Delivery and Verification

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Paul Scherrer Institute

Delivery and Verification

Curative
Local control
Pain control
etc.

Patient is addressed to radiation oncology department

Our aim is to achieve the goal of radiotherapy treatment

Deliver the correct dose at the correct location

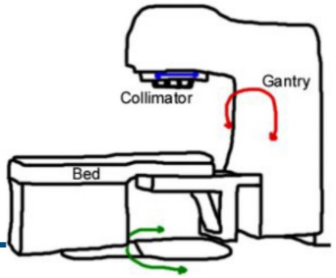
How do we plan the **delivery** of treatment?

How do we **deliver** the treatment?

How do we **verify** the plan?

How do we **verify** that the delivery is correct?

Focus on standard C-arm linac



Topics of this lecture:

1. Patient simulation
2. Treatment preparation
3. Delivery techniques on a C-arm linac
4. Patient specific quality assurance
5. Daily imaging and setup corrections
6. Organs motion and motion mitigation strategies
7. In-vivo dosimetry

3 main phases for patient RT treatment

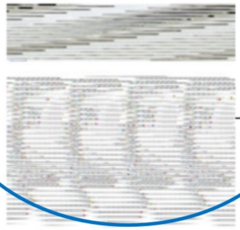
- **Simulation CT** (CT scan, immobilization devices, CT protocols)
- **Treatment preparation and verification** (contouring, prescription, treatment planning, PSQA, DICOM data transfer)
- **Treatment delivery and verification** (linac, imaging devices, setup corrections, motion mitigation, Record&Verify, in-vivo dosimetry)

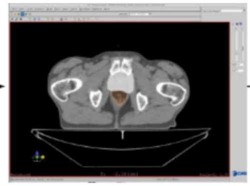
Patient workflow

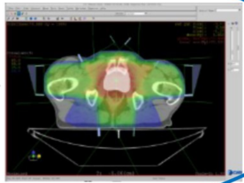
2. Treatment preparation

3. Delivery techniques

4. Patient specific QA







1. Patient simulation

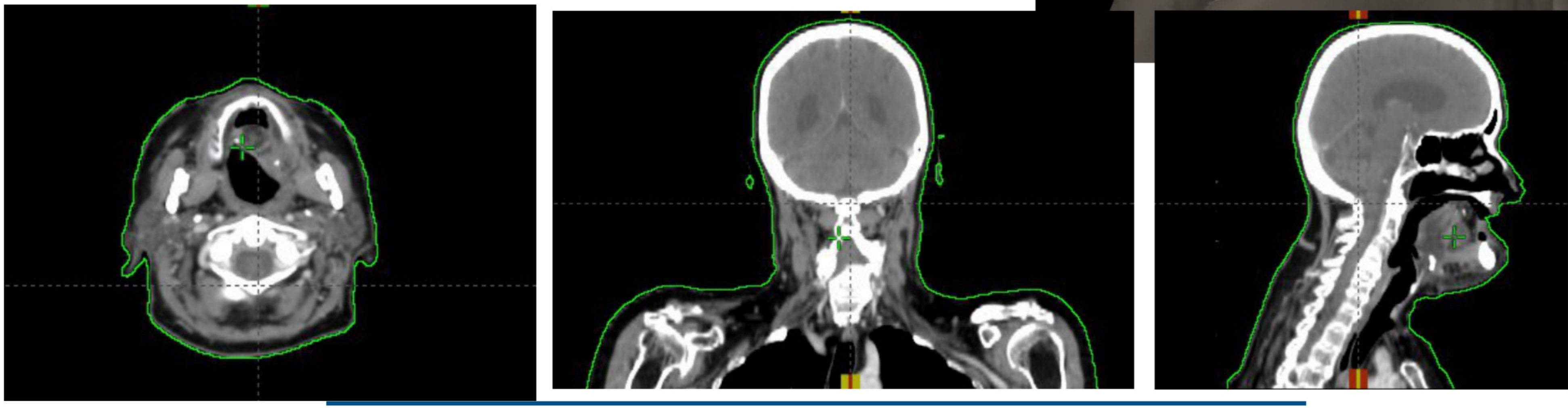
5. Daily imaging and setup corrections

6. Motion mitigation strategies

7. In-vivo dosimetry

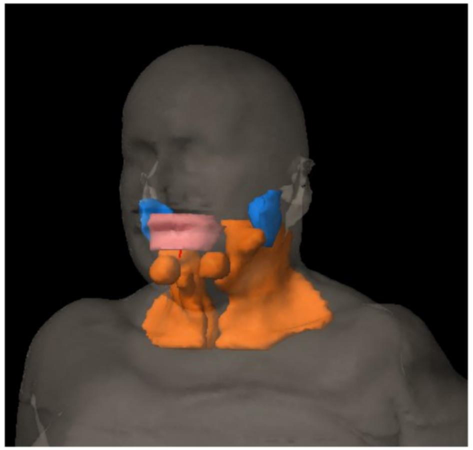
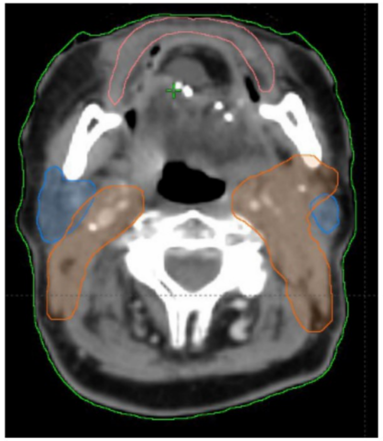
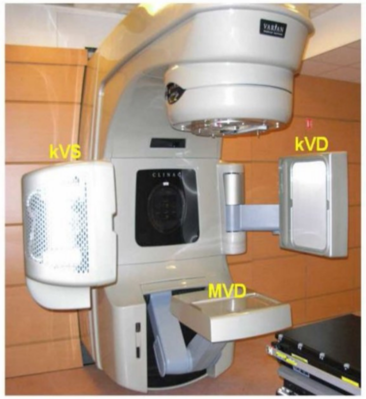
1. Simulation CT

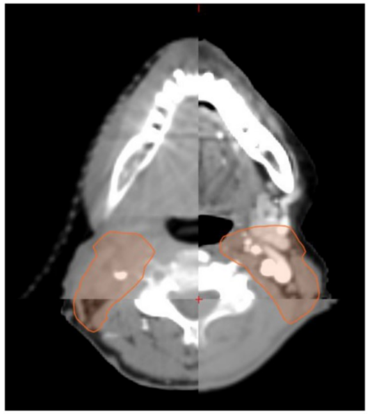
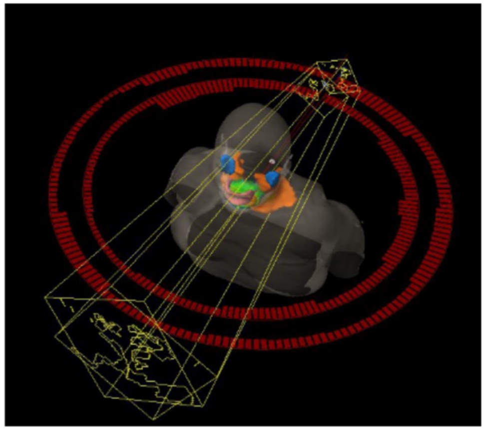
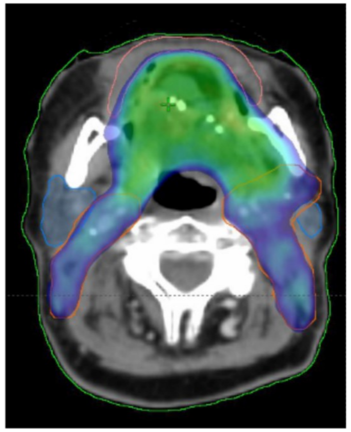
- **Aim:** obtain a 3D modelisation of the patient in the treatment position
- Simulation CT = reference image for the whole treatment



1. Simulation CT

- Contouring of reference volumes (GTV, CTV, PTV, OAR)
- Treatment planning
- Reference for image-guided radiotherapy (IGRT)

Sim-CT equipment

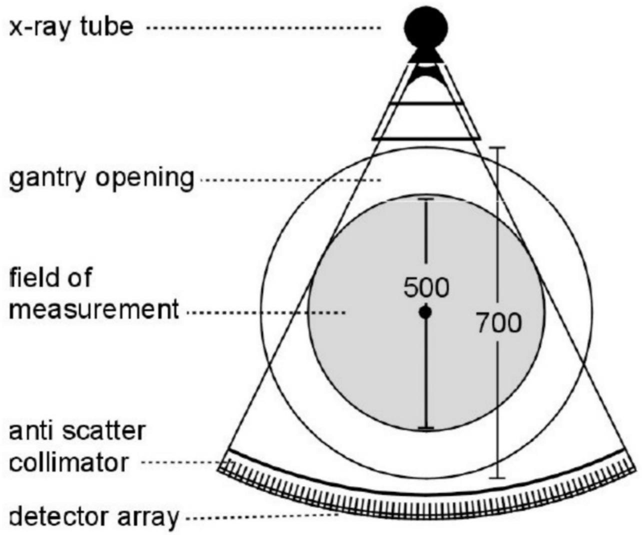
- Large bore
- Laser
- Flat table top
- Immobilization devices
- CT software with protocols
- Options: injector, gating device, optical surface monitoring system, etc

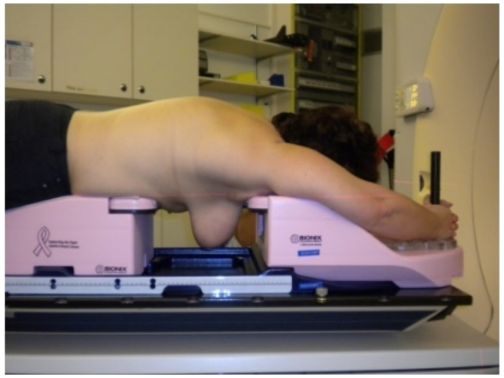
Large bore

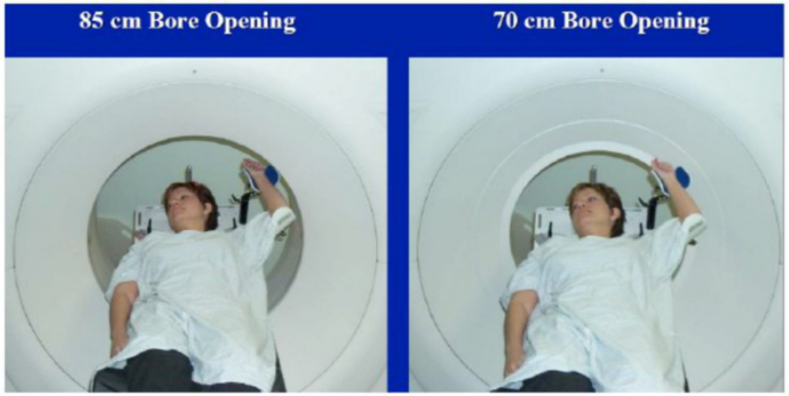
- At least 80 cm (up to 90 cm)

(diagnostic CT: 60-70 cm)

- Large FOV
- For the setup of adequate immobilization devices

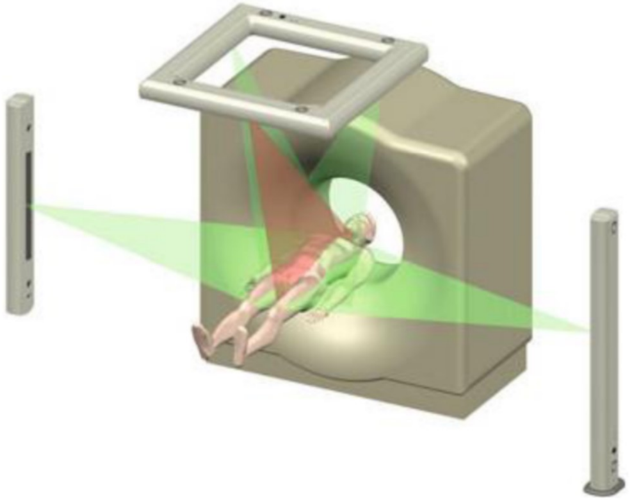


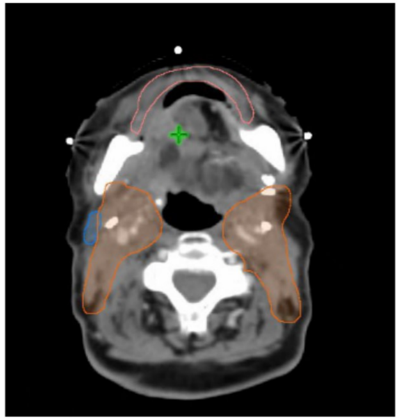


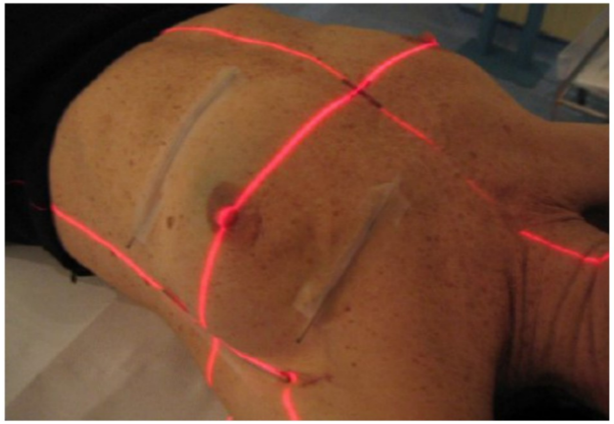


Laser

- In room laser (can be integrated to the CT itself)
- Intersect at the CT point of origin
- Radio-opaque markers used to localize CT point of origin
- Patient is tattooed at laser intersection





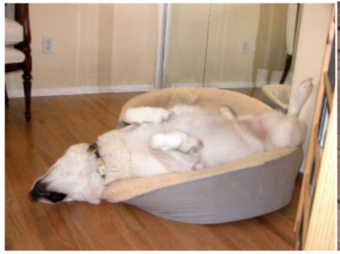


Table

- Flat (like the table in the treatment room)
- Usually in carbon
- Compatible with immobilization devices
- Indexed

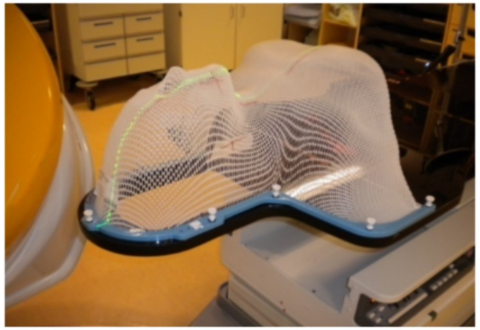
Immobilization devices

- Reference position must be **reproducible** and **comfortable**



Prostate (combifix + feet blocker)

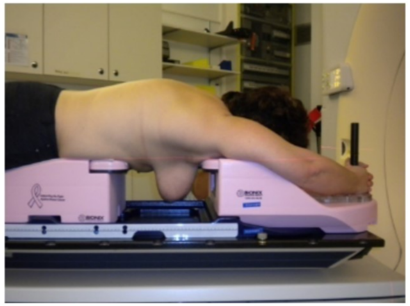
H&N mask (Brainlab 5 points)



Frameless mask (Brainlab)

Encompass open mask

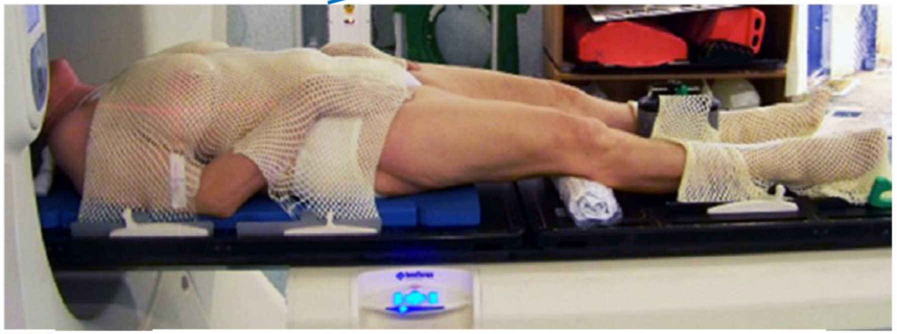
Breast, supine or prone devices



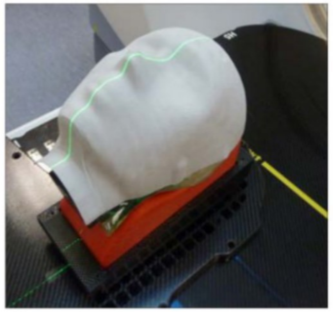
Immobilization devices

- Abdominal compression
- Thermoplastic masks for TMI immobilization
- 3D printed immobilization devices

Orfit system



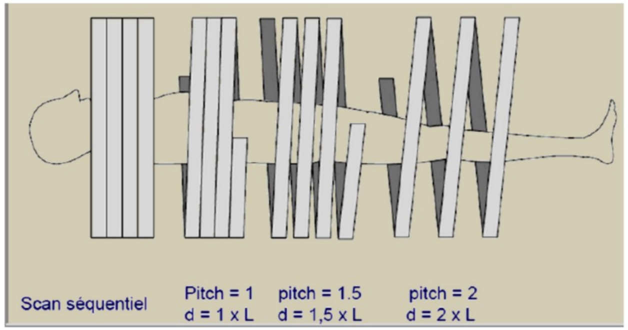
M. Zeverino et al. / Medical Dosimetry 37 (2012) 314-320



Evaluation of 3-D Printed Immobilisation Shells for Head and Neck IMRT

Mark Fisher*, Christopher Applegate[1], Mohammad Ryalat[1], Stephen Laycock[1], Mark Hulse[2], Daniel Emmens[2], Duncan Bell[1,2]

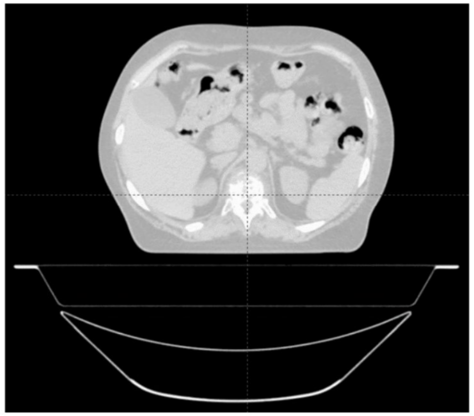
Acquisition parameters



- **Helicoidal** acquisition
- **Pitch** = table displacement in 1 rotation / beam collimation ≤ 1
- **Voltage**, kV: linked to energy and amount of X-ray, dose ~ kV^2, impacts the calibration curve, usually 120-140 kV, use lower kV for pediatric cases
- **Current (charge)**, mAs: linked to amount of X-ray, dose ~ mAs, to be optimized, use higher mAs for corpulent patient

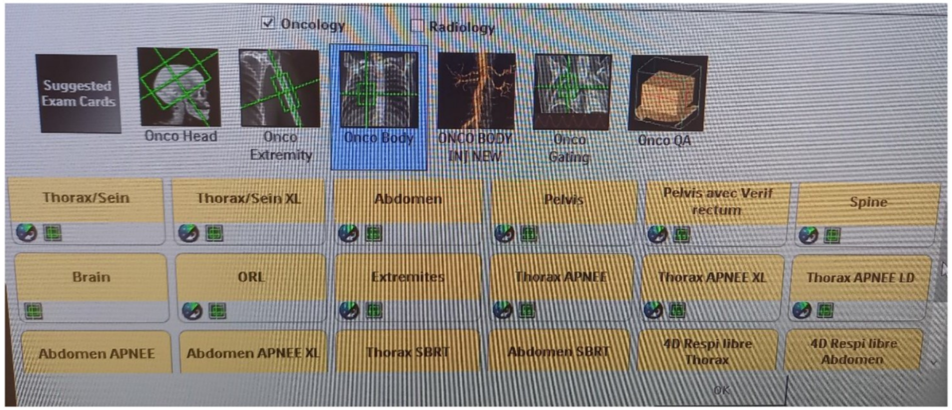
Acquisition parameters

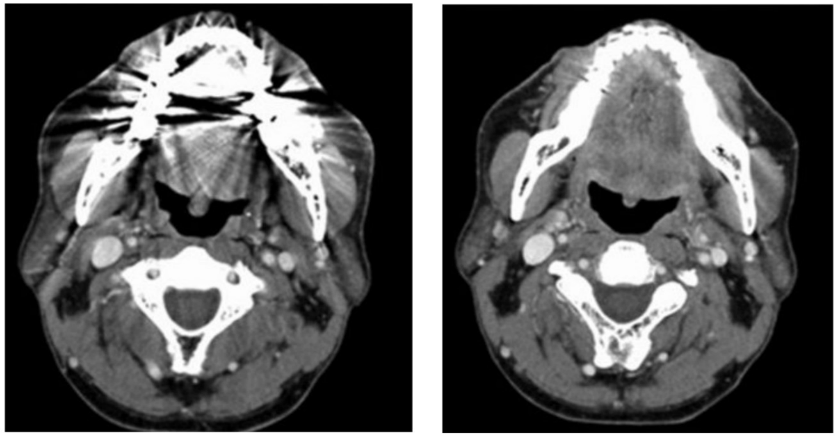
- **Rotation time** (fast or slow CT)
  E.g.: *Slow Thorax* (1.5 s) to get an image averaged over the respiratory cycle, or *DIBH breast* (0.5 s) to get a full CT in one breath hold
- **sFOV** (scanned field of view), table must be visible, axial resolution decreases if sFOV increases
- **Length**, to be optimized, include enough length above and below PTV for correct computation of scattering, include entire OAR (lungs, liver, etc.)
- **Collimation**, beam width at the detector level, impacts slice thickness (0.5 - 3mm), resolution and contrast



CT protocols

- Common protocols are defined and optimized at CT commissioning (calibration curve + dose estimation)
- Adapt protocols for new treatment modality or for special cases (e.g.: Calypso, stereotactic, pediatric cases)
- Use special reconstruction for metal artifact reduction (O-mar, Imar, SEMAR)

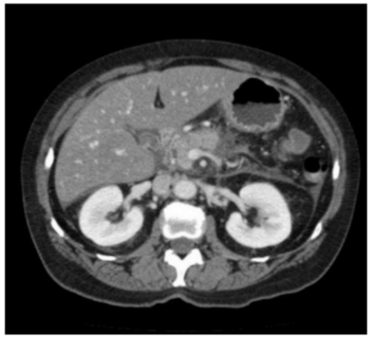




From Kubo et al. 2020

Options

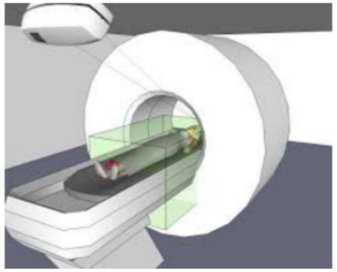
- **Contrast injection** (modifies the HU and the dose calculation)



- **4D** and **gated** CT (ITV definition, DIBH, etc.)

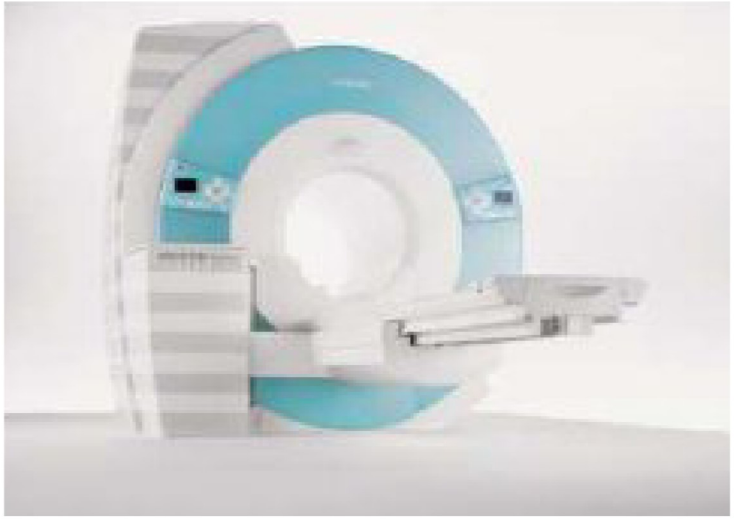
- **Dual energy CT** (dual-source, kV-switching, dual layer detector, better image quality)

- **Optical surface monitoring system** (acquire a reference image of the patient surface during CT)



Other simulation devices

- PET-CT simulation
- MRI simulation



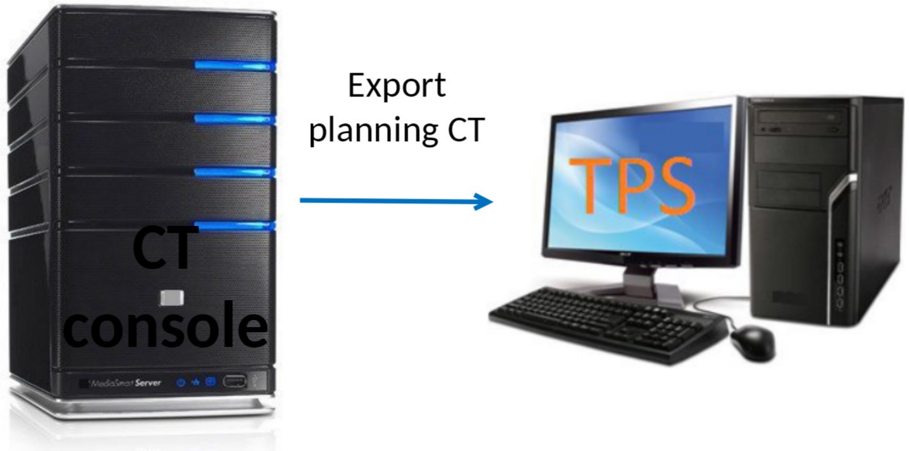
See also J.-F. Germond lecture

2. Treatment preparation

- CT data transfer
- Contouring and prescription → Topic 3
- Treatment planning/Delivery techniques
- Plan approval and transfer to R&V system
- Patient specific quality assurance → Topic 4

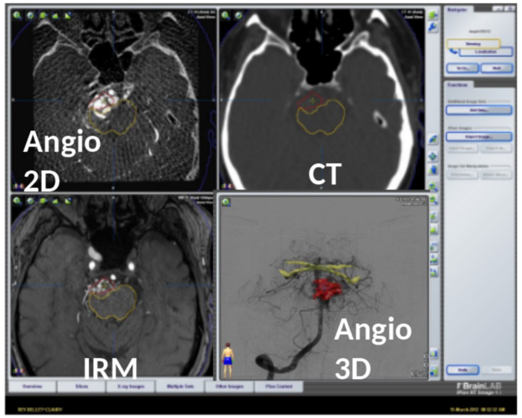
Data transfer

- Once the simulation CT is reconstructed, transfer the images to the contouring software (Eclipse, Velocity, Pinnacle, RayStation, Iplan, etc.)
- DICOM compatibility is necessary
- Also transfer the setup notes, gating parameters, etc. in the patient file



Contouring

- With or without other imaging modality (CT, MRI, PET, angio, etc.)
- Variations in target delineation (inter and intra-observer) is well-documented and measurable
- Can be larger than set up uncertainties
- Image-modality dependent
- Can be reduced by strict contouring guidelines



8X. A. Li, A. Tai, D. W. Arthur, T. A. Buchholz, S. Macdonald, L. B. Marks, J. M. Moran, L. J. Pierce, R. Rabinovitch, A. Taghian, F. Vicini, W. Woodward, and J. R. White, "Variability of target and normal structure delineation for breast cancer radiotherapy: An RTOG multi-institutional and multiobserver study," Int. J. Radiat. Oncol., Biol., Phys. 73, 944–951 (2009).
9A. C. Riegel, A. M. Berson, S. Destian, T. Ng, L. B. Tena, R. J. Mitnick, and P. S. Wong, "Variability of gross tumor volume delineation in head-and-neck cancer using CT and PET/CT J. Radiat. Oncol., Biol., Phys. 65, 726–732 (2006).

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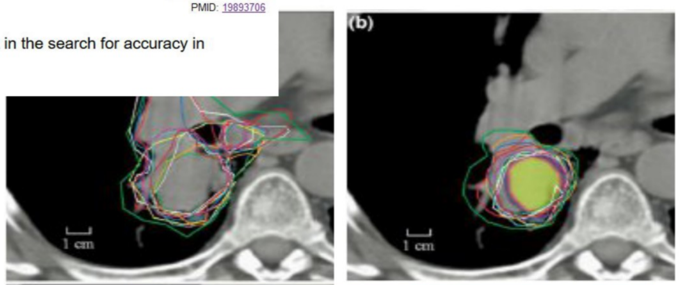
J Med Phys. 2008 Oct-Dec; 33(4): 136–140. PMCID: PMC2772050
doi: 10.4103/0971-6203.44472 PMID: 19893706

Tumor delineation: The weakest link in the search for accuracy in radiotherapy

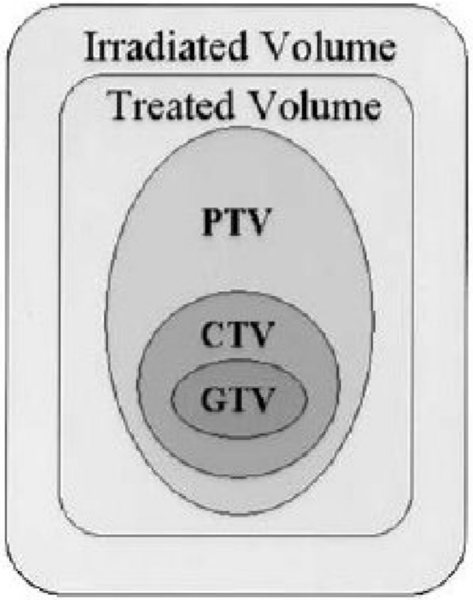
C. F. Nieh



CT delineations of 11 radiation oncologists
Steenbakkers et al - Radiother Oncol 2005 77:182-190

Contouring

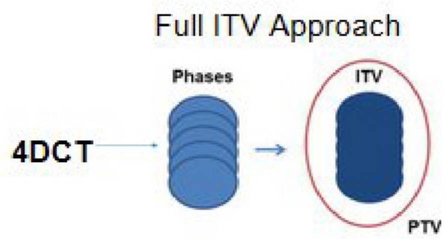
- **GTV** (gross tumoral volume): clinically visible tumor extension
- **CTV** (clinical target volume): includes infra-clinical extensions
- **PTV** (planning target volume): geometric concept, safety/setup margin aiming to ensure that the CTV is treated with the correct dose.
- Note: CTV-PTV margins depends on immobilization devices, localization, IGRT, irradiation technique (≈ 1 mm-1 cm)



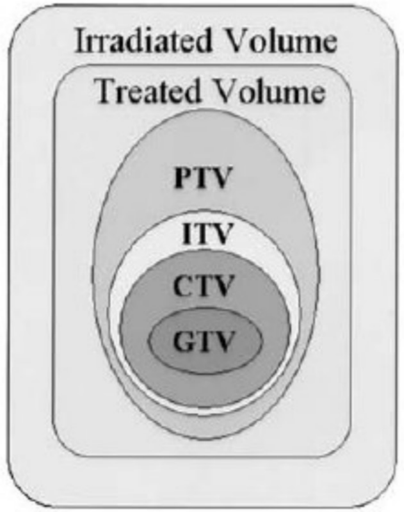
(B) ICRU 50

Contouring

- **ITV** (internal target volume), accounts for GTV/CTV motion
- **OAR** (organ at risk), must be delineated in order to be avoided in the planning process. Must be contoured entirely if you are interested in volumetric dose constraint (e.g. V_{5Gy}<60%)
- **PRV** (planning organ at risk volume), similar to a PTV for OAR, usually used for max dose objectives



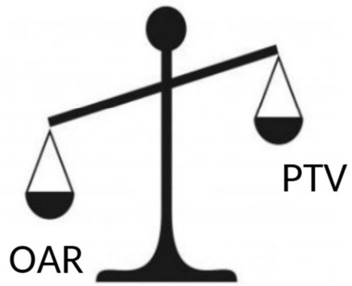
From Prusator et al.

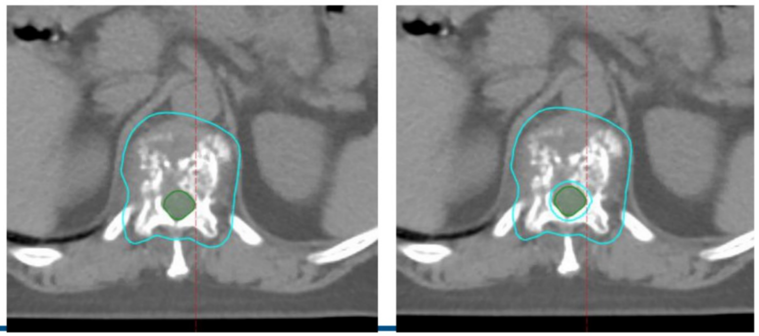


(C) ICRU 62

Medical prescription

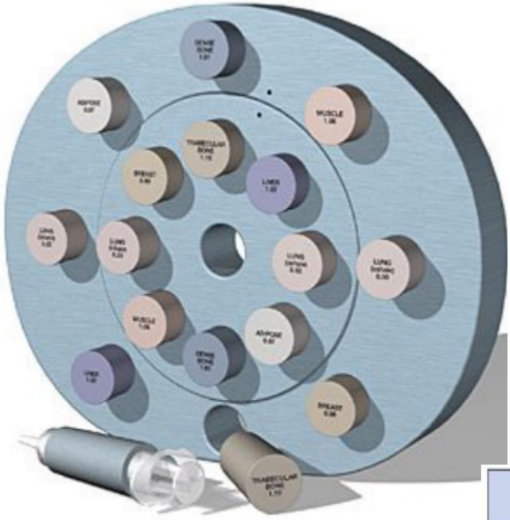
- Dose and fractionation to the PTV
- Frequency
- Dose constraints on PTV, OAR and PRV
- If PTV and OAR constraints are in contradiction, specify what is priority: PTV coverage or OAR sparing
- IGRT (e.g. CBCT every day)



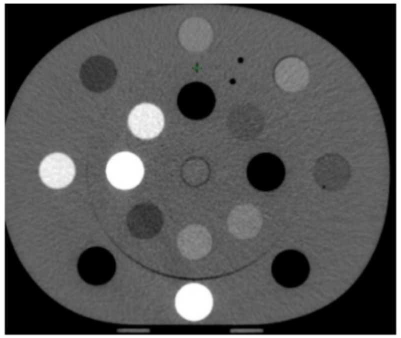


CT calibration curve

- For dose calculation, we need to transform the grey values of the CT (HU) into physical or electron densities
- Use a calibration phantom
- Scan the phantom with inserts of known density with a given CT protocol



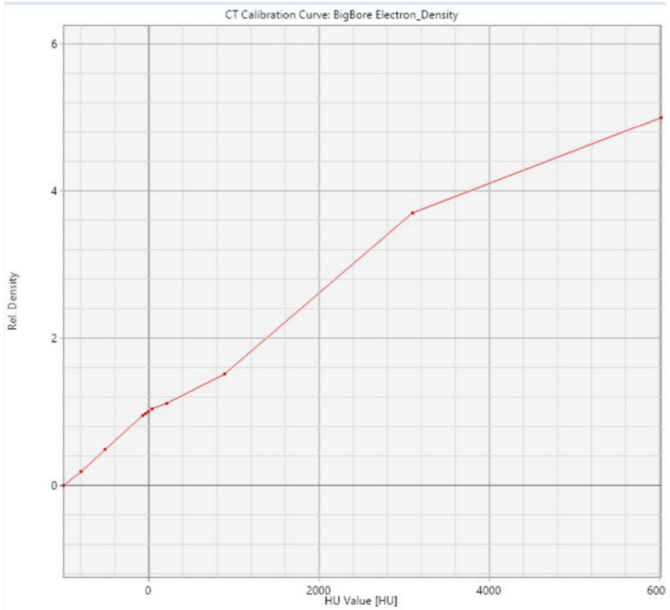
Electron density phantom (CIRS 602)



	Model 062 Includes Quantity	Physical Density	Electron Density Per cc X 10^{23}	RED (Relative to H_2O)
PHANTOM HEAD PHANTOM BODY (water equivalent)	1 1	1.01	3.346	1.002
INSERTS				
SYRINGE H_2O	1	1.00	3.340	1.000
Lung (Inhale)	2	0.20	0.634	0.190
Lung (Exhale)	2	0.50	1.632	0.489
Adipose	2	0.96	3.170	0.949
Breast (50/50)	2	0.99	3.261	0.976
Muscle	2	1.06	3.483	1.043
Liver	2	1.07	3.516	1.052
Trabecular Bone	2	1.16	3.730	1.117
*Dense Bone 800mg/cc	2	1.61	5.052	1.512
Distance Marker	2	1.01	-	-
*Dense Bone 1000mg/cc	Optional	1.66	5.243	1.570
*Dense Bone 1250mg/cc	Optional	1.83	5.718	1.712
*Dense Bone 1500mg/cc	Optional	2.00	6.209	1.859
*Dense Bone 1750mg/cc	Optional	2.17	6.698	2.005
Titanium	Optional	4.51	12.475	3.735

CT calibration curve

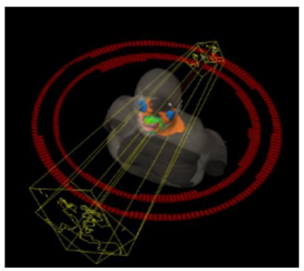
HU Value [HU]	Rel. Density
-1000.000	0.000
-794.000	0.190
-511.000	0.489
-71.000	0.952
-37.000	0.976
-7.000	1.000
39.000	1.043
49.000	1.052
213.000	1.117
888.000	1.512
3095.000	3.700
6018.000	5.000

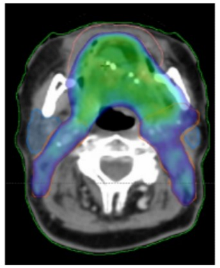


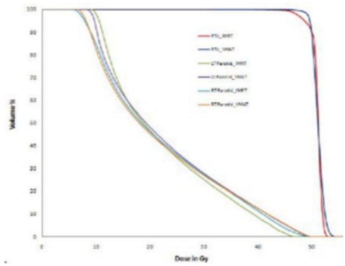
- Associate grey levels with densities

  → calibration curve
- Treatment planning will be discussed later

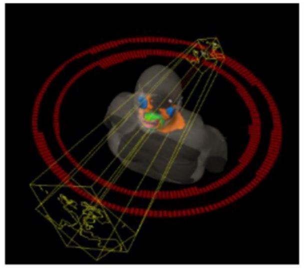
  Aim: maximize TCP and minimize NTCP

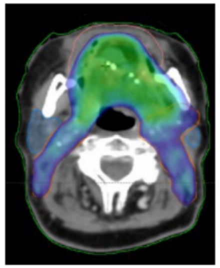


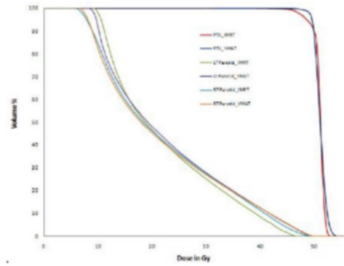




Plan approbation





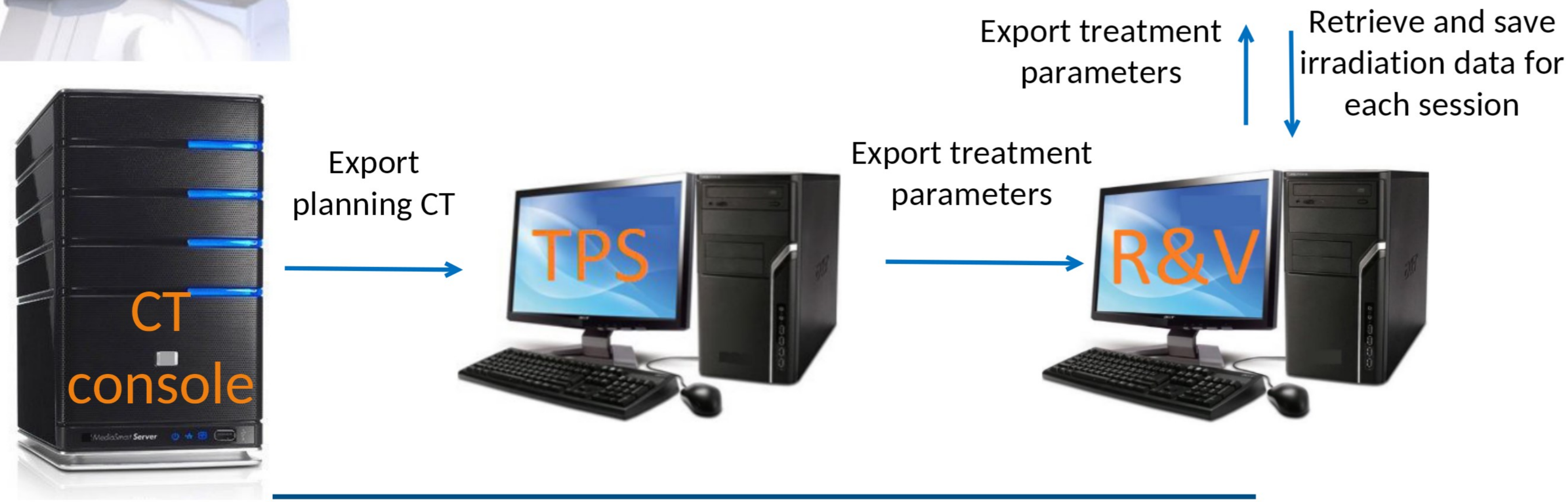


- Planning is performed by physicist or dosimetrist
- Plan is reviewed by radiation oncologist
- Final check of the plan is performed by physicist and the plan is approved (make deliverable at the treatment machine)
- PSQA is prepared and performed (dosimetrist, physicist, RTT) → Topic 4

Record and Verify (R&V)

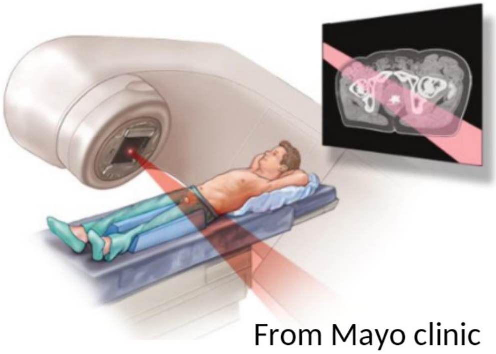
- Treatment parameters are transferred to the treatment machine via the R&V system (Mosaiq, Aria, RayCare, etc.)
- The R&V checks if treatment is allowed, and retrieves and saves treatment data for each RT session
- Essential to ensure safety

Record and Verify (R&V)



3. Treatment delivery techniques

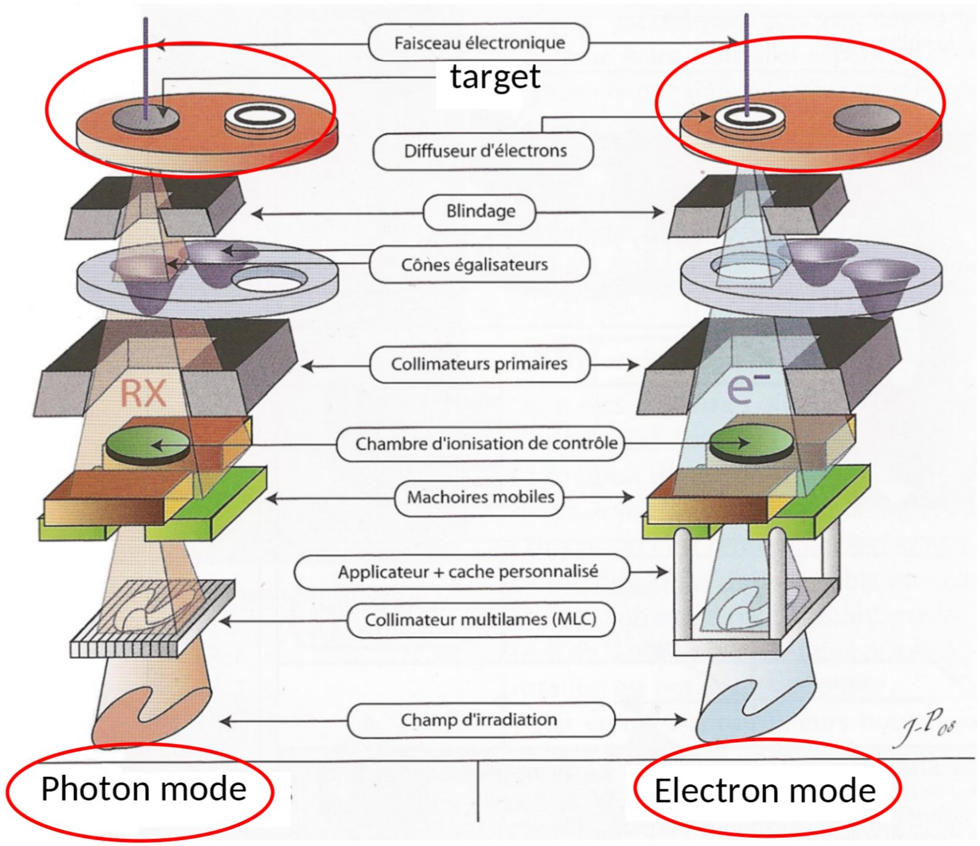
- External beam radiotherapy (EBRT)
- Delivered by a C-arm linac
- Not considered here:
  - Brachytherapy
  - Intra-operative RT
  - Superficial X-ray
  - Gammaknife
  - Halcyon
  - Tomotherapy, CyberKnife
  - Vero
  - Proton or heavy ion therapy



From Mayo clinic

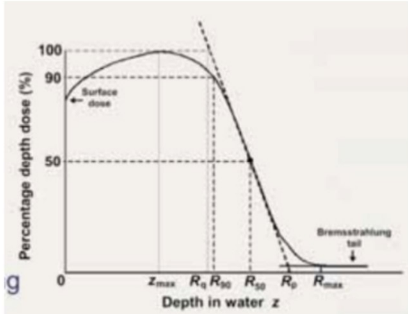
Photons or electrons beams

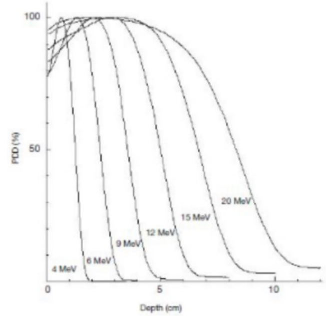
- The linac accelerates electrons
- Either use the beam directly → **electron mode**
- Or convert it with a target into X-ray → **photon mode**
- Photon mode can be with or without flattening filter (FFF)
- Beam energy between 4-25 MeV
- See lecture from U. Schneider on Beam Shaping



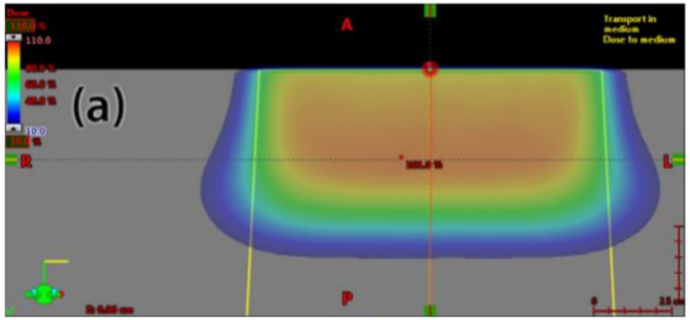
Electron delivery

- For superficial targets
- Therapeutic range: R_{80} [cm] ≈ E [MeV] /3 or R_{90} [cm] ≈ E [MeV] /4
- Single field with applicator and customized-field shaper
- With or without planning CT



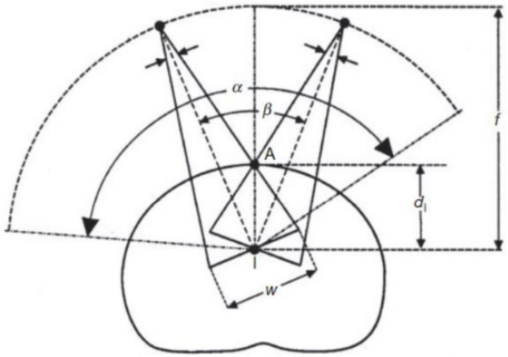


From Podgorsak, Radiation Oncology Physics: a handbook for teachers and students

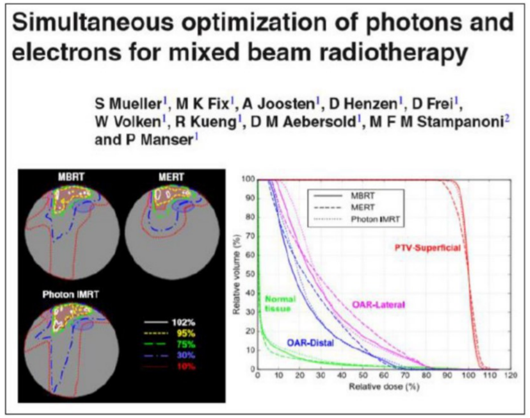


Electron delivery

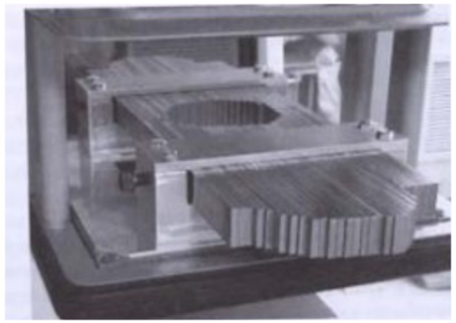
- Much less standard:
  - Electron arc therapy (rotational)
  - Modulated electron RT (MERT or IMET) (with a specific MLC)
  - Mixed beam RT (MBRT), combination of photon and electron beams



From Podgorsak, Radiation Oncology Physics: a handbook for teachers and students



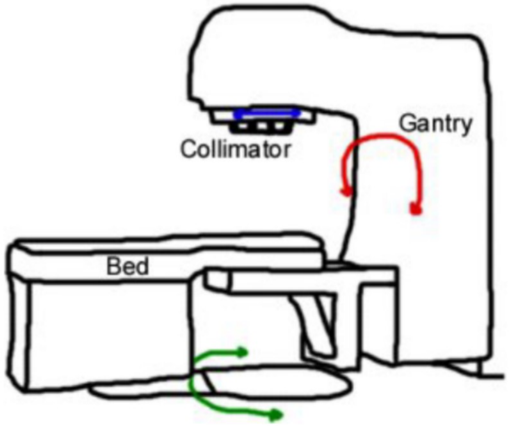
Phys. Med. Biol. 62, 5840-5860, 2017

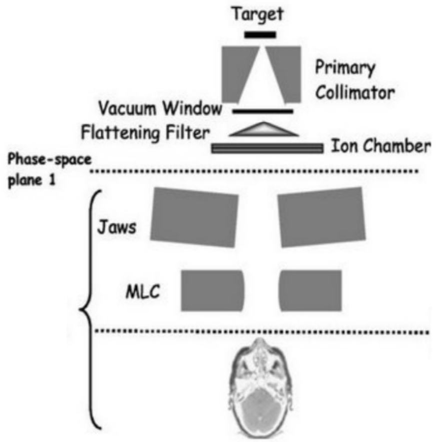


Electron MLC
From Ma et al., 2000

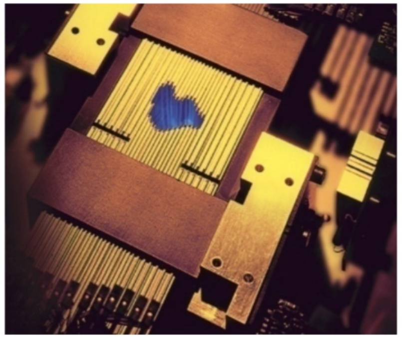
Photon delivery

- Beam ballistic defined by
  - Gantry angle
  - Collimator angle
  - Table angle
- Beam is shaped by:
  - Jaws
  - Blocks (less and less)
  - Multi-leaf collimator (2.5 mm to 1 cm)
  - SRS cones

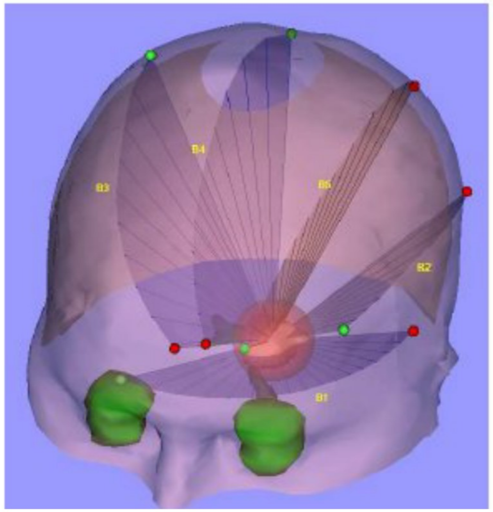


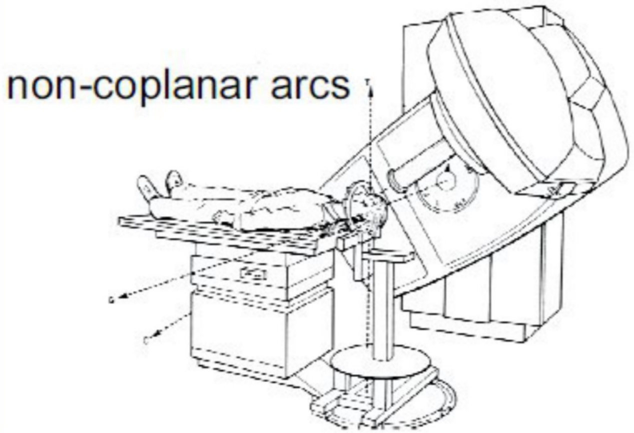


Chetty et al, Med Phys, 2008



SRS cones





Photon delivery

- Delivery techniques
  - 3D conformal
  - (Dynamic) conformal arc

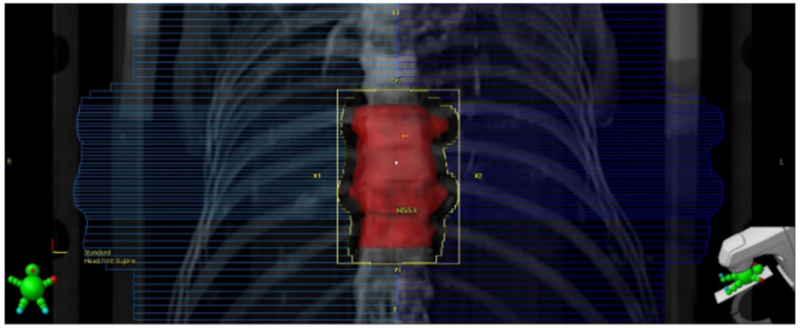
  Unmodulated techniques

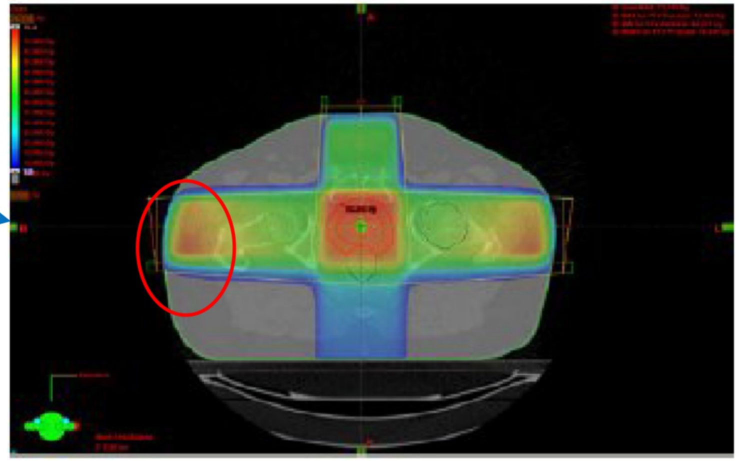
  - Intensity modulated radiotherapy (IMRT)
  - Volumetric modulated arc therapy (VMAT)

  Modulated techniques
  → Need for patient specific quality assurance with a measurement (Topic 4)

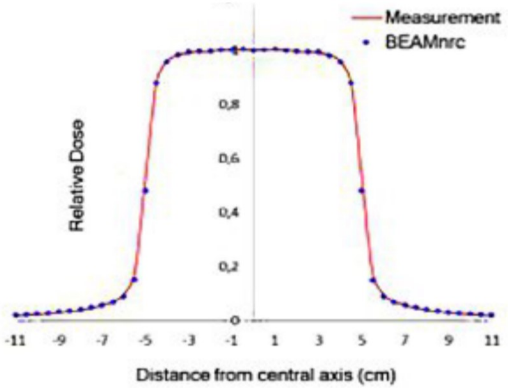
3D conformal

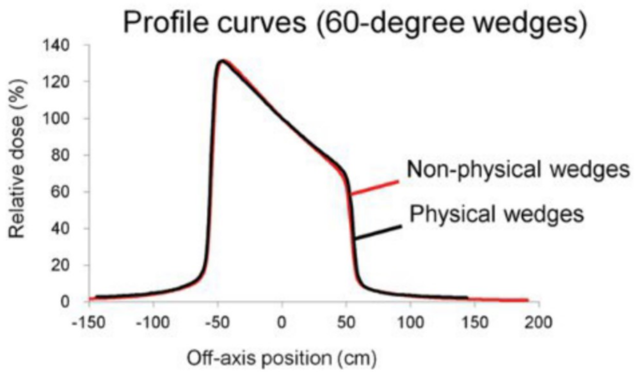
- Everything is fixed during delivery
- Each beam is shaped with MLC
- With flattened filter beams
- With or without wedge filters





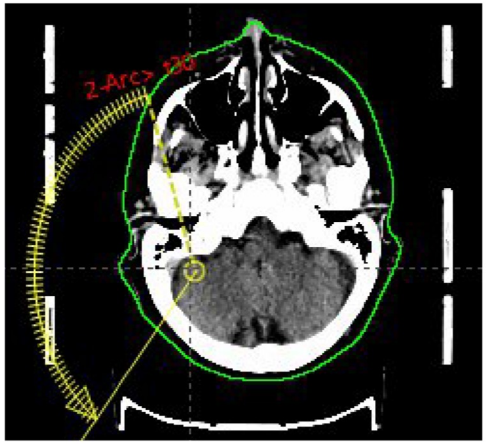
Ex: Prostate 3D conformal treatment planned with 4 beams and 2 wedge filters

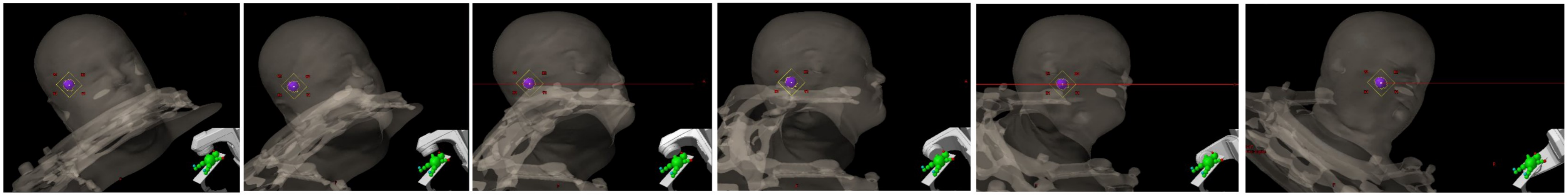




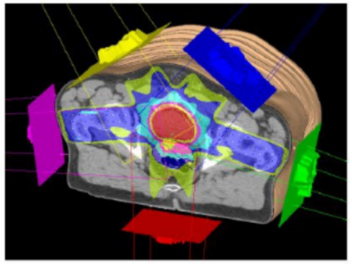
(Dynamic) Conformal arc RT

- Rotational technique (gantry, variable speed)
- Dynamic: MLC continuously adapts its shape to the target volume
- No beam modulation

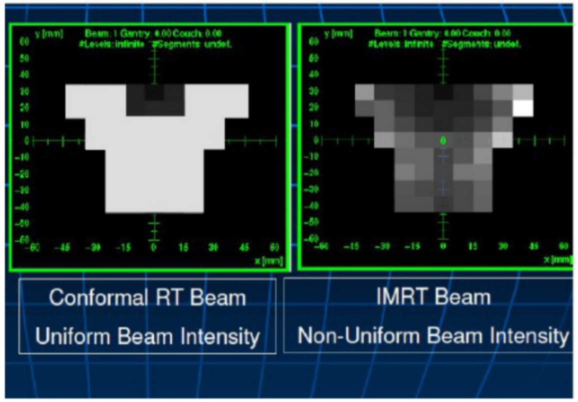




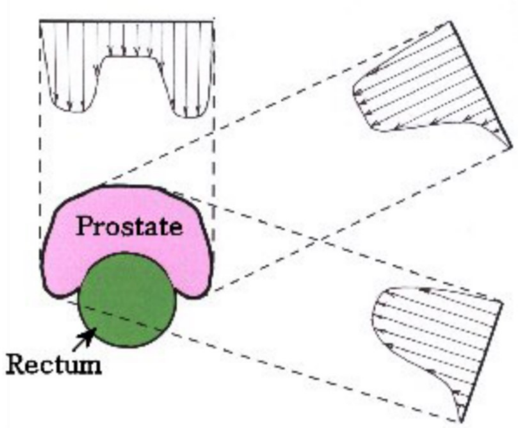
IMRT



- Gantry and collimator are fixed
- Modulated technique, use of multiple MLC-shaped beam segments, the total dose will be the sum of these resulting in a non-uniform intensity
- Allows for concave dose distribution and better OAR sparing

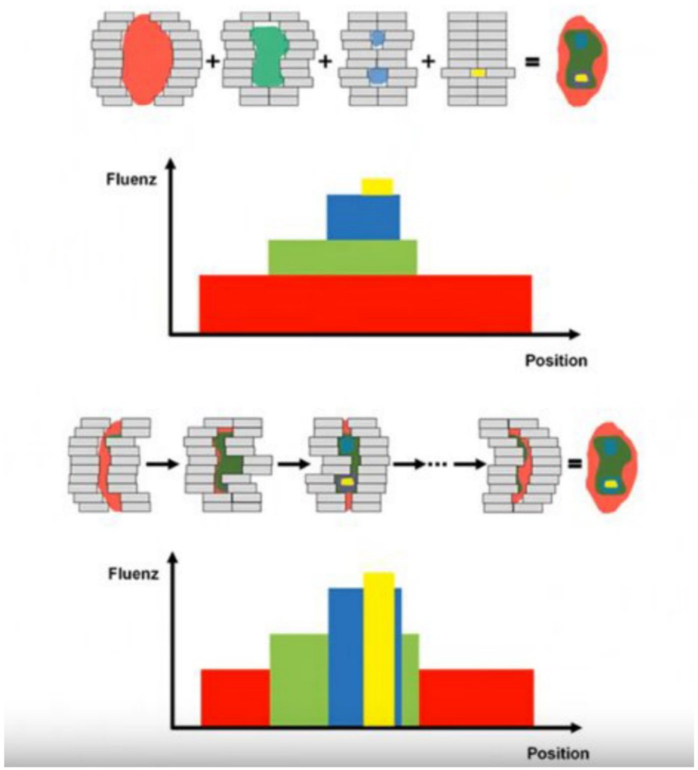


From M. Gubanski 2014



IMRT

- Two types of delivery
  - Step and Shoot (fixed MLC during delivery)
  - Sliding window (MLC moves during delivery, variable speed)

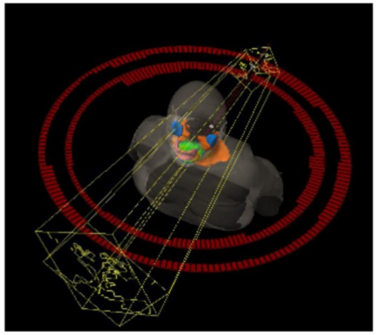


- Dose-rate can also vary
- With or without flattening filter

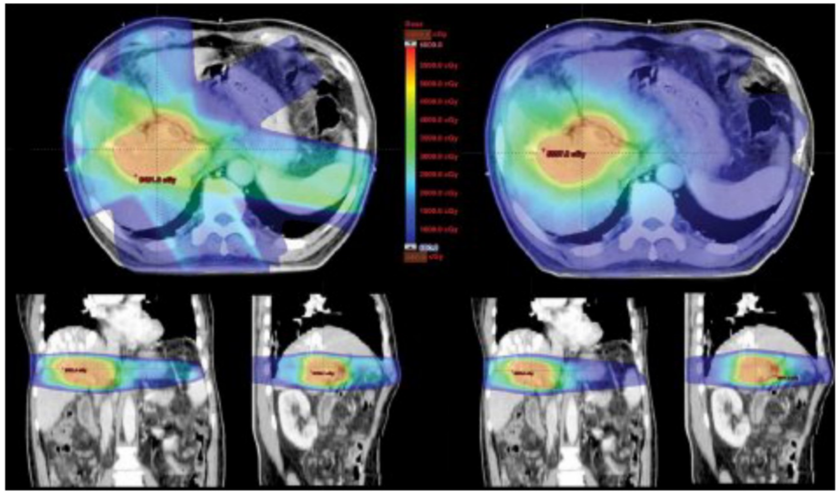
From Tumor target therapy, Prof. Vorwerk.
https://www.youtube.com/watch?v=3FZs1B3gjO0

VMAT

- Rotational technique (gantry rotates around patient, variable speed)
- Modulated technique
- MLC moves during delivery (variable speed)
- Jaws can also move (jaw tracking)
- Dose-rate can also vary
- With or without flattening filter



Ex: H&N VMAT treatment with 2 full arcs



IMRT *vs*. VMAT

Clinical impact of modulated therapy

- More conformality
- Concave shape
- Planning of simultaneous integrated boost (SIB)
- Aim is always to maximize TCP and minimize NTCP

Clinical Oncology 22 (2010) 643–657

Contents lists available at ScienceDirect

Clinical Oncology

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journal homepage: www.elsevier.com/locate/clon

Overview

A Review of the Clinical Evidence for Intensity-modulated Radiotherapy

J. Staffurth on behalf of the Radiotherapy Development Board[1]

Cardiff University, Velindre Hospital, Whitchurch, Cardiff, UK

of 61 identified comparative studies only 6 randomized

Only 2014 patients randomized (1809 of these breast)

Toxicity significantly lower in IMRT

Not enough power to detect differences in tumor control

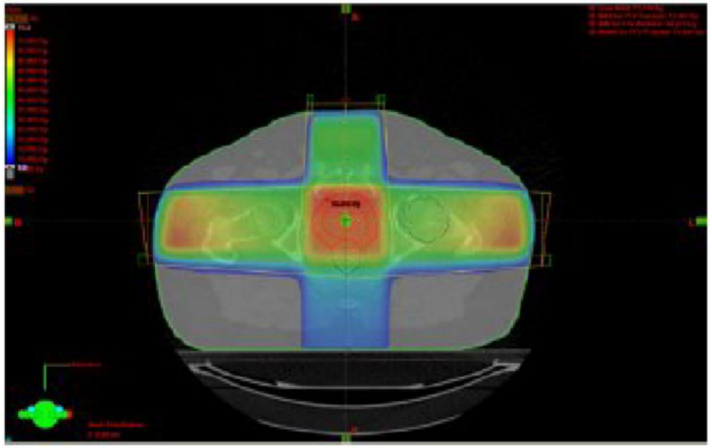
From M. Gubanski 2014

4. Patient specific quality assurance

- Planning verification for simple/unmodulated treatments
- Principles and legal aspects of PSQA
- PSQA measurements for complex treatments
- PSQA workflow
- Example of measurements devices

Simple treatments verification

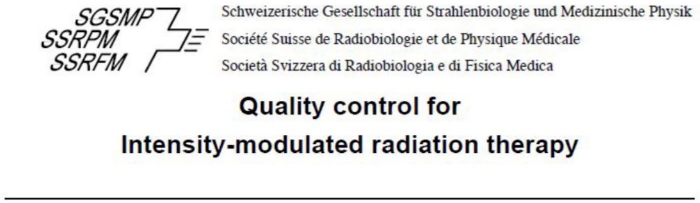
- For 3D treatments, an independent dose calculation (± in-vivo dosimetry) is considered a sufficient verification
- Independent calculation of MU performed with a dedicated software (commercial or in-house developed)



$$UM = \frac{D(z,c,f_R,w)}{\frac{D_R}{UM_R} \cdot FOC(c) \cdot k_w(z,c) \cdot k_t(c) \cdot k_b(c,s_b) \cdot RTM(z,s_b)}$$

Principles and legal aspects

- PSQA measurement is necessary for **complex treatments** (modulated treatments
  e.g. IMRT, VMAT)
- SSRMP recommendation n°15:

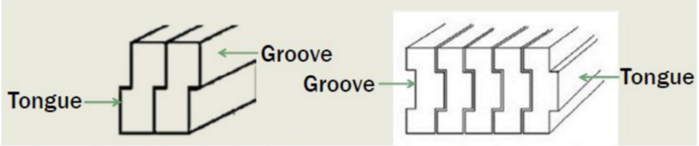

SGSMP SSRPM SSRFM
Schweizerische Gesellschaft für Strahlenbiologie und Medizinische Physik
Société Suisse de Radiobiologie et de Physique Médicale
Società Svizzera di Radiobiologia e di Fisica Medica

Quality control for
Intensity-modulated radiation therapy

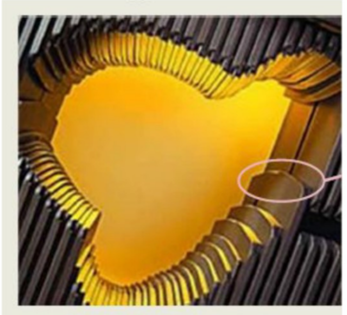
"Patient specific dosimetry should be performed for each individual treatment plan. Such a dosimetric verification involves the **measurement of dose distributions** in a phantom and the **measurement of the absolute dose** for a representative point"

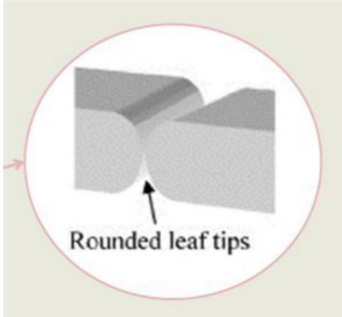
→ Compare TPS calculation and measurements for every plan of every patient

PSQA meas. For complex treatments

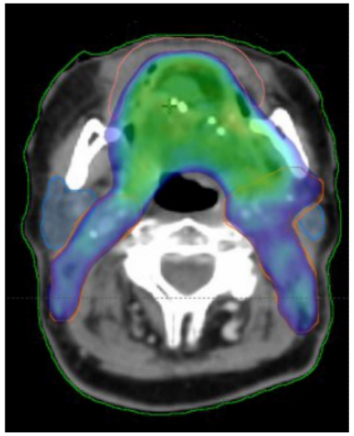


- MU-dose relationship not intuitive
- Plan made of many (small field) MLC segments, more complex dose calculation (leaf positioning and speed, transmission, tongue and groove, dosimetric leaf gap, small field dosimetry)
- Impact of mechanical accuracy of the linac (gantry, collimator, table, MLC, typically <1 mm and 1°)
- Impact of beam stability (for step-and-shoot IMRT), low MU field lead to short beam-on times, beam output, flatness and symmetry can be unstable at start up)



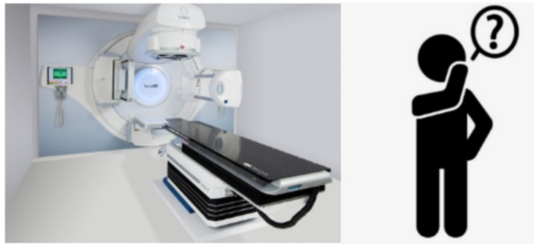


PSQA workflow



In the TPS

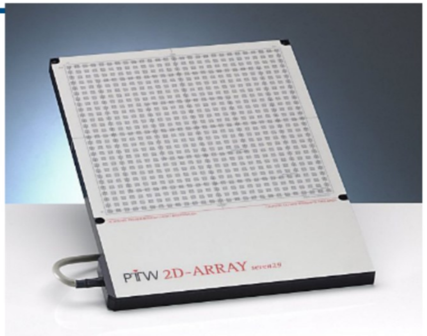
- The dose computed by the TPS might not be the dose actually delivered by the linac
- Solution: check the dose distribution with a measurement
- **Workflow:**
  - A. Prepare PSQA on the TPS
  - B. Deliver the treatment at the machine on the measurement device
  - C. Analyze the result and make a decision about the clinical use of the plan



In real life ?

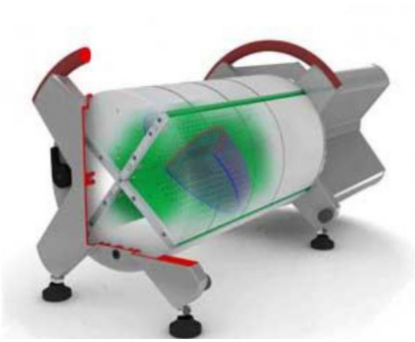
2D measurements devices

- Ionization chambers arrays (liquid or air-filled)
- Diodes arrays
- Gafchromic film
- EPID



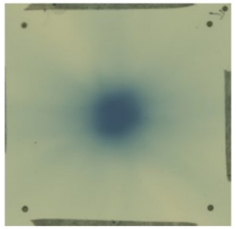
2D-ARRAY 729 (PTW)
27x27 ionization chambers
Meas. field: 27x27 cm^2

Octavius phantom (PTW)

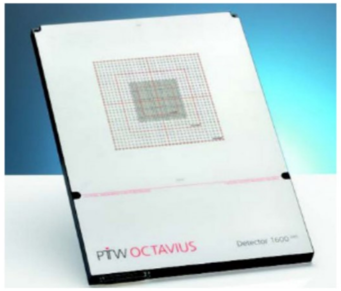


Delta4 (ScandidDos)
1069 diodes

EPID dosimetry



Gafchromic XD films (Ashland)



1600 SRS array(PTW)
27x27 liquid-filled ionization chambers
Meas. field: 15x15 cm^2

Parameters of 2D devices

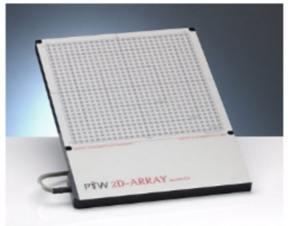
- Calibration (absolute dose or cross calibration)
- Detector resolution
- Detector size
- Size of measurement area
- Energy dependence
- Dose-rate dependence
- Directional dependence

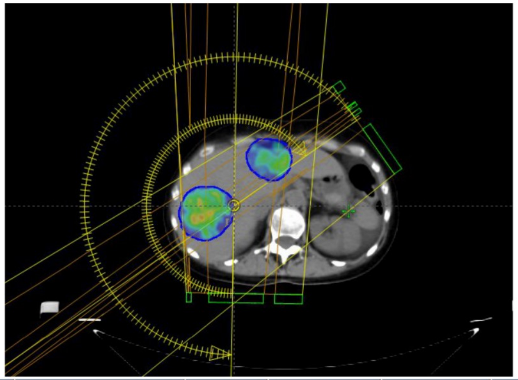
> Choose the material depending on the specificity of the plan to check !

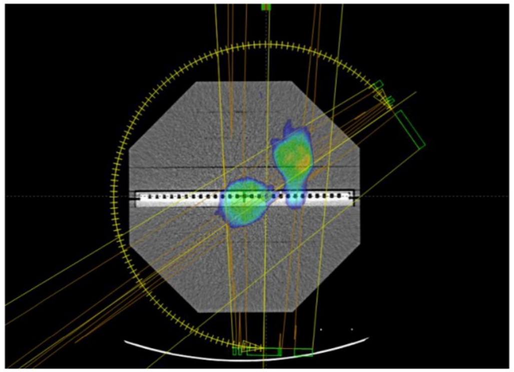
A. Prepare PSQA on the TPS

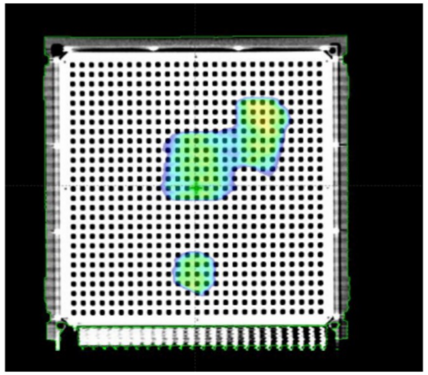
- Plan is copied to the measurement device
- Plan dose is recalculated
- Calculated dose is exported

E.g.: Liver treatment (5x6 Gy) with 2 VMAT arcs, PSQA with 2D-array and Octavius phantom (PTW)









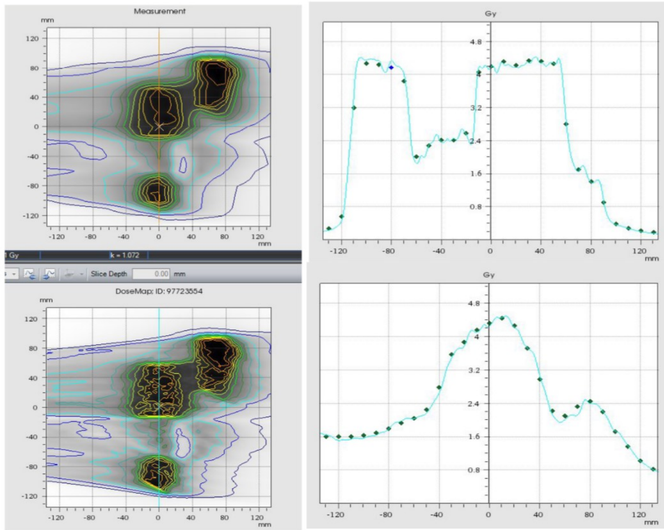
Field ID	Technique	Machine/Energy	MLC	Field Weight	Scale	Gantry Rtn [deg]	Coll Rtn [deg]	Couch Rtn [deg]	Wedge	Field X [cm]	X1 [cm]	X2 [cm]	Field Y [cm]	Y1 [cm]	Y2 [cm]	X [cm]	Y [cm]	Z [cm]	Calculated SSD [cm]	MU
2_55_181_Hyp	SRS ARC-I	BLUE_3826 - 6X-FFF	VMAT	1.948	Varian IEC	55.0 CCW 181.0	330.0	0.0	None	12.0	+6.0	+6.0	22.0	+11.0	+11.0	3.00	0.00	0.00	85.9	1123.6
1_181_55_Hyp	SRS ARC-I	BLUE_3826 - 6X-FFF	VMAT	1.899	Varian IEC	181.0 CW 55.0	30.0	0.0	None	12.0	+6.0	+6.0	22.0	+11.0	+11.0	3.00	0.00	0.00	83.9	1095.8

B. Deliver treatment plan

- Phantom with measurement device is positioned at the treatment machine
- Patient treatment plan is delivered exactly as it will be treated
- Alternatively, plan is delivered with gantry, collimator or table set to 0°
- PSQA is time consuming! have dedicated reserved time-slot at the machine…

C. Analysis

- Measured and calculated dose distribution are compared
- Many methods exist (γ **analysis**, dose differences, normalized agreement test, gradient, etc.)
- Ideally: evaluate the clinical impact on treatment

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Review paper

Treatment plan verification: A review on the comparison of dose distributions

Stefanos Diamantopoulos[a,*], Kalliopi Platoni[a], Georgios Patatoukas[a], Pantelis Karaiskos[b], Vassilis Kouloulias[a], Efstathios Efstathopoulos[a]

31 comparison methods

Gamma analysis for dose comparison

- Gamma index γ computed for each pixel (Low et al. Med Phys 1998), combines:
  - *r* or *DTA*: **distance to agreement**, for high gradient dose regions
  - δ or *DD*: **dose difference** in one pixel, for low gradient dose regions
- Δd_M : tolerance on DTA (mm)
- ΔD_M :tolerance on DD (dose %)
- Allows more dose differences in high gradient regions

$$\gamma(\mathbf{r}_m) = \min\{\Gamma(\mathbf{r}_m, \mathbf{r}_c)\} \forall \{\mathbf{r}_c\},$$

where

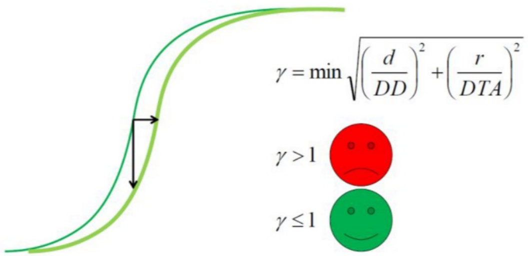
$$\Gamma(\mathbf{r}_m, \mathbf{r}_c) = \sqrt{\frac{r^2(\mathbf{r}_m, \mathbf{r}_c)}{\Delta d_M^2} + \frac{\delta^2(\mathbf{r}_m, \mathbf{r}_c)}{\Delta D_M^2}},$$

$$r(\mathbf{r}_m, \mathbf{r}_c) = |\mathbf{r}_c - \mathbf{r}_m|,$$

and

$$\delta(\mathbf{r}_m, \mathbf{r}_c) = D_c(\mathbf{r}_c) - D_m(\mathbf{r}_m)$$

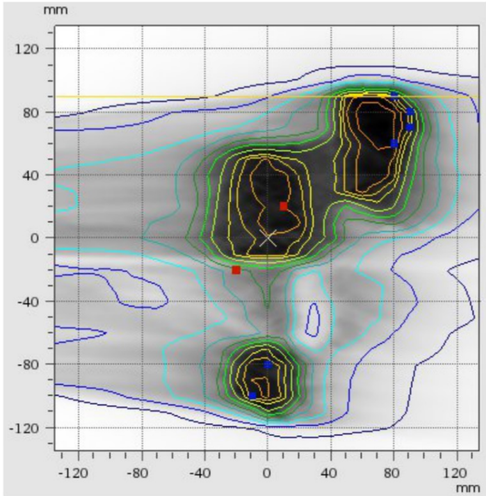
Computed Dose   Measured Dose



From T. Depuydt 2014

Gamma analysis for dose comparison

- Choose γ criteria: e.g.: 2%/2mm, 3%/3mm, 3-5%/1mm (SRS), etc.
- Local or global dose (for dose % calculation)
- Obtain a γ map with failed points
- Typically a plan is accepted if more than 90-95% of points have γ <1



Decision

- If PSQA measurement is satisfying→ final acceptation of the plan for treatment
- If differences are too important:
  - Check measurement setup
  - Check the appropriateness of the measurement device
  - Replan! (complexity, linked to MU numbers, is often associated with worse PSQA results)

SWISS MEDICAL NETWORK

5. Daily imaging verification and setup corrections

GÉNÉRALE-BEAULIEU
Swiss Radio Oncology Network

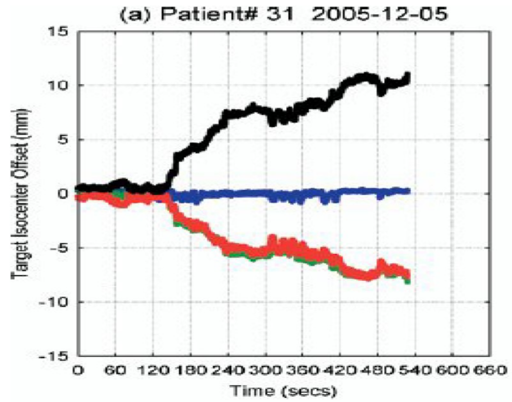
- Treatment plan is ready and verified, we want to deliver it to the patient
- We want to verify that we deliver the plan at the correct location

- Inter and intrafraction motions
- IGRT, definition, systems and examples
- Random and systematic setup errors
- Clinical use and impact of IGRT

Inter and intrafraction motion

- **Interfraction motion**: day-to-day variation in the patient setup
- **Intrafraction motion**: variation in setup happening during the session
- In this section, we focus on inter-fraction motion and its correction

e.g., day-to-day variation of prostate position



e.g. prostate drift during RT session,
Kupelian et al., IJORPB 2007

Image guided radiotherapy (IGRT)

- IGRT is the use of imaging in the course of RT treatment, in particular before (for interfraction motion correction) or during (for intrafraction correction) the RT session, with the aim of improving precision of treatment delivery
- Principle: we want the patient image at the linac to be similar to the planning image
- Aim: deliver the dose at the correct location
  - Margin reduction (ITV or PTV)
  - Reduce risk of target geometrical miss
  - Dose-escalation
  - Toxicity reduction

IGRT systems characteristics

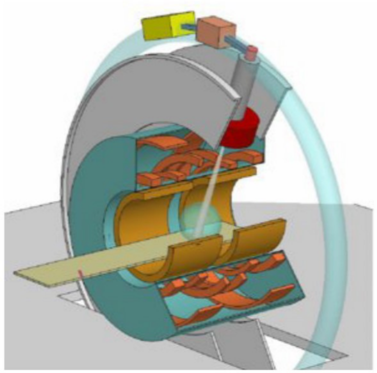
- 2D/3D imaging
- Ionizing radiation or not, if yes, acquisition dose can vary, IGRT dose must be documented
- Acquisition time, continuous or not
- Soft tissue visualization or not
- Integrated to the treatment machine or not
- Most systems can be used both for daily setup (interfraction motion control) or for intrafraction motion control

IGRT systems

- 2D MV imaging
- 2D kV imaging
- kV-CBCT → 3D imaging

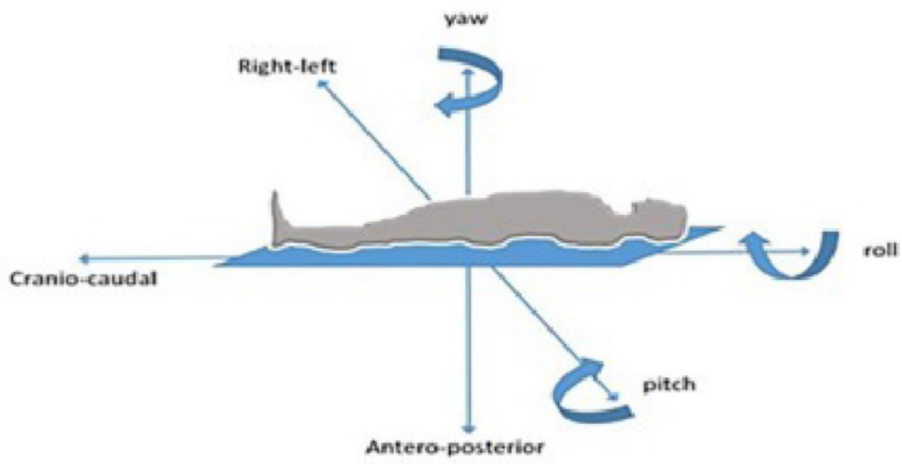
Standard systems on a C-arm linac

- Ultrasound (Clarity), radiofrequency localization (Calypso), optical/infra-red surface monitoring
- Independent stereo-kV (ExacTrac, Cyberknife), MV-CBCT (Halcyon), MVCT (Tomotherapy), MRI, CT, PET-CT, etc.



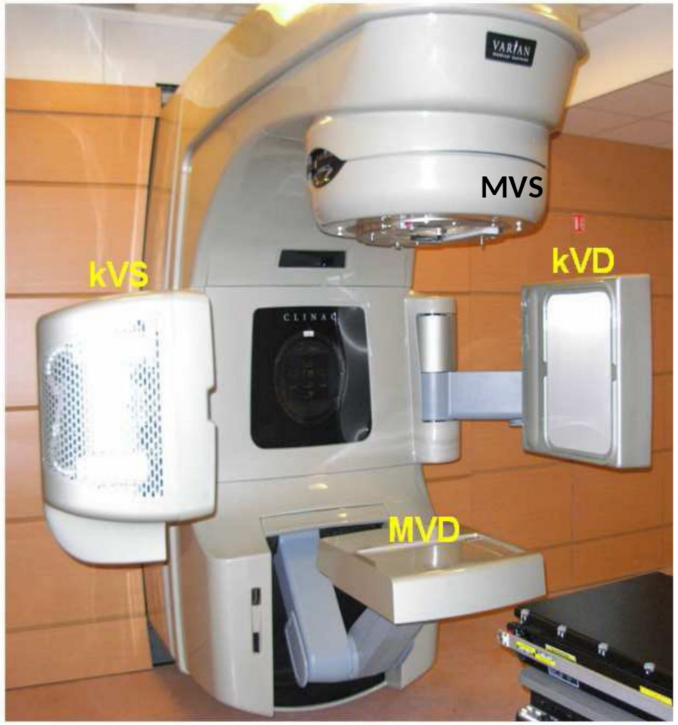
4D and 6D couch

- Setup corrections after imaging verification are applied by moving the table
- On 4D couch, translations can be applied (3D) + rotation (yaw) (1D)
- Pitch and Roll corrections can be applied on 6D couch (≈3° max)



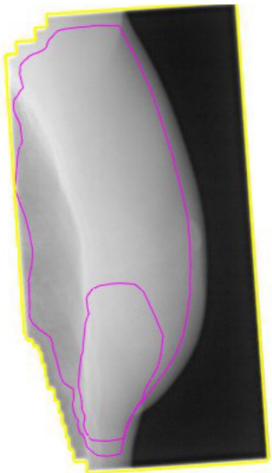
Common systems on C-arm linac

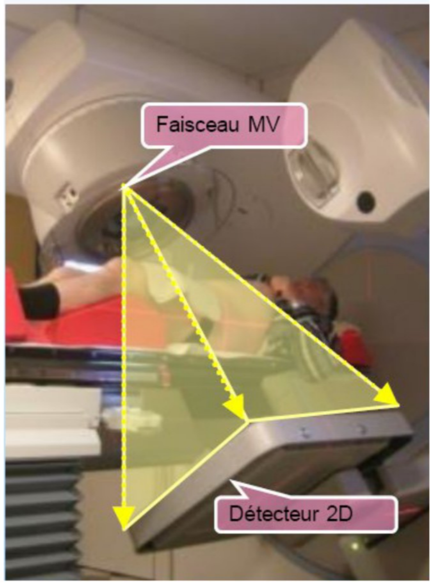
- 2 types of sources and associated detectors
  - **MV beam** and **portal imager** (EPID, amorphous silicon)
  - Embarked **kV source** and **kV detector**



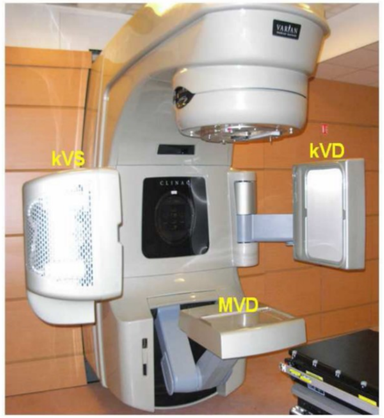
2D MV imaging

- Image is acquired with treatment beam
- Usually with lower energy (e.g. 2.5 MV)
- Check of irradiation geometry and patient positioning
- Imaging with open field or with MLC (3D conformal treatment)
- Cons:
  - Poor soft tissue contrast
  - Dose is not negligible, 1-2 MU



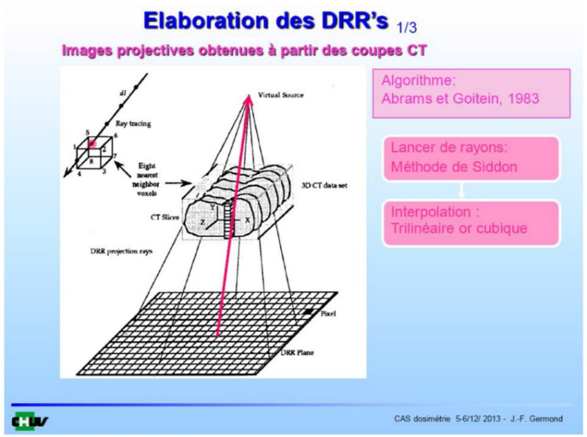


2D kV imaging

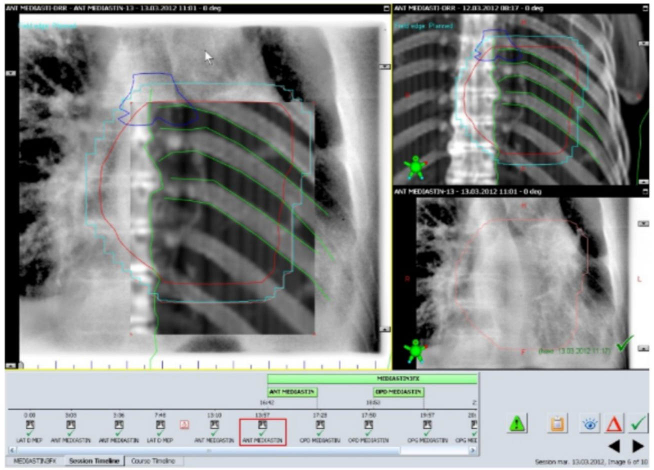


- Radiological X-ray tube
- Positioned at a 90° angle with respect to treatment beam
- OBI for Varian, XVI for Elekta
- Better contrast since energy is lower

2D images reference: DRR

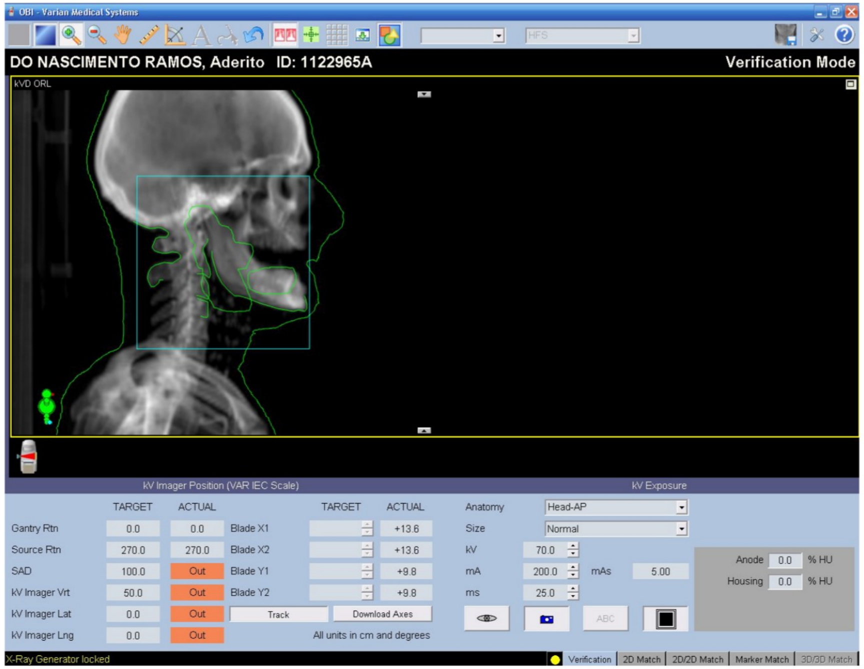


- The reference for matching is a DRR (digitally reconstructed radiograph) computed from the planning CT (depends on the acquisition angle)
- 2D images acquired at the linac is compared to the DRR
  - manual or automatic matching
  - corrections are sent to the table



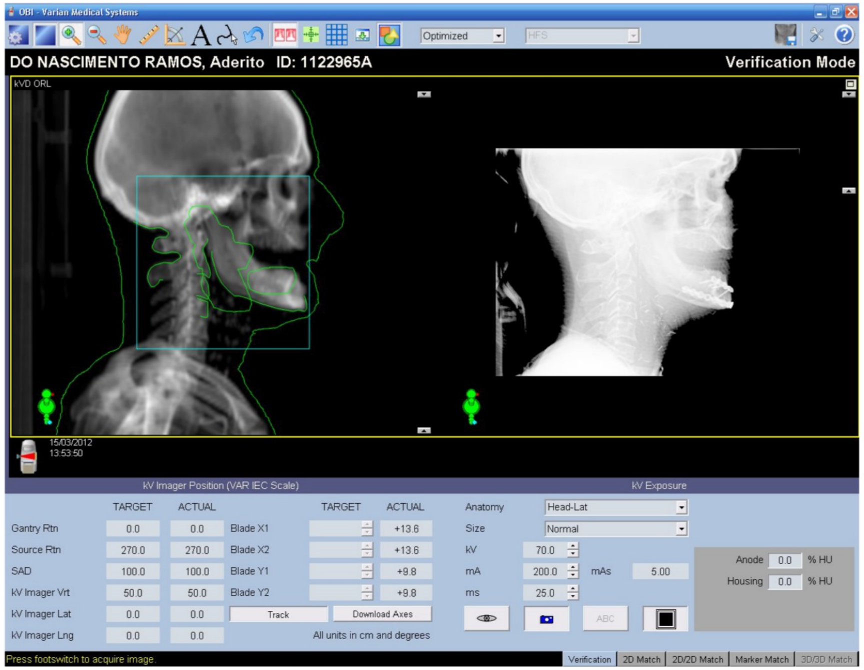
Example: kV/kV 2D/2D matching

- Acquire 2 orthogonal kV images: ANT or POST + LAT L or LAT R
- Here: Varian OBI
- Reference DRR
- LAT Right



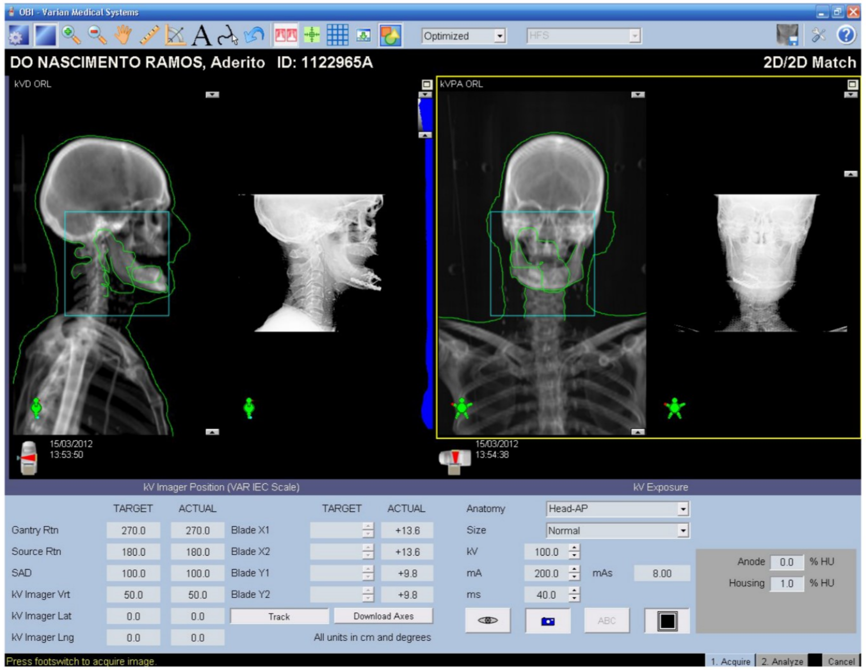
Example: kV/kV 2D/2D matching

- DRR + kV image
- LAT Right



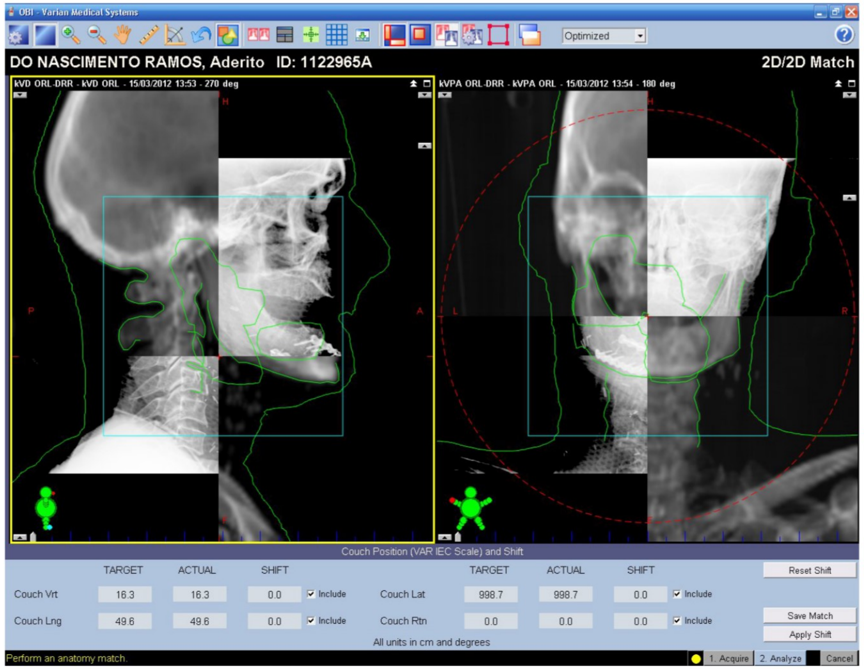
Example: kV/kV 2D/2D matching

- LAT Right+ANT



Example: kV/kV 2D/2D matching

- 2D/2D match
- Manual or automatic
- Visualization tools (spy glass, split image, color overlay, etc.)

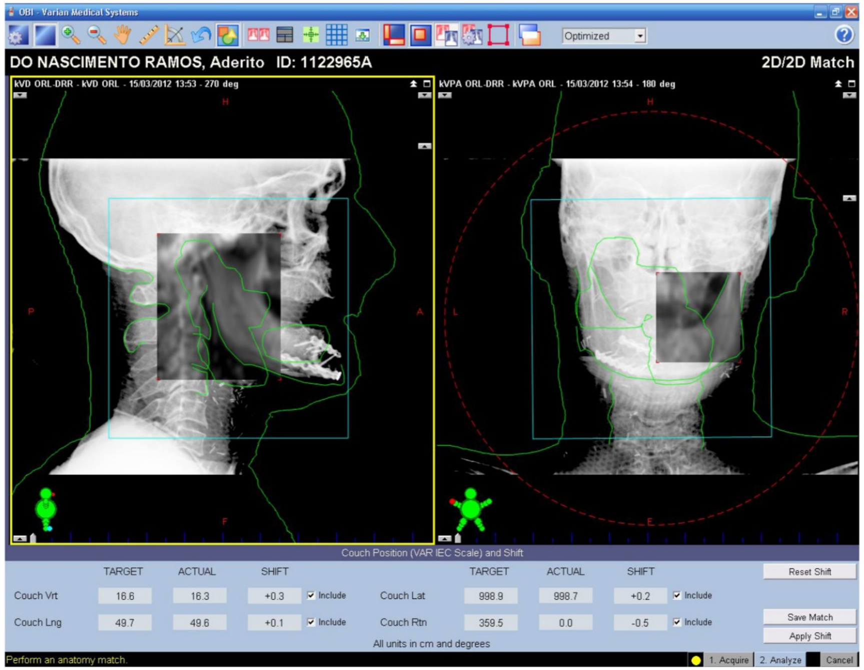


Example: kV/kV 2D/2D matching

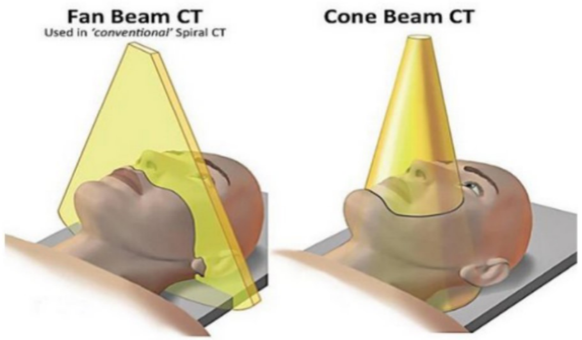
- Online matching validation

(by RTT or radiation oncologist)

- Save the matching
- Apply shift: i.e. automatically send the information to move the table



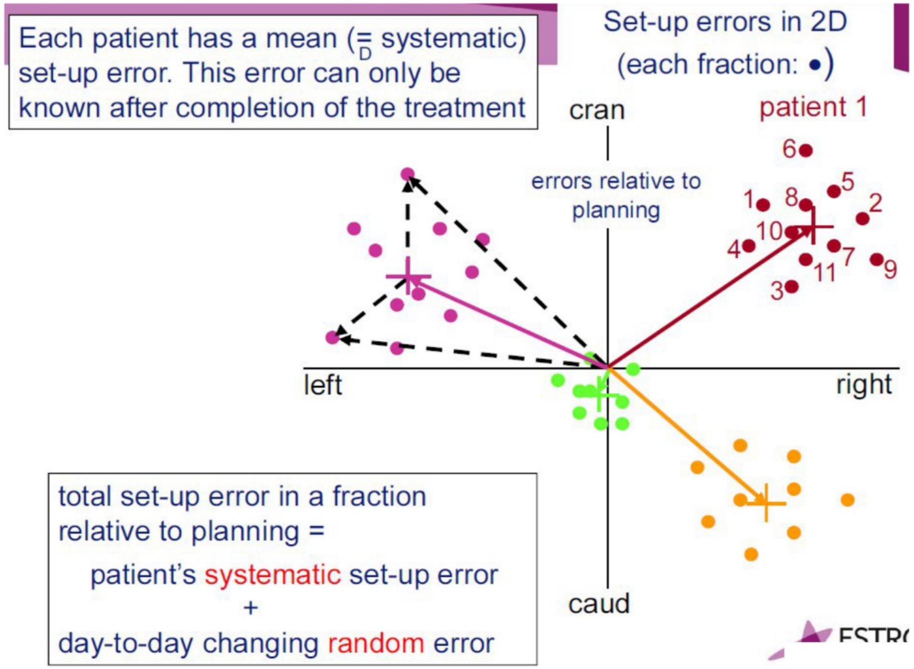
3D imaging: kV-CBCT



Yavuz et al. 2017

- Cone beam CT (as opposed to fan beam used on CT)
- Acquisition in on half or full rotation (see J.F. Germond lecture)
- Acquisition protocols are defined according to anatomic localization
- Reference image is the planning CT
- 3D/3D matching

Random vs. Systematic setup errors



IGRT strategy

- IGRT protocol should be clearly defined
- Decide what imaging system to use (e.g.: kV-kV or CBCT) and on what frequency (e.g.: CBCT once a week, otherwise kV-kV)
- Depends on:
  - Anatomical localization
  - Fractionation
  - PTV margin
  - Irradiation technique

- Online/offline review
- Adaptative strategy (weight loss, oedema, etc.)

Clinical impact of IGRT

- Studies comparing clinical outcome with or without IGRT are rare (ethical issue)

ELSEVIER
International Journal of Radiation Oncology*Biology*Physics
Volume 84, Issue 1, 1 September 2012, Pages 125-129

Clinical Investigation

Improved Clinical Outcomes With High-Dose Image Guided Radiotherapy Compared With Non-IGRT for the Treatment of Clinically Localized Prostate Cancer

Michael J. Zelefsky M.D. *, Marisa Kollmeier M.D. *, Brett Cox M.D. *, Anthony Fidaleo B.A. *, Dahlia Sperling B.A. *, Xin Pei Ph.D. *, Brett Carver M.D., Ph.D. ‡, Jonathan Coleman M.D. ‡, Michael Lovelock Ph.D. †, Margie Hunt B.S. †

"IGRT is associated with an improvement in biochemical tumor control among high-risk patients and a lower rate of late urinary toxicity compared with high–dose IMRT"

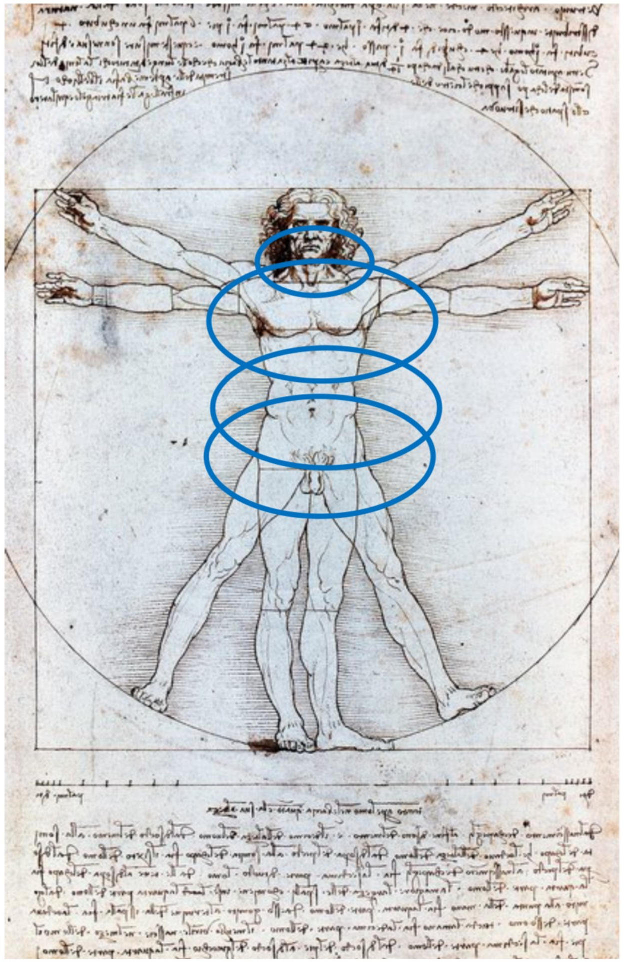
6. Organs motion

- Let's say we have a well-prepared treatment:
  - Good simulation CT with proper immobilization devices
  - Good contouring and planning
  - Plan verified with PSQA
  - Patient setup verified with IGRT; table corrections applied
- You can still miss the aim of you RT treatment because of intrafraction motion
- Motion can lead to PTV under-dosage or OAR over-exposure
- Motion mitigation is essential for SBRT (tighter margins, longer treatment time, no compensation of random errors)

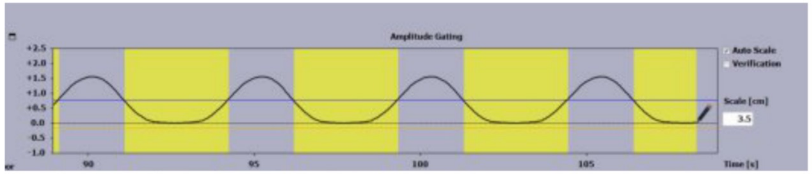
6. Organs motion

- Sources of organs motion:
  - Patient motion
  - Breathing
  - Gastrointestinal activity: stomach/rectum filling, peristalsis, swallowing
  - Urinary activity: bladder filling
  - Etc.

- Impacted organs:
  - Lungs, breast, liver, pancreas
  - Prostate, bladder, cervix
  - Etc.



6. Organs motion



Varian RMP breathing signal

- Type of motions:
  - Periodic
  - Random, erratic
  - Transient
  - Drift, etc.
- Day-to-day variations *vs*. intrafraction motion
- Let's focus on **intrafraction motion** (change over the timescale of minutes)

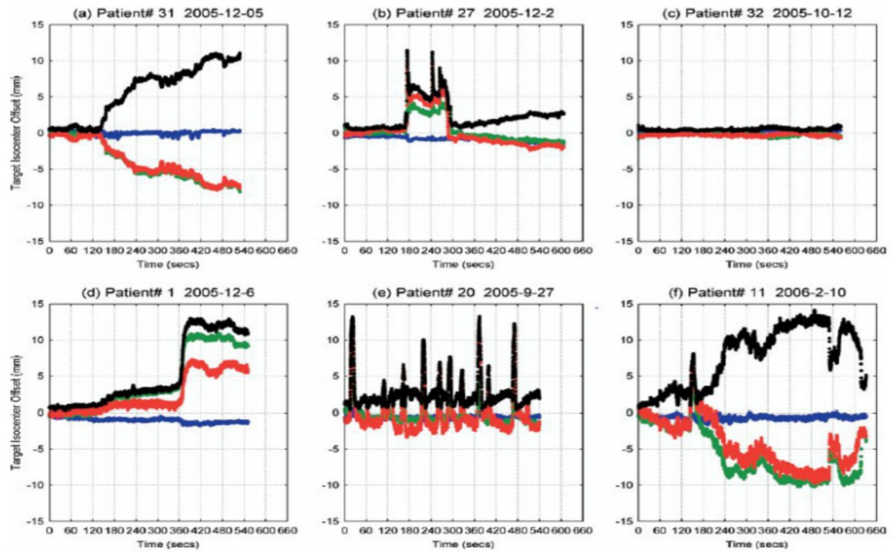


Fig. 6. Examples of behaviors observed in the continuous tracking data: (a) continuous target drift; (b) transient excursion; (c) stable target at baseline; (d) persistent excursion; (e) high-frequency excursions; (f) erratic behavior. Red: vertical, green: longitudinal, blue: lateral, black: vector length.

Kupelian et al, IJORPB 2007

Motion mitigation strategies

- Active motion reduction:
  - Voluntary breath hold
  - Abdominal compression
- Add margins:
  - ITV strategy
  - Mid-ventilation strategy
  - PTV margin (e.g.: prostate)
- Gating
- Tracking

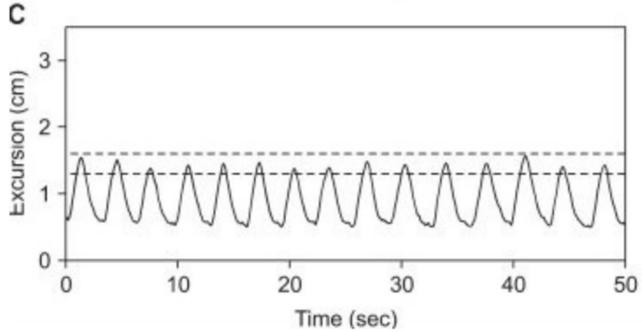
Passive approaches (ITV strategy, Mid-ventilation strategy, PTV margin)

Active approaches (Gating, Tracking)

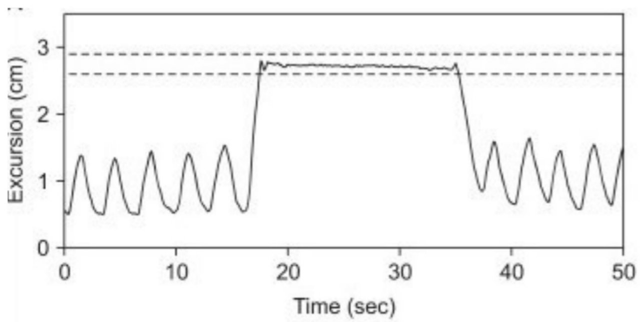
Motion reduction

- **Voluntary breath hold**
  - DIBH (e.g. for heart sparing in breast RT)
  - Breath hold (more reproducible and easier to hold)

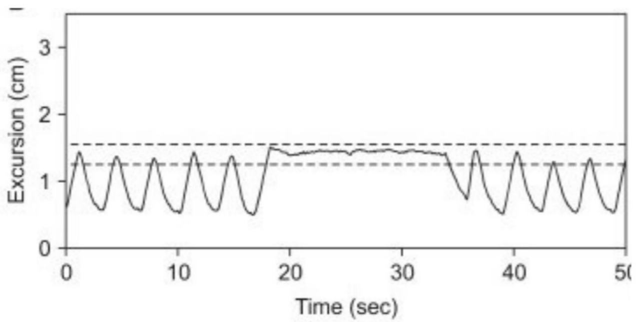
Free breathing



Deep inspiration breath hold



Inspiration breath hold



Sung et al, Radiat Oncol J 2014

Motion reduction

- **Abdominal compression**, can help reduce respiratory motion
- Used for lung and liver tumors

Orfit system

ELSEVIER
Physica Medica
Volume 29, Issue 4, June 2013, Pages 333-340

Original paper

Is abdominal compression useful in lung stereotactic body radiation therapy? A 4DCT and dosimetric lobe-dependent study

Gauthier Bouilhol [a, b], Myriam Ayadi [b], Simon Rit [a, b], Sheeba Thengumpallil [b], Joël Schaerer [a, b], Jef Vandemeulebroucke [c, d], Line Claude [b], David Sarrut [a, b]

"The mean reduction of tumor motion amplitude was 3.5 mm (*p* = 0.009) for lower lobe tumors and 0.8 mm (*p* = 0.026) for upper/middle lobe locations. Compression increased tumor motion in 5 cases."

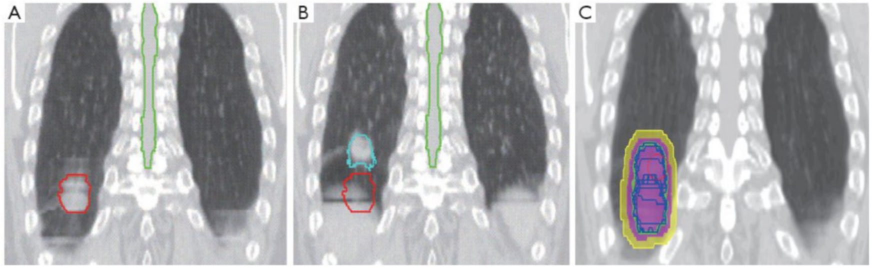
The Effectiveness of a Pneumatic Compression Belt in Reducing Respiratory Motion of Abdominal Tumors in Patients Undergoing Stereotactic Body Radiotherapy

D. Michael Lovelock, Ph.D.*, Joan Zatcky, ACNP-BC., Karyn Goodman, M.D., more... Show all authors

First Published June 1, 2014 | Research Article | Find in PubMed | Check for updates
https://doi.org/10.7785/tcrt.2012.500379

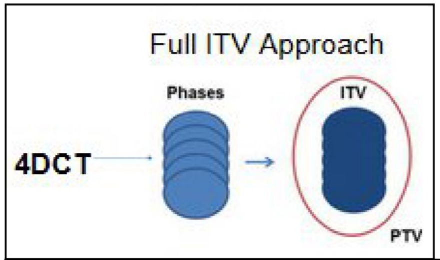
"The mean CC motion with the belt in place, but no additional air pressure was 11.4 mm with a range of 5–20 mm. With the pressure applied, the mean CC motion was reduced to 4.4 mm with a range of 1–8 mm (*P*-value < 0.001)."

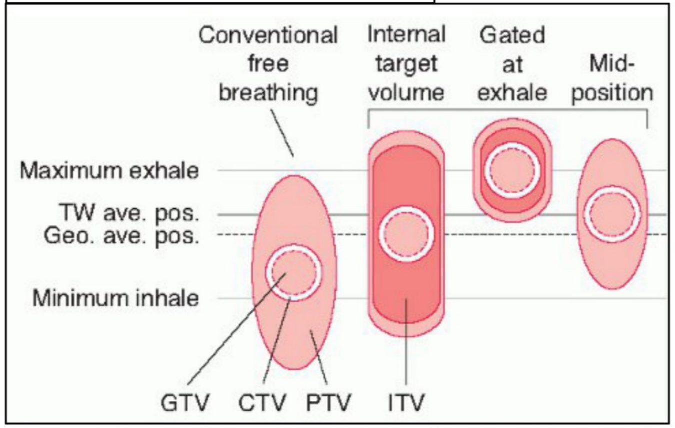
Respiratory motion



Glide-Hurst et al., Journal of thoracic disease, 2014

- GTV motion known from the 4DCT (10 phases →10 positions)
- **ITV approach**: ITV is defined as the sum of the 10 GTV
- **Mid ventilation approach**: GTV is treated in its most probable position, margins are computed from the breathing motion (Stroom and Heijmen 2002, van Herk 2004)

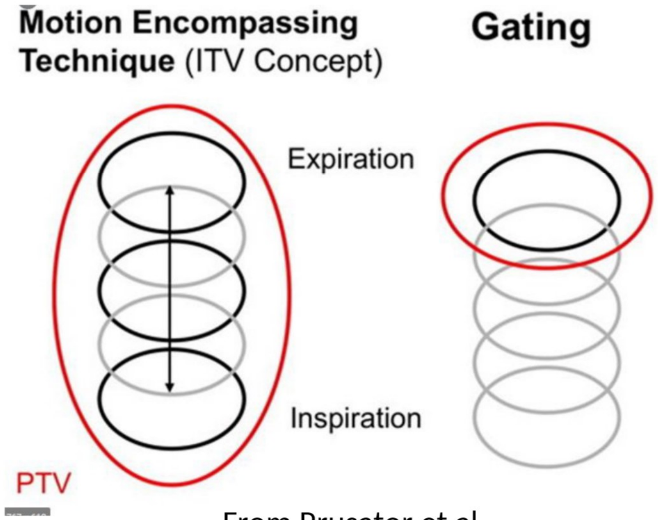




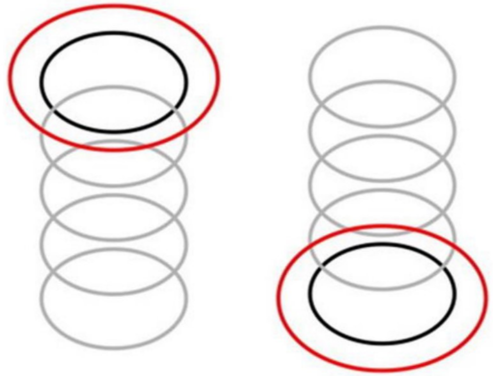
From: https://thoracickey.com/physical-basis-of-modern-radiotherapy-dose-and-volume/

Respiratory motion

- **Gating**: GTV is defined on a single/few phase(s) and treated only when the tumor is in this location (increases treatment time)
- **Tracking**: GTV is treated over the whole cycle, motion is compensated by table motion (couch tracking, e.g. Ehrbar 2017) or by irradiation field adaptation (e.g. CyberKnife, Radixact, MLC tracking on C-arm linac (e.g. Keall 2014, Booth 2016 etc.))

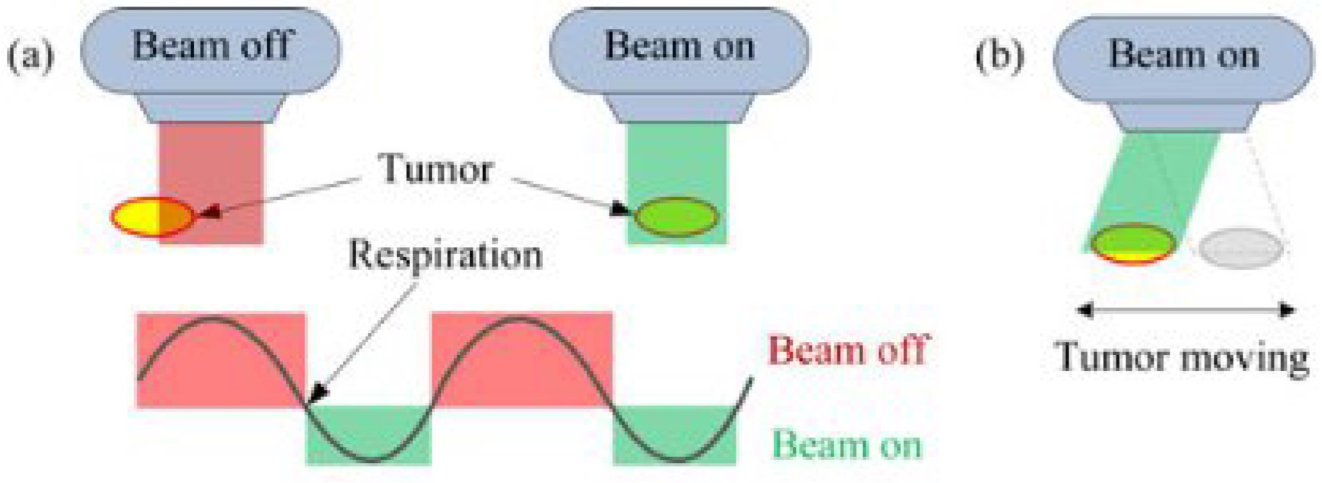


From Prusator et al.



Gating vs Tracking

Gating Tracking



From Gu et al. 2012

Techniques for intrafraction motion monitoring

- Surface guided radiotherapy (optical or IR surface guided)
- Breathing sensors (RGSC, Anzai, ABC)

→ External surrogates

- Radio-opaque implanted fiducials in combination with kV imaging (ABH, stereo kV CK or ExacTrac)
- Electromagnetic transponders (Calypso)
- Ultrasound (Clarity system for prostate)

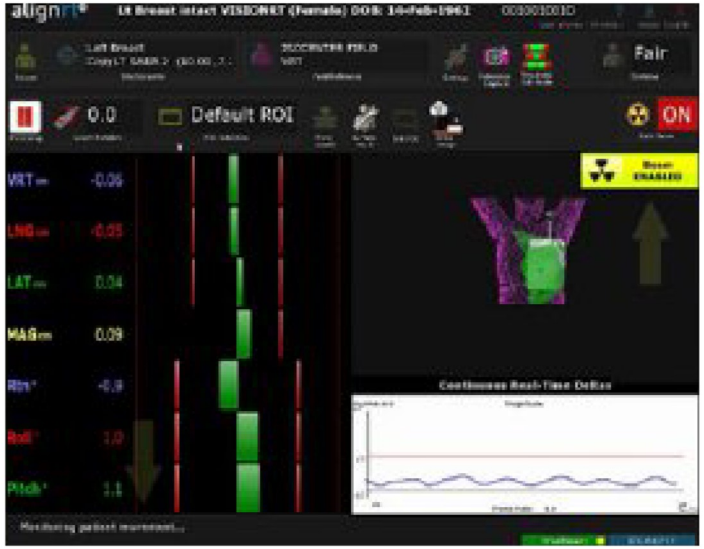
→ Internal surrogates

- Markerless tracking (CK, Dynamic ExacTrac)
- MRI linac

→ Direct tumor visualization

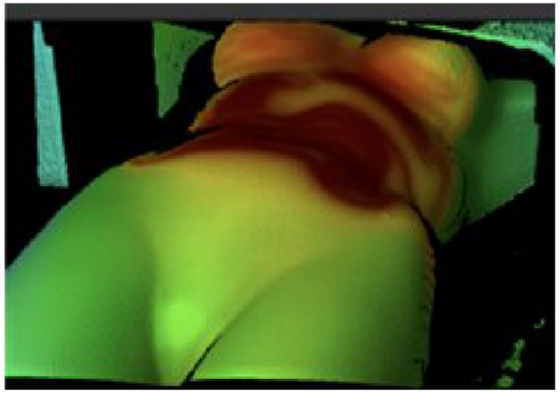
Optical surface monitoring

- Reference surface obtained from the planning CT or from a surface monitoring system in CT room
- In-room image acquired with 1-3 optical cameras in the linac room and compared to reference image for a given ROI
- Continuous monitoring
- Can be used to monitor breathing
- AlignRT (VisionRT), Catalyst (C-rad), Identify (Varian)



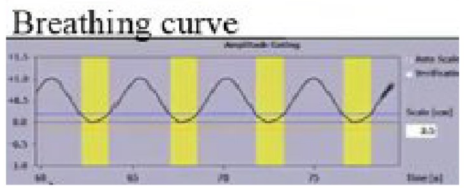
Infrared surface monitoring

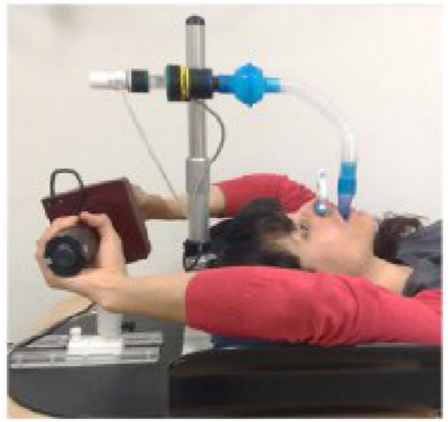
- ExacTrac dynamic system (Brainlab), thermal image surface is detected and compared to a reference coming form the planning CT



Sensors for breathing monitoring

- **Varian RGSC system**: box with reflective marker put on patient thorax/abdomen and detected by a camera
- **Elekta ABC system**: spirometer that monitors the lung volume
- **Anzai pressure belt**: monitors changes in the abdominal circumference





From Bertholet *et al* *2019 Phys. Med. Biol.*

Pitfalls of external or breathing sensors

- Does not always correlate with internal motion (e.g.: Ross et al. 2005, Koch et al. 2004)
- Correlation depends on tumor location, external point monitored and breathing patterns
- Risk of tumor miss

Implanted fiducials

- Internal surrogate for tumor motion
- High contrast markers
- Implantation: percutaneous, trans-rectal, transperineal transbronchial, etc.
- Prostate, liver, lung, pancreas, etc.

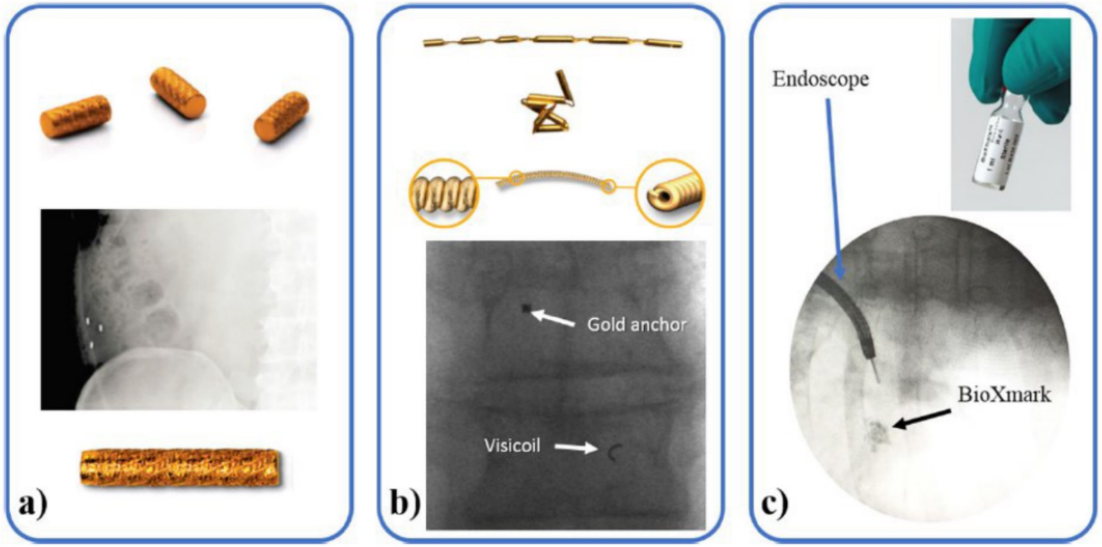
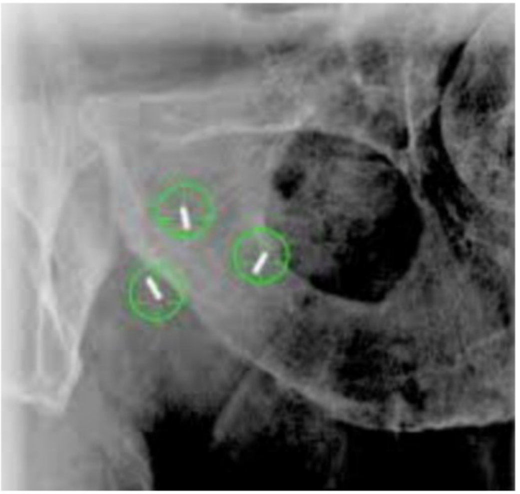


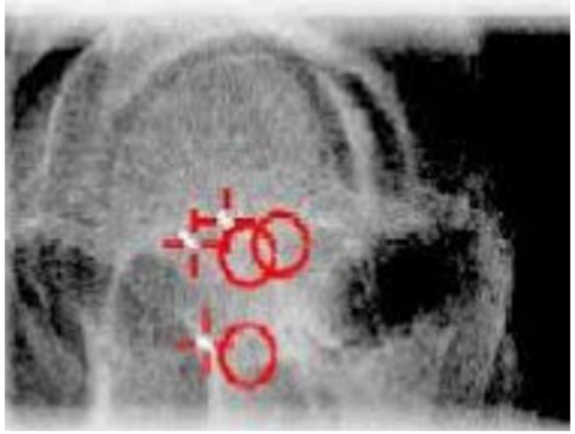
Figure 3. Examples of FM. (a) 3 mm-long gold markers (civco, diameter between 0.8 and 1.2 mm) (top) can be implanted in any soft tissue (middle) for image guidance. The similar 5 × 1 mm CyberMark™ was developed specifically for use with CyberKnife® (bottom) (civco Radiotherapy, Coralville, IA). (b) Gold anchor (Naslund Medical, Sweden) (diameter of 0.28 or 0.4 mm) (top) and Visicoils (IBA dosimetry, Barlett, TN) (diameter between 0.35 and 1.1 mm) (middle) take an arbitrary shape once implanted (bottom). (c) The liquid fiducial BioXmark (Nanovi, A/S, Denmark) before (top) and after endoscopic assisted implantation (bottom).

From Bertholet *et al 2019 Phys. Med. Biol.*

Auto beam hold system

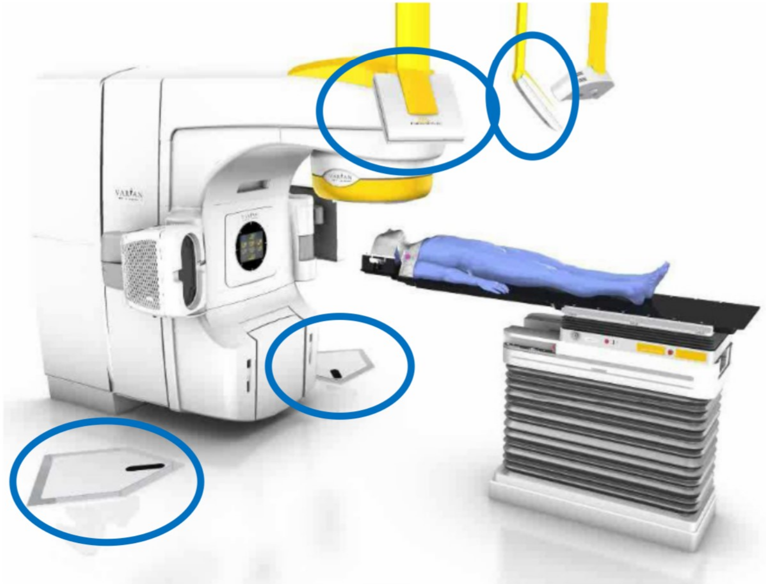
- Available on TrueBeam Varian linac with the advanced imaging module
- kV images acquired during treatment (trigger defined by the user, time, MU or angle)
- Fiducials automatically detected
- Beam is gated if fiducials are out of pre-defined margins





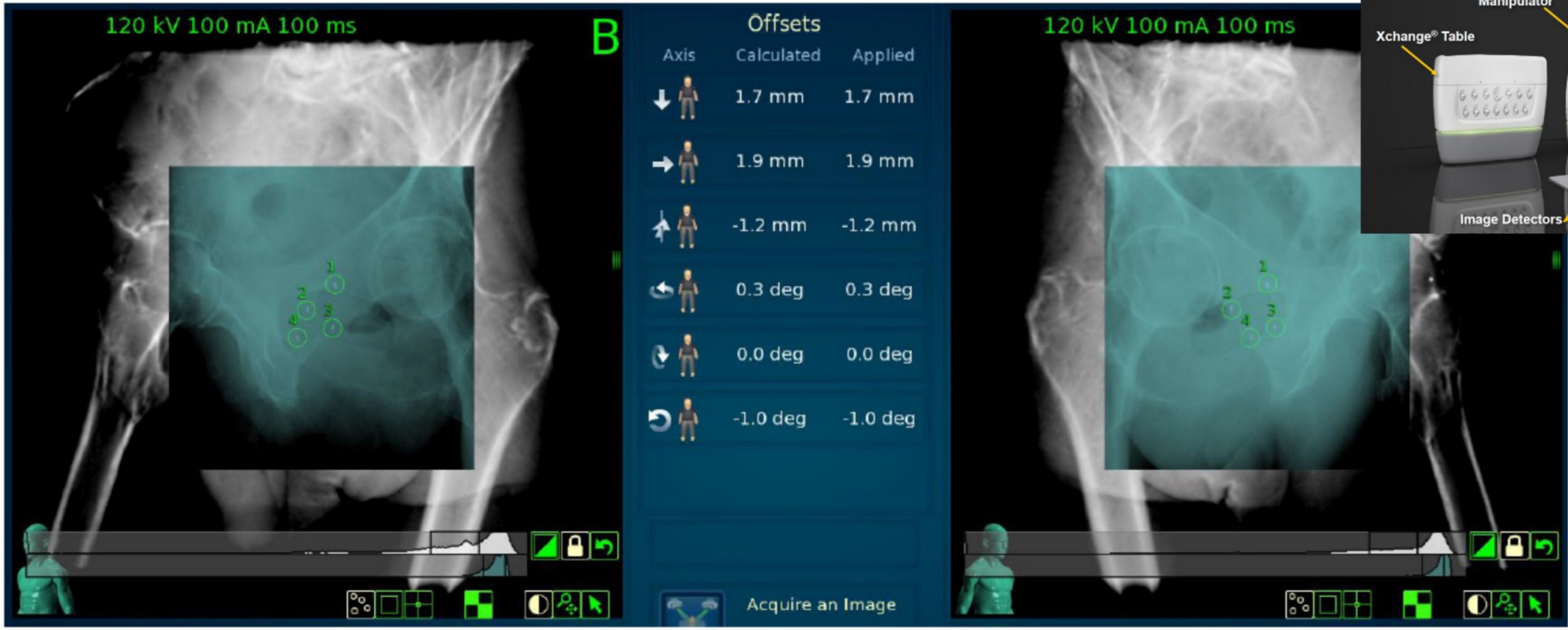
Exactrac system (Brainlab)

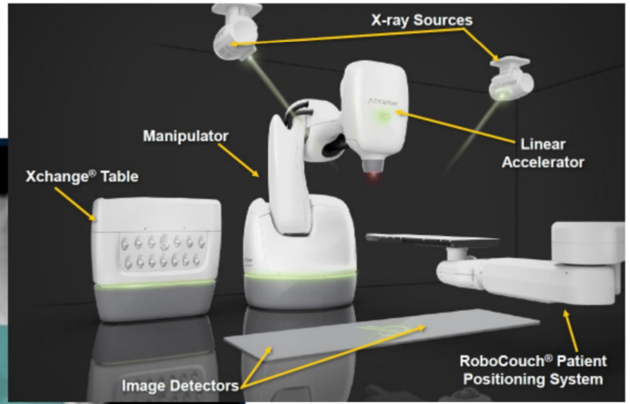
- In-room X-ray based monitoring system
- 2 orthogonal X-ray tubes and detectors
- Installed on C-arm linac
- Allows for no-coplanar verification



Fiducial tracking with the CyberKnife

- Tracking of 3-5 implanted fiducials

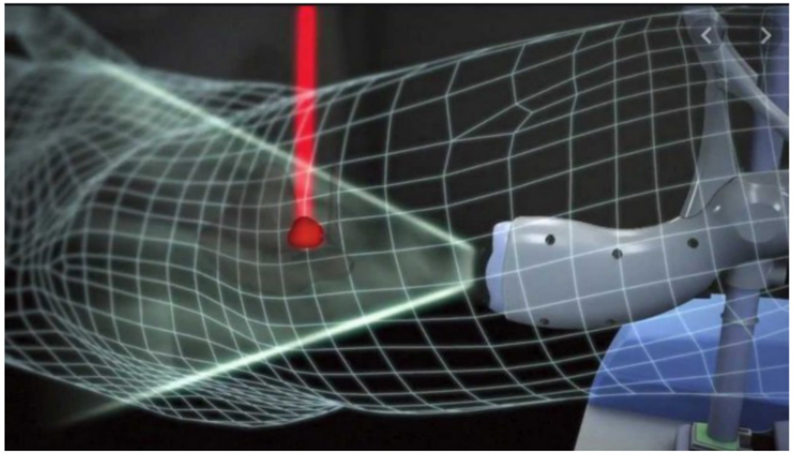


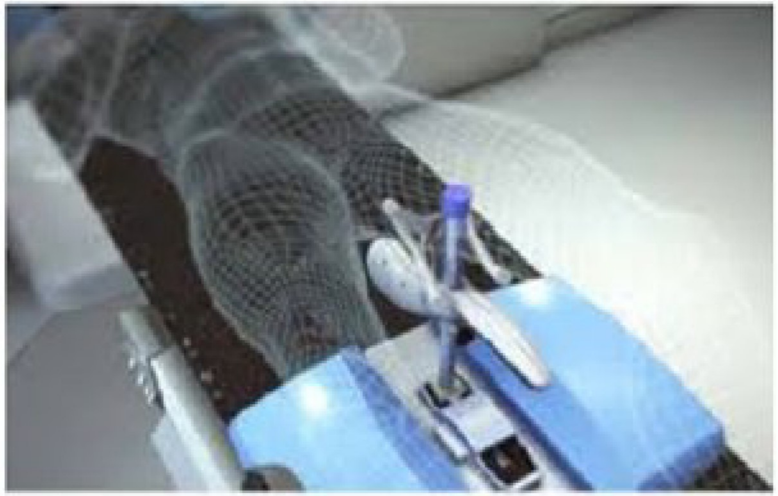


From Accuray

Clarity system

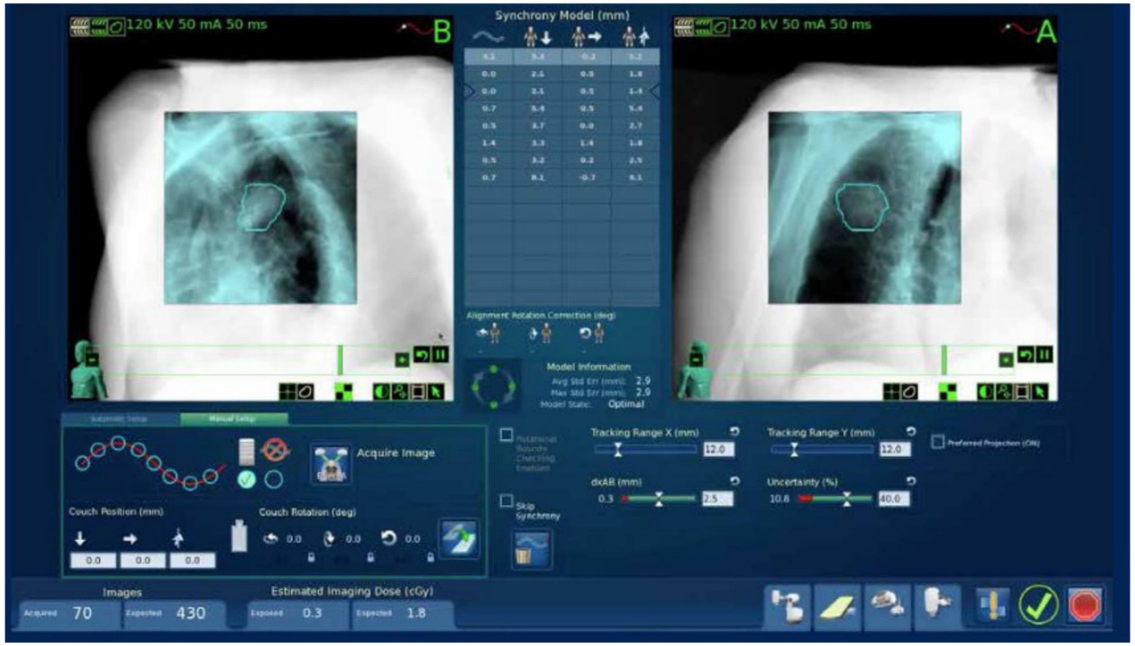
- Clarity autoscan probe (Elekta)
- Ultrasound system for prostate location
- Beam holds if motion out of thresholds (Elekta linac)





Markless tracking on CyberKnife

- Xsight Lung tracking mode
- Automatic detection of tumor based on contrast



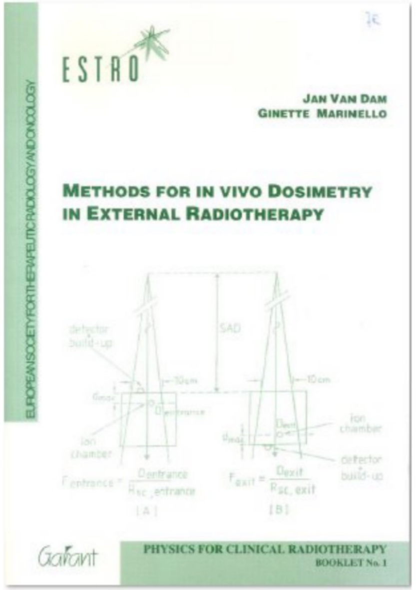
From Accuray

MRI Linac

- RT machine with integrated MRI
- MRIdian (ViewRay) and Unity systems (Elekta)
- Good soft tissue contrast
- 2D cine MRI imaging to determine directly tumor intrafraction motion, or to detect an internal surrogate
- Gating of thoracic-abdominal tumor (e.g. Fischer-Valuck et al. 2017)

7. In vivo dosimetry

- Dose measurement during patient treatment
- Also a form of PSQA
- Recommended by several national and international organizations
- Incorporated in some legislations
- **Ultimate verification of the whole planning and delivery procedure**, ideally, we would put dosimeter in the tumor or in OAR.



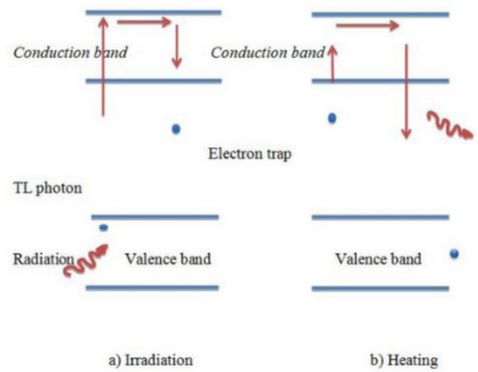
"In vivo dosimetry is the methodology of choice in verifying whether a correct dose is actually being delivered to the patient, and is as such a crucial tool in quality assurance of the treatment of the individual patient."

Principles

- Dosimeters are positioned on patient skin or cavity
- Usually at the first fraction
- Direct way to measure the dose delivered to the skin
- Indirect way to measure delivered dose in depth
- Measured dose is compared to the predicted dose from the TPS
- Deviations can be due to: patient motion, patient setup, wrong data transfer, inappropriate measurement method, linac calibration, mechanical deviation, incorrect dose calculation etc.

Detectors

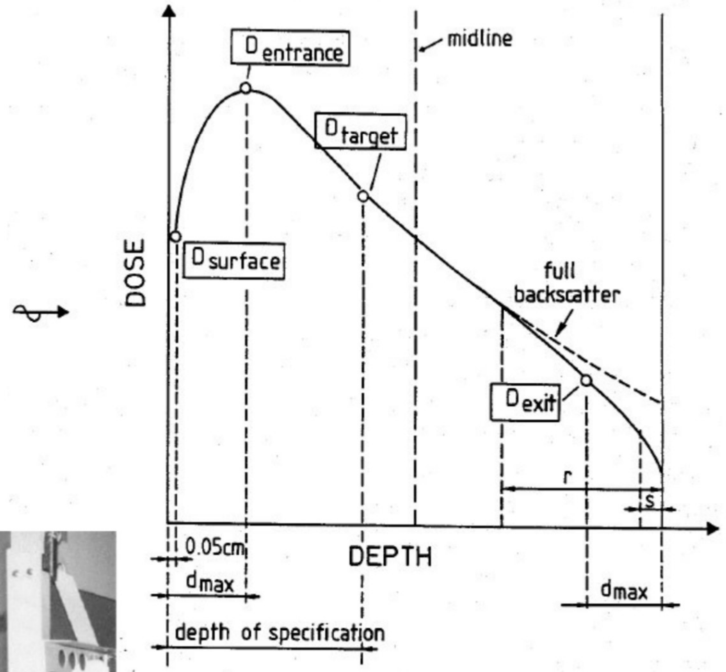
- **Semiconductors** (diodes or MOSFET), in combination with an electrometer, online measurement, requires frequent calibration, reading depends on accumulated dose, dose-rate, beam energy, etc.
- **Thermo-luminescent dosimeters** (TLD), LiF type are the most common, offline reading with a TLD oven reader, very small, etc.
- **Gafchromic films**, offline reading with a scanner, variable size, 2D, flat, etc.

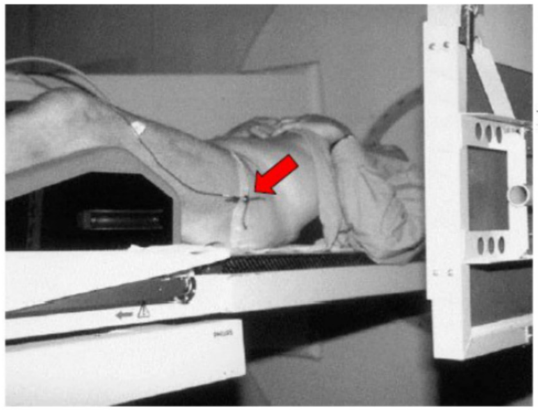


From Hassan 2020

Measurement configuration

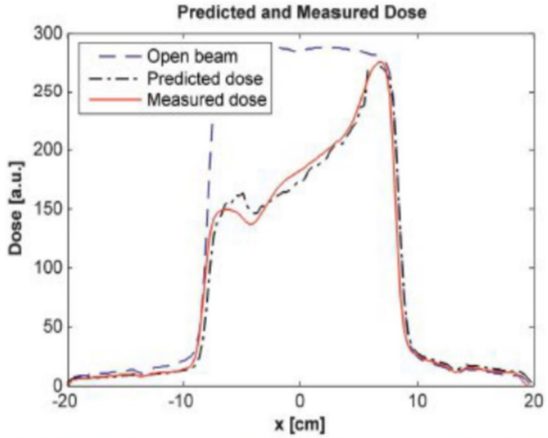
- Measurement of the entrance dose
- Comparison with the planned dose
- From the measurement of exit and entrance dose, we can deduce the target dose depending on its depth





EPID-based in-vivo dosimetry

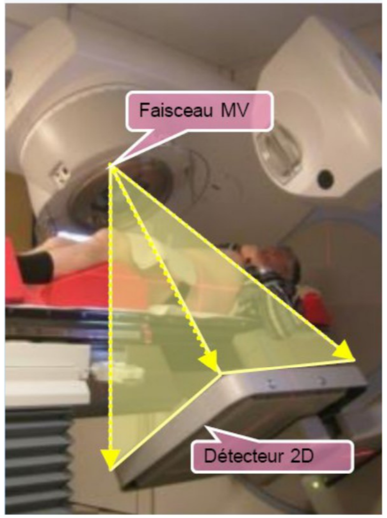
- Can be used to measure the 2D dose distribution behind the patient
- Comparison with a predicted dose allows for treatment verification



Experimental verification of a portal dose prediction model

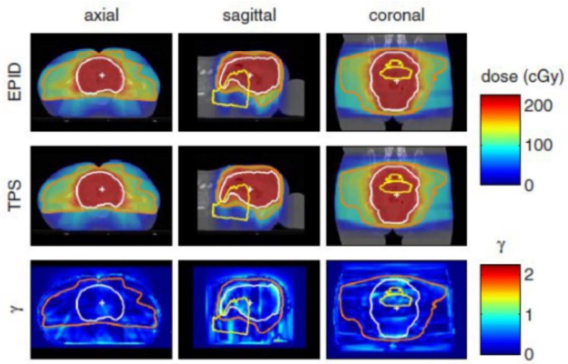
W. J. C. van Elmpt, S. M. J. J. G. Nijsten,[a] B. J. Mijnheer, and A. W. H. Minken
Department of Radiation Oncology (MAASTRO Physics), GROW, U.H. Maastricht, Maastricht, The Netherlands

Med. Phys. 32 (9), September 2005



EPID-based in-vivo dosimetry

- Can be used for IMRT or VMAT treatment verification
- Use back-projection to reconstruct dose distributions inside the patient



A simple backprojection algorithm for 3D in vivo EPID dosimetry of IMRT treatments

Markus Wendling, Leah N. McDermott, Anton Mans, Jan-Jakob Sonke, Marcel van Herk, and Ben J. Mijnheer

Citation: Medical Physics **36**, 3310 (2009); doi: 10.1118/1.3148482

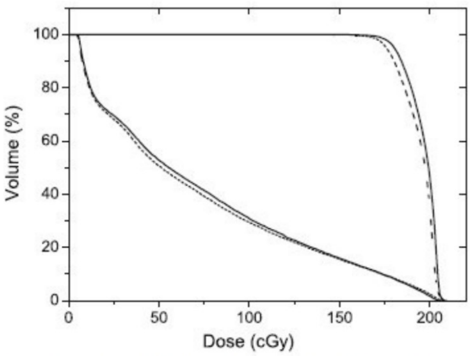


Fig. 5. DVHs of the PTV and the rectal wall from the *in vivo* verification of prostate plan A (Fig. 4). The planned and EPID-reconstructed dose distributions are represented by solid and dashed lines, respectively.

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3D Dosimetric verification of volumetric-modulated arc therapy by portal dosimetry

Anton Mans *, Peter Remeijer, Igor Olaciregui-Ruiz, Markus Wendling [1], Jan-Jakob Sonke, Ben Mijnheer, Marcel van Herk, Joep C. Stroom
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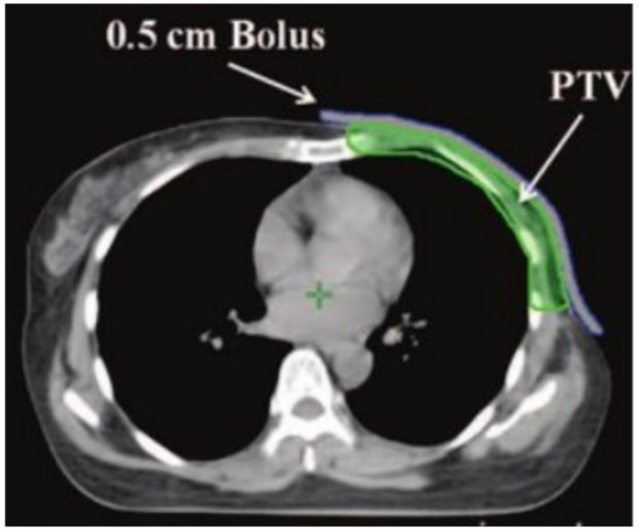
Typical clinical cases

- Chest wall treatment with bolus
- 3-4 TLD positioned between skin and bolus at 1st fraction
- TLD position is detected on CBCT
- Skin dose measured by TLD is compared to TPS dose



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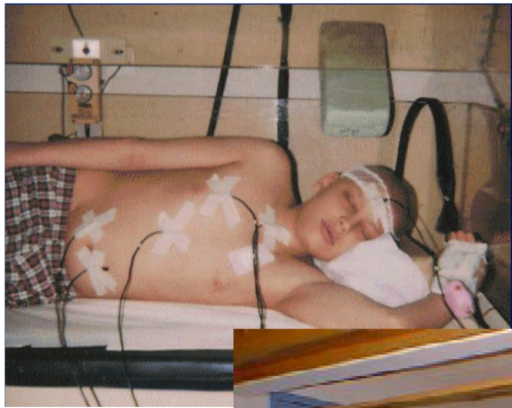
Typical clinical cases

- Total body irradiation performed with AP-PA fields (1-6 sessions)
- Online in-vivo dose measurements with diodes (head, neck, lung, abdomen, mediastin, legs). Beam is stopped when the correct dose is reached
- Also TLD measurement at first 2 sessions)



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Many thanks to Maud Jaccard

Questions ?