Radiation Therapy Treatment Delivery Systems

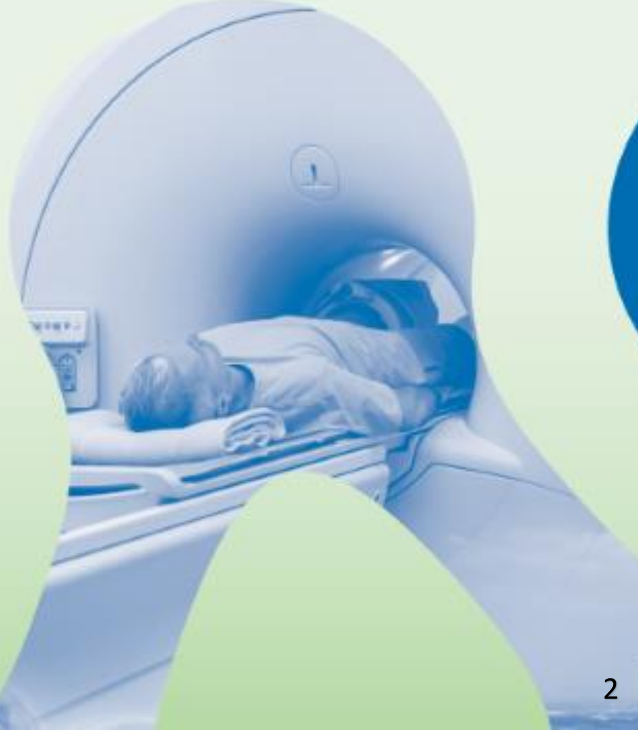
Modern Technologies and Future Directions

Pedro Cardoso

Medical Physicist @ Hospital Vila Nova Star

Overview

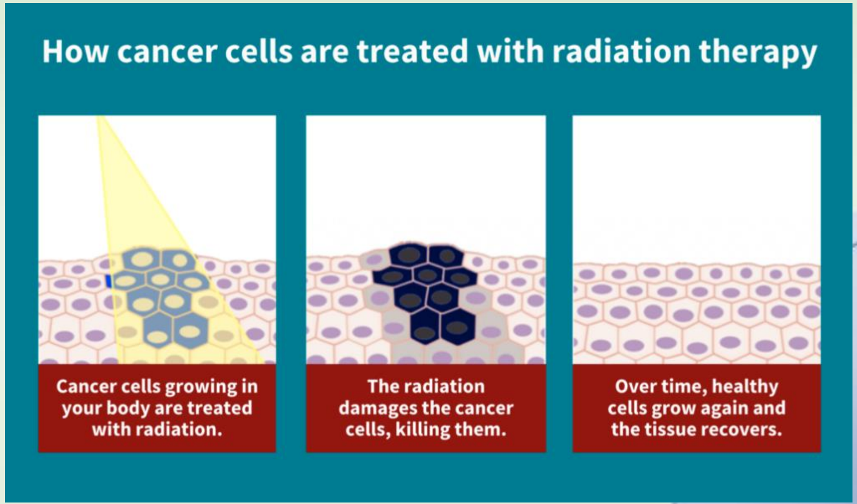
- What is Radiation Therapy (RT) and how it's done
- What's "mainstream" in modern RT delivery technology
- What's trending
- What might be coming



Radiation Therapy

- Use of ionizing radiation to treat diseases
- Mostly used to target and destroy cancer cells

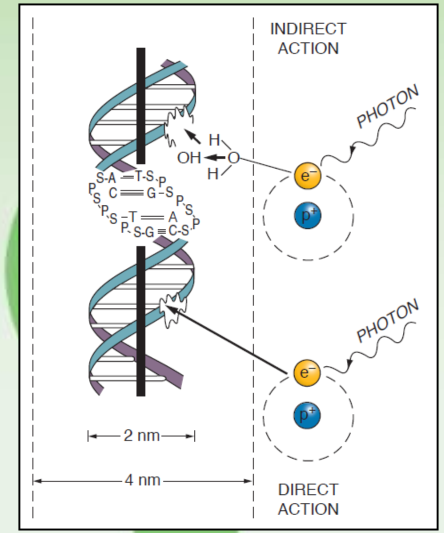
YouTube: UPMC

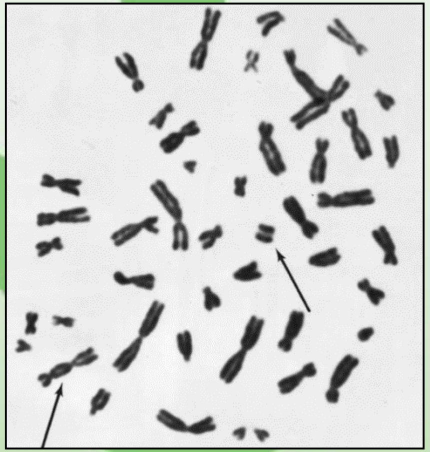


Stanford Medicine

- Radiation sources can be natural (radionuclides) or artificial (particle accelerators)
- In Brazil, the applications of radiation in therapy date from the 1920s

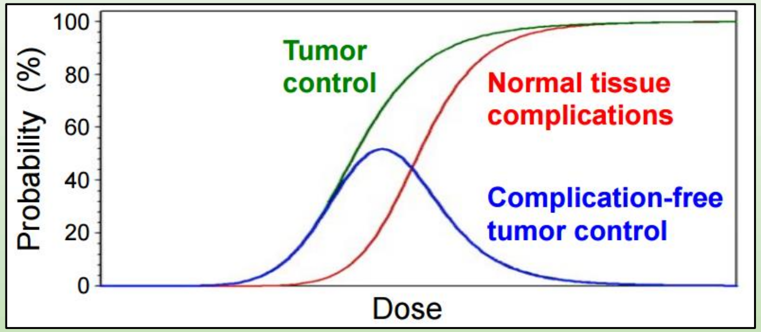
Radiation Therapy

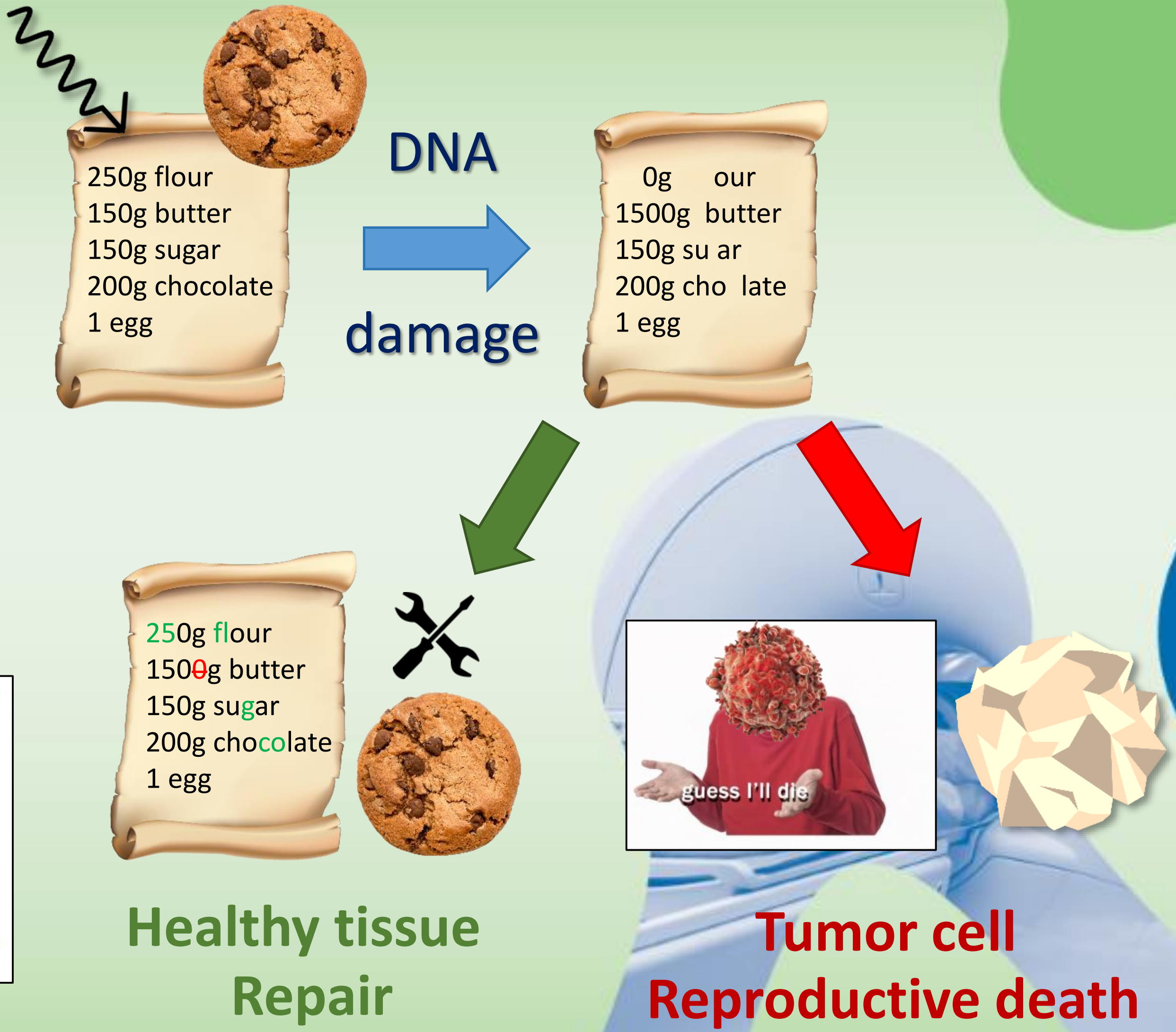




Hall "*Radiobiology for the Radiologist*", 7ª ed

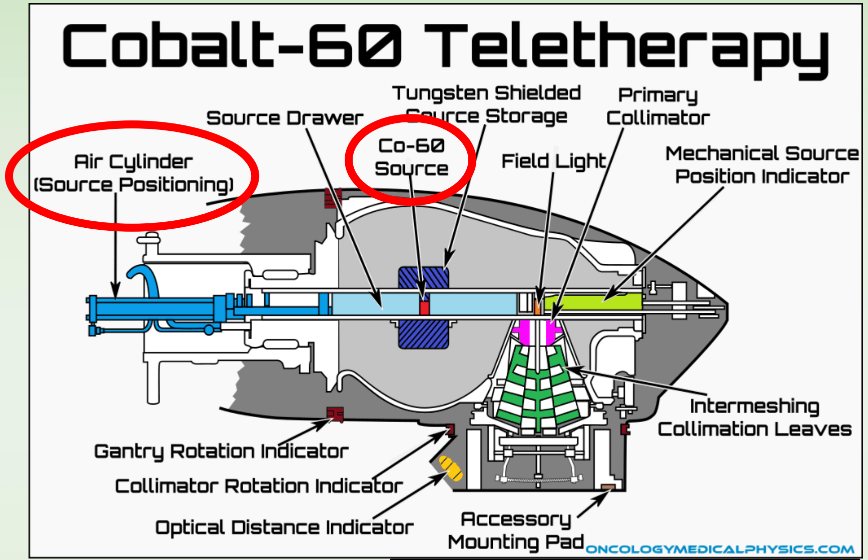
- Ionizing radiation can damage the DNA
- Healthy tissue can repair some of the damage
- With correct dose and fractionation, we can destroy more cancer cells than healthy tissue

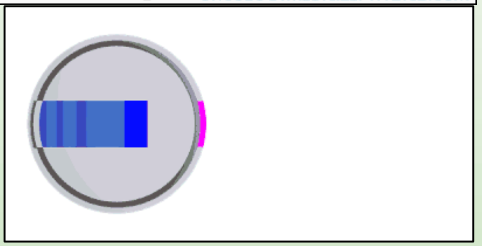




Radionuclide units

- Gamma radiation (Cobalt-60 and Cesium-137)





- Very uncommon in the developed world

- In Brazil: 20 cobalt-60 units in 2019

- Still common in developing countries

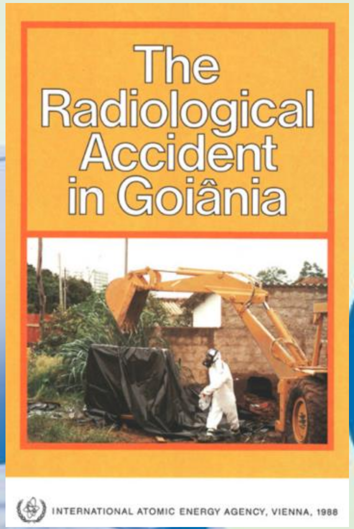
- Simplicity (source calibration and maintenance)

<u>1987 Goiânia, Brazil</u>

Deactivated Cs-137 stolen

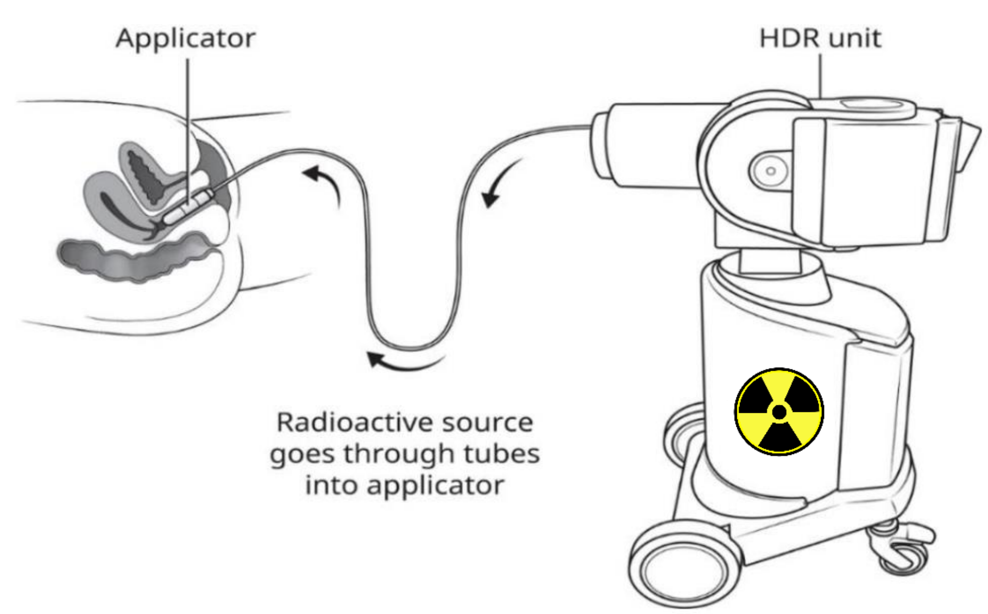
Source capsule broken

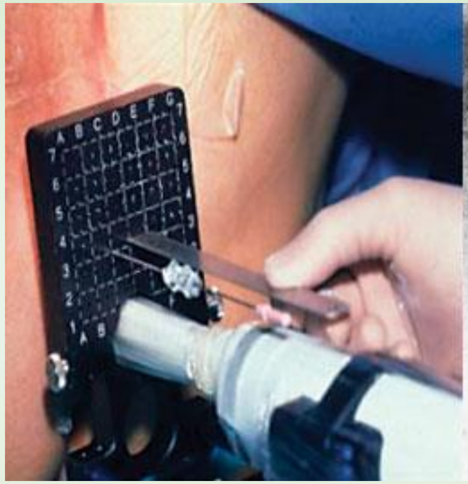
"Special mention must be made of CNEN, which co-ordinated the response to the accident within Goias' State and at the national and international levels."

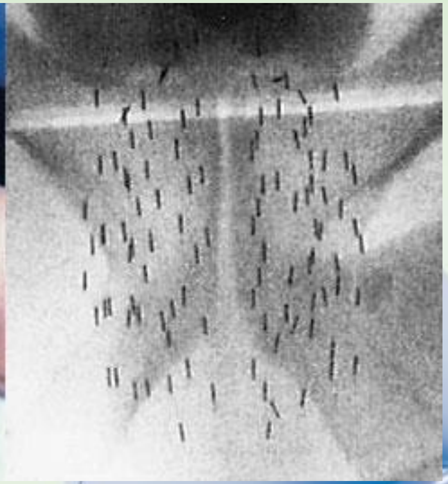


Brachytherapy (BT)

- Use of small radioactive sources in close proximity to the target
- Intracavitary, implants (seeds and wires) or contact



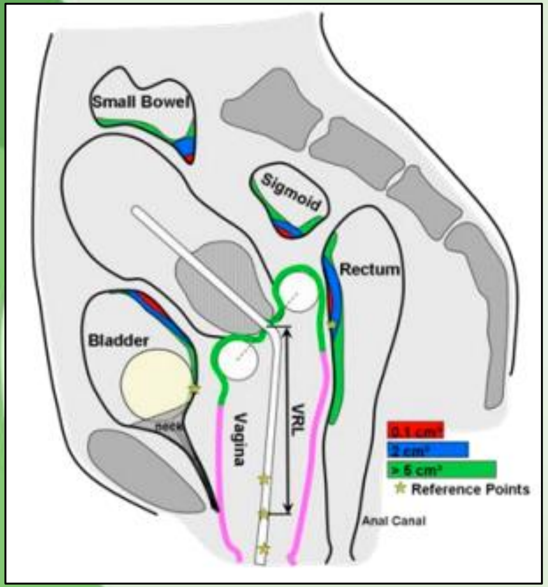




Brachytherapy (BT)

- In Brazil, >95% of BT procedures are gynecological

(only site covered by the national public health insurance)

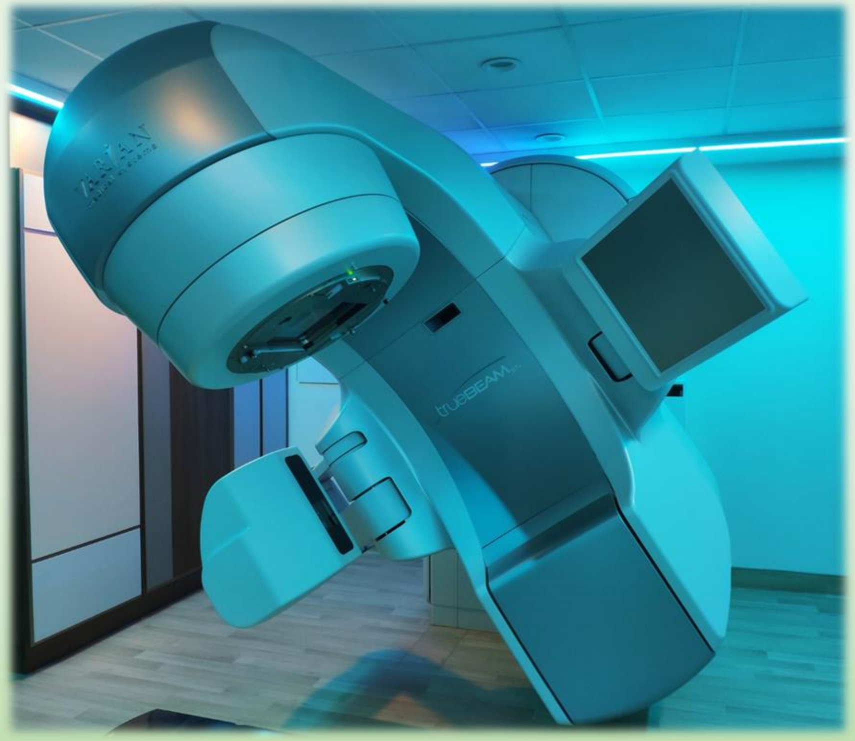


- Has been in decline worldwide
- Ex: in USA, GYN patients that received BT went from ≈85% in 1990 to ≈60% in 2010

EMBRACE protocol
Han et al "Trends in the utilization of brachytherapy in cervical cancer in the United States" IJROBP 2013

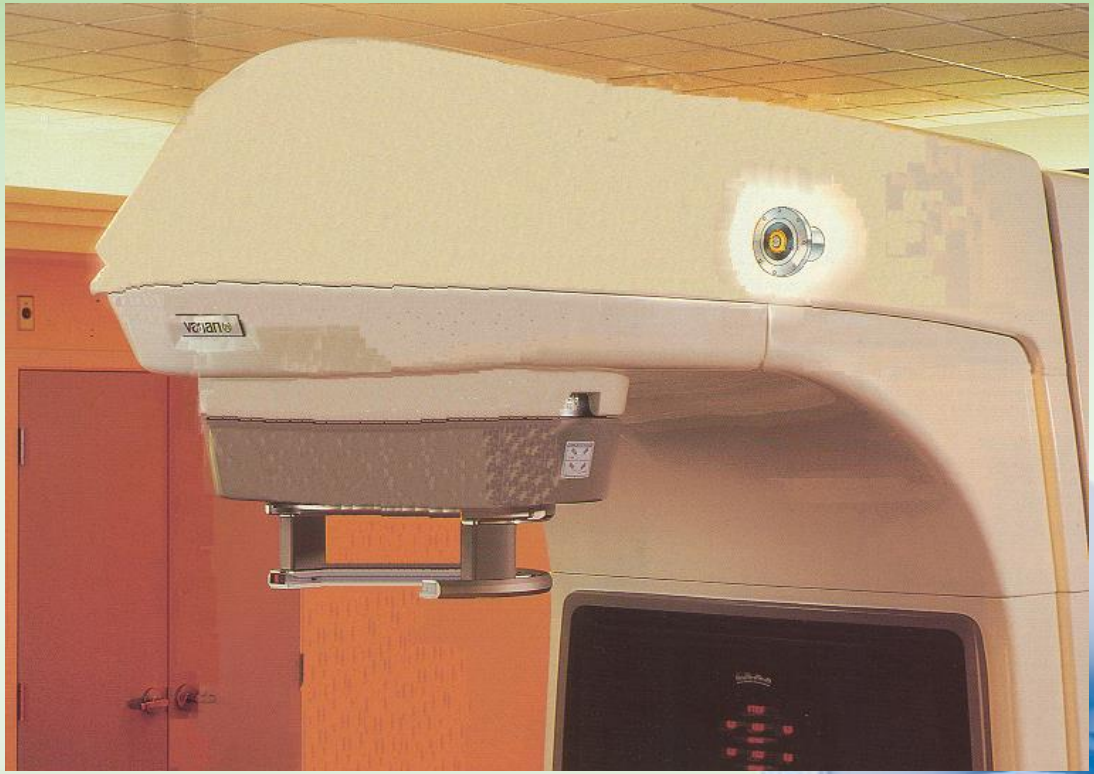
Linear accelarators (LINACs)

- Most common source of radiation in RT (photons and electrons)
- Replaced most cobalt and cesium in the 1960s-1980s
- In Brazil, fist Linac in 1971, 363 Linacs in 2018



LINAC: Beam production

- Injection Gun
- Source of electrons
- Thermionic effect of heated filament



LINAC: Beam production

- Accelerator tube
- Accelerates electrons with microwaves in resonating cavities
- Most common energy used in RT is 6MV, but there are usually a few discrete options of higher energies

LINAC: Beam production

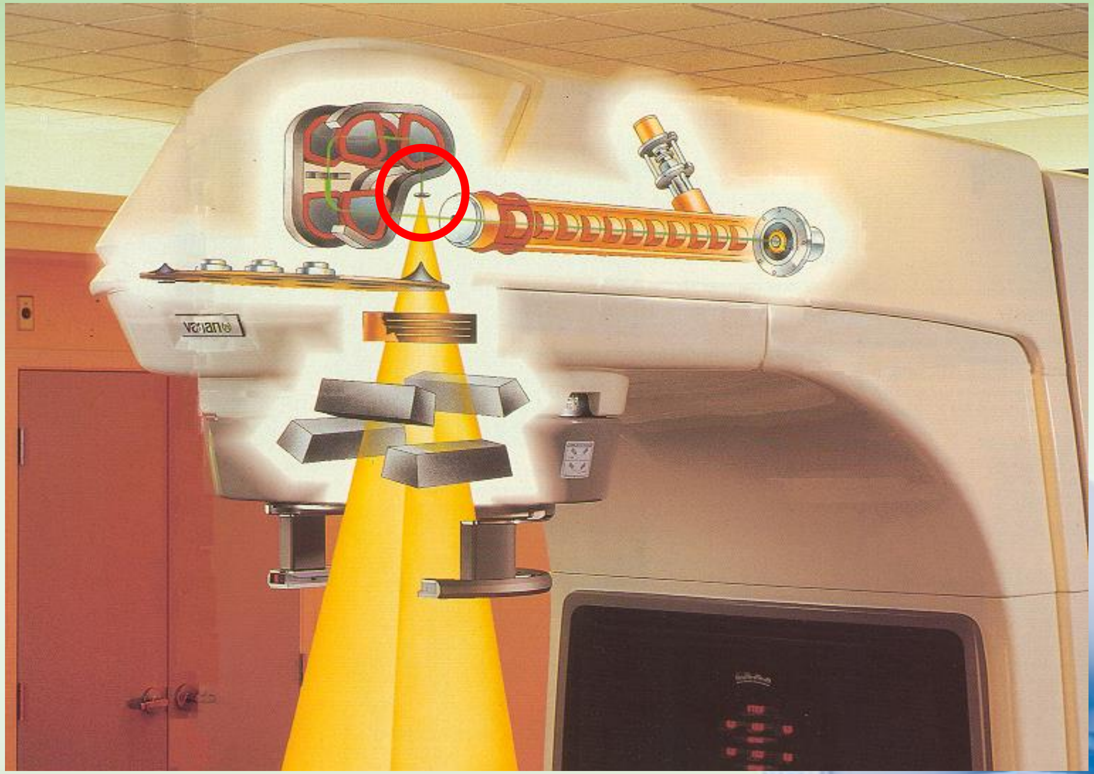
- Microwave source
- Magnetron (generator) and klystron (amplifier)

LINAC: Beam production

- Bending magnets
- Redirects the electron beam towards the patient
- Acts as energy filter

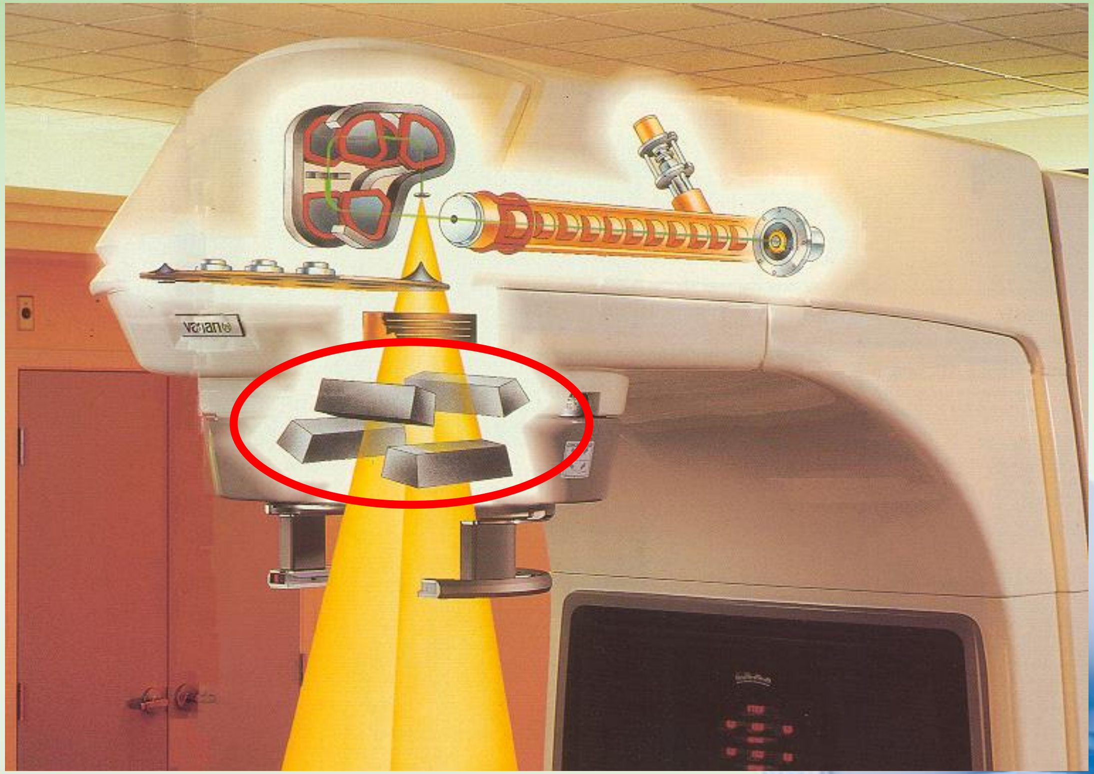
LINAC: Beam production

- Target
- Tungsten disc
- Produces X-Ray photons through deceleration of the incident electrons (bremsstrahlung)



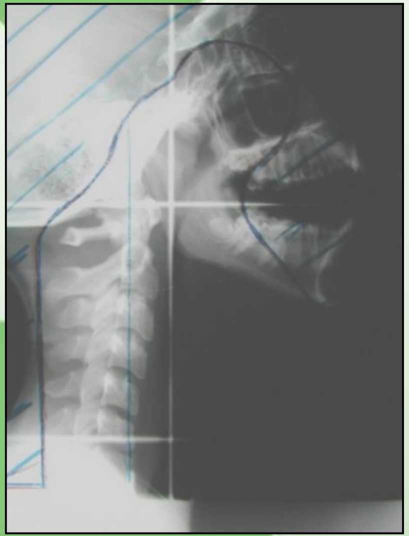
LINAC: Beam production

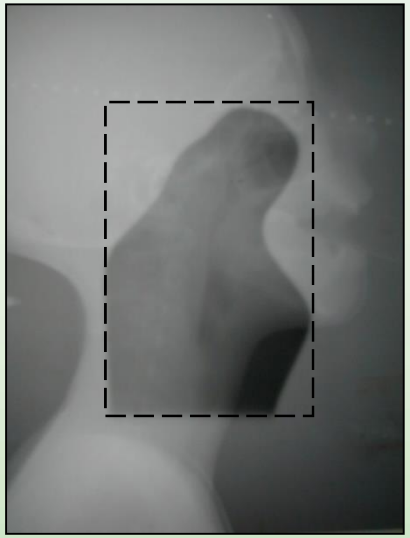
- Collimators
- Shape the beam into desired clinical shape

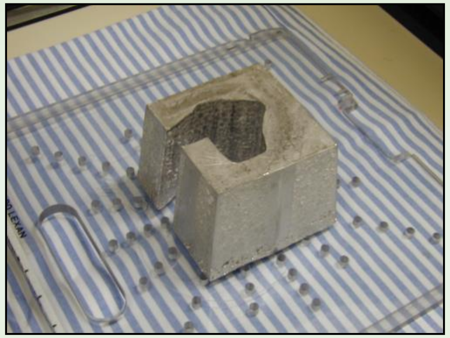


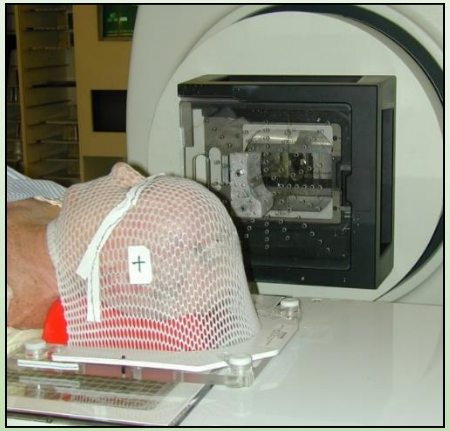
Early treatments: 2-Dimensional

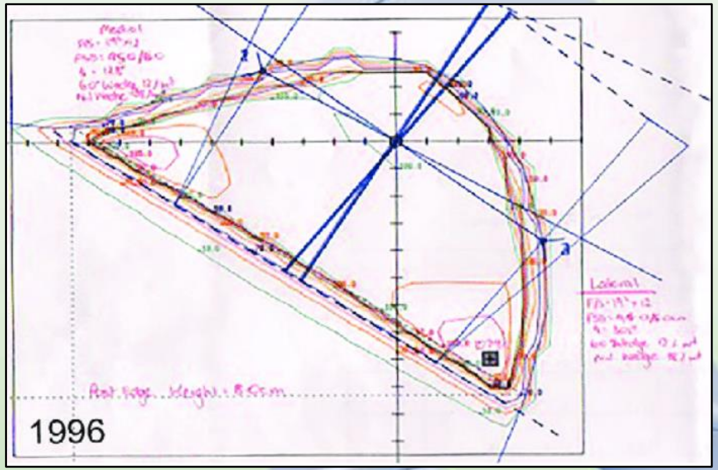
- Treatment region based on planar images, usually very overestimated
- Beam shaping done with metal blocks mounted on trays
- Simple beam configuration and manual dose calculation





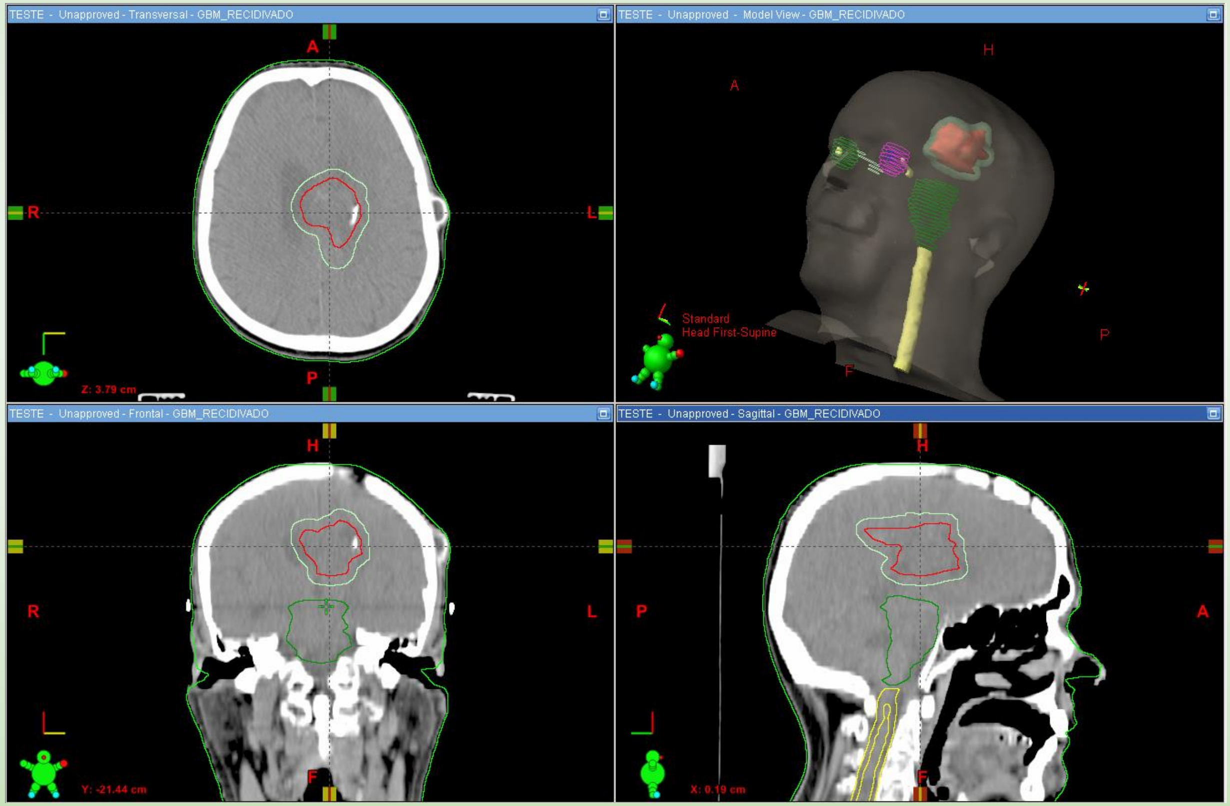


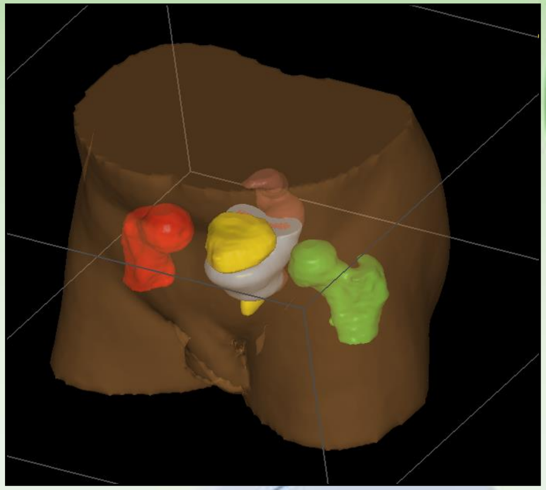


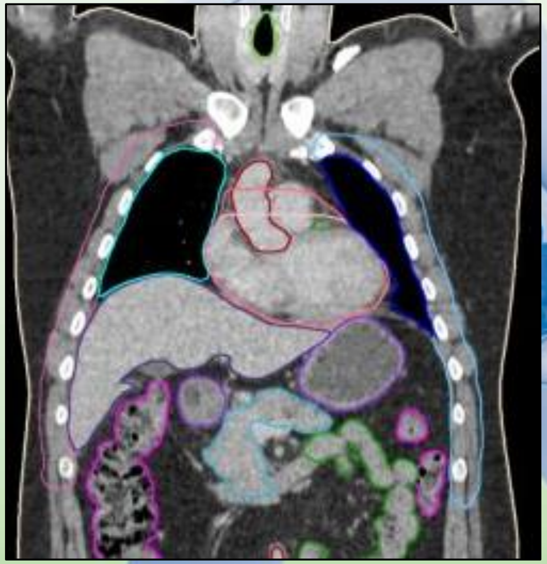


3-Dimensional RT

- Targets and organs-at-risk are defined in volumetric images (CT)

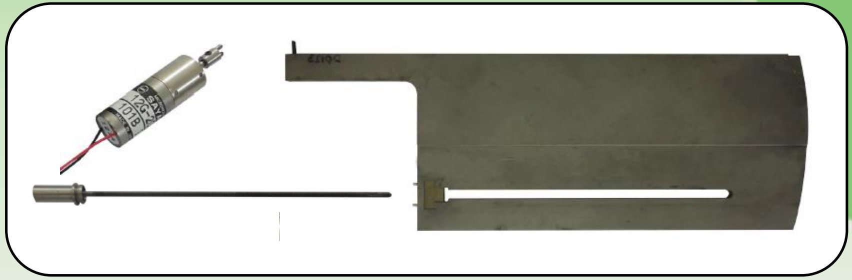


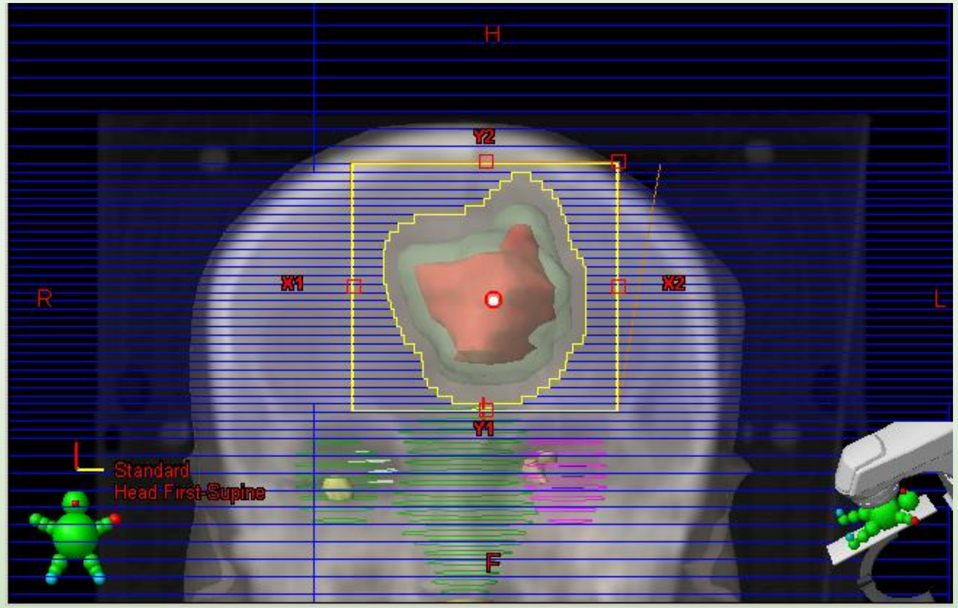


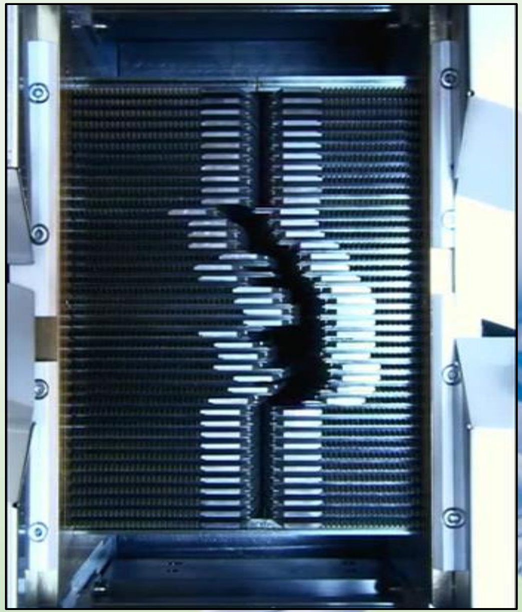


Multileaf collimators (MLC)

- 1980s-1990s (first in Brazil in 1995)
- Tungsten leaves with individual motors
- Capable of dynamic beam shaping

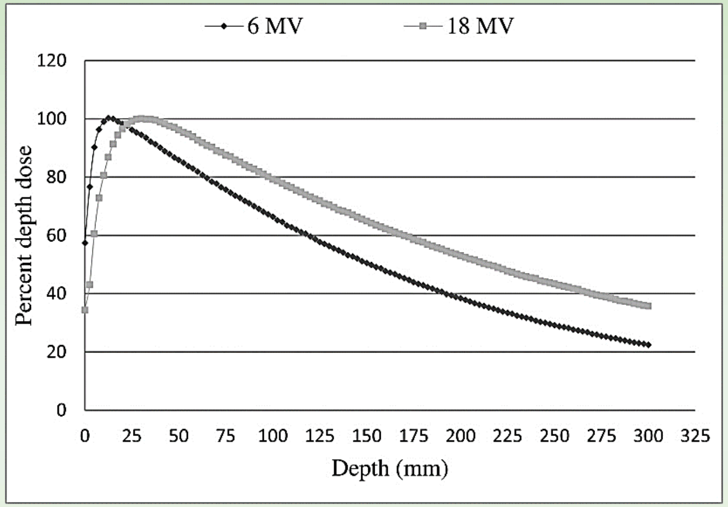


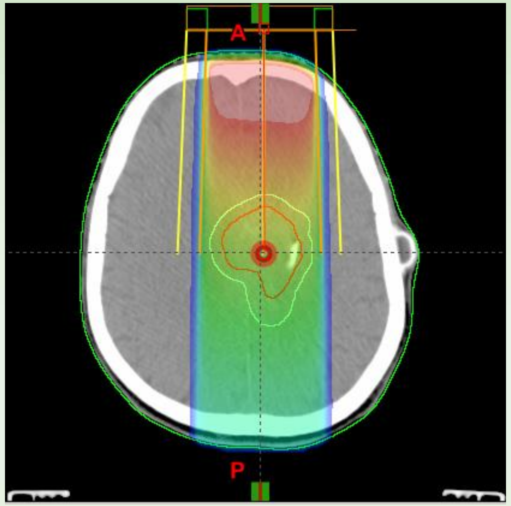




X-Ray Dose distribution

- X-ray dose deposition decreases with depth





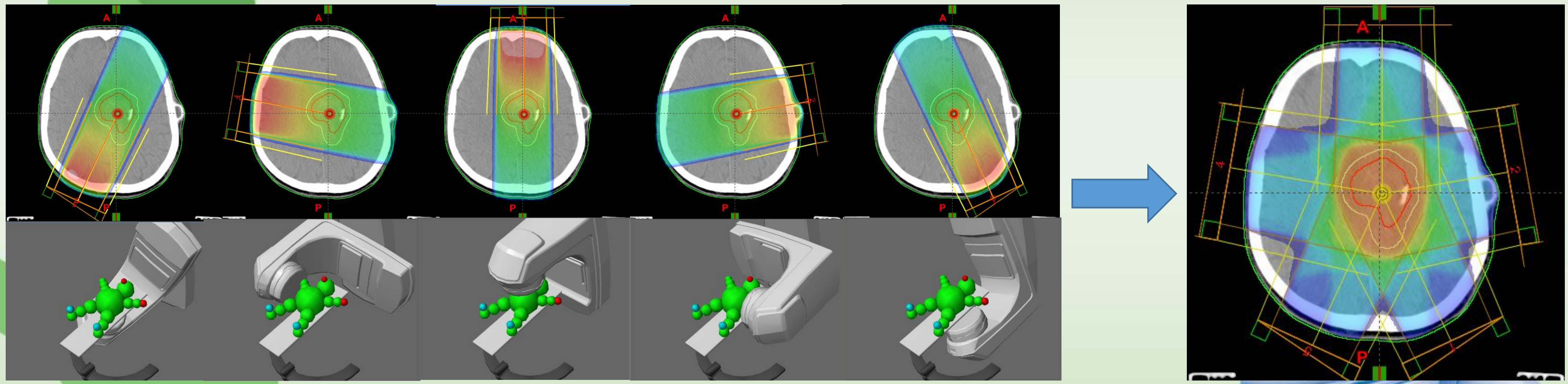
Single beam is often unacceptable

$$D(d) \propto \left(\frac{1}{d}\right)^2 . \boldsymbol{e^{-d}} . k_s(d)$$

- $\left(\frac{1}{d}\right)^2$ → inverse square distance
- e^{-d} → **exponential attenuation**
- $k_s(d)$ → scatter

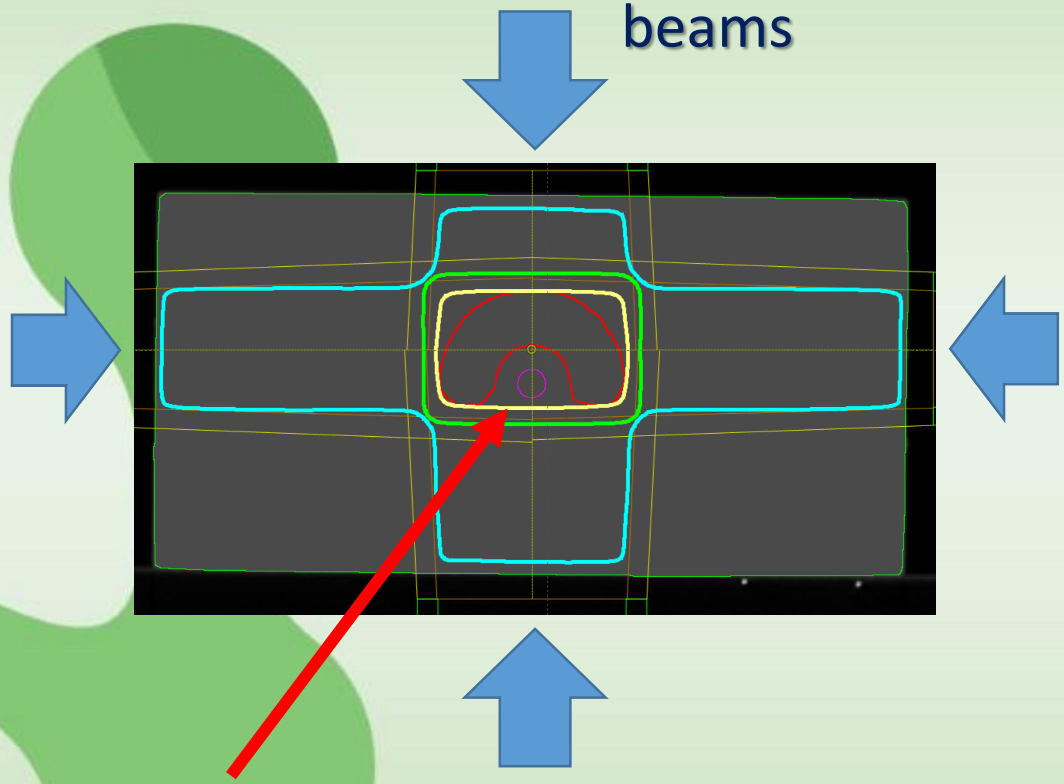
3D Conformal (3DCRT)

- Use of multiple beams to conform the dose to the target shape
- Treatment planning system (TPS) software used for dose calculation



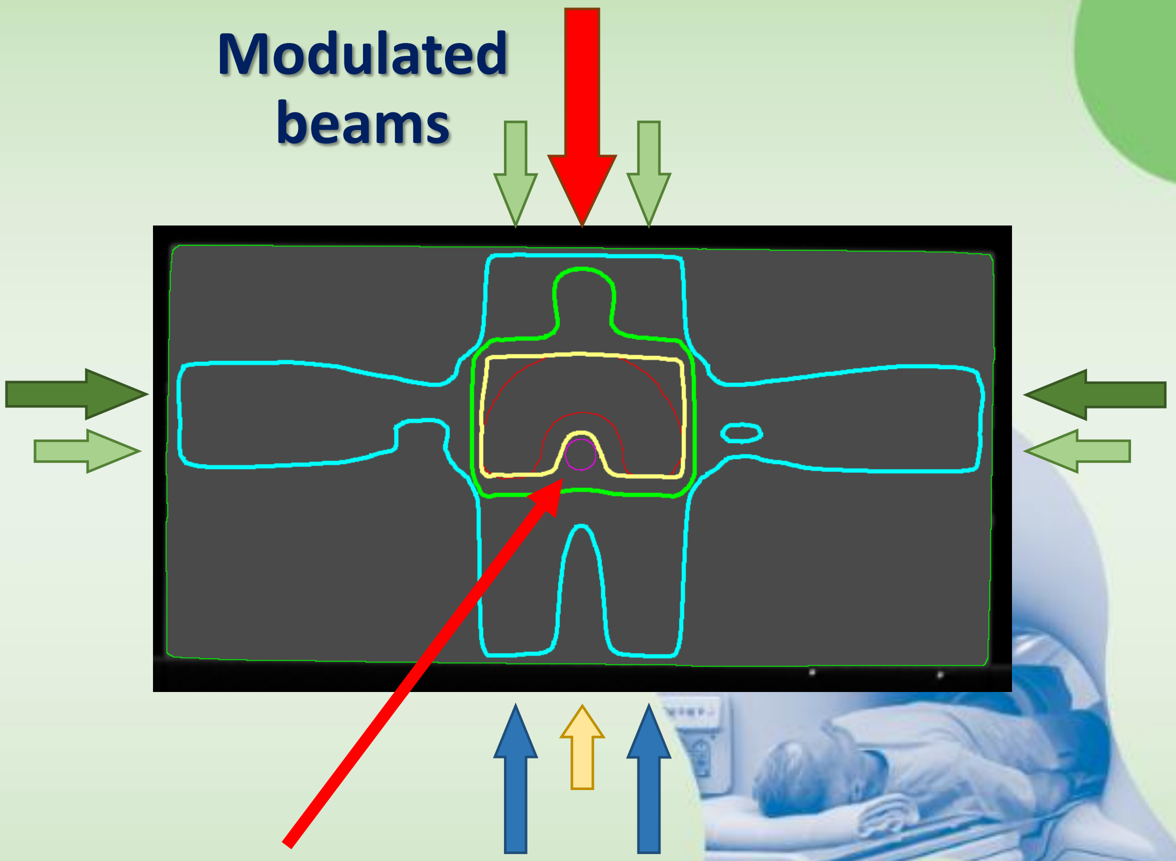
Beam modulation

Homogeneous beams



Healthy normal tissue inside a concave target receiving high dose of radiation

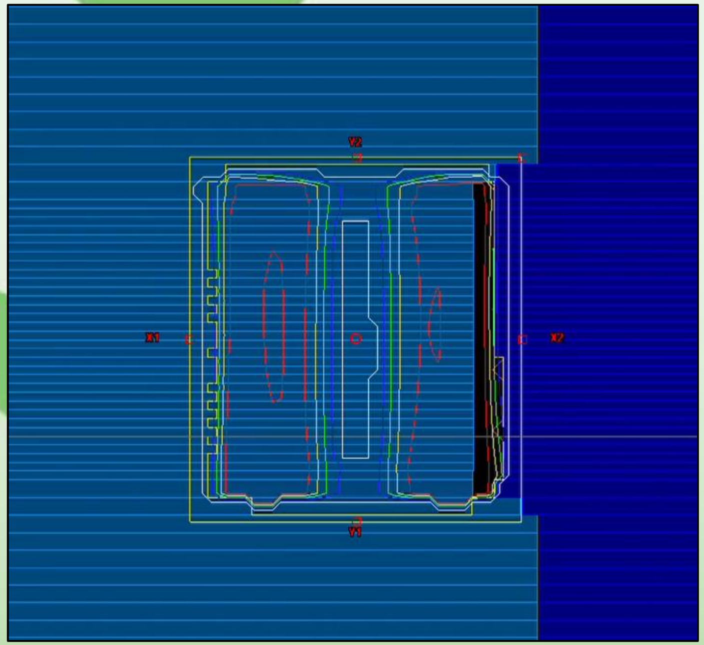
Modulated beams

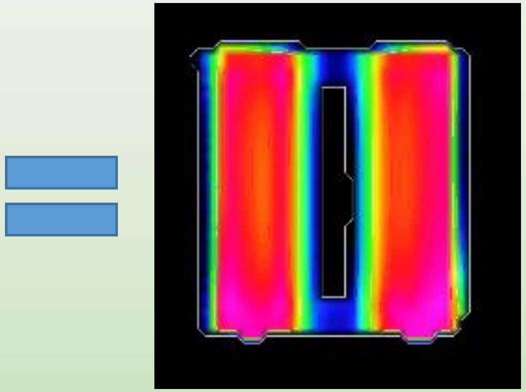


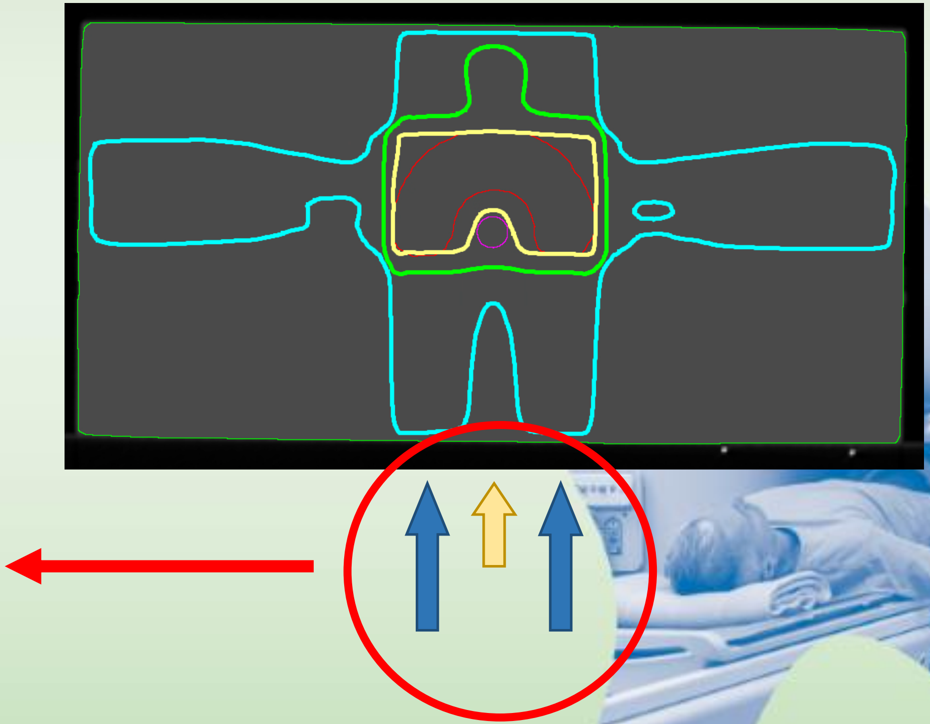
Superior sparring of normal tissue

Beam modulation

Intensity modulation can be achieved with dynamic MLC motion

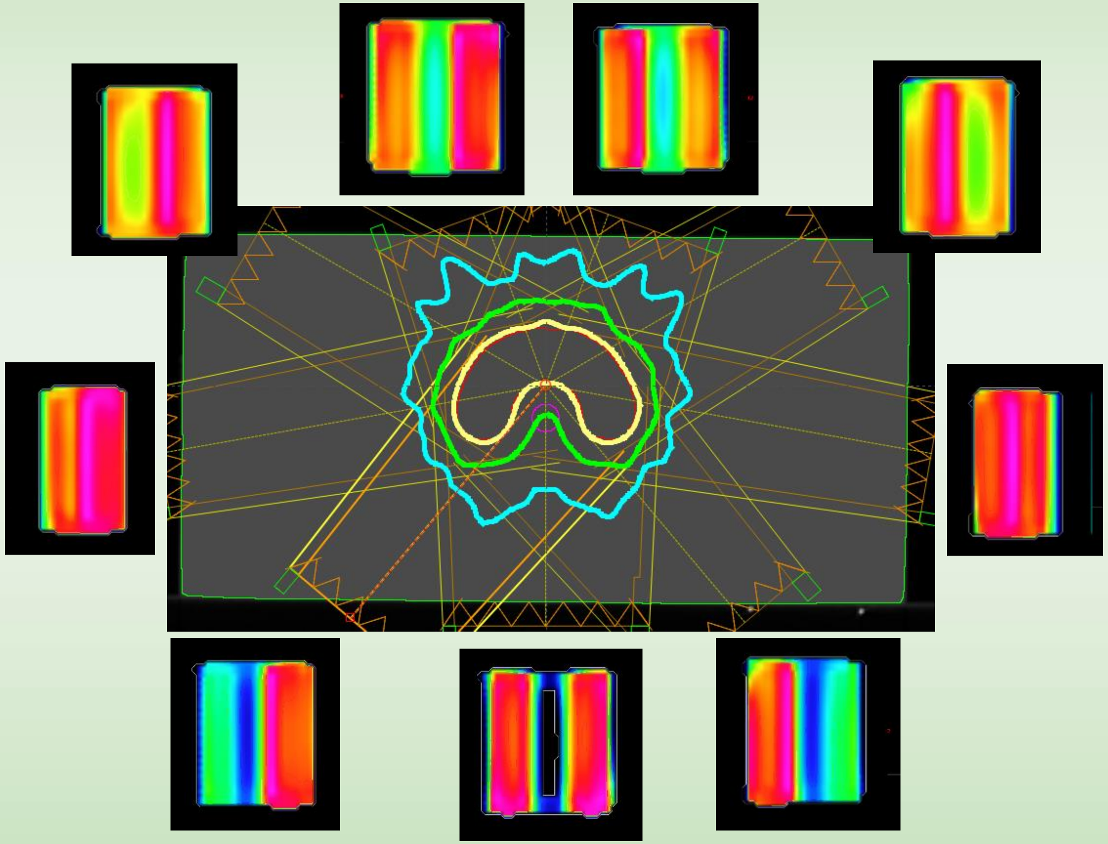






Intensity modulated RT (IMRT)

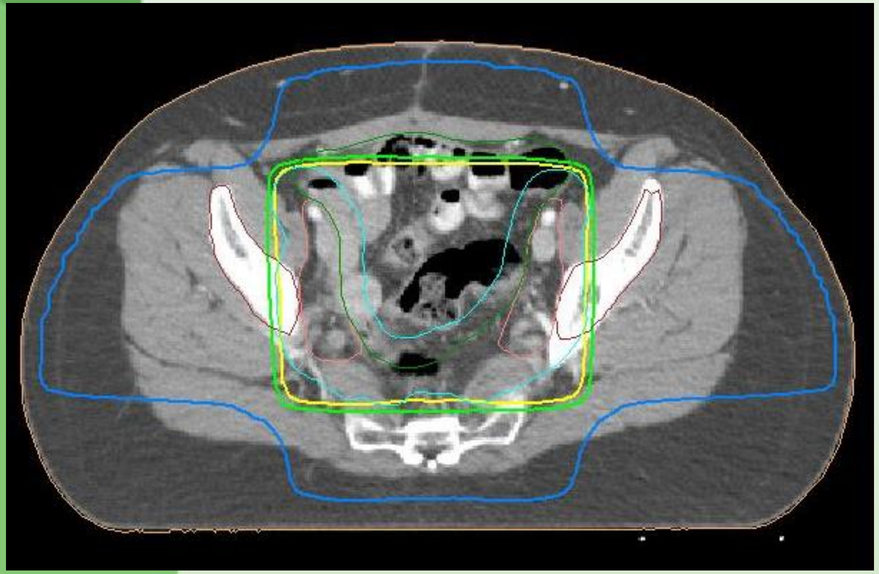
- Multiple modulated beams = optimal sparring of normal tissue



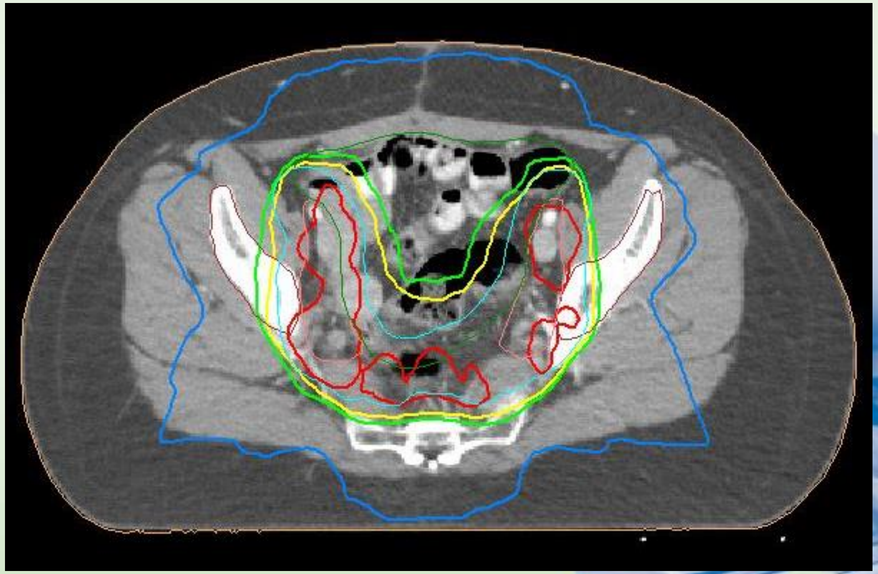
Intensity modulated RT (IMRT)

- IMRT: 1990s-2000s (first in Brazil in 2000)
- Better conformality to target and sparring of normal tissue

Conformal (3D)



IMRT



- Done in about 55% of services in Brazil

Modulated arc therapy (VMAT)

- VMAT 2000s-2010s (first in Brazil in 2010)
- Dynamic gantry rotation + MLC motion + dose rate variation
- Combines high modulation with delivery speed

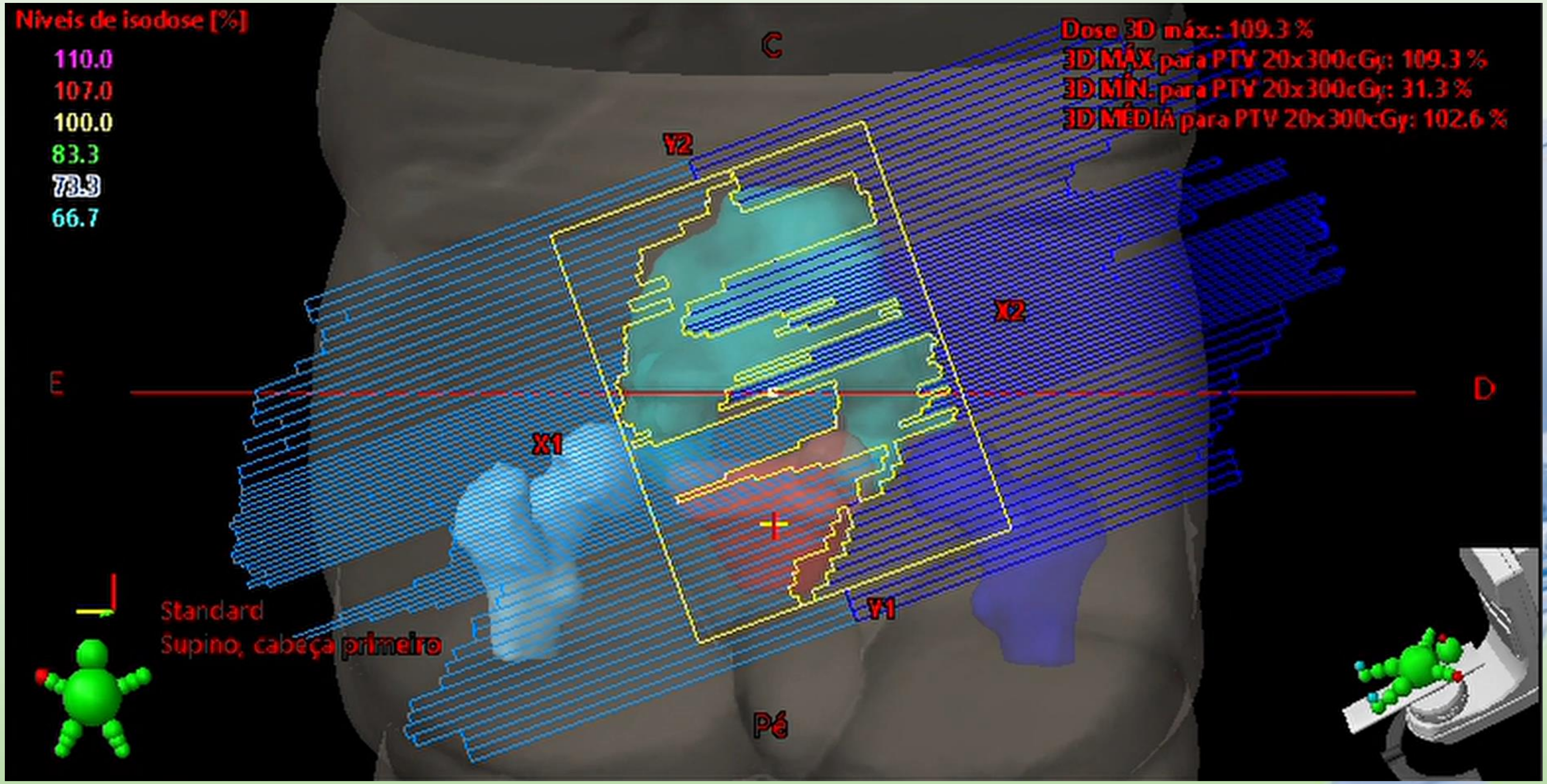
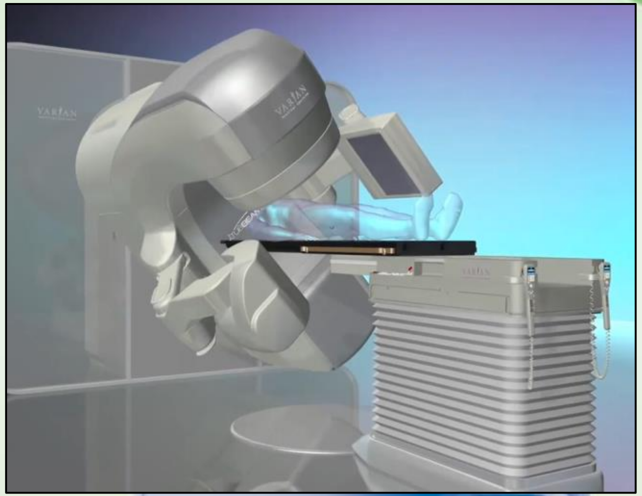
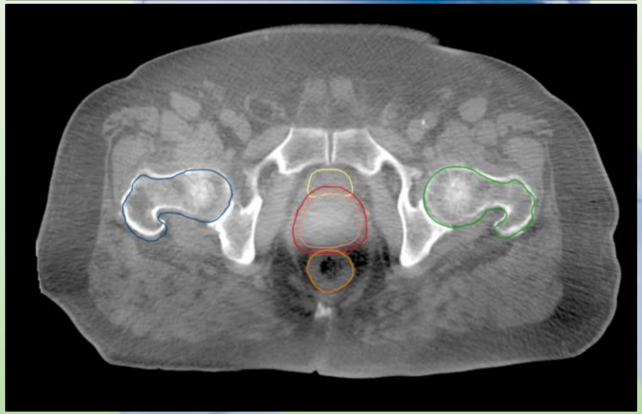


Image-guided RT (IGRT)

- Quality image guidance allows smaller margins
- MV image → On-board kV image → Cone-beam CT

First in Brazil in 2007





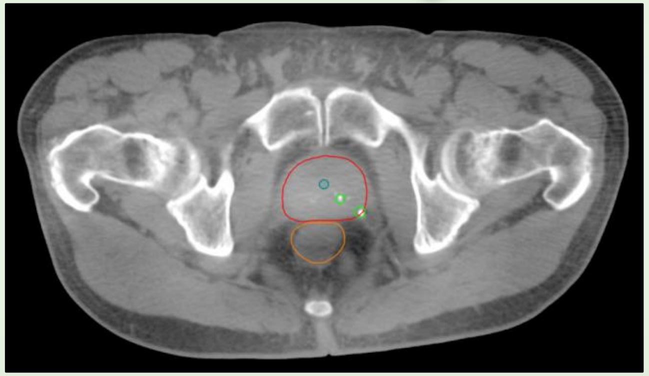
IGRT

- Main contributing factor for the precision of modern RT
- Several modalities of image guidance available
- Many hardware developments in the last few decades

Fiducial matching/tracking

Surface guidance

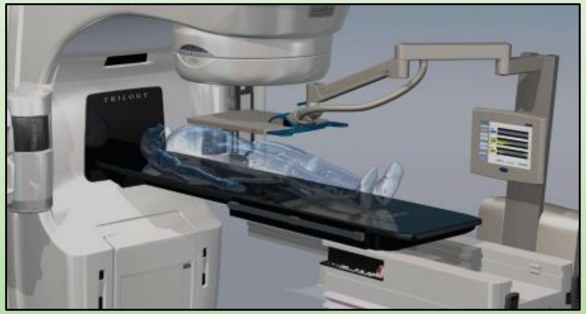
CBCT



MRI-Linacs

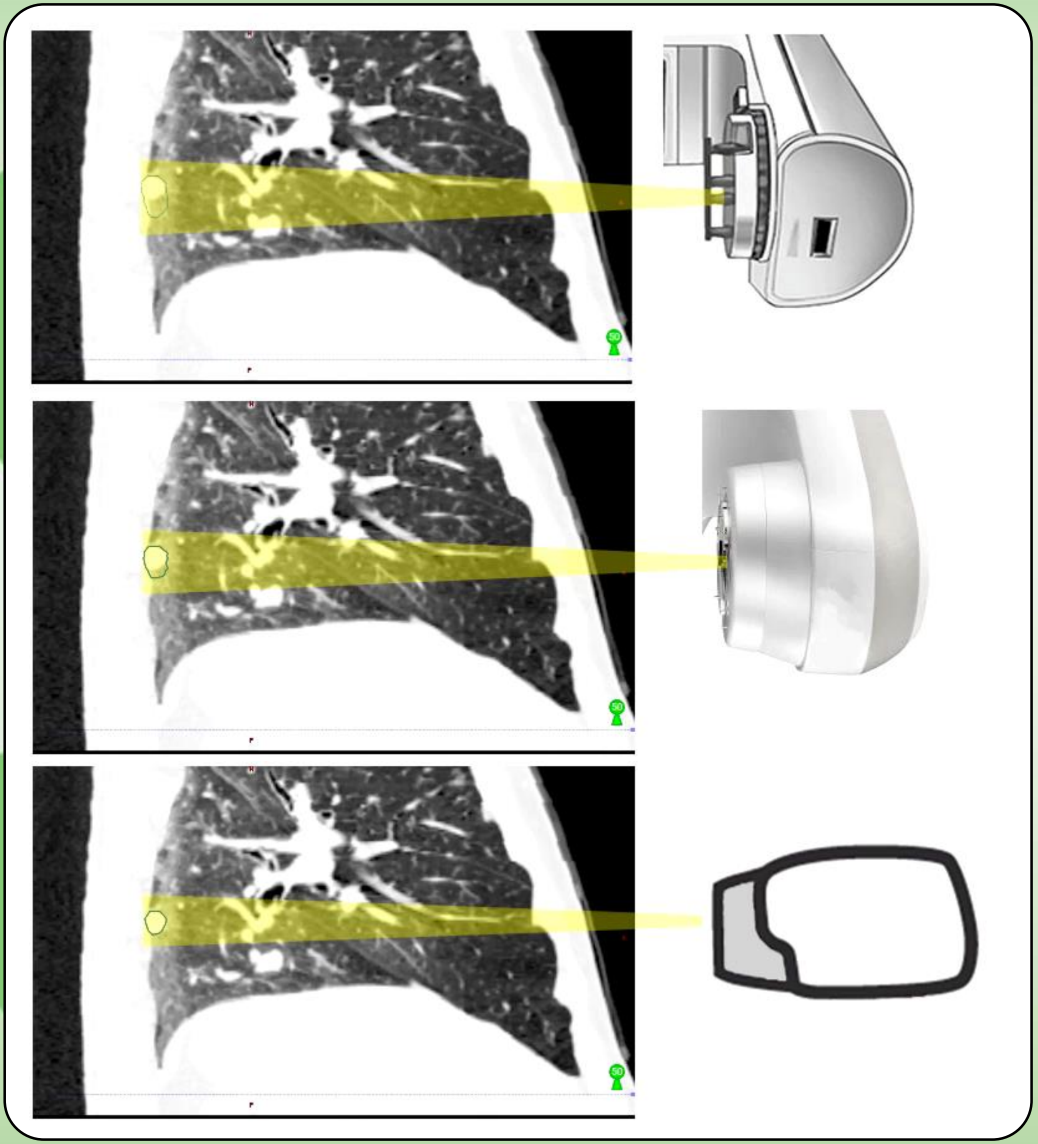
PET-Linacs

Transponders



Ultrasound

Breathing motion



- Moving targets pose a challenge in sparring normal tissue

- Motion management

(reduction of irradiated volume)

- Gating
- Tracking

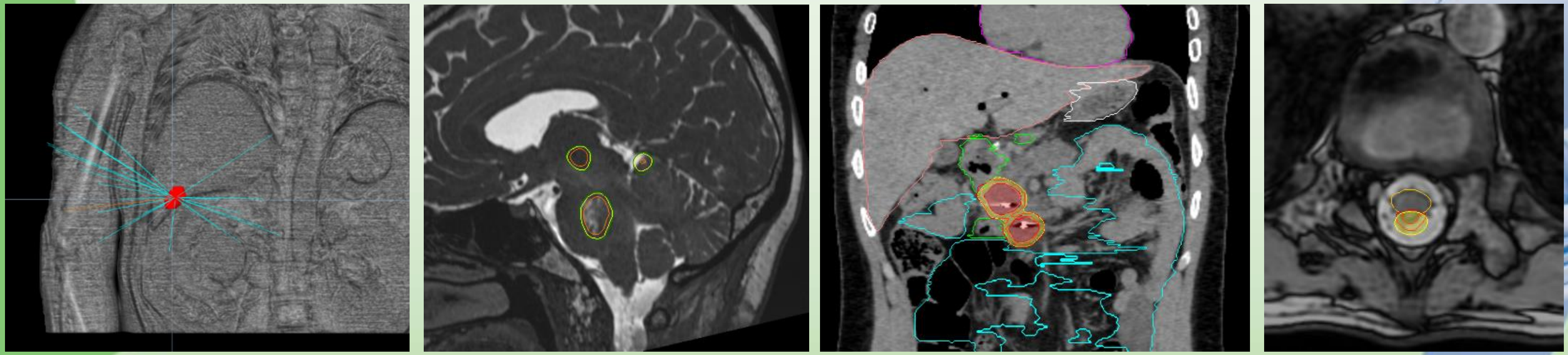
Hypofractionation

- Technology advances have enabled more precise treatments
- Intensity modulation
- Image guidance
- Tighter mechanical accuracy
- Safe use of **higher doses in fewer fractions** (hypofractionation and radiosurgery)

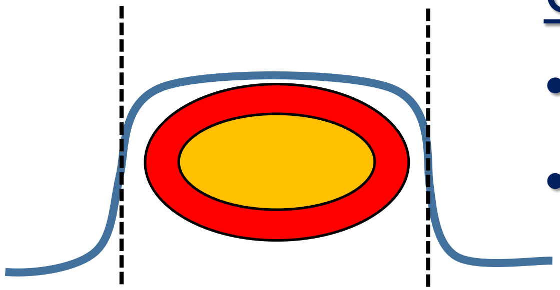
The application of different hypofractionation schemes is a major trend in clinical practice

Ex: Prostate

40 fractions → 20 → 5 → 1

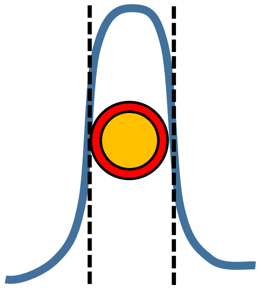


Radiosurgery and ablative RT



Conventional RT

- Large margins
- Homogeneous dose with smooth dose falloff



Stereotactic ablative RT (SABR)

- Tight margins
- Heterogeneous dose with sharp dose falloff
- Much less dose outside the target
- **Geometric miss is more severe**

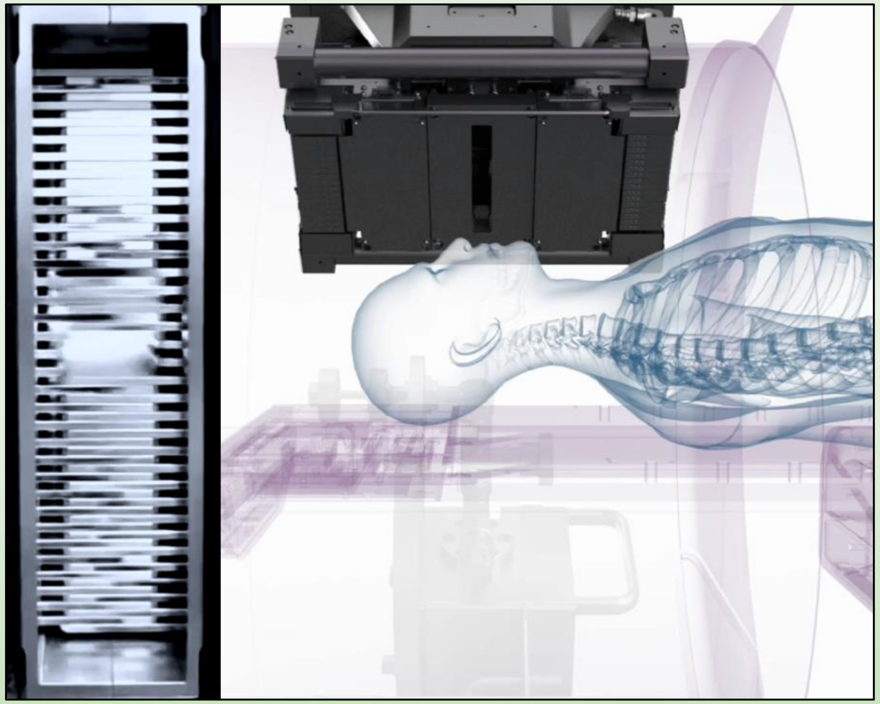
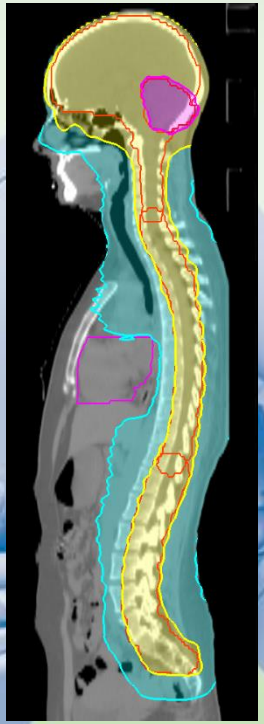
Special LINACs: CyberKnife

- Robotic tracking
- Automatic detection and correction of offsets in near real time
- Continuous compensation of breathing motion

- Only 1 in Brazil

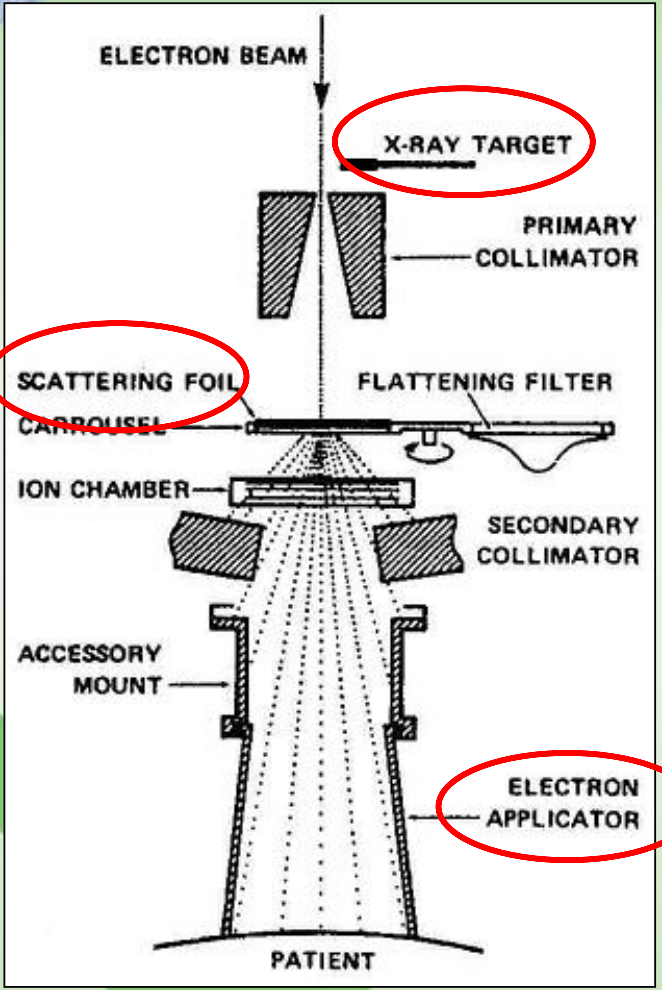
Special LINACs: Tomotherapy

- Helical delivery of fan beam with fast binary MLC
- Superior capability of beam modulation
- Continuous compensation of breathing motion

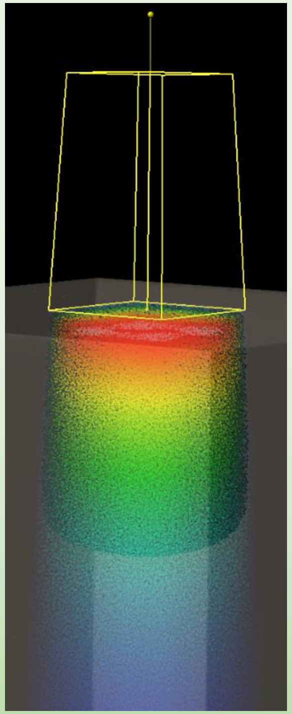
- Only 1 in Brazil

Electron Beams

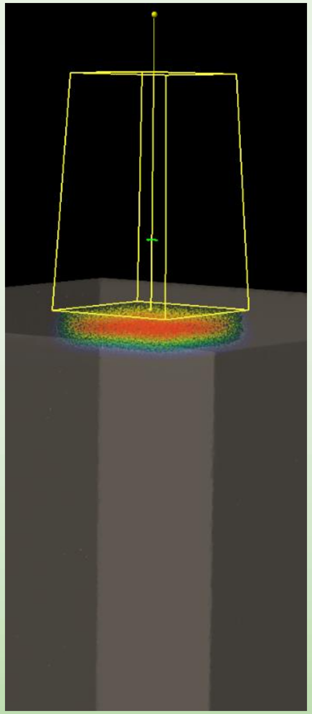


- Shallow dose distribution, rapid dose falloff
- Easy to shield with a few mm of lead
- Used for skin and superficial targets

X-Rays



Electrons



Intraoperative RT (IORT)

- Conventional Linacs (electron beam)
- Brachytherapy
- Dedicated mobile units

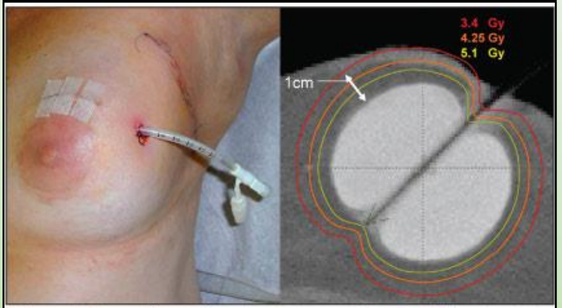
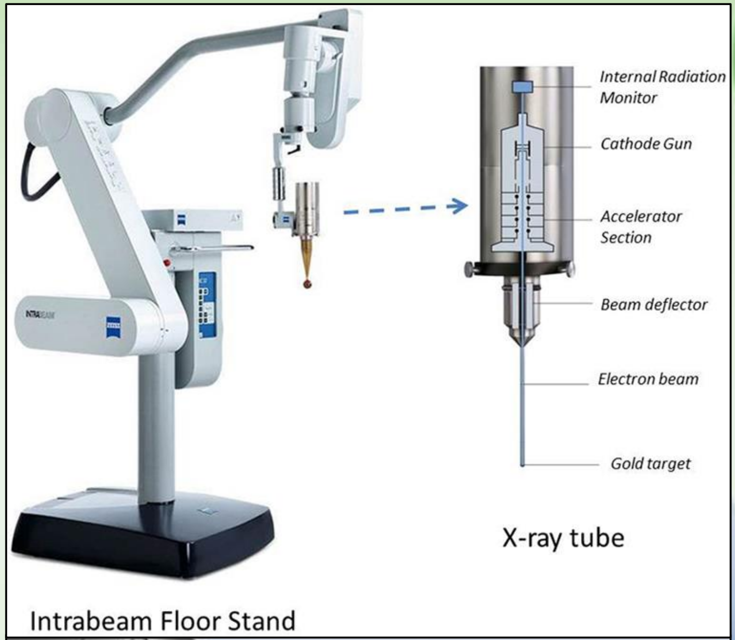
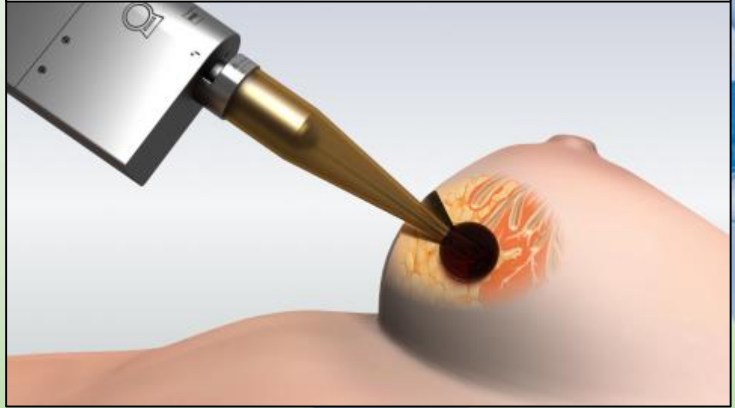


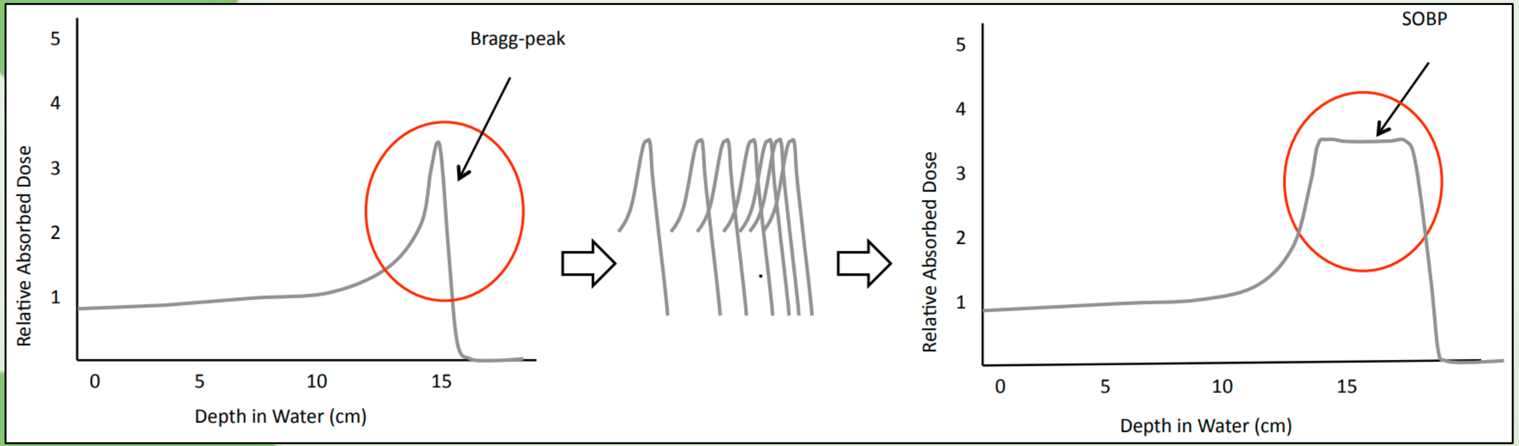
Figure 2: MammoSite Balloon Brachytherapy—External (left) and sagittal (right) views of balloon with dosimetric target coverage. Photographs courtesy of Douglas Arthur, with permission from the *Journal of Clinical Oncology*.



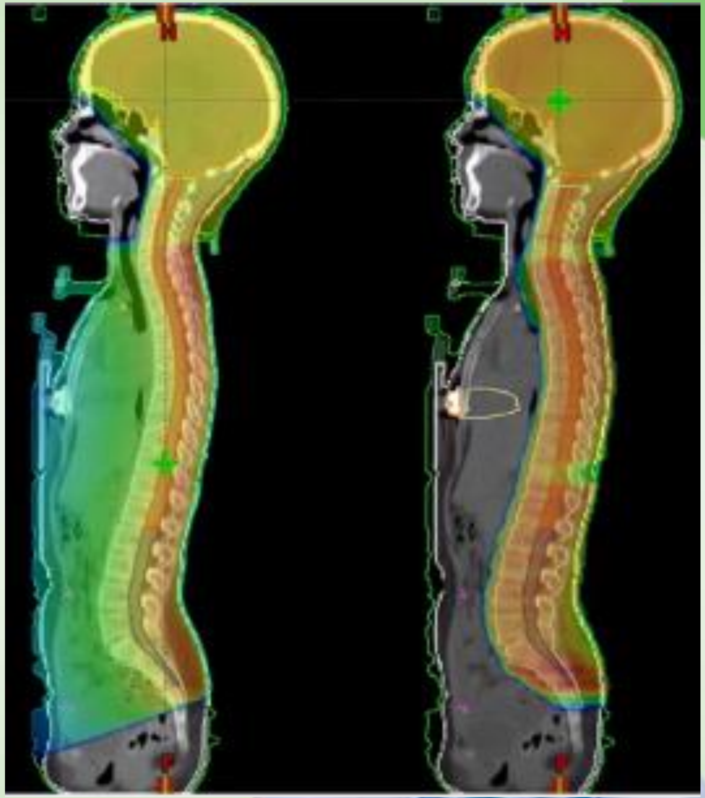


Proton therapy

- Protons and heavy ions → Bragg peak
- Deep range with virtually zero exit dose
- Range depends on energy



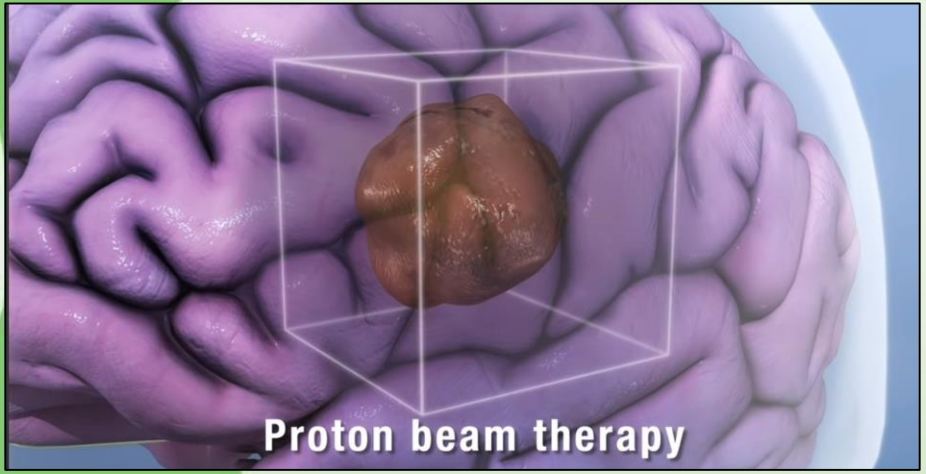
X-Rays
Protons

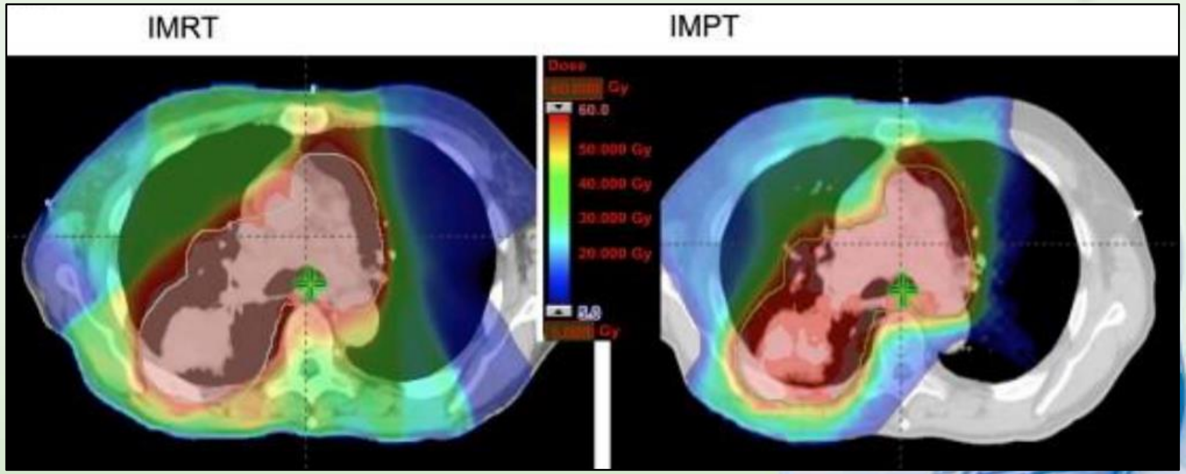


Kumar JPHO 2013

Proton therapy

- Pencil beam scanning: dose conformity possible with even a single beam
- Intensity modulated PT: potential to minimize integral dose
- Challenge: uncertainties (particle range, biological effectiveness, plan robustness, motion management)

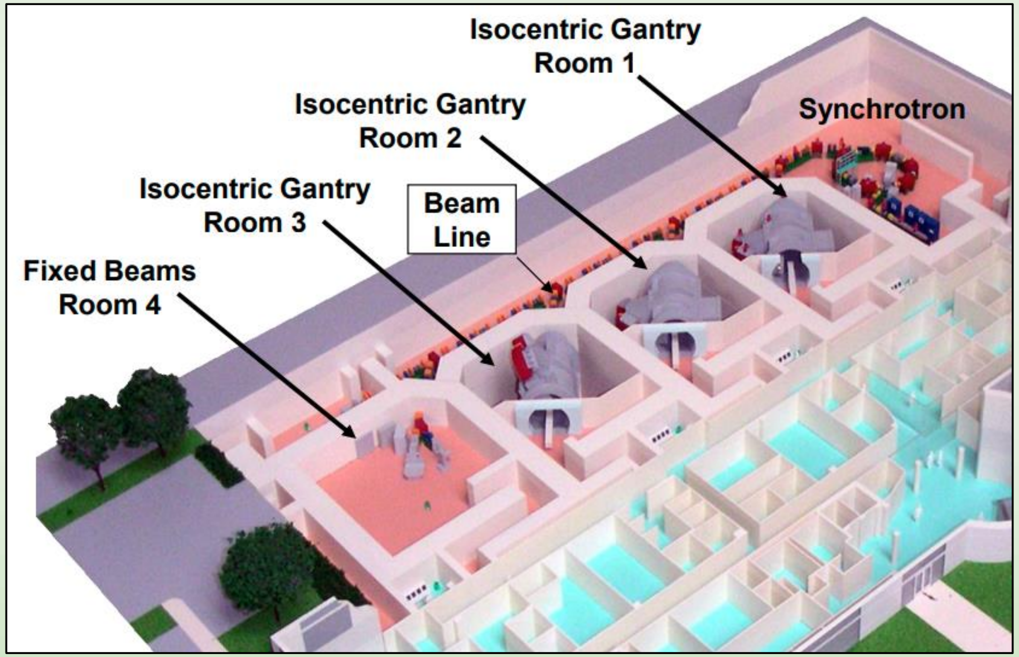




Mohan, Grosshans “Proton Therapy – Present and Future” 2016

Proton therapy

- Biggest challenges: cost and size
- Most current facilities are dedicated regional PT centers with multiple treatment rooms



MD Anderson Proton Center

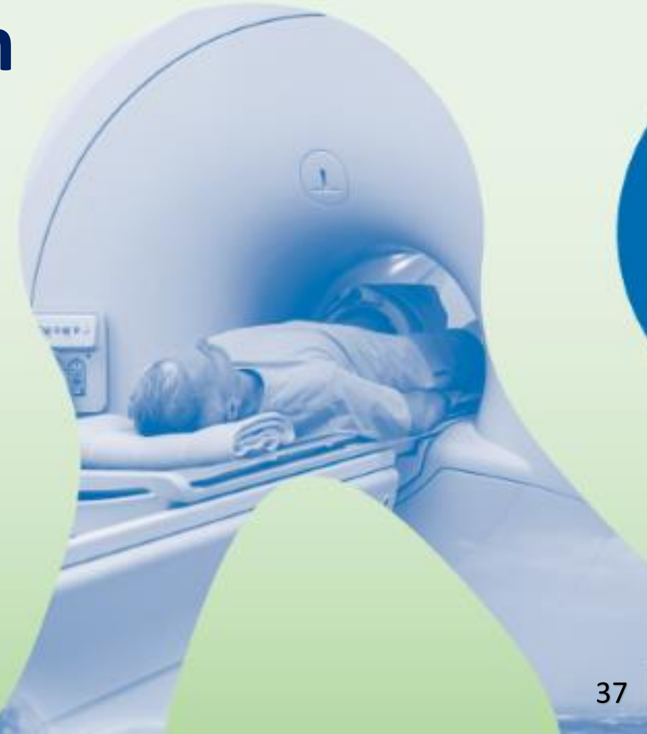
- None in Brazil (nor Latin America)

Future directions

- Most research efforts are in the use of artificial intelligence <u>software</u> (won't be covered here)

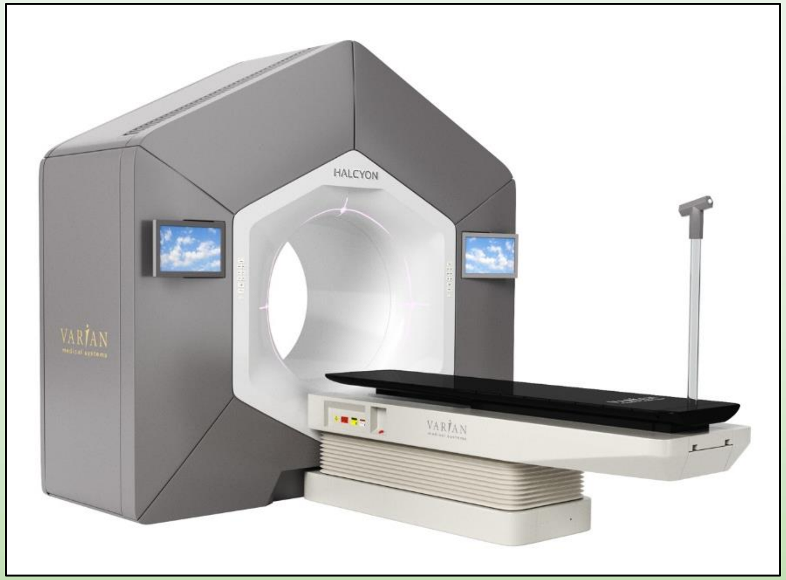
- Currents trends in treatment delivery <u>hardware</u>:

- **Improved workflow and cost reduction**
- **Better imaging and adaptive RT**
- **Ultra-high dose rate (FLASH)**



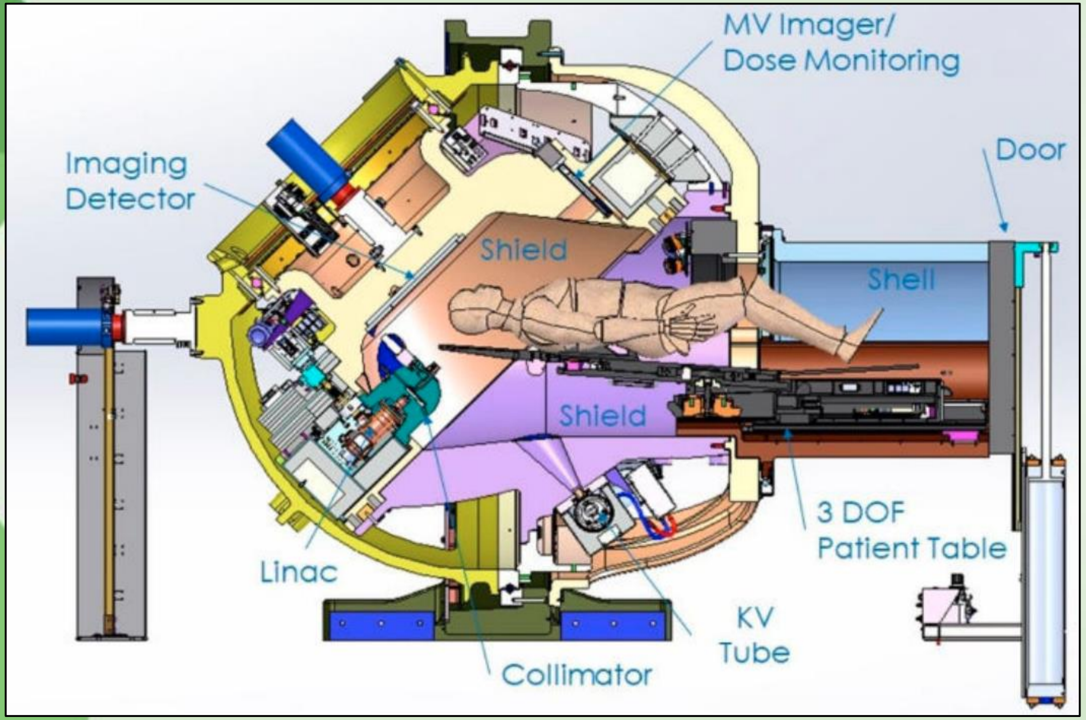
Linacs: Simpler can be better 🕶

- Compact blueprint (single energy, no couch rotation, self-shielded)
- FASTER! (fast rotation, faster imaging, fast modulation)
- Maintenance: modular parts (replace instead of repair, increase uptime)
- Reduced or simplified features, but still advanced machines
- Reduce costs and treatment time to make technology more available



ZapX

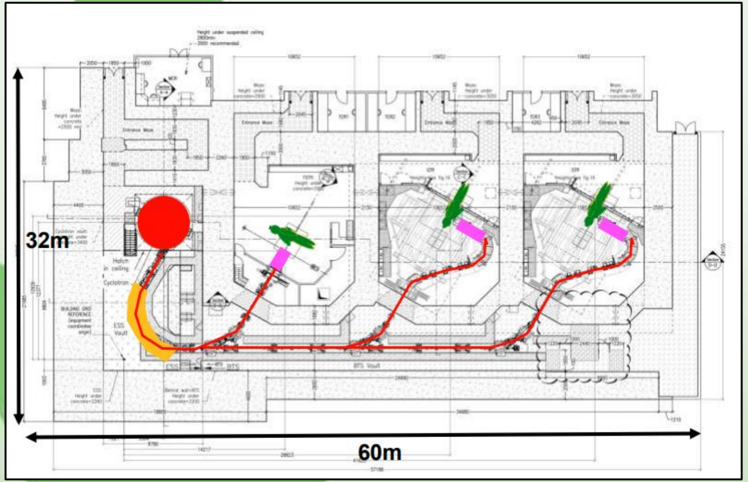
- Compact vaultless gyroscopic radiosurgery Linac



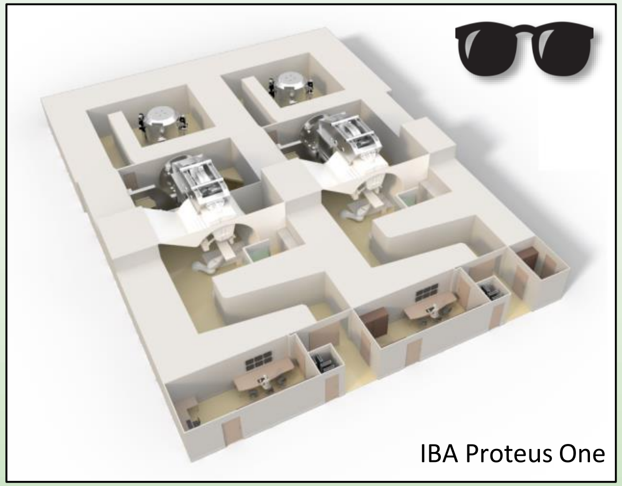
Protons: Smaller and cheaper

- Price of acquiring proton therapy treatment has greatly decreased, but is still unaffordable in most settings (in the order of 10^7 to 10^8 USD)
- Room size requirements have decreased dramatically

Specialized proton centers

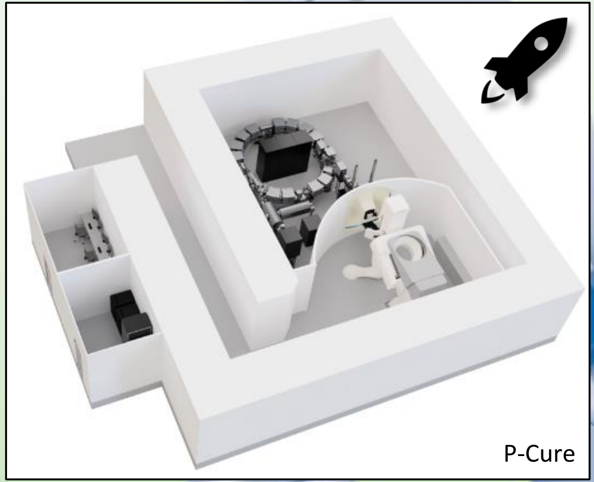


Dedicated proton rooms



IBA Proteus One

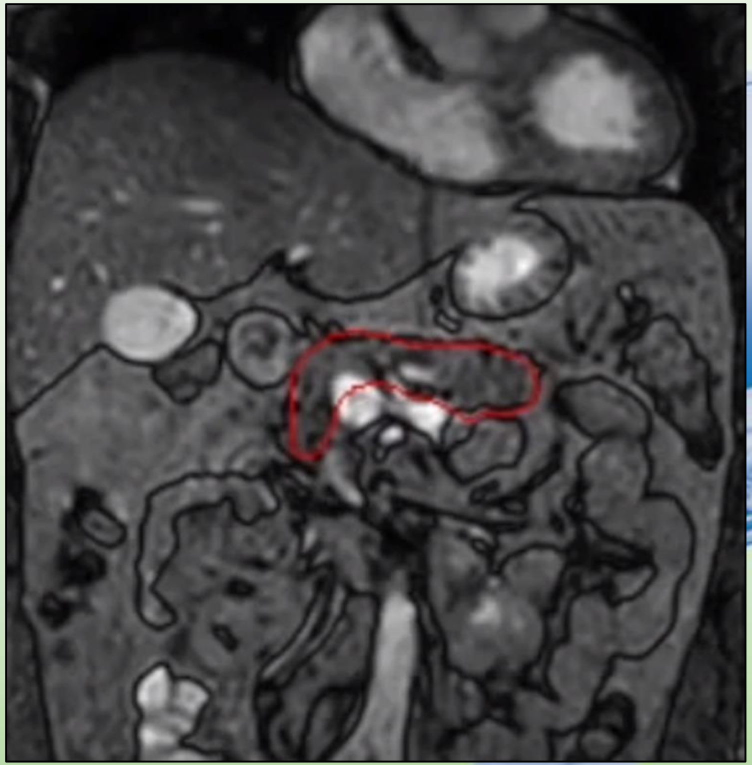
Replacing old Linacs in existing rooms



P-Cure

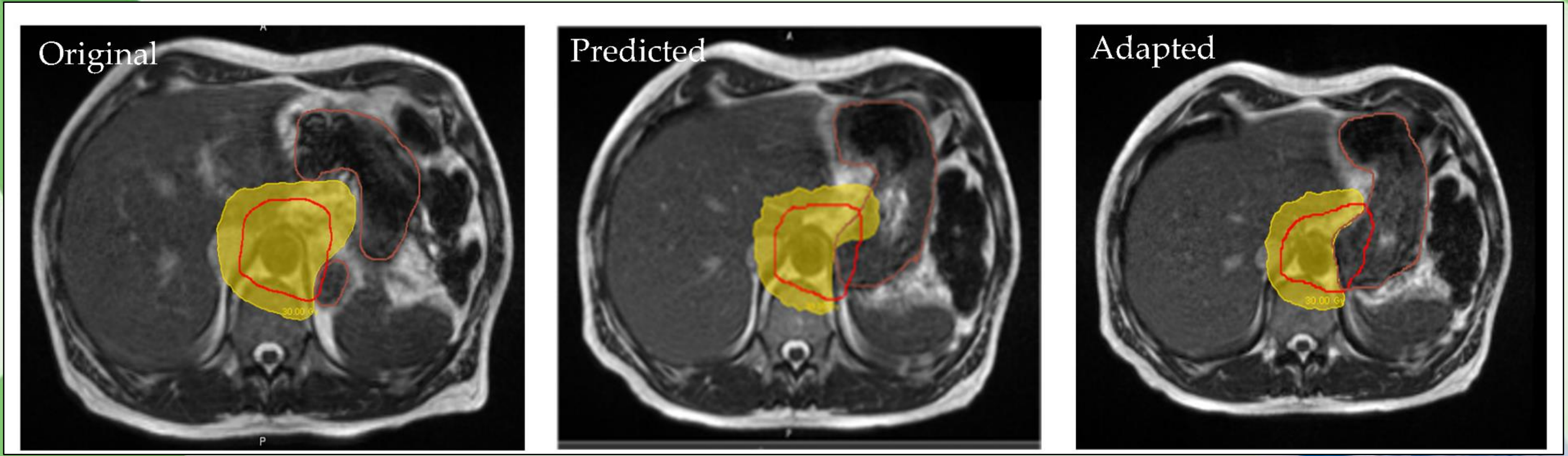
Magnetic Resonance guided RT

- LINAC + MRI
- Better target definition and real-time motion assessment
- In development for a couple of decades due to MANY engineering challenges, but finally becoming mainstream



MRgRT

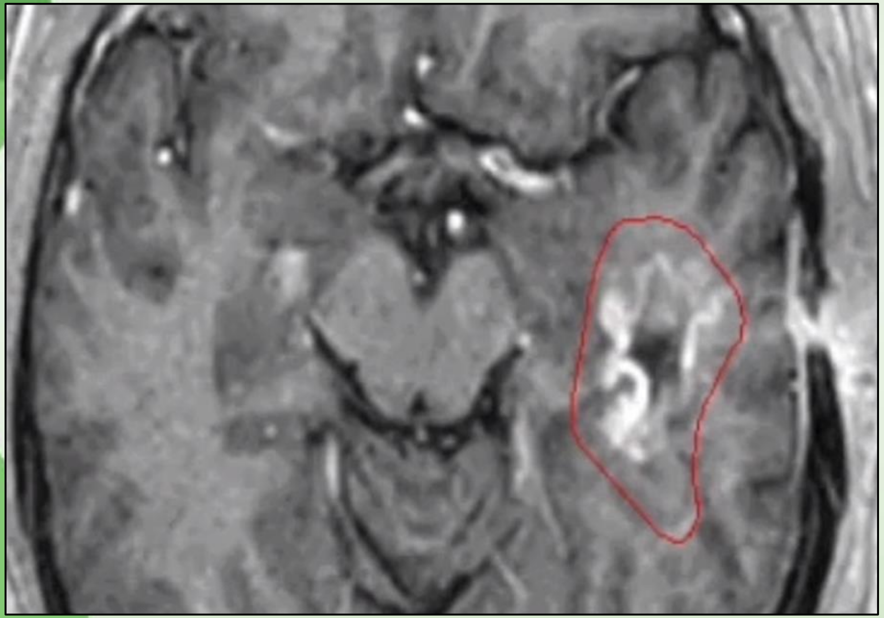
- Daily online plan adaptation to target position and deformation

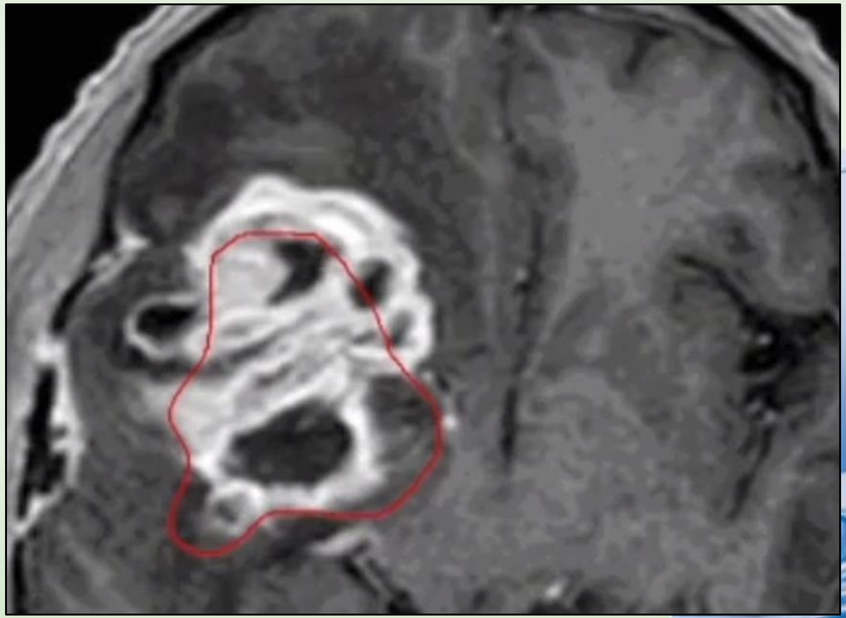


Lee et al "Online Adaptive MRI-Guided Stereotactic Body Radiotherapy for Pancreatic and Other Intra-Abdominal Cancers" Cancers 2023

MRgRT

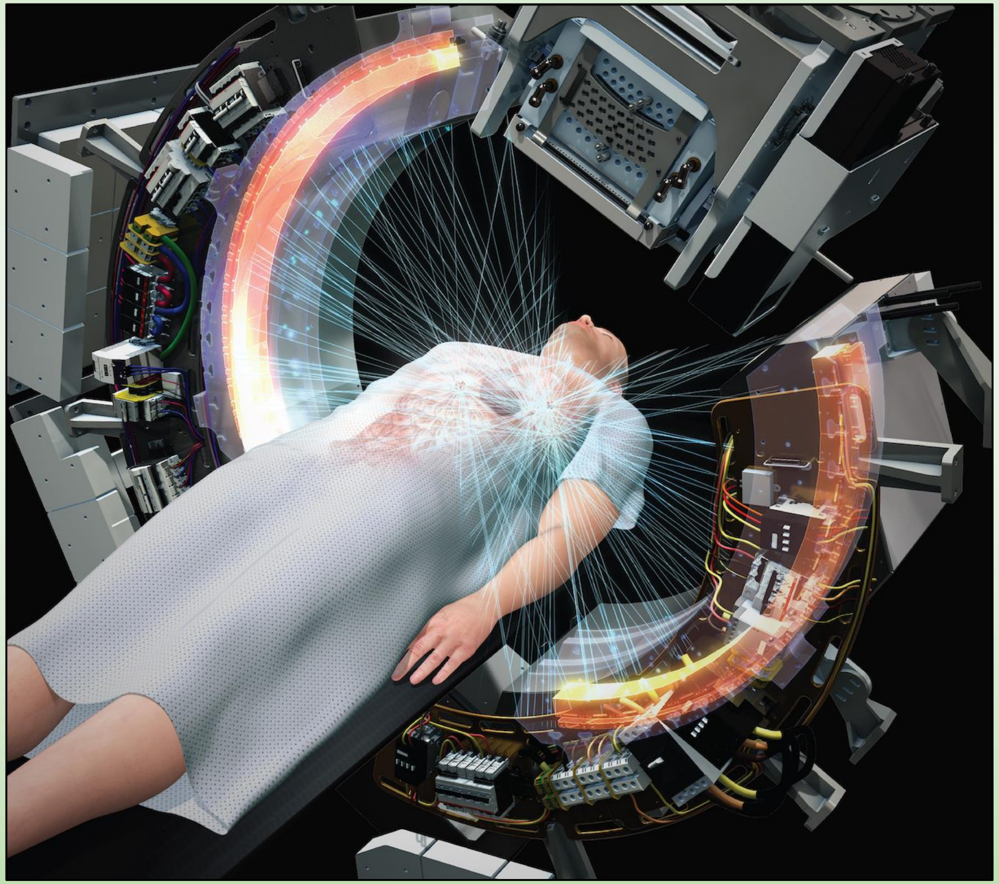
- Online assessment and adaptation of target response
  - Shrinkage/growth 🕶
  - Biomarkers 🚀

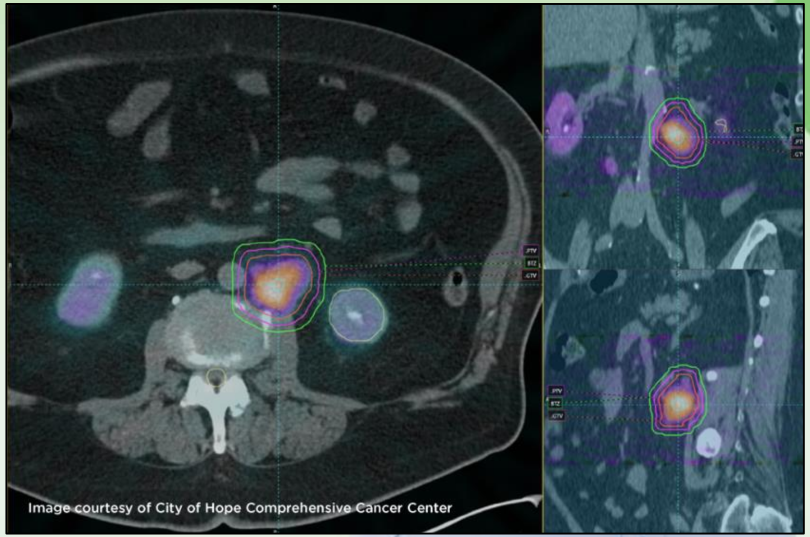


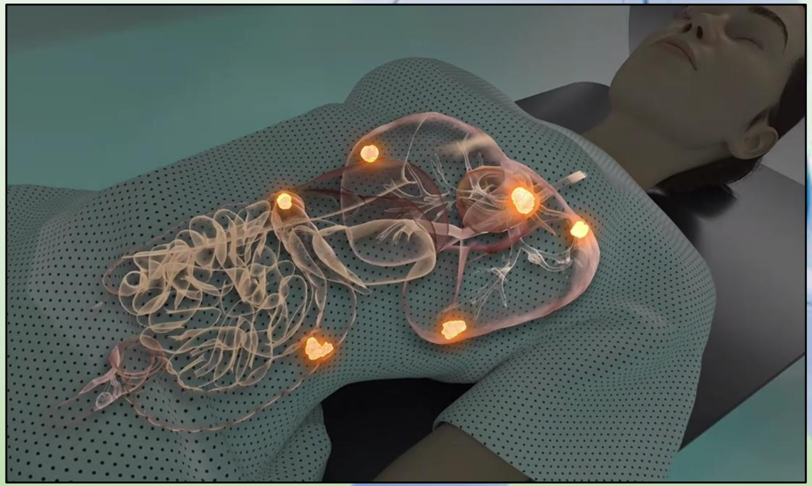


Biological guided RT (BgRT)

- LINAC+PET
- Identify, adapt and track “active” regions





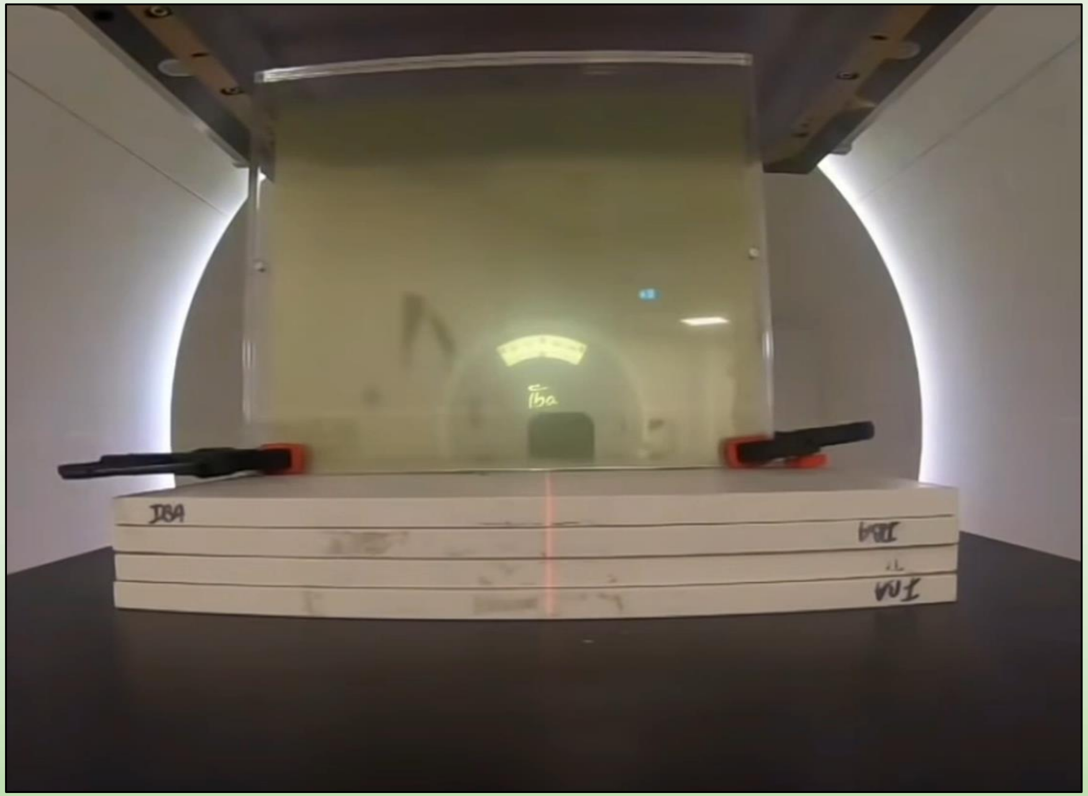


Reflexion.com

Ultra High Dose Rate (FLASH)

- Typical dose rate of SRS Linac ≈ 10Gy/min
- FLASH: 40-100Gy/s (“clinical”) (can reach >10^3 Gy/s)

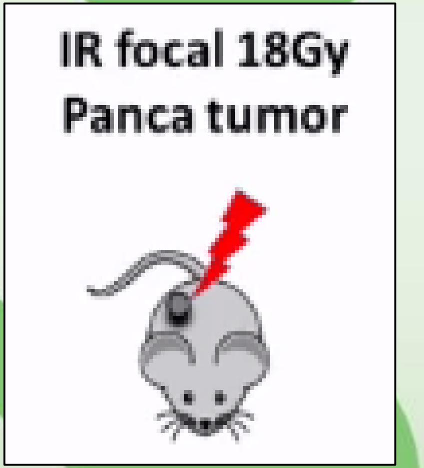
\- Treatment delivery in a few ms → further improve precision therapy?

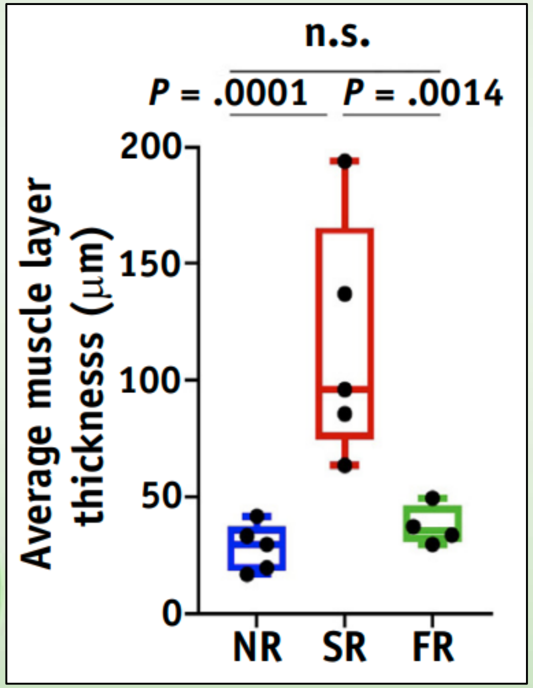


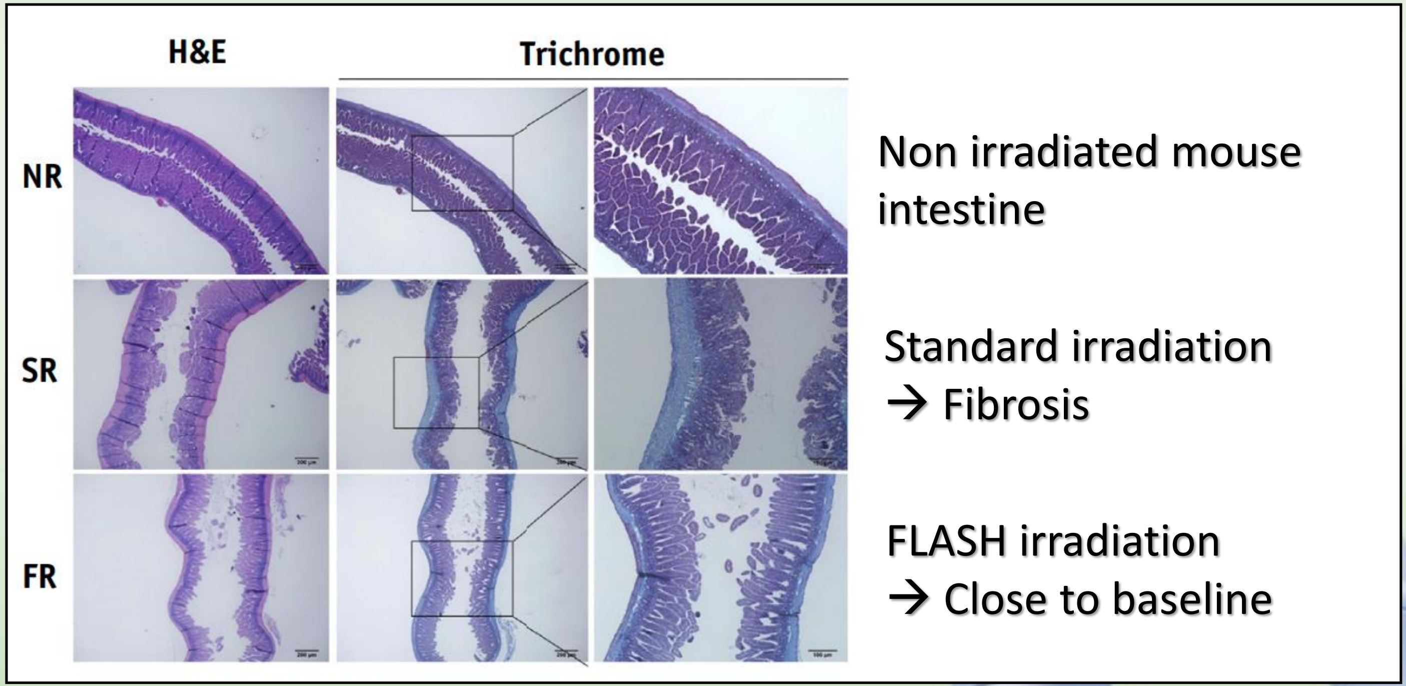
YouTube: IBA

FLASH effect

- Evidence of better normal tissue sparring, not yet fully understood
- Potential for sparing normal tissue <u>within</u> the field (i.e. using biology instead of avoiding the tissue and potentially underdosing the tumor)





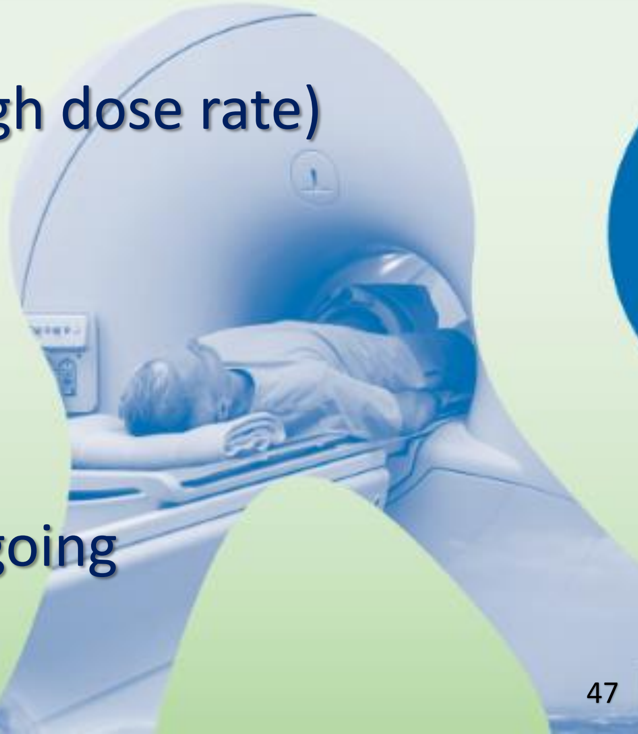


Diffenderfer IJRBOP 2020

FLASH Challenges

- Mostly done with **charged particles**
- currently **unachievable with MV X-Rays** (bremsstrhalung yield and heat)
- Electrons: limited to superficial lesions
- Feasibility issues with pencil beam scanning and IMPT (effective dose rate to produce FLASH effect)
- Quality assurance challenges (detectors for ultra high dose rate)

- Currently: pre-clinical, transition
- More questions than answers
- Mostly animal studies
- Feasibility studies and very limited clinical trials ongoing



Thank you!

Contact: pedrohbcardoso@gmail.com