Trending Issues of Radiation Protection for External Beam Radiation Oncology

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Disclosure and Potential Conflicts of Interest Statement

PROVISION CARES
PROTON THERAPY

- I am a advisor to Provision CARES, a company building and operating proton cancer centers.

LEO
Cancer Care

- I am a co-founder and board member of Leo Cancer Care™, a company developing an upright radiotherapy system.

Outline

- Medical radiation exposure is increasing.
- Modern radiation therapy is devoted to decreasing acute exposure to sensitive tissues using 3D conformal radiation therapy and intensity modulated radiotherapy (IMRT).
- Proton beams vs. x-ray beams.
- Image-guidance in radiotherapy.
- Integral dose – a simple measure of patient harm.
- Types of photon beam radiotherapy.
- Emergence of MRI-guided radiotherapy.
- Reduction in radiation bunker (vault) sizes.

Medical Radiation Exposure

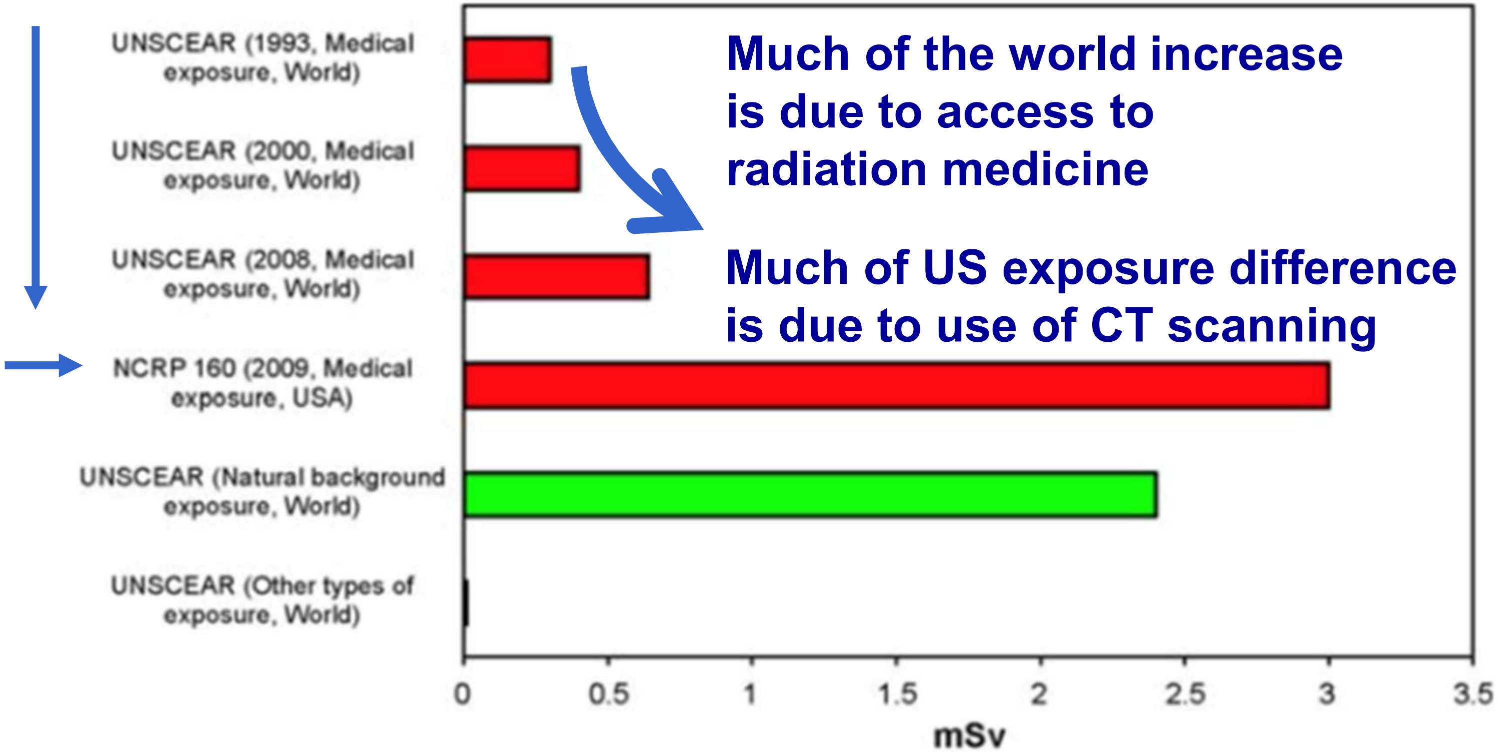
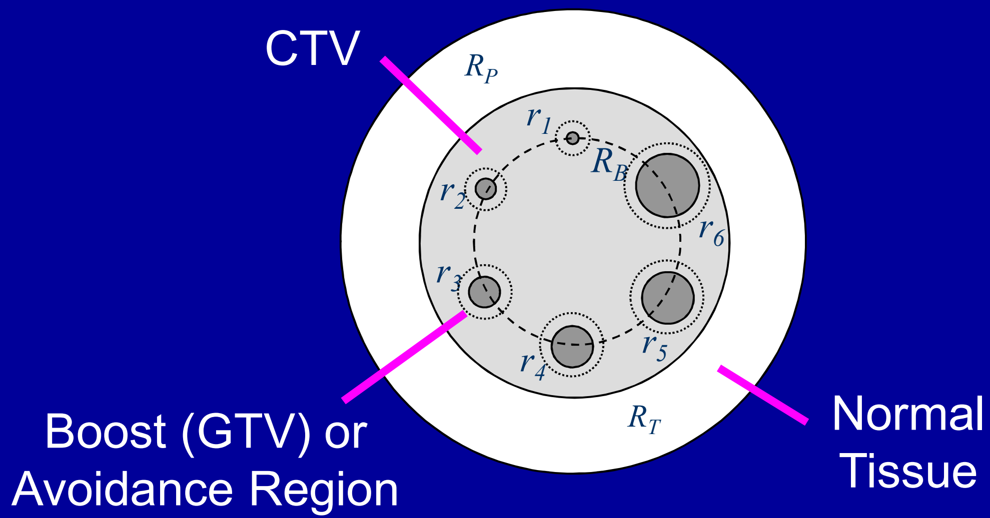


Fig. 1. Increasing annual per caput effective dose to the worlds population from medical exposure, compared with natural background and other exposure [1,2], and the annual per caput effective dose from medical exposure to the U.S. population [3].

Holmberg O et al., Current issues and actions in radiation protection of patients European Journal of Radiology 76:15–19 (2010)

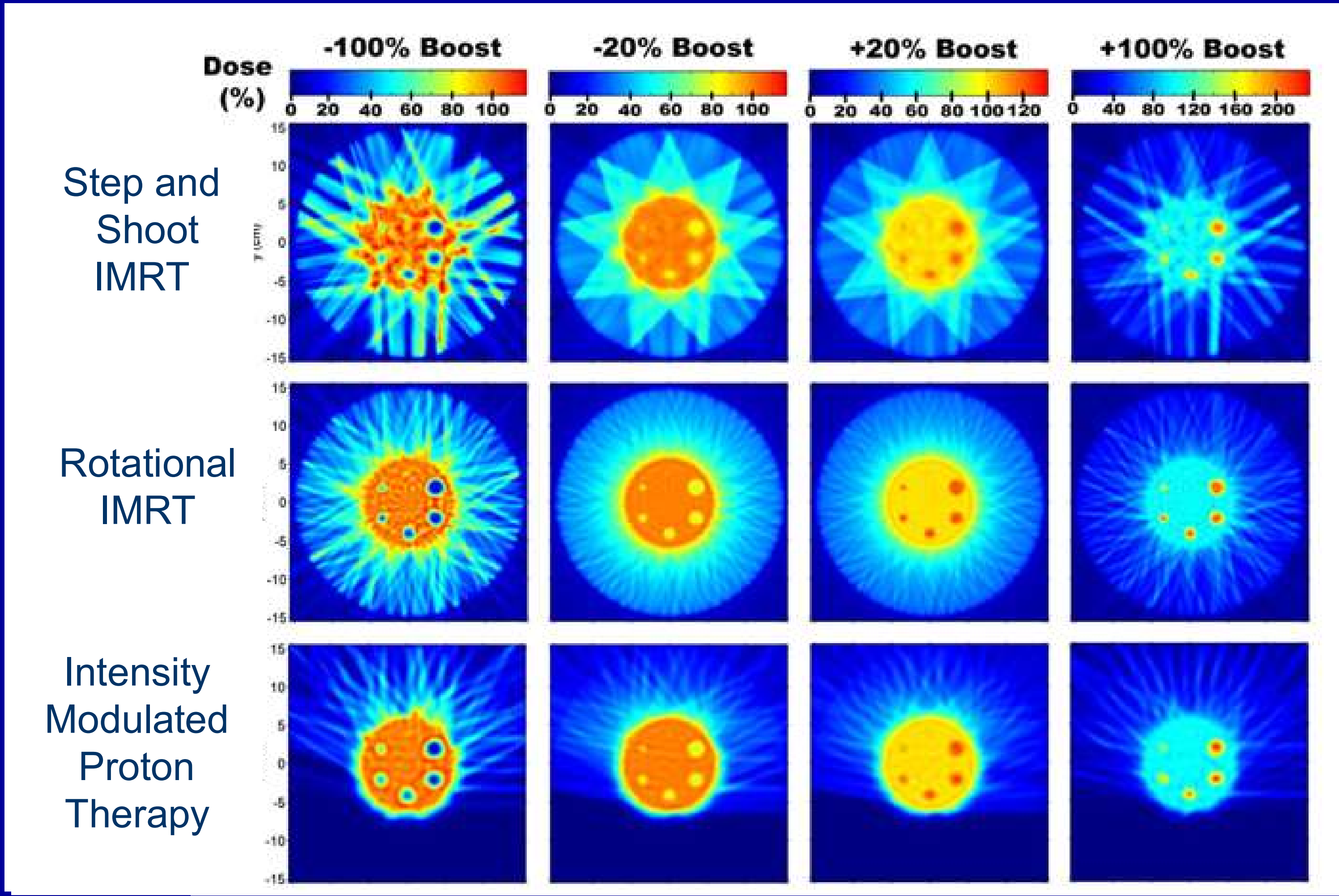
Dose Contrast Resolution

Apply Boost or Avoidance (Negative Boost) Dose to Regions of Varying Size

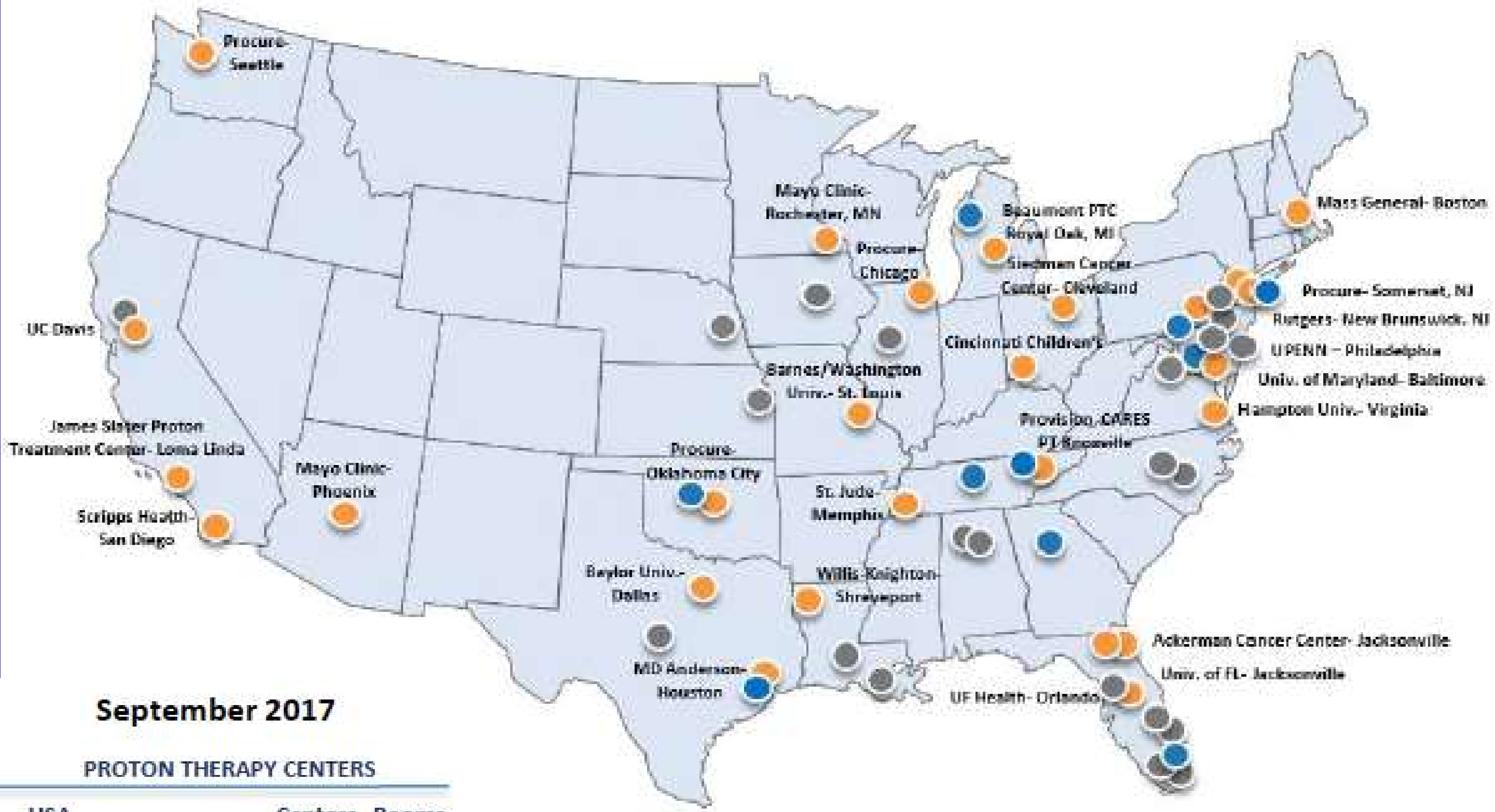


Flynn et al., Comparison of intensity modulated x-ray therapy and intensity modulated proton therapy for selective subvolume boosting: A phantom study. Phys. Med. Biol. 52, 6073-6091 (2007).

Dose Contrast Resolution



US Proton Centers



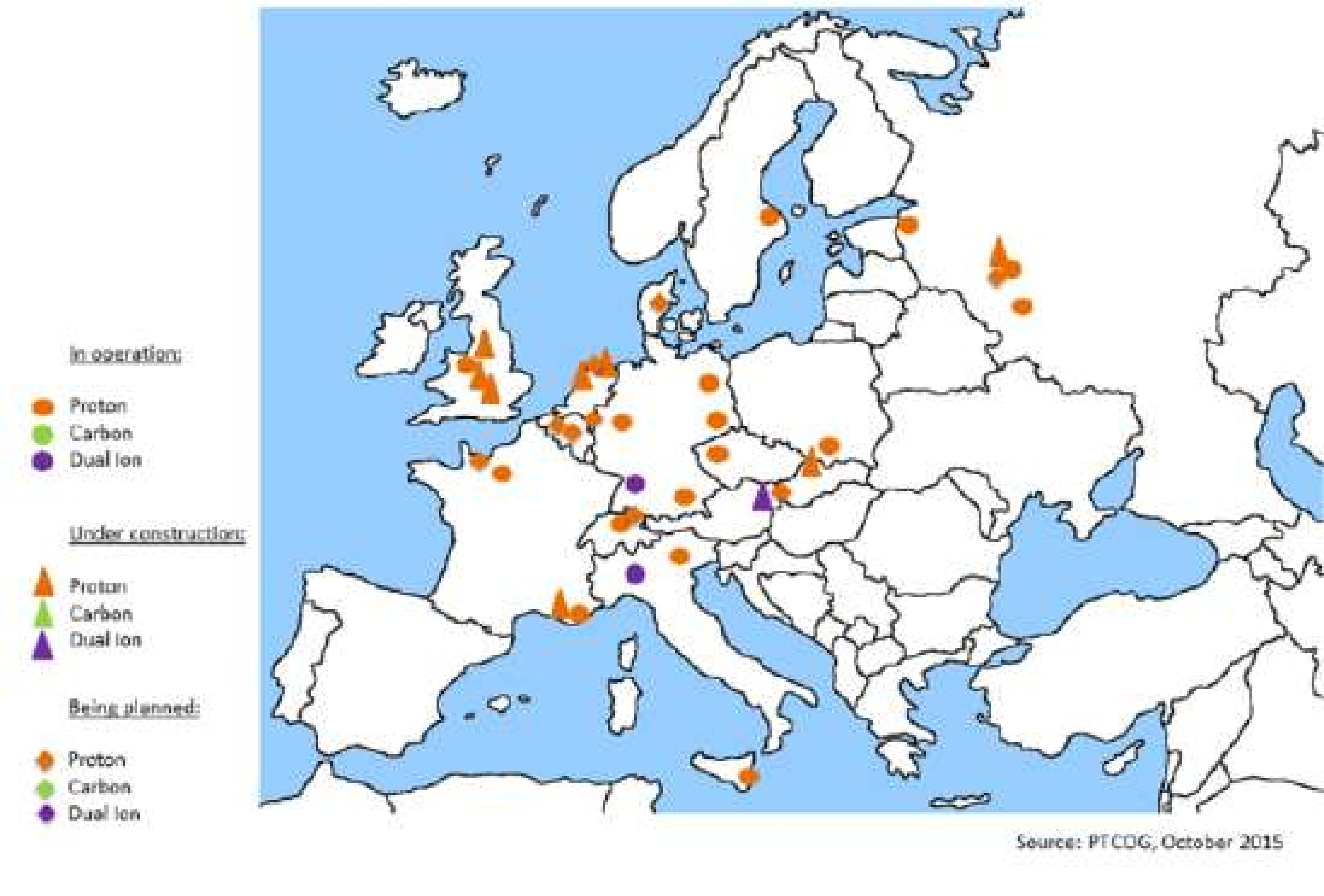
September 2017

PROTON THERAPY CENTERS

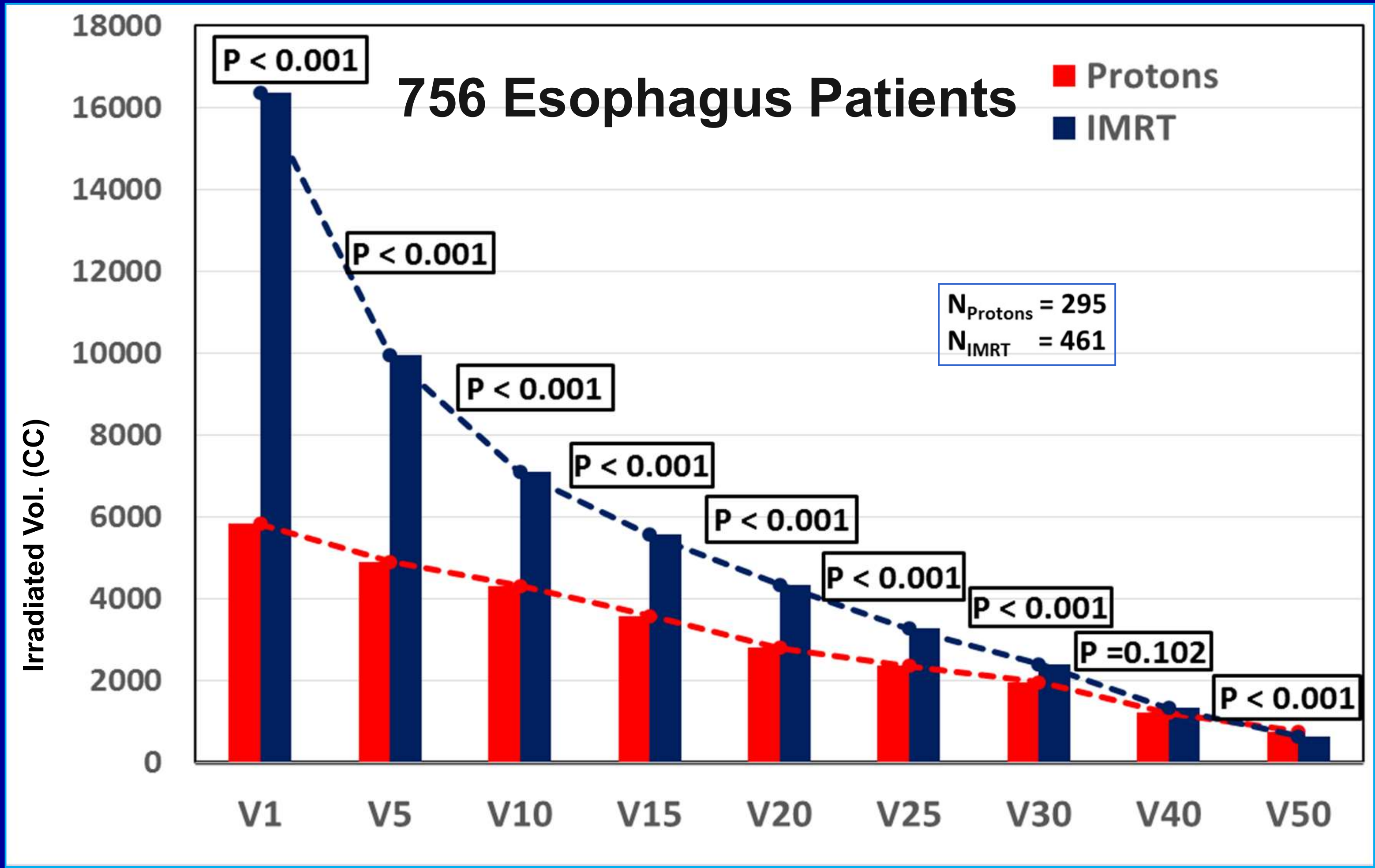
USA	Centers	Rooms
In Operation	26	79
Under Construction	10	32
In Development	22	36
TOTAL	58	147

Number of proton centers is accelerating in the US.

European Proton Centers

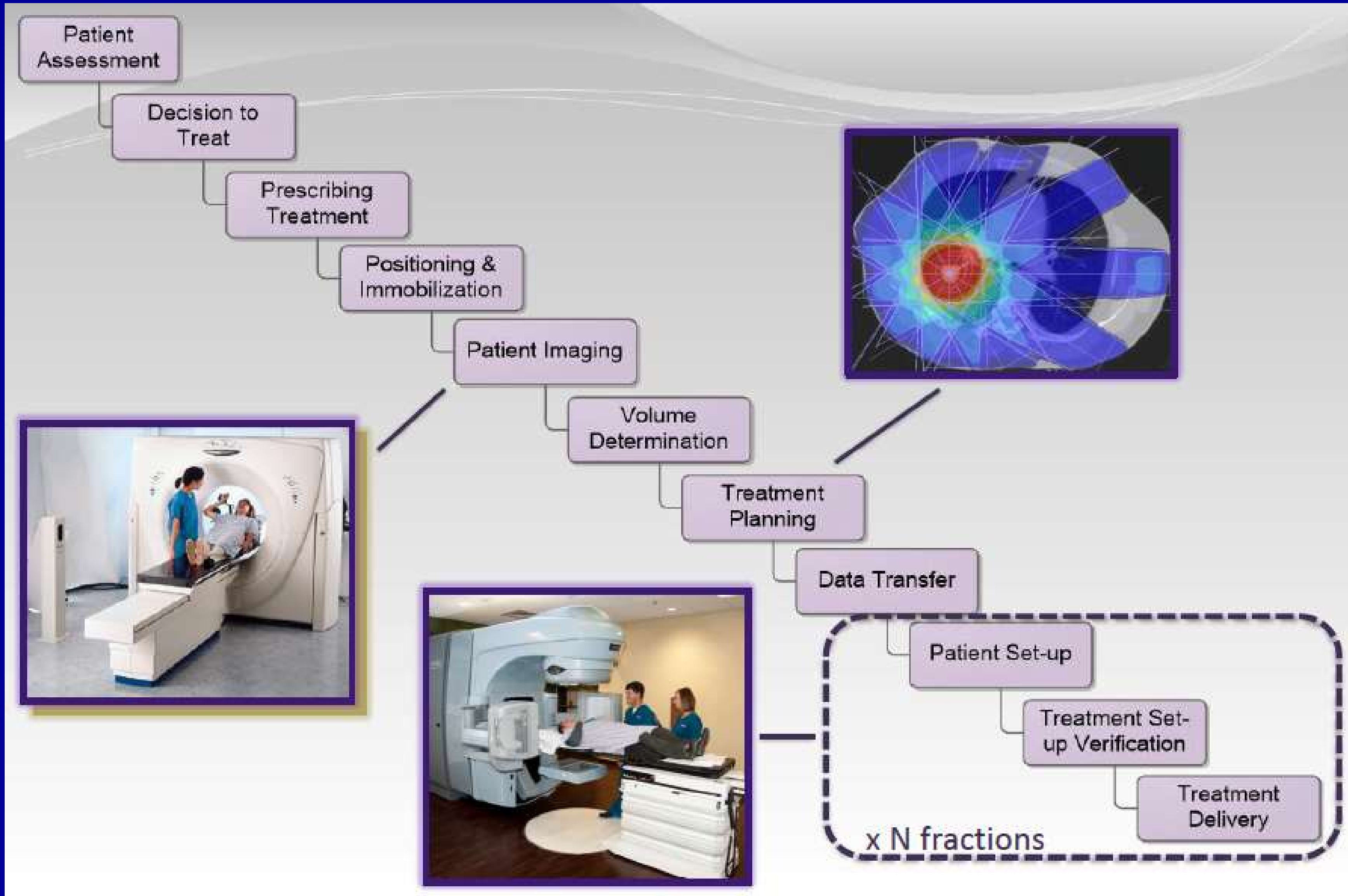


Body Volume Exposed to Specified Dose Levels (or Higher): Protons vs. Photons



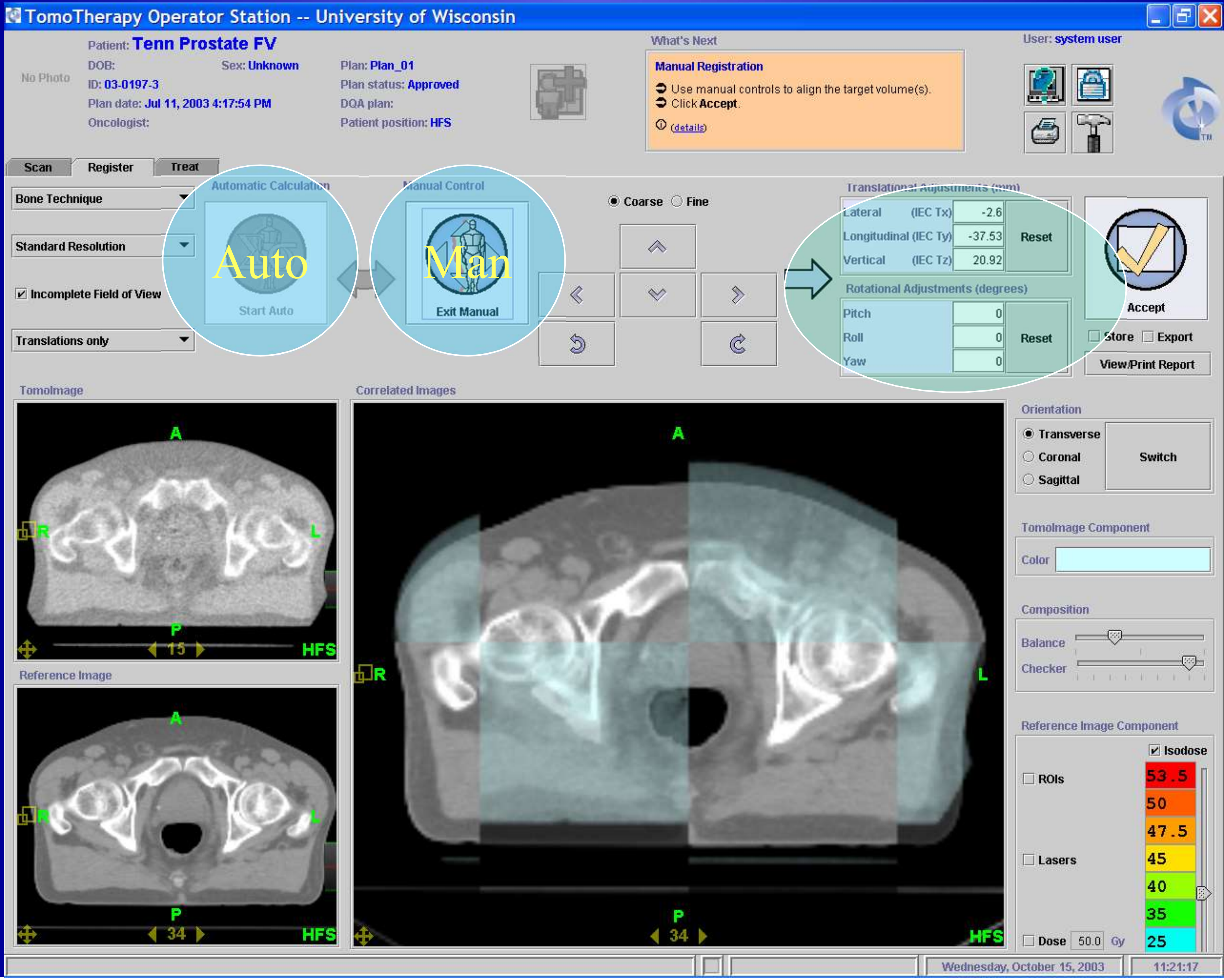
From Radhe Mohan, MD Anderson Cancer Center

Processes of External Beam Radiotherapy



From Jake Van Dyk, London Regional Cancer Center, London ON

Register Verification CT to Planning CT



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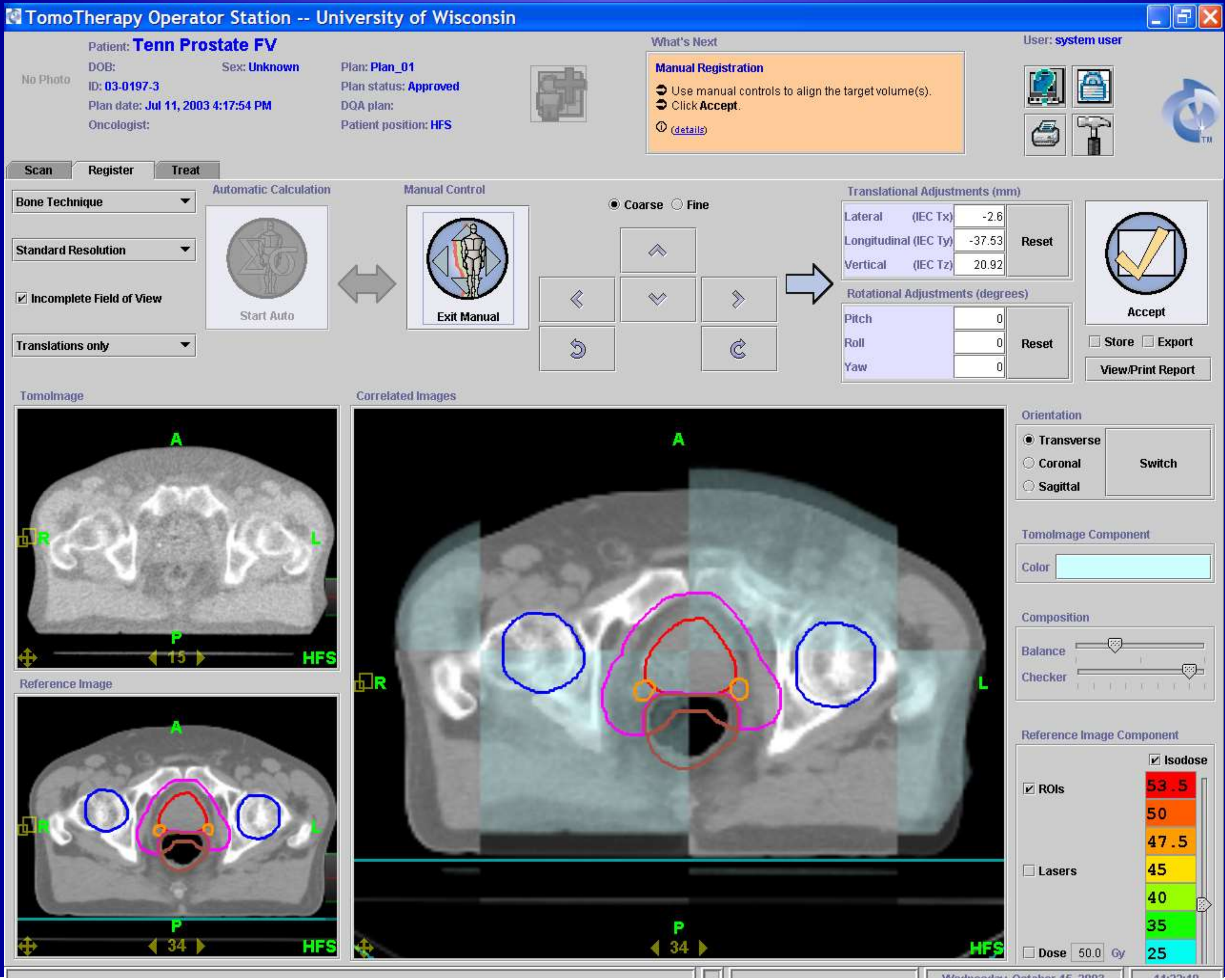
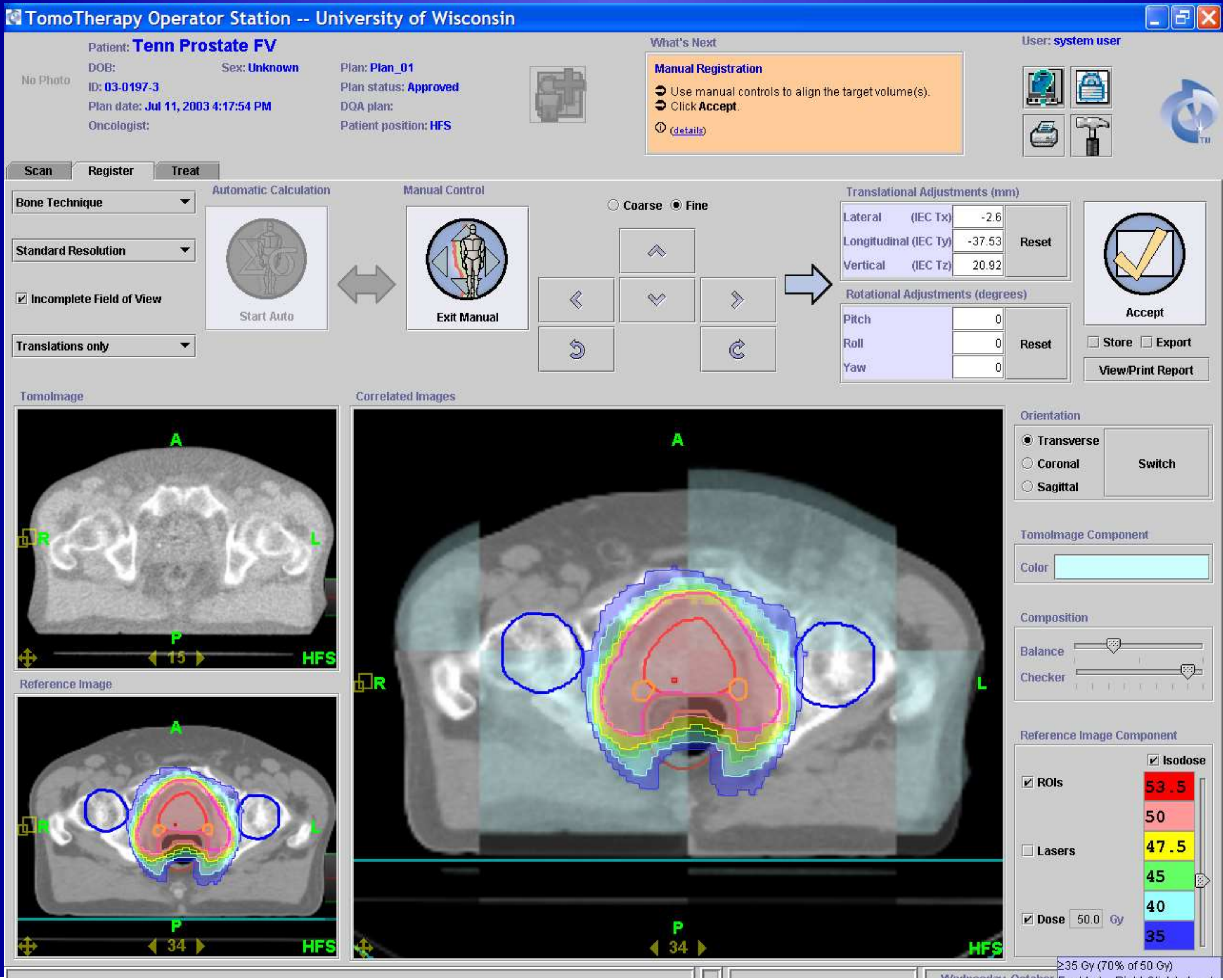
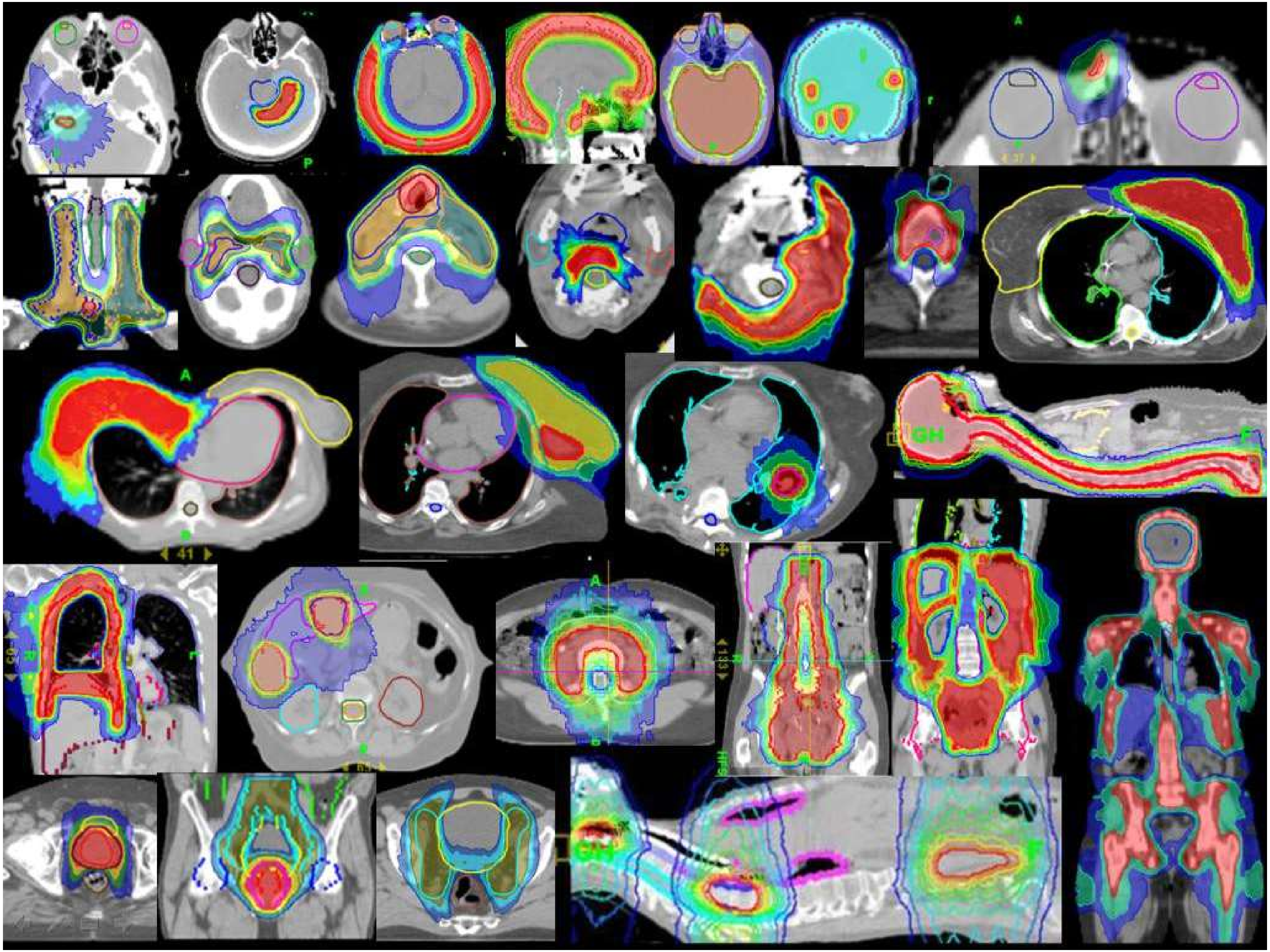


Register Verification CT to Planning CT





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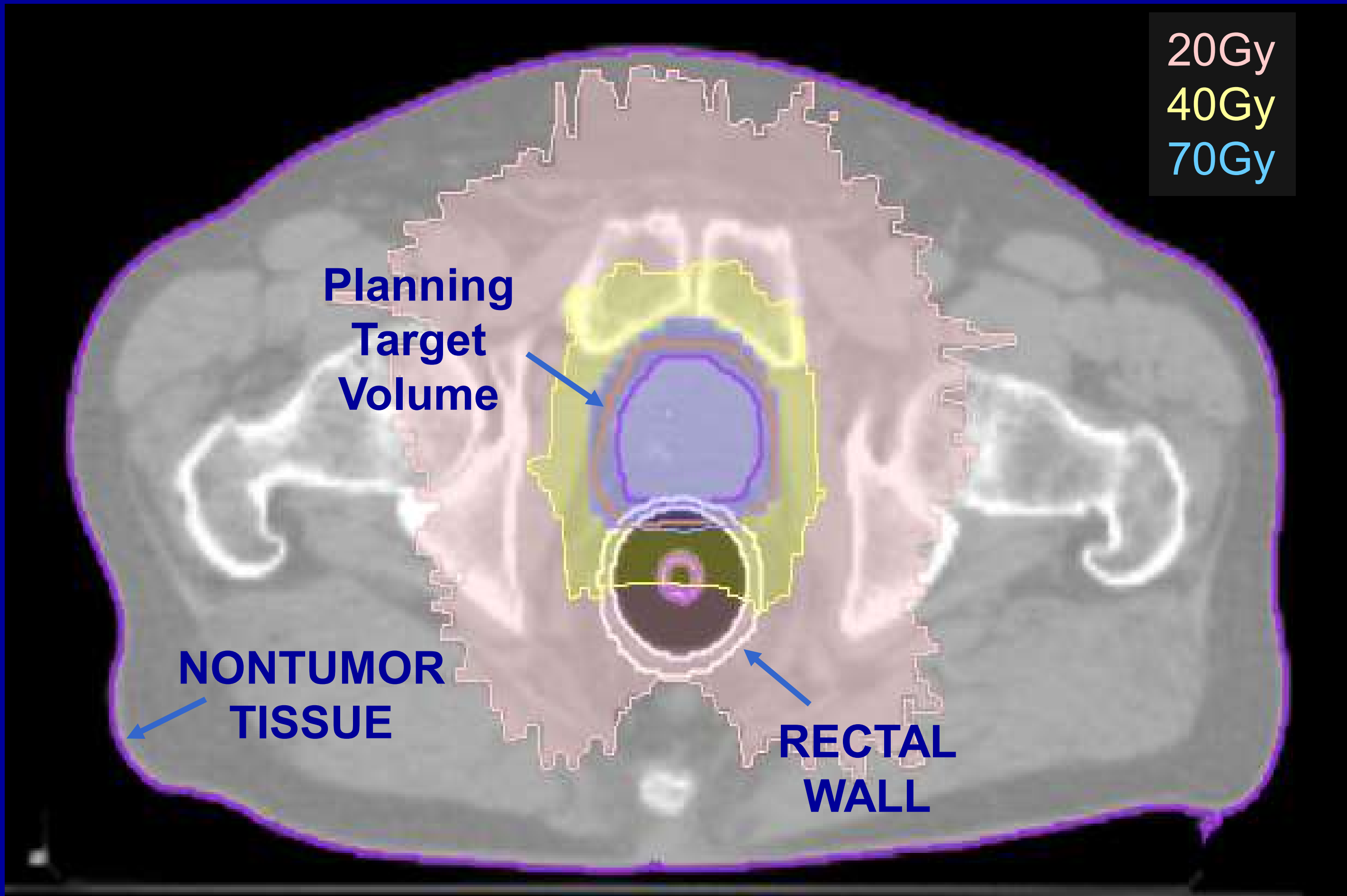
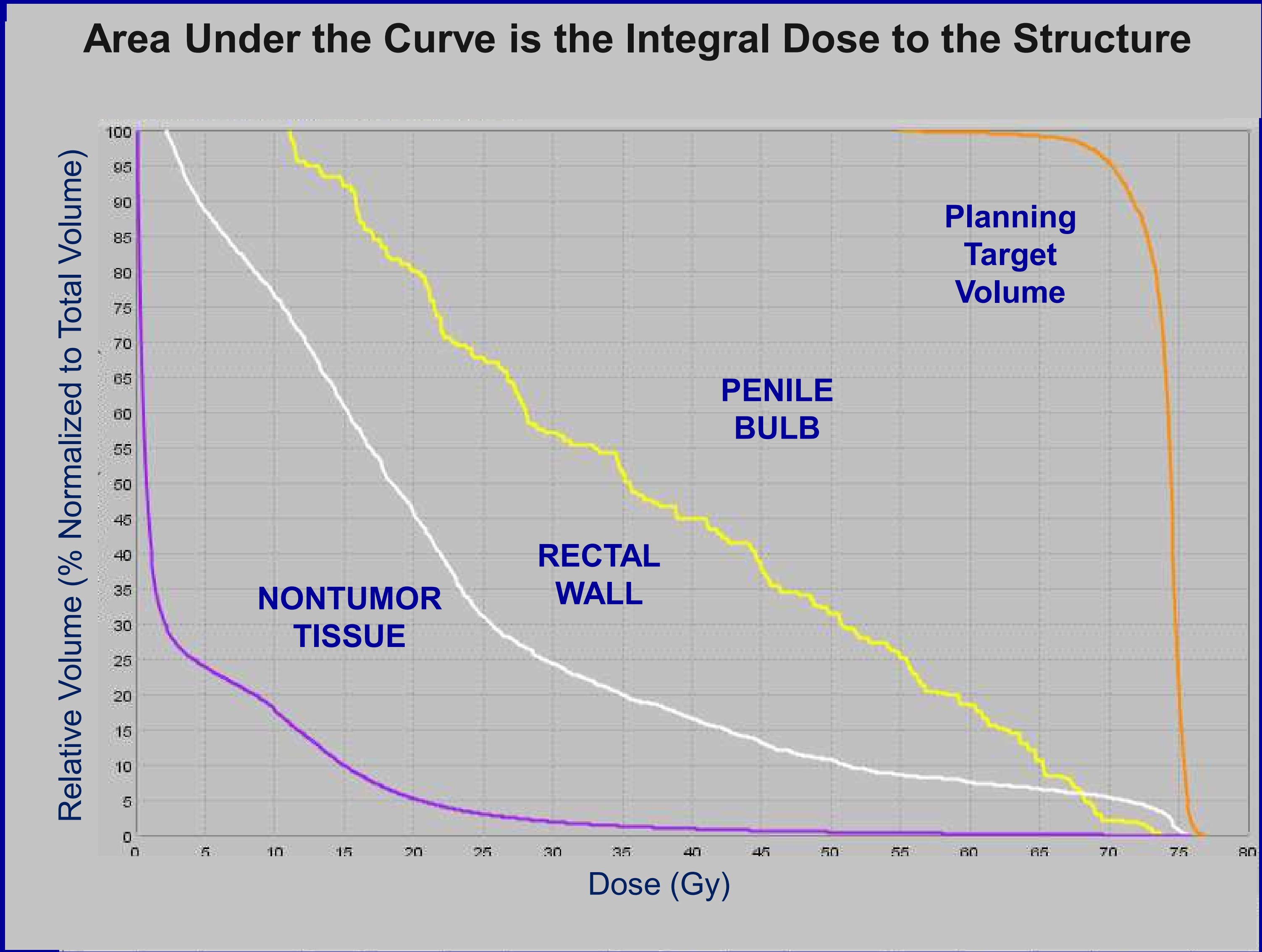
Dose Distribution for IMRT



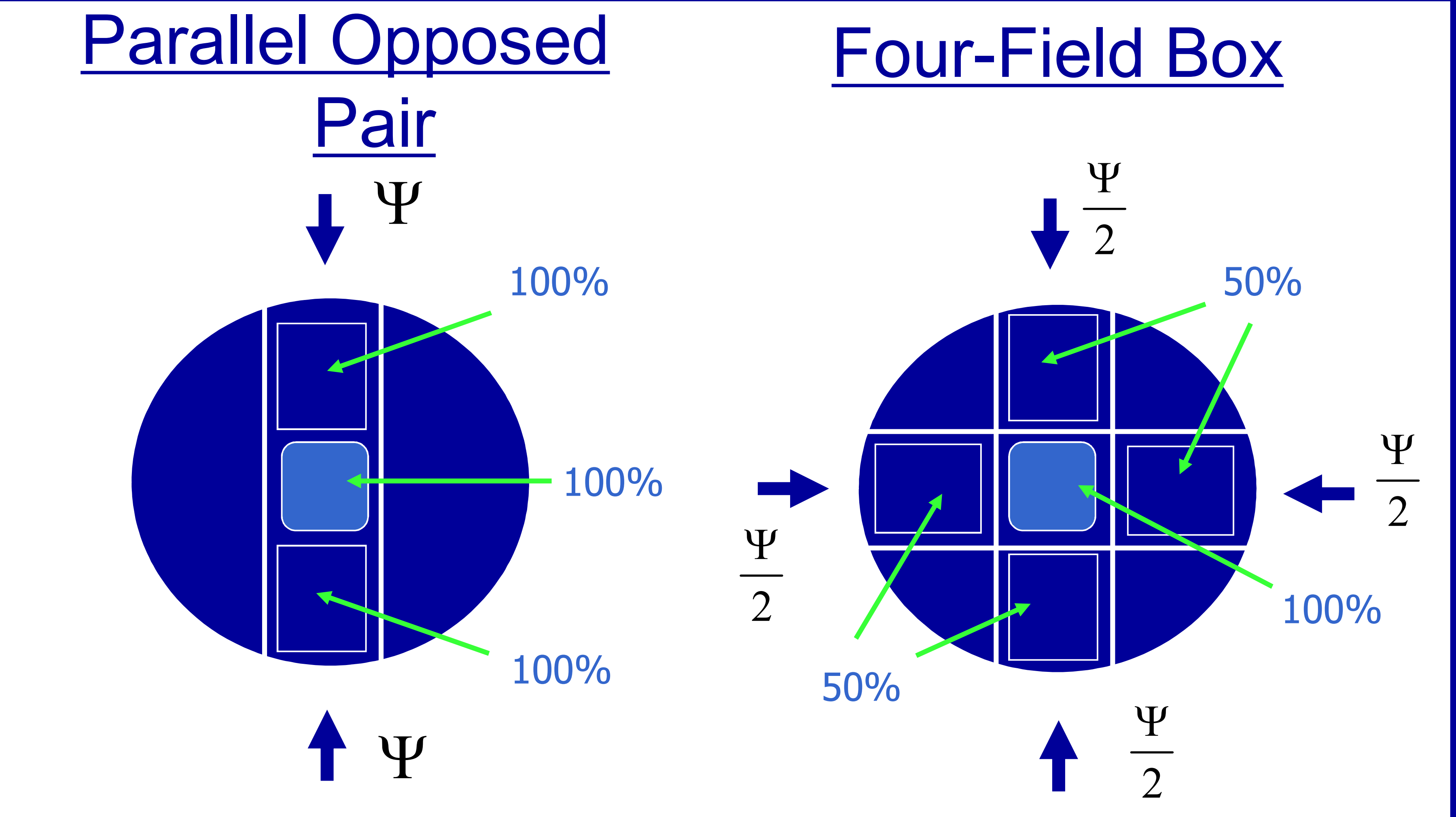
Cumulative Dose-Volume Histogram



Integral Dose

- For megavoltage photon beams the integral dose to patients is nearly invariant with technique of delivery.
- Integral dose in units of Gy-liter for a structure is equal to the product of mean dose and volume of the structure.
- Note that using a definition of integral dose as energy in J instead of Gy-liter reduces the impact of low density tissues like lung and raises the impact of high density tissues like bone.
- The components of integral dose are:
  - In-field dose including electron contamination
  - Outside-field leakage dose
  - Neutron contamination

Integral Dose is Independent of the Number of Fields

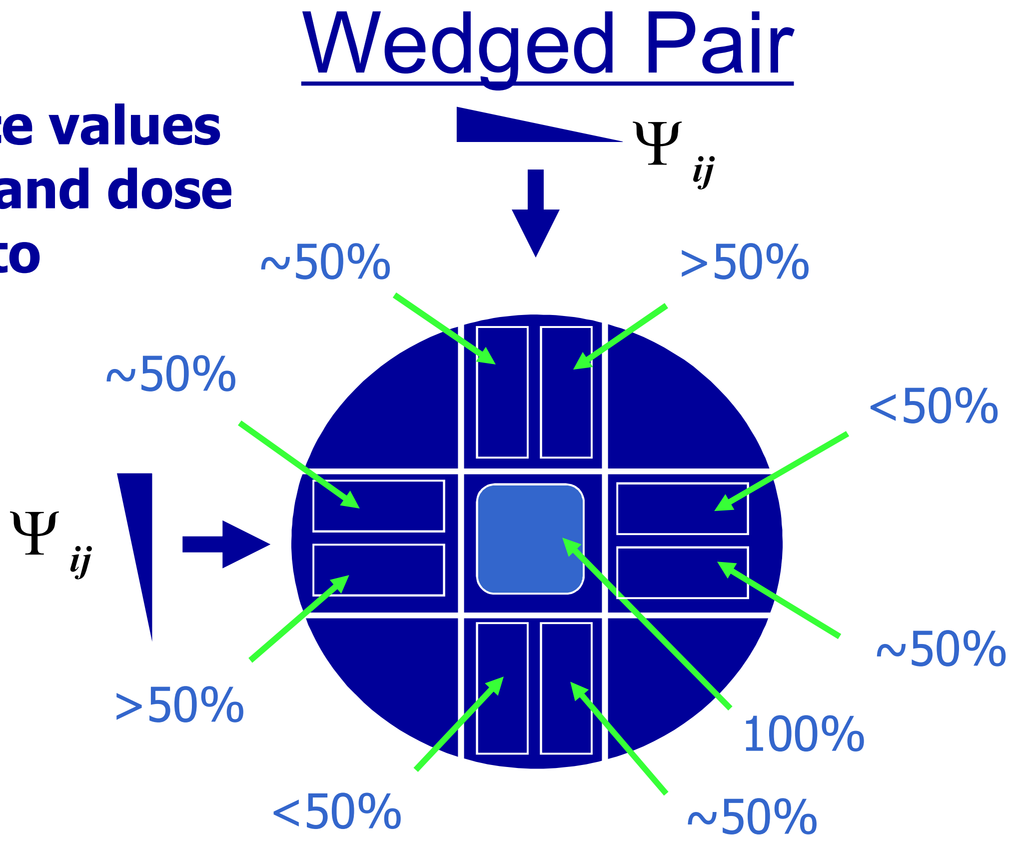


A four-field box has half the energy fluence from each of the beams and results in double the volume of normal tissue irradiated to half the dose.

Intensity Modulated Radiation Therapy (IMRT)

A wedge is a primitive form of IMRT delivery.

The energy fluence values are non-uniform and dose values now refer to volume averages.



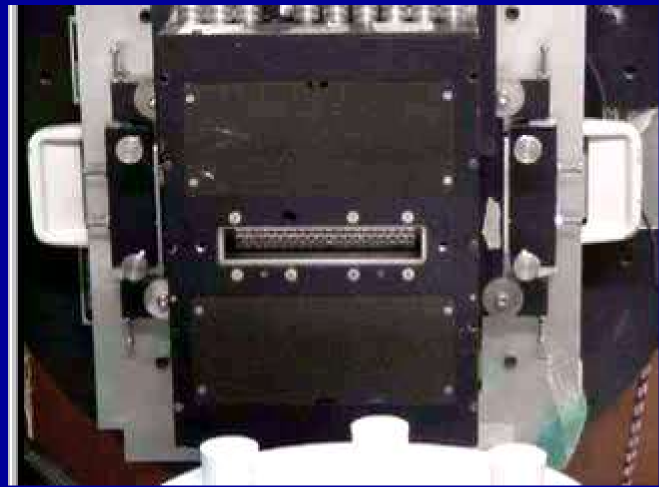
With leakage neglected, the integral dose is invariant with technique for both uniform and non-uniform delivery.

Radiobiology of Integral Dose

- Intensity Modulated Radiation Therapy (IMRT) tends to deliver less dose to a larger volume.
- However with IMRT it is possible to avoid high doses to those structures, such as the thyroid and breast, that have the highest probability of a radiation-induced malignancy.
- A low dose bath is produced well away from the tumor volume due to beam entrance and exit (for photons only), leakage from the collimation system, and neutron production.

Multileaf Collimators

Conventional | **Binary**

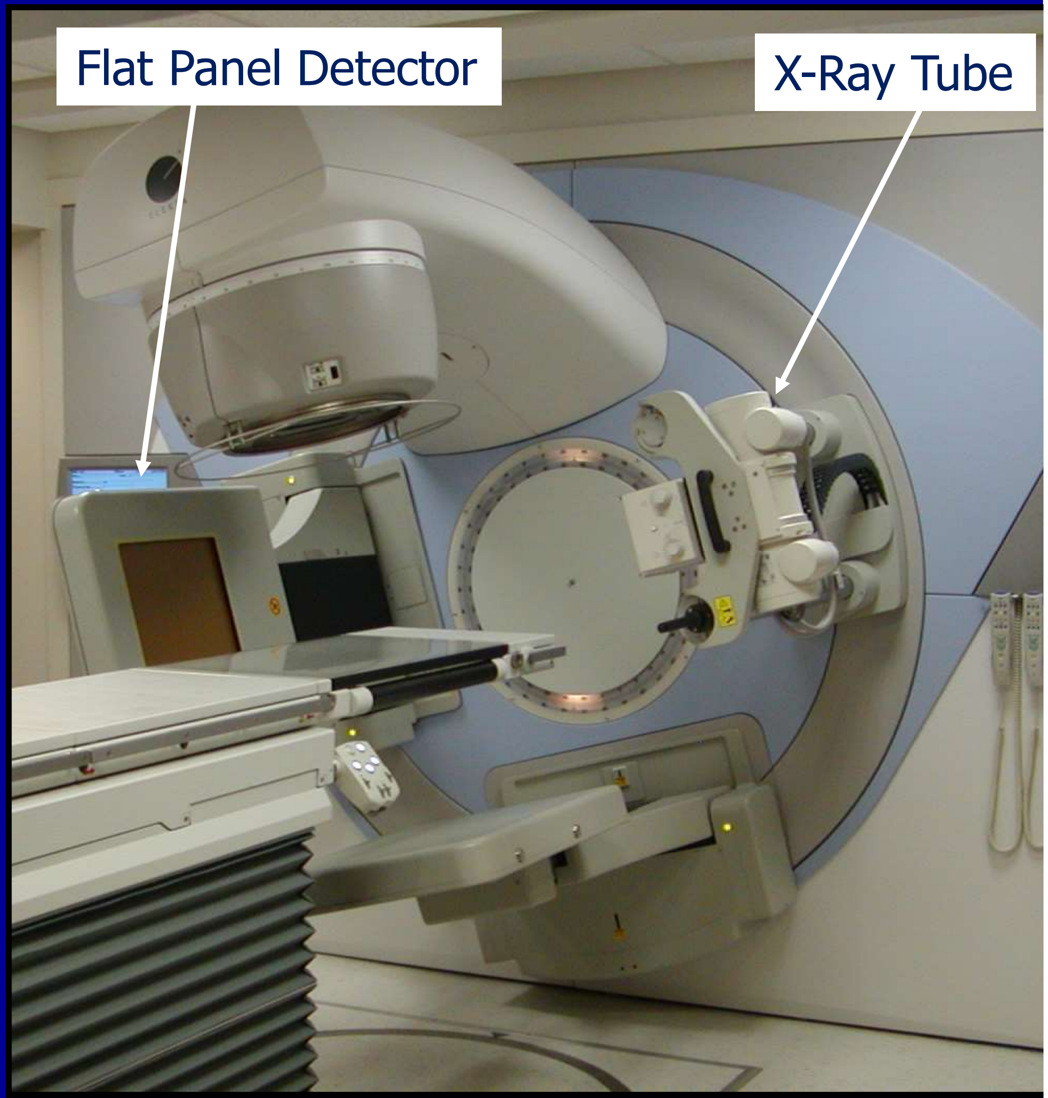


- Conventional MLC's were designed for field shaping and have limitations when used for IMRT.
- Binary (off-on) MLC's are designed for IMRT and are the easiest to model and verify.

Cone Beam CT

- David Jaffray pioneered cone beam CT at Beaumont Hospital Hospital in Michigan.
- kV CT scanning with some speed limitations due to detector response

David Jaffray

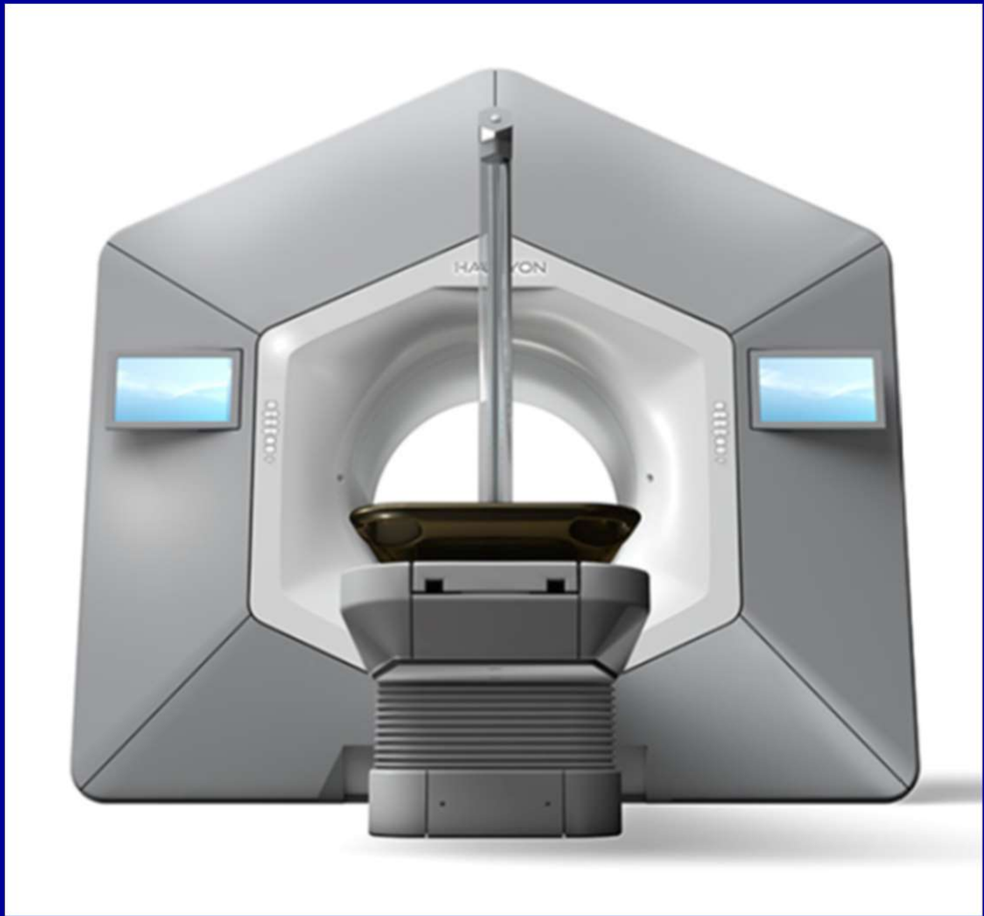


Elekta Synergy

Accuray TomoTherapy

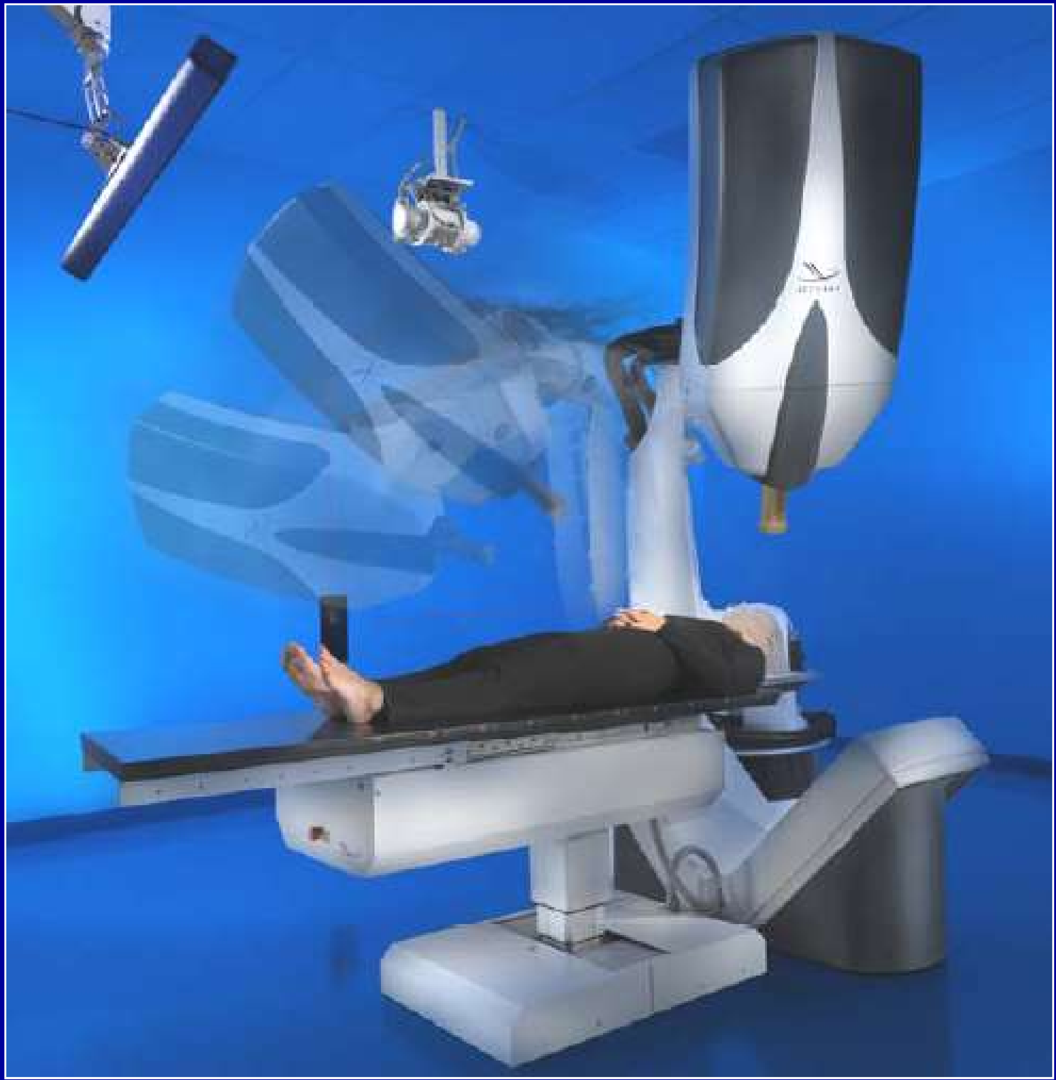
- TomoTherapy pioneered:
  - Daily CT guided radiotherapy.
  - Rotational Intensity Modulated Radiation Therapy (IMRT) using helical tomotherapy.
  - Helical delivery (to obtain long treatment fields).
  - Thicker primary collimation and multileaf collimator.

Varian Halcyon



- The Halcyon is designed to do rotational IMRT (Rapid Arc).
- KV cone-beam.
- Halcyon has a slower gantry than Tomo.
- Halcyon does not have a slip ring so it cannot do extended field lengths.
- Fastest selling Varian linac.

Accuray CyberKnife



- Multi-axis robot attached linac and collimation system
- Designed for stereotact radiosurgery (SRS) but also used for prostate, lung, and other body radiotherapy sites
- Dual real-time fluoroscopy

Comparison of External Beam Techniques

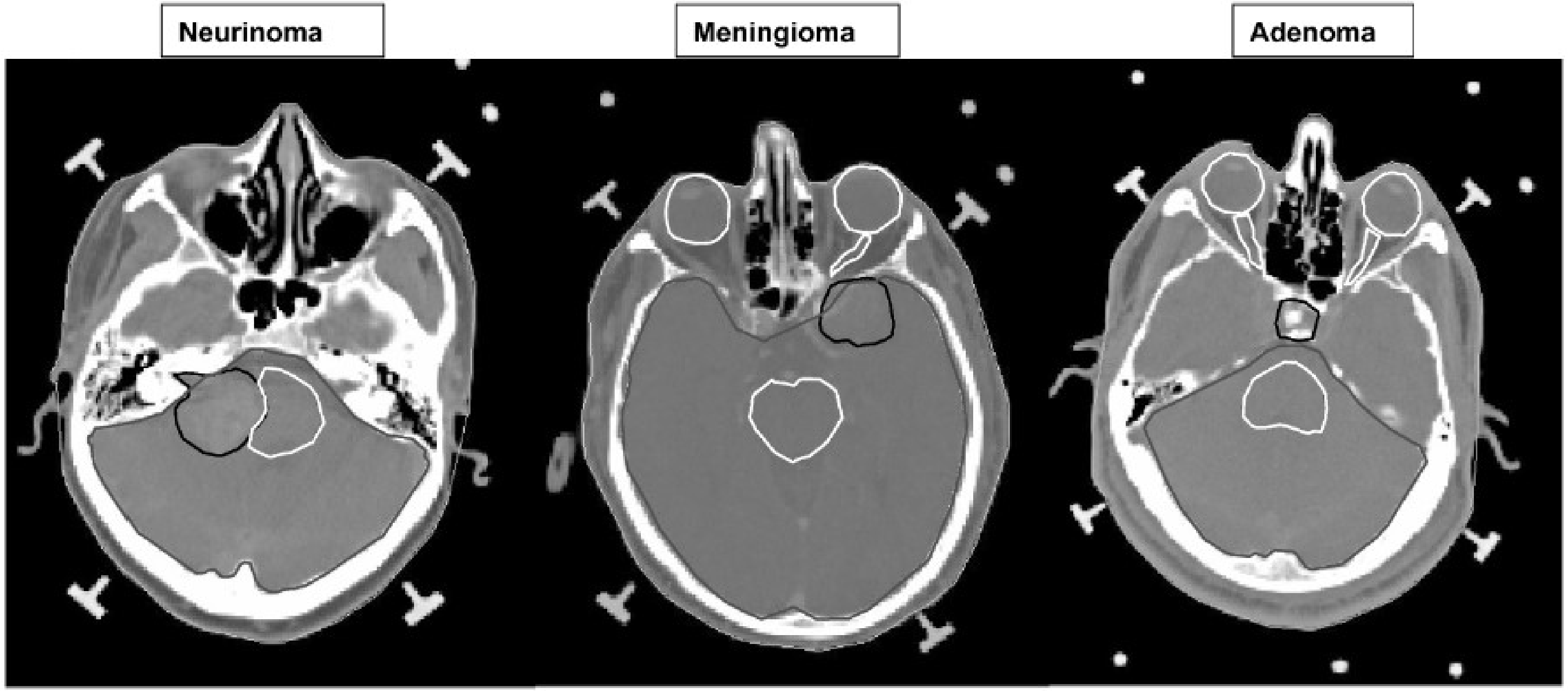


Fig. 1. Shape and relative position of volumes of interest (target and OARs) for three cases included in the study. Data are shown on a CT slice corresponding to roughly the centre of the target.

Comparison between:
Protons, Stereotactic Radiosurgery, 3D Conformal, Conventional IMRT, Helical Tomotherapy

Yartsev et al, Radiotherapy and Oncology 74 (2005) 49-52

Comparison of External Beam Techniques

Table 1
Results of dose distribution for the target and OARs

Organ	Parameter (%)	HT	SRS/T	3DCRT	IMRT	PSp	SSP
PTV	SD	1.31 ± 0.32	3.13 ± 1.1	3.00 ± 0.54	2.34 ± 0.59	1.82 ± 0.44	2.83 ± 0.56
	Min pt	96.1 ± 0.32	81.0 ± 11.4	91.0 ± 2.5	93.2 ± 1.3	92.8 ± 4.5	91.0 ± 2.7
	V_{90}	100 ± 0.0	98.8 ± 1.0	99.8 ± 0.2	100.0 ± 0.0	99.9 ± 0.4	99.8 ± 0.6
	V_{95}	99.5 ± 1.0	94.9 ± 2.8	94.8 ± 2.6	98.2 ± 1.9	99.0 ± 0.4	96.0 ± 2.4
Brain stem	Mean	26.8 ± 11.3	14.1 ± 10.7	26.4 ± 14.9	29.8 ± 14.4	7.6 ± 7.9	8.0 ± 0.7
	V_{20}	60.9 ± 25.6	21.7 ± 25.3	55.6 ± 29.3	59.9 ± 29.5	11.7 ± 12.3	12.8 ± 12.7
	V_{40}	20.1 ± 19.0	8.4 ± 11.2	23.3 ± 26.0	28.9 ± 21.2	7.6 ± 8.8	7.4 ± 8.3
Chiasm	Mean	34.3 ± 28.6	26.1 ± 28.4	34.8 ± 30.9	41.5 ± 35.1	20.9 ± 27.6	21.4 ± 26.8
	Max pt	57.9 ± 40.5	51.3 ± 46.8	54.9 ± 43.4	59.0 ± 43.8	47.5 ± 50.8	50.0 ± 52.4
Optic nerve	Mean	20.7 ± 16.0	8.2 ± 11.3	16.2 ± 17.5	18.6 ± 18.3	4.7 ± 9.9	6.6 ± 11.1
omolateral	Max pt	34.6 ± 30.6	22.7 ± 30.7	32.4 ± 29.5	36.5 ± 33.8	21.6 ± 33.3	24.7 ± 33.3
Optic nerve	Mean	14.0 ± 8.7	5.3 ± 6.3	10.4 ± 8.8	14.2 ± 13.4	0.4 ± 0.7	0.7 ± 1.3
controlateral	Max pt	19.3 ± 12.0	8.1 ± 12.1	18.4 ± 13.6	24.3 ± 18.4	4.8 ± 11.1	5.6 ± 10.8
Eyes	Mean	9.6 ± 4.5	2.9 ± 1.4	6.7 ± 5.5	8.4 ± 5.8	0.0 ± 0.1	0.1 ± 0.1
	Max pt	16.8 ± 7.7	4.9 ± 3.3	14.5 ± 6.4	18.7 ± 8.3	0.8 ± 2.0	1.0 ± 1.9
Brain—(brain	Mean	6.7 ± 3.4	7.3 ± 2.8	6.7 ± 2.7	8.0 ± 2.8	2.2 ± 1.3	1.8 ± 0.9
stem + target)	V_{20}	3.7 ± 3.3	7.8 ± 5.9	9.8 ± 6.0	11.2 ± 5.9	3.6 ± 2.3	3.2 ± 1.5

	Mean Brain Dose:	
Photons	Rotation IMRT	6.7%
	SRS	7.3%
	3DCRT	6.7%
	IMRT	8.0%
Protons	PSP	2.2%
	SSP	1.8%

- Mean dose (mean dose is proportional to integral dose) is similar to or less than other photon techniques
- Proton radiotherapy has much smaller mean dose.

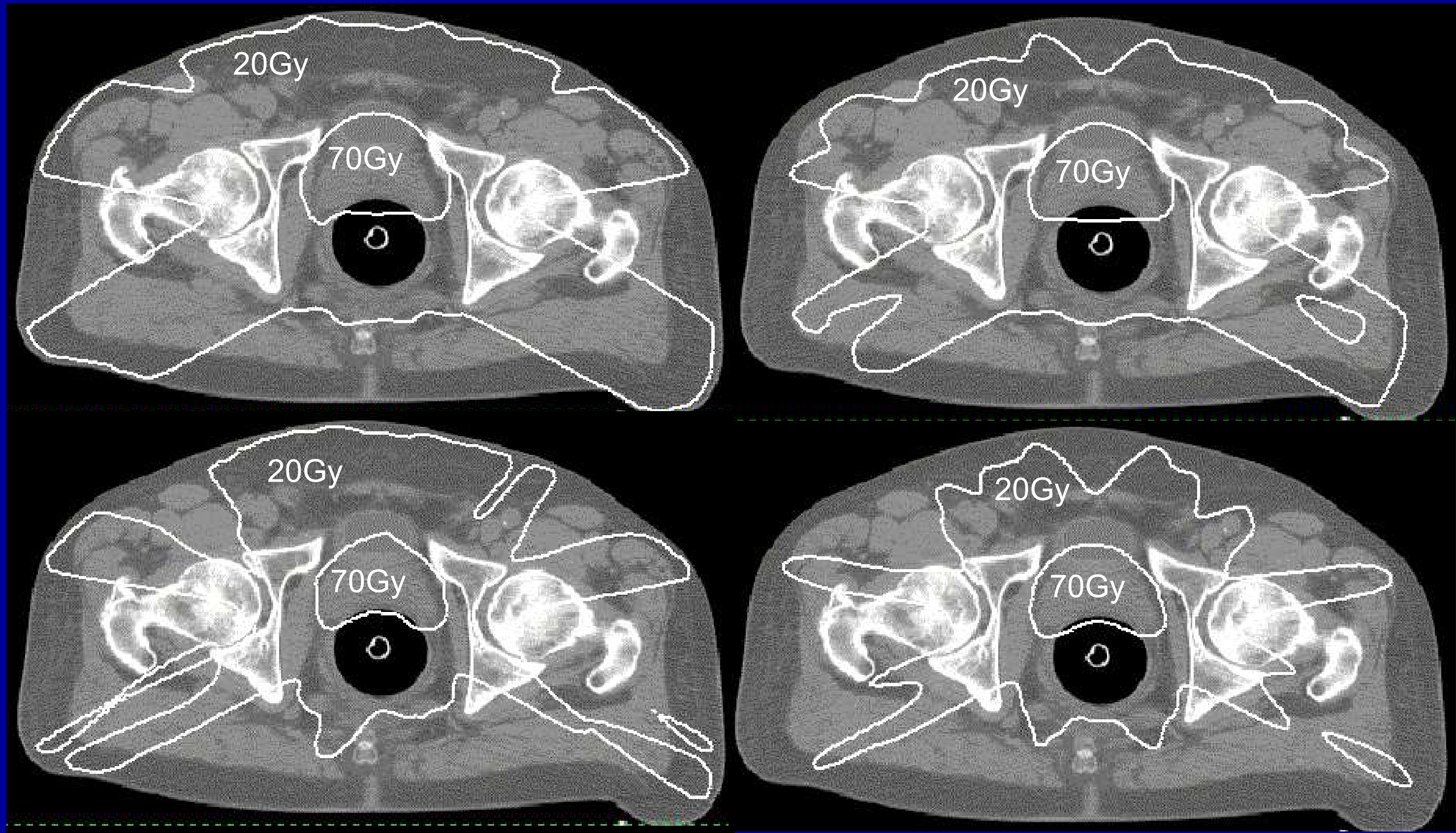
A Study On Integral Dose for Prostate Radiotherapy

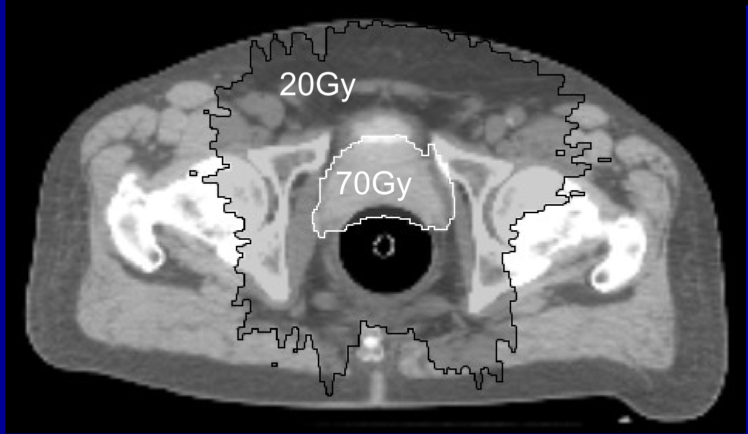
5 consecutive prostate patients were planned.
Clinital Target Volume: prostate
Planning Target Volume (PTV): 5 mm expansion
70Gy to 95% of PTV

6MV-3DConformal Radiation Therapy (3D CRT)
6MV-Intensity Modulated Radiation Therapy (IMRT)
20MV-3DCRT
20MV-IMRT
Tomotherapy

The Integral Dose to the PTV was Forced to be Constant

Aoyama et al. Int J Radiat Oncol Biol Phys 64:962-967 (2006)





a. 6MV-3DCRT	**d. 20MV-3DCRT**
b. 6MV- IMRT	**e. 20MV-IMRT**
c. Tomo-IMRT	

Aoyama et al. Int J Radiat Oncol Biol Phys 64:962-967 (2006)

Unwanted Dose
From Leakage Photons and Neutrons

In vivo **and phantom measurements of the secondary photon and neutron doses for prostate patients undergoing 18 MV IMRT**

Chester S. Reft[a)]
Department of Radiation and Cellular Oncology, The University of Chicago, 5841 South Maryland Avenue, Chicago, Illinois 60637

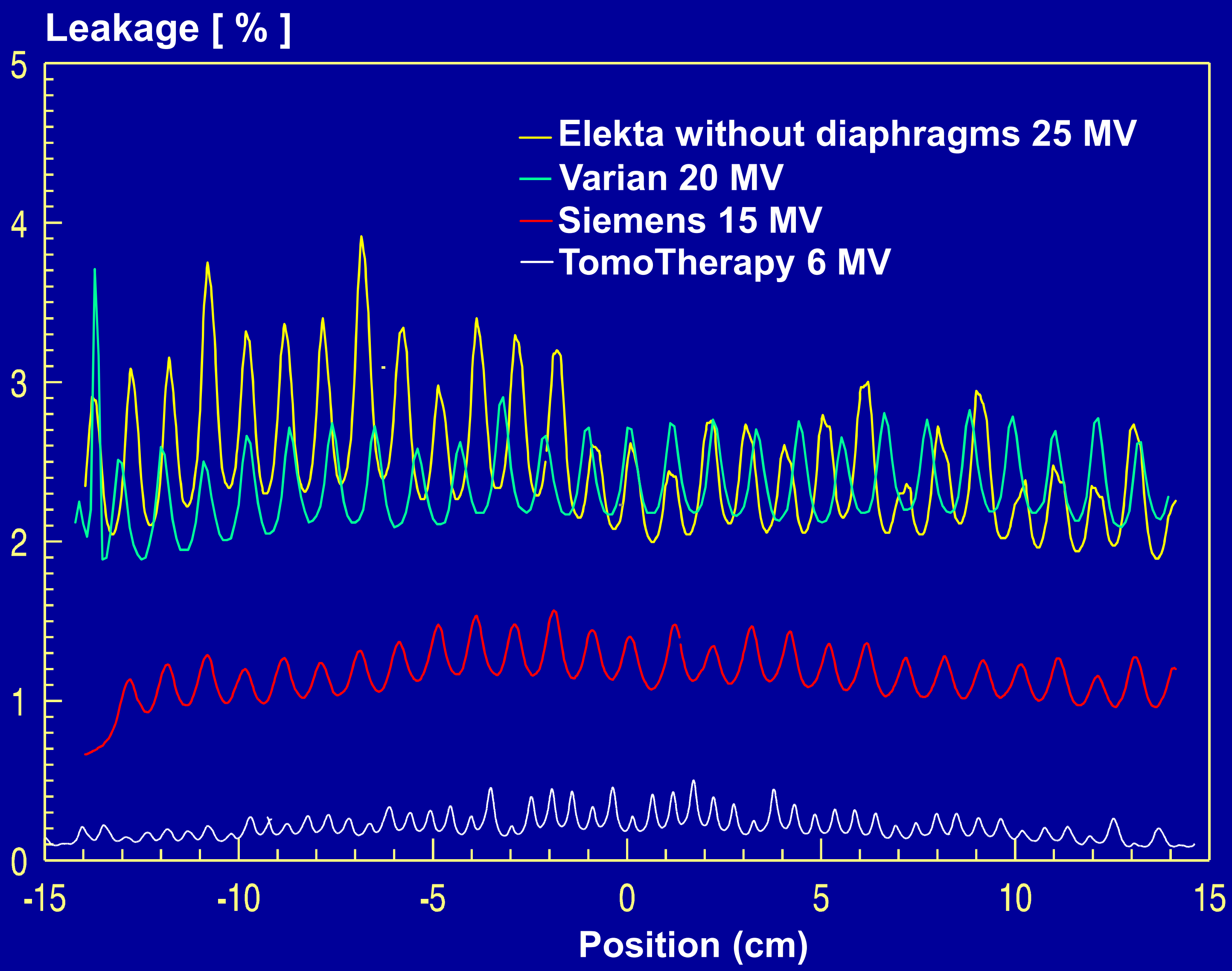
Renate Runkel-Muller
Radiation Oncology Center, St Margaret Mercy Healthcare Centers, Hammond, Indiana 46320

Leon Myrianthopoulos
Department of Radiation and Cellular Oncology, The University of Chicago, 5841 South Maryland Avenue, Chicago, Illinois 60637

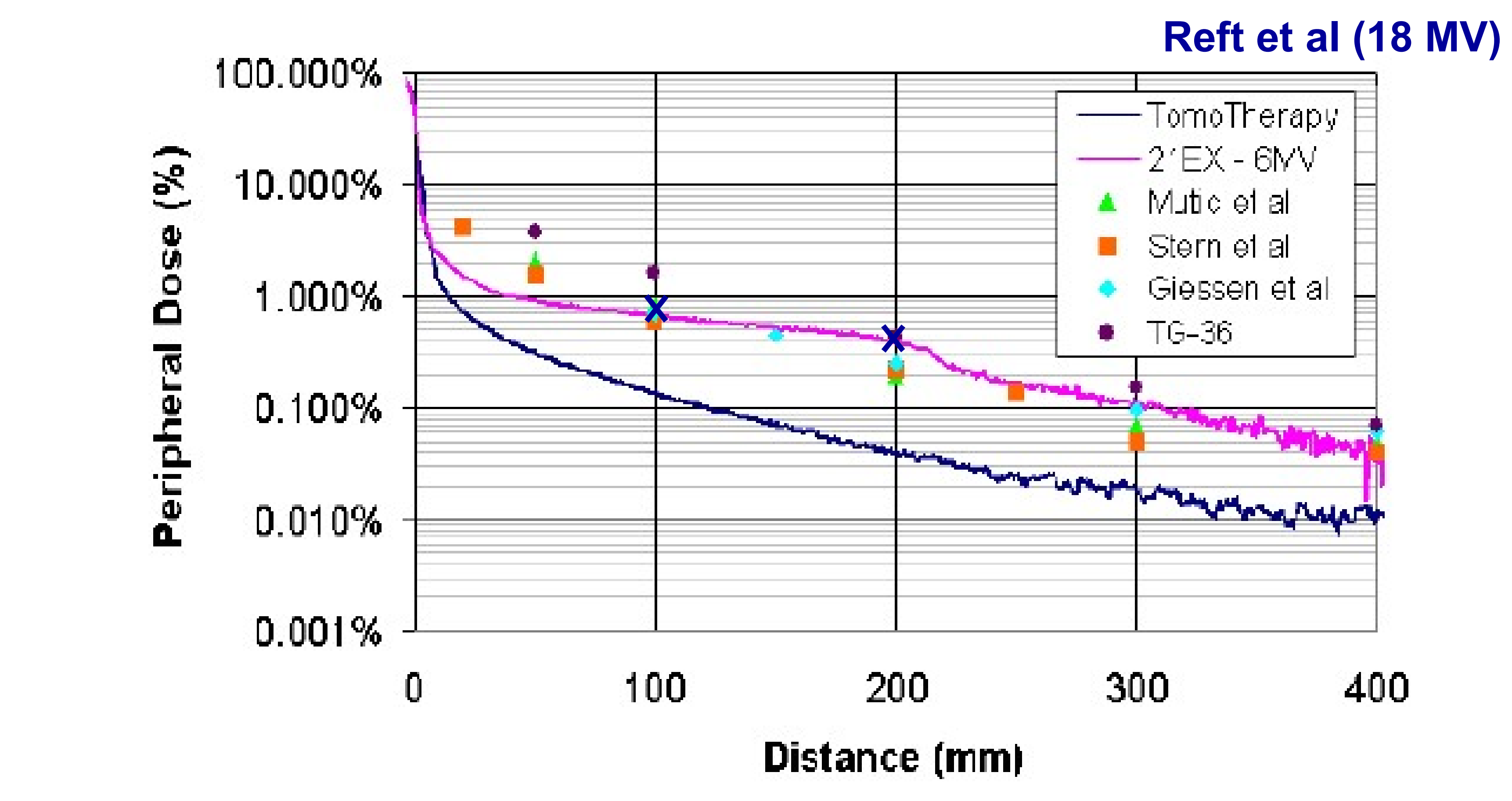
Distance From Field	Leakage Photons	Neutrons
10 cm	0.9 %	0.1 %
20 cm	0.5 %	0.1 %

Medical Physics (2006) 33:3734-3742

Leaf Leakage



Peripheral Dose



From Ramsey et al, (2006) J. App. Clin. Med. Phys 7:11

Integral Dose for 3D CRT and IMRT

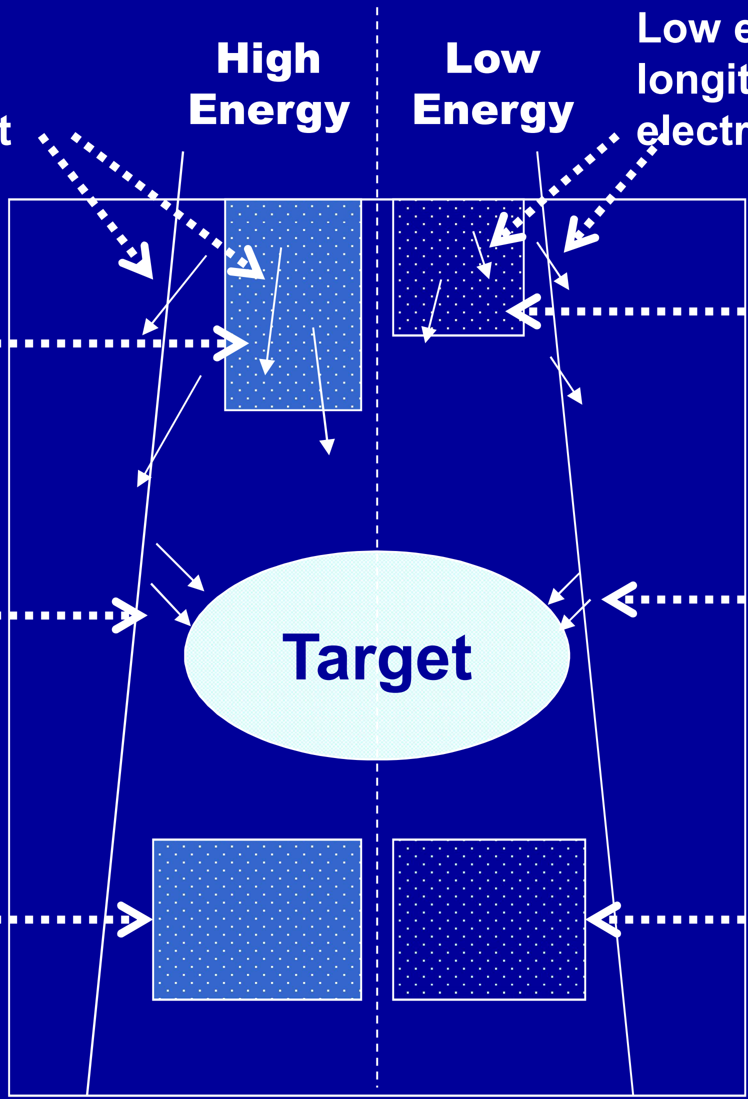
Units are Gy-Liter

	In-Field (Aoyama)	Photon Out-Field (Ramsey and Reft)	Neutron (Reft)	Total	Change From 6MV 3D CRT
6 MV 3D CRT	122.9	3.4	0	126.3	0 %
6 MV IMRT	116.7	16.9	0	133.6	+6 %
20 MV 3D CRT	113.4	4.2	1.1	118.8	-6 %
20 MV IMRT	109.1	21.2	5.6	135.9	+8 %
Tomo (6 MV)	117.9	3.0	0	120.9	-4 %

Why In-Field Integral Dose Is Nearly Beam Quality Independent

High energy has both longer longitudinal and lateral electron transport

Low energy has both shorter longitudinal and lateral electron transport



High energy does have deeper buildup which reduces integral dose.

Low energy has smaller buildup

High energy needs wider field boundary which increases integral dose.

Low energy needs narrower field boundary

High energy has higher exit dose which increases integral dose.

Low energy has smaller exit dose

Neutron Dose

No Neutron Dose

AMERICAN ASSOCIATION
of PHYSICISTS IN MEDICINE

Medical Physics
The International Journal of Medical Physics Research and Practice

Higher energy: Is it necessary, is it worth the cost for radiation oncology?

Indra J. Das, Kenneth R. Kase

First published: July 1992
https://doi.org/10.1118/1.596779

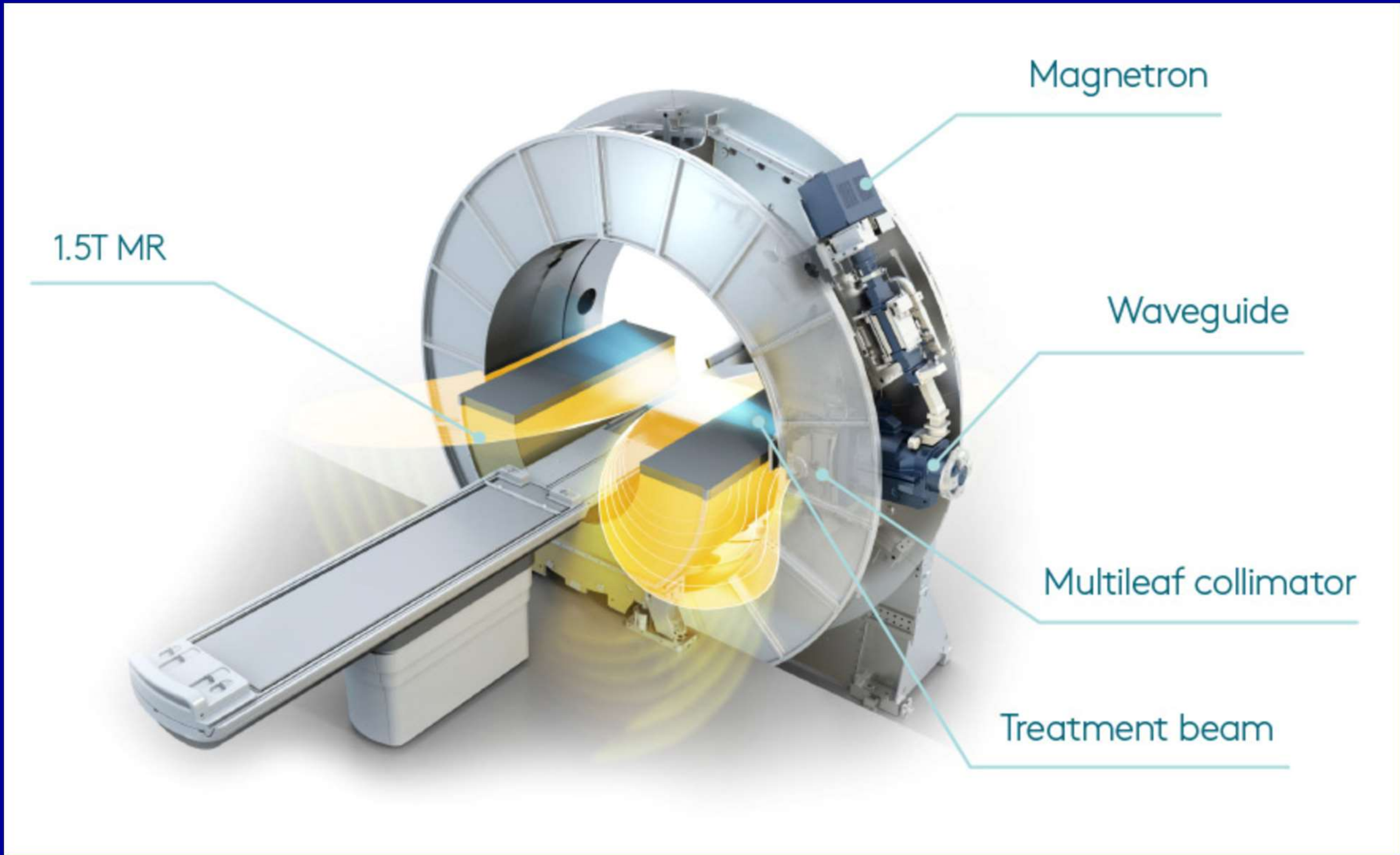
ViewRay MRIdian

- ViewRay MRIdian uses a 0.35 T split magnet system.
- A beam goes between the magnets.
- Real-time imaging.
- Built-in gating to manage motion.
- Delivers 3D conformal and IMRT.

Elekta Unity

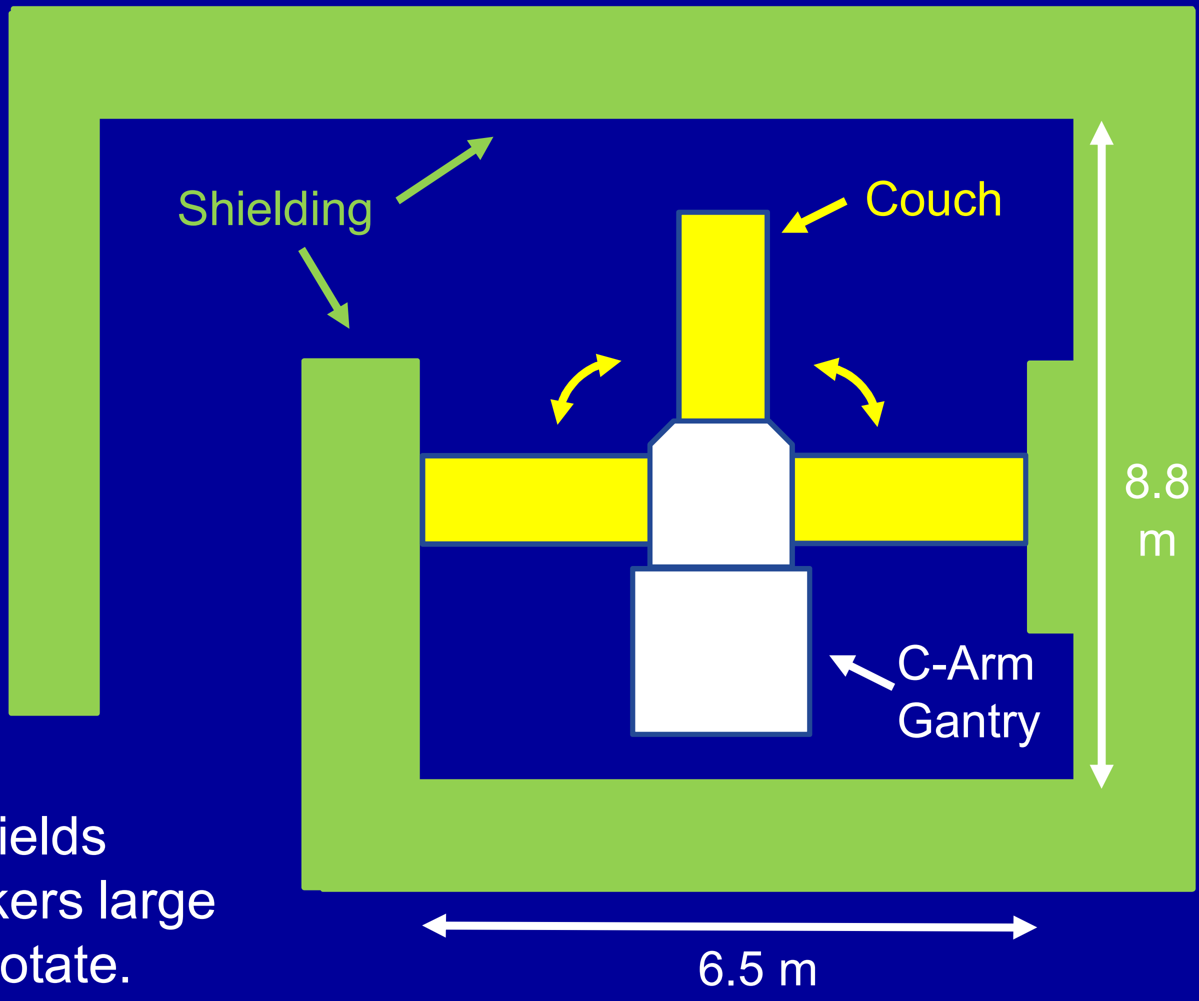
- The Elekta Unity is similar to the ViewRay except:
- Uses 1.5 T magnetic field so better images.
- Does not yet facilitate gating.
- More expensive.
- Beam goes through magnet system.

Elekta Unity



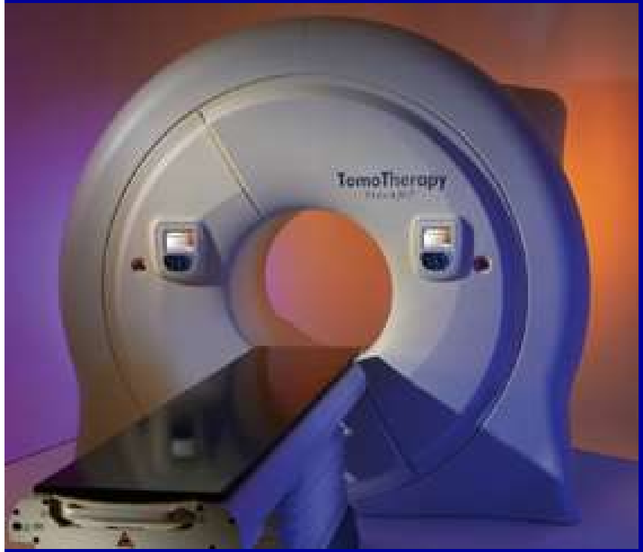
Minimum Conventional Bunker for a C-Arm Gantry

Varian Trilogy



Using non-coplanar fields makes classical bunkers large as the couch has to rotate.

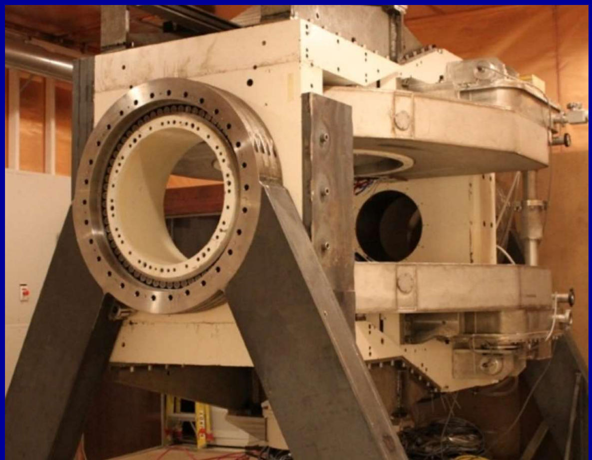
Examples of Ring Gantries



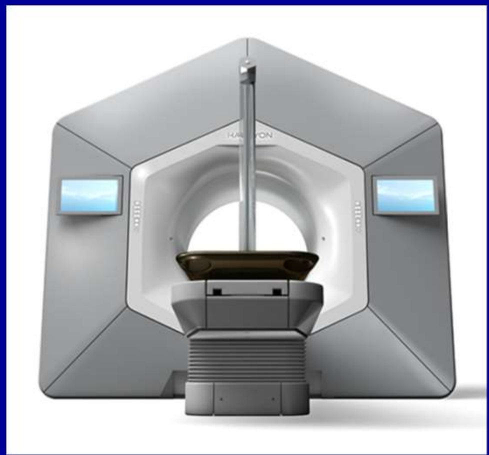
TomoTherapy

Elekta Unity

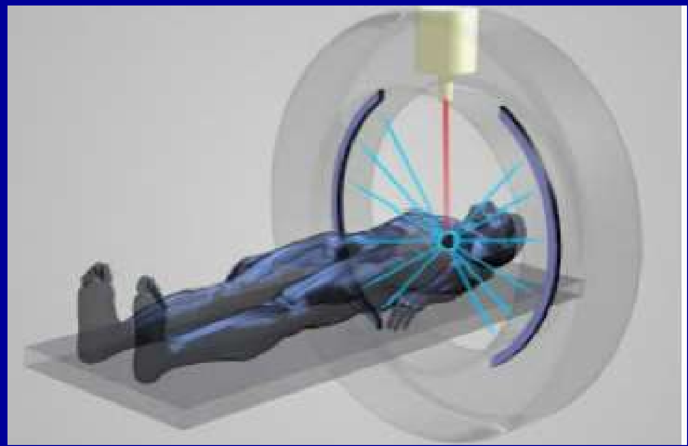
View Ray



Edmonton Linac-MRI



Varian

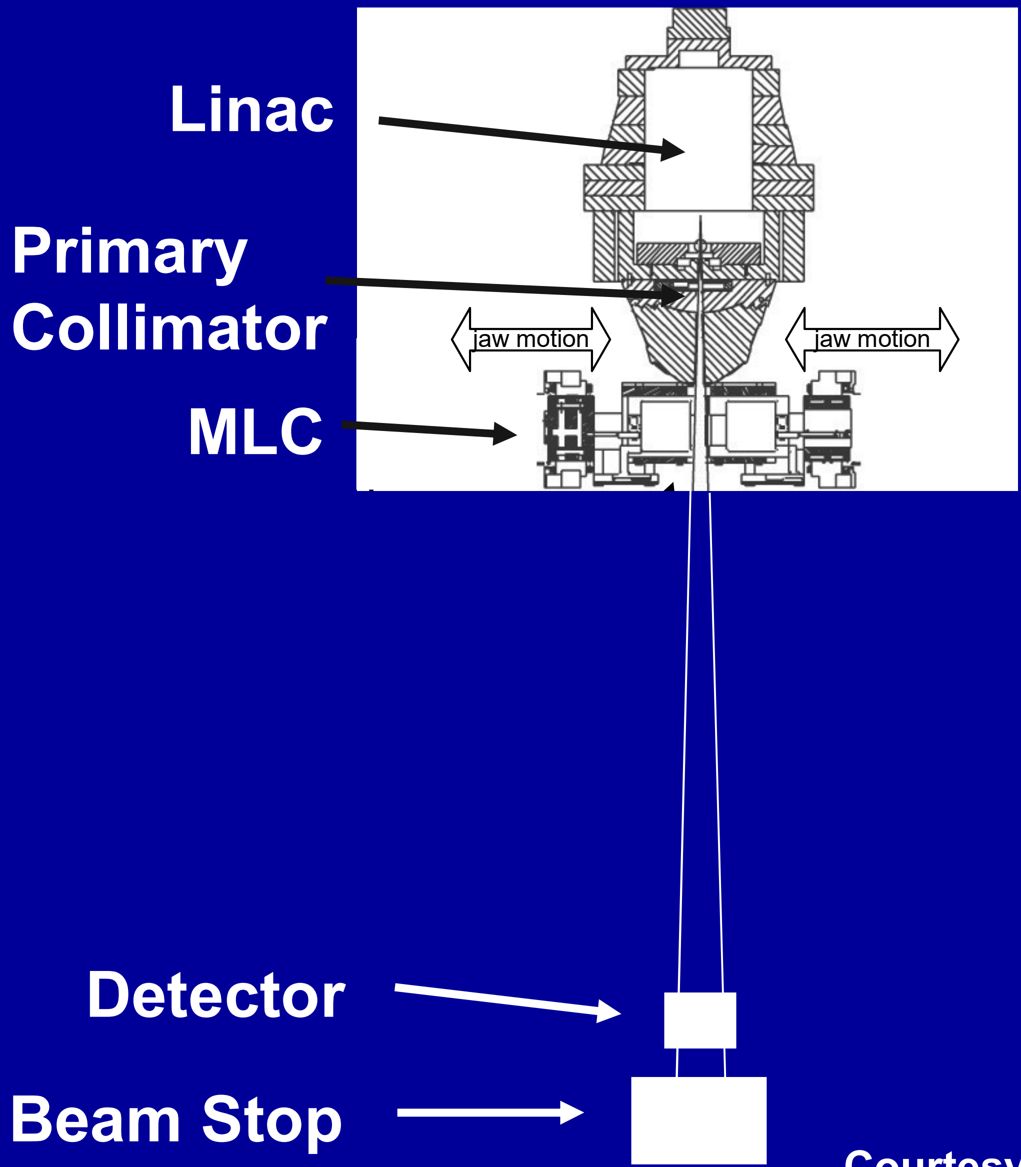


Reflexion Medical

Shielding Issues with Ring Gantries

- Cannot deliver non-coplanar fields but modern radiotherapy rarely uses non-coplanar fields.
- Easy to put a beam stop built into the machine.
- Patient scatter becomes the dominant contribution for unwanted radiation.
- Can also put extra shielding into the machine covers.
- Rooms can be smaller so less total shielding required.

Decreasing Unwanted Integral Dose



Up to 23 cm of Tungsten In the Primary Collimator.
< 0.01% Leakage

Leaves are 10 cm of Tungsten.
< 0.3% Intraleaf Transmission
< 0.5% Interleaf Transmission

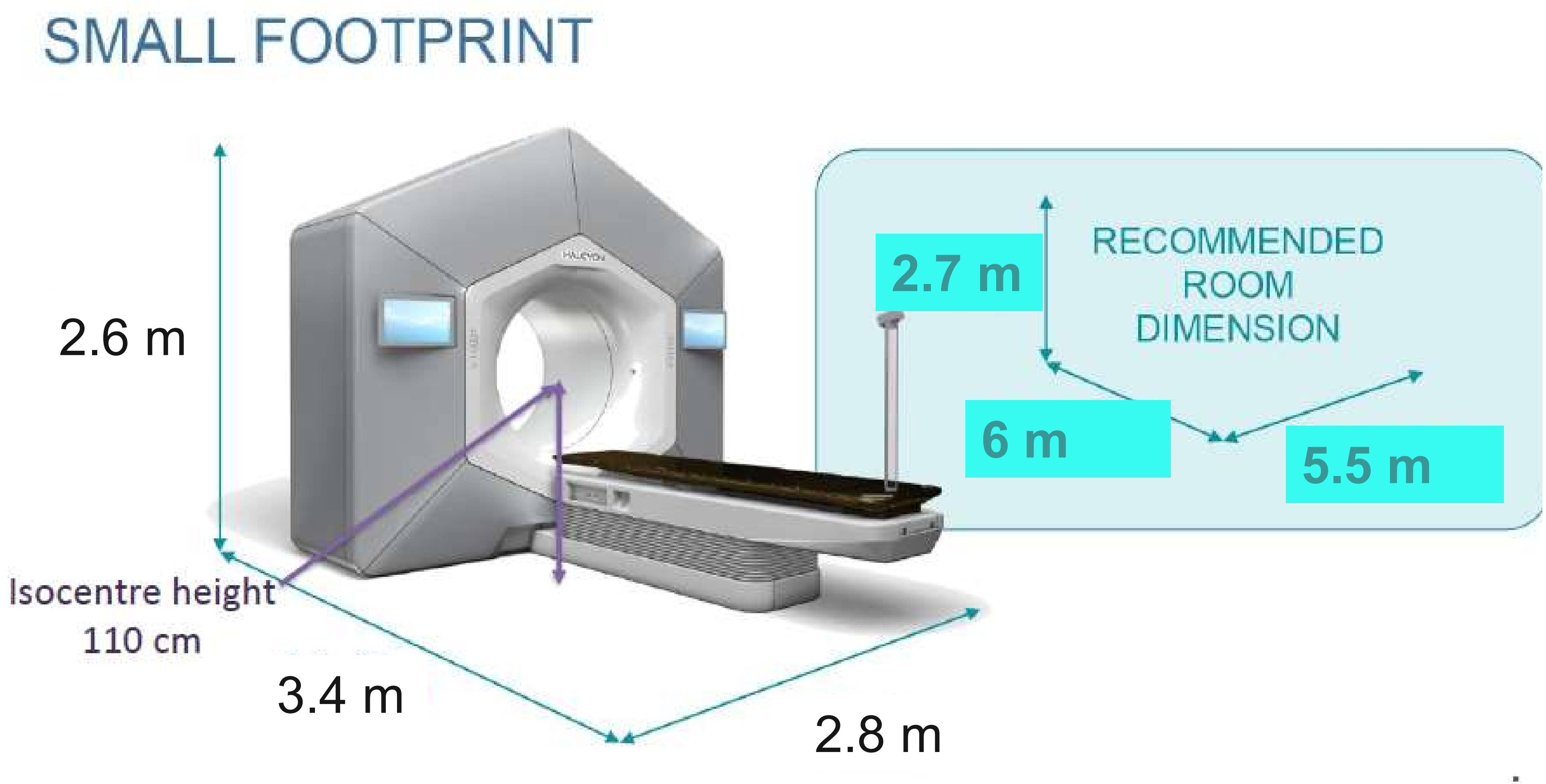
No Field Flattening Filter to Cause Scatter Outside the Field.

Less Head Scatter from Narrow Fields.

10 cm Thick Lead Beam Stop Behind the Radiation Detector.

Courtesy TomoTherapy

Varian Halcyon ... 2017



From Jake Van Dyk, London Regional Cancer Center, London ON

Shielding Blocks

Blocks add flexibility to construction projects but are much more expensive for large facilities.

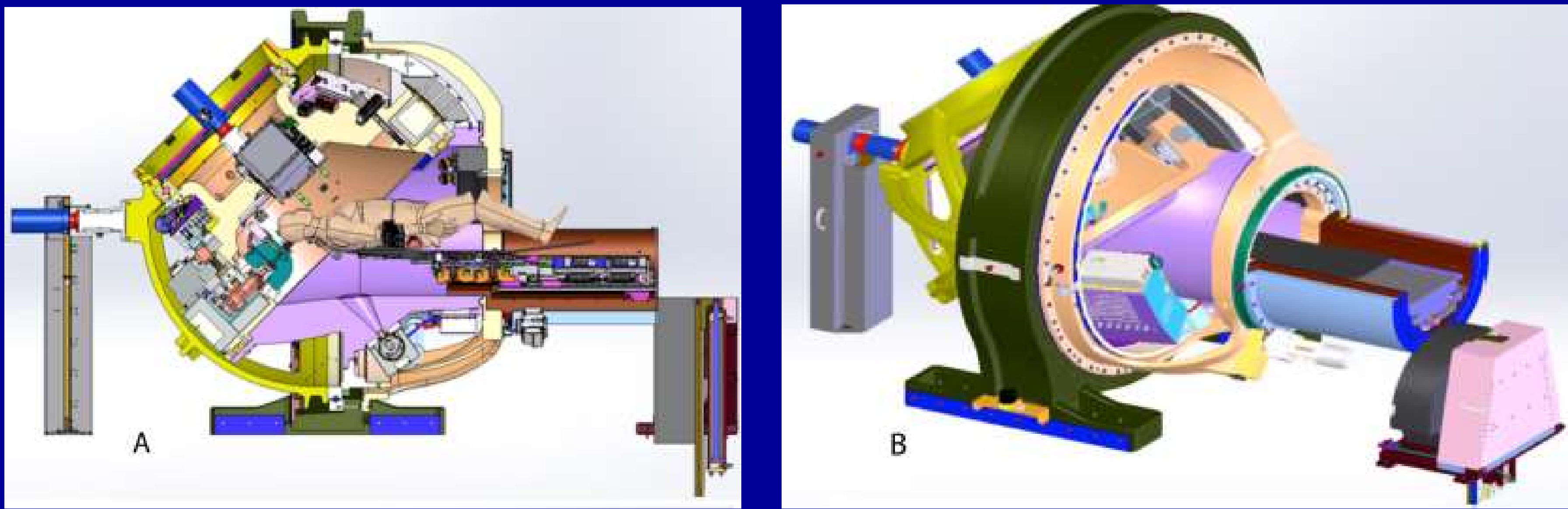
Concrete Blocks

Lead Blocks

Radiation Therapy Products Inc

Nelco

Self-Shielded Stereotactic Radiosurgery Unit, the Zap-X



Zap-X: A: Cross-Section and B: Room View

Weidlich et al Self-Shielding Analysis of the Zap-X System. Cureus 9(12)

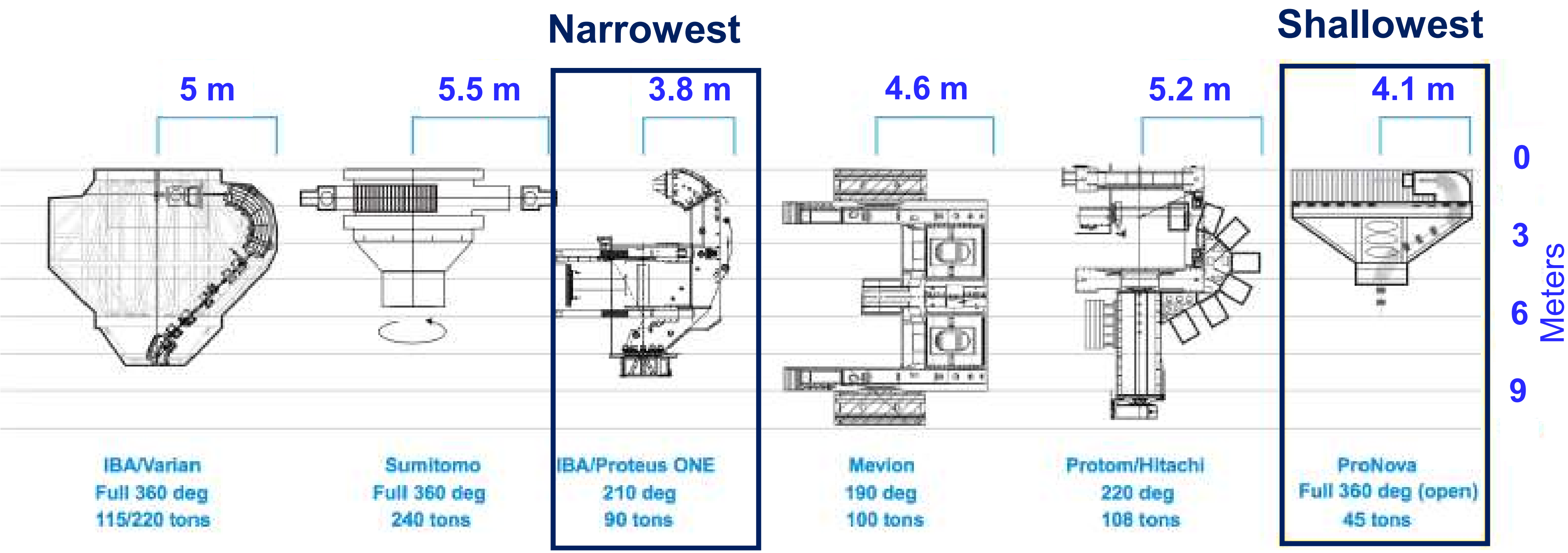
Leo Cancer Care Upright Radiotherapy System with a Small Footprint

Machine Fixed

Patient Rotated Upright

- **Upright radiotherapy may be better medicine for many sites.**
- **Also with potential to self-shield.**

Proton Gantry Sizes



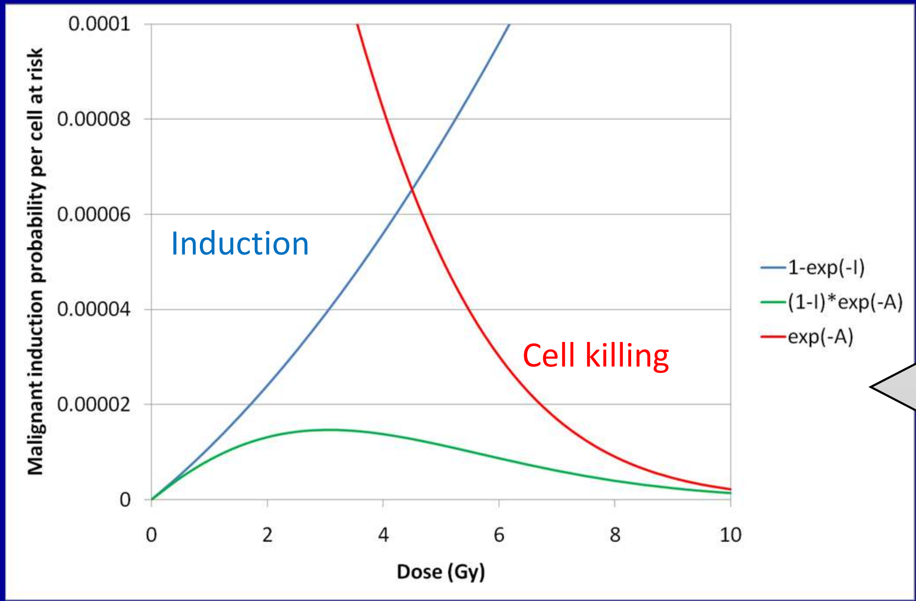
Gantry size is the major determinant in the high capital cost of proton radiotherapy

Take Home Messages

- Modern radiation therapy is devoted to decreasing acute exposure to sensitive tissues using 3D conformal radiation therapy and intensity modulated radiotherapy (IMRT).
- Proton beams reduce integral dose.
- Image-guidance using CT and MRI assures less normal tissue is in the high dose field.
- Integral dose is a simple measure of patient harm.
- The ring gantry is rivaling the C-arm gantry and enables less unwanted radiation to escape the machine.
- Reducing vault size with ring gantries and smaller proton gantries will reduce the cost of radiotherapy.

Cancer Induction and Cell Kill

What is the form of the induction function? Linear, quadratic?



Form of cell killing function known with some certainty at clinical energies, the parameters are tissue dependent and can have large uncertainties.

Probability of induced cell surviving

Probability the cell survives

$$P_{tr} = P_I P_S$$

Probability of inducing a potentially malignant mutation

Risk needs to be:

- accurately modelled
- confirmed experimentally
- taken into account when deciding on the optimal treatment plan

From Clair Timlin, Oxford

3D Prediction of Cell Transformations

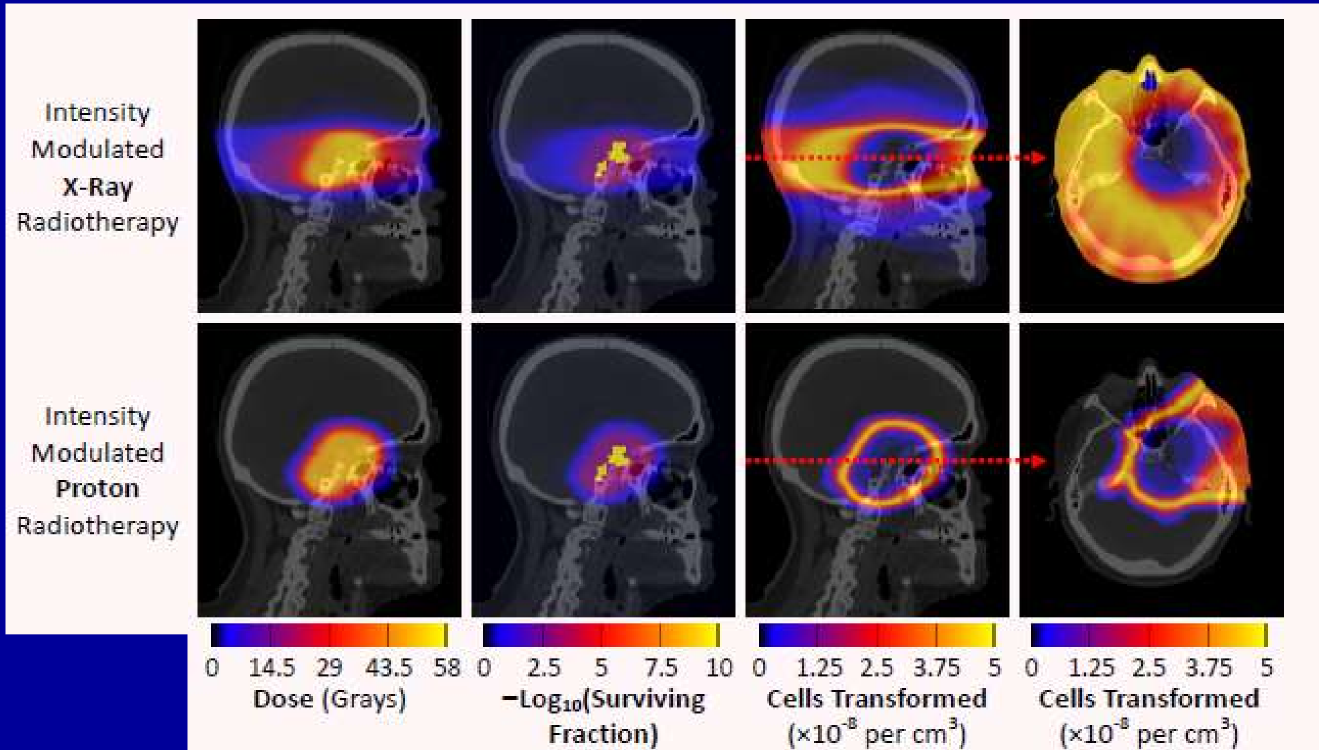


Figure 5: 2D slices of the 3D maps output by the CERR-based MIP calculation program for a meningioma plan. Parameters used: for the tumour α=0.3, β=0.08; for nerve and brain tissue α=0.06, β=0.03; for mucosal tissues α=0.3, β=0.03; for most other tissues α=0.09, β=0.03.

- Model and parameter sensitivity analyses
- Validation with clinical data on secondary malignancies

From Clair Timlin, Oxford

Hans

I think this is a good title:

Trending Issues with Radiation Protection for External Beam Radiation Oncology

I will talk about several issues. Perhaps the most important one is the changing whole body dose in radiation oncology. A number of factors including IMRT, CT image guidance and near universal use of PET imaging for treatment planning tend to increase the dose while a tendency towards hypofractionation decreases it . The growth of proton and heavy ion radiotherapy introduces challenges due to the RBE. I will also talk about self-shielded radiotherapy machines being introduced or in the planning stages. I will close with cost-benefit arguments justifying changes to whole body dose and radiation protection efforts to lower it.