matRad

Particle Therapy Masterclass

Treatment planning : How to localize and accurately irradiate a tumor

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Radiation therapy - structure

Patient fixation

Imaging (esp. CT, but also MRT or PET)

Identification & delineation of tumor volume and organs on 3D image

Treatment planning

Verification & quality assurance

Patient positioning

Irradiation (several “fractions“)

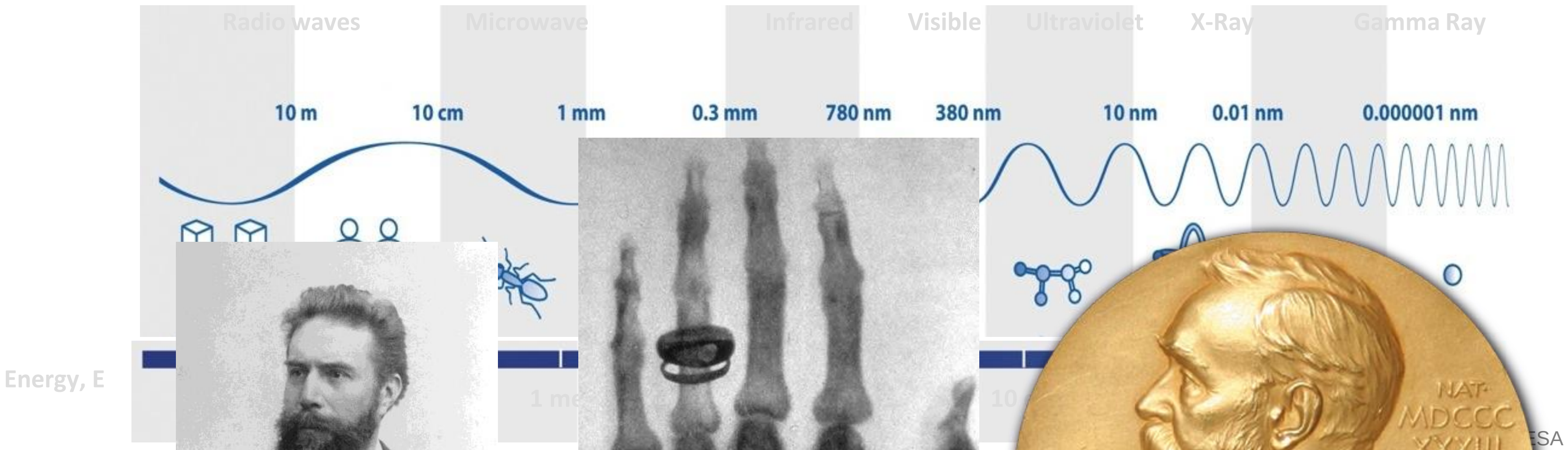
Adapted from W. Schlegel & A. Mahr: 3D Conformal Radiation Therapy Springer Multimedia DVD

A treatment plan should …

- ... fulfil clinical requirements (“The physician prescribes”) …
- ... based on biological processes (cell death) …
- ... induced by chemical & physical processes (reactions & interactions) …
- ... by means of numerical simulation (dose calculation / optimization)

→ Interdisciplinary **inverse problem**

Imaging: X-ray



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8/11/1895

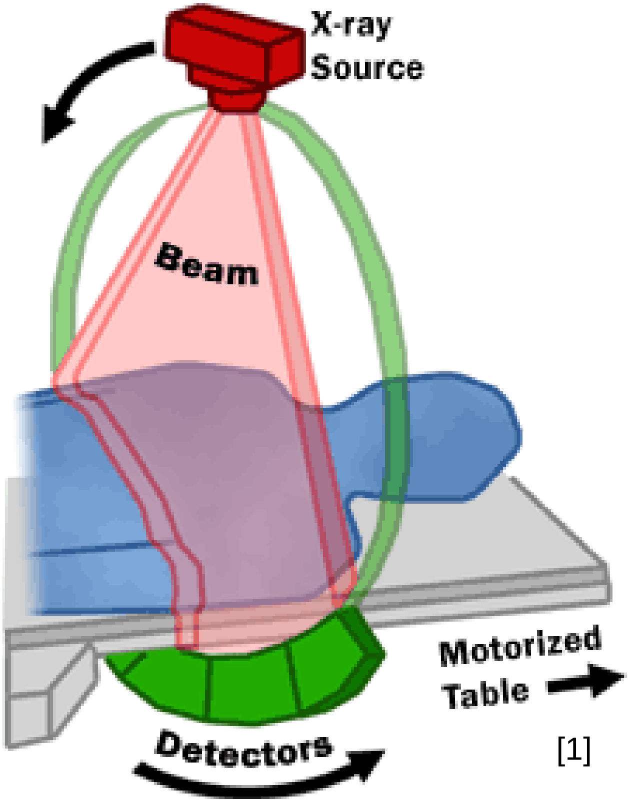
22/12/1895

1901

[1] anonym (https://commons.wikimedia.org/wiki/File:Roentgen2.jpg), „Roentgen2“, marked as public domain, more details on Wikimedia Commons: https://commons.wikimedia.org/wiki/Template:PD-EU-no author disclosure
[2] Wilhelm Röntgen; current version created by Old Moonraker. (https://commons.wikimedia.org/wiki/File:X-ray_by_Wilhelm_Röntgen_of_Albert_von_Kölliker's_hand_-_18960123-02.jpg), „X-ray by Wilhelm Röntgen of Albert von Kölliker's hand - 18960123-02“, marked as public domain, more details on Wikimedia Commons: https://commons.wikimedia.org/wiki/Template:PD-old
[3] Photograph: JonathunderMedal: Erik Lindberg (1873-1966) (https://en.wikipedia.org/wiki/File:Nobel_Prize.png), „Nobel Prize“, marked as public domain, more details on Wikimedia Commons: https://commons.wikimedia.org/wiki/Template:PD-US

Imaging: Computed tomography

"3D X-ray"

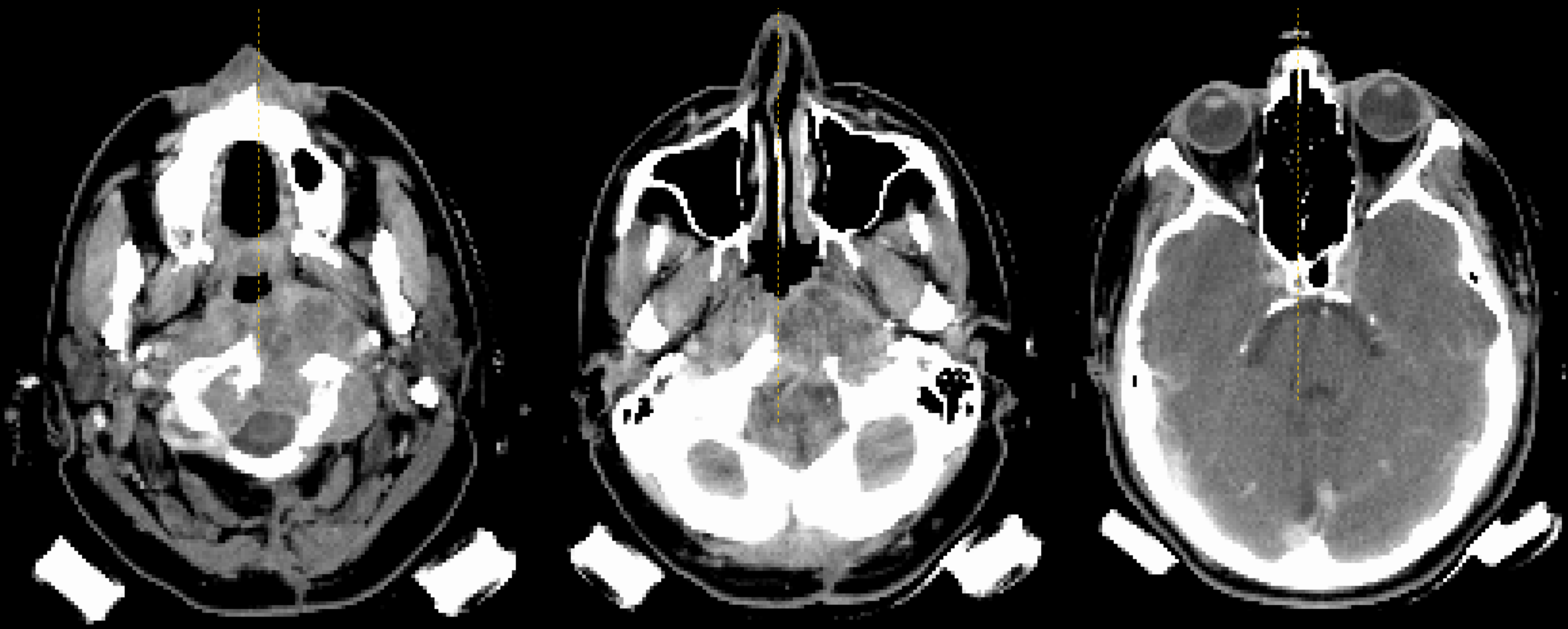


[1]

[2]

[1] FDA – Radiation emitting products – Medical X-ray Imaging – What is Computed Tomography? - Accessed from https://www.fda.gov/radiation-emitting-products/medical-x-ray-imaging/what-computed-tomography on 15.02.2021.
[2] daveynin from United States (https://commons.wikimedia.org/wiki/File:UPMCEast_CTscan.jpg), „UPMCEast CTscan", https://creativecommons.org/licenses/by/2.0/legalcode

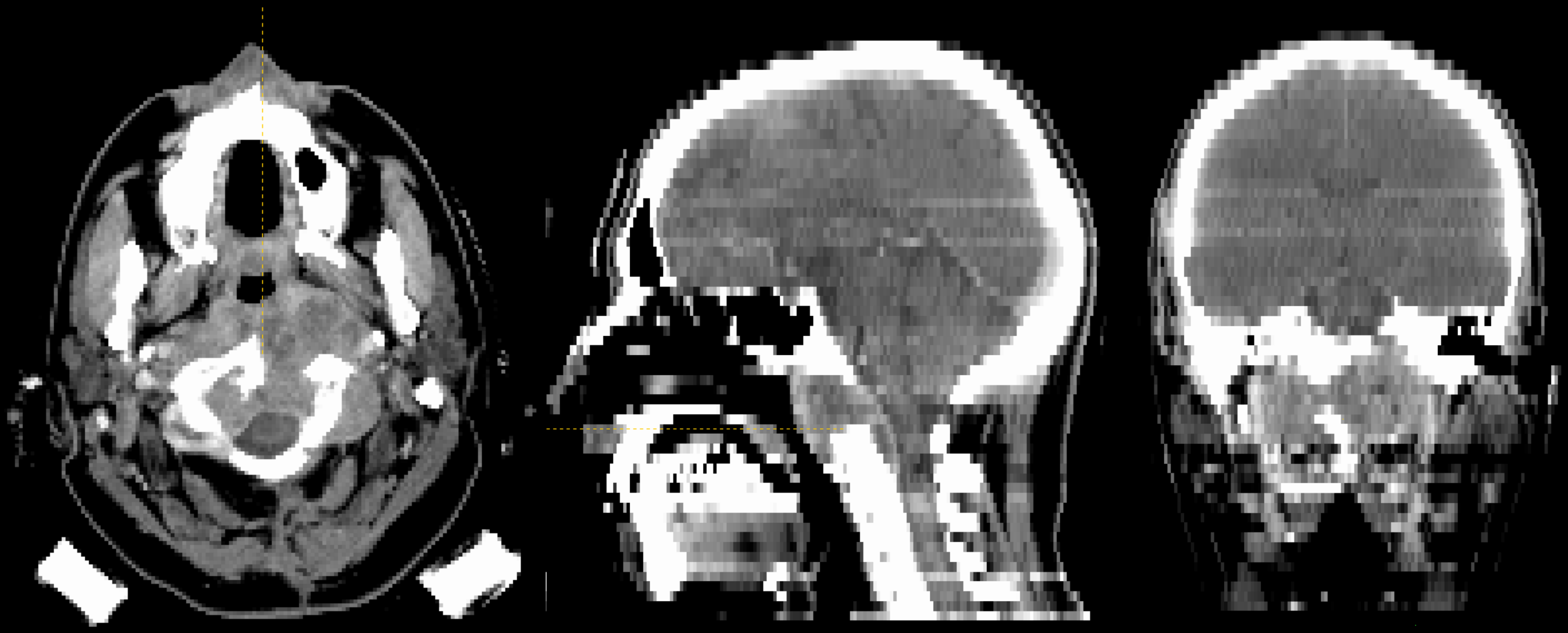
CT scans for treatment planning



transversal slices

Slide by courtesy of Dr. Simeon Nill

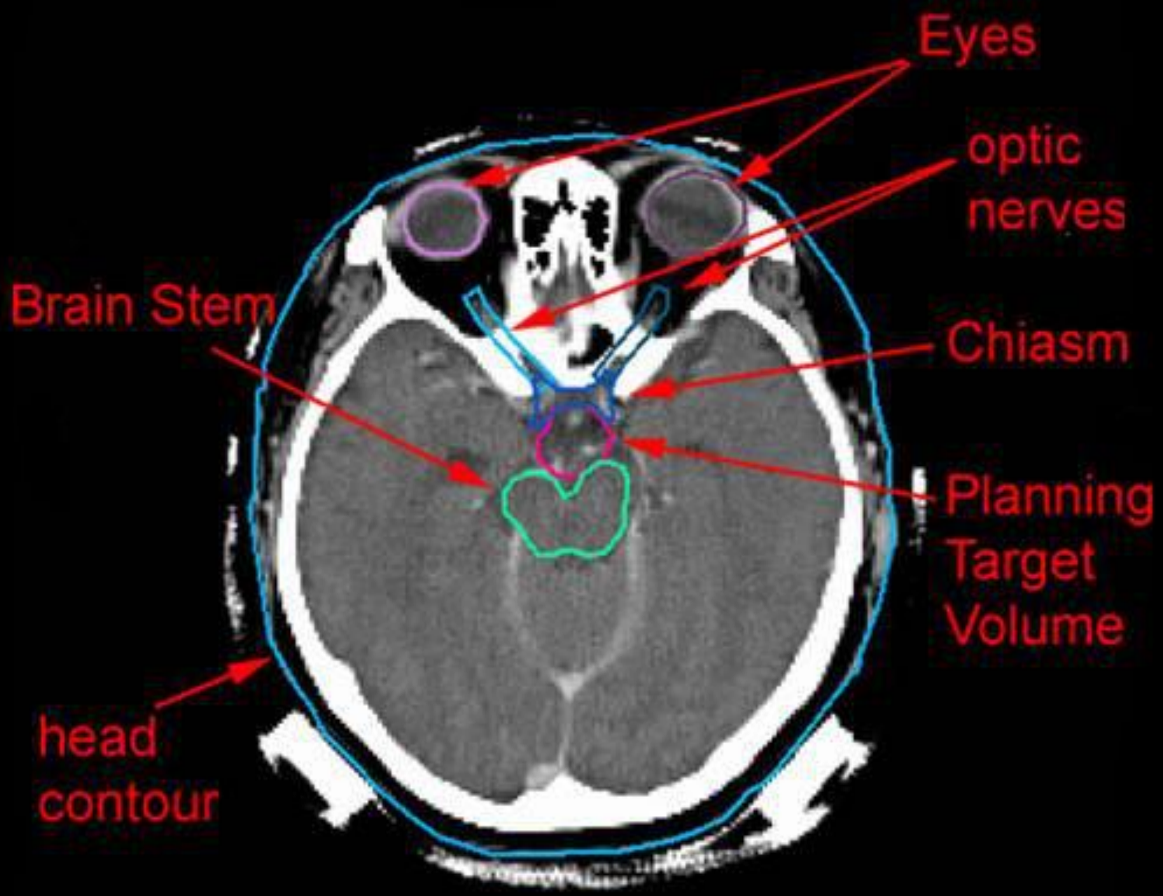
CT scans for treatment planning



transversal sagittal frontal

Slide by courtesy of Dr. Simeon Nill

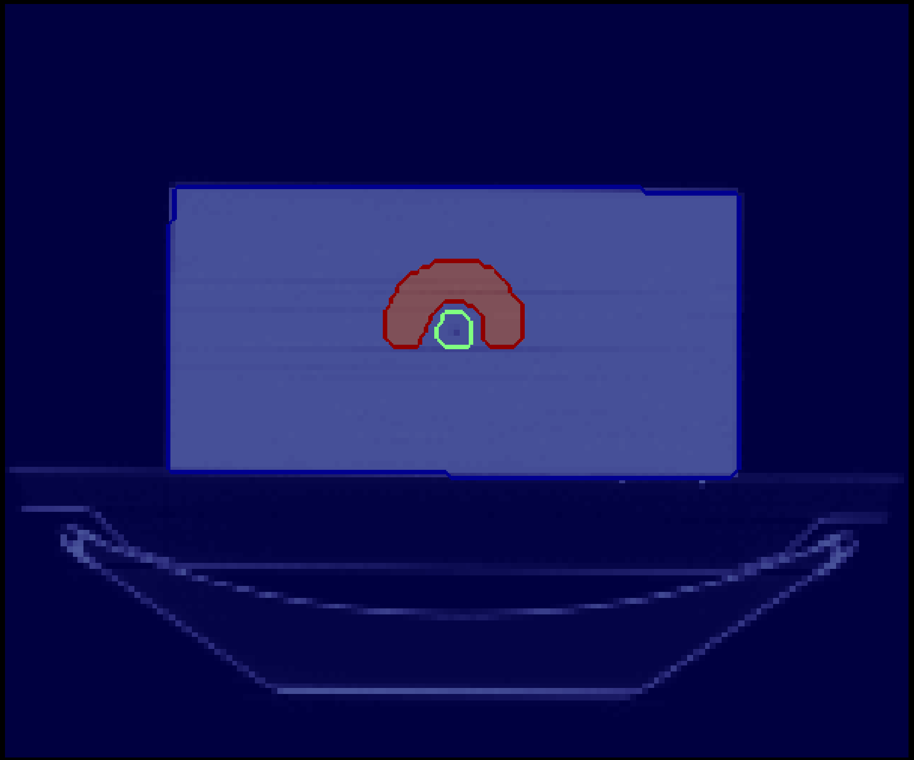
Delineating volumes of interest



W. Schlegel & A. Mahr: 3D Conformal Radiation Therapy Springer Multimedia DVD

Slide by courtesy of Dr. Simeon Nill

The ideal dose distribution

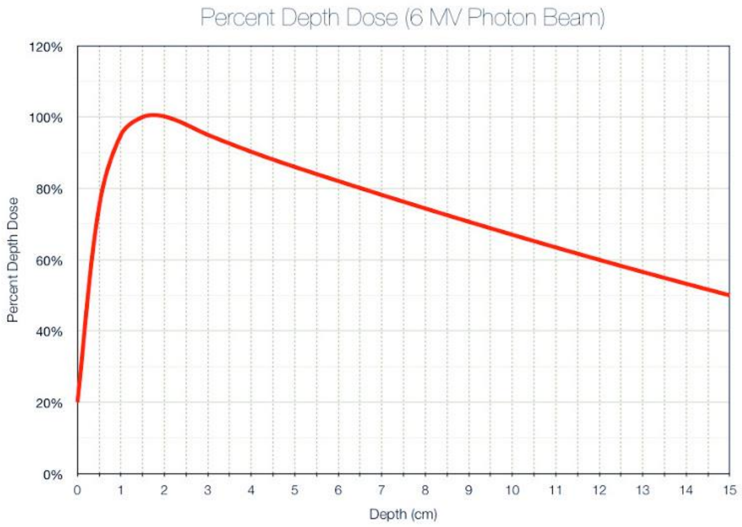


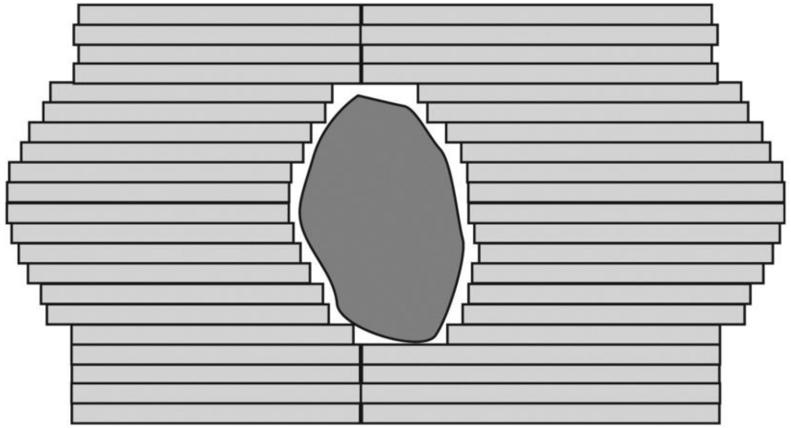
- High / prescribed dose in the tumor
- No dose in normal tissue

Modern 3D-planning with photons

Photon beam

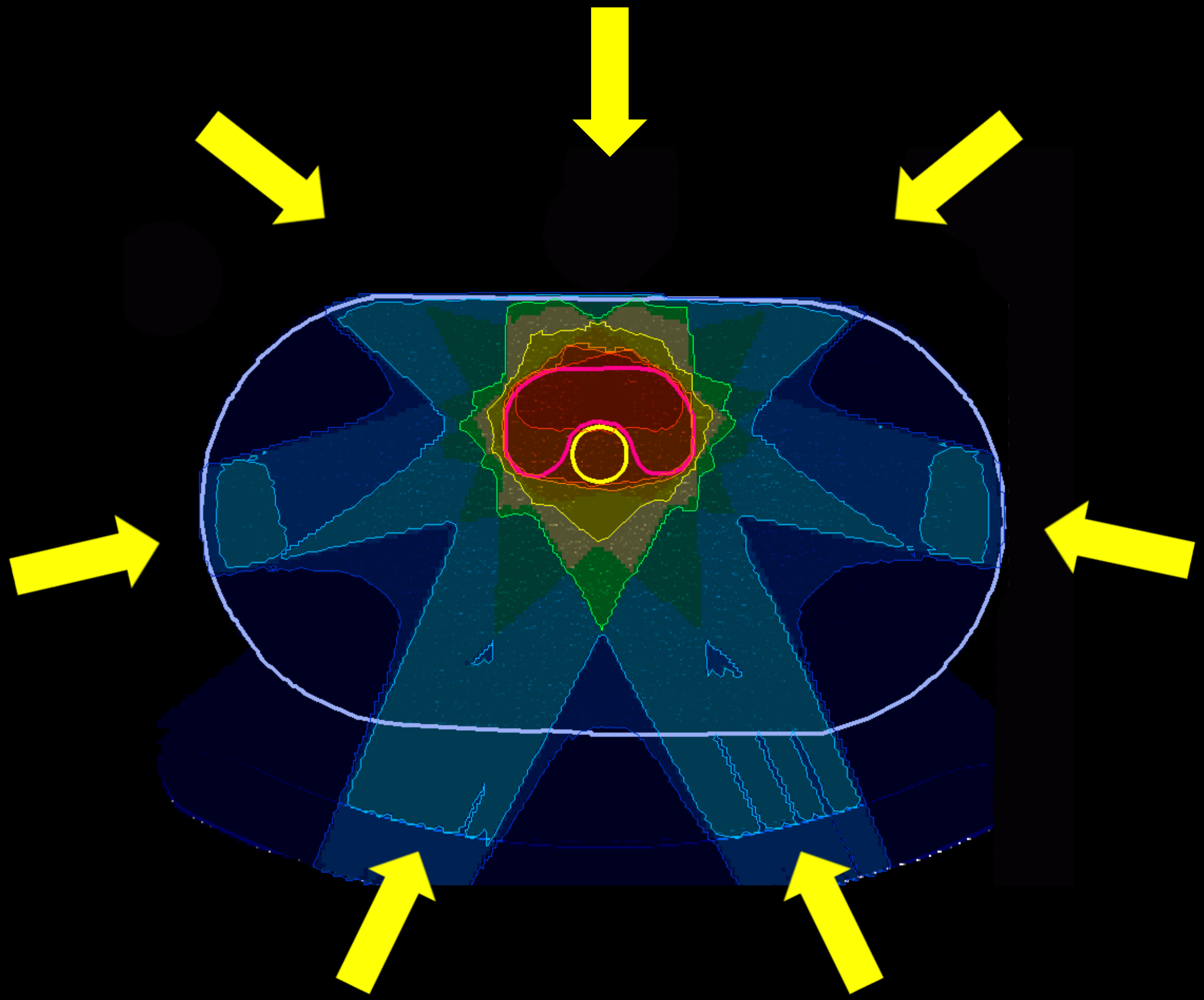
collimator





→ Adaptation of the photon beam to the tumor shape

A realistic dose distribution



Can we do better?

YES WE CAN

[1]

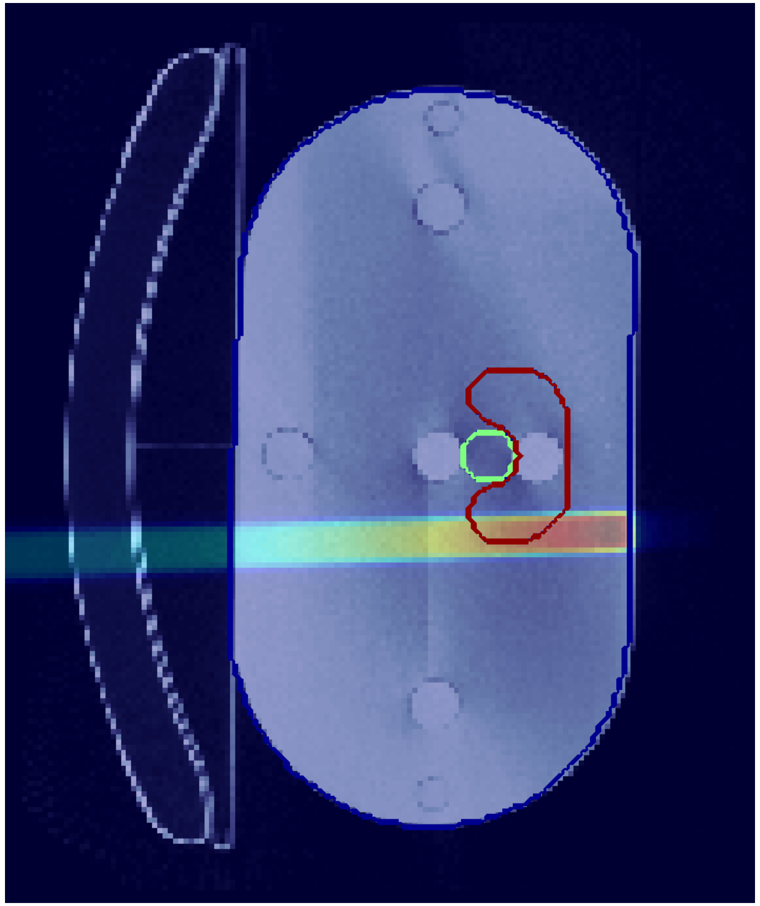
[1] The Obama-Biden Transition Project (https://commons.wikimedia.org/wiki/File:Poster-sized_portrait_of_Barack_Obama_OrigRes.jpg), „Poster-sized portrait of Barack Obama OrigRes“, size adapted, https://creativecommons.org/licenses/by/3.0/legalcode

The concept of the „pencil beam“

- „Multi-leaf“ collimator are able to generate fine beams (pencil beams)

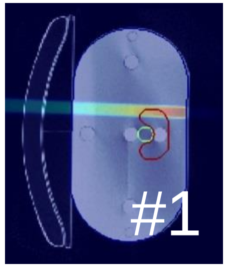
- We calculate their dose using various algorithms. Examples:
  - **Analytical Pencil beam**
    Precomputed / measured dose curves in water are “scaled” to the patient
    → deterministic, very quick, but inaccurate
  - **Monte Carlo**
    Simulation of individual particle trajectories (“histories”) through the patient
    → stochastic, slow, but mostly more accurate

#4



i.e.: We are able to simulate and “modulate” our beams

The concept of the „pencil beam“



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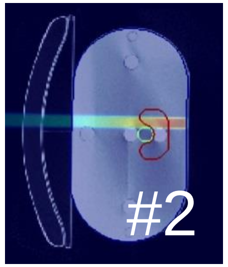

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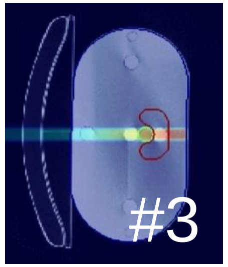

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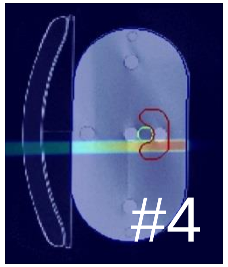

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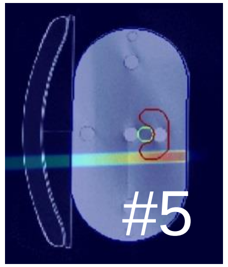
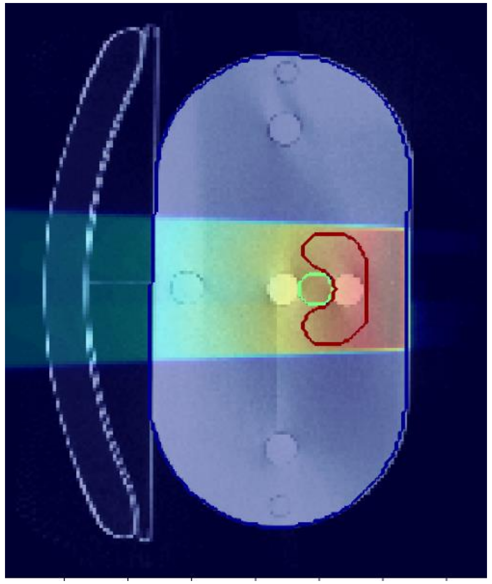




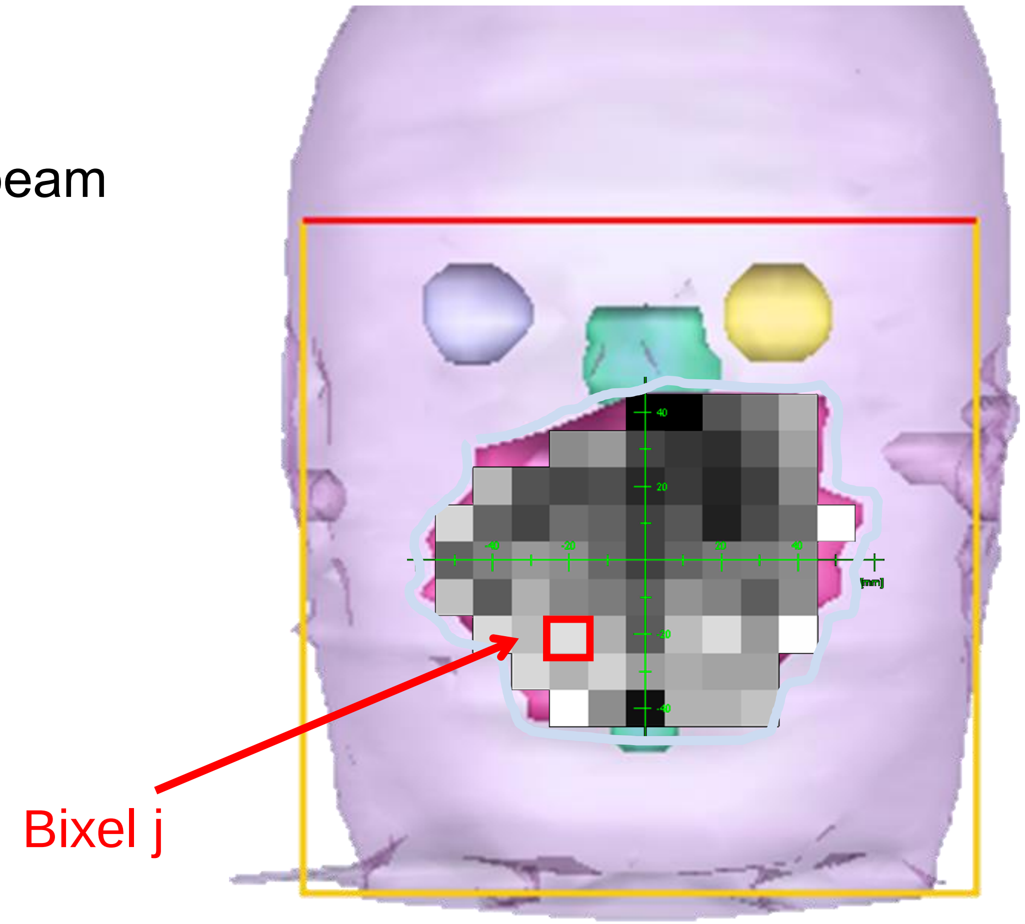
= homogeneous beam

Intensity modulation with pencil beams

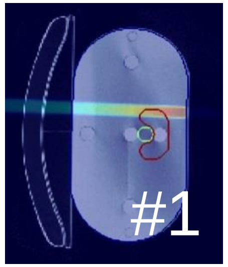
Pencil beams form “pixel” in the beam cross-section
(or the fluence, respectively)

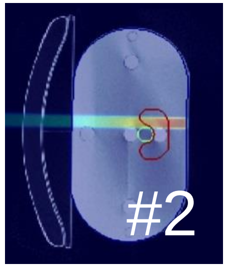
= “bixel” (**B**eam + P**ixel**)

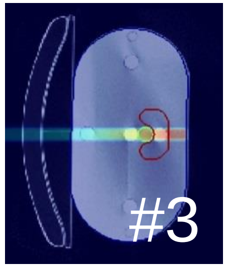
We weight all pencil beams (more/less photons) differently

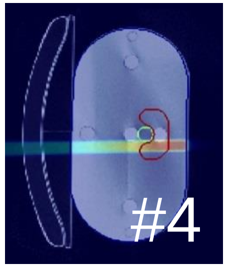


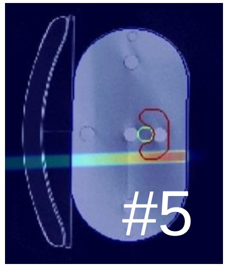
Intensity modulation with pencil beams

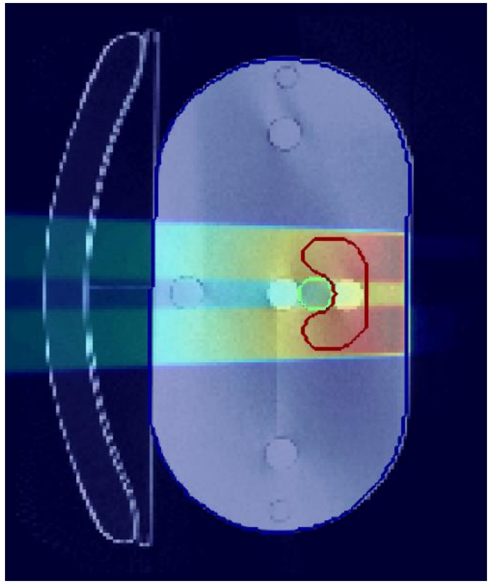
3x


+ 3x


+ 2x


+ 3x


+ 3x




Different bixel weights
= intensity modulated beam

- Number of pencil beams: ~100-1000 per beam
- Number of beams: 5 to 12

→ Not manually determinable

Objective functions for minimization

- Clinical requirements for the radiation plan are translated into mathematical functions

„ Irradiate the tumor homogeneously with 54 Gy....“

$$f_{\mathrm{Tumor}} = \frac{1}{N_T} \sum_{i \in T} (d_i - d_T)^2$$

„ with minimal average radiation dose in the tissue“

$$f_{\mathrm{OAR}_1} = \frac{1}{N_S} \sum_{i \in S} d_i$$

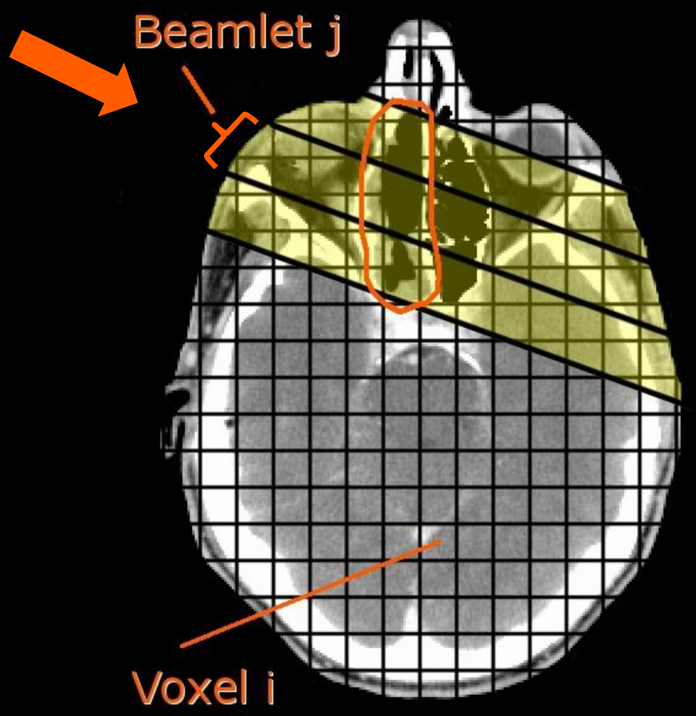
„ and simultaneous reduction of dose in an organ at risk below 10 Gy.

$$f_{\mathrm{OAR}_2} = \frac{1}{N_S} \sum_{i \in S} \Theta\left(d_i - d_M\right)\left(d_i - d_M\right)^2$$

➢ Minimization of these functions under consideration of the physical beam properties!

… the intensity profiles are determined by means of ‘Inverse Planning‘ by minimizing a quadratic objective function on a discrete patient anatomy.

$$F = f_{\text{Tumor}} + f_{\text{OAR}_1} + f_{\text{OAR}_2}$$



$$d_i = \sum_{j}^{N} D_{ij} w_j$$

$$w_j \geq 0$$

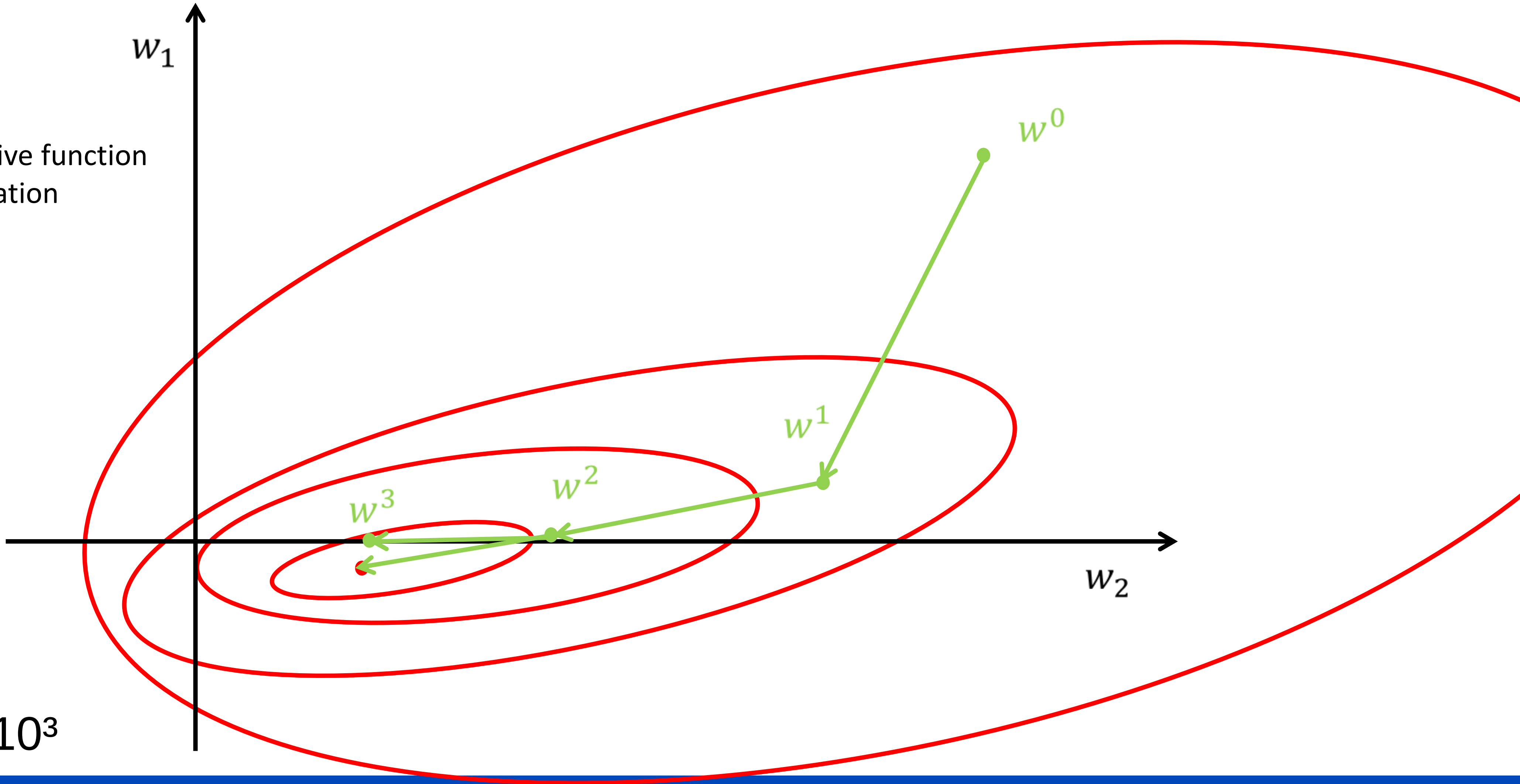
typically: 0.2 – 2 GB

photons ~ 1000 parameter
particles ~ 30000 parameter

Solution by means of optimization algorithms
→ Find the extreme value! (compare “curve sketching”)

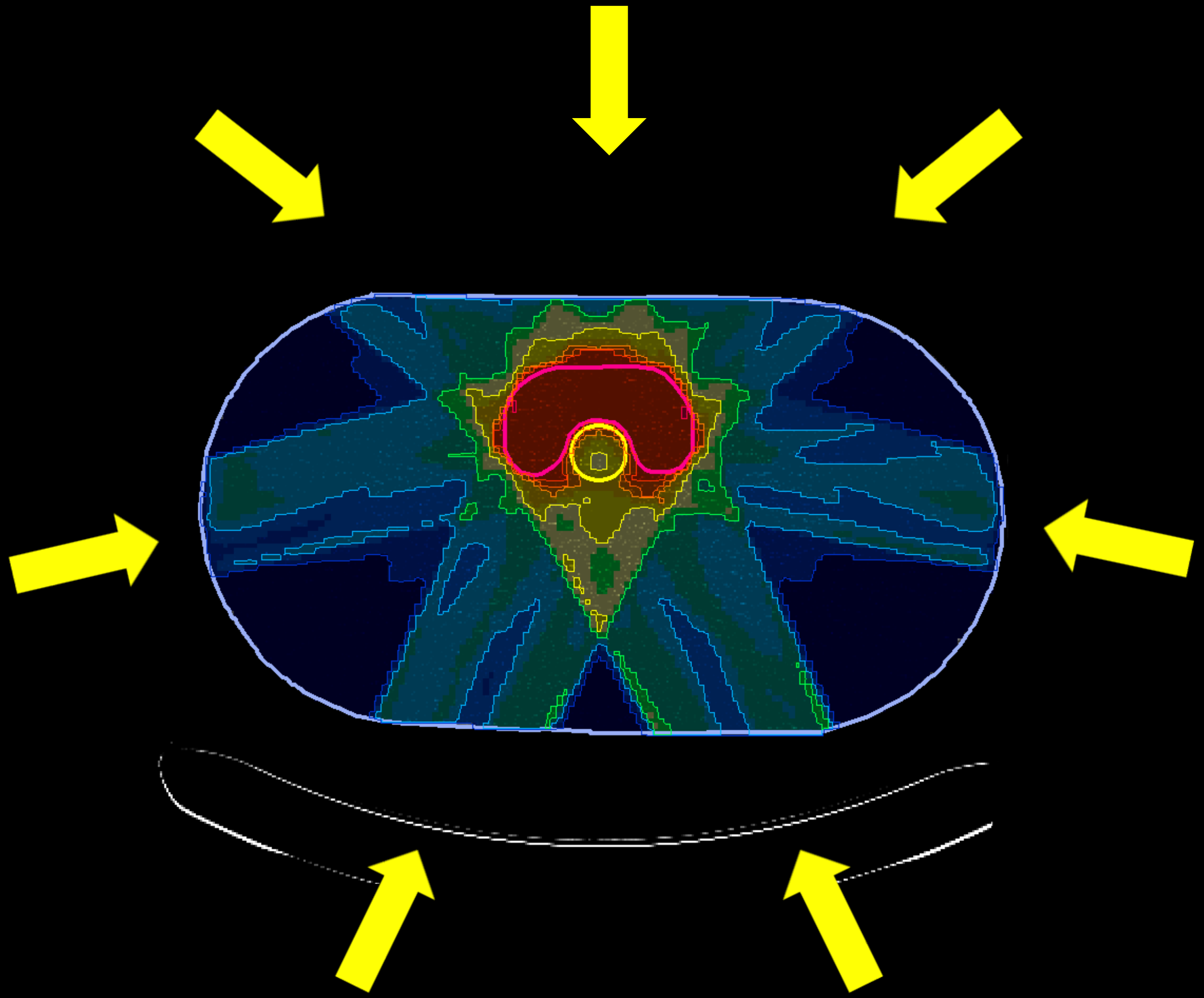
Optimizing the weights – finding the minimum by Newton's method

1. starting point
2. calculate objective function
3. gradient / derivation
4. search direction
5. step size
6. back to step 2



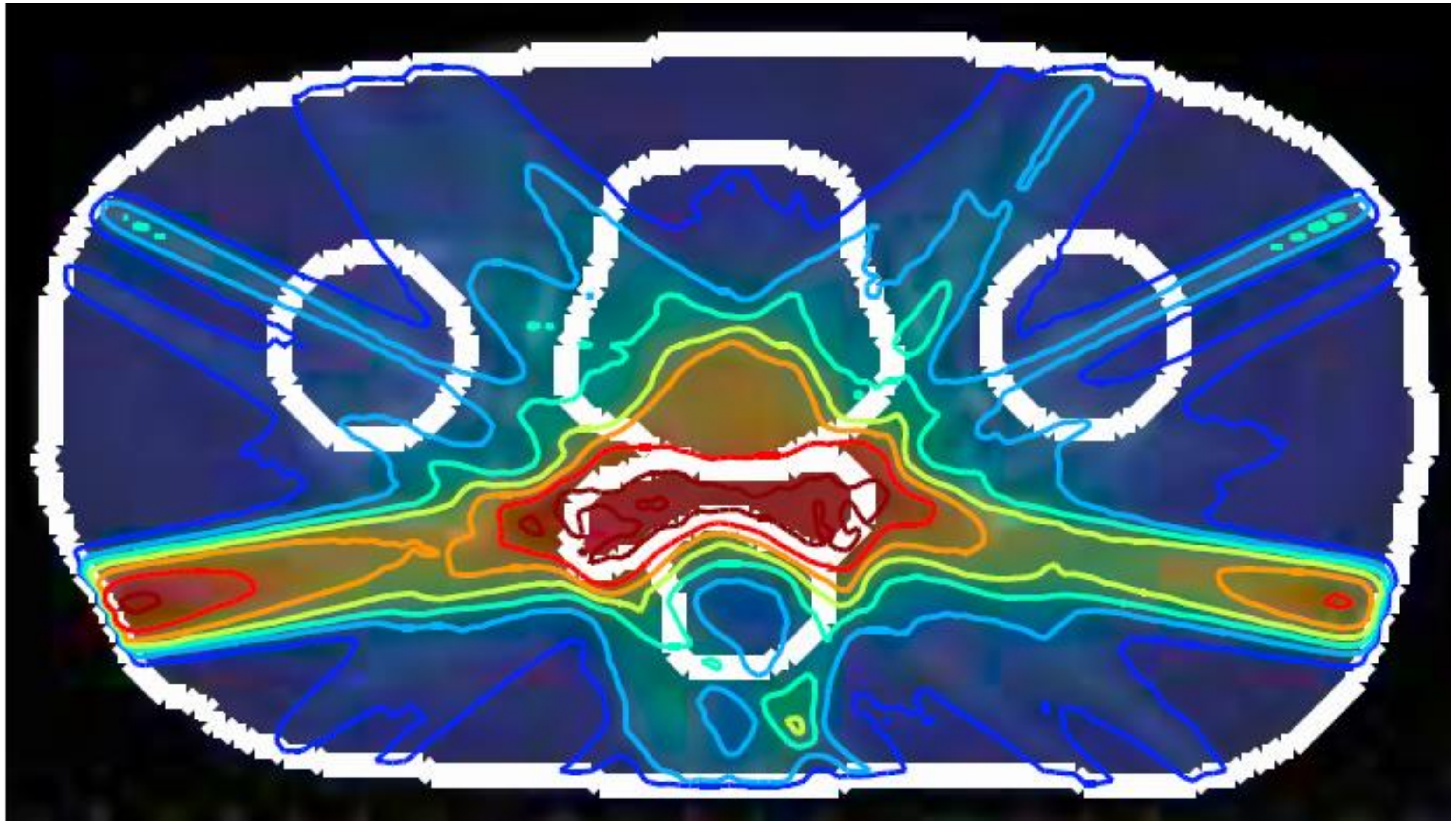
dimensionality: 10^3

Intensity modulated treatment plan – dose distribution



How do we analyze a plan / a dose?

Evaluation of the
2D tomographic images



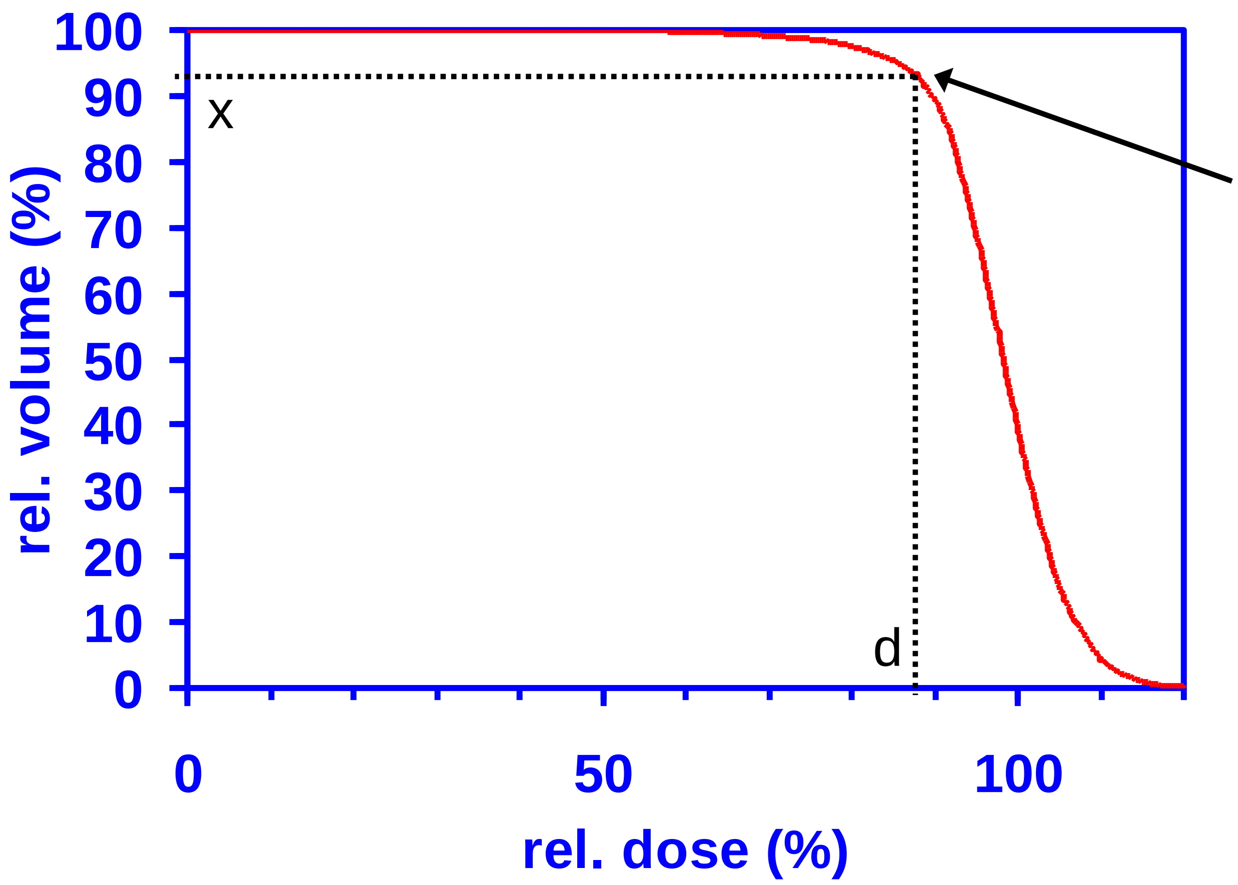
Dose statistics:

Mean, maximum, minimum dose

Dose-volume histograms

2D display of the 3D dose distribution

Dose-volume histograms

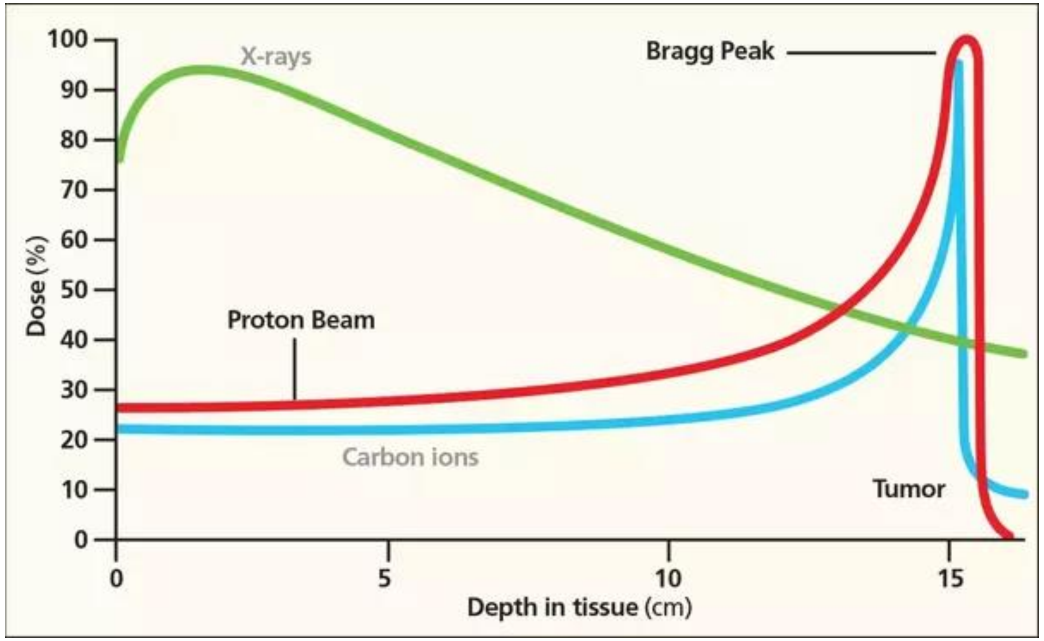


x% of the volume obtains at least d% of the prescribed dose

With particles it gets much better…

- particle accelerators produce “natural“ pencil beams

  improved dose distribution (Bragg-Peak) in theory



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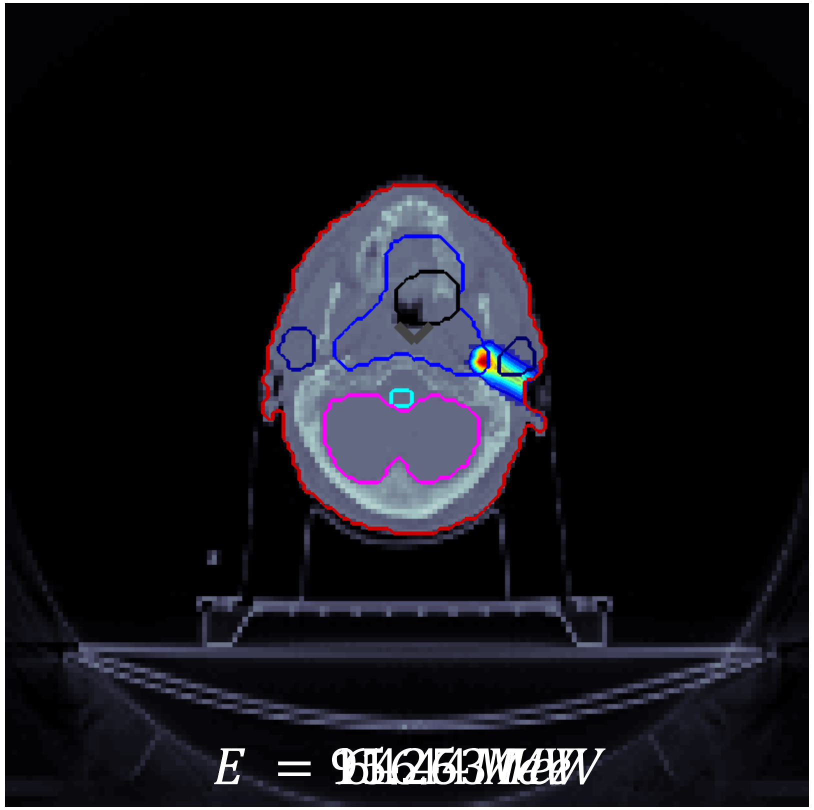
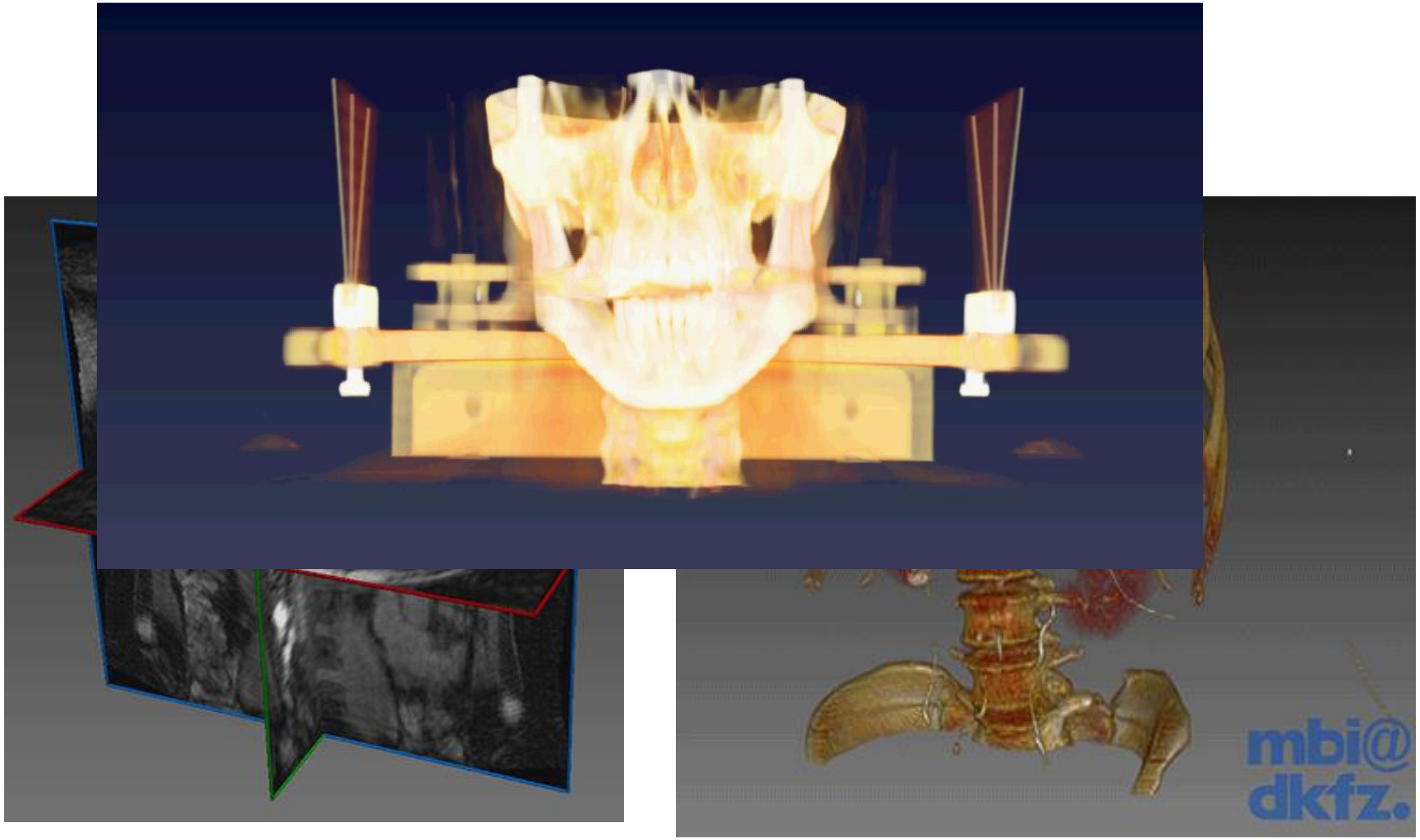


[1] Quora – In which ways could gold atoms, protons or neutrons be brought safely into human brain tissue – lBragg Peak and the Proton Difference. Accessed from https://www.quora.com/In-which-ways-could-gold-atoms-protons-or-neutrons-be-brought-safely-into-human-brain-tissue on 15.02.2021.

Problem: Dealing with uncertainties



Animations courtesy of Paul Merca & Markus Stoll

Summary

- a CT with delineated organs / tumors servers as a basis for treatment planning
- we can calculate the dose in the CT
- using numerical optimization we are able to weight particle beams differently to obtain suitable dose distributions
- finally, we are able to statistically analyze our plans with dedicated methods (e.g. dose-volume histograms)

dkfz.

Questions?