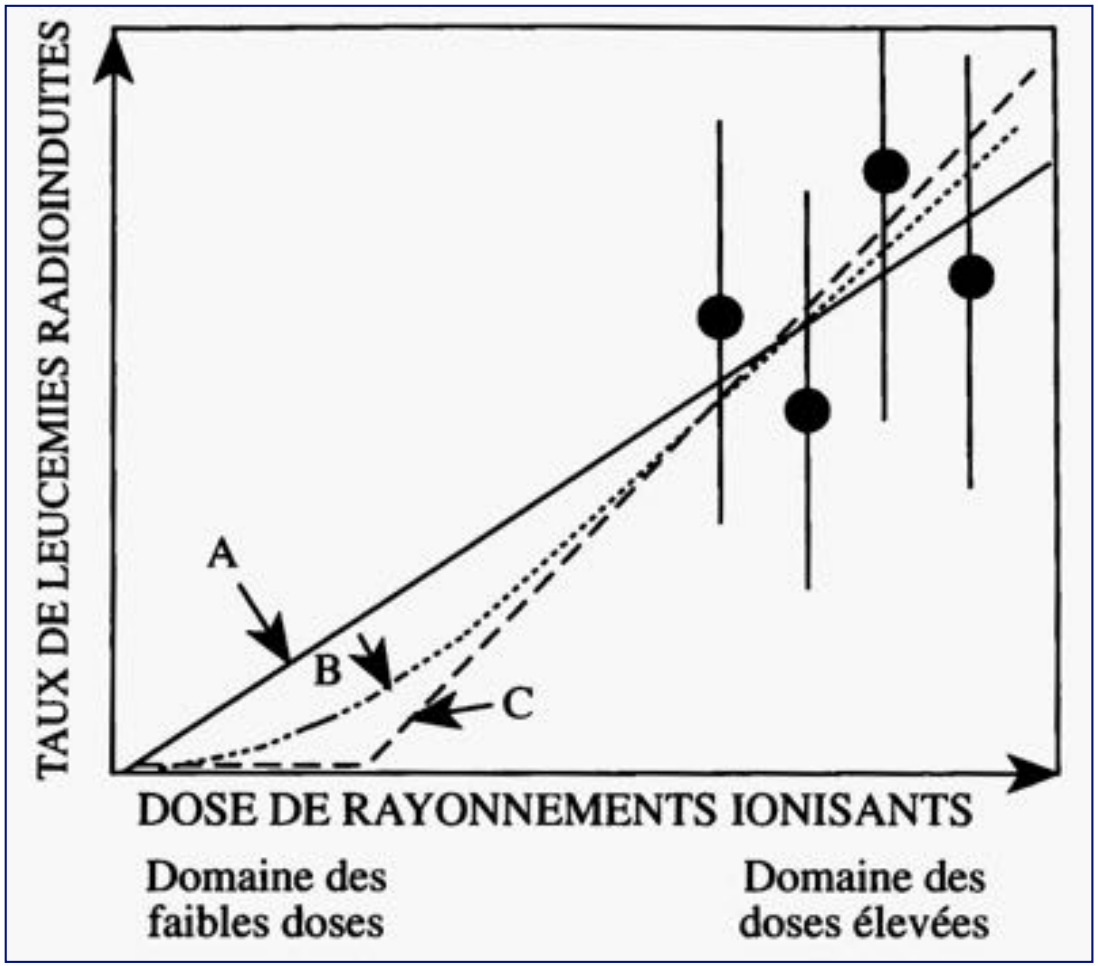


Figure 22
Radiation injury to the skin of a Spanish-American War soldier as a result of an x-ray examination (1898)

Basics of radioprotection

- Radiations do damage



A: linear extrapolation
B: linear-quadratic extrapolation
C: linear extrapolation with threshold

Basics quantities

- The physical dose
- The equivalent dose in radiation protection
- The effective dose in radiation protection

Absorbed dose

Expressed in the unit Gray [Gy]

$$1\ \mathrm{Gy} = 1\ \frac{\mathrm{J}}{\mathrm{kg}} = 1\ \frac{\mathrm{m}^2}{\mathrm{s}^2}$$

"In typical radiotherapy treatments, radiation doses are delivered in the range of 8 J/kg to 80 J/kg"

In comparison:
"To rise the temperature of water by 1 °C, requires an energy of 4200 J/kg (C_p of water)"

From T. Depuydt

Insufficiencies of the absorbed dose as a surrogate for biological effects

The effect of radiations is not linked only to the dose

Other features play a role, e.g. the density of ionizations

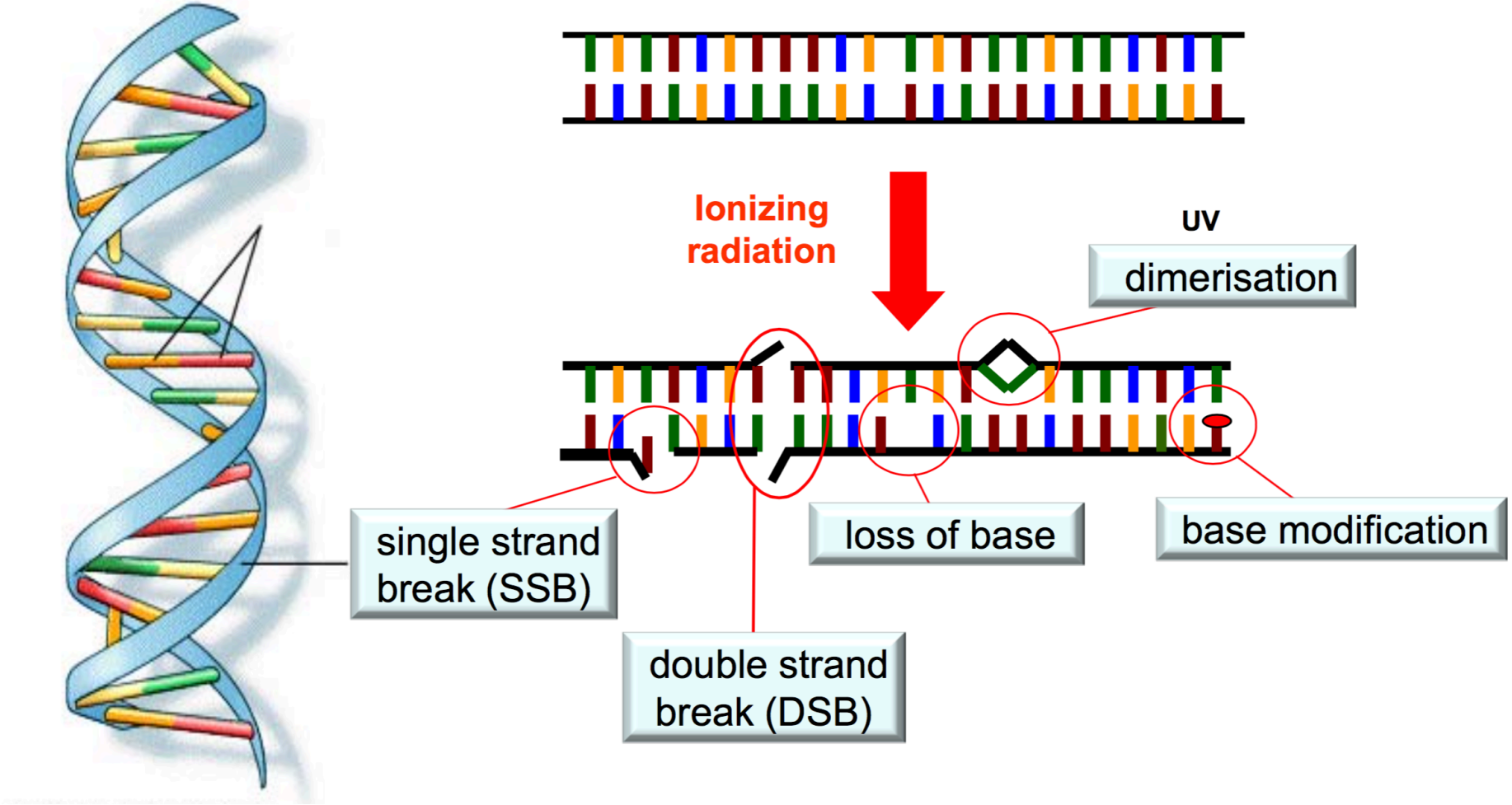
Thus, we introduce other quantities to **scale** the physical dose, according to the **biological effects** of radiations.

In radiotherapy, we use the so-called Relative Biological Effectiveness (RBE) --> leads to the concept of biological dose (in Gy)

In radioprotection, we use the **equivalent dose**. It is expressed in Sievert (Sv)

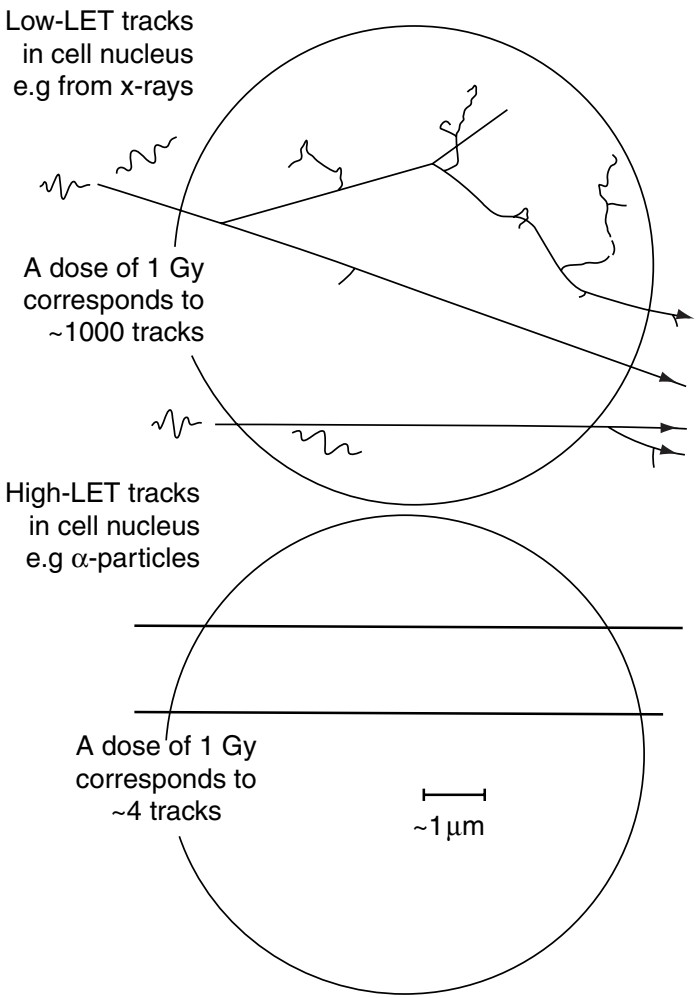
Different particles do not cause the same damage to DNA for the same energy absorbed

DNA effects of ionizing radiations



Different particles do not cause the same damage to DNA for the same energy absorbed

LET: linear energy transfer
➔ Density of ionizations along a particle track



Photons: low energy released per track

Alpha, Carbon ions…: more energy released per "track"

FIGURE 7.14
Particle track structure for low-LET radiation (upper picture) and for α-particles (lower picture). The circles represent the size of the nucleus of a typical mammalian cell. The tortuous nature of the (low-LET) secondary electron tracks are in complete contrast to the high-LET particles, of which only around *four* are required to deposit a dose of 1 Gy in that small volume. (From Goodhead, D. T., *Health Phys.*, 55, 231–240, 1988. With permission.)

Concept of equivalent dose *in radiation protection*

Equivalent dose = absorbed dose * radiation weighting factor (W_R) in Sievert (Sv).

Type	Energy range	W_R
Photons, electrons	all	1
Neutrons	< 1 MeV	$2.5 + 18.2\exp[-(\ln(E))^2/6]$
	1 MeV - 50 MeV	$5.0 + 17.0\exp[-(\ln(2E))^2/6]$
	> 50 MeV	$2.5 + 3.25\exp[-(\ln(0.04E))^2/6]$
Protons		2
Alpha, fission fragments, heavy nucleai (Carbon)	all	20

Insufficiencies of the equivalent dose as a surrogate for the *risk* of biological effects

The risk of developing a secondary cancer (or genetical mutation) will depend on the equivalent dose but also on the **type of organ irradiated**

In order to make comparable a given equivalent dose delivered to one organ to another dose delivered to another organ, we introduce the concept of **effective dose**

Effective dose = $\sum_T D_{abs} * W_R *$ tissue weighting factor (W_T) in Sievert (Sv)
Where *T* loops over all tissues

Tissue or organ	W_T
Gonads	0.08
Bone Marrow	0.12
Colon	0.12
Breast	0.12
Skin	0.01

Imaging systems in radiotherapy

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The RT problem
Imaging systems
Image quantif.
QA
Proton therapy


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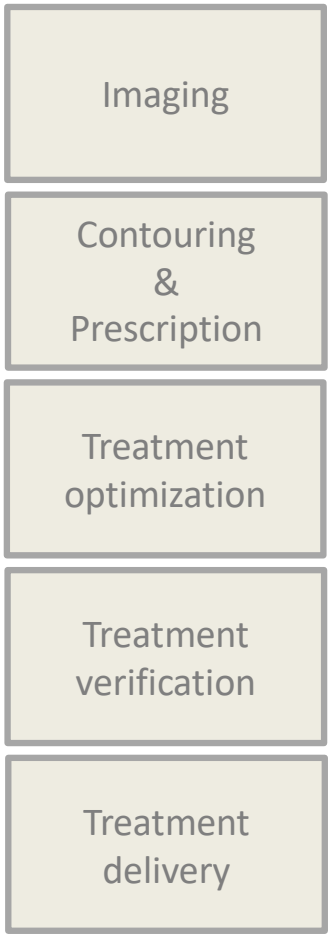
RT workflow



From K. Souris

RT workflow

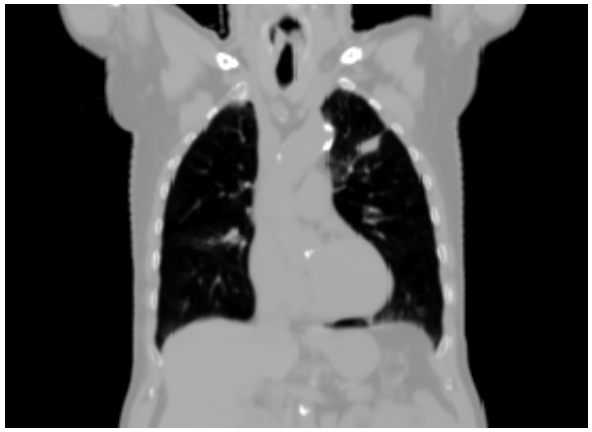
Imaging

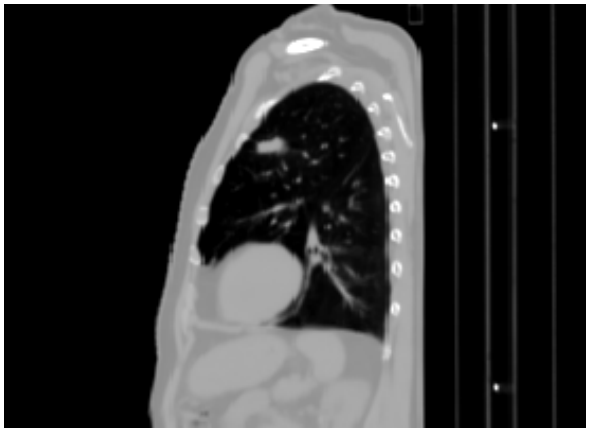
Contouring & Prescription

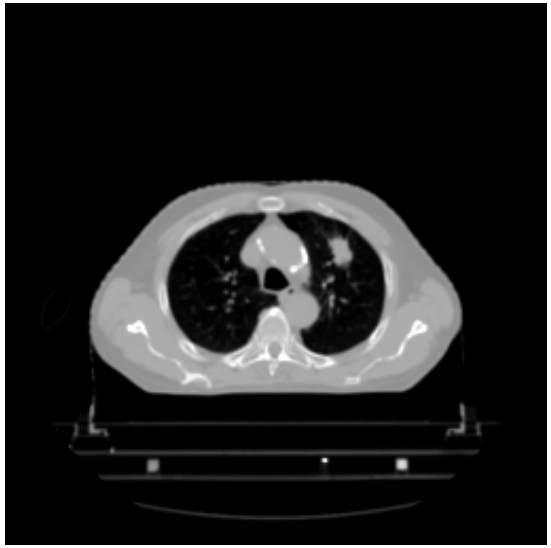
Treatment optimization

Treatment verification

Treatment delivery







CT scanner

From K. Souris

RT workflow

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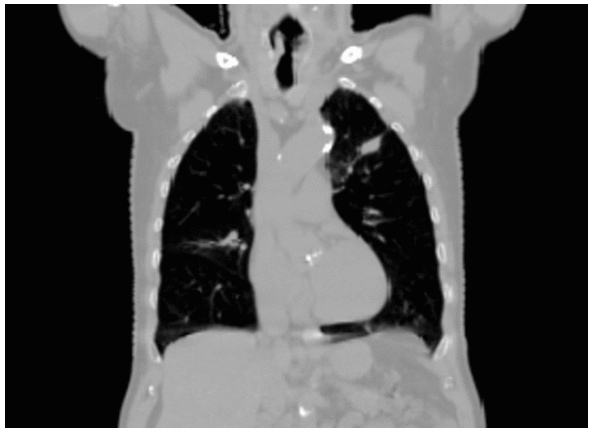
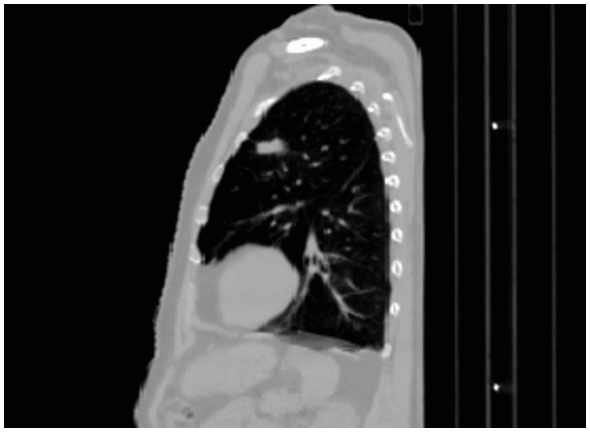
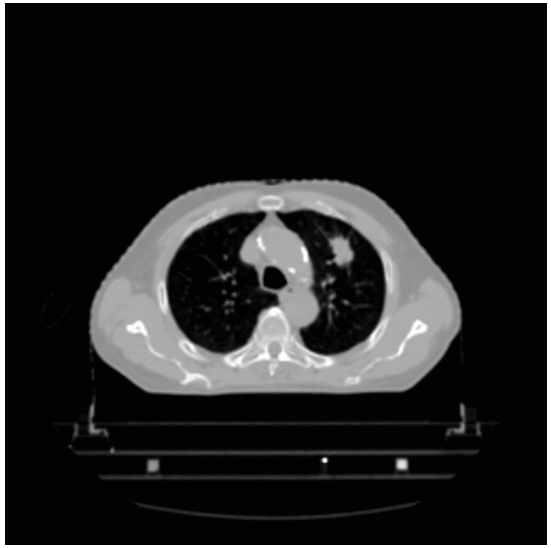




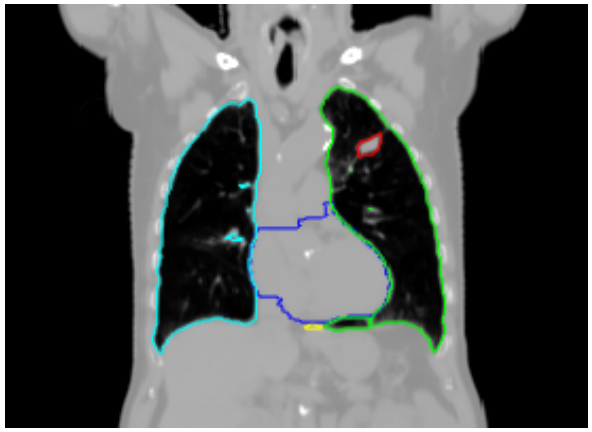


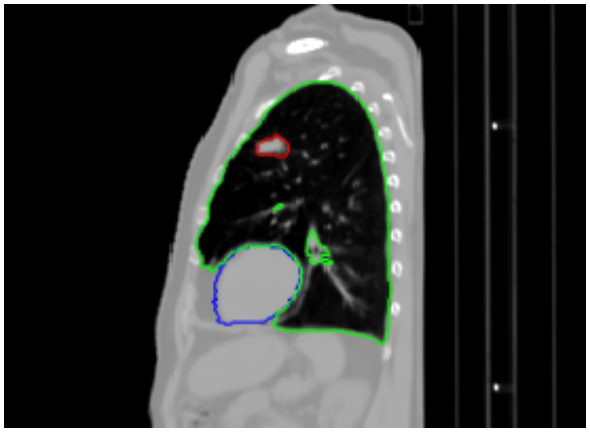
CT scanner

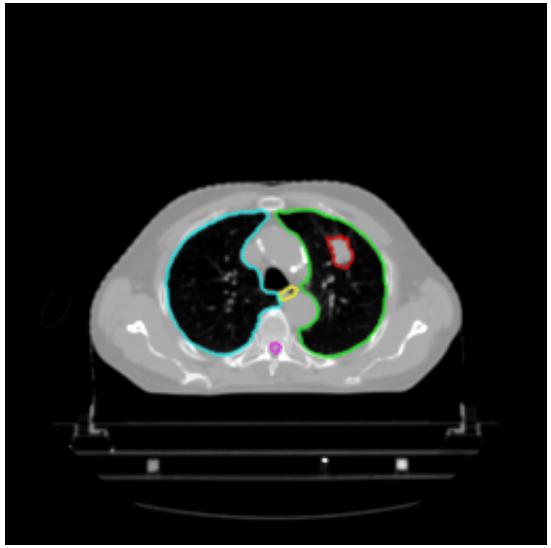
From K. Souris

RT workflow

- Imaging
- **Contouring & Prescription**
- Treatment optimization
- Treatment verification
- Treatment delivery







From K. Souris

RT workflow

- Imaging
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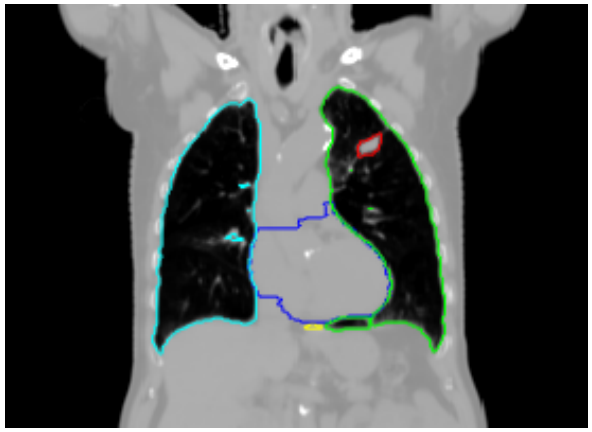
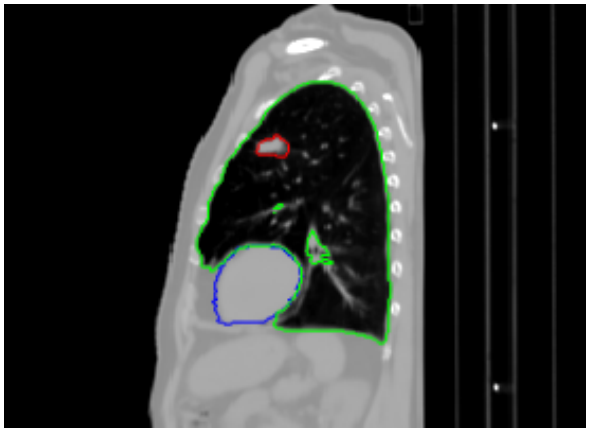
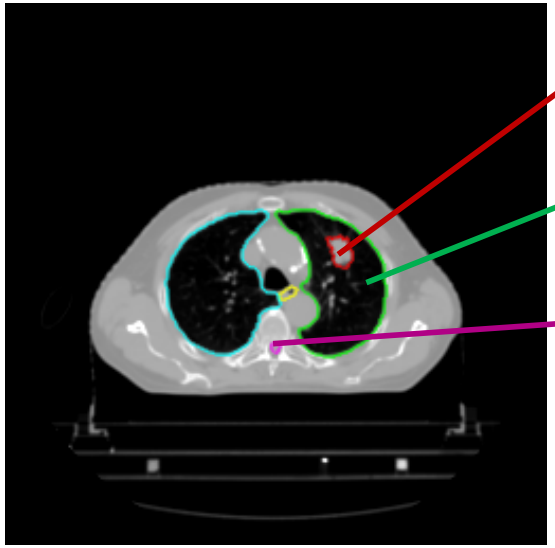






Dose prescription for the tumor: 60 Gy

Lung limit: Mean dose < 20 Gy

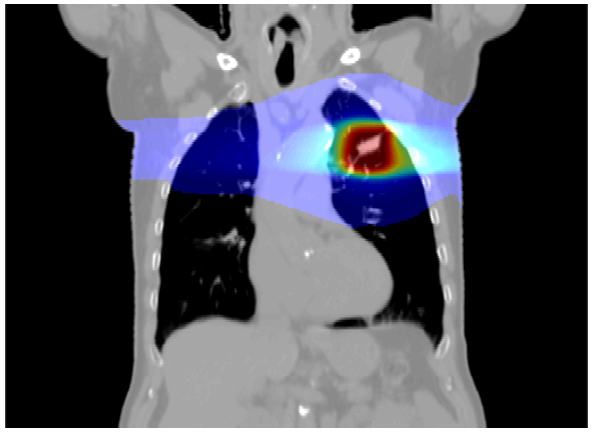
Spinal cord limit: Max dose < 50 Gy

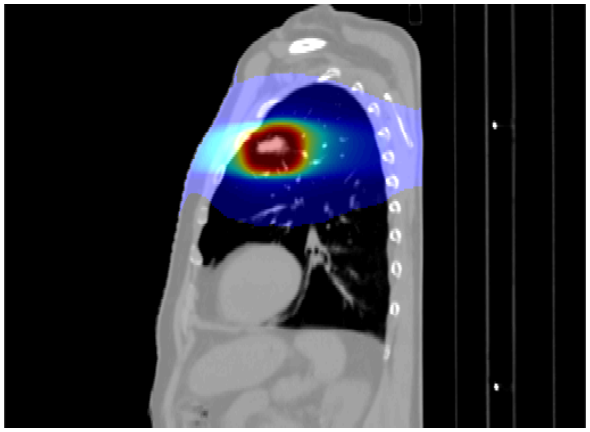
Dose quantifies the amount of energy deposited by the radiations per unit of mass (expressed in Gy).

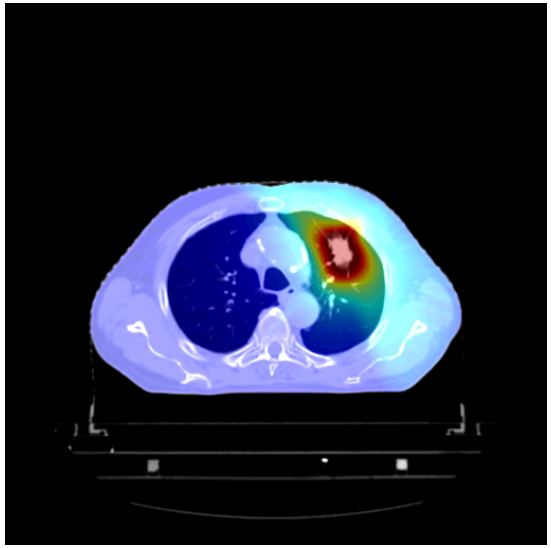
From K. Souris

RT workflow

- Imaging
- Contouring & Prescription
- **Treatment optimization**
- Treatment verification
- Treatment delivery







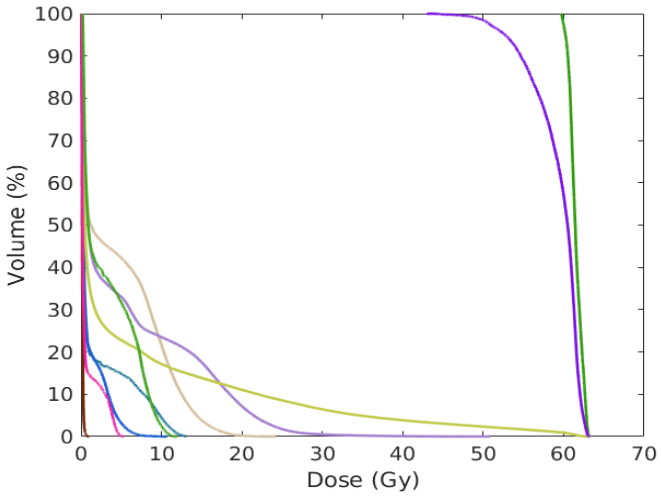
Optimization of the treatment plan to deliver an optimal dose distribution, conform to the prescriptions

From K. Souris

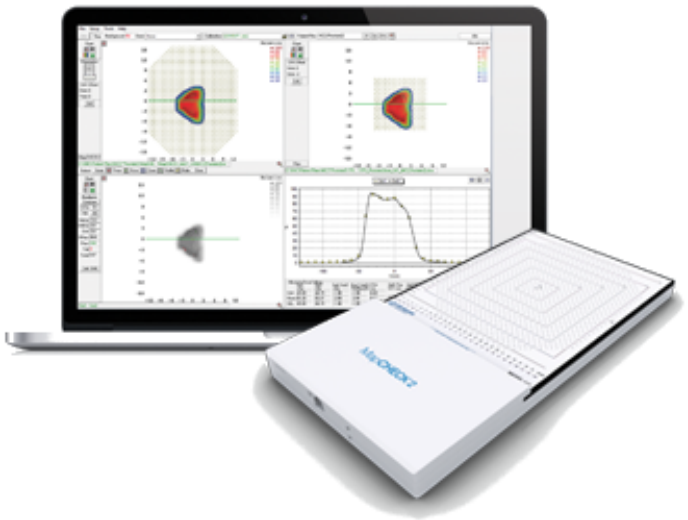
RT workflow

- Imaging
- Contouring & Prescription
- Treatment optimization
- **Treatment verification**
- Treatment delivery

Treatment plan evaluation



Measurements



From K. Souris

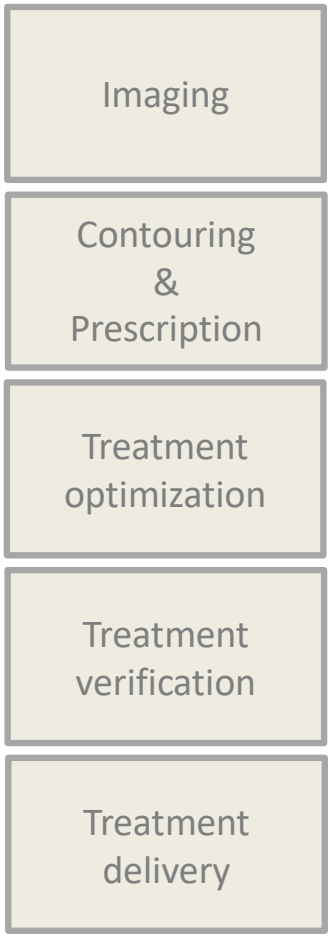
RT workflow

- Imaging
- Contouring & Prescription
- Treatment optimization
- Treatment verification
- **Treatment delivery**

The treatment is delivered in multiple fractions

From K. Souris

Where radiotherapy medical physics kicks in

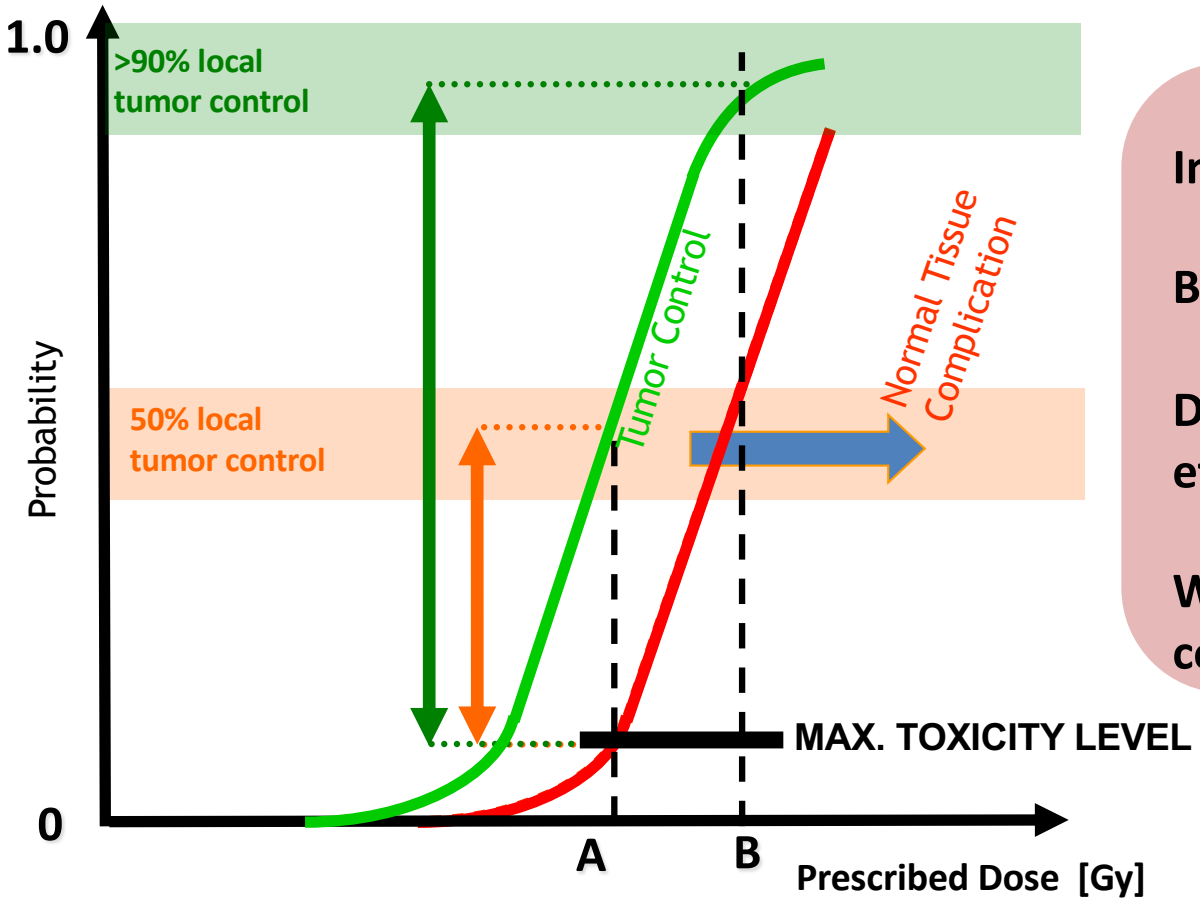


This process must work!

And with accuracy!

The deal of RT

HIGHEST dose to tumor volume
LOWEST dose to healthy tissues



Improved ballistics

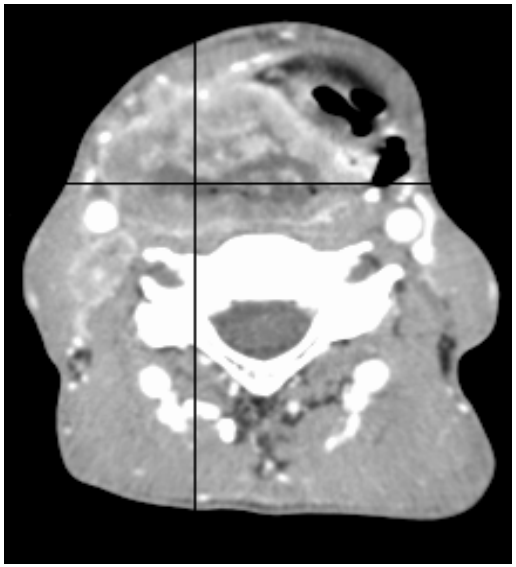
Better choice of particles

Differential radiobiological effects

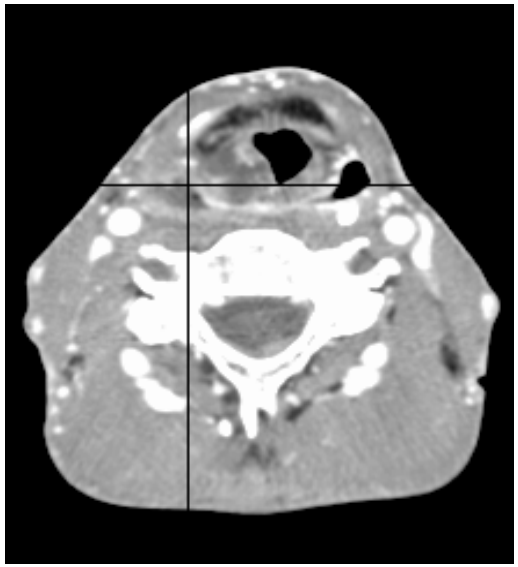
We can also impact tumor control curve (radiosensitization)

From T. Depuydt

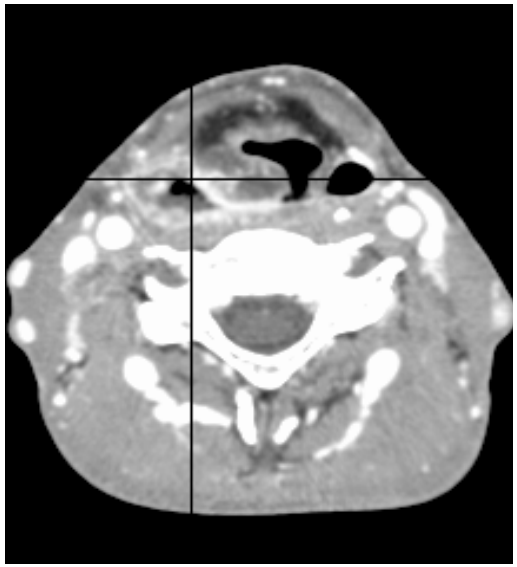
Patient changes



PRE-R



Week 3

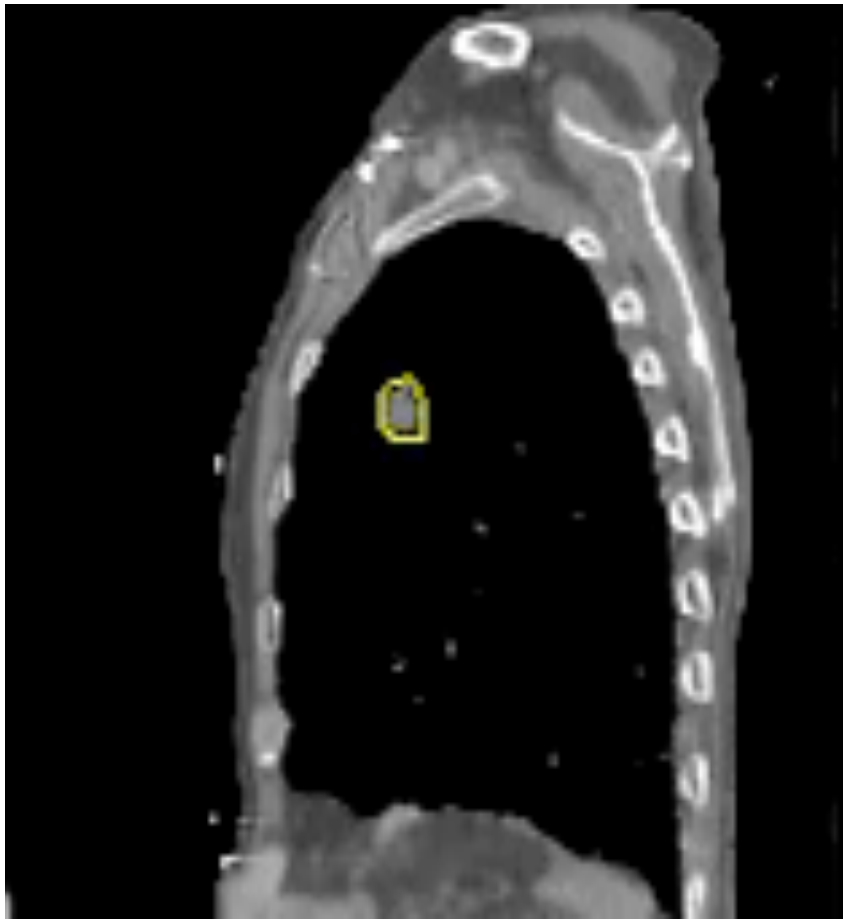


Week 5

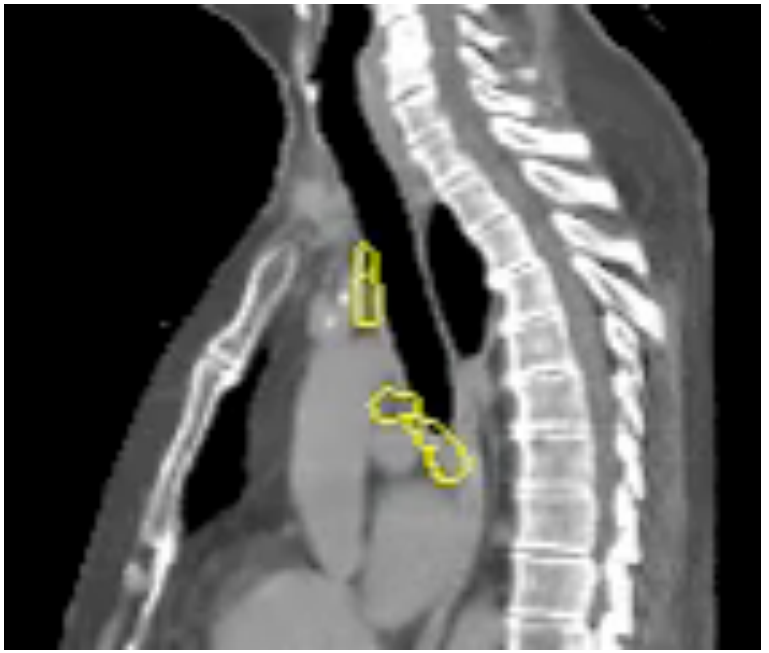
From V. Grégoire

Patient is still alive…

Primary lung tumor



Mediastinal lymph nodes

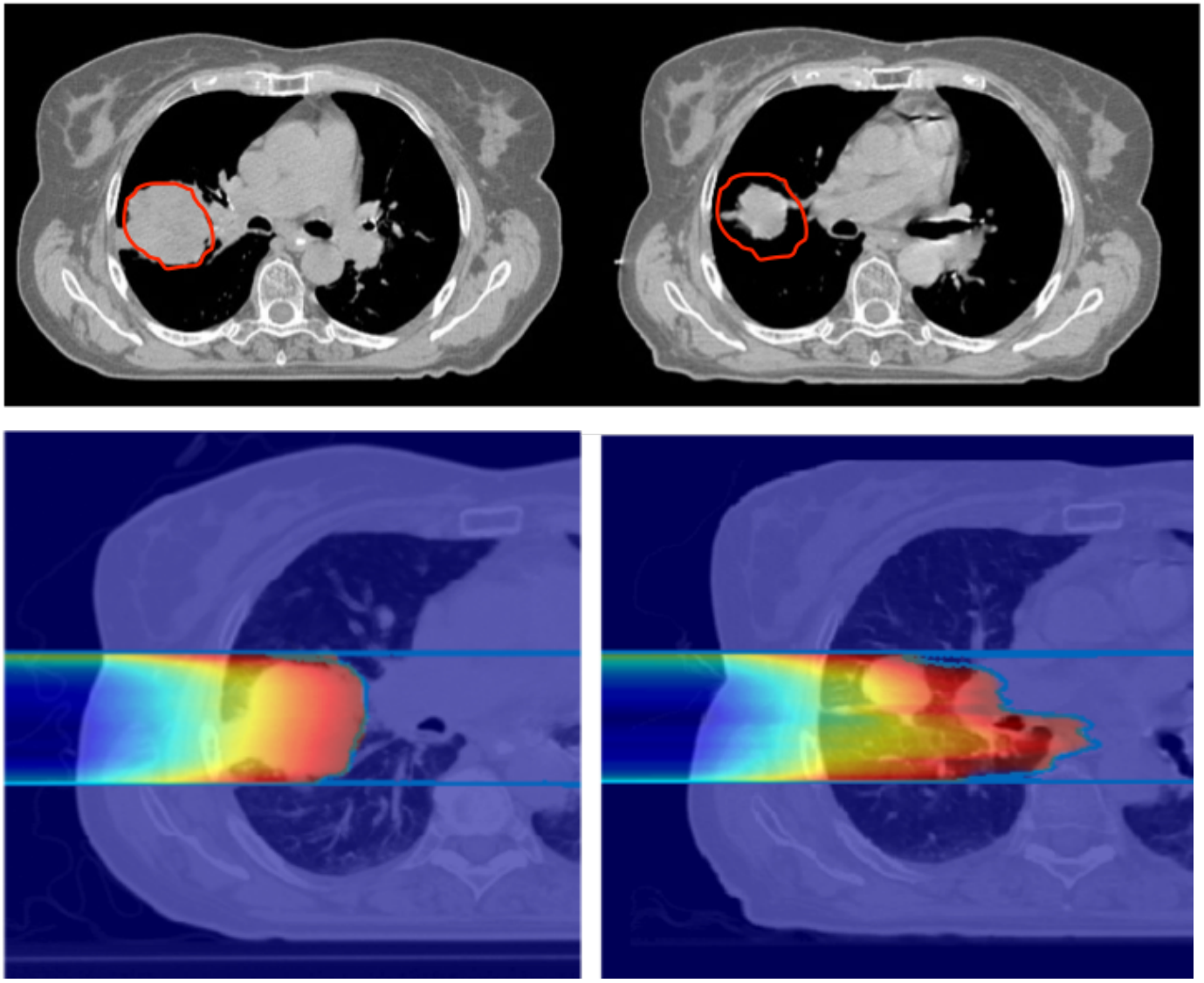


Motion is a major source of geometric uncertainty

From X. Geets

The impact can be catastrophic, especially in PT

Day 0 Day 35



From Lomax (2006)

Ensuring tumor local control in the presence of uncertainties

In radiotherapy, we use margins to ensure adequate irradiation of tumour cells. These margins include, among others, geometrical uncertainties (uncertainties on the position of the tumor)

The larger the margin, the smaller the therapeutic window

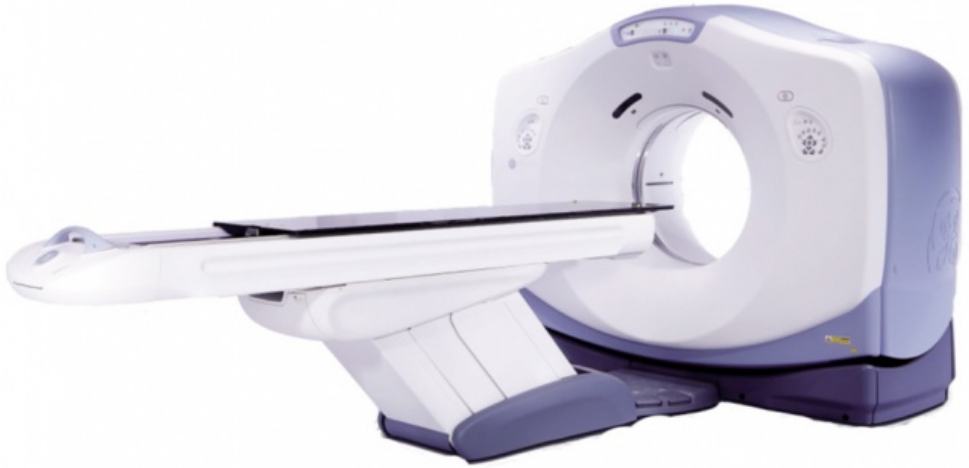
More imaging → reduced margins, reduced doses to healthy tissues, increased therapeutic window

But…

- Additional workload
- Additional doses from the imaging system itself


The RT problem
Imaging systems
Image quantif.
QA
Proton therapy

Fan KV beam CT scanner

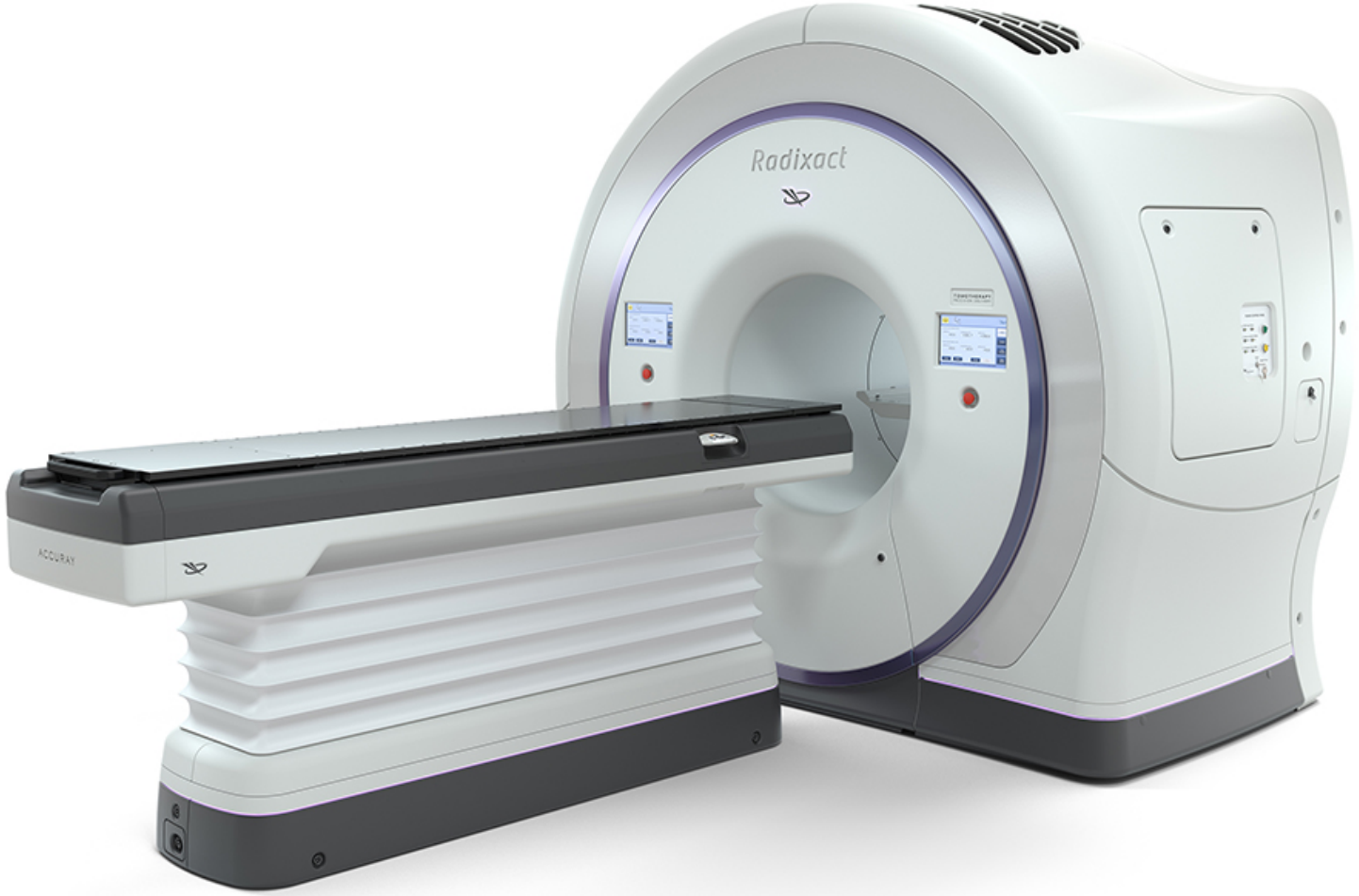


Simulation CT scan for contouring and treatment planning

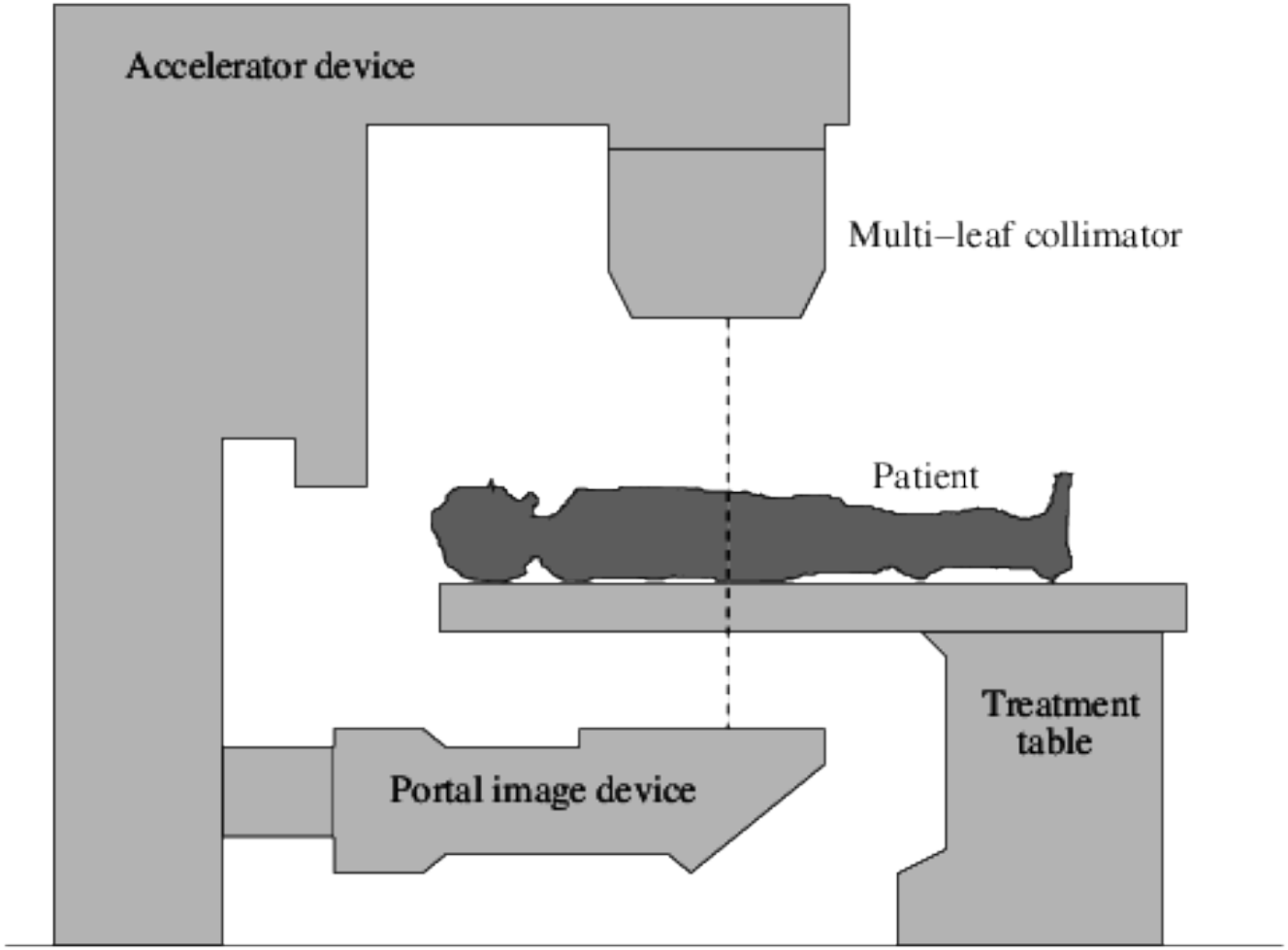
CT on-rails for precise positioning and/or replanning strategies

Fan KV beam CT scanner is the gold standard for image quantification and conservation of physical distances

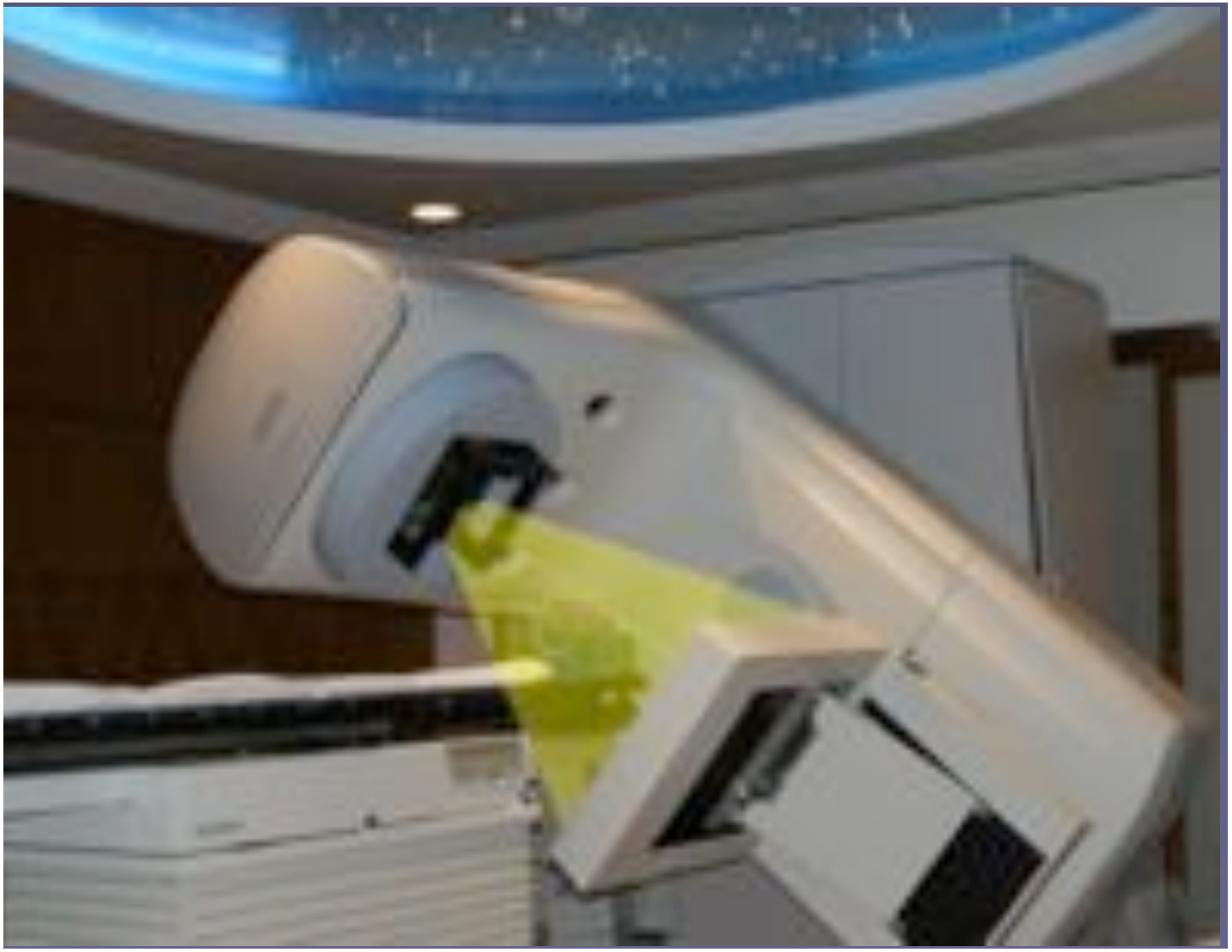
Fan MV beam CT scanner (embedded in RT treatment unit)



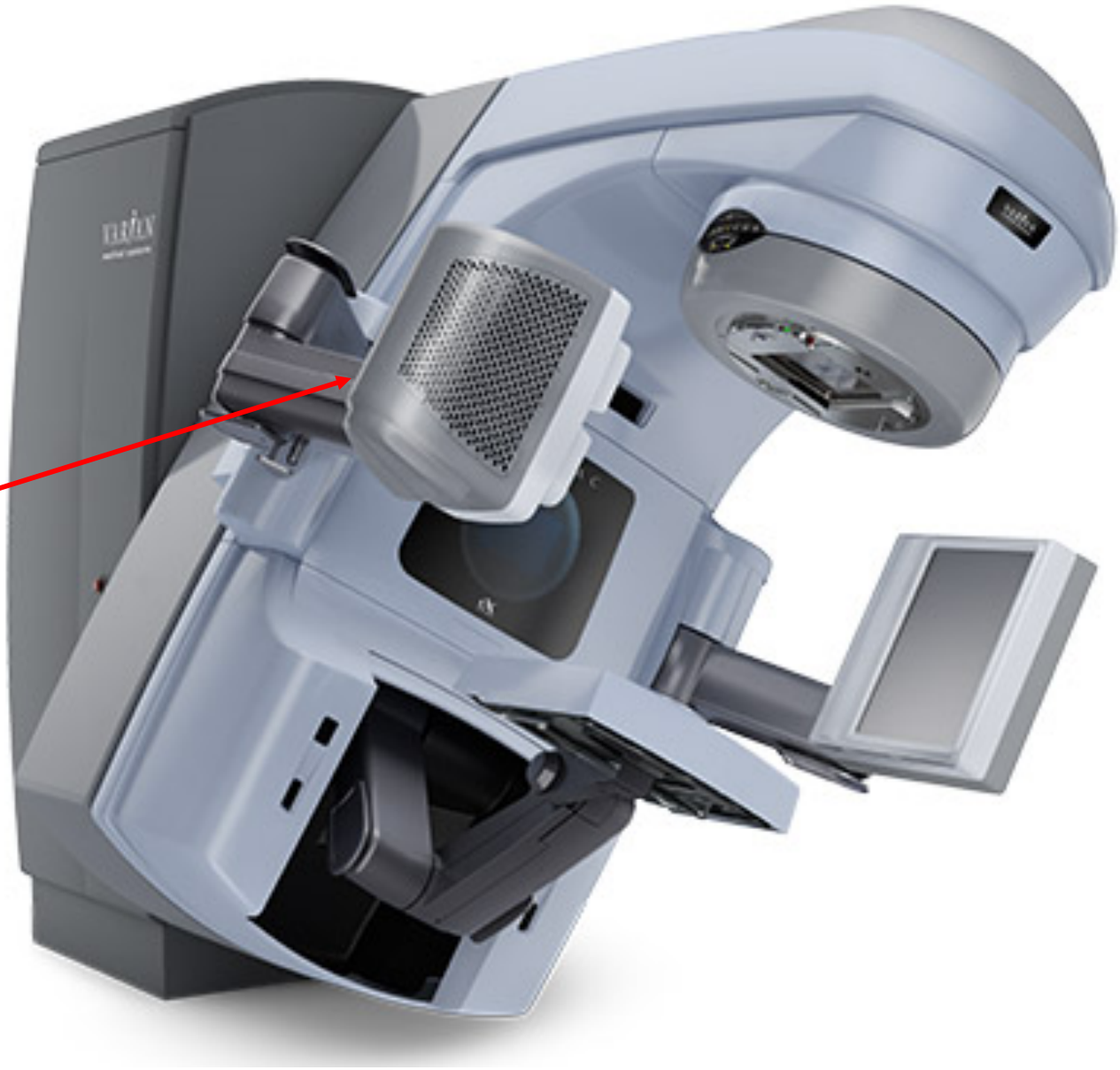
Flat panel 2D imagers (using MV beam)



MV CBCT

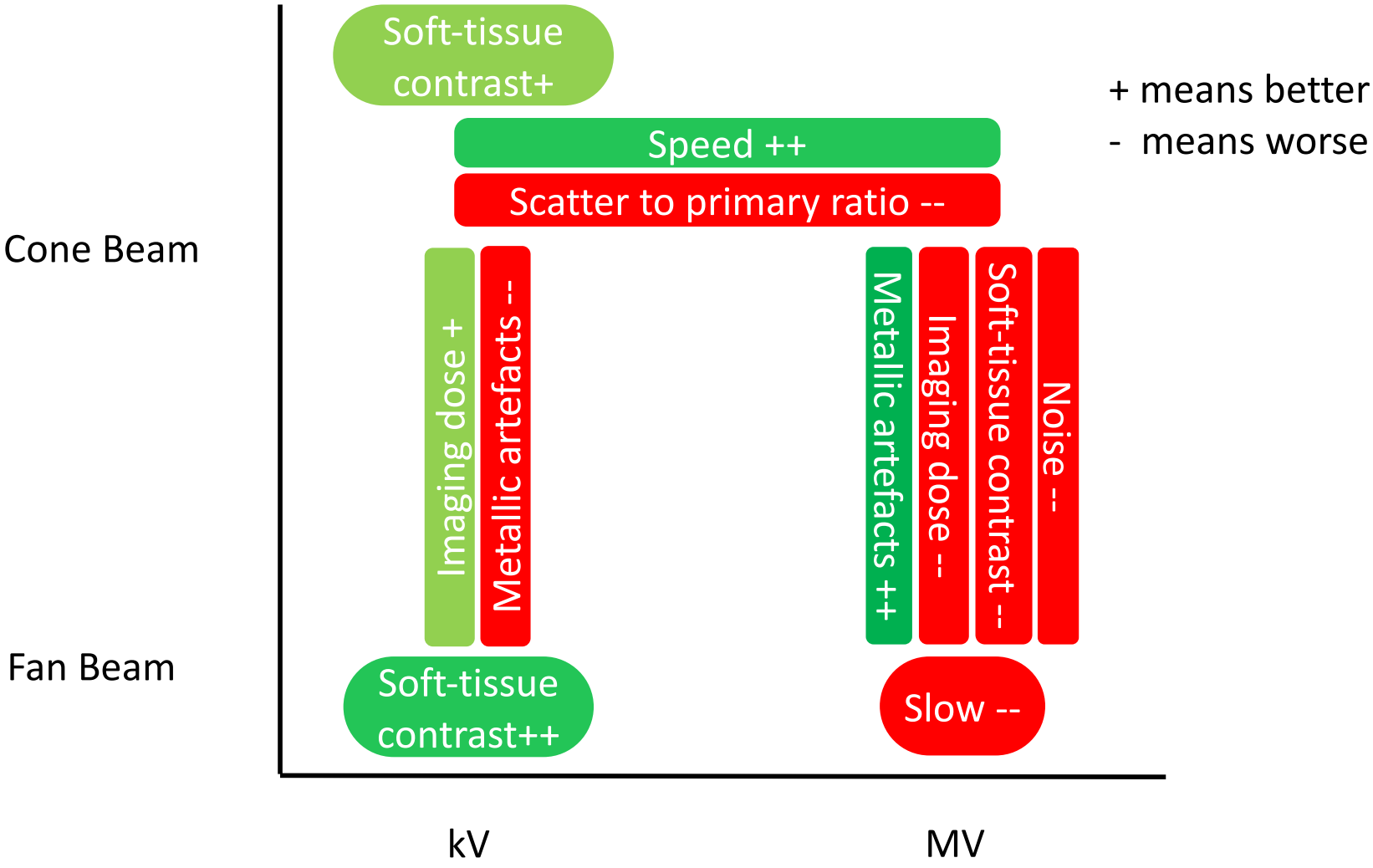


KV CBCT

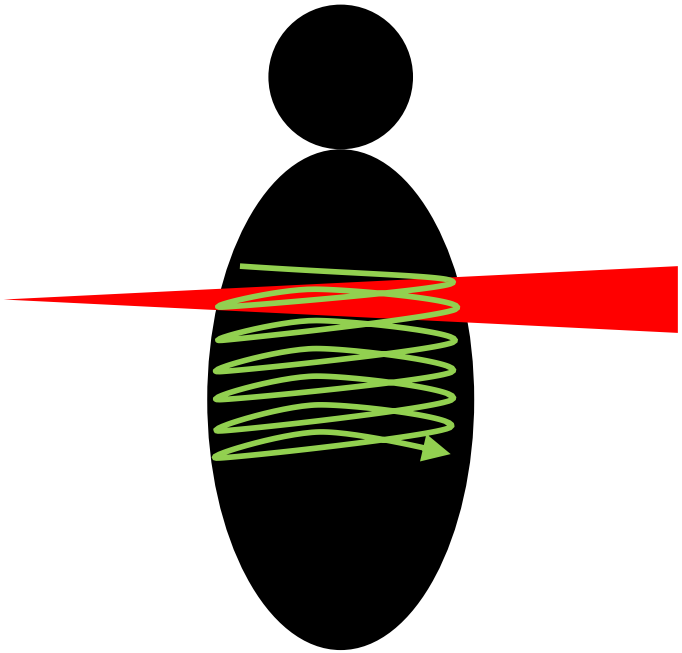


Rough comparison of imaging systems

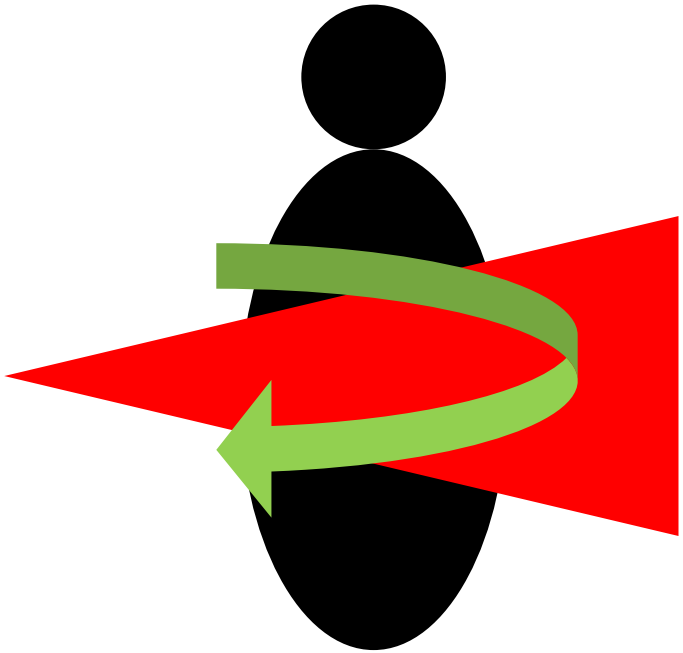
Rule of thumb: imaging dose goes as first approximation with the square of the voltage



FBCT and CBCT principles



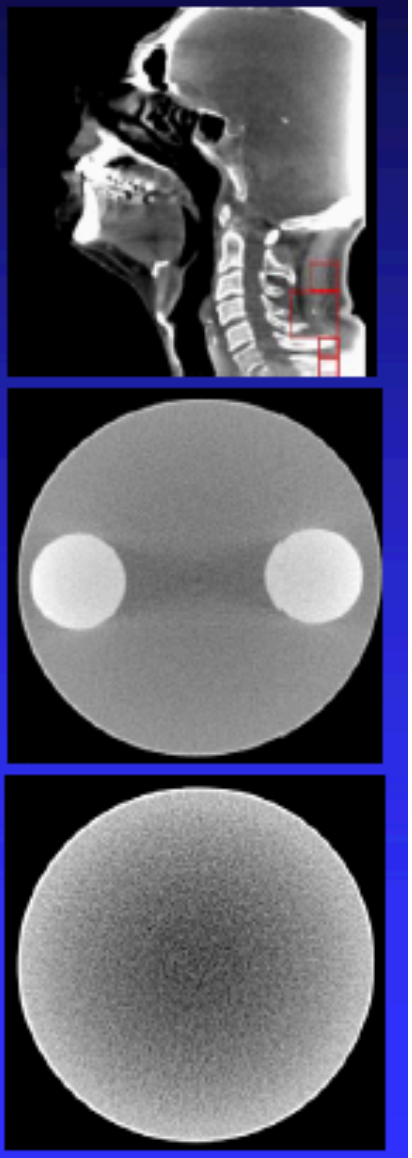
Fan beam
1D detector
Volume acquired with multiple rotations (helicoïdal acquisition)



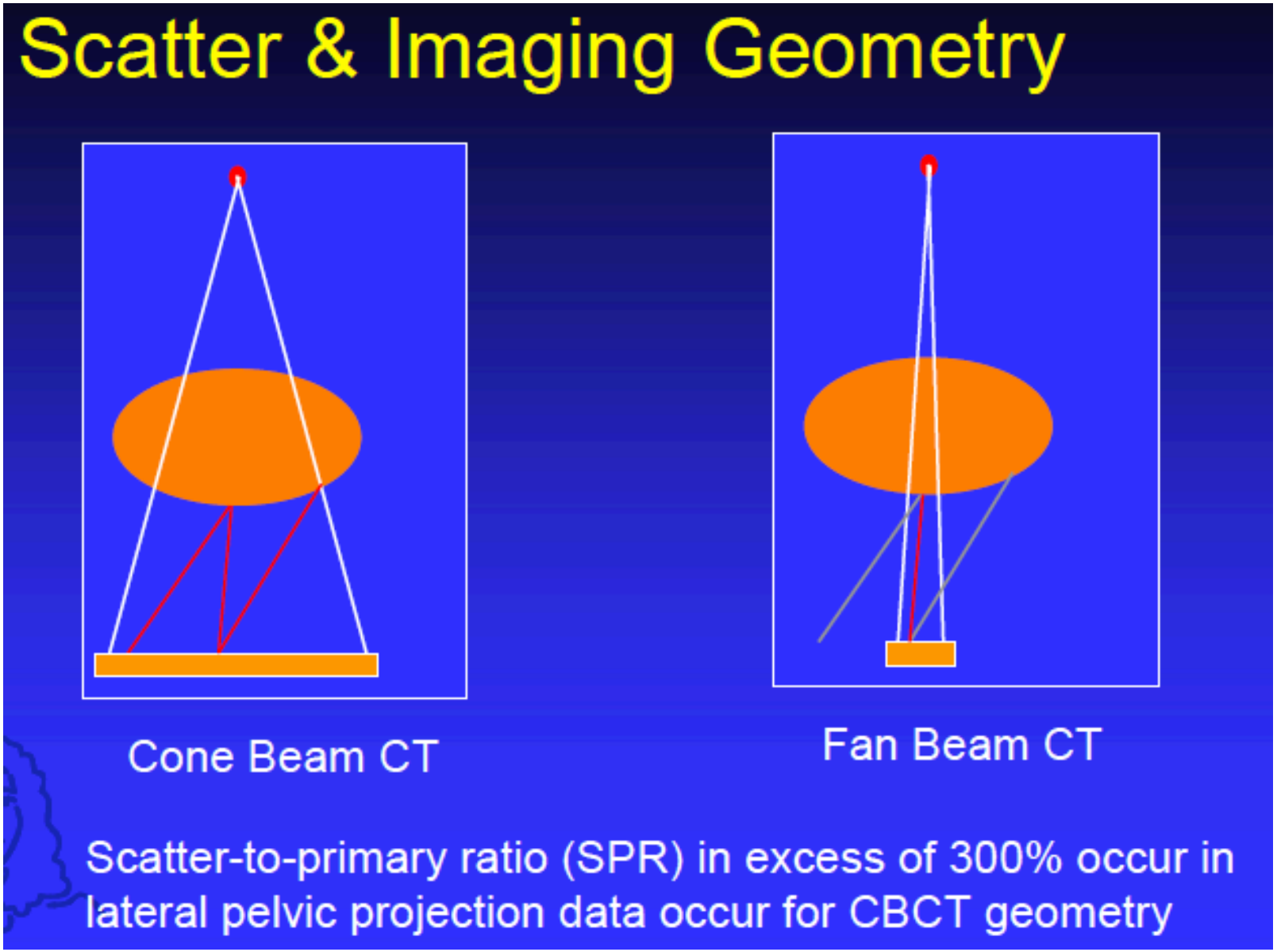
Cone beam
2D detector
Volume acquired in one rotation

CBCT issues

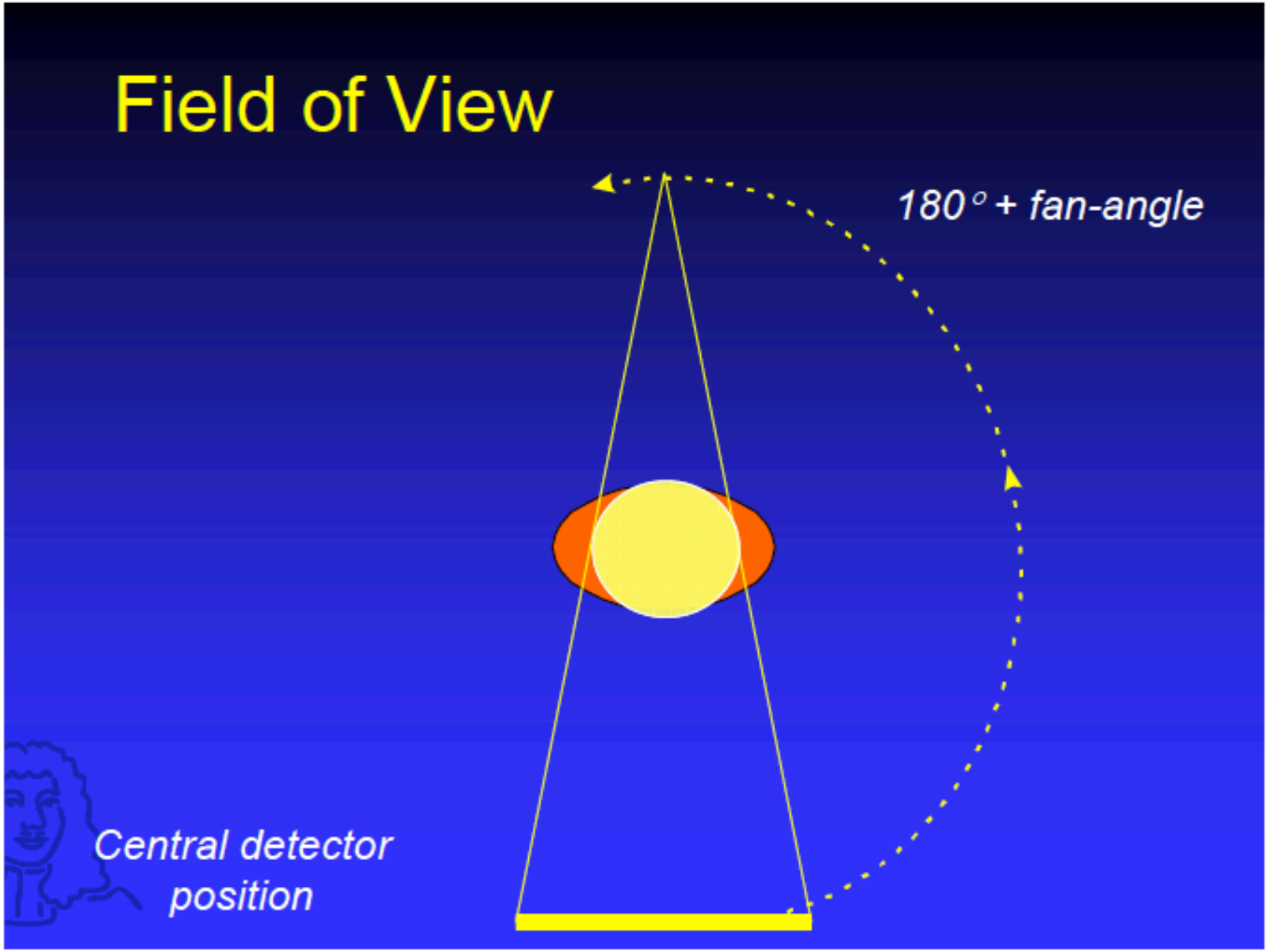
- Missing data (truncation)
  - Detector field of view 25 cm
- Scattered radiation
  - Extra signal not from local anatomy
  - Adds noise !
- Beam hardening
  - Attenuation of patient smaller than expected
- Ghosting
  - High exposure signal gives residual extra signal later



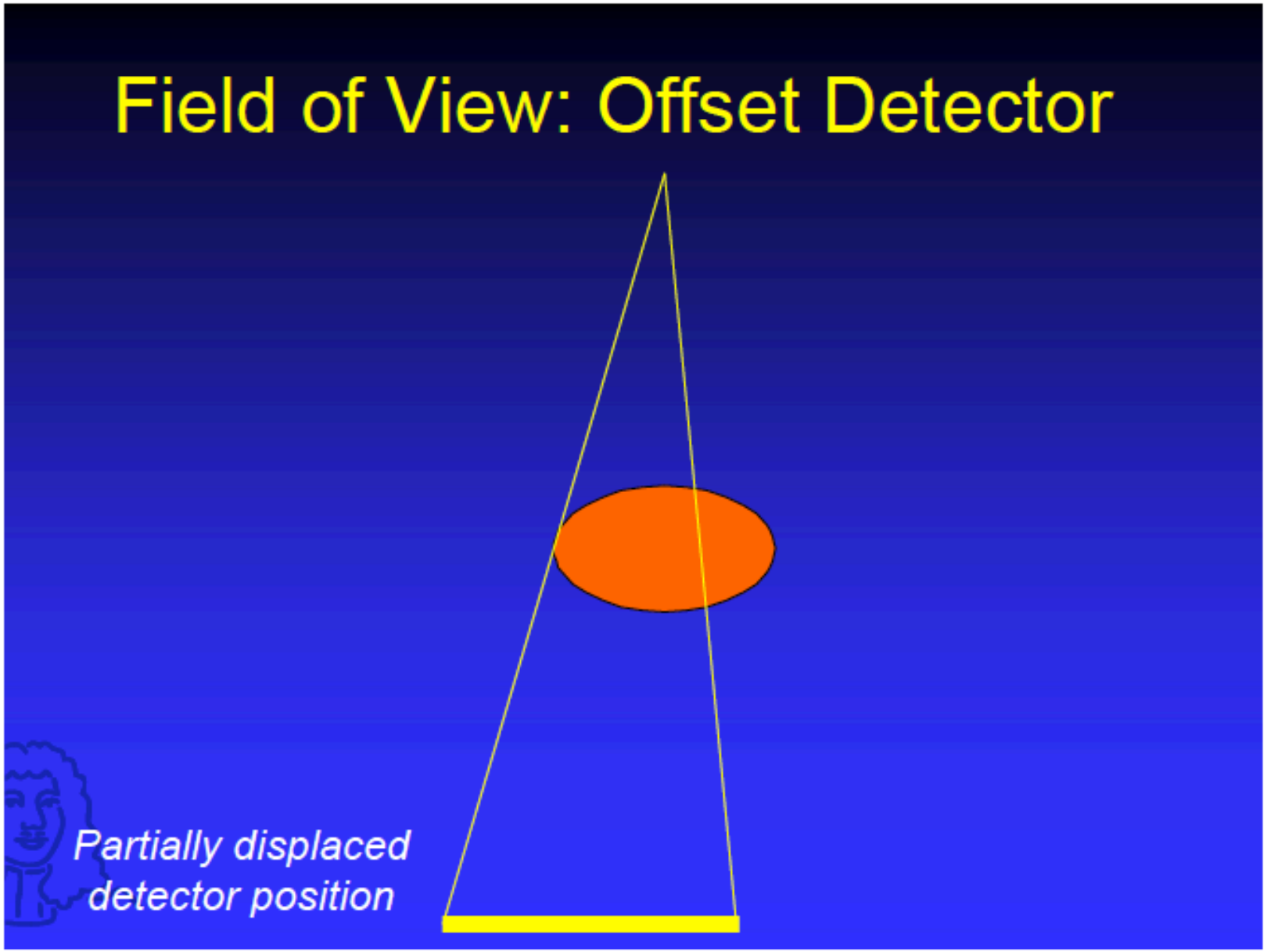
Scatter to primary ratio



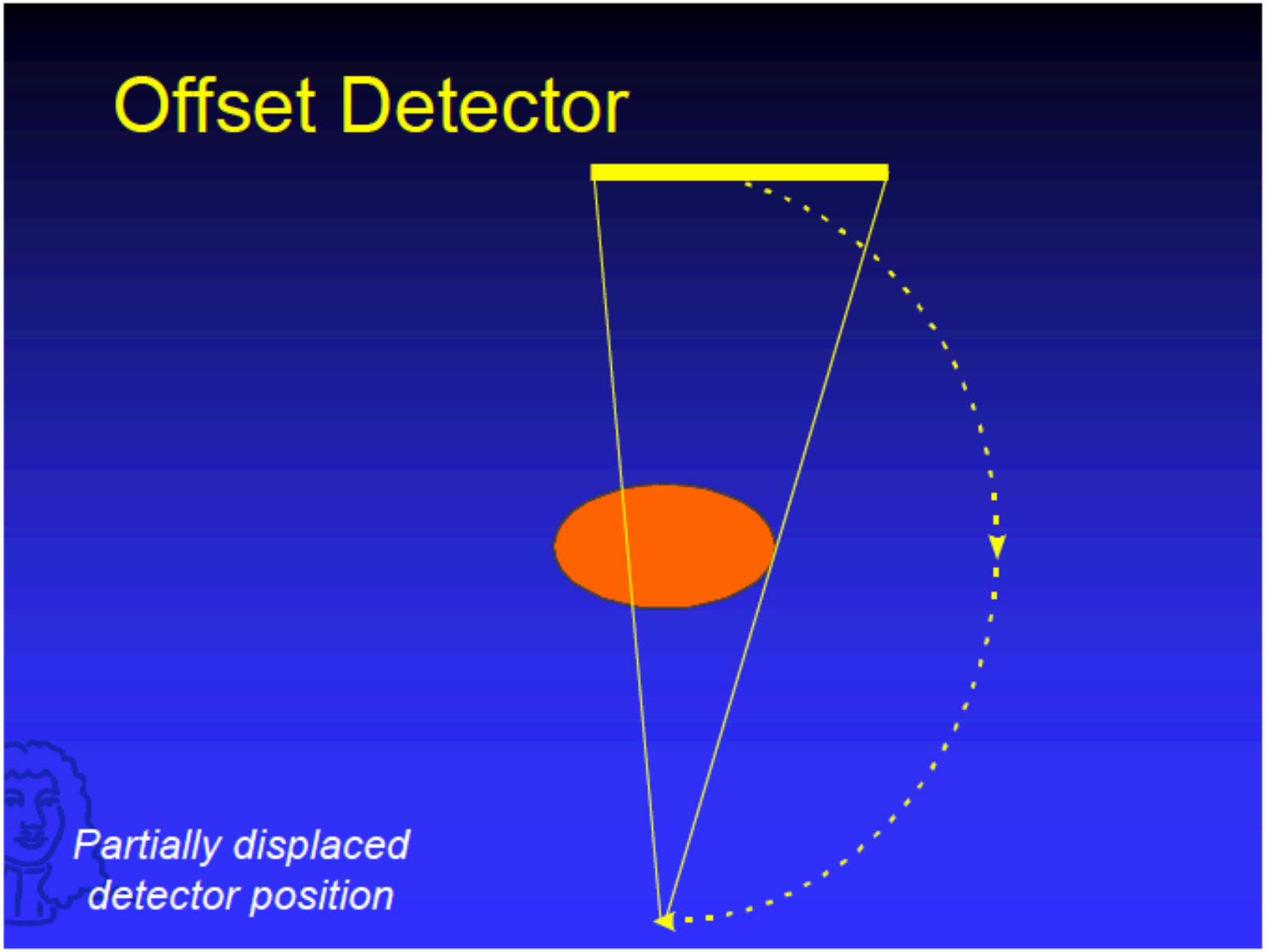
Reduced field-of-view in CBCT systems



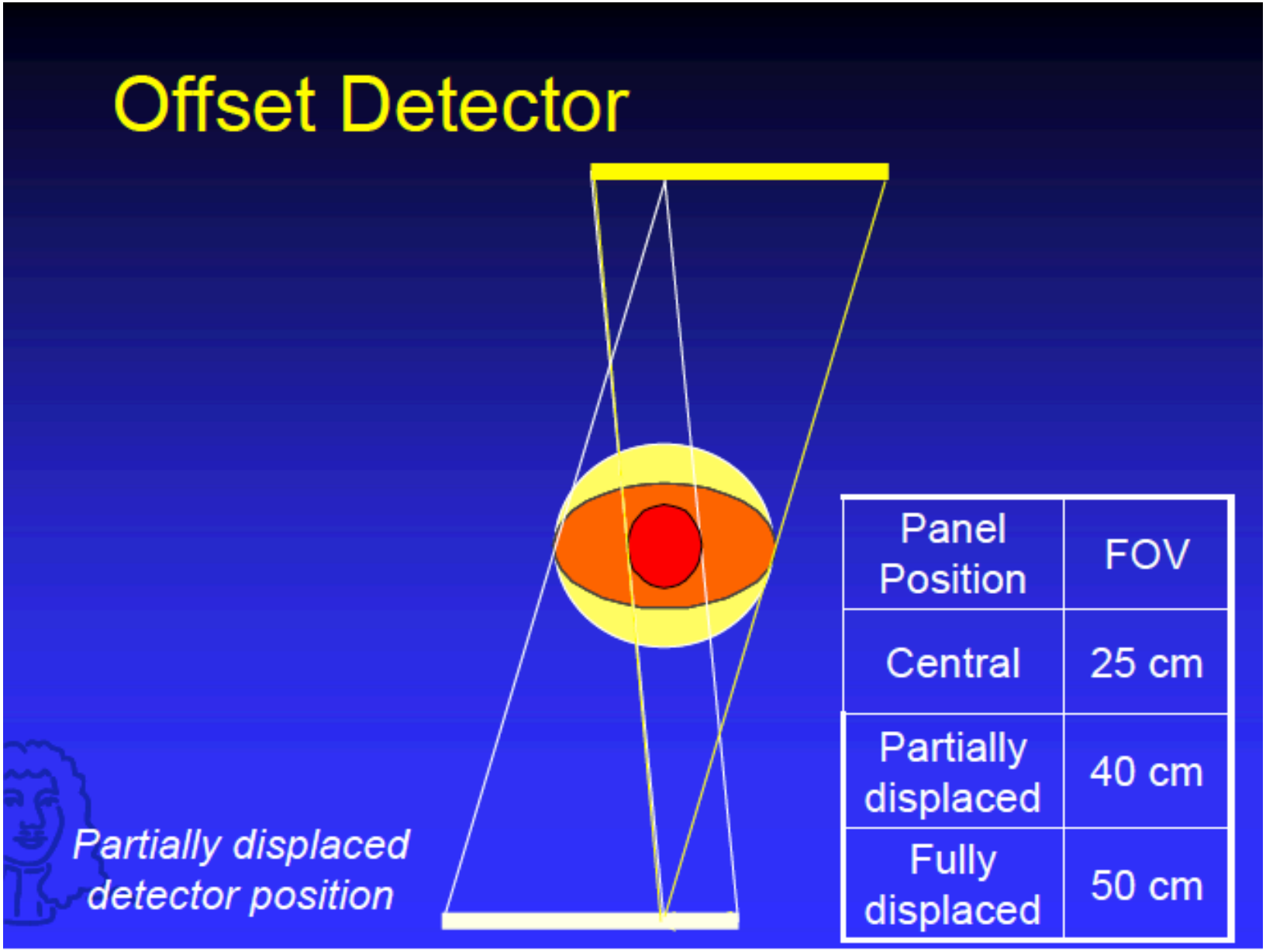
Increase field-of-view



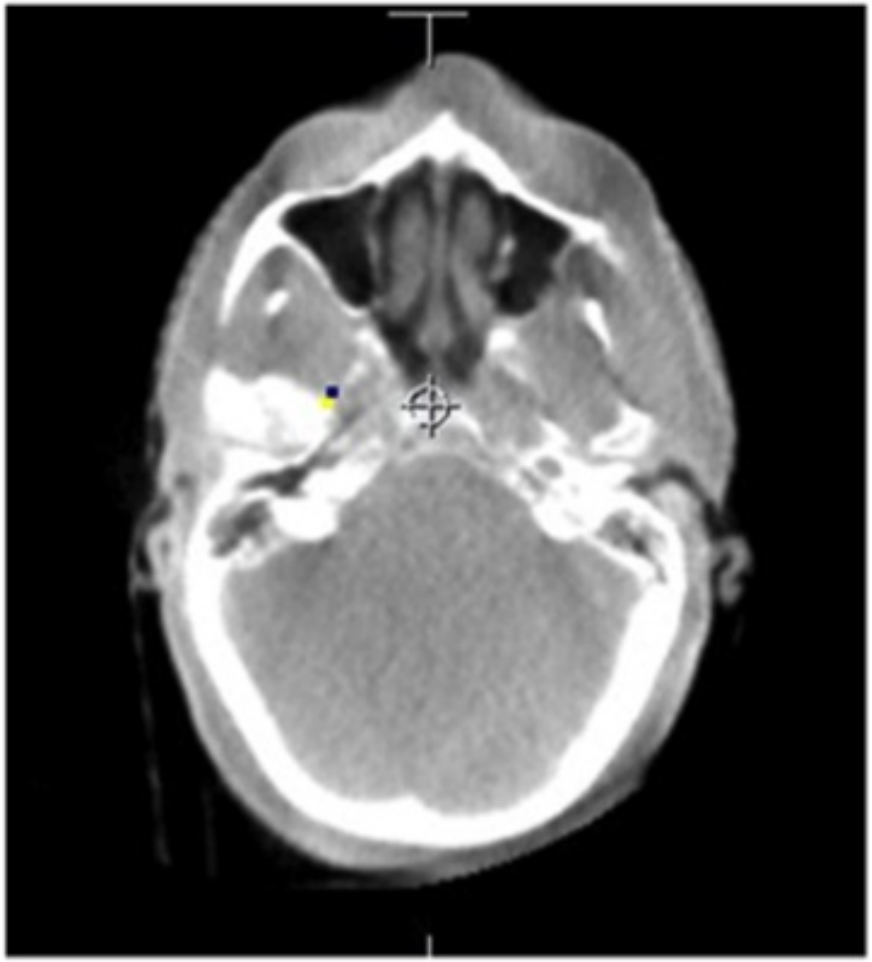
Increase field-of-view



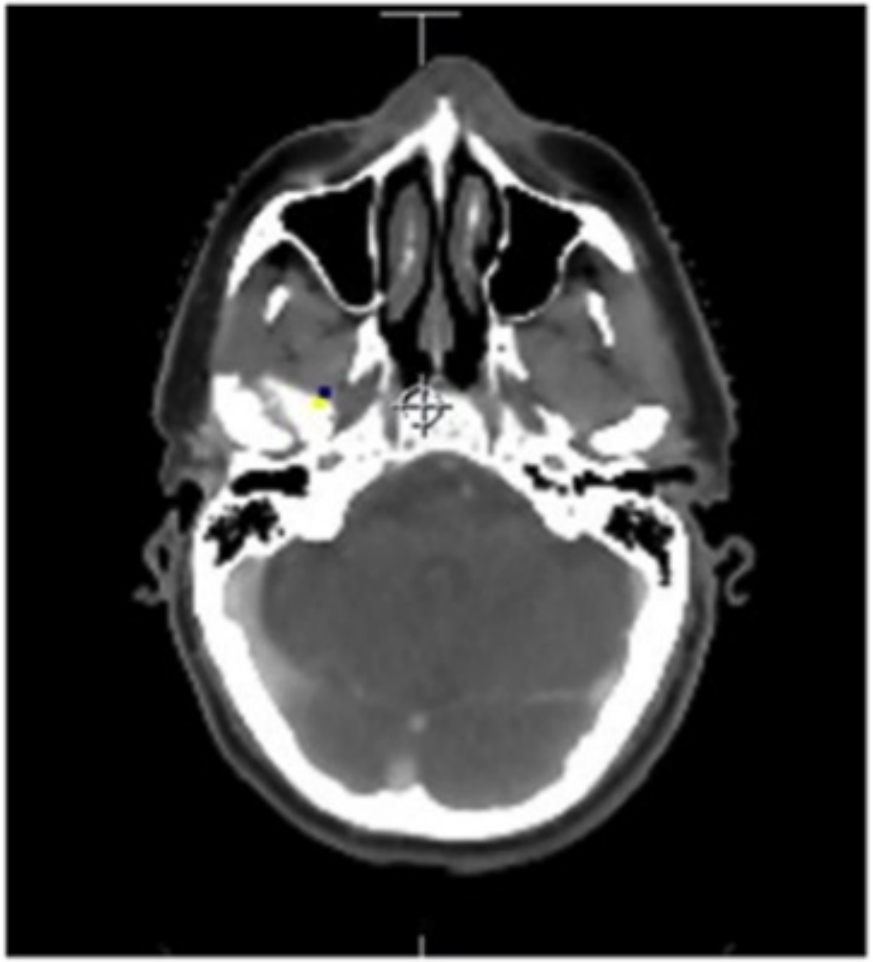
Increase field-of-view



Fan beam KVCT vs Cone beam KVCT



Cone Beam CT

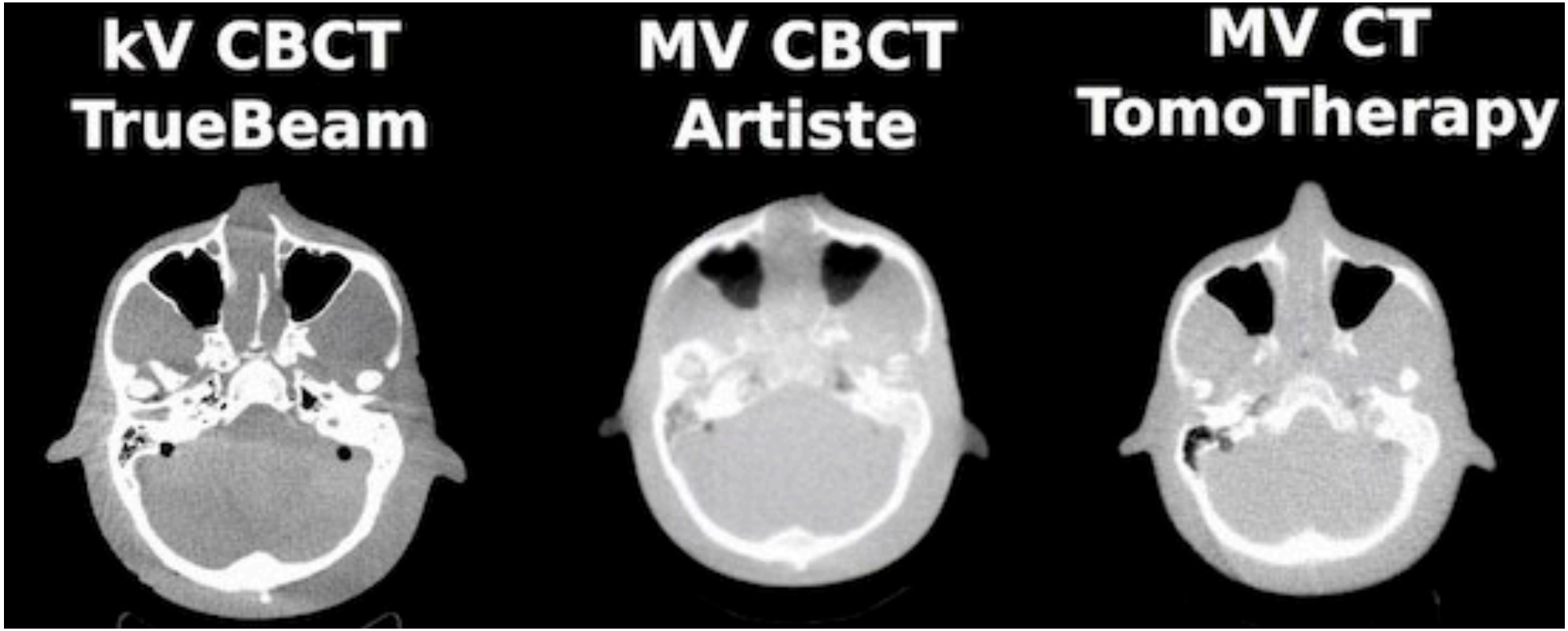


Fan Beam CT

Cone Beam CT vs. Fan Beam CT: A Comparison of Image Quality and Dose Delivered Between Two Differing CT Imaging Modalities

Lawrence Lechuga [1], Georg A. Weidlich [2]

Comparison of imaging systems



JOURNAL OF APPLIED CLINICAL MEDICAL PHYSICS, VOLUME 17, NUMBER 2, 2016

Assessment of image quality and dose calculation accuracy on kV CBCT, MV CBCT, and MV CT images for urgent palliative radiotherapy treatments

Mareike Held,[1] Florian Cremers,[2] Penny K. Sneed,[1] Steve Braunstein,[1] Shannon E. Fogh,[1] Jean Nakamura,[1] Igor Barani,[1] Angelica Perez-Andujar,[1] Jean Pouliot,[1] and Olivier Morin[1a]
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Comparison of imaging systems

Feasibility study on effect and stability of adaptive radiotherapy on kilovoltage cone beam CT

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[2] Department of Medical Physics, University of Wisconsin, Madison, WI, USA
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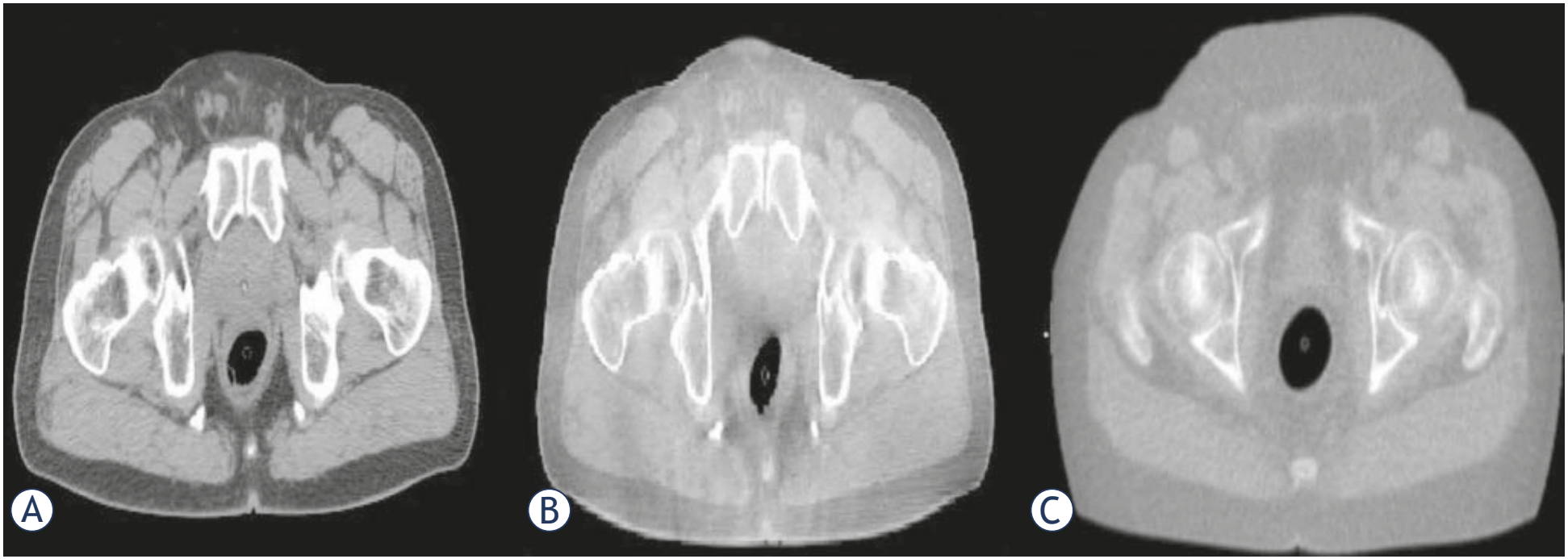
Received 7 February 2011
Accepted 24 March 2011



Fan beam KVCT

Cone beam KVCT

Fan beam MVCT

Metal artifacts

Topical Review

Metal artifacts in computed tomography for radiation therapy planning: dosimetric effects and impact of metal artifact reduction

Drosoula Giantsoudi[1], Bruno De Man[2], Joost Verburg[1], Alexei Trofimov[1], Yannan Jin[2], Ge Wang[3], Lars Gjesteby[3] and Harald Paganetti[1]

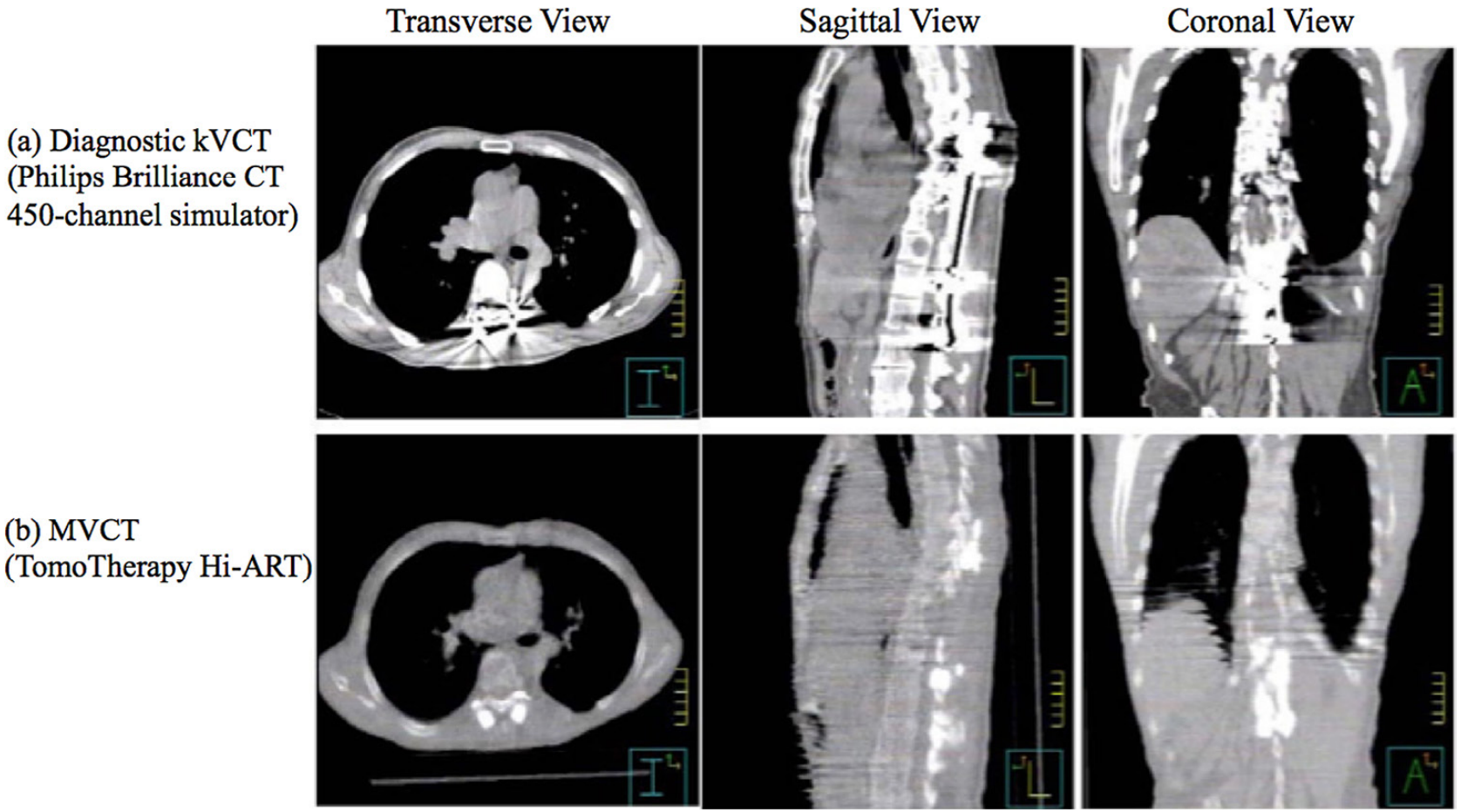
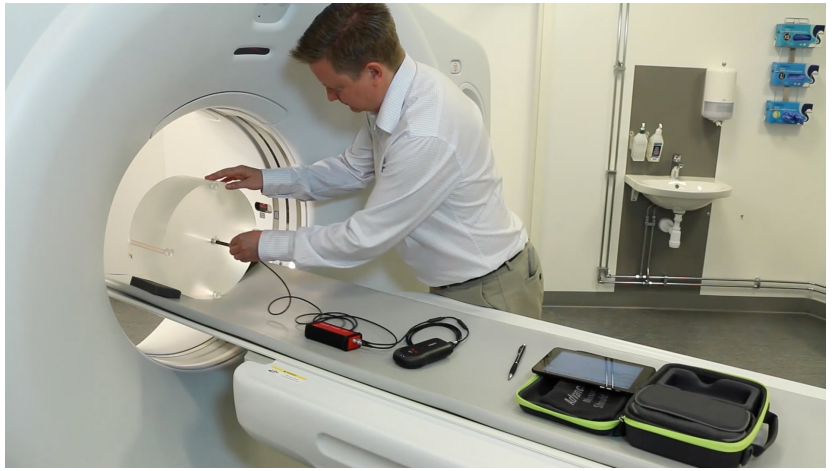


Figure 9. Diagnostic kVCT scan (a) and MVCT scan (b) on the TomoTherapy Hi-Art system for a patient with metal implants in the spine (Reproduced with permission from Rong *et al* 2011. CC BY 3.0).

Quantities for imaging doses



$CTDI_{100}$: average dose imparted by a single axial acquisition to a standard 100 mm pencil chamber dosimeter inside a PMMA phantom

$CTDI_{100} = \int_{-50mm}^{50mm} \frac{D(z)}{ST} dz$ where ST is the slice thickness

$CTDI_w$: $1/3CTDI_{100}^{central} + 2/3CTDI_{100}^{peripheral}$

$CTDI_{vol} = CTDI_w/PITCH$ (used for CT only)

https://www.youtube.com/watch?v=Ip9W8Z5B7fo

Imaging doses

Radiation Protection Dosimetry (2008), Vol. 132, No. 3, pp. 339–345 doi:10.1093/rpd/ncn305
Advance Access publication 13 December 2008

COMPARISON OF RADIATION DOSES BETWEEN CONE BEAM CT AND MULTI DETECTOR CT: TLD MEASUREMENTS

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Received September 8 2008, revised November 18 2008, accepted November 20 2008

Table 3. Comparison of $CTDI_w^{CBCT}$, $CTDI_w^{CBCT}$ per 100 mAs, $CTDI_{vol}^{MDCT}$, $CTDI_{vol}^{MDCT}$ per 100 mAs and console displayed $CTDI_{vol}^{MDCT}$ for the head and body phantoms.

Scan protocols	CBCT			MDCT			
	Measurements (mGy)			Measurements (mGy)		Console display	
	$CTDI_w^{CBCT}$		$CTDI_w^{CBCT}$ per 100 mAs	$CTDI_{vol}^{MDCT}$	$CTDI_{vol}^{MDCT}$ per 100 mAs	$CTDI_{vol}^{MDCT}$	Difference (%)
	This Study	Song *et al.*					
Head	89.7 ± 4.0	83	6.69 ± 0.30	137.0 ± 7.4	31.6 ± 1.7	106.0	23
Body	37.9 ± 1.4	54	2.84 ± 0.10	74.3 ± 5.3	17.2 ± 1.2	47.4	36

MDCT: conventional CT (multi-detector CT)

Imaging doses

JR Sykes[1], R Lindsay[1], G Iball[1] and DI Thwaites[12]
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Table 1: Cone Beam dose measurements (similar to $CTDI_w$) for standard imaging protocols on the Varian OBI and Elekta Synergy CBCT systems published in the UK Centre of Evidence Based Purchasing report [28]. Manufacturers recommended protocol settings may change over time based on the introduction of new technology or feedback from customers.

Varian OBI Imaging Protocol	Dose (mGy)	Elekta Synergy Imaging Protocol	Dose (mGy)
Low Dose Head	2.8	Low Dose Head	1.4
Standard Dose Head	5.6	Medium Dose Head	5.4
High Quality Head	27.8	High Dose Head	9.4
Pelvis	24.9	Pelvis M10	15.3
Pelvis Spotlight	20.2	Pelvis M15	12.5
		Pelvis M20	13.7

Table 2: Monte Carlo calculated patient doses (cGy) for three anatomical sites for the Elekta Synergy CBCT system and the Varian OBI CBCT system. Doses reported are for the body i.e. not to a specific organ.

	Pelvis/Abdomen	Head and Neck	Chest
Elekta XVI (Spezi *et al*) [8]	1.5 - 2.1	0.1 - 0.2	1.2 - 2.2
Varian OBI (Ding *et al*) [60]	1 - 5	3 - 9	2 - 9

Imaging doses (CBCT)

Review paper

Imaging dose from cone beam computed tomography in radiation therapy

Parham Alaei [a, *], Emiliano Spezi [b, c]

[a] University of Minnesota, Minneapolis, MN, USA
[b] School of Engineering, Cardiff University, Cardiff, Wales, UK
[c] Velindre Cancer Centre, Cardiff, Wales, UK

Kilovoltage CBCT	Manufacturer (Version, if specified)	kVp	mAs/acquisition	Phantom type	Dosimeter	Dose in phantom/ fraction (cGy)
Sykes [18]	Elekta XVI (v3.1)	130	0.56	Rando head	TLD	1.9–2.9
Islam [20]	Elekta XVI	100	2	Cylindrical (16 & 30 cm dia.)	Chamber	0.7–3.5
		120	2			
		140	2			
Amer [21]	Elekta XVI	100	0.1	Rando head	TLD	0.13
		120	0.4	Rando chest		0.72
		130	1.2	Rando pelvis		2.1
Wen [22]	Varian OBI	125	2	Rando pelvis	TLD	2.1–4.7
Kan [6]	Varian OBI	125	2	Female Rando head, chest, pelvis	TLD	3.6–6.7
		125	0.4			
Osei [25]	Varian OBI	125	2	Rando pelvis	TLD	3.0–11.5
Winey [26]	Varian OBI	125	1.6	CIRS Thorax	Chamber/OSL	2.4–9.1
Marinello [27]	Varian OBI	125	2	Rando	TLD/Gafchromic	4.7–6.2
Tomic [29]	Varian OBI (v1.4)	100	0.2	Rando head, chest, pelvis	Gafchromic	0.1–4.7 (surface)
		100	0.4			
		100	1.6			
		125	1.04			
		125	1.6			
Tomic [30]	Varian OBI (v1.4)	100	0.2	Rando head, chest, pelvis	Gafchromic	0.03–2.8 (surface)
		100	0.4			
		100	1.6			
		125	1.04			
		125	1.6			
Hyer [31]	Varian OBI (v1.4)	100	0.4	Male Anthro head, chest, pelvis	Scintillator	0.2–2.8
		110	0.4			
		125	1.04			
	Elekta XVI (v.4)	100	0.1			0.1–2.9
		120	1.6			
		120	2.56			
Palm [32]	Varian OBI (v1.3)	125	0.4	Female Rando head, chest, pelvis	TLD	8.7–13
		125	2			
	Varian OBI (v1.4)	125	1.04			0.25–3.42
		125	2			
		100	0.2			
		100	0.4			
		100	2			

Imaging doses (MVCT)

MSAD: MultiSlice Average dose

JOURNAL OF APPLIED CLINICAL MEDICAL PHYSICS, VOLUME 17, NUMBER 1, 2016

Evaluation of MVCT imaging dose levels during helical IGRT: comparison between ion chamber, TLD, and EBT3 films

Jean-Pierre Mege,[1a] Sun Wenzhao,[2] Attila Veres,[3] Guillaume Auzac,[1] Ibrahima Diallo,[4] Dimitri Lefkopoulos[1]

Table 3. MSAD (for 1 MVCT) evaluated with radiochromic films for three anatomical regions (ATOM phantom) and comparison with the doses obtained in the cylindrical phantom. For comparison, results obtained by Shah et al.[33] for different localizations.

	Our Measurements			*Shah[33]*
	Fine	*Normal*	*Coarse*	*Normal Mode*
		Head & Neck		
Average MSAD (cGy)	3.9±0.3	2.1±0.2	1.4±0.1	1.45
MSAD range	[3.5-4.5]	[1.5-2.7]	[1-1.8]	(parotids)
Maximal dose / Central dose	1.15	1.3	1.3	1.2
		Thorax		
Average MSAD (cGy)	3.5±0.3	2±0.2	1.3±0.1	1.14
MSAD range	[3 - 4.1]	[1.5-2.6]	[0.9-2.1]	(lungs)
Maximal dose / Central dose	1.17	1.3	1.6	1.44
		Abdomen		
Average MSAD (cGy)	3.3±0.3	1.7±0.2	1.2±0.1	1.05
MSAD range	[2.8-4.1]	[1.3-2.3]	[0.7-1.9]	(bladder)
Maximal dose / Central dose	1.24	1.35	1.6	1.25
Cylindrical phantom ϕ = 30 cm $MSAD_w$ (cGy)	3	1.5	1.1	1.06
Maximal dose / Central dose	1.26	1.21	1.5	1.08

Under certain conditions, the MSAD is approximately equivalent to $CTDI_{vol}$

Global comparison

JOURNAL OF APPLIED CLINICAL MEDICAL PHYSICS, VOLUME 17, NUMBER 2, 2016

Assessment of image quality and dose calculation accuracy on kV CBCT, MV CBCT, and MV CT images for urgent palliative radiotherapy treatments

Mareike Held,[1] Florian Cremers,[2] Penny K. Sneed,[1] Steve Braunstein,[1] Shannon E. Fogh,[1] Jean Nakamura,[1] Igor Barani,[1] Angelica Perez-Andujar,[1] Jean Pouliot,[1] and Olivier Morin[1a]
Department of Radiation Oncology,[1] University of California San Francisco, CA, USA; Department of Radiation Oncology,[2] Universitätsklinikum Schleswig-Holstein, Lübeck, Germany
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Received 2 September, 2015; accepted 18 November, 2015

TABLE 2. Image dose, noise, CNR, uniformity, and spatial resolution.

	$CTDI_{vol}$ (cGy) rFOV/eFOV	*Noise*	*CNR (bone/water)*	*Uniformity*	*Spatial Resolution 50% cf (1/cm)*
kV CT (MX 8000)	0.20	0.53	161.5	0.1	4.1
kV CBCT (TrueBeam)	0.29/1.43[a]	2.10	52.2	-1.0	4.1
kV CBCT (Versa)	0.12/2.20[a]	3.07	36.7	6.7	2.1
MV CBCT (Artiste)	5.00/15.00[b]	1.91	14.9	-4.5	1.6
MV CT (Tomo)	~ 2.00[b]	3.14	15.7	0.0	2.1

[a] $CTDI_w$, [b] dose

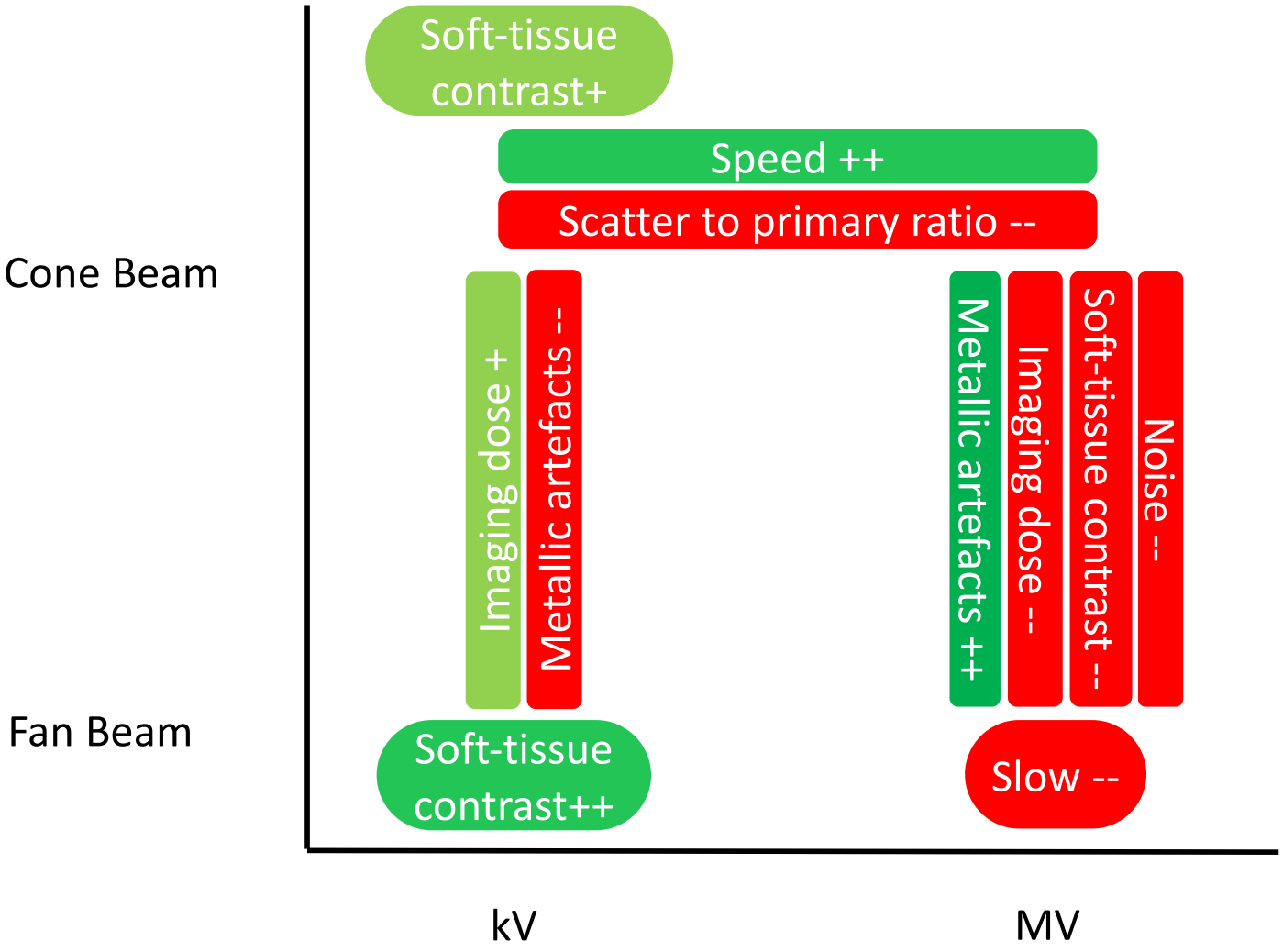
$CTDI_{vol} = CTDI_w/pitch$

Contrast to noise ratio

rFOV = regular FOV
eFOV = extended FOV

Rough comparison of imaging systems

+ means better
- means worse




The RT problem
Imaging systems
Image quantif.
QA
Proton therapy

Why do we need image quantification?

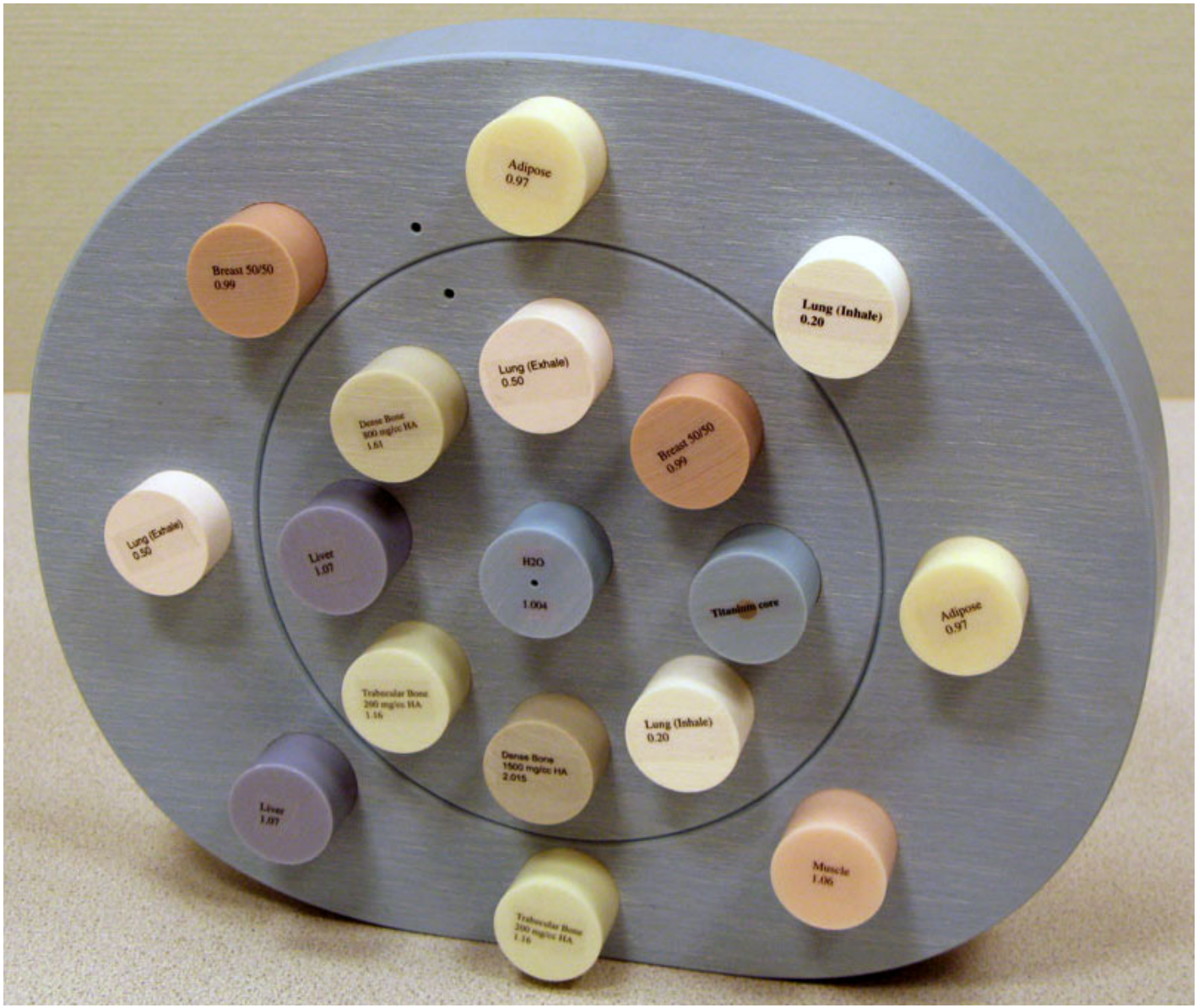
Having the imager on-board enables image acquisition in treatment position

This is a fantastic opportunity to estimate dose distributions in the patient using the most up-to-date anatomical data. It could enable **on-line** and **off-line** adaptive strategies. In such strategies, the quality of the image is an **essential** piece of the workflow

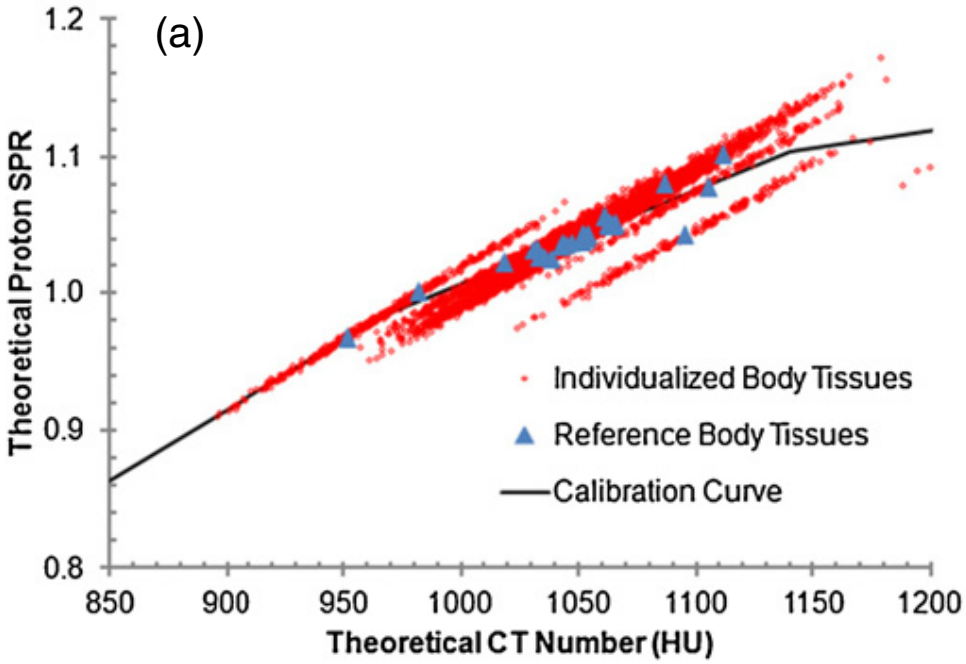
For computing dose distributions, accurate conversion of imaging data into physical quantities must be performed. We need to predict for every tissue:

- The attenuation of the photons for high energy X-rays
- The deceleration rate for high energy protons

Use of plastic inserts of known compositions and densities to calibrate the CT



A new comer: dual energy CT calibration



Comprehensive analysis of proton range uncertainties related to patient stopping-power-ratio estimation using the stoichiometric calibration

Ming Yang[1,2], X Ronald Zhu[1,2], Peter C Park[1,2], Uwe Titt[1,2], Radhe Mohan[1,2], Gary Virshup[3], James E Clayton[3] and Lei Dong[1,2,4]

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[2] Medical Physics Program, Graduate School of Biomedical Sciences, The University of Texas Health Science Center at Houston, 7000 Fannin St, Houston, TX 77030, USA
[3] Ginzton Technology Center, Varian Medical Systems, 3120 Hansen Way, Palo Alto, CA 94303, USA

There is no unicity between HU and atomic composition for a given CT energy. By acquiring images with several energies, it is possible to better characterize the tissues

There are multiple methods to convert DECT into quantities of interest

CBCT is not a good natural image quantifier

CBCT quantification depends on a number of parameters and issues, among which:

- Image acquisition parameters
- Image artefacts due to scatter, scanned object size, and number of projections

Take home messages

Imaging has three main functions in RT:

1. For delineating contours and organs-at-risk → **Visual quality!**
2. For computing the dose distributions → **Quantitative quality!**
3. For reducing uncertainties (positioning uncertainties, motion model, trigger replanning if necessary, …) → **Practical requirements (on-board, fast, …)**


The RT problem
Imaging systems
Image quantif.
QA
Proton therapy

What are the specificities of QA of imaging devices in radiotherapy?

What applies to radiology AND:

- Positioning consistency must be well ensured at all times → lasers placed for positioning must reflect actual position in the scanner
- For on-board imagers, the isocenter of the imaging device must remain aligned with the isocenter of the treatment device
- Geometrical distances must be consistent with baseline
- Image quantification must be properly checked, with a frequency and tolerances adapted to the device considered

QA protocols

Quality assurance for image-guided radiation therapy utilizing CT-based technologies: A report of the AAPM TG-179

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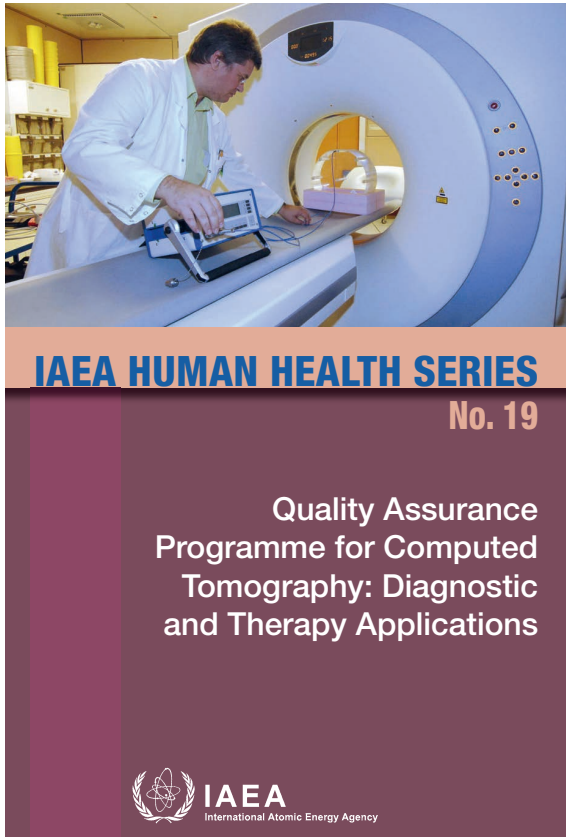

A quality assurance program for image quality of cone-beam CT guidance in radiation therapy

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ORIGINAL PAPER

Quality control in cone-beam computed tomography (CBCT) EFOMP-ESTRO-IAEA protocol (summary report)

Hugo de las Heras Gala[a,*], Alberto Torresin[b], Alexandru Dasu[c,d], Osvaldo Rampado[e], Harry Delis[f], Irene Hernández Girón[g], Chrysoula Theodorakou[h], Jonas Andersson[i], John Holroyd[j], Mats Nilsson[k], Sue Edyvean[l], Vesna Gershan[m], Lama Hadid-Beurrier[n], Christopher Hoog[o], Gregory Delpon[p], Ismael Sancho Kolster[q], Primož Peterlin[r], Julia Garayoa Roca[s], Paola Caprile[t], Costas Zervides[u,v]

QA FOR RT SUPPLEMENT

QUALITY ASSURANCE FOR THE GEOMETRIC ACCURACY OF CONE-BEAM CT GUIDANCE IN RADIATION THERAPY

JEAN-PIERRE BISSONNETTE, PH.D., DOUG MOSELEY, PH.D., ELIZABETH WHITE, B.SC., MICHAEL SHARPE, PH.D., TOM PURDIE, PH.D., AND DAVID A. JAFFRAY, PH.D.

Radiation Medicine Program, Princess Margaret Hospital, Toronto, Ontario, Canada

The introduction of volumetric X-ray image-guided radiotherapy systems allows improved management of geometric variations in patient setup and internal organ motion. As these systems become a routine clinical modality, we propose a daily quality assurance (QA) program for cone-beam computed tomography (CBCT) integrated with a linear accelerator. The image-guided system used in this work combines a linear accelerator with conventional X-ray tube and an amorphous silicon flat-panel detector mounted orthogonally from the accelerator central beam axis. This article focuses on daily QA protocols germane to geometric accuracy of the CBCT systems and proposes tolerance levels on the basis of more than 3 years of experience with seven CBCT systems used in our clinic. Monthly geometric calibration tests demonstrate the long-term stability of the flex movements, which are reproducible within ±0.5 mm (95% confidence interval). The daily QA procedure demonstrates that, for rigid phantoms, the accuracy of the image-guided process can be within 1 mm on average, with a 99% confidence interval of ±2 mm.

CBCT QA

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Table 1
Summary of recommended image quality tests.

Parameter	Procedures	Frequency*			Action level		
		Dental	Interventional radiology	Radiotherapy	Dental	Interven-tional rad.	Radiotherapy
3.1 Uniformity	XYZ uniformity curves	Annual		Monthly	Manufacturer specifications, or >10% difference air water		Deviation from baseline >10 HU
	DIN method				Uniformity parameter U < 5		
3.2 Geometrical precision	Geometrical accuracy	Annual (or none)		Monthly	>1 mm	>2 mm	>2 mm for conventional
	Linearity						
	Spatial Stability	(not relevant)		Monthly (coincidence of isocentres daily)	(not relevant)	(not relevant)	treatments, >1 mm for SRS/SBRT
3.3 Voxel density values	Voxel values for different materials	Annual		Monthly	Manufacturer specifications, or >25% difference air water	Deviations >50 HU from the baseline value (still under research)	
3.4 Noise	ROI standard deviation	Annual		Monthly	Differences from baseline >20%		
3.5 Low contrast resolution	Contrast-to-noise ratio	Annual			Differences from baseline >40%		
					Acceptance indicator <100§		
3.6 Spatial resolution	Frequency at 10% of the modulation transfer function	Annual			<10 lp/cm (high resolution mode)	<5 lp/cm	

* Depending on the complexity of the treatment techniques used and the weight of CBCT for image guidance, the monthly tests in radiotherapy facilities may be carried out quarterly or every half a year. In addition to the indicated frequency, the tests should be performed at acceptance of the device as well as after maintenance work or upgrades that could affect the integrity of the system.

CBCT QA

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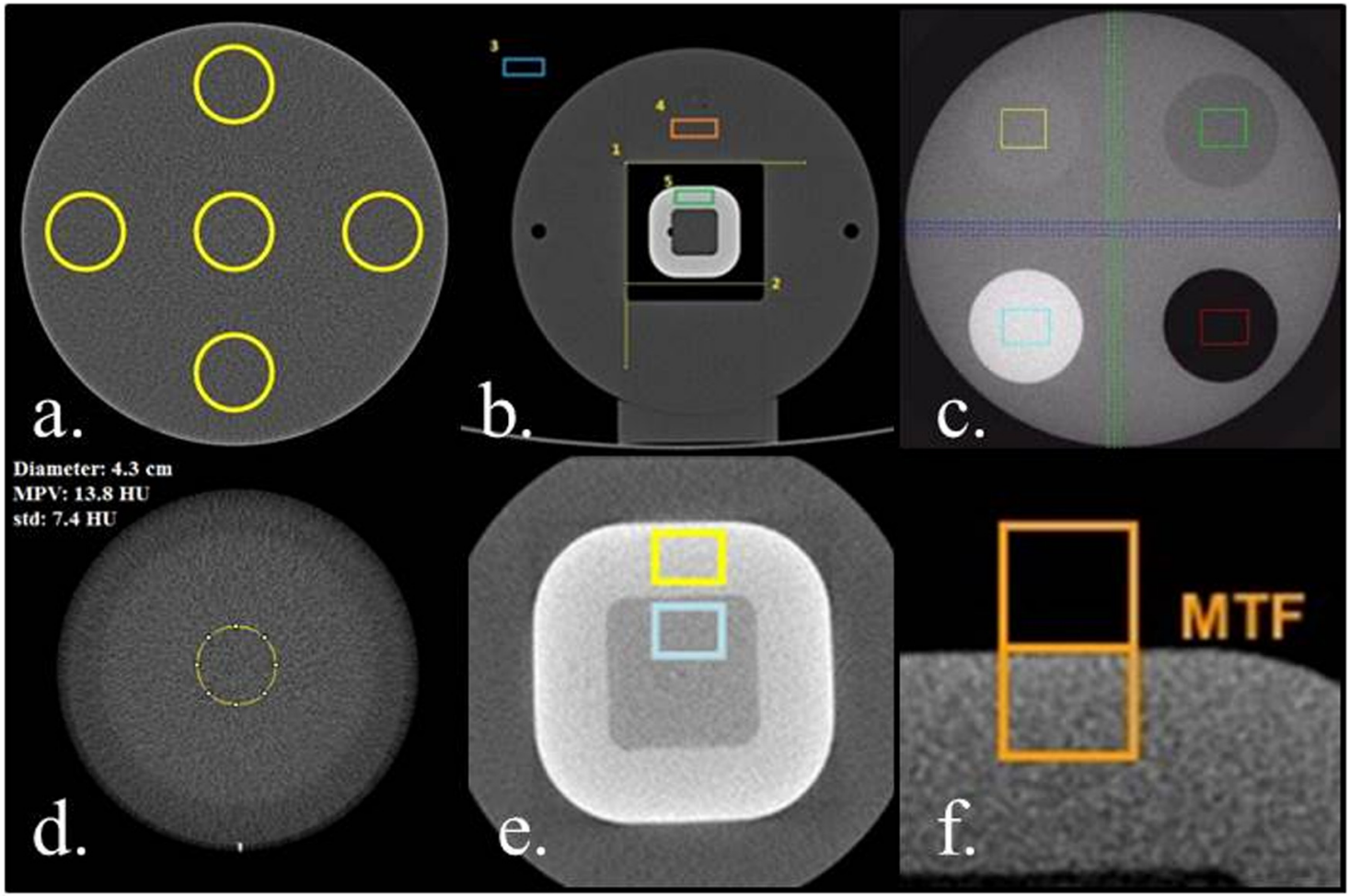
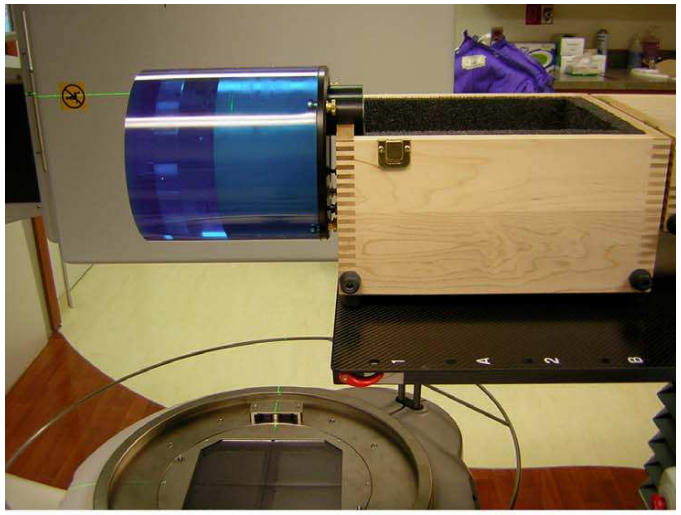


Fig. 2. An example of the measurement of uniformity (a), geometrical linearity (b), density values or Hounsfield units (c), noise (d), contrast-to-noise ratio (e) and modulation transfer function (f).

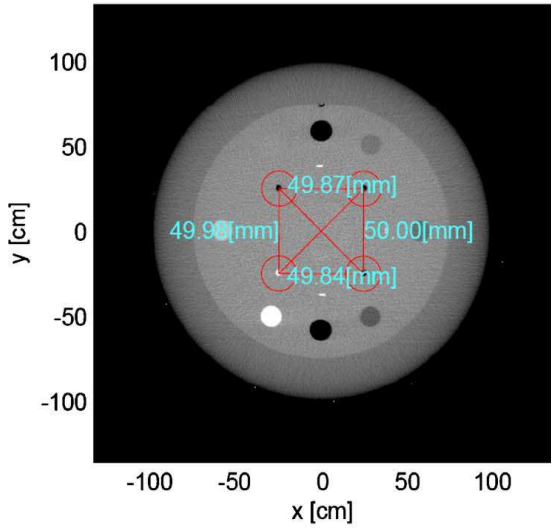
CBCT QA

A quality assurance program for image quality of cone-beam CT guidance in radiation therapy

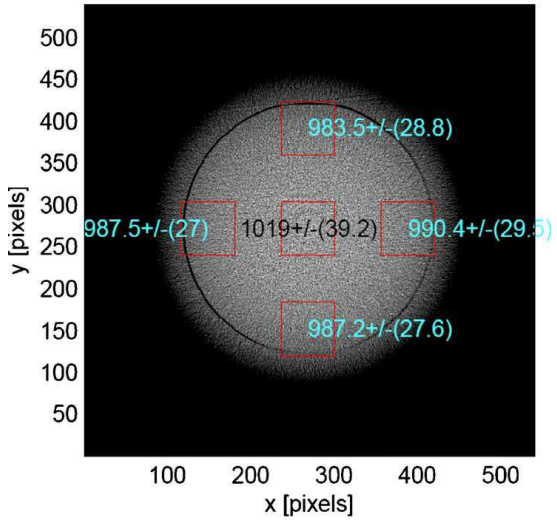
Jean-Pierre Bissonnette,[a)] Douglas J. Moseley, and David A. Jaffray
Radiation Medicine Program, Princess Margaret Hospital, 610 University Avenue, Toronto, Ontario M5G 2M9, Canada



(a)



(c)



(d)

Images acquired with volumetric CT showing the definition of QA metrics used to analyze image quality. A) Image of the CatPhan phantom. C) Verification of image scale. D) Assessment of image uniformity.

CBCT QA

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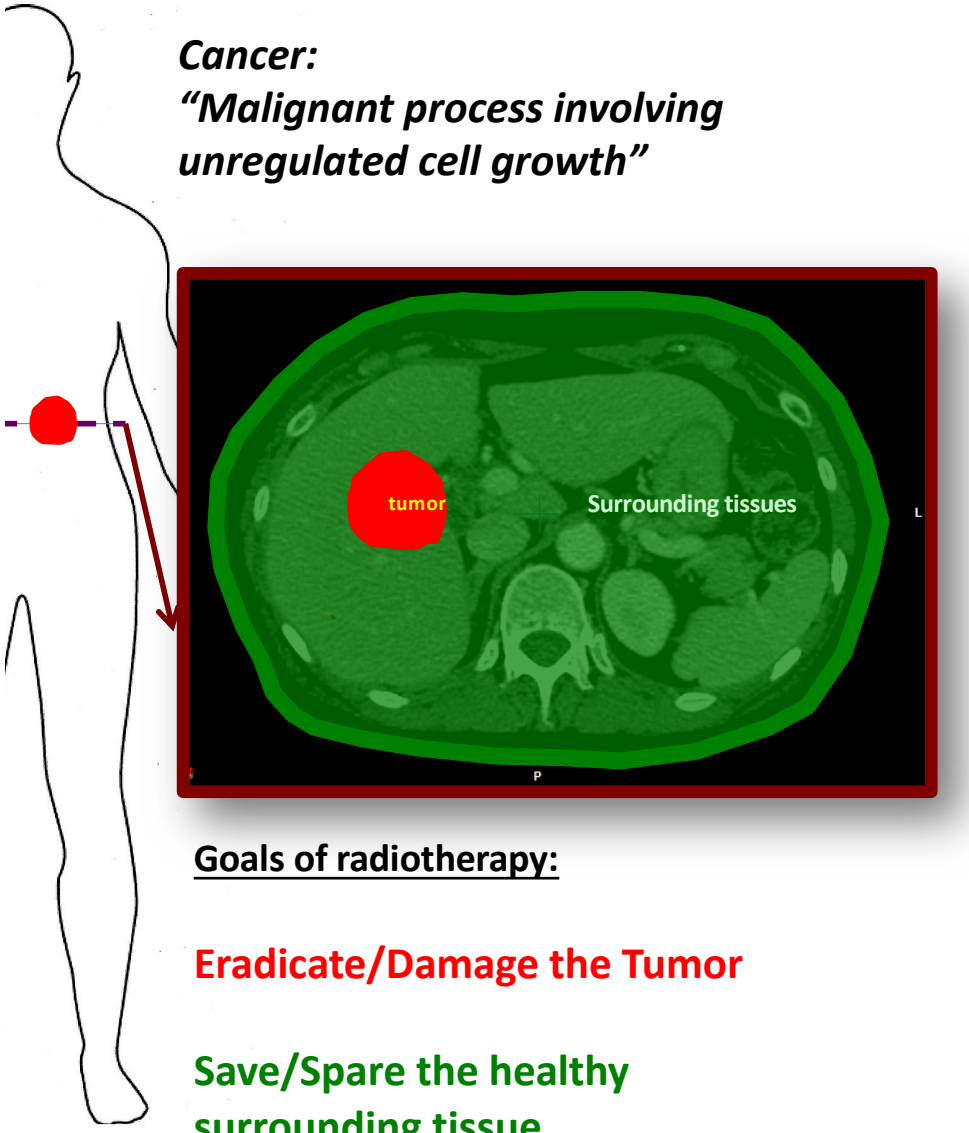
TABLE I. Recommended image quality QA for a kilovoltage imaging system mounted on an accelerator. Tolerances and frequency may change according to expectations, experience, and performance. Tests denoted with an asterisk indicate minimal tests required after replacing system components.

Frequency	Procedure	Tolerance
Daily or each use	Detector stability and system performance	
	Dark image calibration acquisition before each scan	
Six-monthly or after service	Imaging system performance	
	Gain stability*	Replace/refresh
	Defect maps*	Replace/refresh
	Image quality	
	Scale and distances*	±1 mm
	Uniformity	Baseline
	High contrast spatial resolution*	2 mm
	CT number accuracy	Baseline
	Low contrast detectability	Baseline
	Artifacts*	Absence
Annual or after service	Review of daily and monthly test results	Complete


The RT problem
Imaging systems
Image quantif.
QA
Proton therapy

Dose sculpting: spatial differentiation between normal tissue and tumor

Cancer:
"Malignant process involving unregulated cell growth"



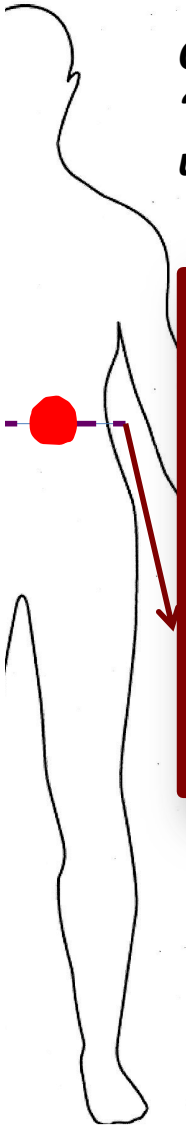
Goals of radiotherapy:

Eradicate/Damage the Tumor

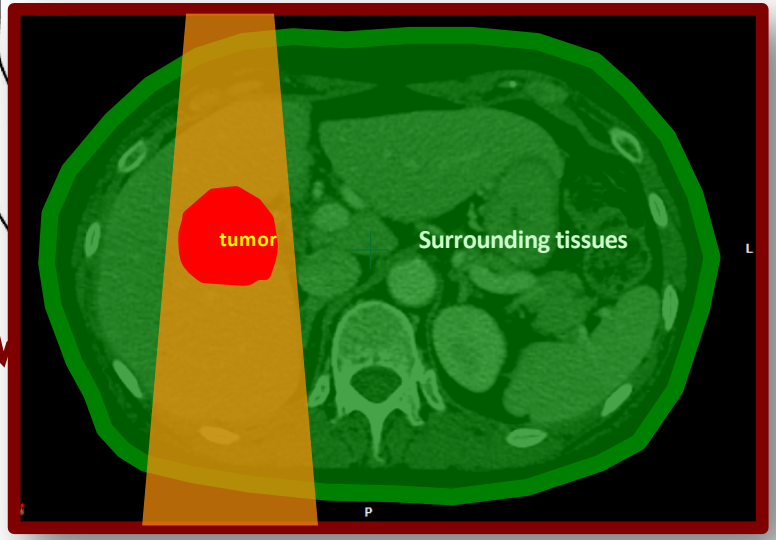
Save/Spare the healthy surrounding tissue

From T. Depuydt

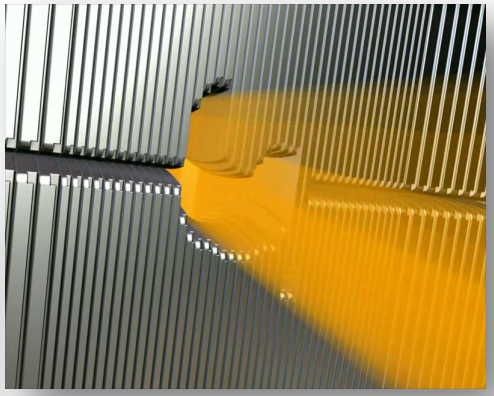
Dose sculpting: spatial differentiation between normal tissue and tumor

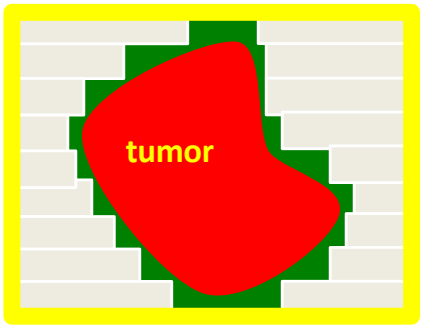


Cancer:
"Malignant process involving unregulated cell growth"



"Shaping" of the beam with a multi-leaf collimator





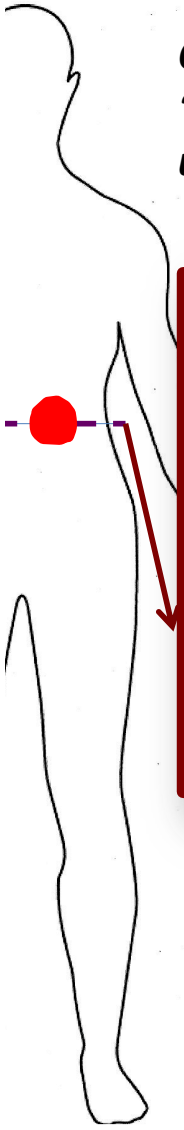
Goals of radiotherapy:

Eradicate/Damage the Tumor

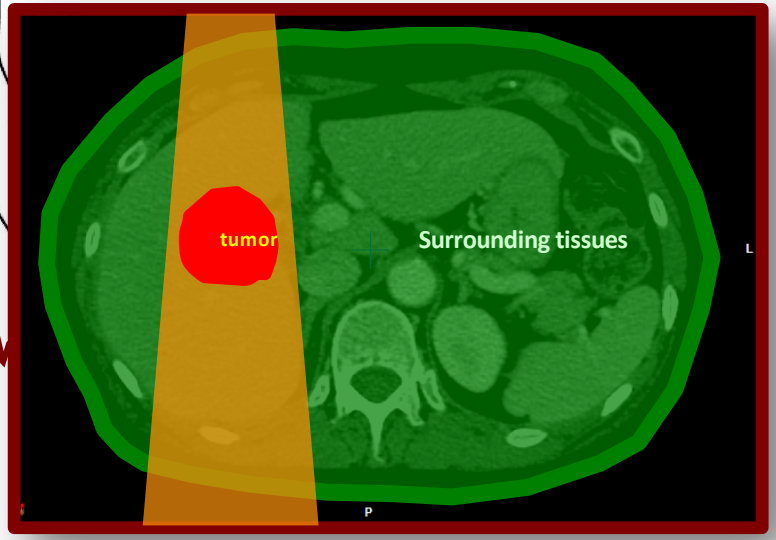
Save/Spare the healthy surrounding tissue

From T. Depuydt

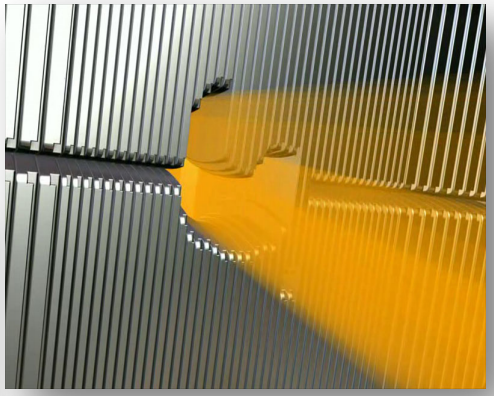
Dose sculpting: spatial differentiation between normal tissue and tumor

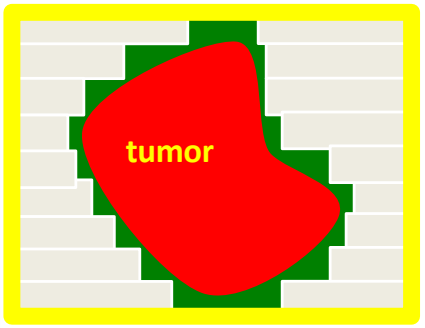


Cancer:
"Malignant process involving unregulated cell growth"

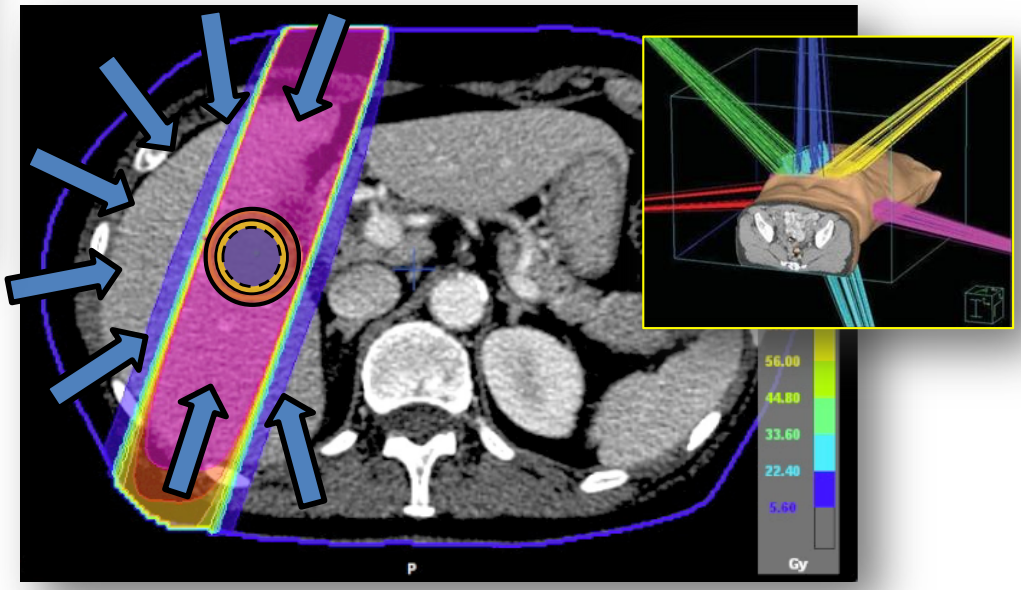


"Shaping" of the beam with a multi-leaf collimator





Multiple beam orientations, coinciding in the tumor



Goals of radiotherapy:

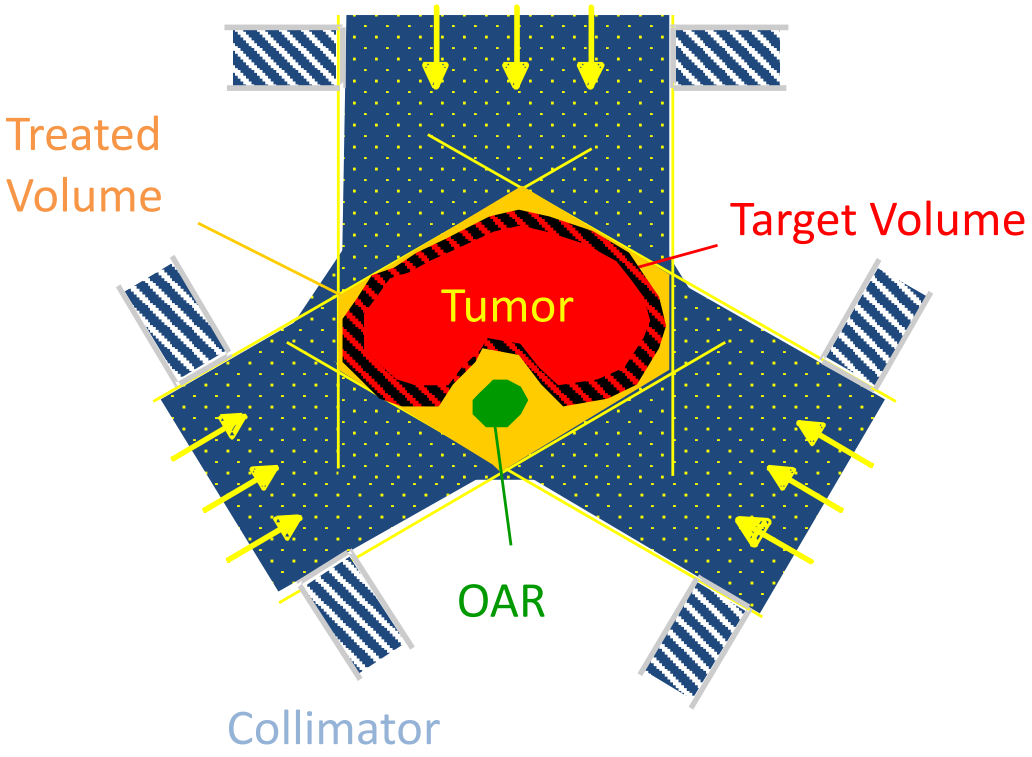
Eradicate/Damage the Tumor

Save/Spare the healthy surrounding tissue

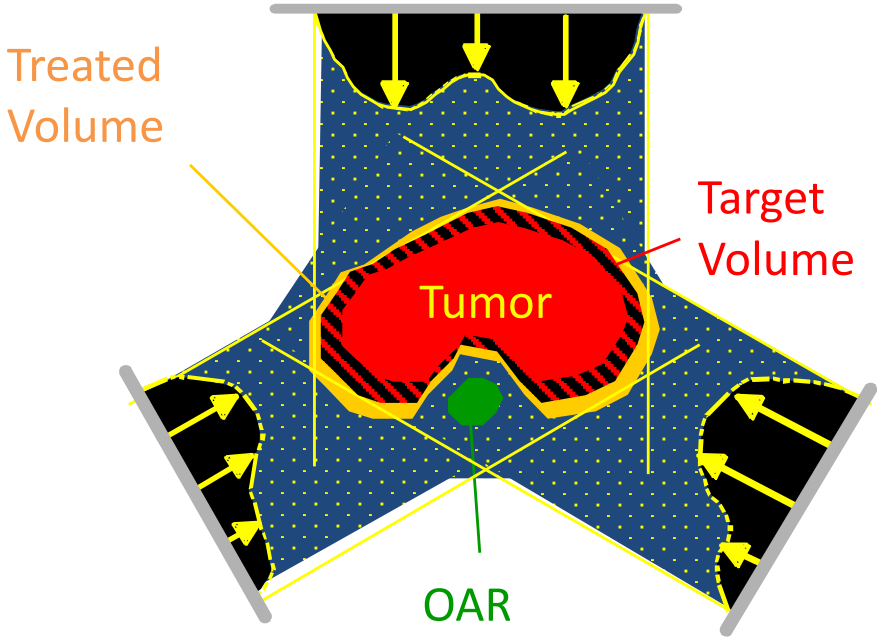
From T. Depuydt

Intensity modulation

"Classical" Conformation



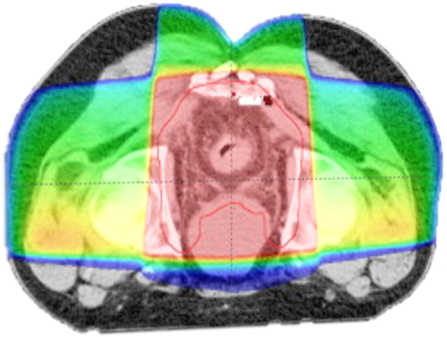
Intensity Modulation



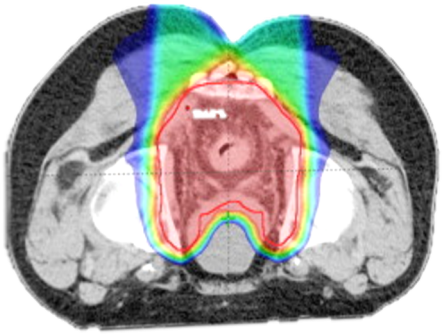
From T. Depuydt

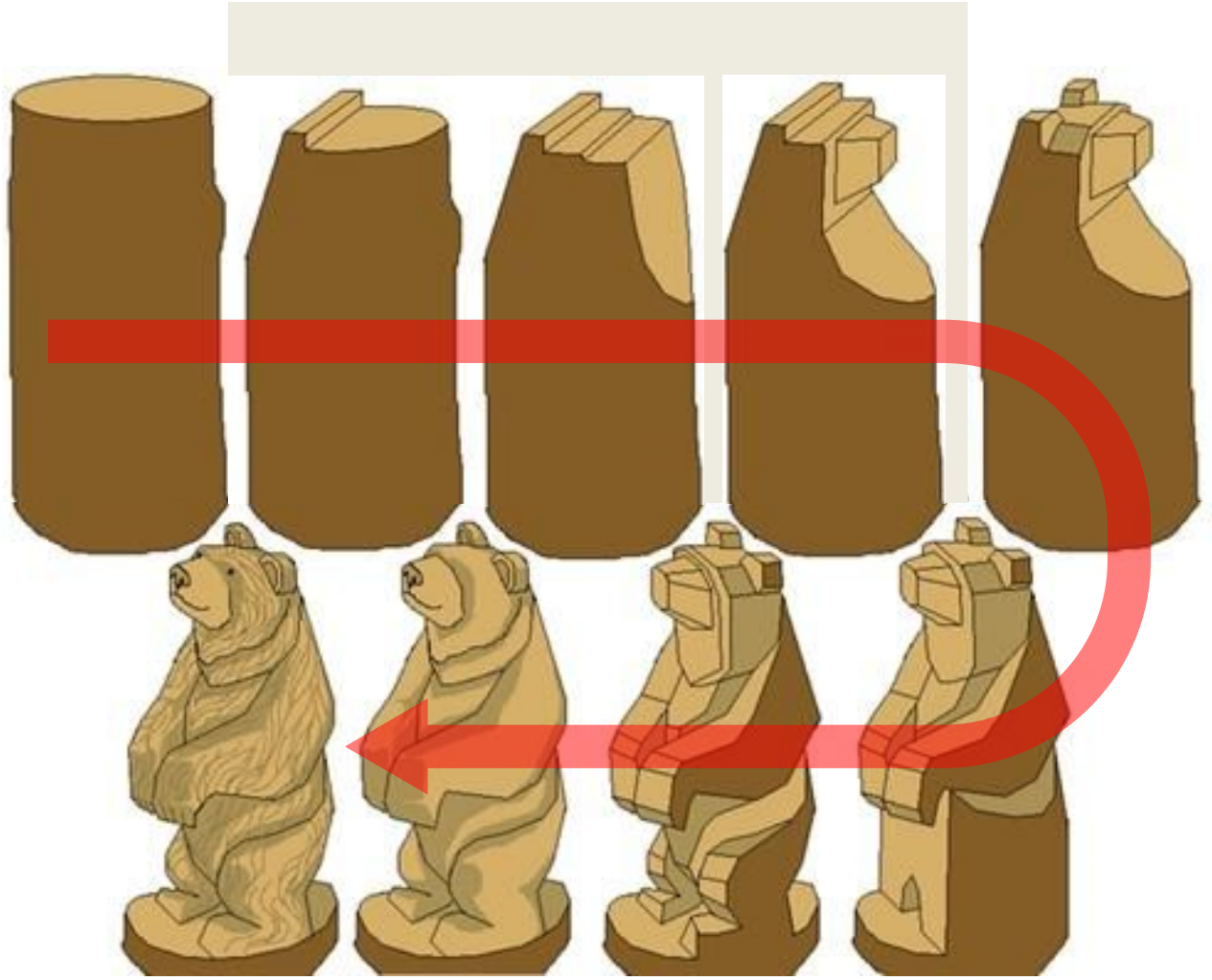
Evolution of delivery techniques of the last 20 years

Classic Radiotherapy



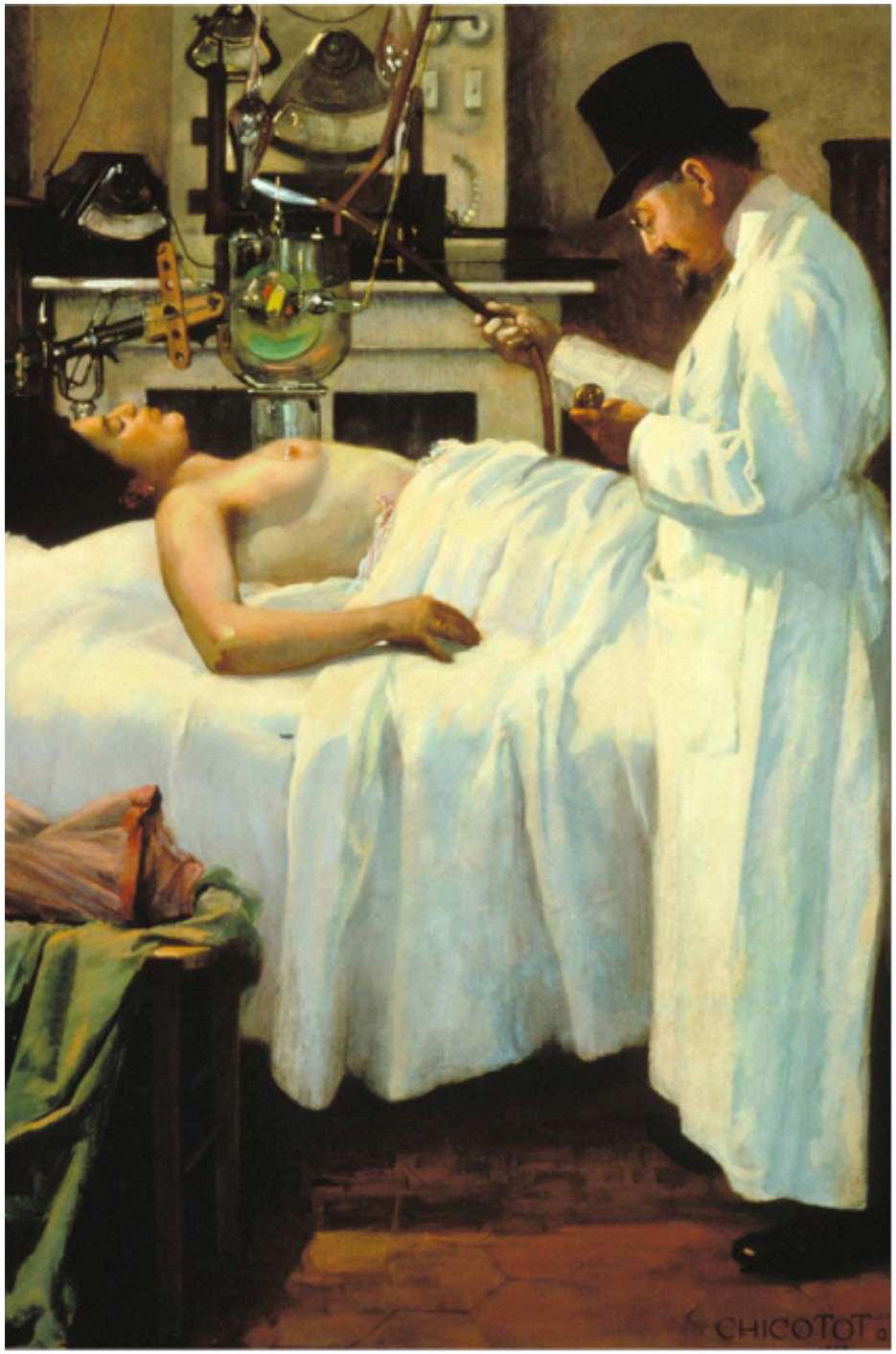
Highly conformal Radiotherapy





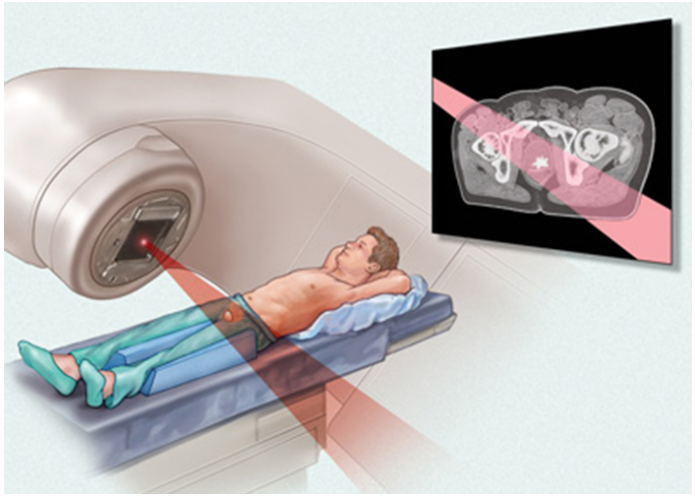
"Dose sculpting hitting the target avoiding other tissues"

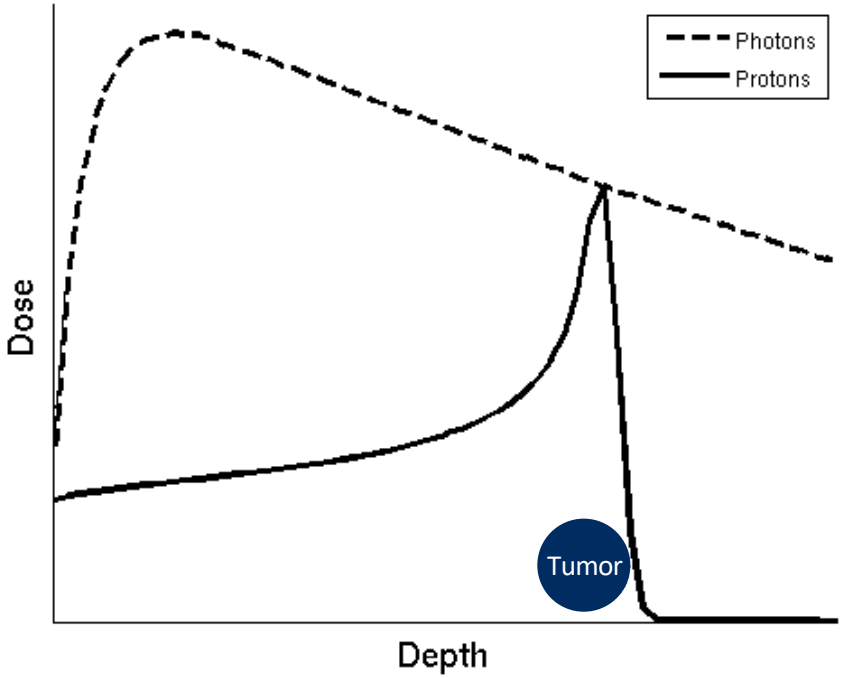
From T. Depuydt



Autoportrait par Georges Chicotot (1908)

Going beyond intensity-modulation

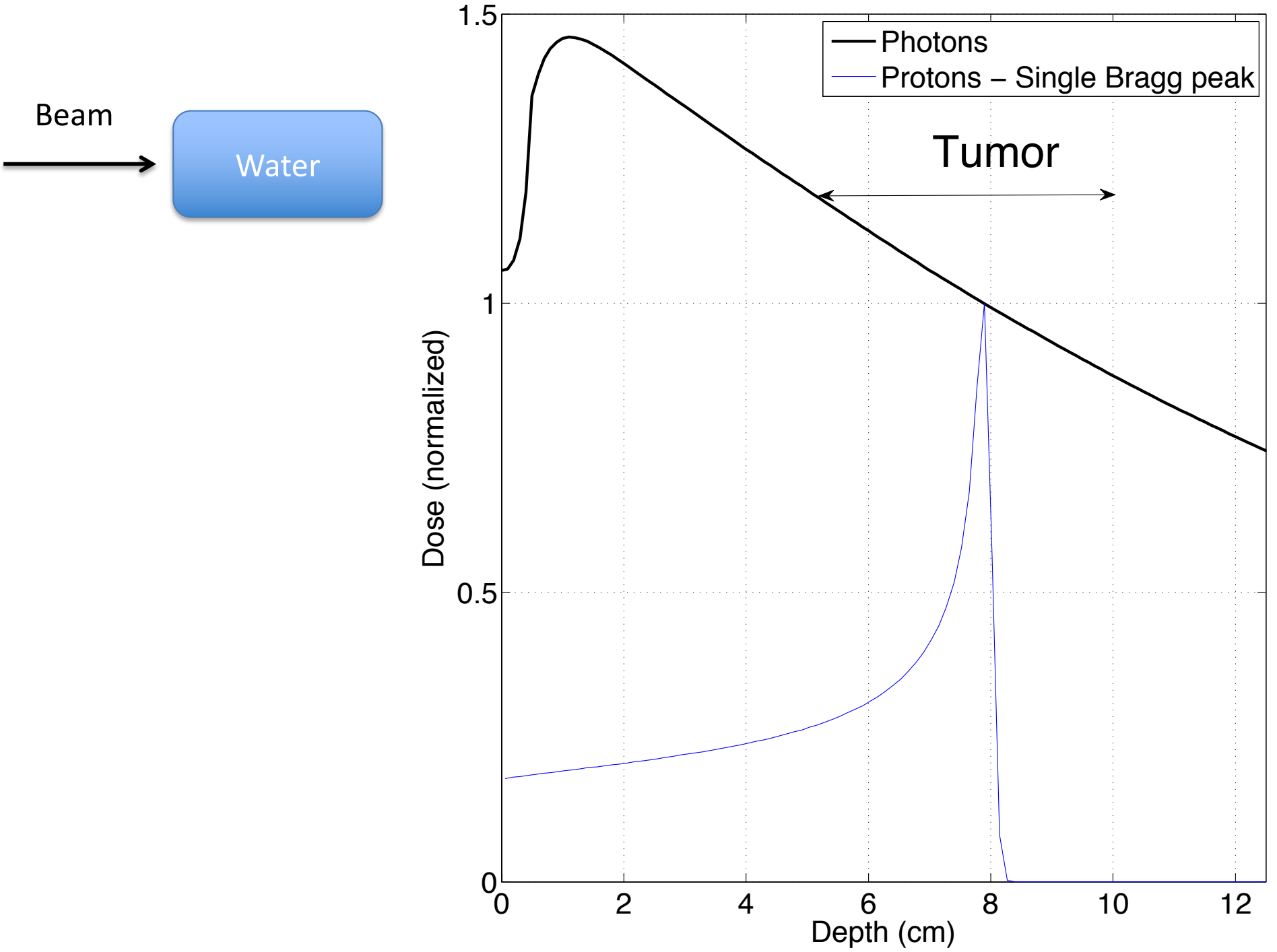


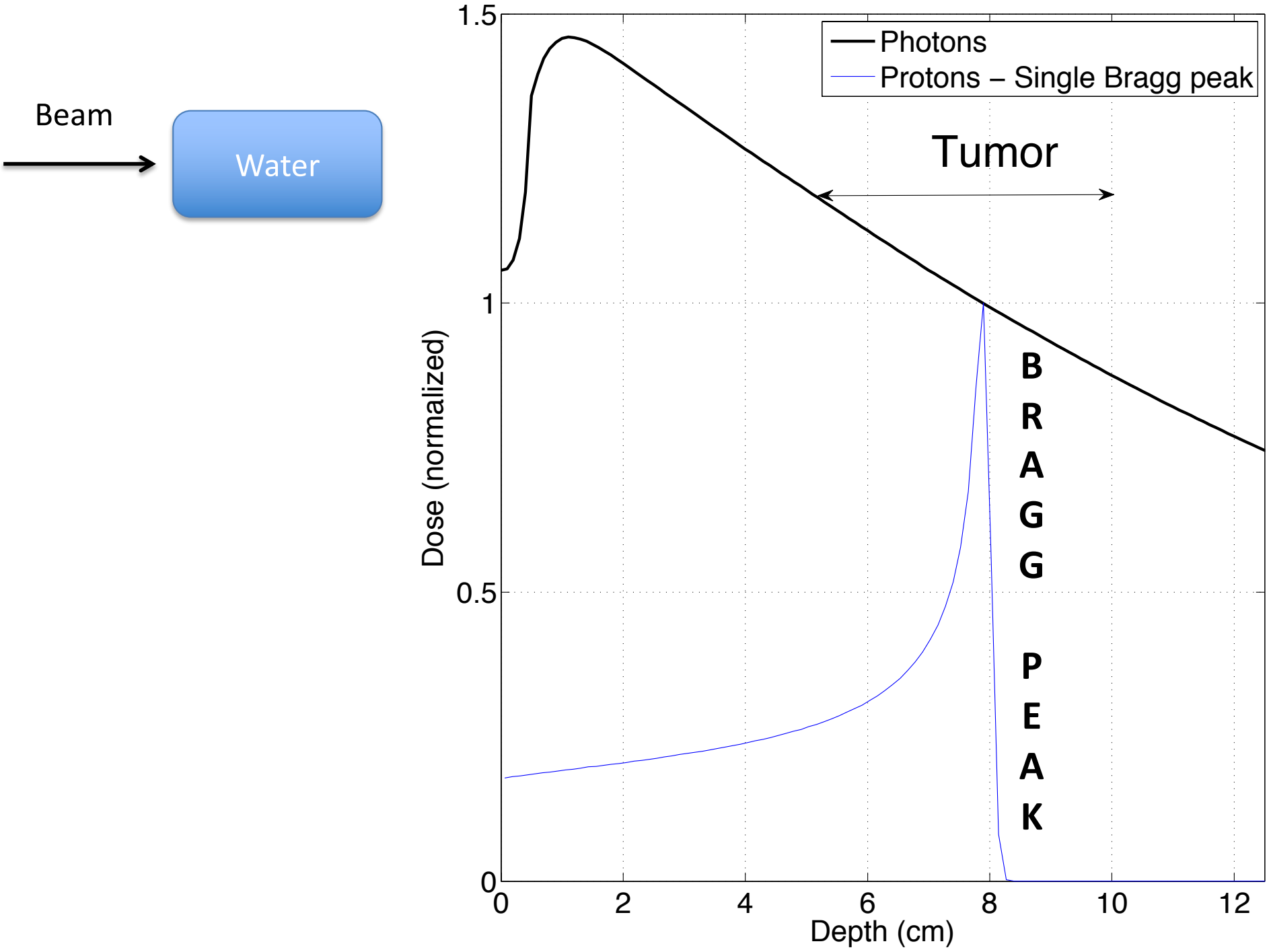


Conventional radiotherapy techniques employ photon beams to treat tumors.

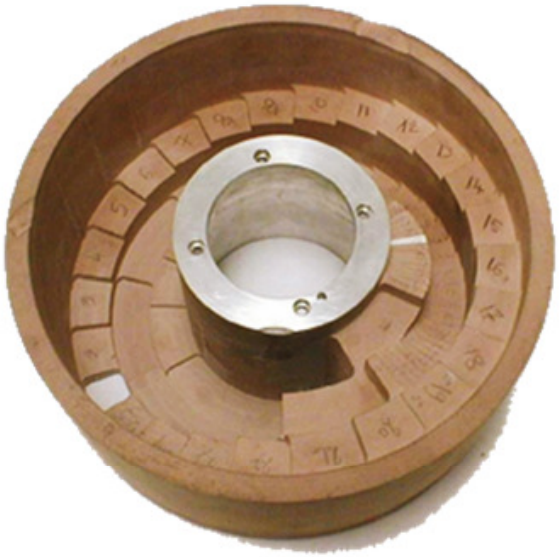
Protons offer a more advantageous depth-dose profile.

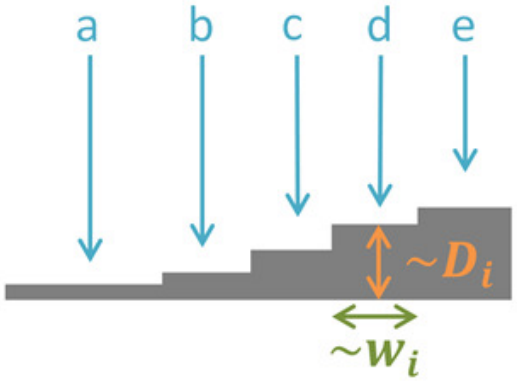
From K. Souris

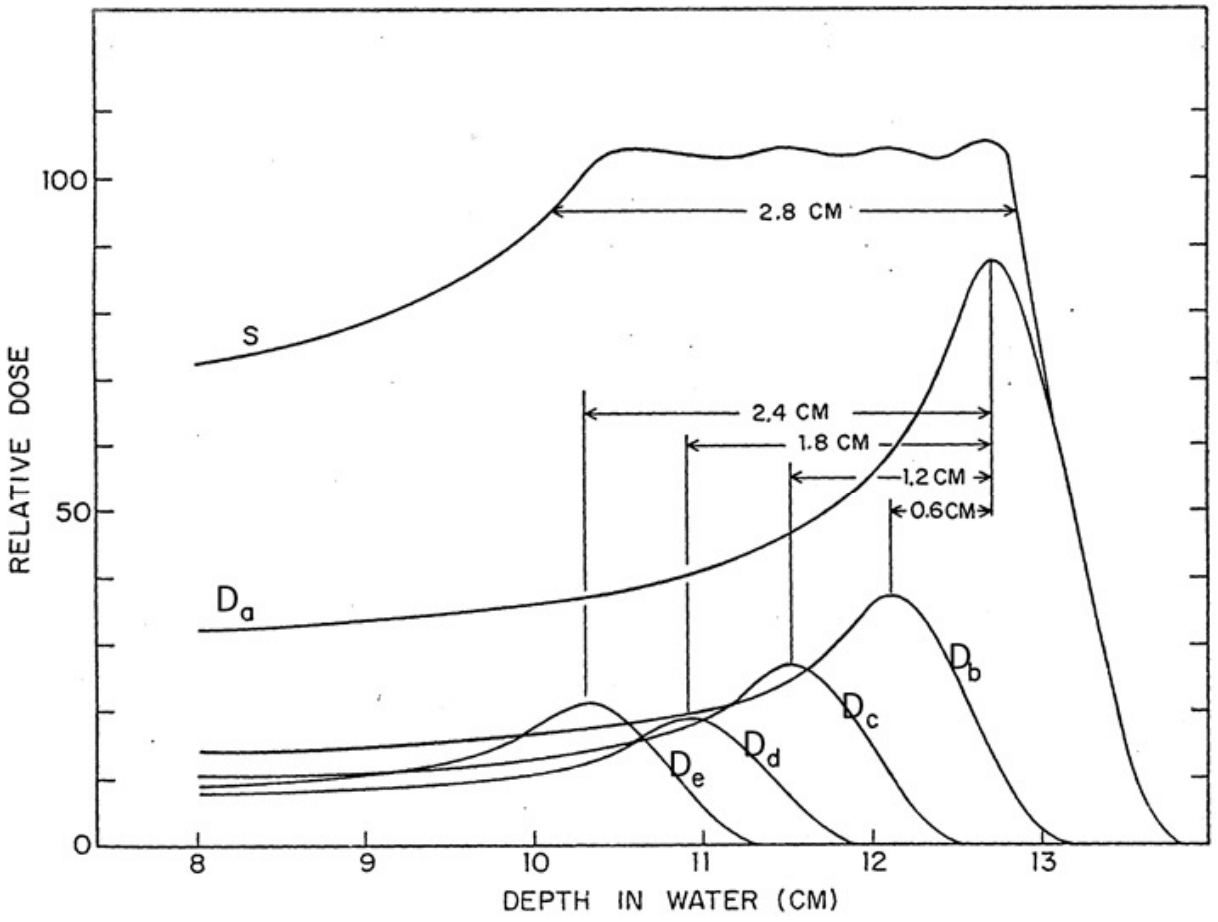

Beam
Water
Photons
Protons – Single Bragg peak
Tumor
Dose (normalized)
Depth (cm)
0
0.5
1
1.5
0
2
4
6
8
10
12


Beam
Water
Photons
Protons – Single Bragg peak
Tumor
BRAGG PEAK
Dose (normalized)
Depth (cm)
0
0.5
1
1.5
0
2
4
6
8
10
12

A modulator wheel produces the SOBP



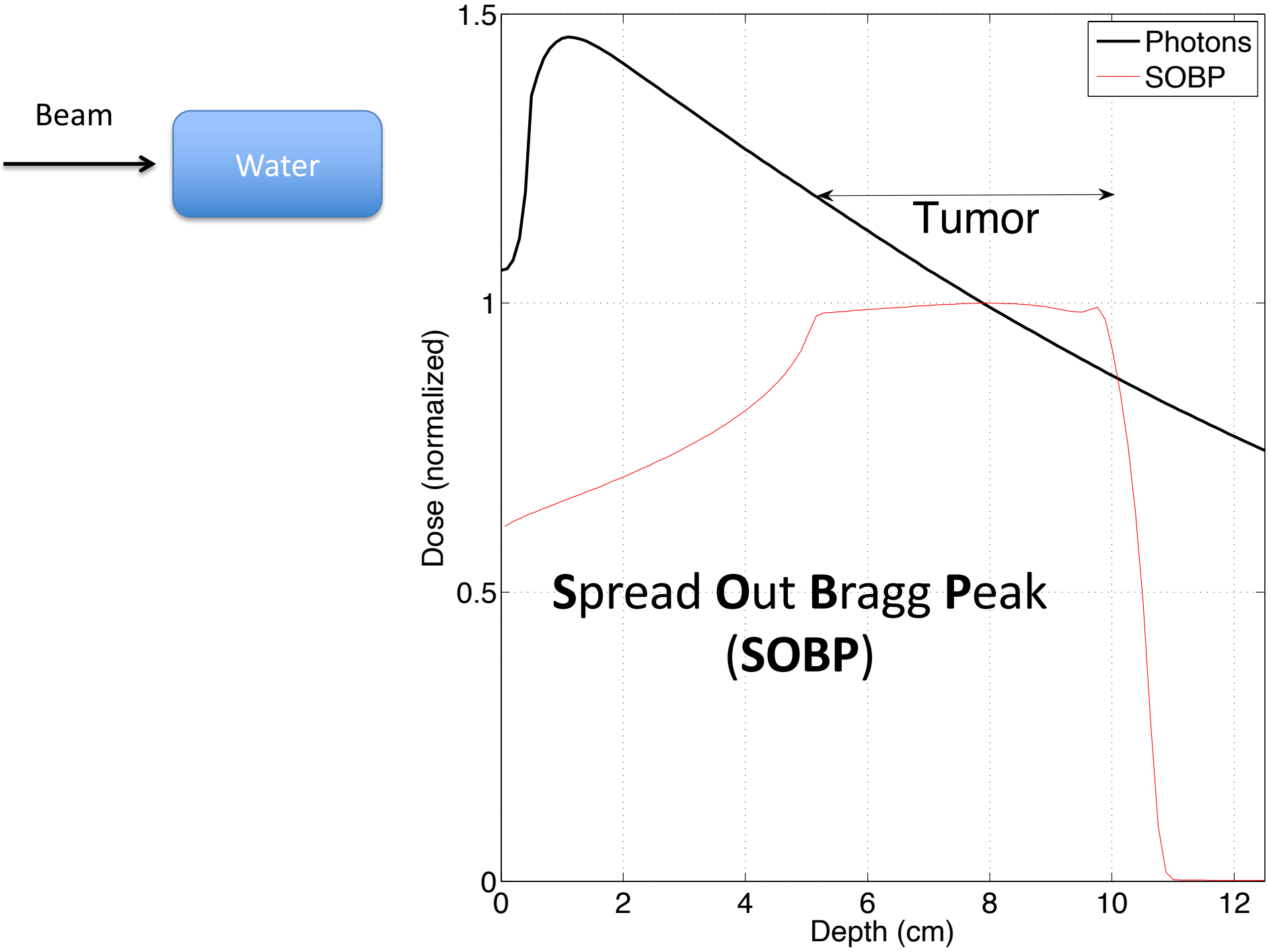




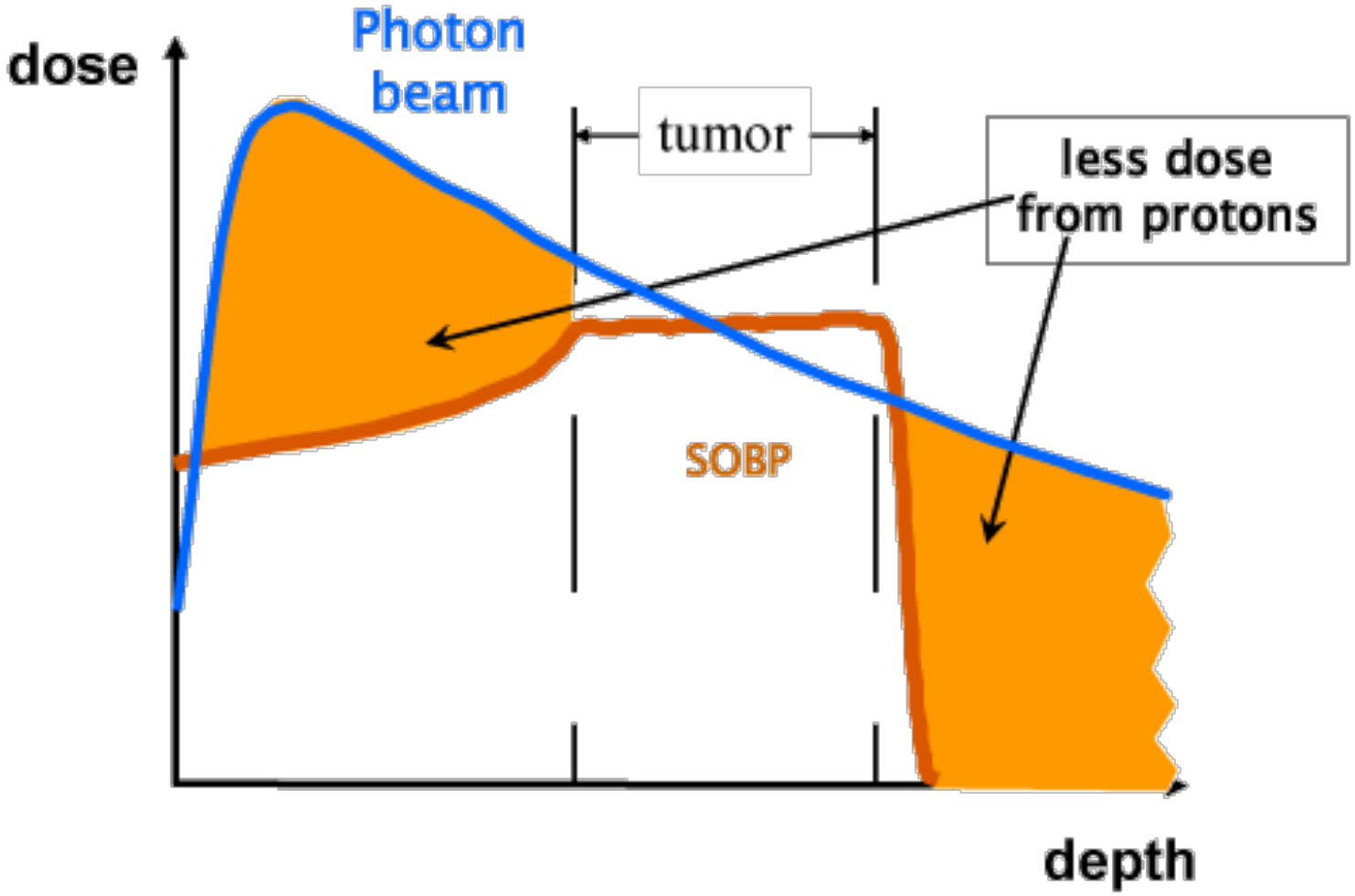
The spead-out Bragg peak (SOBP) :

$$S(z) = \sum_{i=1}^{N} w_i D_i(z)$$

Courtesy G. Janssens

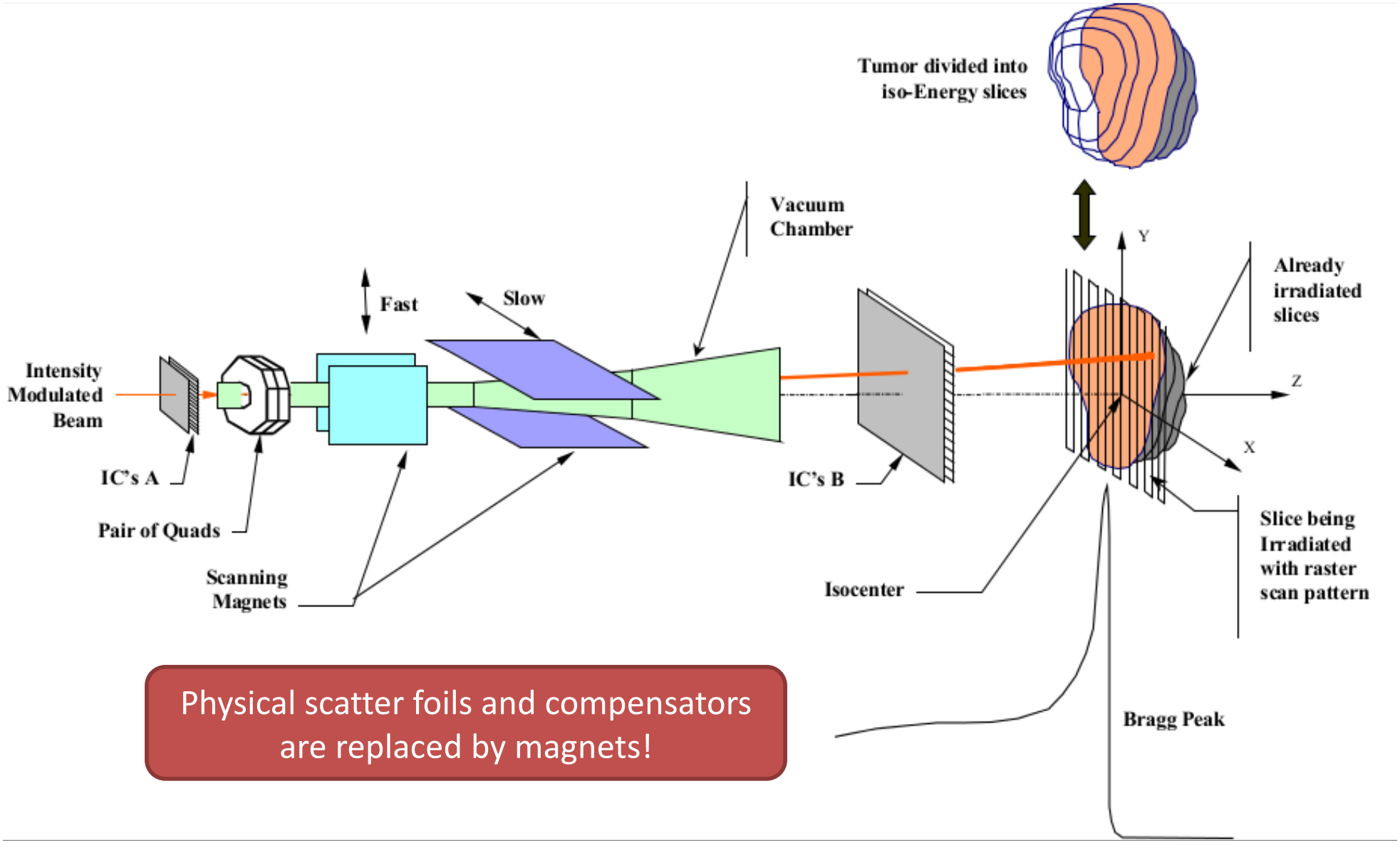

Beam
Water
1.5
1
0.5
0
Dose (normalized)
0
2
4
6
8
10
12
Depth (cm)
Photons
SOBP
Tumor
Spread Out Bragg Peak
(SOBP)

Advantages of proton beams



How do we deliver protons?

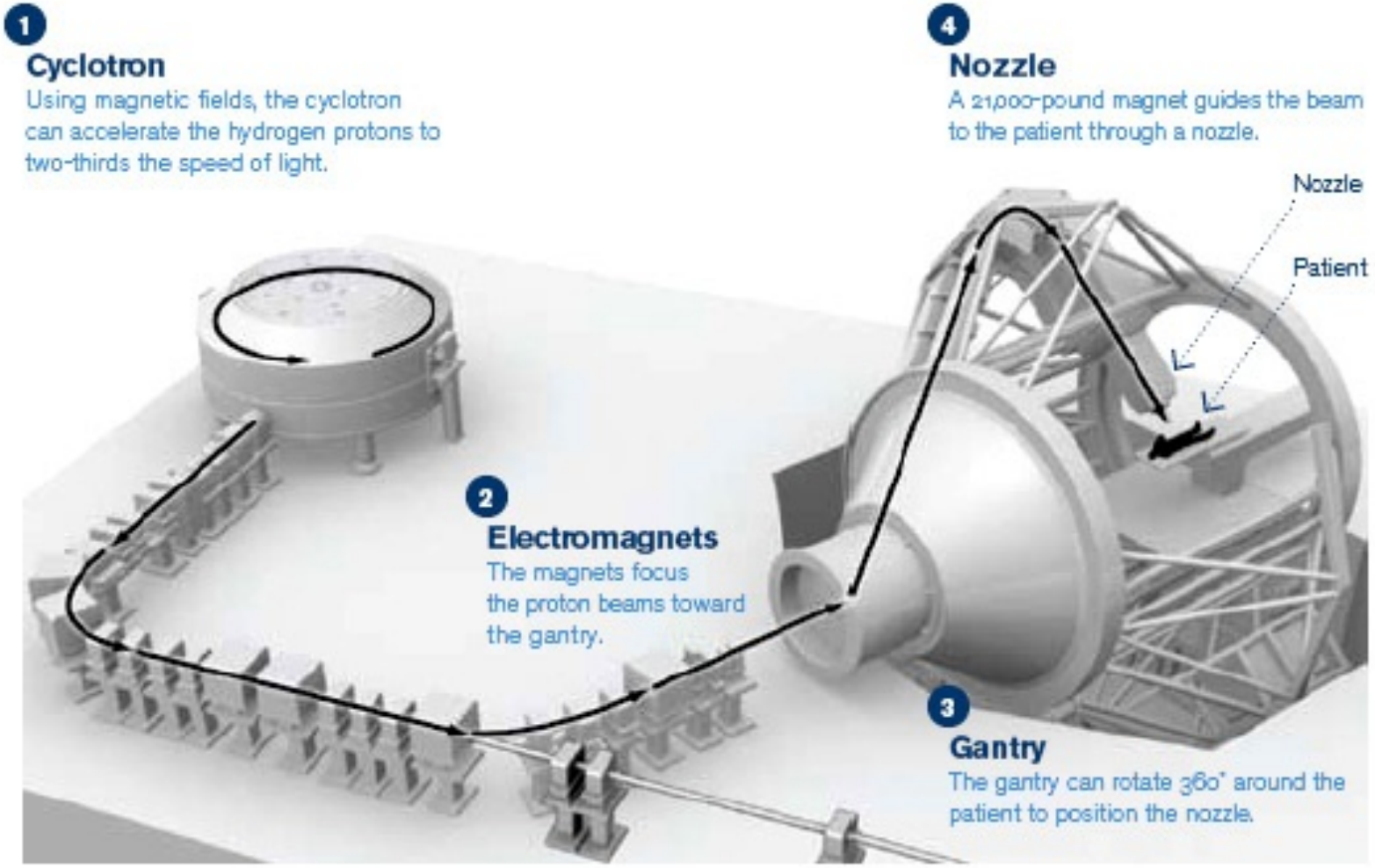
Collimator



Physical scatter foils and compensators are replaced by magnets!

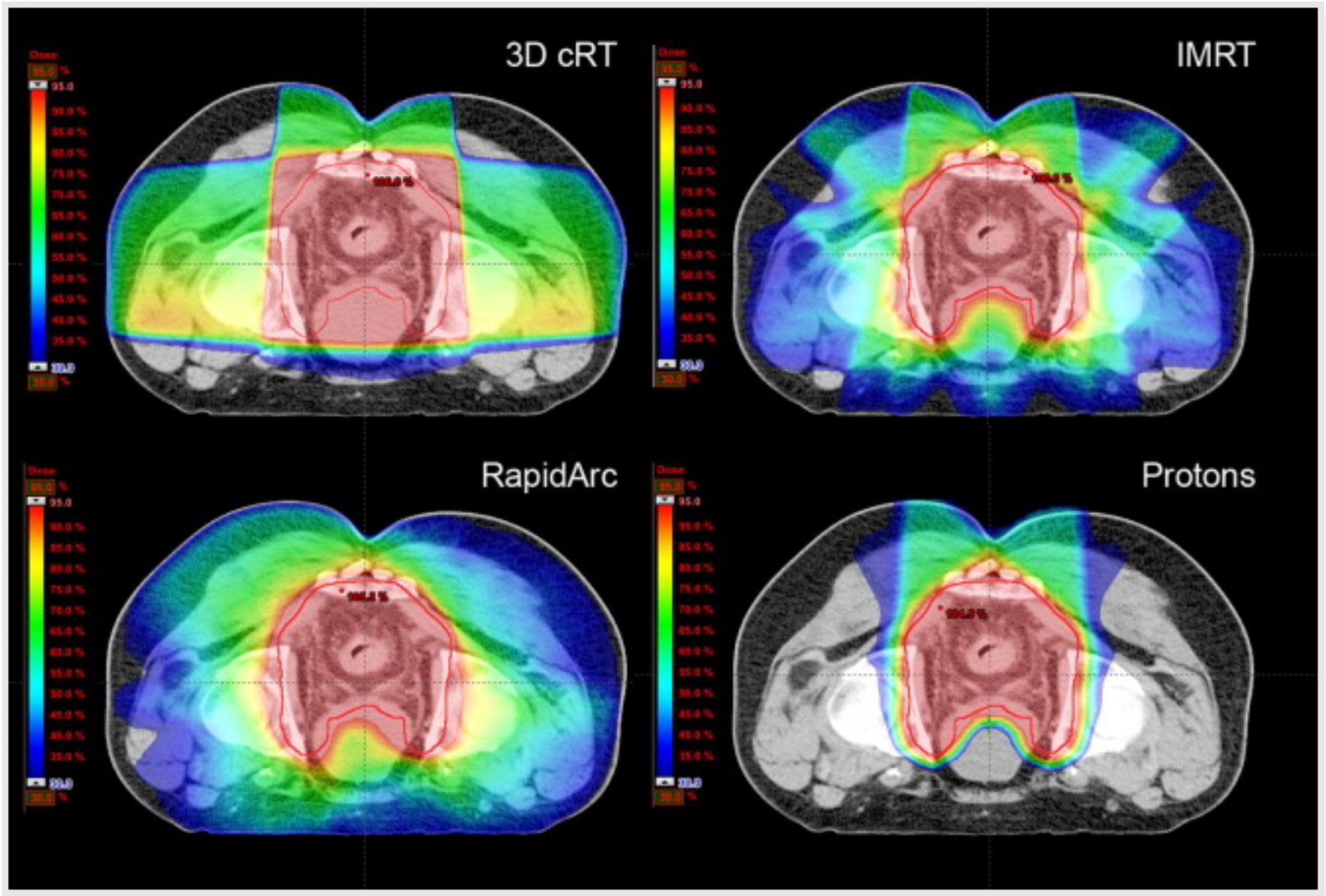
Typical installation: inside the treatment room

Typical installation: behind the walls…



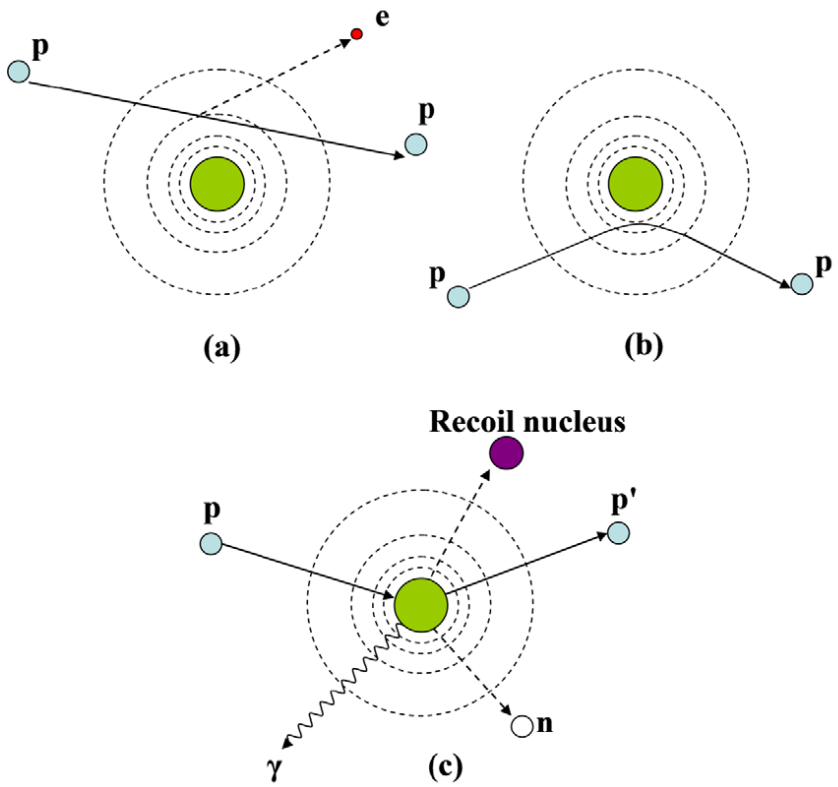
Pencil beam scanning

Dose sculpting

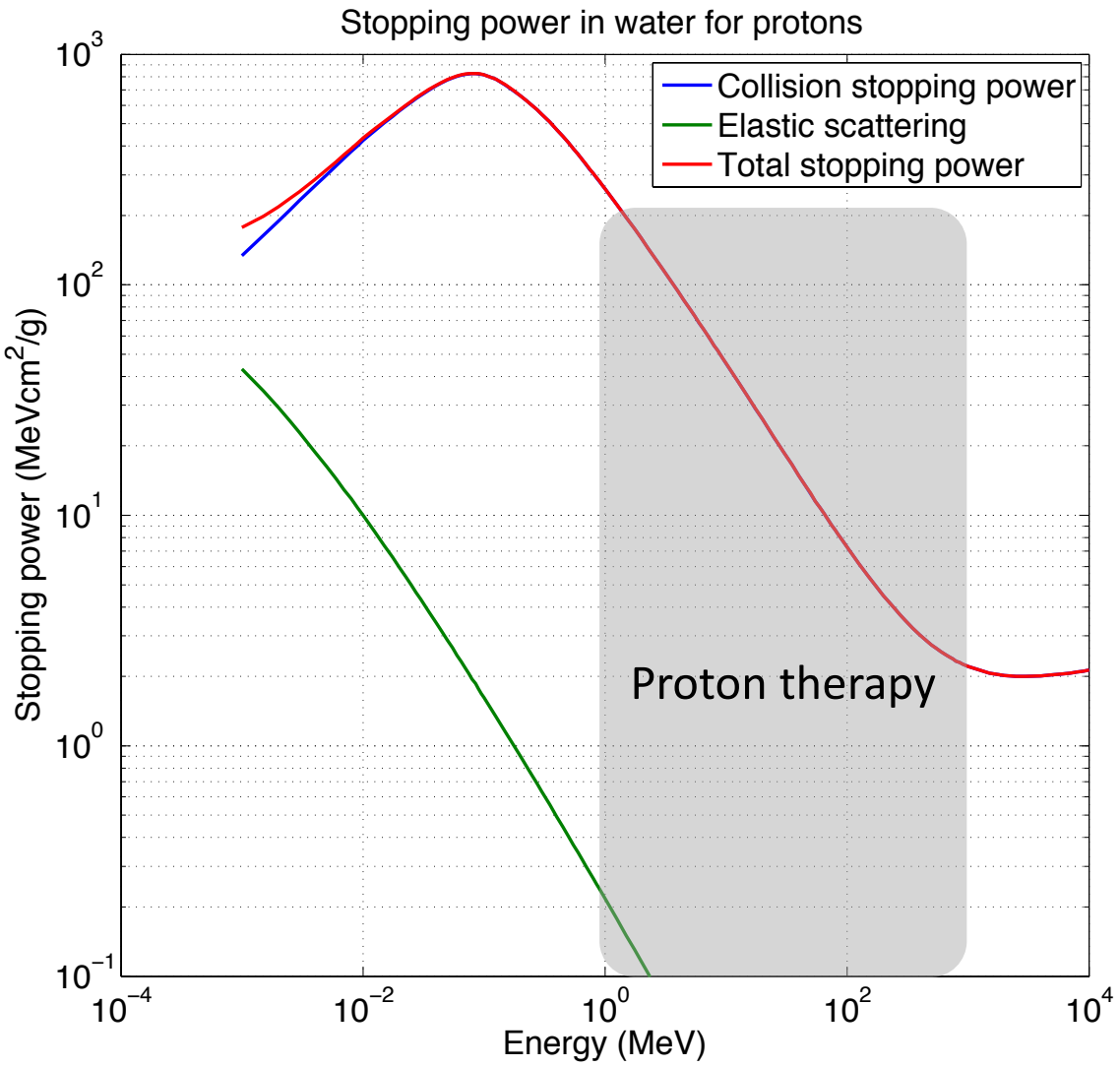


Proton therapy physics in a nutshell

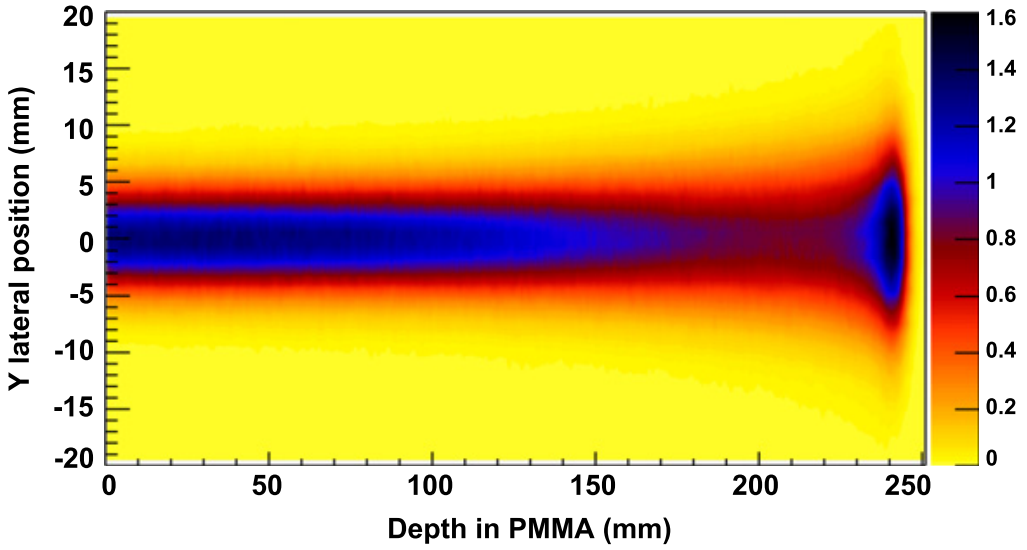
- Important interaction mechanisms for **heavy particles**
  - (Inelastic) collisions with bound atomic electrons (a)
  - Elastic scattering (b)
  - Nuclear interactions (c)

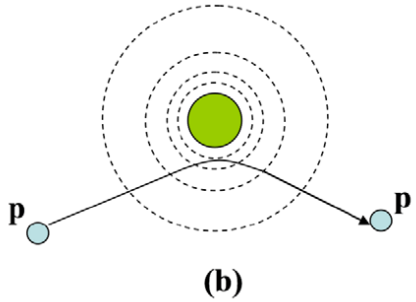


Inelastic collisions with bound atomic electrons are the main cause of the deceleration of the protons, which leads to the stopping powers

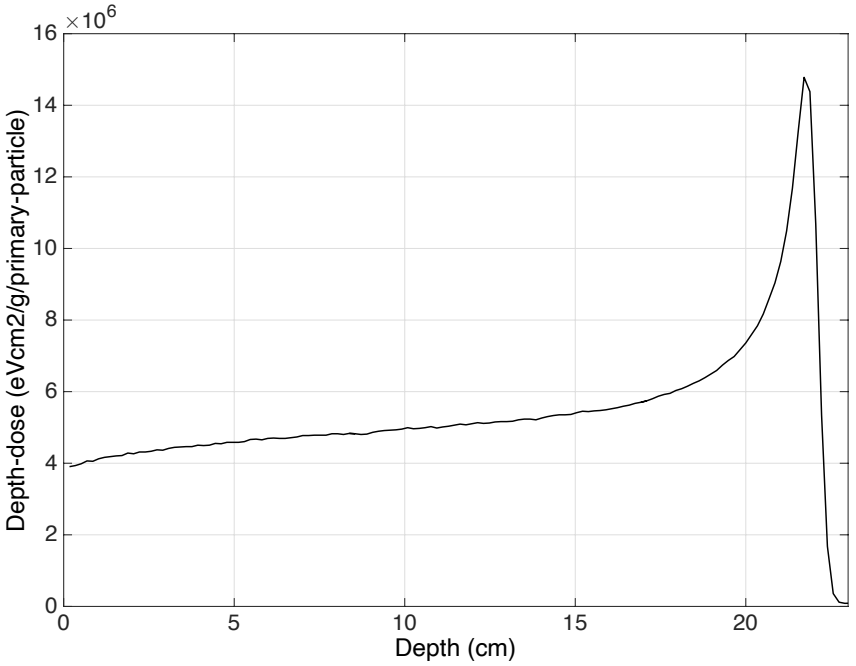


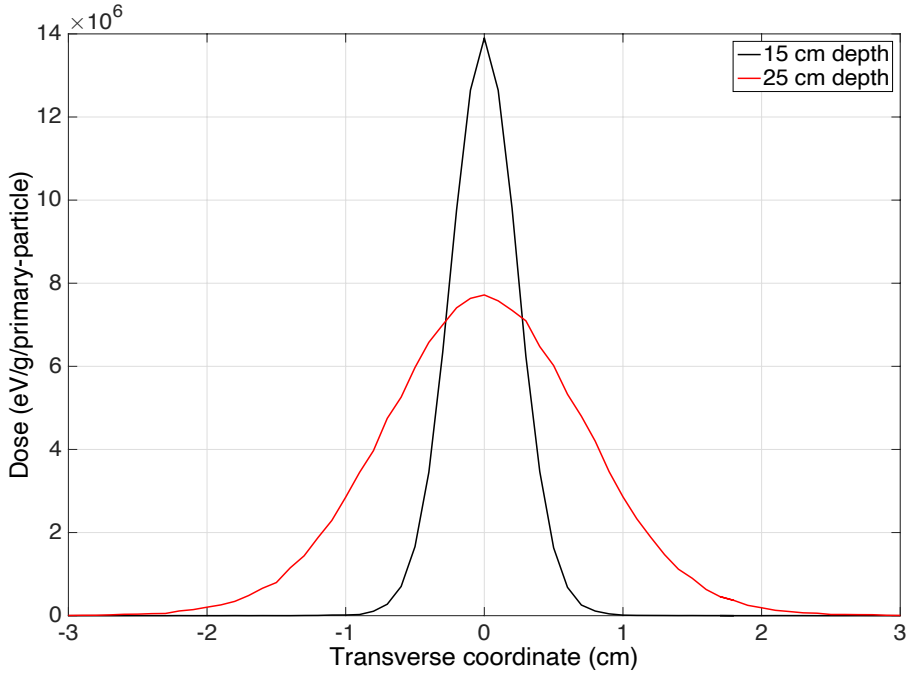
Elastic scattering with target nuclei is the main reason why protons do not travel straight




p
p

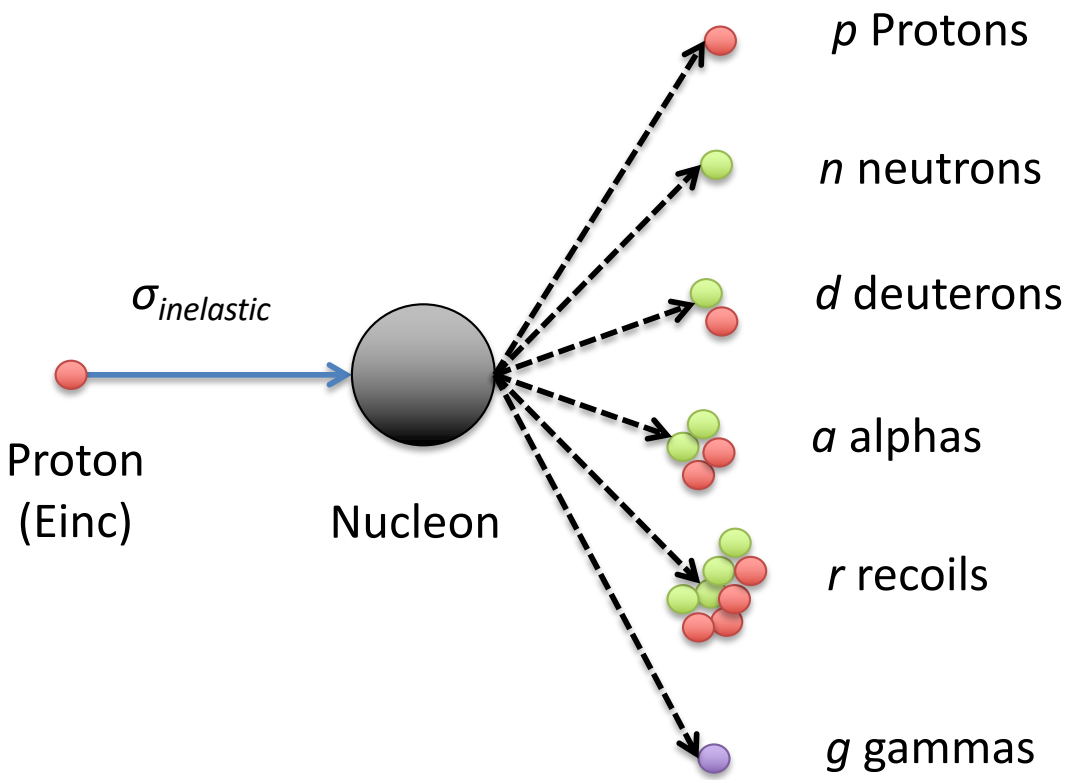
(b)


×10^6
Depth-dose (eVcm2/g/primary-particle)
Depth (cm)

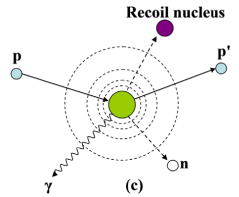

×10^6
15 cm depth
25 cm depth
Dose (eV/g/primary-particle)
Transverse coordinate (cm)

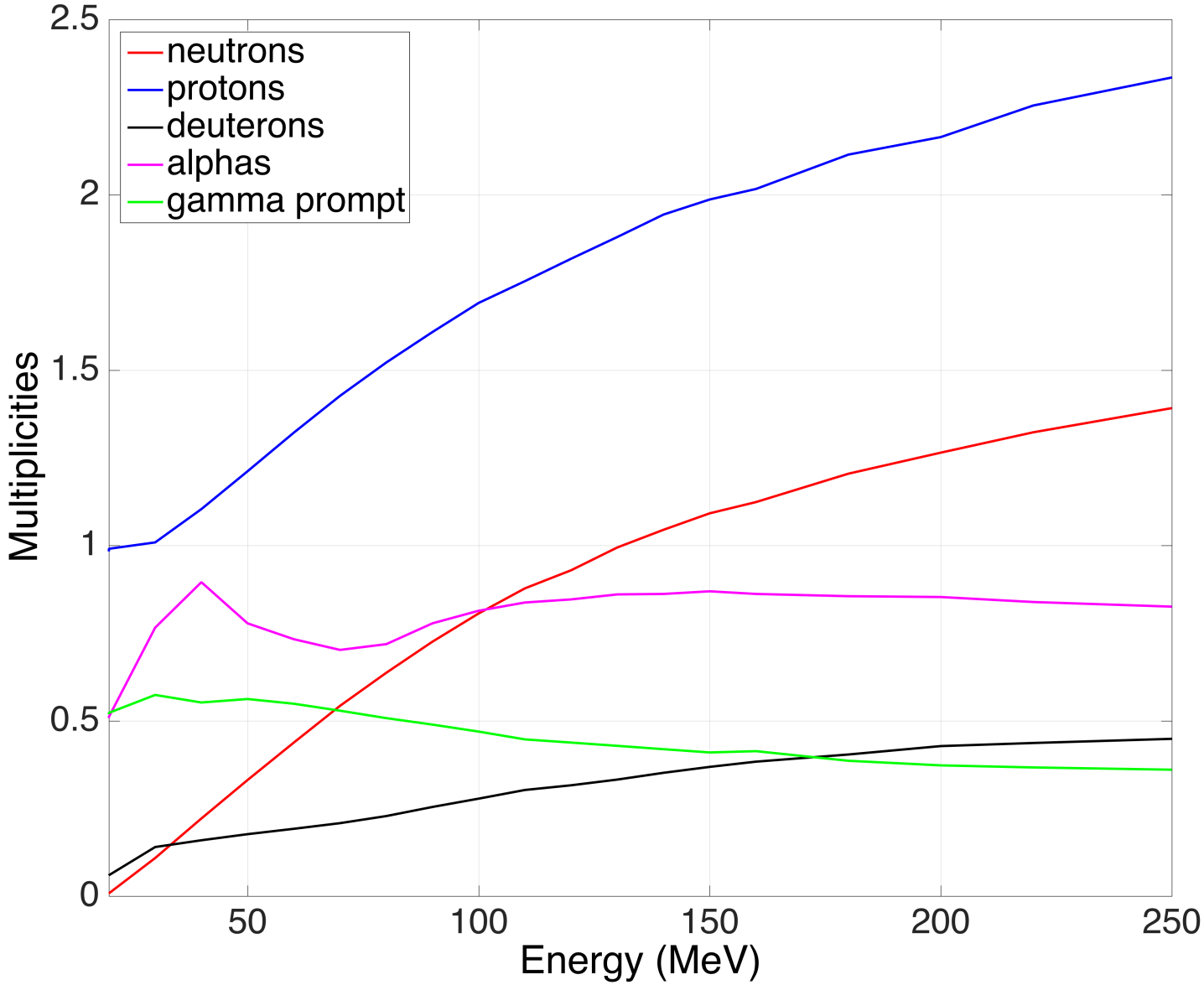
Physics of nuclear reactions

Nuclear inelastic

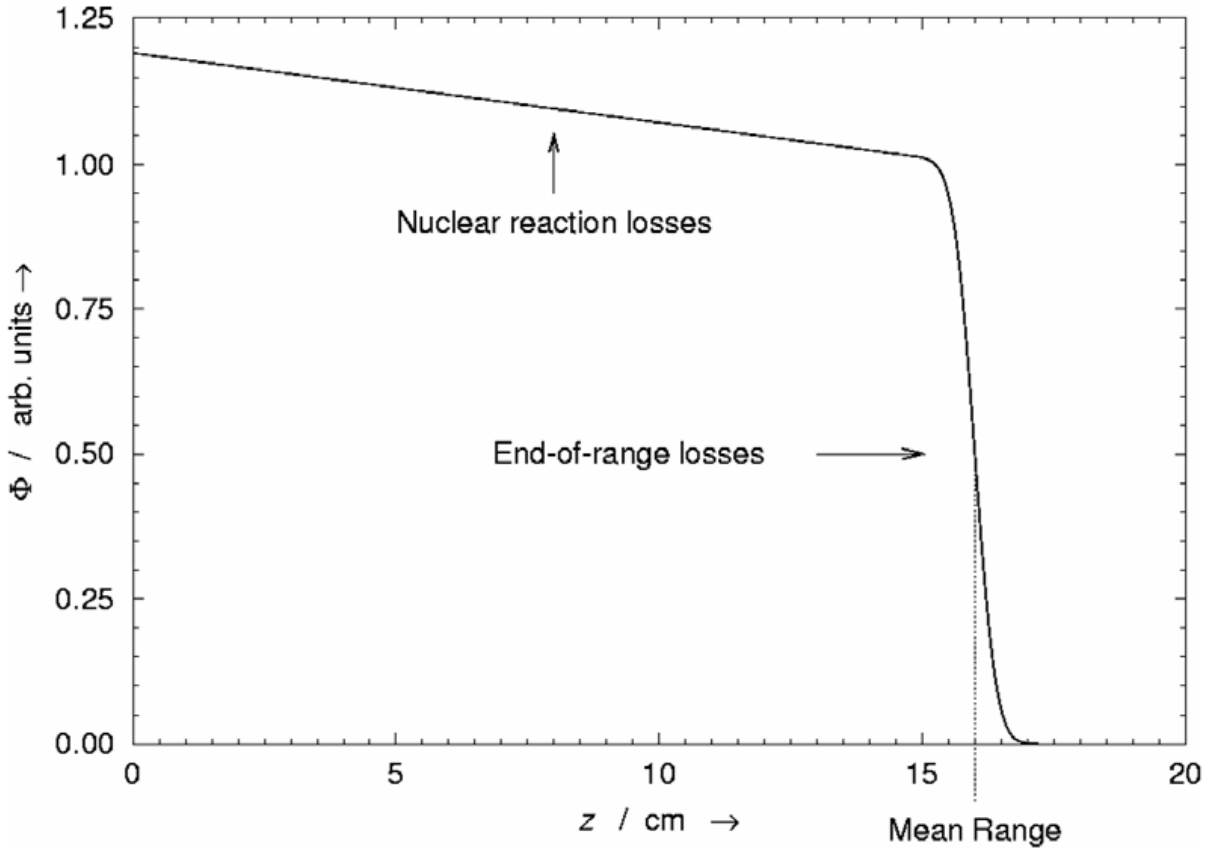


Emission of secondary particles (multiplicity)





Effect on incident particle fluence



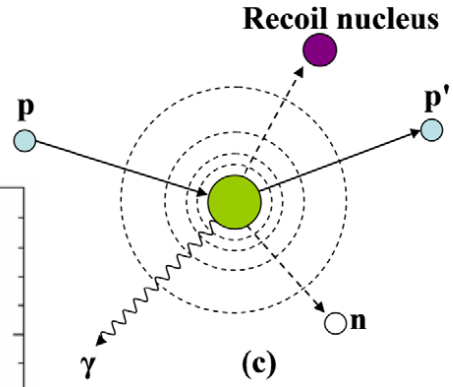
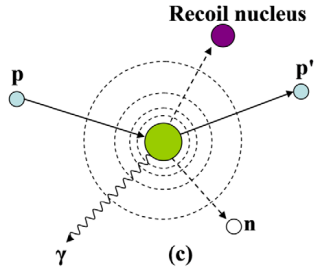
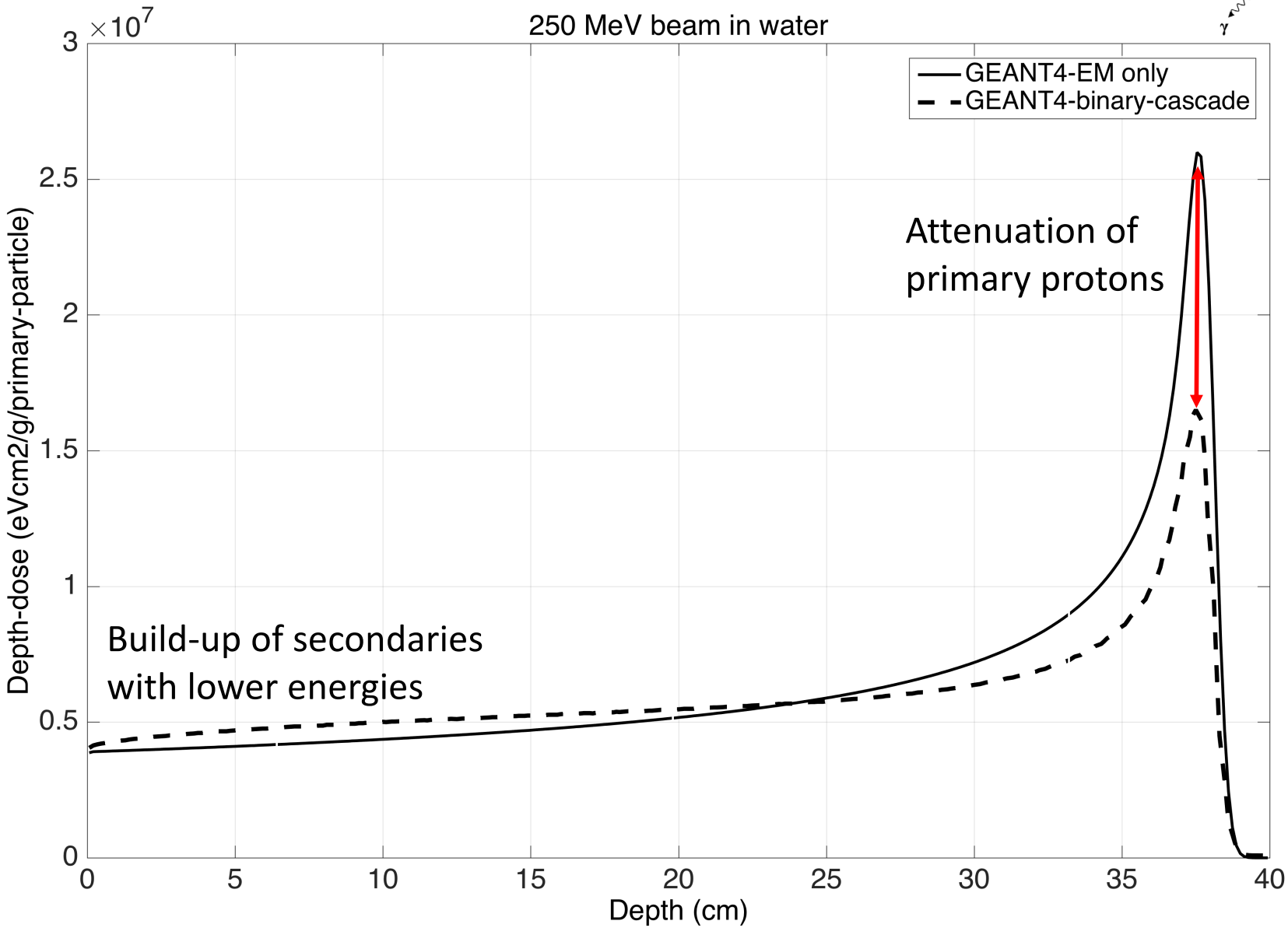


Figure 3. Relative fraction of the fluence Φ in a broad beam of protons remaining as a function of depth z in water. The gradual depletion of protons from entrance to near the end of range is caused by removal of protons from nuclear reactions. The rapid falloff in the number of protons near the end of range is caused by ions running out of energy and being absorbed by the medium. The sigmoid shape of the distal falloff is caused by range straggling or by stochastic fluctuations in the energy loss of individual protons.

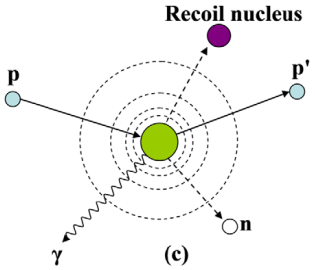
Neuwhauser and Zhang (Phys. Med. Biol. 2015)

Effect on depth-dose distribution





Effect on depth-dose distribution



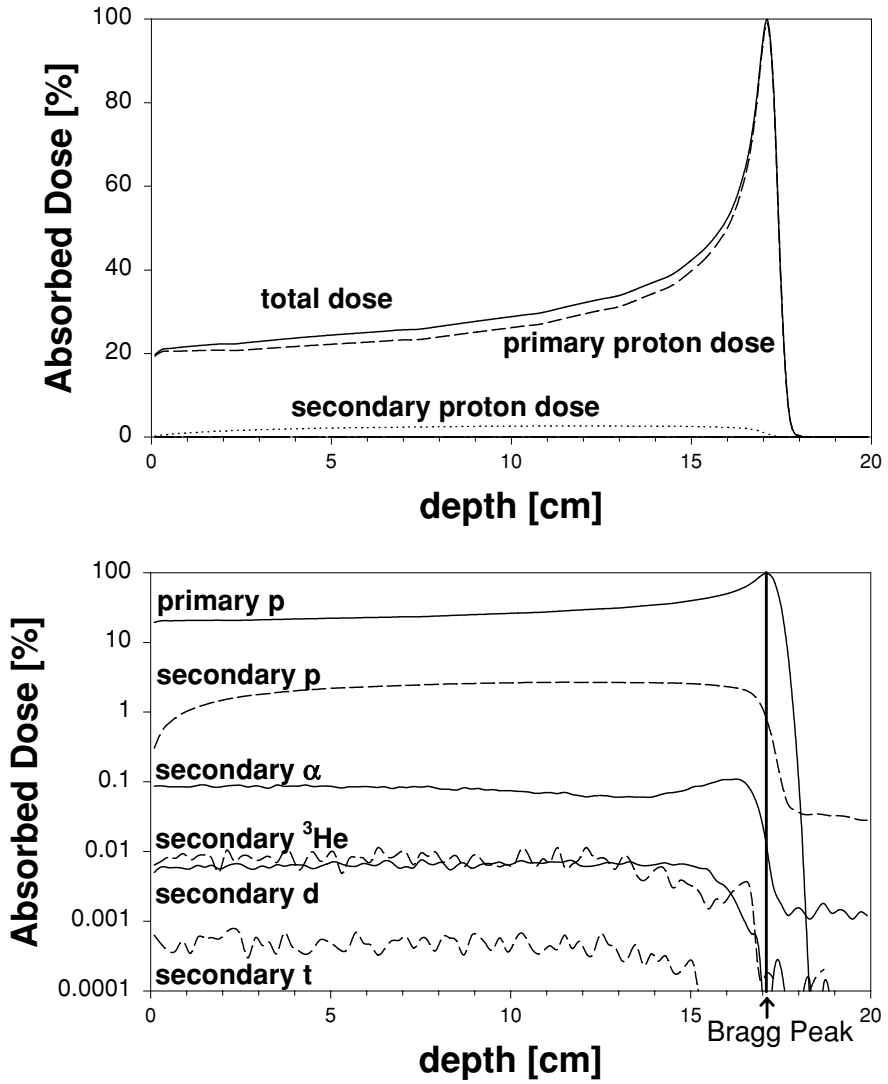
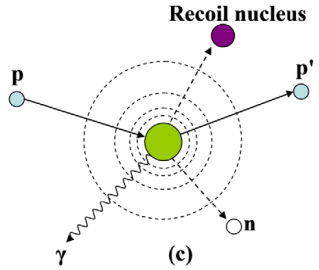


Figure 4. Depth–dose distributions (Bragg peak normalized to 100%) for a 160 MeV proton beam incident on a water phantom. The upper figure shows the total dose and the dose due to primary and secondary protons. The lower figure compares, on a logarithmic scale, the doses due to different types of particles (solid lines: primary p, secondary α and d; dashed lines: secondary p, ^{3}He, t). A vertical line indicates the position of the maximum of the Bragg peak.

Physical neutron dose

- Maximum 1% of therapeutic Gy for passive systems
- Of order of 0.1% for active systems
- Estimated in Paganetti et al 2012 to less than 0.04% (excluding the delivery system)
- !! Needs to be scaled by a proper weighting factor which can be great for neutrons!!

Effect on depth-dose distribution



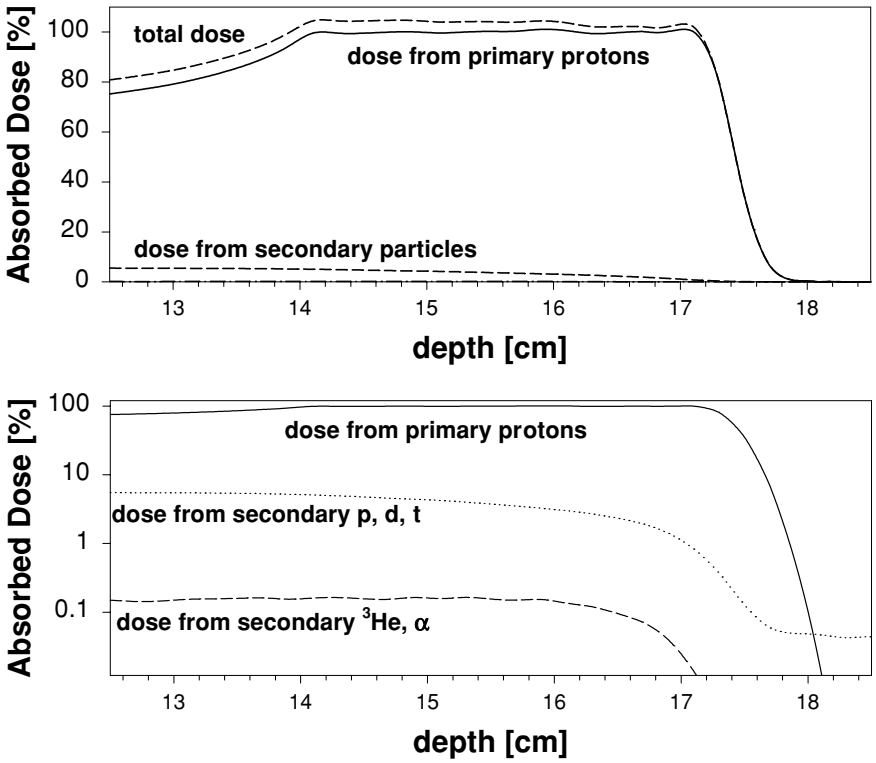


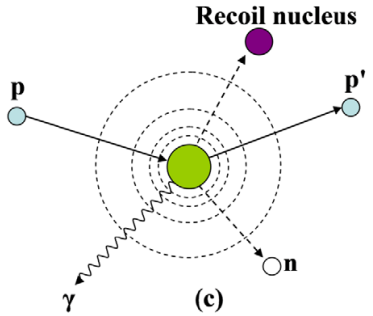
Figure 5. Depth–dose distributions for a modulated 160 MeV proton beam incident on a water phantom in linear scale (upper figure) and in a logarithmic scale showing the contributions of light and heavier secondaries. The dose is laterally summed to the limits of the dose plateau (±3 cm).

Physical neutron dose

- Maximum 1% of therapeutic Gy for passive systems
- Of order of 0.1% for active systems
- Estimated in Paganetti et al 2012 to less than 0.04% (excluding the delivery system)
- !! Needs to be scaled by a proper weighting factor which can be great for neutrons!!

Paganetti (Phys. Med. Biol. 2002)

Physics of nuclear reactions: take-home messages

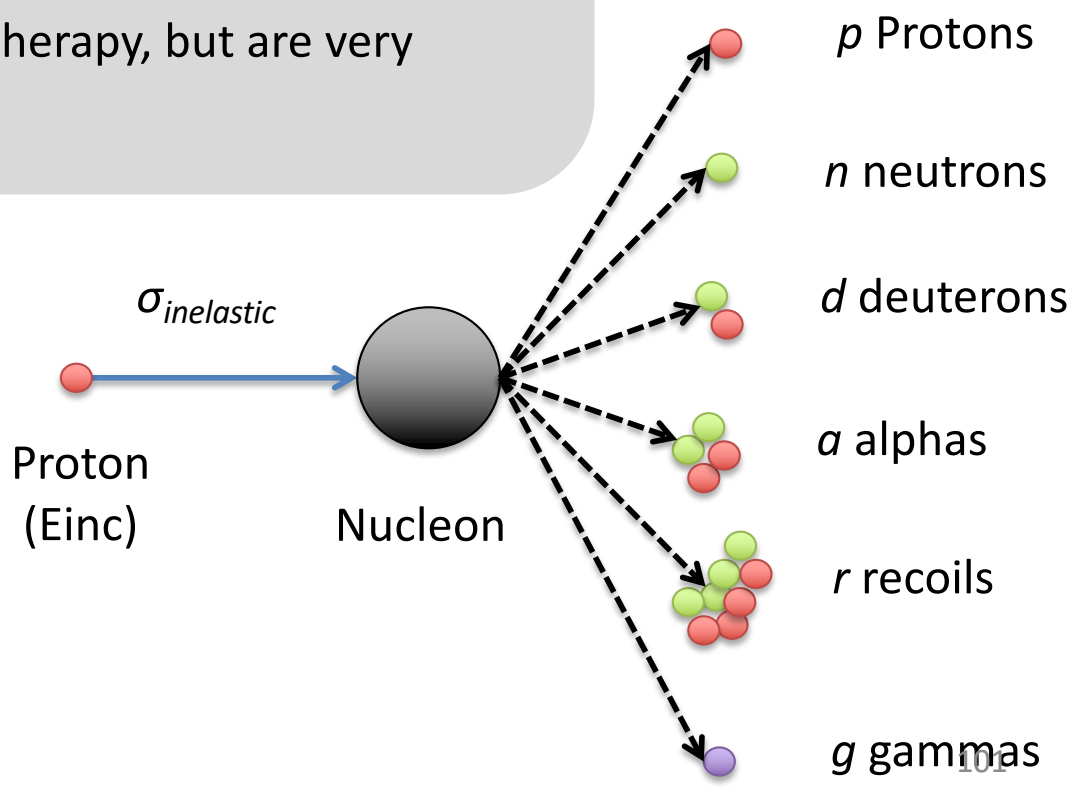


Nuclear reactions cause an attenuation of the primary fluence

Secondary particles ejected are mostly protons and neutrons

Only protons contribute significantly to the dose at moderate distances

Neutrons have low relevance for radiotherapy, but are very important for radioprotection



Radiation protection aspects in proton therapy

Prompt radiation (exposure to staff/public)

Delayed radiation (due to activation):

- Exposure of (maintenance) personnel
  - Procedures/personal dose monitoring

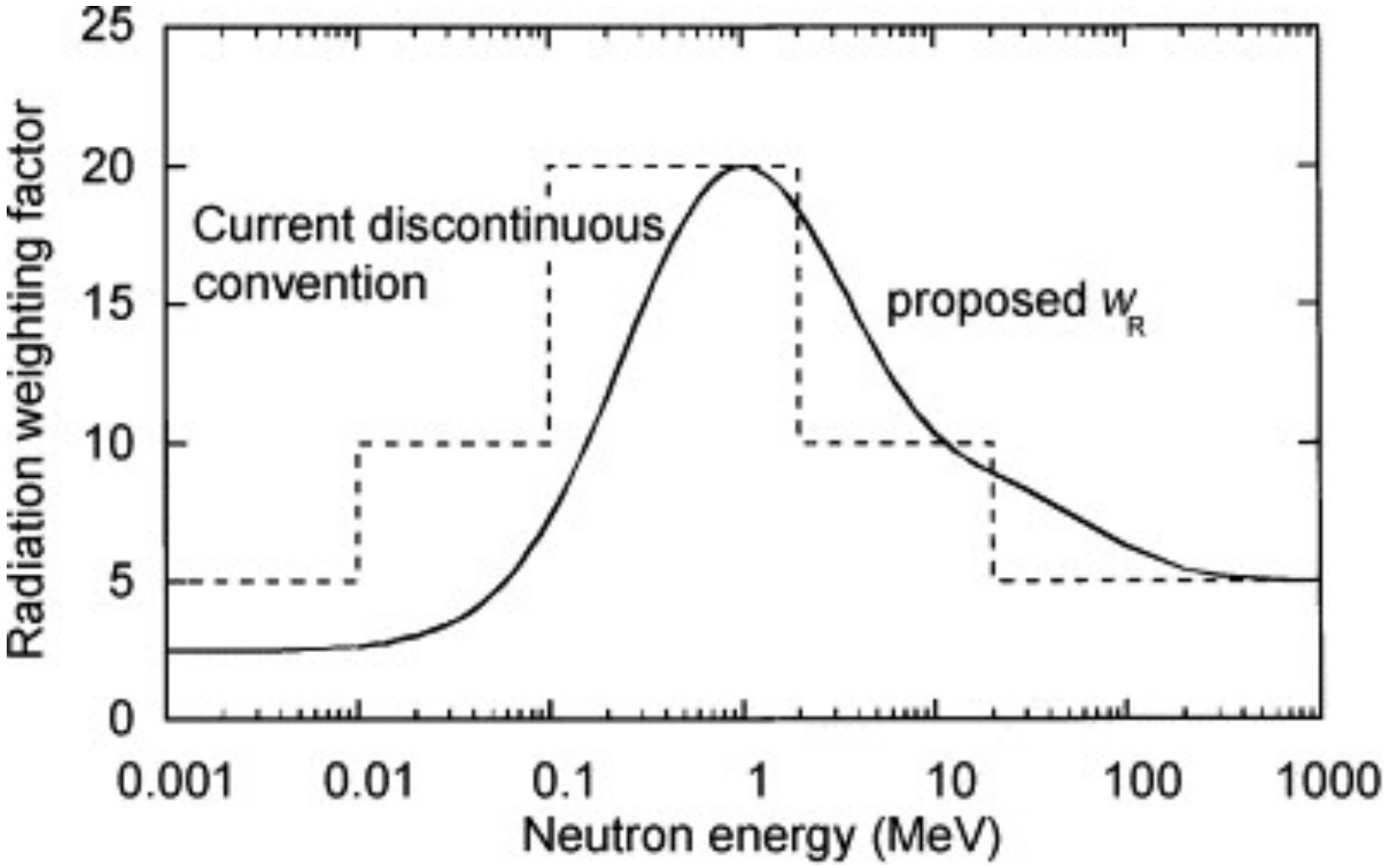
- Emissions to environment can lead to exposure of public
  - Disposal of activated waste, room ventilation

Concept of equivalent dose

Equivalent dose = absorbed dose * radiation weighting factor (W_R) in Sievert (Sv)

Type	Energy range	W_R
Photons, electrons	all	1
Neutrons	< 1 MeV	$2.5 + 18.2\exp[-(\ln(E))^2/6]$
	1 MeV - 50 MeV	$5.0 + 17.0\exp[-(\ln(2E))^2/6]$
	> 50 MeV	$2.5 + 3.25\exp[-(\ln(0.04E))^2/6]$
Protons		2
Alpha, fission fragments, heavy nucleai	all	20

Radiation weighting factor for neutrons



Basics of radiation protection in PT (neutron irradiation)

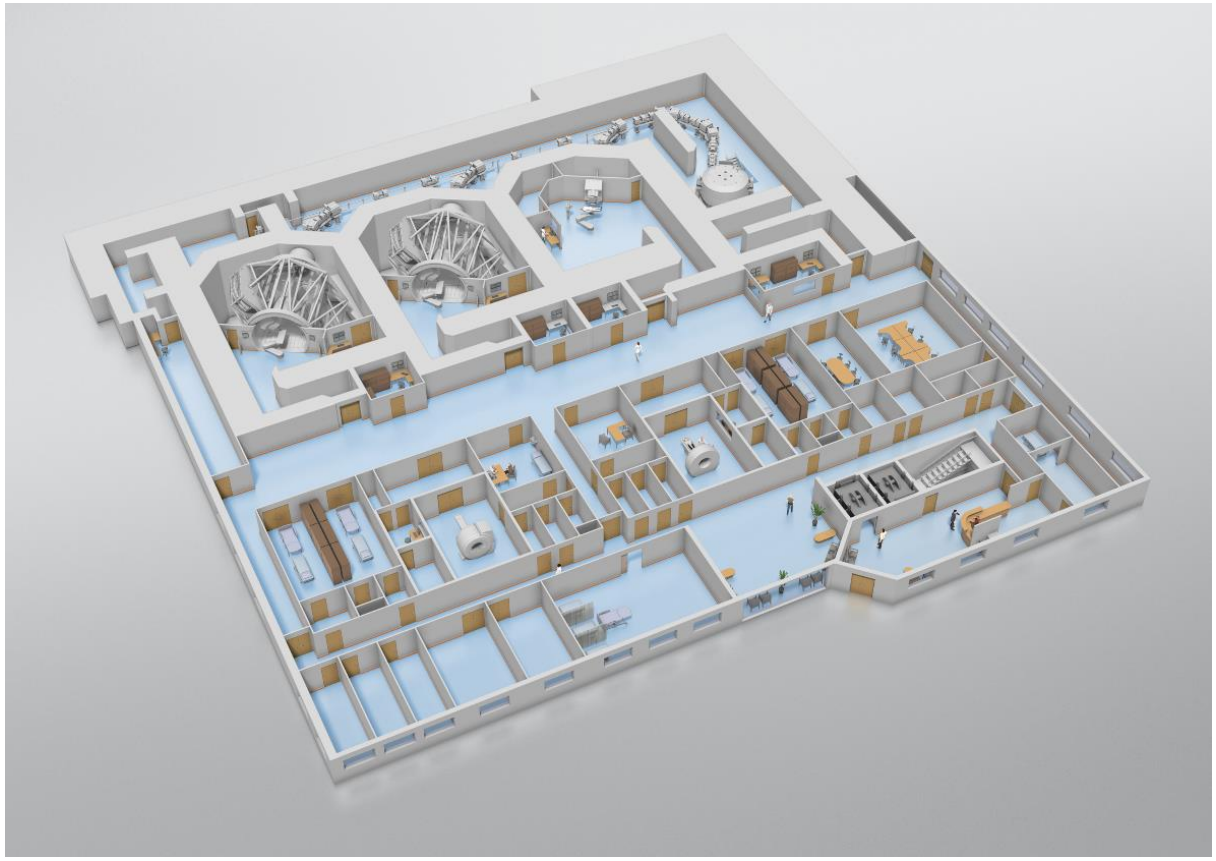
Neutrons have a stronger radiobiological effect than X-rays for a same physical dose

They have complex physics of transport in matter. Hydrogen interacts a lot with neutrons. Therefore, materials enriched with hydrogen are very welcome for shielding

Radiation protection in proton therapy: practical matters

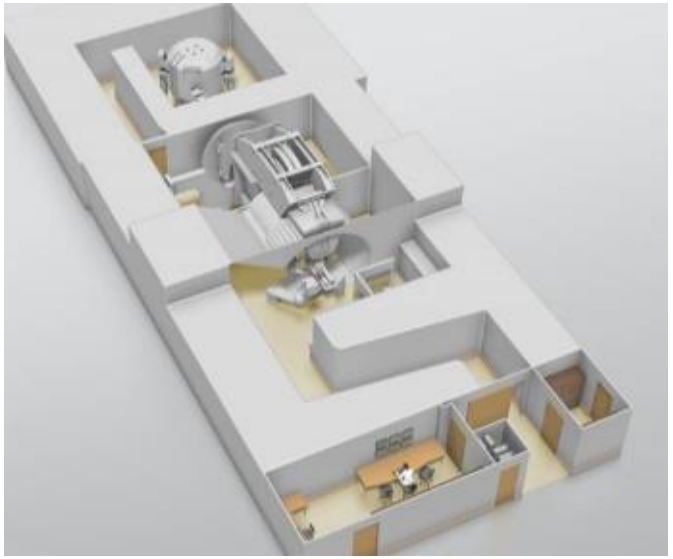
Two main configurations of IBA system

Proteus*PLUS*



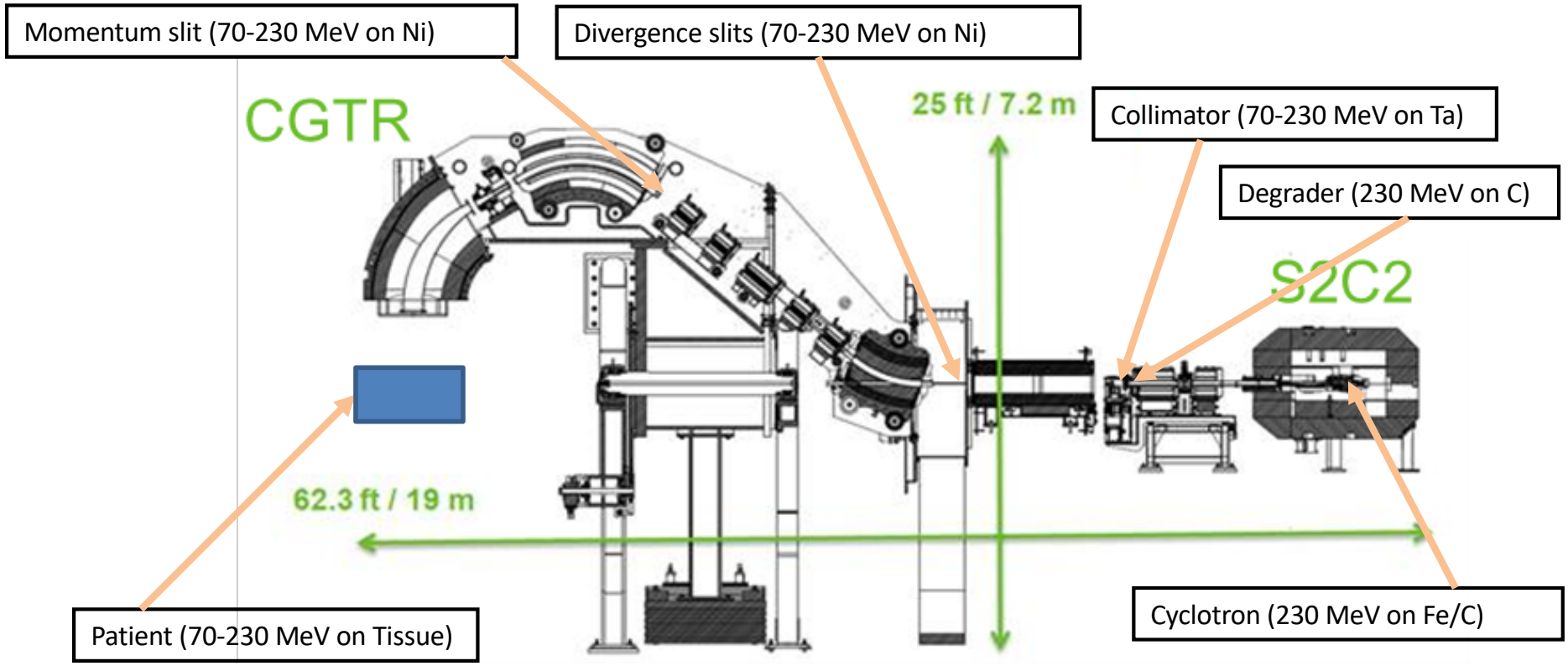
One Isochronous Cyclotron
One Energy Selection System
+ Multiple Rooms (different types)
+ Multiple Beam Delivery Techniques

Proteus*ONE*



One synchro-cyclotron
One Energy Selection System
One Room
One Beam Delivery Technique

Radiation sources in Proteus One (machine foreseen in Leuven and Charleroi)



Energy selection system (degrader + collimator + slits) common to all cyclotron-based systems

Radiation protection questions in proton therapy

- For staff:
  - What is the shielding necessary to obey Belgian law?
- For patients
  - What is the dose due to secondary radiation like neutrons, either coming from machine elements, or the patient itself?

Radiation protection questions in proton therapy

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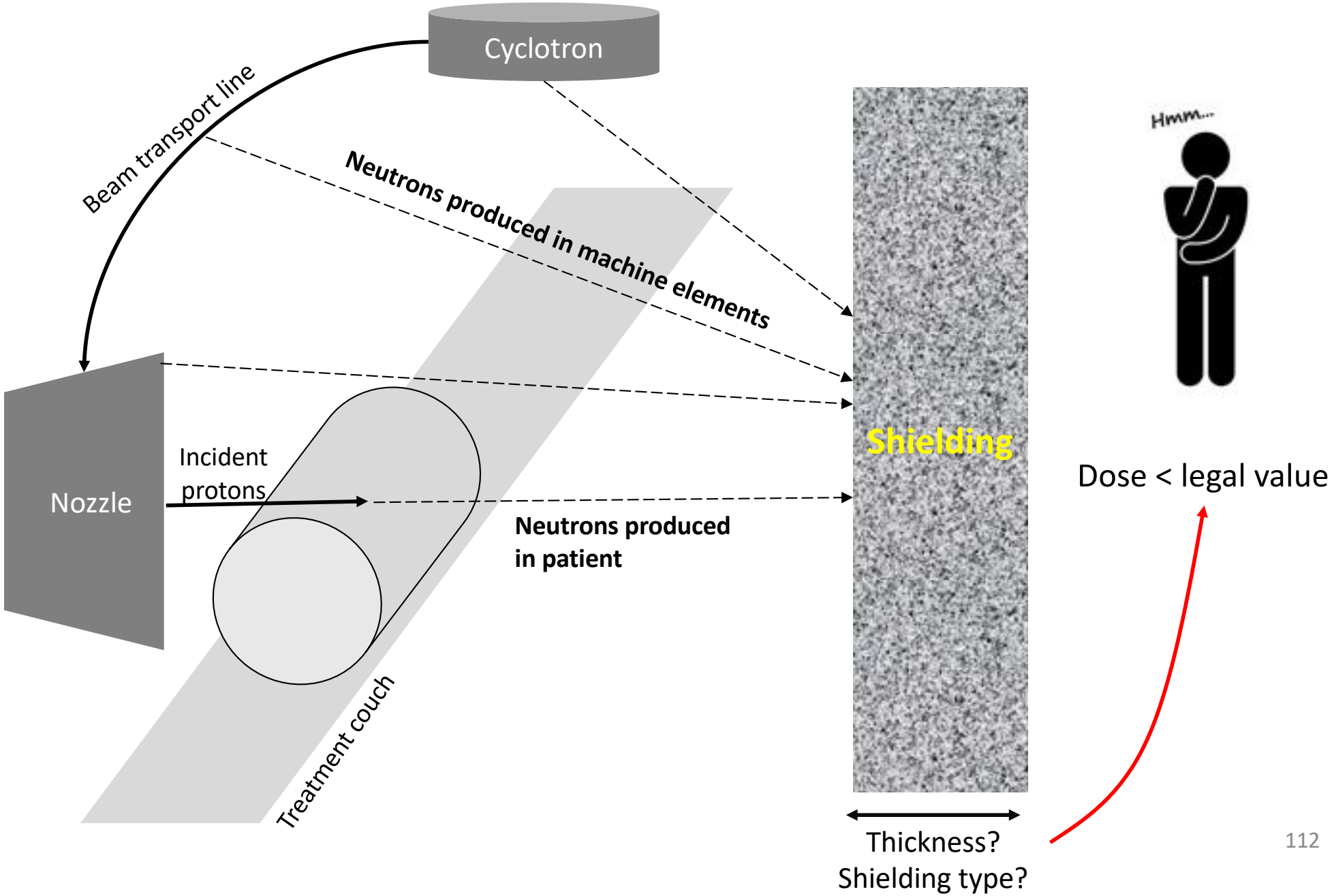
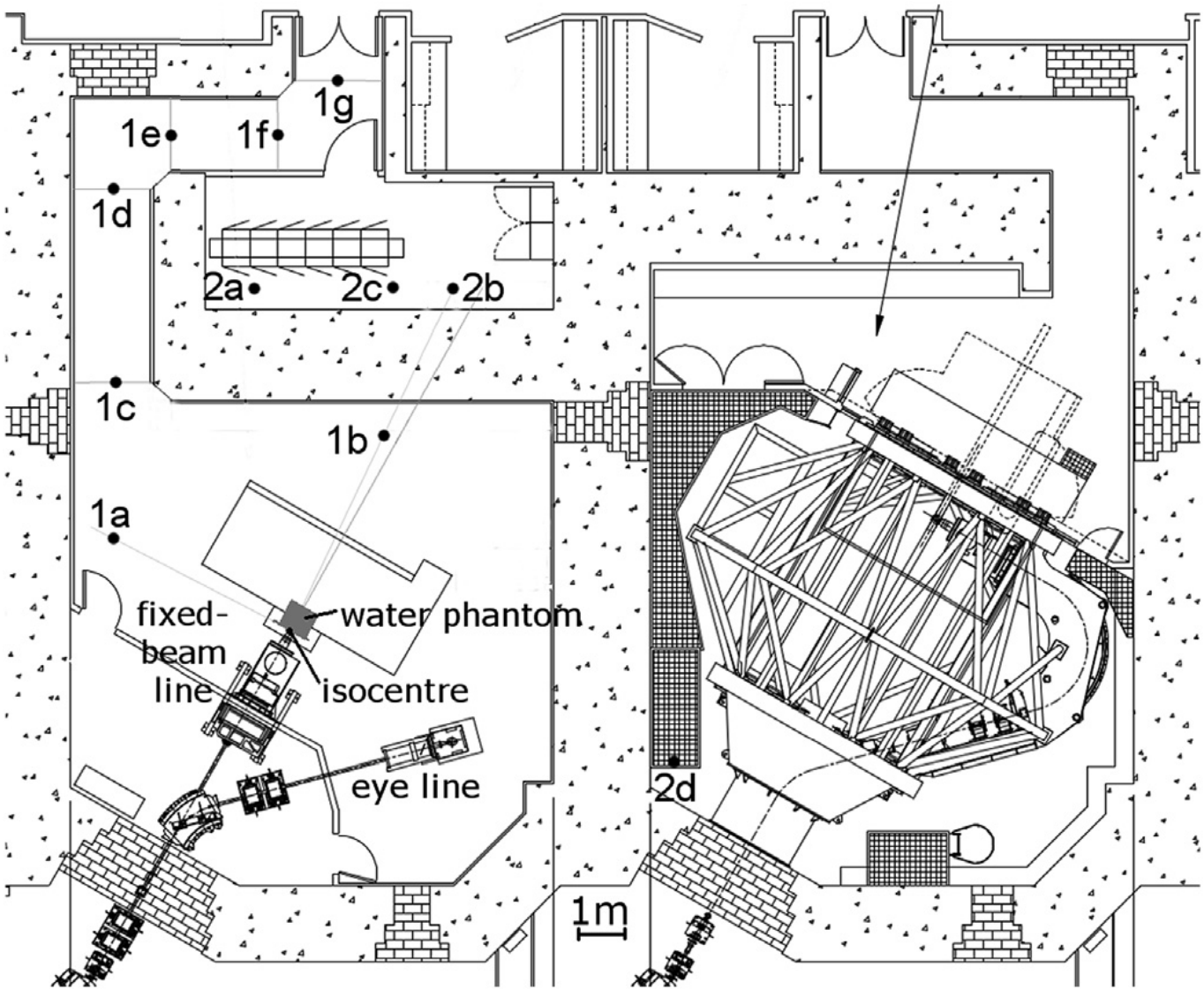
Shielding design for proton therapy facilities



Shielding design for proton therapy facilities



Simulation of shielding design for proton therapy facilities

- Complex task:
  - Multiple sources with different target materials and beam energies;
  - Neutron attenuation properties vary with direction and concrete depth;
  - Complex geometries with thick barriers and mazes.

- Assumptions needed for simulating the amount of shielding needed:
  - Facility drawings
  - Radiation sources and beam losses (vs. Beam energy)
  - Patient case mix:
    - Clinical activities
    - QA activities
    - Maintenance activities
  - Dose limits in public/controlled areas:
    - Yearly dose rates
    - Hourly dose rates
    - Instantaneous dose rates

Mazes should have a smart design

- Radiation at maze entrance consists of neutrons that scatter through the maze
- Forward-directed radiation from target should never be aimed toward the maze opening
- Sum of thicknesses of each maze wall should equal thickness of the direct-shielded wall
- As number of legs increases, the attenuation increases
- The legs should be perpendicular to each other
- Reducing maze cross-section area reduces dose at entrance
- At least two scatters are desirable

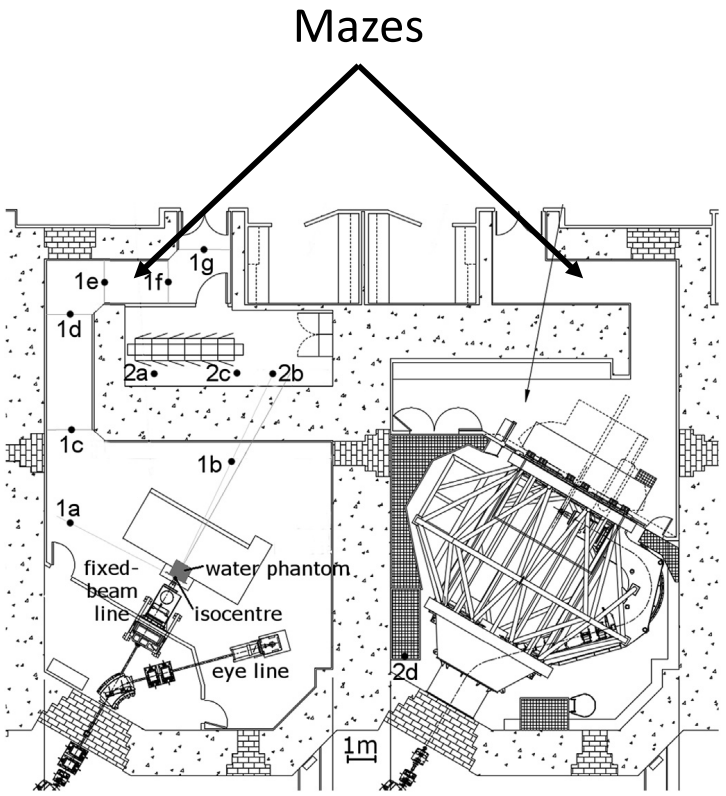
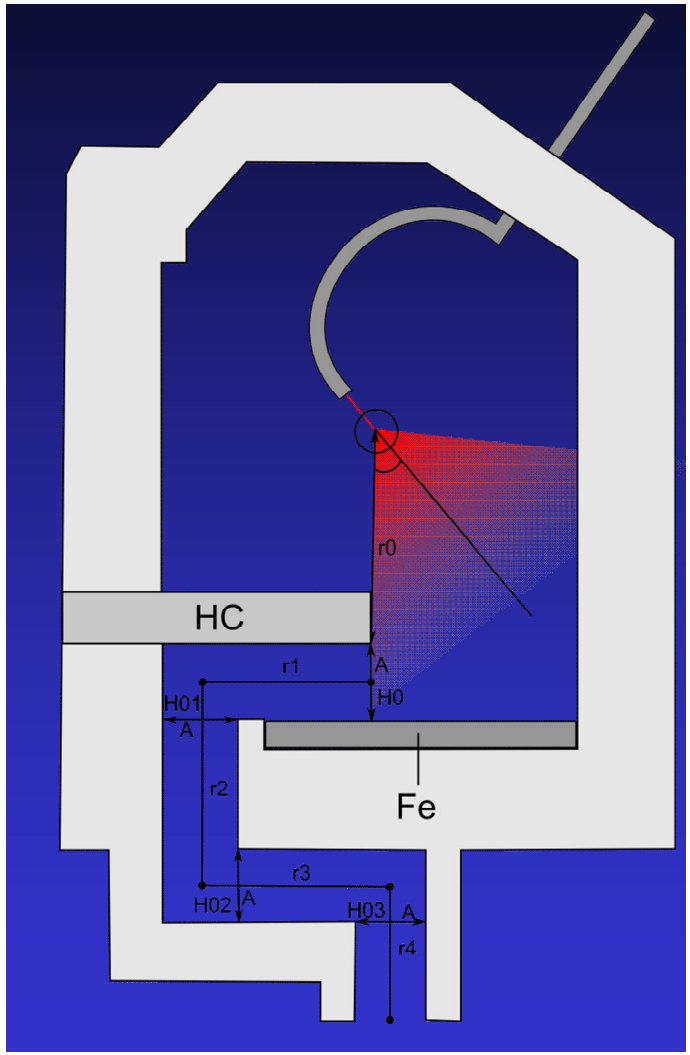


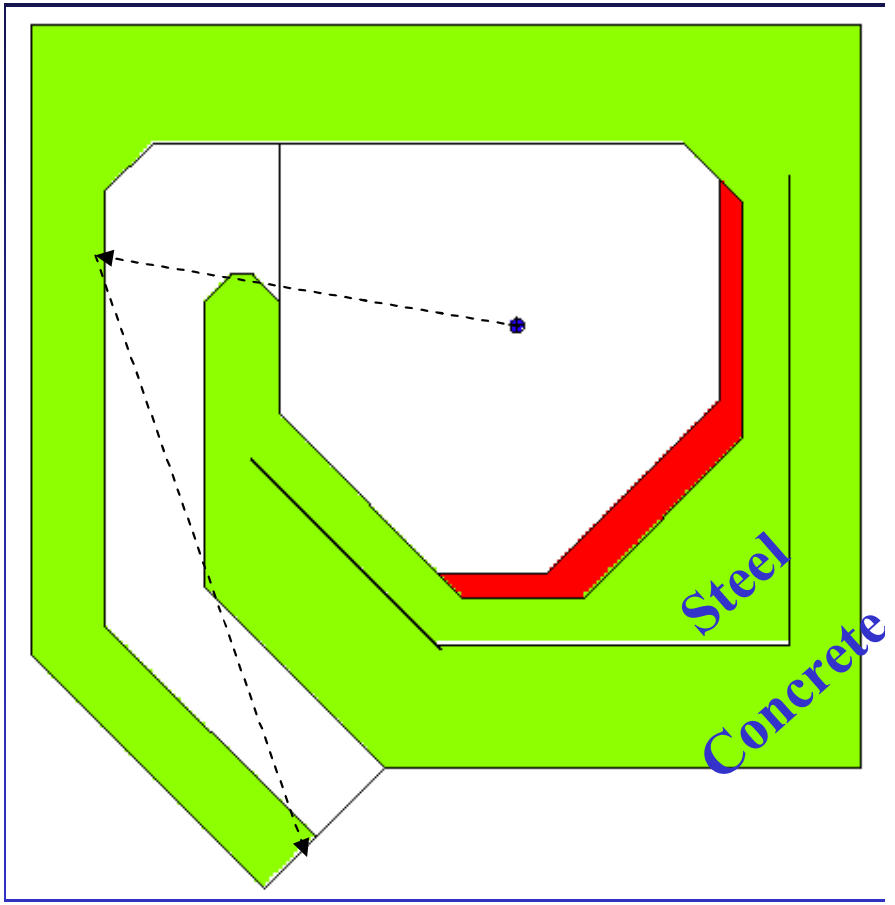
Fig. 3. Neutron measurement positions inside and around the FBTR.

http://ptcog.ch/archive/conference_p&t&v/PTCOG52/PresentationsEW/E-25-Ipe.pdf

Mazes should have a smart design



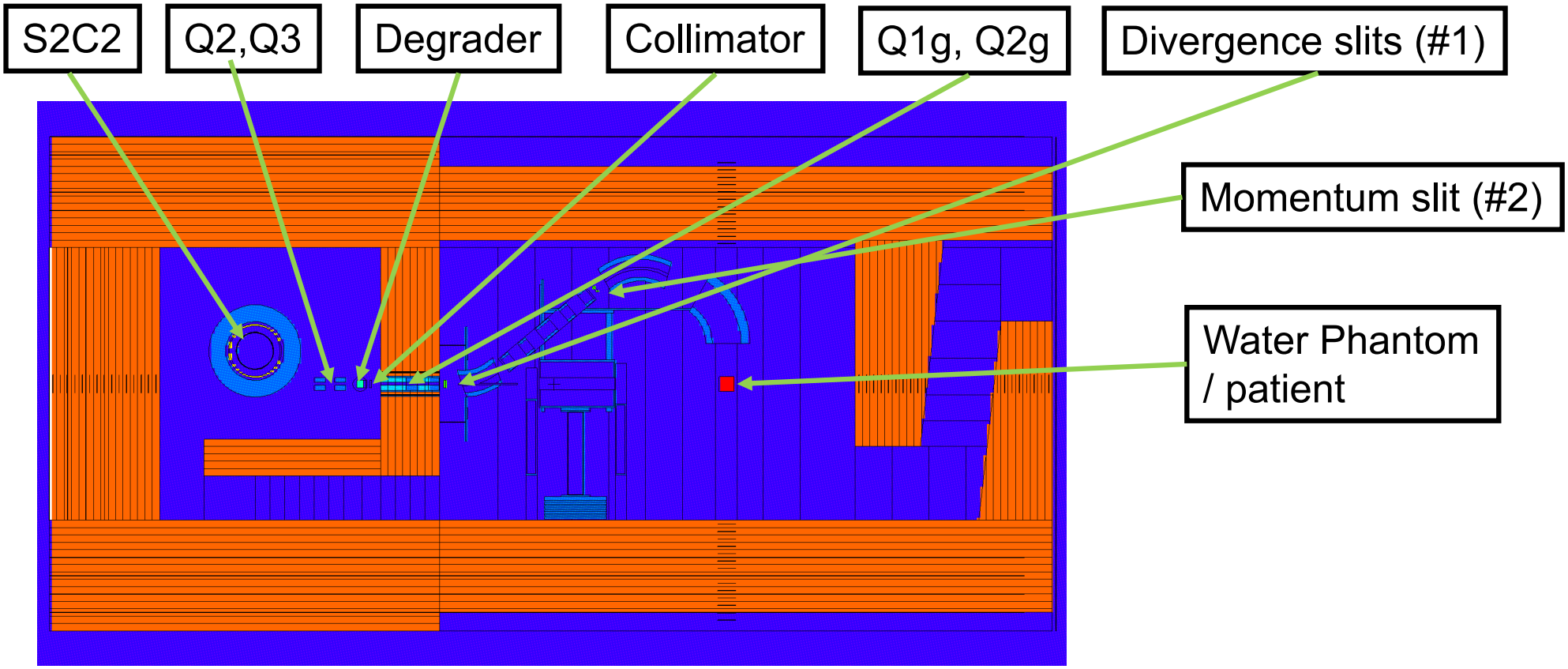
Good maze



Bad maze

http://ptcog.ch/archive/conference_p&t&v/PTCOG52/PresentationsEW/E-25-Ipe.pdf

Proteus ONE modeling (machine in Leuven and foreseen in Charleroi)



Proteus®ONE (machine in Leuven and foreseen Charleroi) : Annual Dose Determination

- The annual dose determination around the *Proteus®ONE* vault is based upon a realistic patient case mix established by IBA clinical director and based upon our experience in PT treatments.
- This *Proteus®ONE* patient case mix is based upon the following usage:
  - Clinical Operation = 4800 hours/year
    - 16 hours/day (2 shifts)
    - 6 days/week
    - 50 weeks/year
  - Patients treated per year = 435
  - Fractions (2 Gy) per year = 16660
- The yearly fractions are divided into 4 major types of indications corresponding to groups of tumors.
- The model also include fractions devoted to QA activities (morning QA and patient QA).

Annual Patient Case Mix

Utilisation de la machine pour obtenir 1Gy (courant de protons x temps d'irradiation)

Utilisation effective de la machine pour 1h de traitement (tout compris (positionnement, prise en charge…))

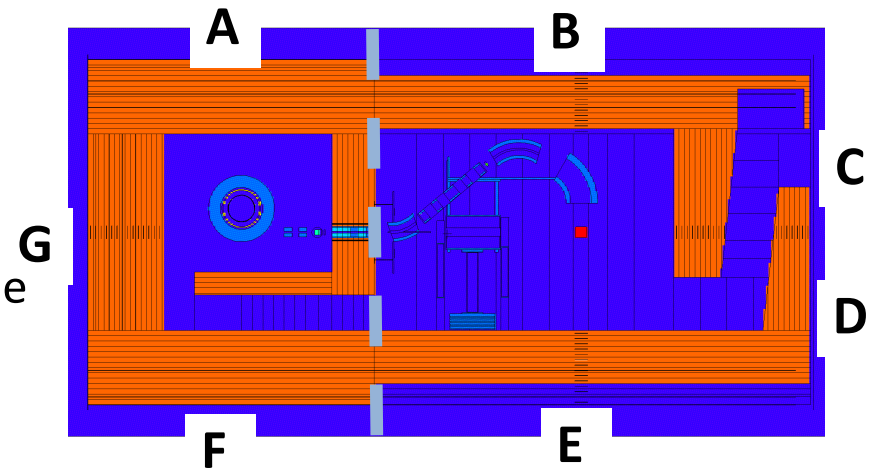
Clinical Activities

QA Activities

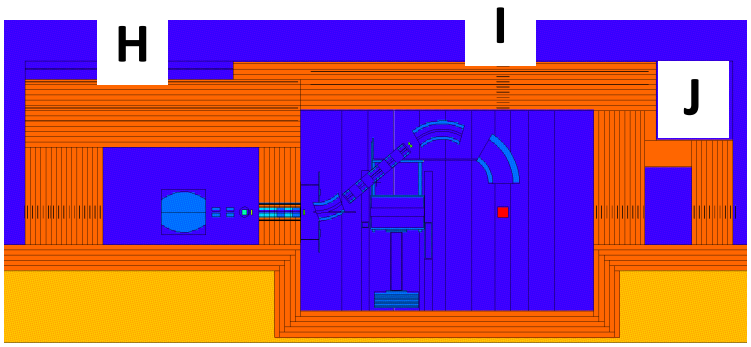
Indications	Min. Range (g/cm^2)	Max. Range (g/cm^2)	Field size (cm^2)	Annual Dose (Gy)	w(1Gy) (nA.s)	w_{iso} (nA.h)
Head & Neck	8	18	7.7 x 7.7	5090	7.29	10.31
	2	12	7.7 x 7.7	5090	6.27	8.87
Lung Tumor	8	20	7.9 x 7.9	4307	8.39	10.04
	4	17	7.9 x 7.9	4307	8.36	10.01
Sarcoma	20	32	10.1 x 10.1	5612	15.42	24.04
	15	27	10.1 x 10.1	5612	14.89	23.22
Pediatric	8	18	18.6 x 18.6	1653	42.09	19.33
	2	12	18.6 x 18.6	1653	36.46	16.74
QA – low R	4	14	10 x 10	1200	12.04	4.013
QA – medium R	13	23	10 x 10	1200	13.78	4.593
QA – high R	22	32	10 x 10	1200	15.75	5.250

Proteus®ONE Annual dose rates

Coupe horizontale



Coupe verticale



Position	Barrier thickness (m)	Max. H*(10) (µSv/year)
A	2.8	392.2
B	2.0	148.5
C	1.8 to 2.4	275.5
D	1.4 to 2.0	108.0
E	2.0	325.2
F	2.8	347.9
G	2.8	397.8
H	2.5	390.2
I	1.9	233.4
J	2.1	356.6

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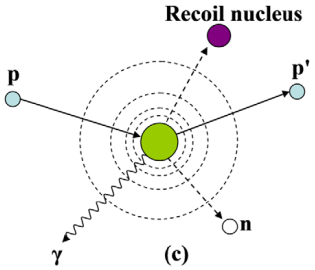
Effect on depth-dose distribution



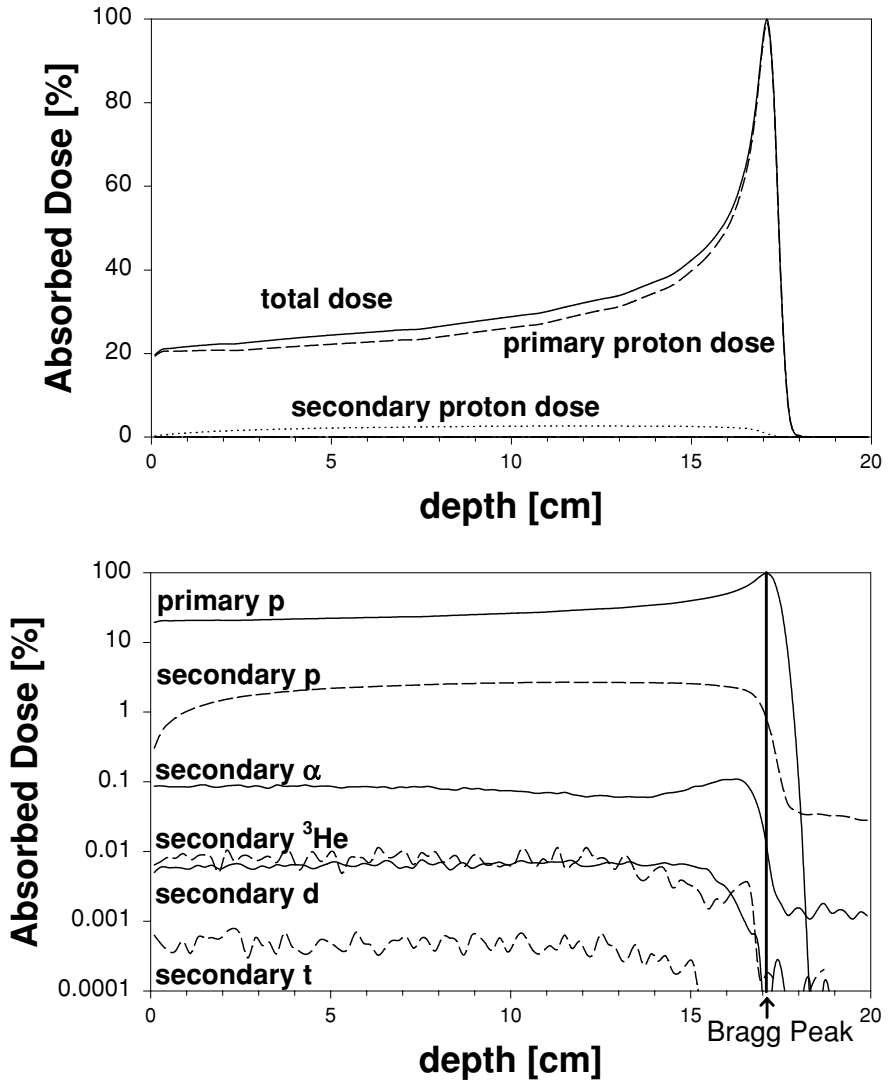


Figure 4. Depth–dose distributions (Bragg peak normalized to 100%) for a 160 MeV proton beam incident on a water phantom. The upper figure shows the total dose and the dose due to primary and secondary protons. The lower figure compares, on a logarithmic scale, the doses due to different types of particles (solid lines: primary p, secondary α and d; dashed lines: secondary p, ^{3}He, t). A vertical line indicates the position of the maximum of the Bragg peak.

Physical neutron dose

- Maximum 1% of therapeutic Gy for passive systems
- Of order of 0.1% for active systems
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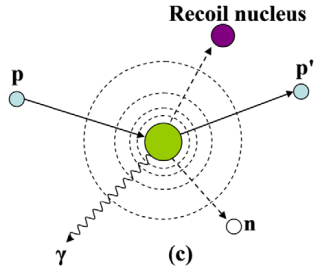

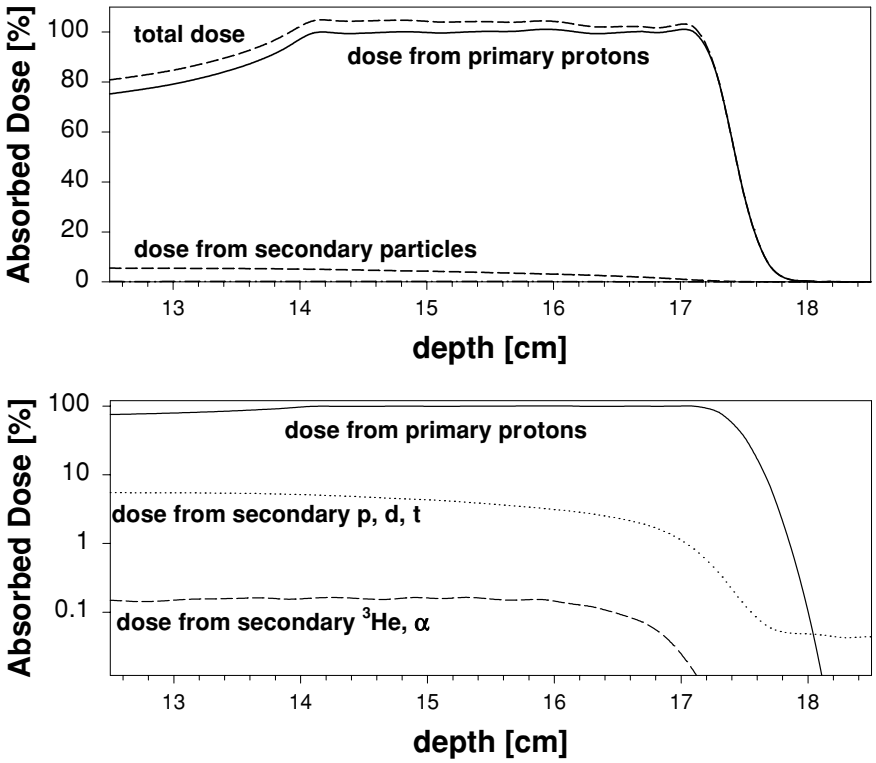

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Paganetti (Phys. Med. Biol. 2002)

Activation of materials

- Neutrons can activate materials
- Recommendations for handling “hot” materials (i.e. phantom that has just been irradiated for long time)
- Recommendations for keeping distance with nozzle and collimation parts

Conclusions

- Interactions of proton beams with matter generate complex fields of secondary neutrons and photons.
- Monte Carlo simulation codes are an ideal tool to address the radiation protection challenges created by this new kind of cancer therapy:
  - Shielding design around the equipment
  - Out-of-field radiation doses to patient

Thank you!