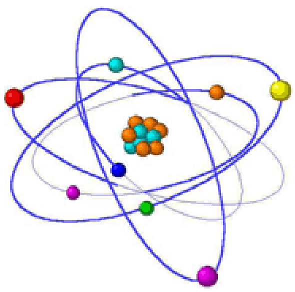
Radioisotope and Radiation Applications (FS2013)



Treatment Planning in Radiotherapy (Week 4b)

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15.10. 2013

Treatment Planning in Radiotherapy: Outline

- ❑ Introduction
- ❑ Treatment Planning with Photon Beams
- ❑ Treatment Planning with Electron Beams
- ❑ Treatment Planning in 3D-Conformal Radiotherapy
- ❑ Treatment Planning in Intensity Modulated Radiotherapy
- ❑ Computerized Treatment Planning
  - Components
  - Elements of dose calculations
  - Principle of Monte Carlo Calculations
  - Commercial Radiation Treatment Planning Systems (RTPS)
  - An example of a RTPS
- ❑ Literature

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Introduction

- Radiotherapy sessions must be carefully planned in order to:
  1. Deliver the desired radiation dose,
  2. to the largest volume of tumor tissue,
  3. while minimizing the adverse effects to the patient.
- **Treatment Planning** (TP) is the process in which a team consisting of radiation oncologists, medical physicists and medical dosimetrists plan the appropriate radiotherapy for a patient with cancer:
  - Typically, medical imaging (CT, MRI, PET) is used to form a virtual patient for a computer-aided design procedure.
  - Treatment simulations are used to plan the geometric and radiological aspects of the therapy using radiation transport simulations and optimization.
  - It involves selecting the appropriate beam type (electron or photon), energy (e.g., 6MV, 12MeV) and arrangements.
- Parts and parcels of TP are:
  - Determining the dose distribution: isodose curves in phantoms, or computed by computerized TP.
  - Adapting the dose distribution to the patient characteristics accounting for:
    - Heterogeneities in patient radiation field.
    - Patient positioning and motion.
    - Minimization of dose to skin and to non-cancerous tissue.
- Today, TP is almost entirely computer based using patient computed CT data sets.

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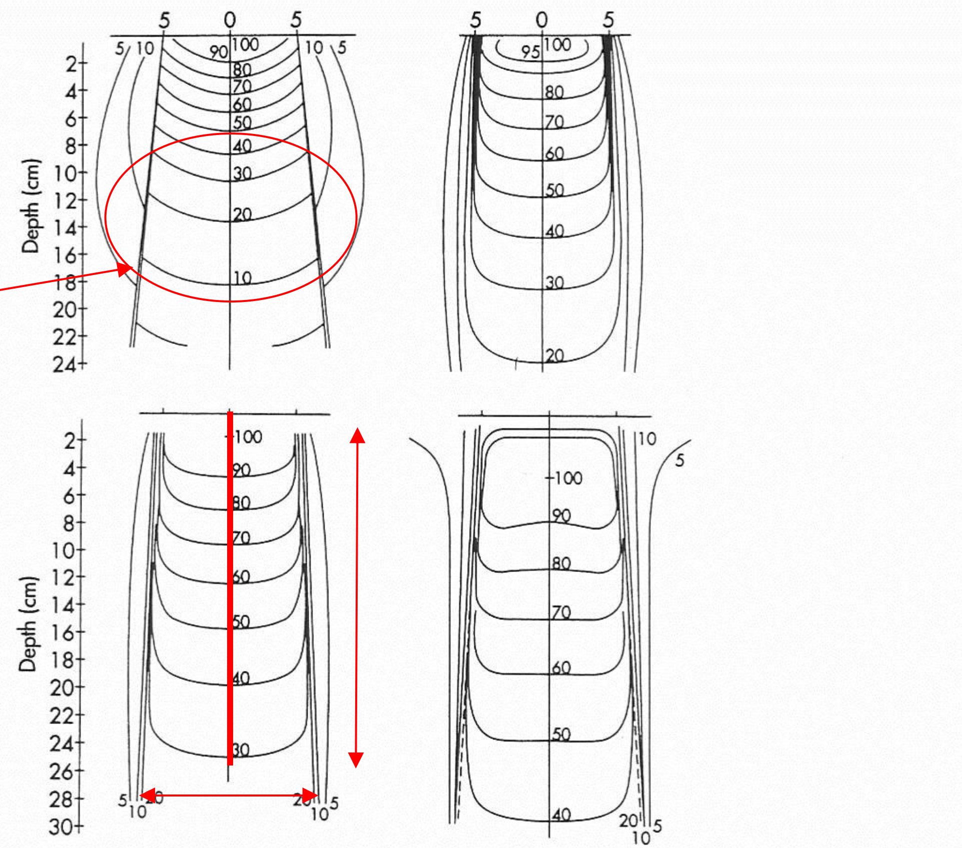
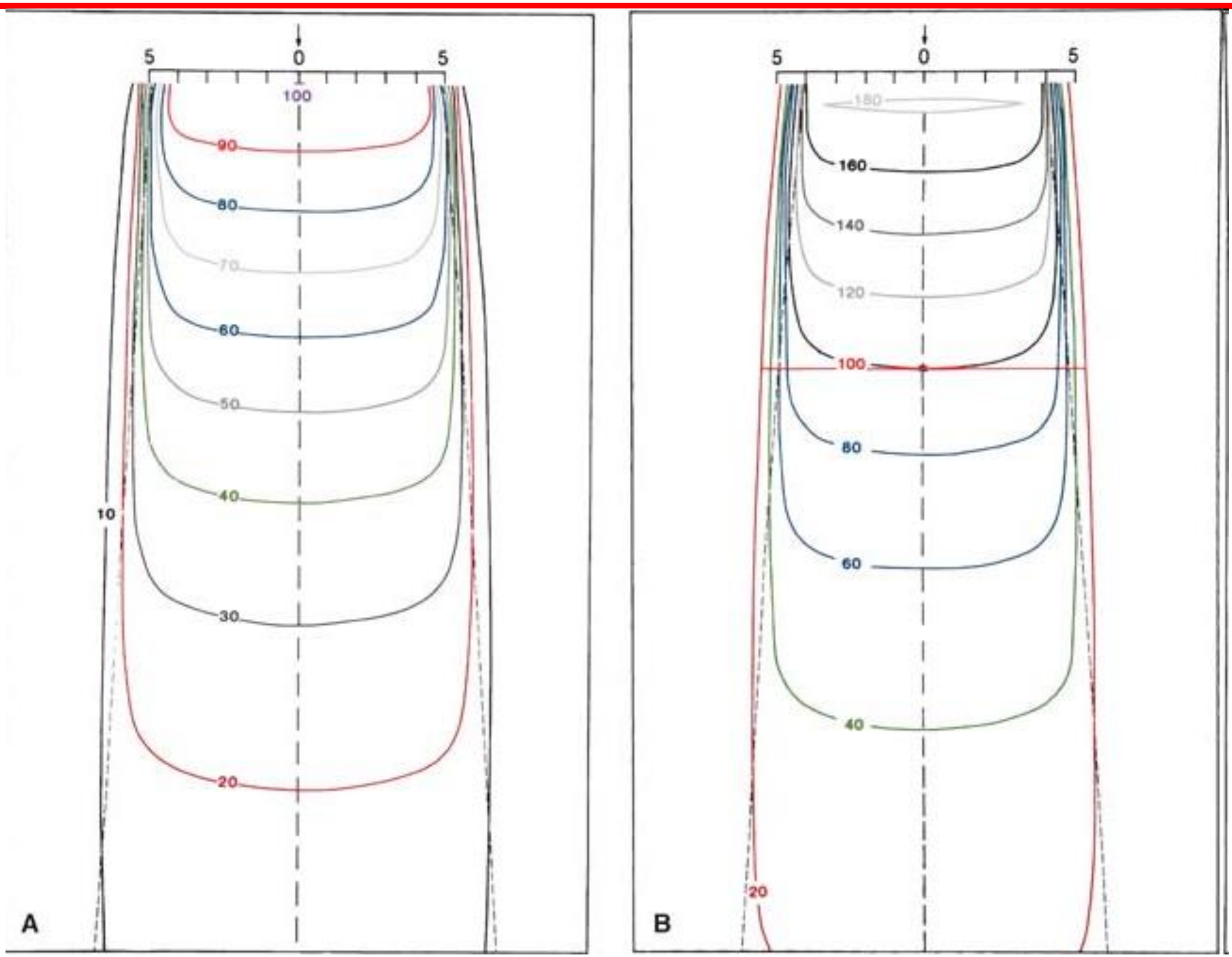
Treatment Planning: Isodose Curves (Chart)

- P (%DD), TAR, TMR determine the dose along the central axis of the radiation beam.
- The central axis depth dose distribution is not sufficient to characterize a 3-D radiation field.
- Real distributions are described by isodose curves.
- Isodose curves drawn at equal dose intervals form an **isodose chart**:
  - Represent percent dose depth as a function of:
    - Field depth.
    - Distance from central beam axis.
  - They are measured in phantoms by means of:
    - Ion chambers,
    - Solid state detectors.
    - Radiographic film.



Isodose distributions for four different qualities of radiation. **Upper left**, orthovoltage X rays (200 kVp, 10 × 10 cm, 50 cm *SSD*, 2.0 mm Cu HVL); **upper right**, 60 Co γ rays (10 × 10 cm, 80 cm *SSD*); **lower left**, X rays from a 6 MV linear accelerator (10 × 10 cm, 100 cm *SSD*); **lower right**, 20 MVX rays from a betatron (10 × 10 cm, 100 cm *SSD*). (From Hendee WR: Medical Radiation Physics, ed 1, Chicago, 1970, Mosby-Year Book. Used with permission.)

Two Types of Isodose Charts



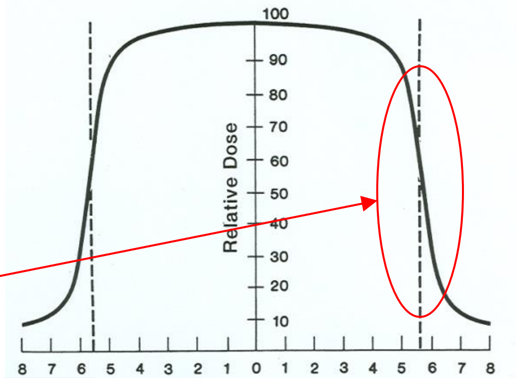
A: Source to surface distance (SSD) type, ^{60}Co beam, SSD=80 cm, field size=10×10cm at surface. **B**: Source to axis distance (SAD) type, ^{60}Co beam, SAD=100 cm, depth of isocenter=10cm, field size at isocenter=10×10cm.

Treatment Planning with Photon Beams

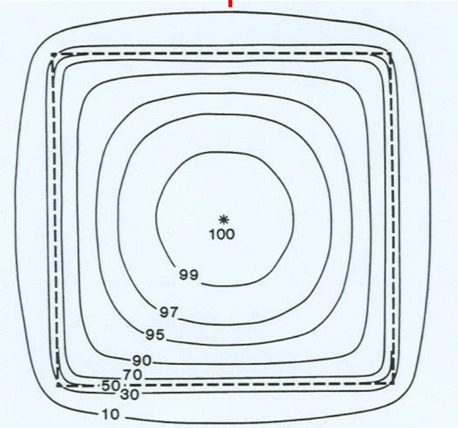
Properties of X-ray and γ-ray dose distributions:

- Dose at any depth is greatest on the central axis of the beam.
- Near the edges of the beam ("penumbra") the dose rate decreases rapidly.
- Near the beam edge, falloff of the beam is caused also by reduced lateral scattering:
  - physical penumbra better than geometric penumbra.
- Outside penumbra, the scattering and leakage from collimator and head are main factors.

"Beam profile"



Depth dose profile showing variation of dose across the field. ^{60}Co beam, SSD = 80 cm, depth = 10 cm, field size at surface = 10 × 10 cm. Dotted line indicates geometric field boundary at a 10-cm depth.



Cross-sectional isodose distribution in a plane perpendicular to the central axis of the beam. Isodose values are normalized to 100% at the center of the field.

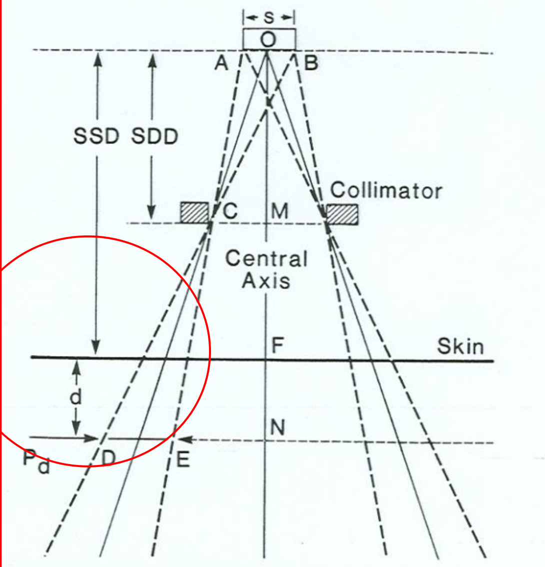


Diagram for calculating geometric penumbra.

Single and Multiple Beam Isodose Charts

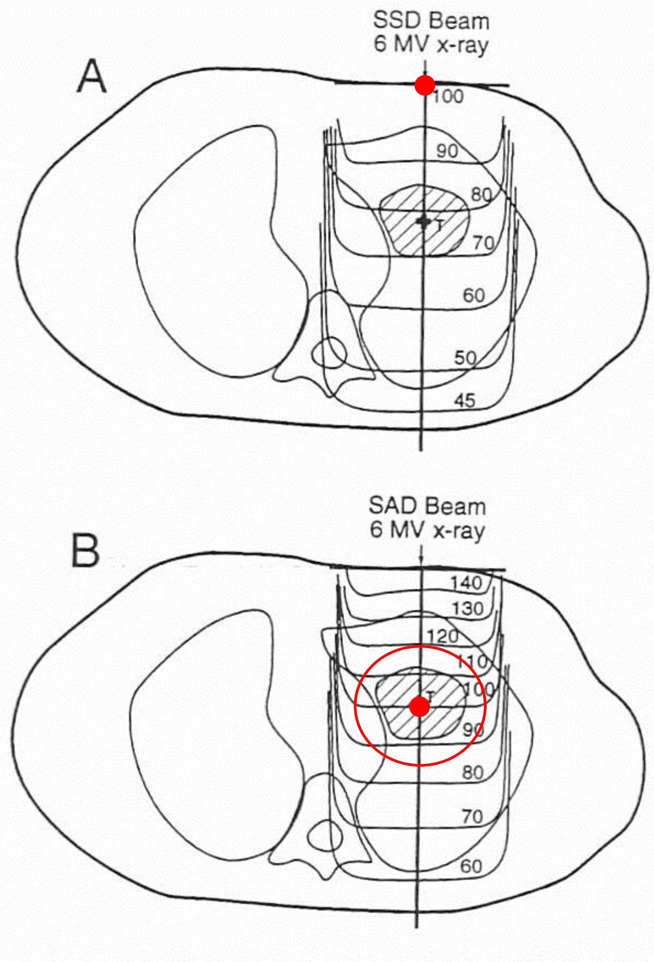
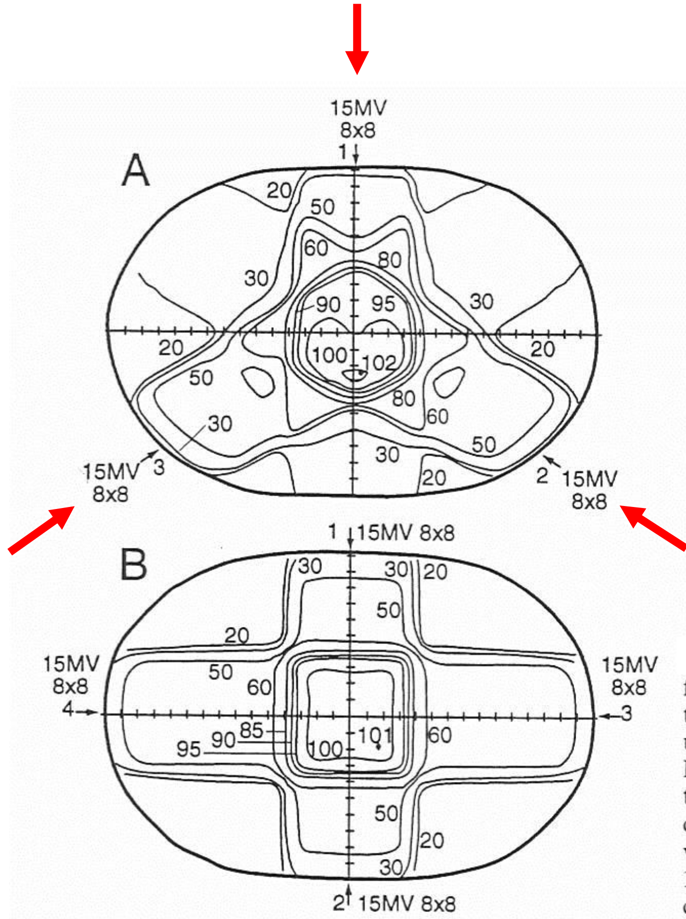


Diagram showing a 6 MV X ray beam treating a tumor of the lung. **A,** Fixed SSD technique. **B,** Isocentric technique.

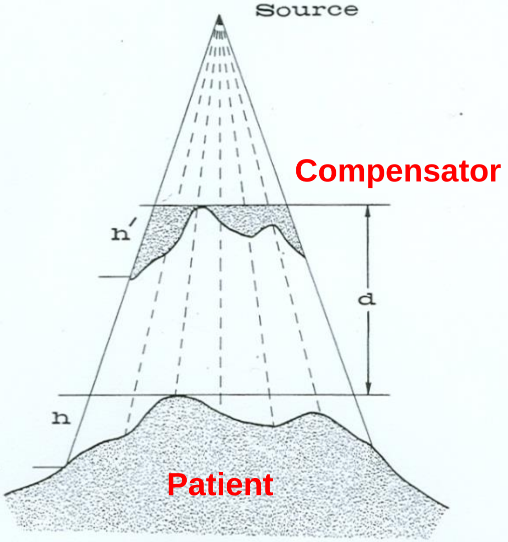


Examples of multiple field plans. **A**, Three-field isocentric technique. Each beam delivers 100/3 units of dose at the isocenter; 15 MV, field size = 8 × 8 cm at isocenter, *SAD* = 100 cm. **B**, Four-field isocentric technique. Each beam delivers 25 units of dose at the isocenter; 15 MV, field size = 8 × 8 cm at isocenter, *SAD* = 100 cm.

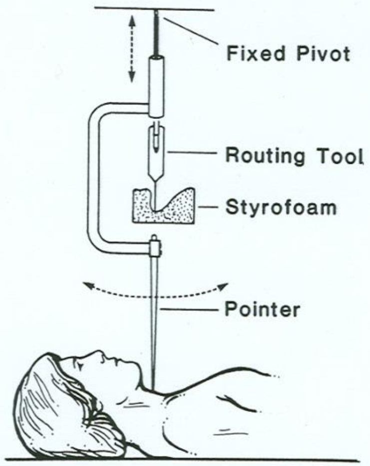
Considerations for Treatment Planning (1)

- **Basic depth-dose data and isodose charts are obtained for standard irradiation conditions.**
- But patients are not homogeneous with flat surfaces like phantoms.
- Accurate patient dosimetry is only possible when patient data are available.
  - Body contours, outlines and density of relevant internal structures.
  - Location and extend of target volume.
- **Acquisition of patient data is best accomplished by CT and MRI.**
- **Phantom based dosimetry must be corrected:**
  - For contour irregularities using:
    - Effective SSD, tissue-air-ratio and the (empirical) isodose shift method.
  - For tissue in-homogeneities:
    - Apply corrections for beam attenuation and scattering.
    - Absorbed dose modification taking into account dose of secondary electrons.
  - Tissue compensation:
    - Use of compensators provide the required beam attenuation in "missing" tissue.
  - Patient positioning and immobilization.
    - Use of isocentric irradiation vs. SSD (fields arranged by gantry rotation vs. displacing patient).

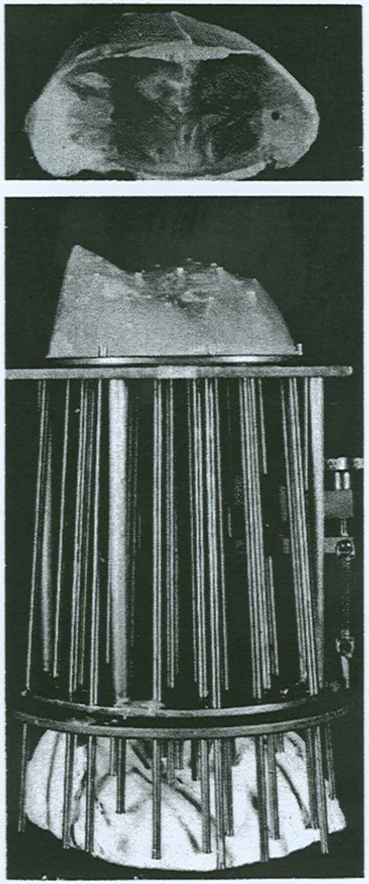
Tissue In-homogeneity Compensation



Schematic representation of a compensator designed for an irregular surface. (From Khan FM, Moore VC, Burns DJ. The construction of compensators for cobalt teletherapy. *Radiology* 1970;96:187, with permission.)



Schematic diagram of a Styrofoam cutter fitted with a routing tool for constructing compensators. (Redrawn from Boge RJ, Edland RW, Mathes DC. Tissue compensators for megavoltage radiotherapy fabricated from hollowed Styrofoam filled with wax. *Radiology* 1974;111:193, with permission.)



An apparatus for the construction of 3-D compensator in one piece. (From Khan FM, Moore VC, Burns DJ. An apparatus for the construction of irregular surface compensators for use in radiotherapy. *Radiology* 1968;90:593, with permission.)

Considerations for Treatment Planning (2)

- **Shielding of vital organs** within a radiation field is one of the major concerns of radiotherapy and **can be performed with thin sheets of lead**.
  - Protect critical organs.
  - Avoid unnecessary irradiation of tumor surrounding tissue.
- **Field shaping**
  - Dictated by tumor distribution: Local extension and regional metastases.
  - Is most commonly achieved **with blocking devices made of Cerrobend®** (eutectic alloy of 50% bismuth, 26.7% lead, 13.3% tin, and 10% cadmium by weight).
  - **Multileaf collimators.**
- Minimize skin dose
  - Mainly of concern for low-E beams, skin sparing appealing feature of high-E beams.
  - However high-E beams have secondary e^- contamination. Can be reduced by using e^- filters, i.e., γ-ray absorbers of medium atomic number (Z in the range of 30–80).
- Field separation
  - For a too large treatment field, the target volume is divided in two parts.
  - Two independent courses of RT: avoid toxicity if a large mass is irradiated.
  - Dose in-homogeneity is a problem: hot spots (high dose) and cold spots (low dose).
  - Methods for matching of adjacent fields exist.

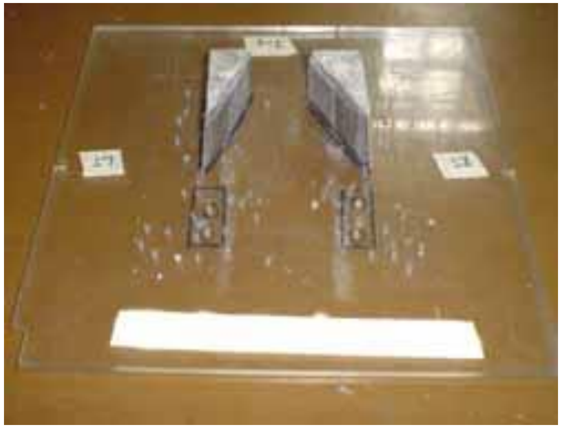
Devices: block cutter, immobilization mask, shielding blocks

Radiotherapy block cutter

http://www.huestismedical.com/HuestisMed/productpgs/

Immobilization mask for radiation therapy

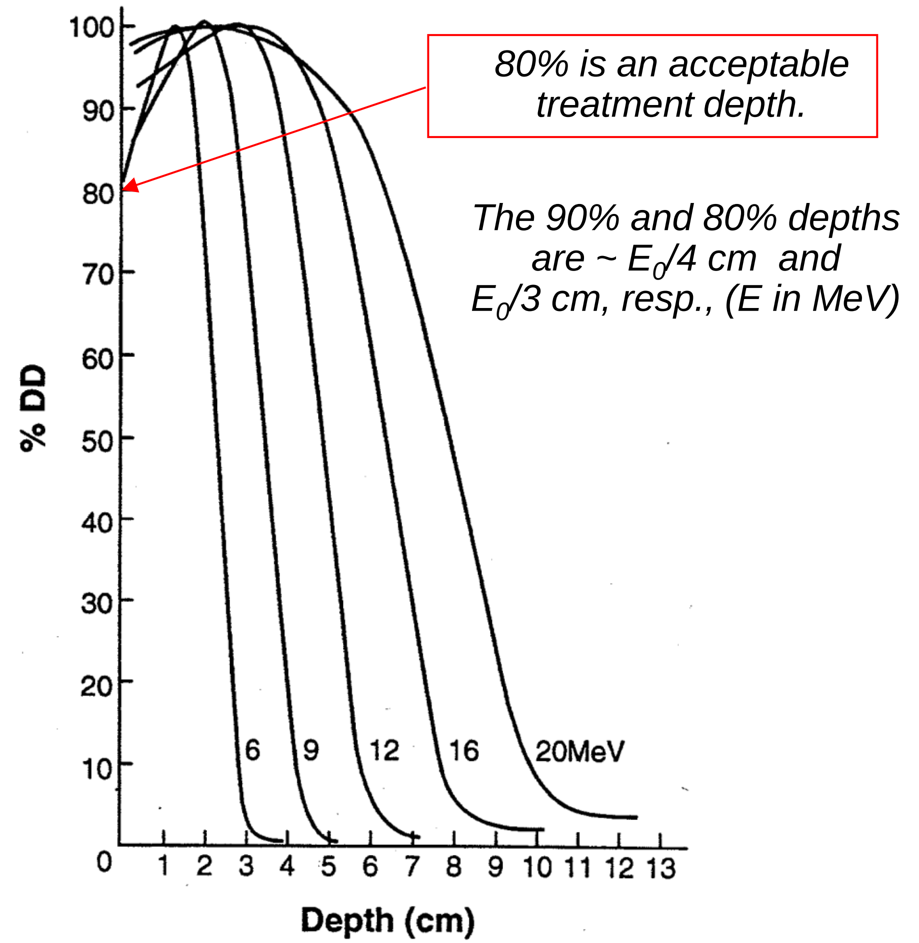
Shielding blocks for radiotherapy



http://www.wits.ac.za/medphysics/radoncology.html

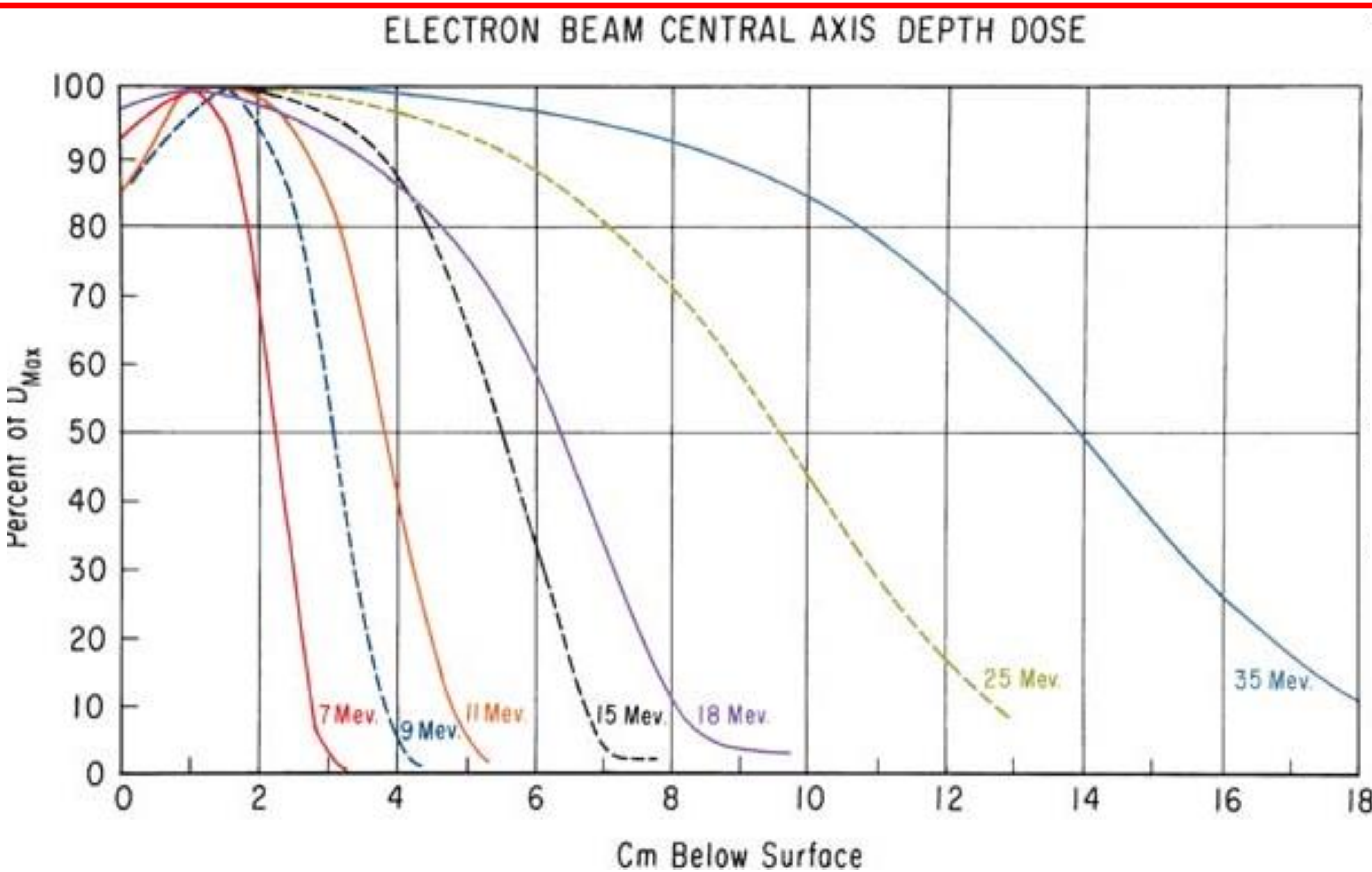
Treatment Planning with e⁻ Beams: Beam Characteristics

- The important beam properties to consider are:
  - Central axis depth dose.
  - Isodose distribution.
  - Size and shape of tumor volume (sharp fall-off in depth dose).
  - Body contour and tissue inhomogeneity.
- Central axis depth dose
  - High surface dose. Build-up, especially for low-E e⁻ beams.
  - Independent of field size for large fields.
  - Usual therapy is done with a single beam at a standard SSD.



Central axis depth dose curves of 6, 9, 12, 16 and 20 MeV electron beams. The depth dose falls off sharply, particularly at the lower energies, and the surface dose increases with increasing energy.

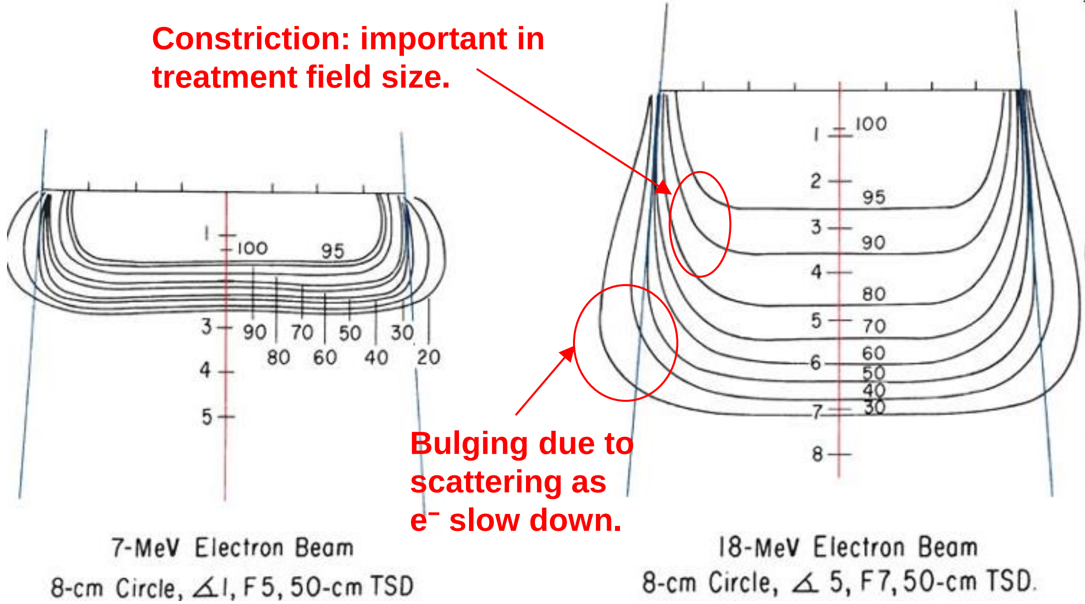
Shape of Isodose Curve depends on Scattering and Machine

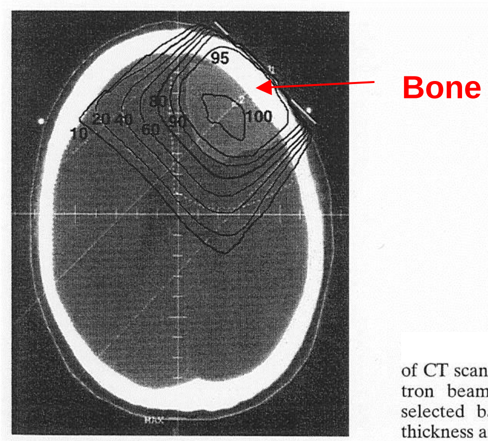


Comparison of central axis depth dose distributions of the Sagittaire linear accelerator (continuous curves) and the Siemen's betatron (dashed curves).

Treatment Planning with e^- Beams

- Isodose distribution:
  - Beam energy and field size determine the dose distribution.
  - Clinical applications include the tumor volume within 90% and 80% isodose.
  - "Bulging" and "constriction" depending on the beam energy.
  - Edge effects are important when matching two adjacent e^- beams.
- Tissue in-homogeneities:
  - Significantly affect the dose distribution, which must be corrected for the effect.
  - Clinically:
    - Bone (head and neck treatment) has a higher e^- density: shadowing effect.
    - Lung tissue has lower e^- density, beam penetrates deeper.





Picture illustrating the application of CT scan in treatment planning with an electron beam. Beam energy and field size is selected based on tumor volume and bone thickness and its density relative to water.

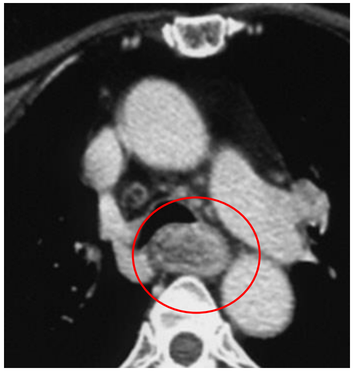
Treatment Planning in 3D-CRT

- Requirements:
  - 3D anatomic information, i.e., images of high quality:
    - in most cases from CT or MRI in transverse sections (slices),
    - but also from ultrasound, SPECT, and PET.
  - A treatment planning system that optimizes dose distribution according to the clinical objectives.

- Process steps in treatment planning (**forward planning**):
  - **Registration:** correlate different image data sets to identify structures.
  - **Segmentation:** outline of target volumes in each slice (PTVs).
  - **Treatment field and beam design:** using 3D treatment planning software.
    - Set field margins (distance between field edge and the PTV outline)
    - Taking account of penumbra regions cover the entire PTV with sufficiently high dose and spare the sensitive tissues.
  - **Optimization** of a treatment plan requires:
    - Design of optimal field apertures.
    - Appropriate beam directions, number of fields, and beam weights.
    - Intensity modifiers like wedges, compensators, and dynamic multileaf collimators.

- One of the most useful features in computer software supporting 3D-CRT are graphic systems that allow beam's-eye-view (BEV) visualization of the delineated targets and other structures:
  - display in a plane perpendicular to the central axis of the beam,
  - as if being viewed from the vantage point of the radiation source.

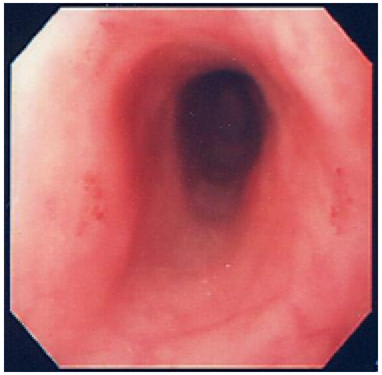
3D-CRT: Imaging and Planning



MRI or CT: identification

Radiography (contrast: extension)

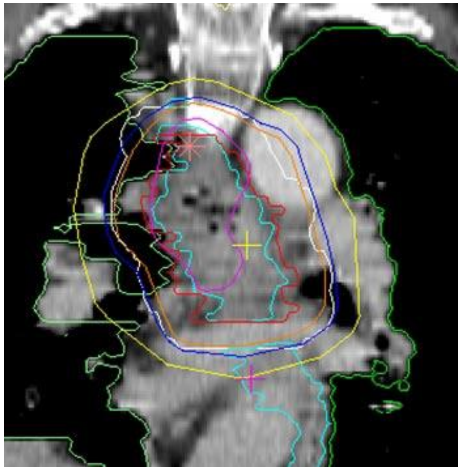
Imaging Techniques

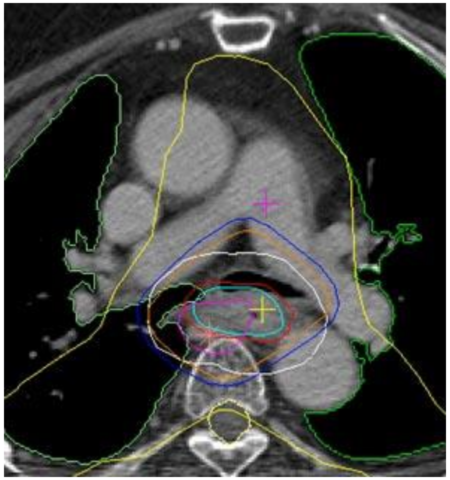


Endoscopy: clear view , anatomical identification

- The definition of the tumor volumes (PTV) is made by using several diagnostics techniques

Contour Determination for ORGANS, TISSUES and LESIONS





IMRT: Treatment Planning (1)

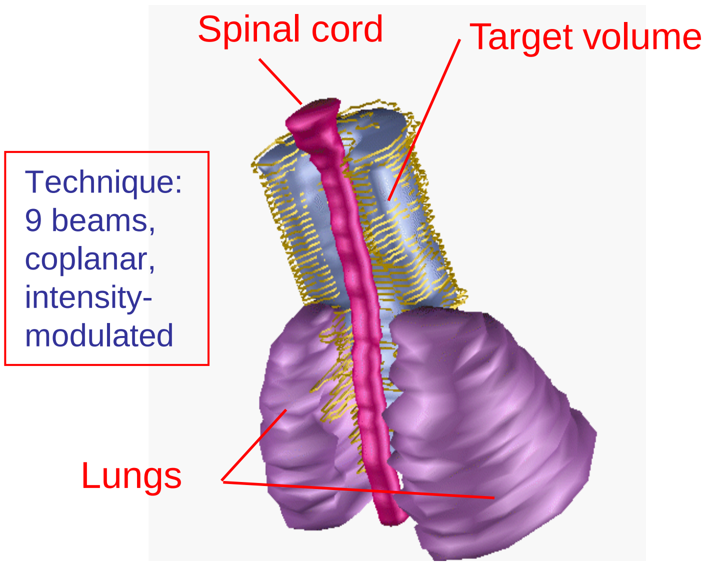
- Treat patient with beams from a number of different directions (or continuous arcs).
- Divide each beam into a large number of *beamlets*.
- The objective is to determine the optimal values of their intensities or weights.
- The optimization is done through inverse planning:
  - Beamlet intensities are adjusted to satisfy predefined dose distribution criteria for the composite plan.
  - Done using computer methods of two broad categories:
    - **Analytic**: similar to CT reconstruction, but with possibility of negative weights.
    - **Iterative**: similar to optimization methods with "cost functions" of the form:

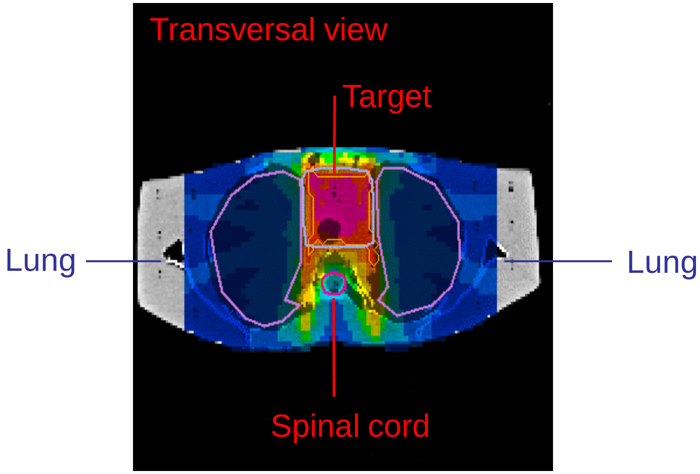
$$C_n = \left[\left(\frac{1}{N} \right) \sum_r W(\vec{r}) \left(D_0(\vec{r}) - D_n(\vec{r}) \right)^2 \right]^{0.5}$$

$D_0(r)$=desired dose at point r, W(r)=weight, r is mapped over target and critical structures.

IMRT: Treatment Planning (2)

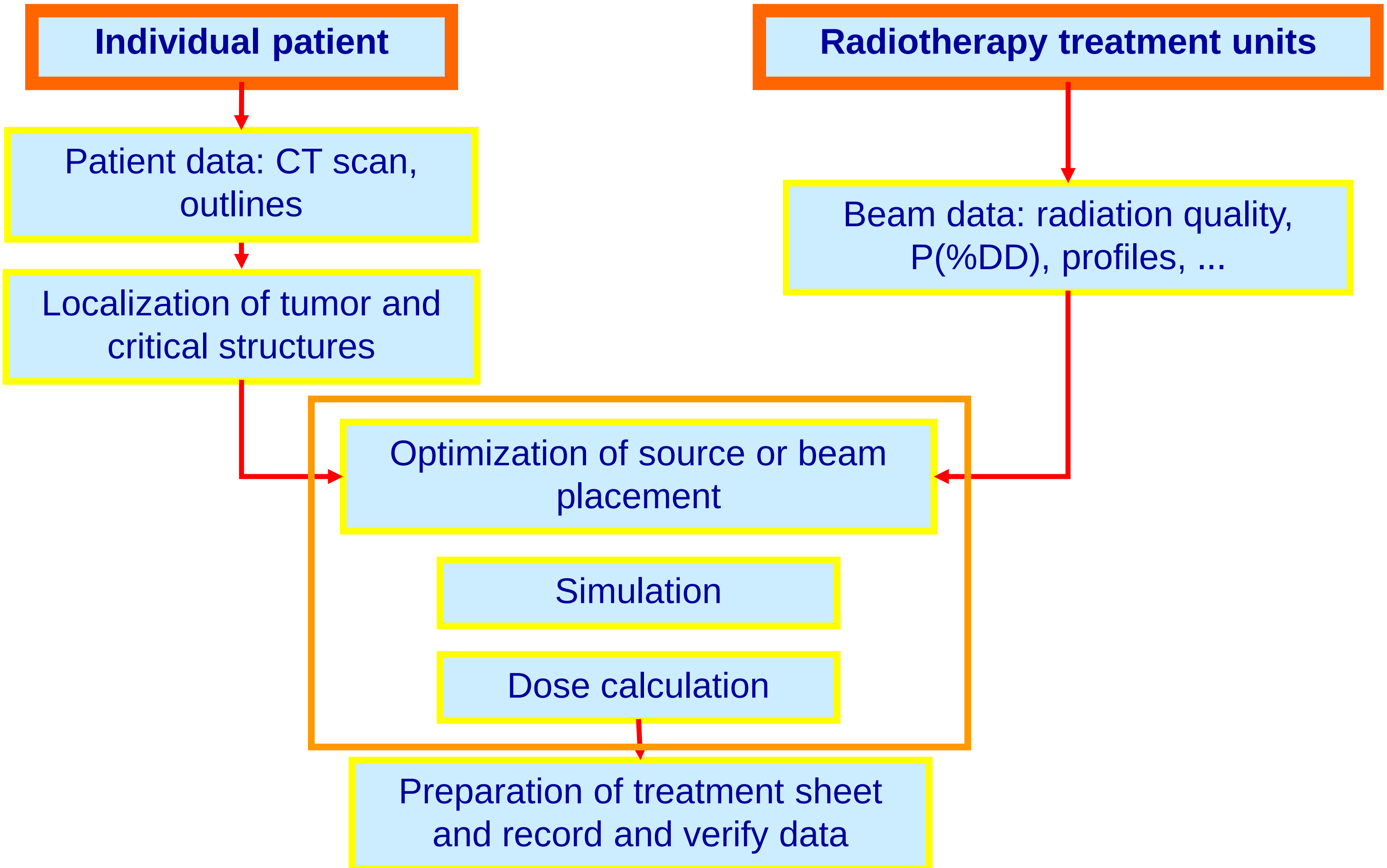
- Patient input data:
  - Same as for the **forward planning** performed in 3D-CRT.
    - 3-D image data.
    - Image registration.
    - Image segmentation.
- Information for each target volume (PTV):
  - Maximum dose.
  - Minimum dose.
  - Dose volume histogram.
- Information for critical structures:
  - Desired limiting dose.
  - Desired dose volume histogram.
- Output:
  - Delivery information.
  - Isodose charts: orthogonal projections, individual slices, 3D surfaces.
  - Calculated dose volume histograms.





www.cri.haifa.ac.il/events/2004/imrt2004/presentations/bortfeld_use.ppt

Computerized Treatment Planning: Components



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Elements of Dose Calculations

- Dose calculation algorithm
- Software coding and implementation
- Beam data
- Clinical set-up (data entry options, macros, evaluation sheet, hardcopy devices)

Photon Dose Calculation Approaches

Data measured in water and air

Parameterized water data

"Correction" based methods

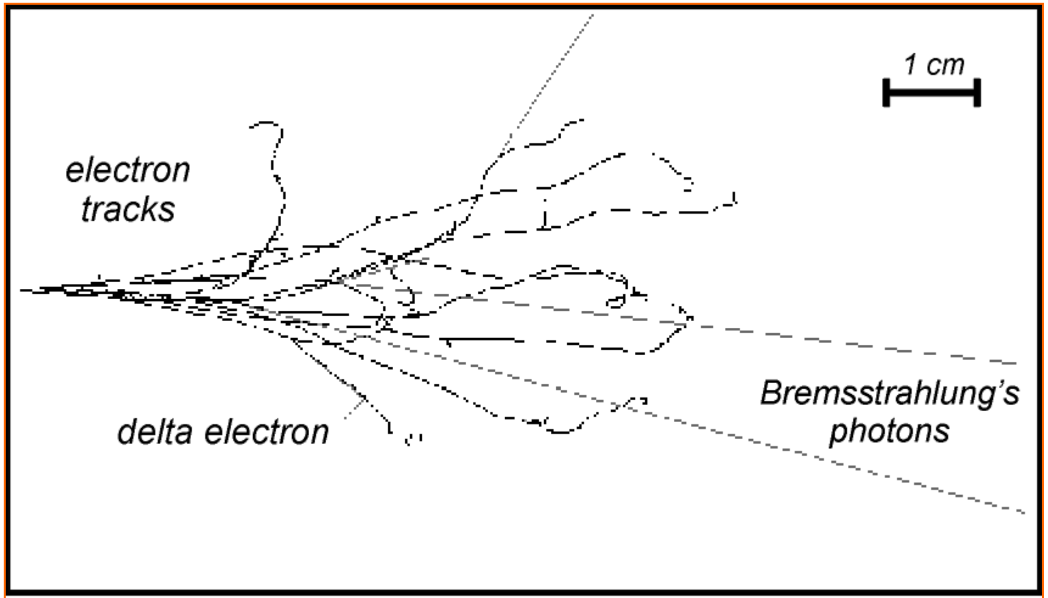
- Conventional approach.
- Measured data used to create data which (hopefully) are adequate for patient treatment.

"Model" based methods

- Most recent planning systems use this.
- Measured data only used to tune and verify a beam model.
- Examples: Superposition/convolution, **Monte Carlo Calculations**.

Principle of Monte Carlo Calculations

- Produce very accurate data:
  - Calculates the path of individual particles using ‘random’ decisions.
  - Interaction models for particles based on physical principles.
  - Possibility to consider many types of interaction and particles.
  - Tracking of secondary particles.
  - Uncertainty depends on number of particle histories.
- Highly computer intensive.
- Codes:
  - Peregrine
  - GEANT
  - MCNP
  - PENELOPE



Tracks of ten 12MeV electrons in water as calculated using Monte-Carlo calculations. Bremsstrahlung’s photons and delta electrons can also be seen.

Commercial Radiation Treatment Planning Systems (RTPS)

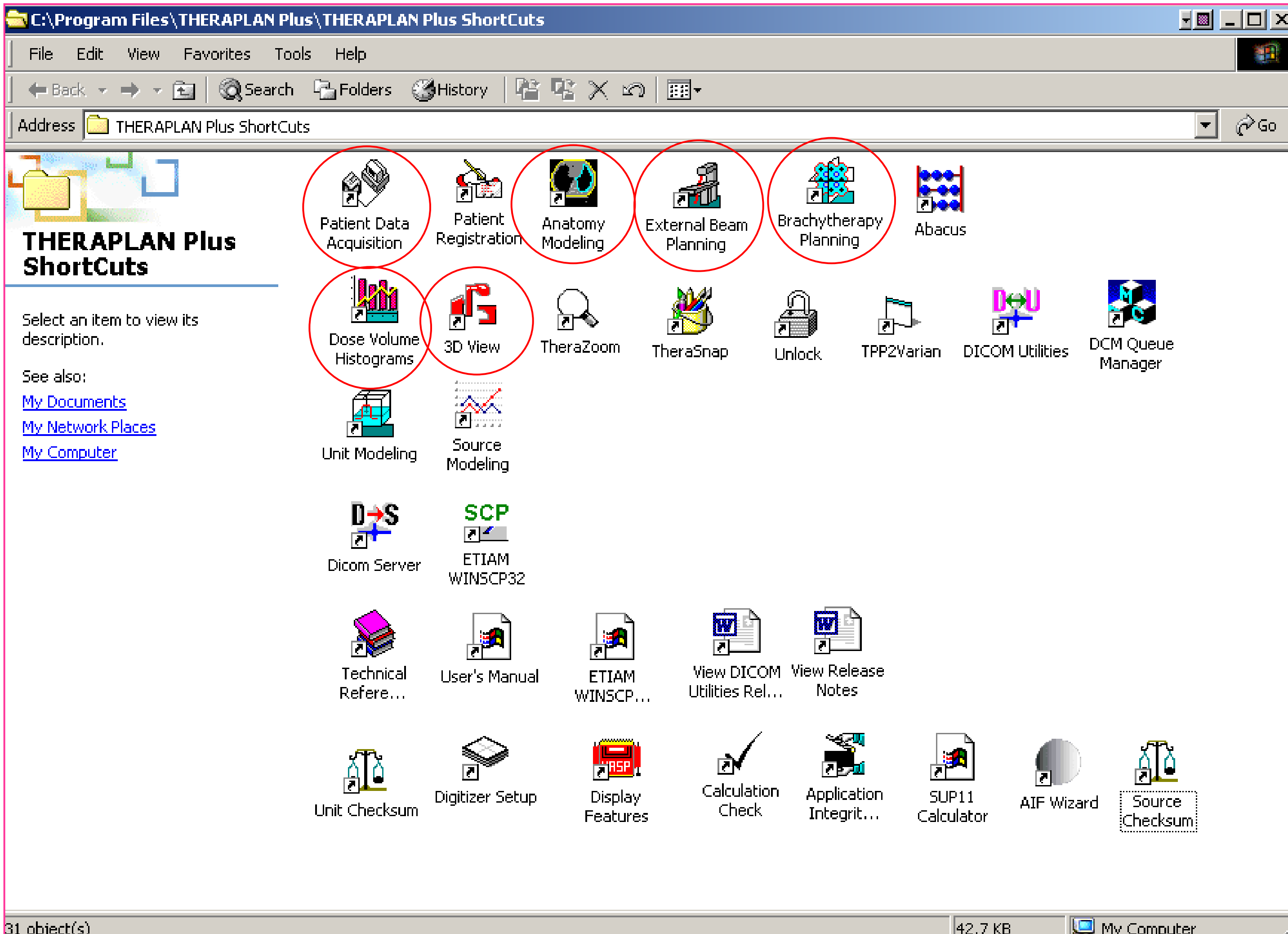
- ADAC -> Pinnacle3(Philips Healthcare)
- BrainSCAN -> BrainLAB
- CAT3D -> Mevis
- Focus -> XiO (CMS, recently purchased by Elekta)
- iPlan RT Dose -> BrainLAB
- Render-Plan 3-D -> PrecisePLAN (Elekta)
- MonacoCMS)
- **Theraplan Plus** (Theratronics -> Nucletron)
- Oncentra MasterPlan - External Beam and Brachy Therapy (Nucletron)
- Plato RTS (Nucletron)
- Plato BPS (Nucletron)
- Cad Plan -> Eclipse(Varian Medical Systems)
- Corvus(Nomos)
- RAHD
- ROCS
- GE
- Prowess
- Brachyvision (Varian)
- Gammaknife (Elekta)
- RIT
- ISOgray (DOSIsoft)

Quality Assurance of Treatment Planning Computer Systems

- Generally: The term quality assurance (QA) describes a program that is designed to control and maintain the standard of quality set for that program.
- Acceptance testing and commissioning of the treatment-planning computer system include:
  - Hardware tests: checking the accuracy and linearity of input digitizers, output plotters, and printers.
  - Software testing:
    - algorithm verification: its precision, limitations, and special features.
    - code validation: checking the accuracy of dose distributions for a selected set of treatment conditions against measured distributions, benchmarks, or manual calculations.
- It is imperative for the user to understand the algorithm as it pertains to beam generation, normalization, beam weights, contour corrections, field blocking, off-axis distribution, asymmetric collimation, tissue heterogeneities, wedged beams, blocked wedged beams, etc.
- It is the responsibility of the medical physicist to oversee proper use of the system and interpretation of the treatment plan.
- A periodic quality assurance program is designed to maintain the system within its acceptable performance standards.

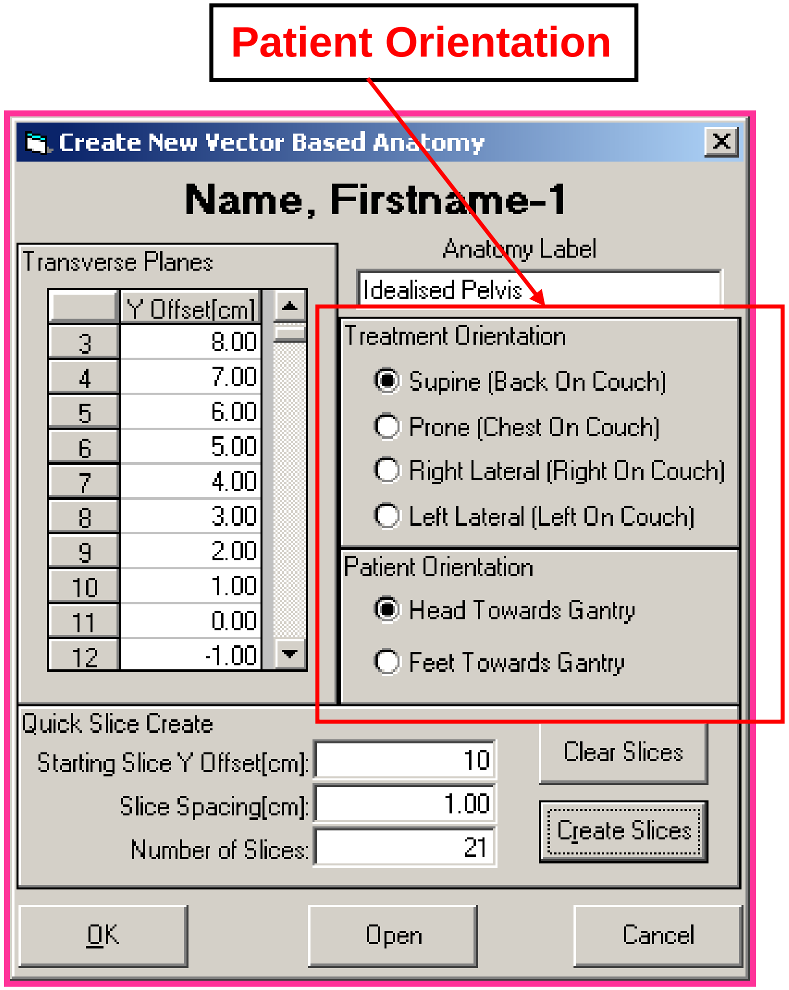
Example of a commercial RTPS (for Illustration)

- **THERAPLAN** Plus **(Windows or Linux Based Systems)**

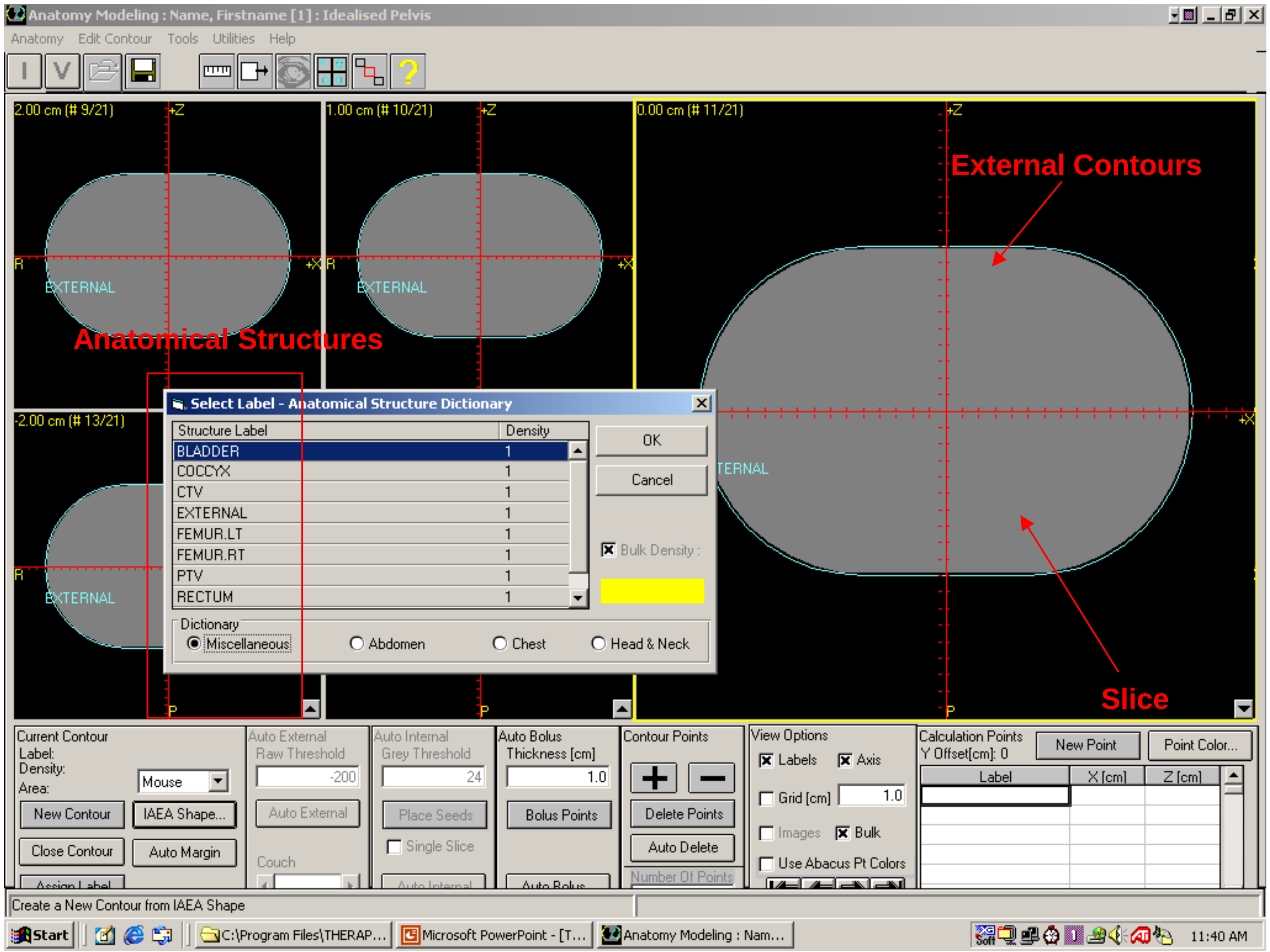


Patient Data Entry and Definition of Patient Anatomy

- May be from patient imaging data
  - Outlines
  - CT scans
- Can be
  - One slice
  - Many slices
- Here 21 slices in 1cm distance are created.

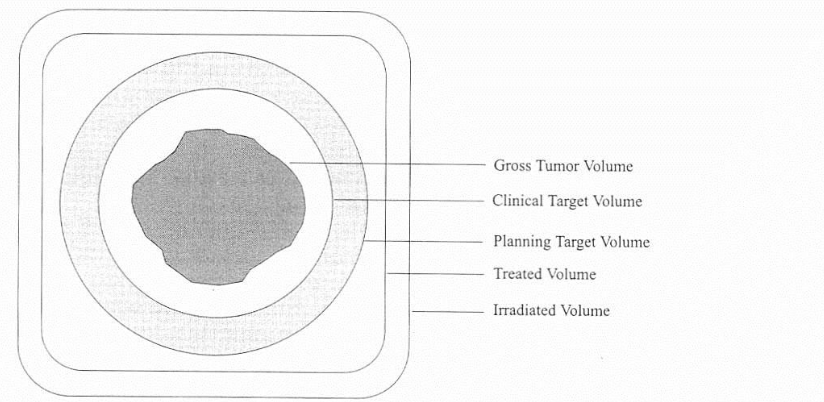


Creation of external contours on all slices

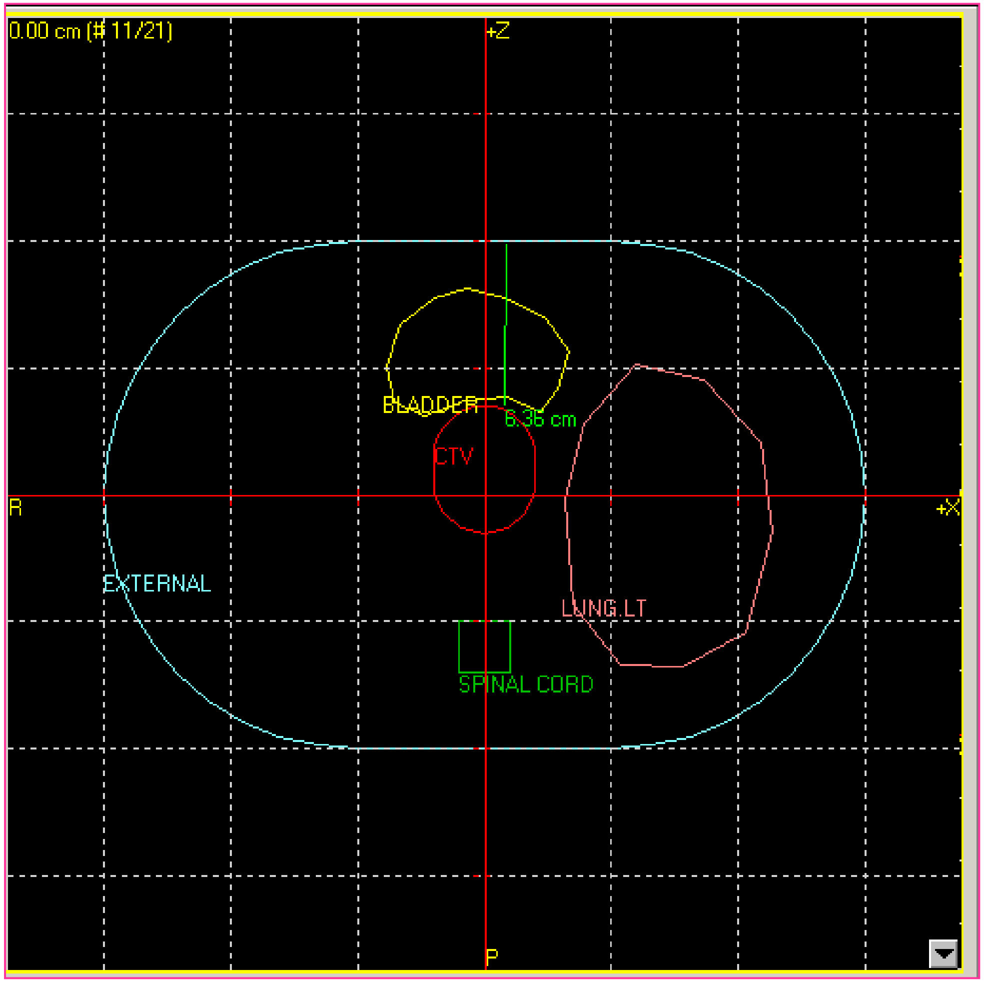


"Filling" the Patient Model

- A patient outline is filled with target structures (CTV=clinical target volume) and other organs of interest.

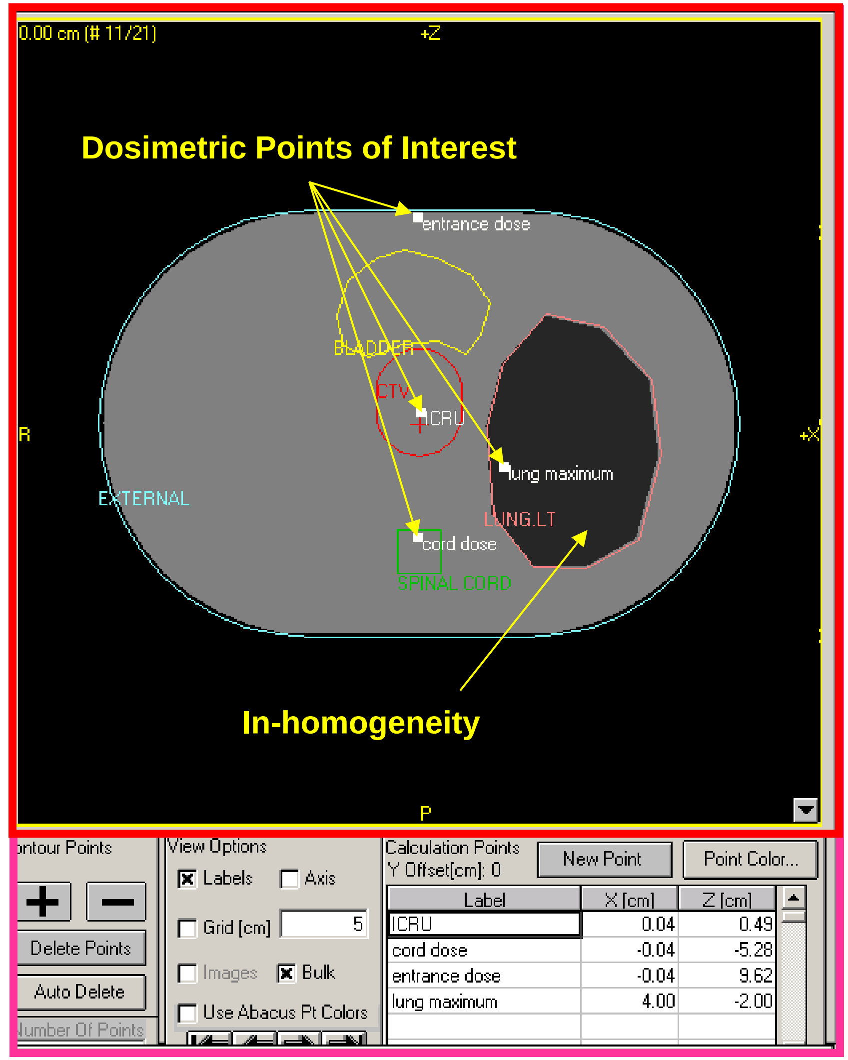


ICRU recommended volumes. (Adapted form IRCU Report 50, *Prescribing, recording, and reporting photon beam therapy,* Semptember 1993, Bethesda, MD.)

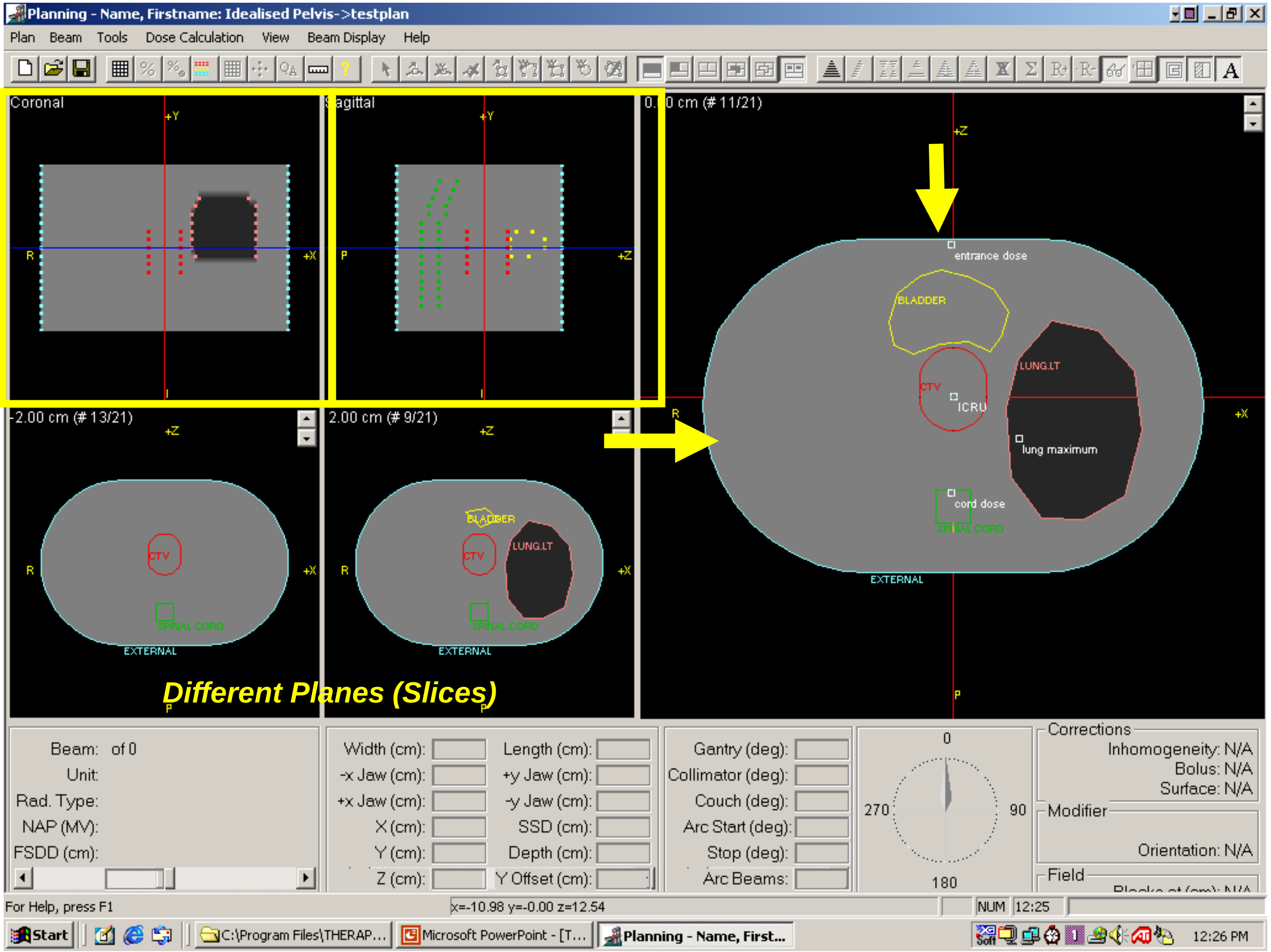


Dosimetry Points and In-Homogeneities

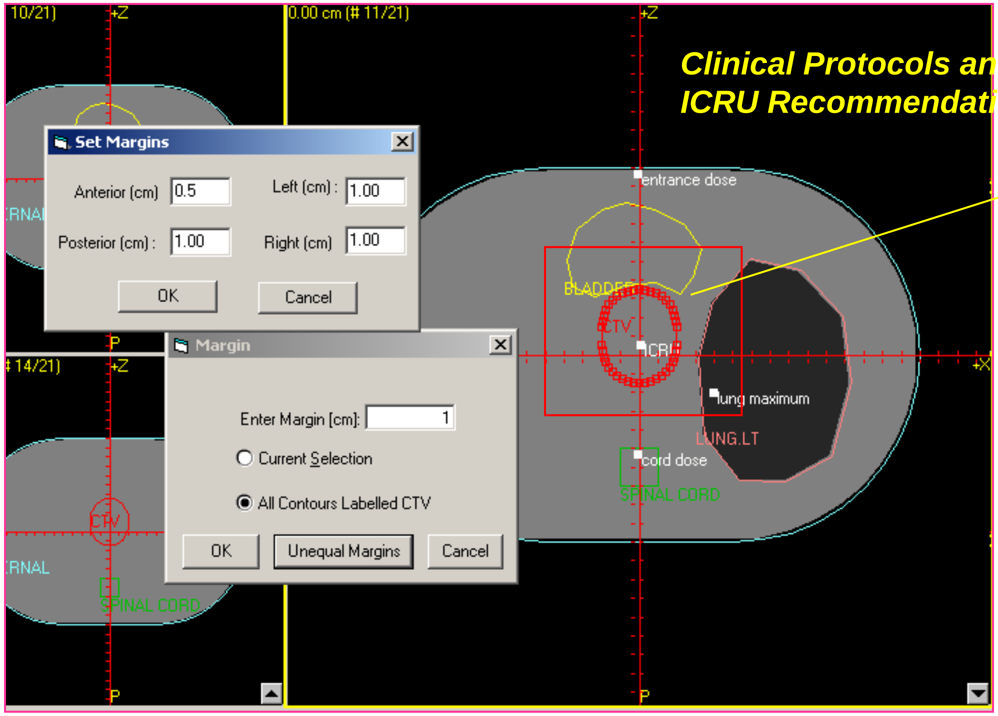
- Points of interest are added:
  - Dosimetric reference points and
  - Dose points relevant to effects in normal structures.
- In-homogeneities are included:
  - low density is associated with lung
- In case of a CT scan these are typically automatically created by the system.

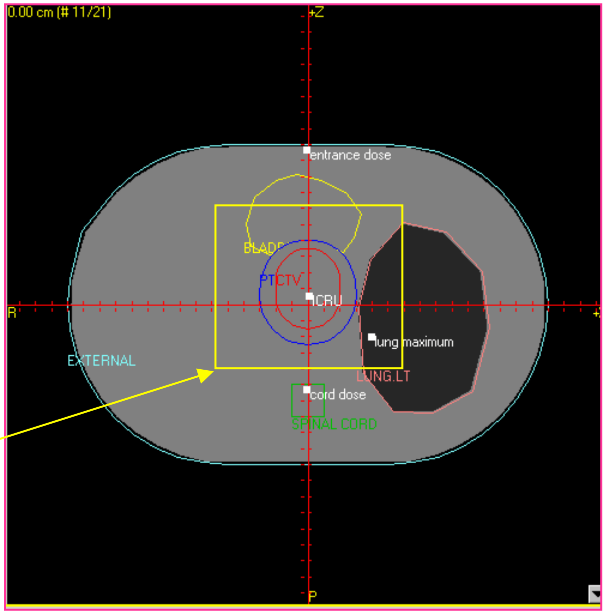


It is a 3-D Model

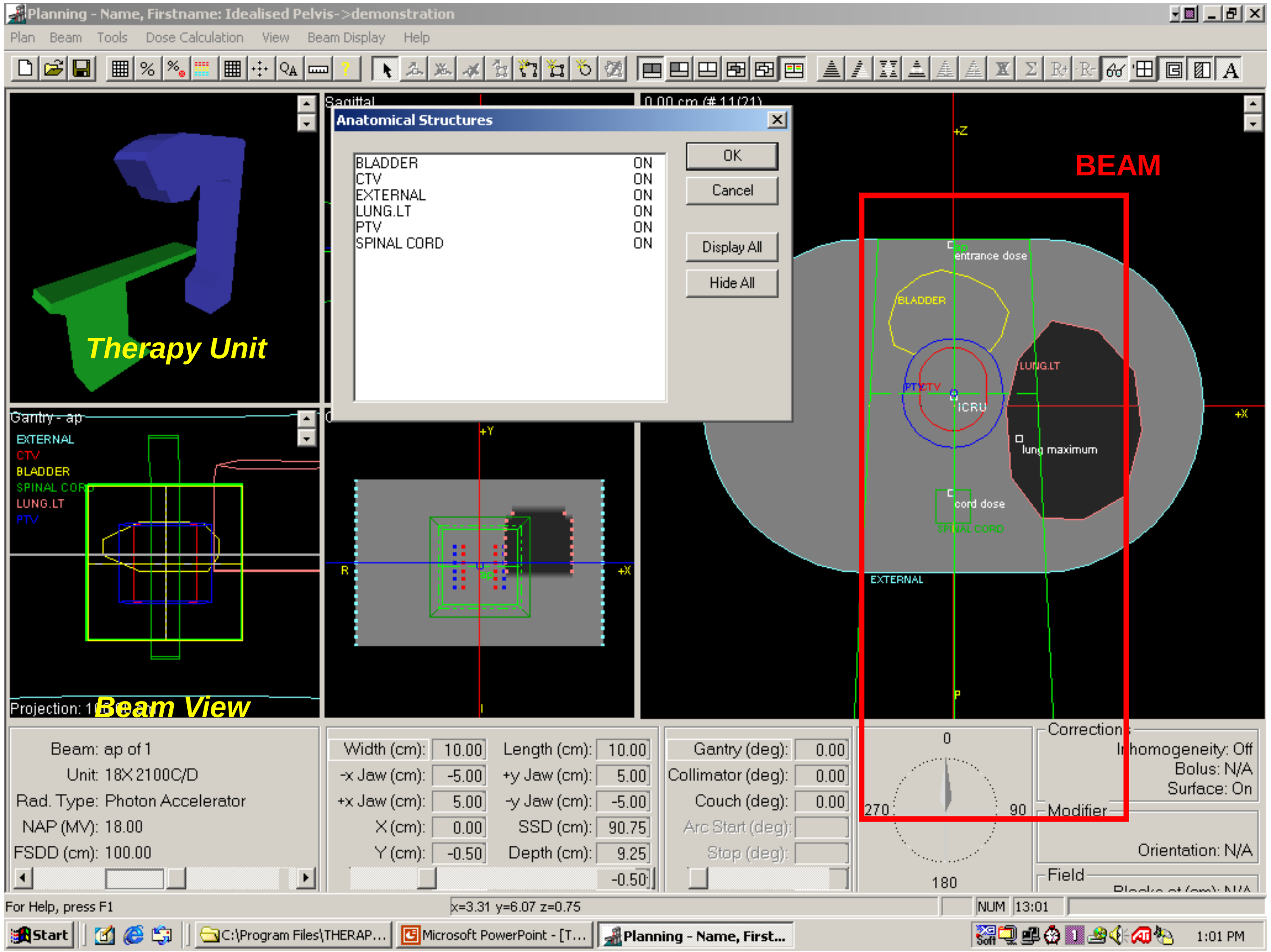


Creation of the Planned Target Volume (PTV)

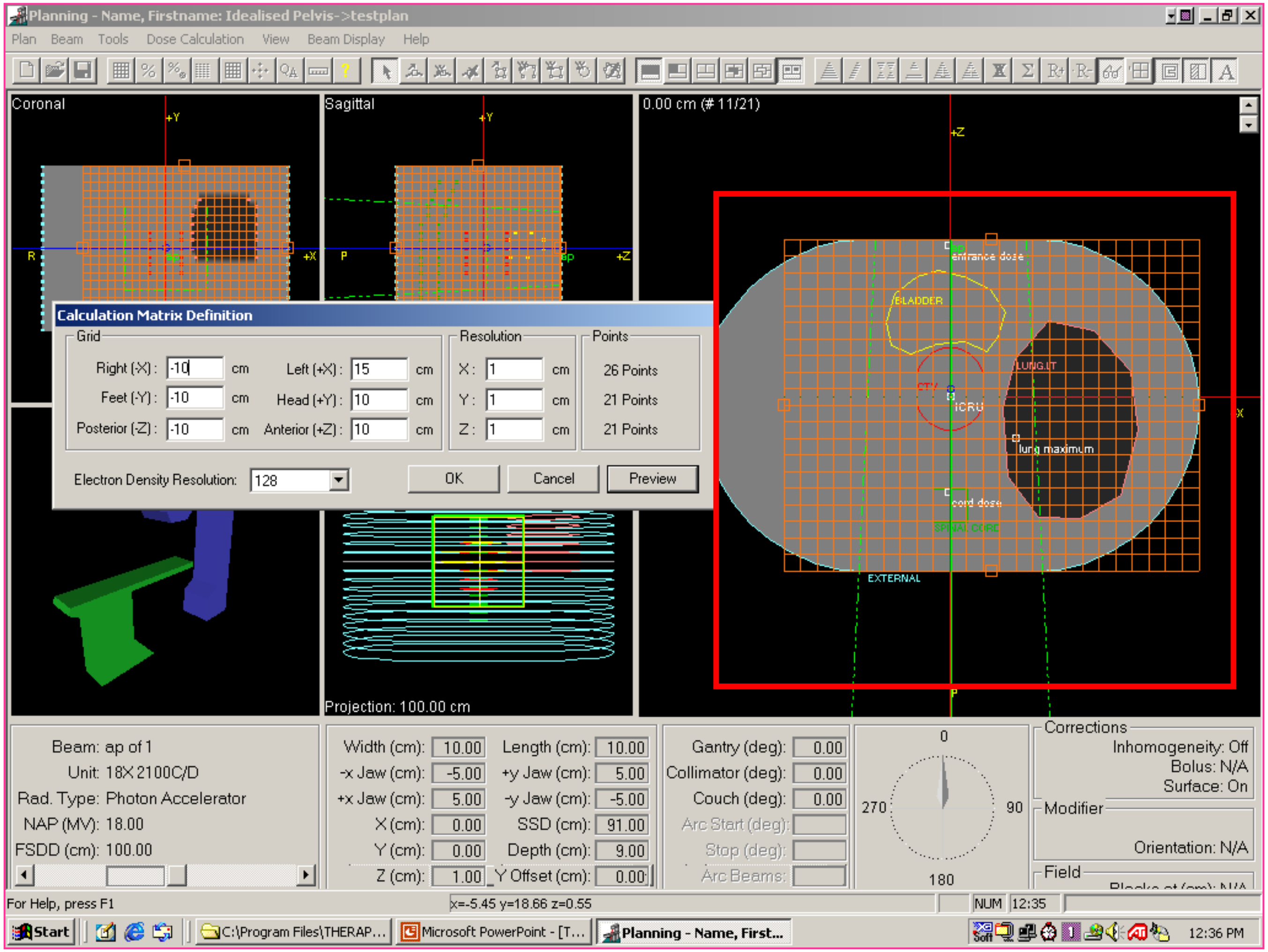




Adding the Beam

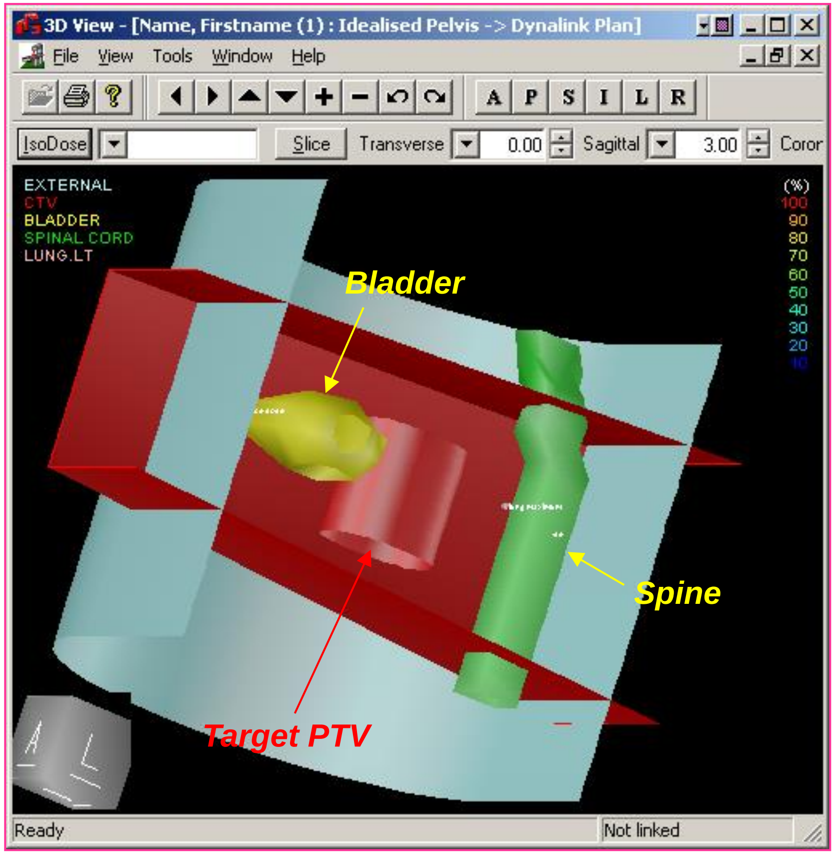


Adding the Calculation Grid

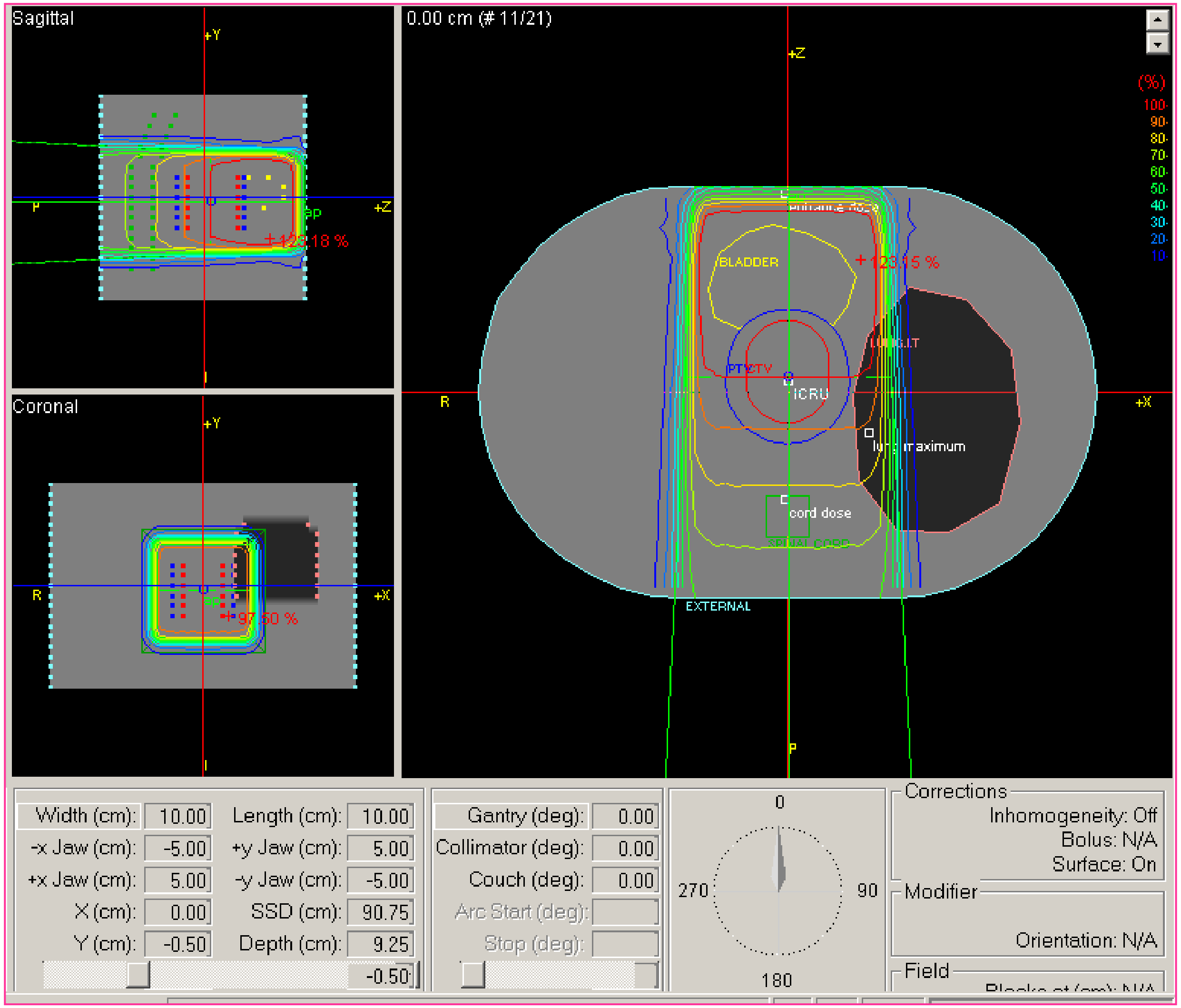


The Dose Calculation Grid

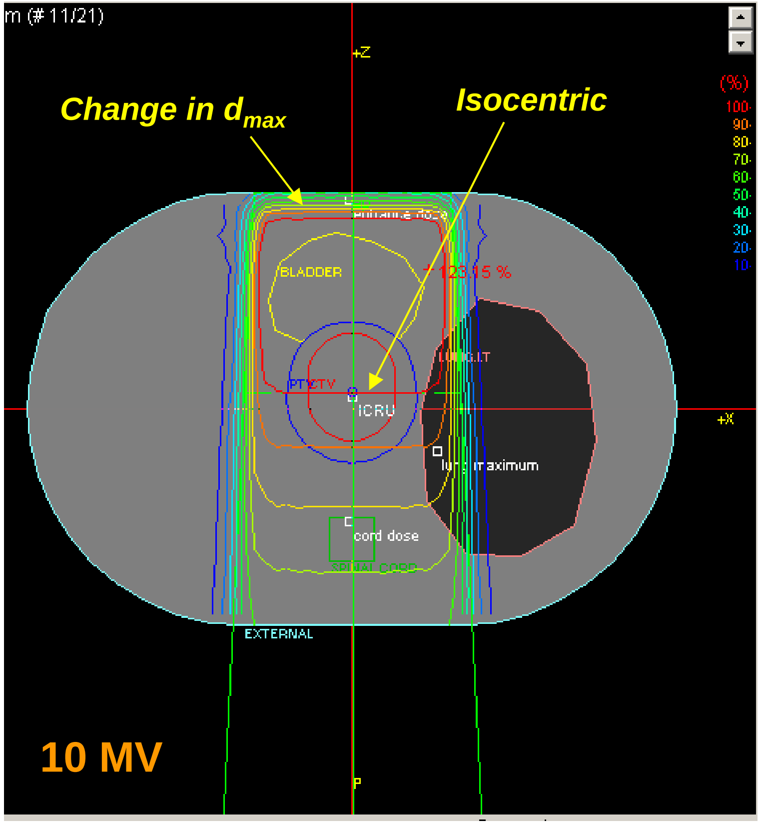
- The Dose Calculation grid determines:
  - How detailed the dose distribution is calculated
- Typical Sizes:
  - Usually around 2 to 5mm.
  - Depends on treatment situation.
- Increases calculation time dramatically.

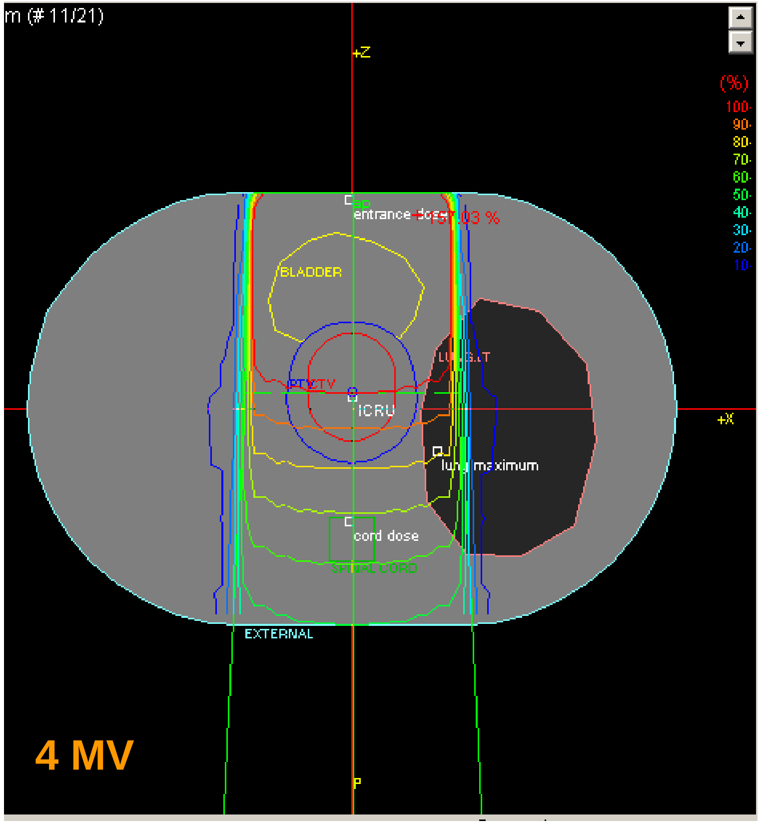


Dose Calculation

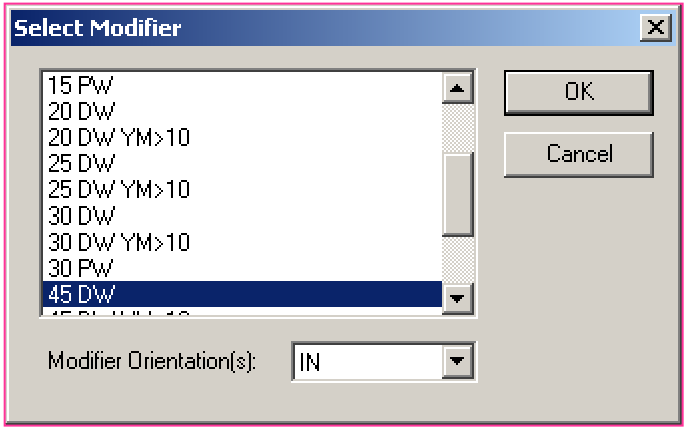


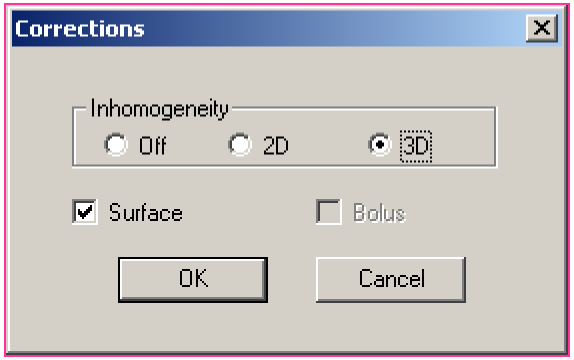
Isodose Charts for Different Energy Options

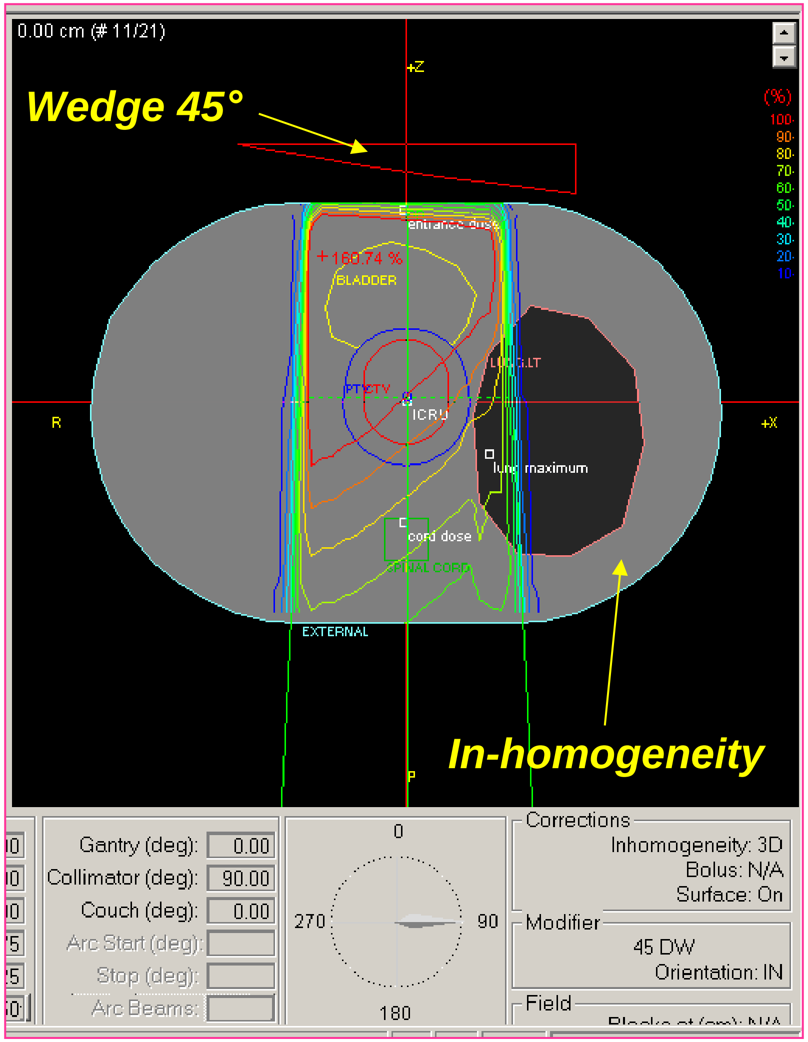




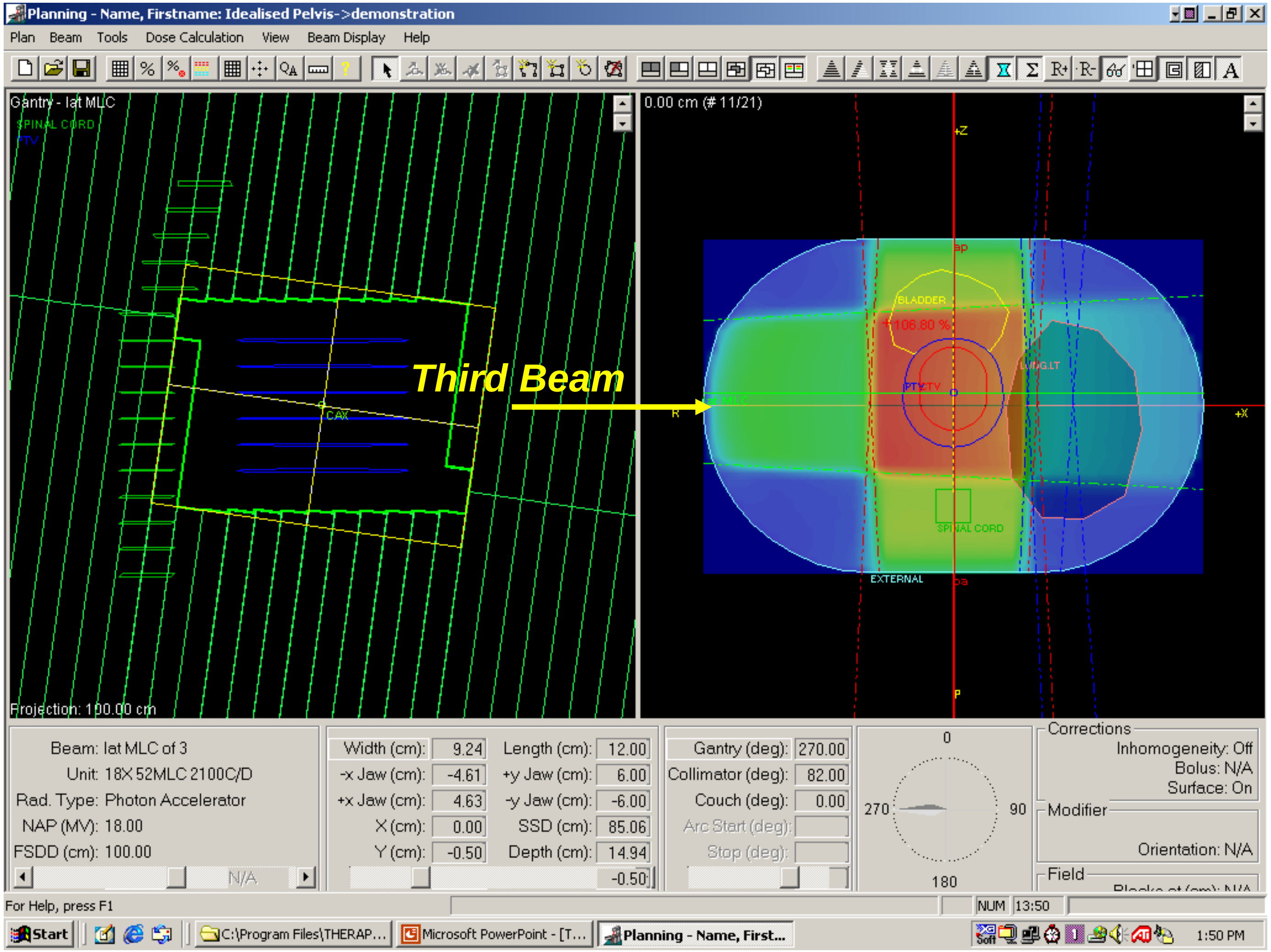
Adding a Wedge and In-Homogeneities Treatment



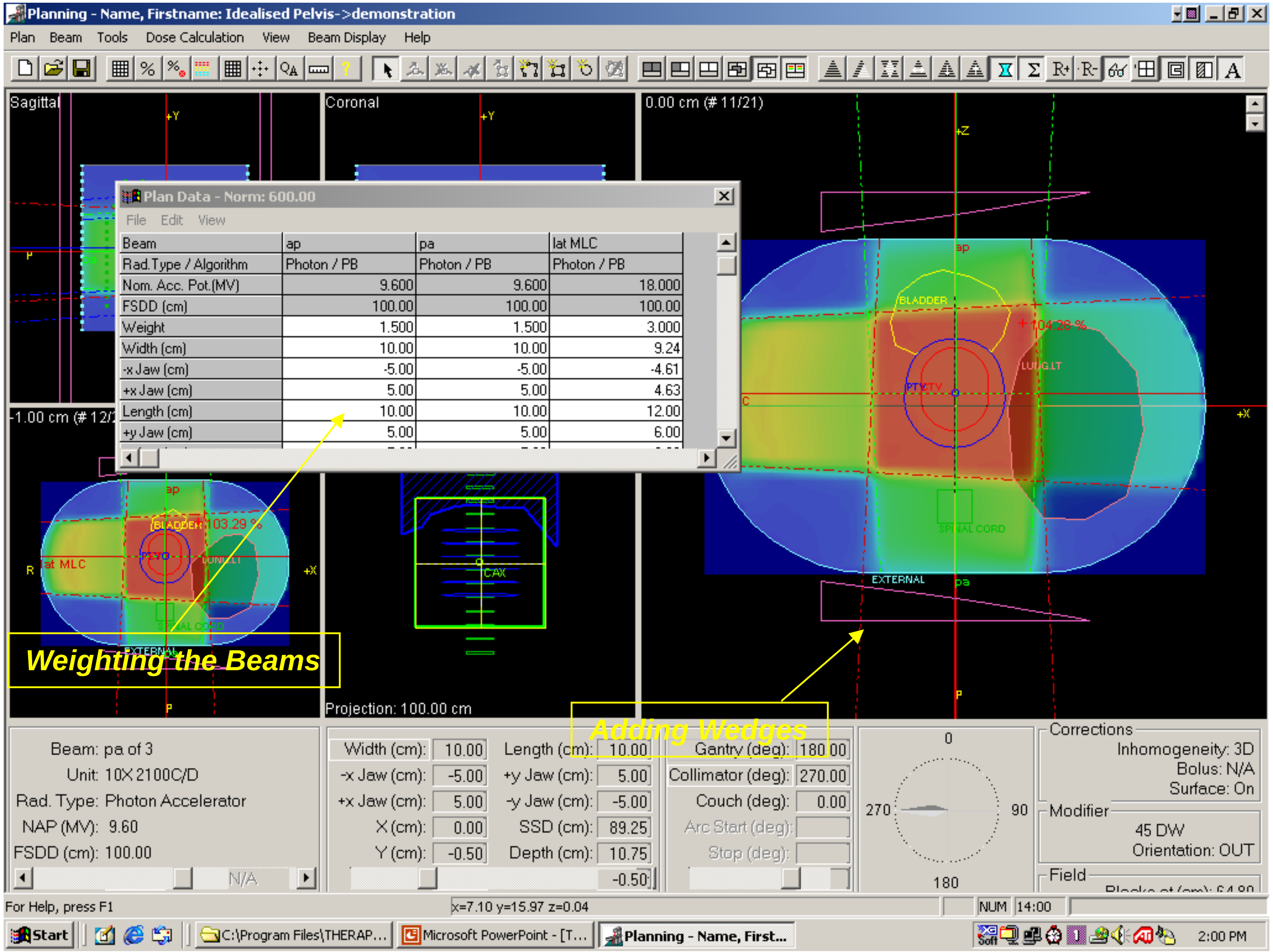




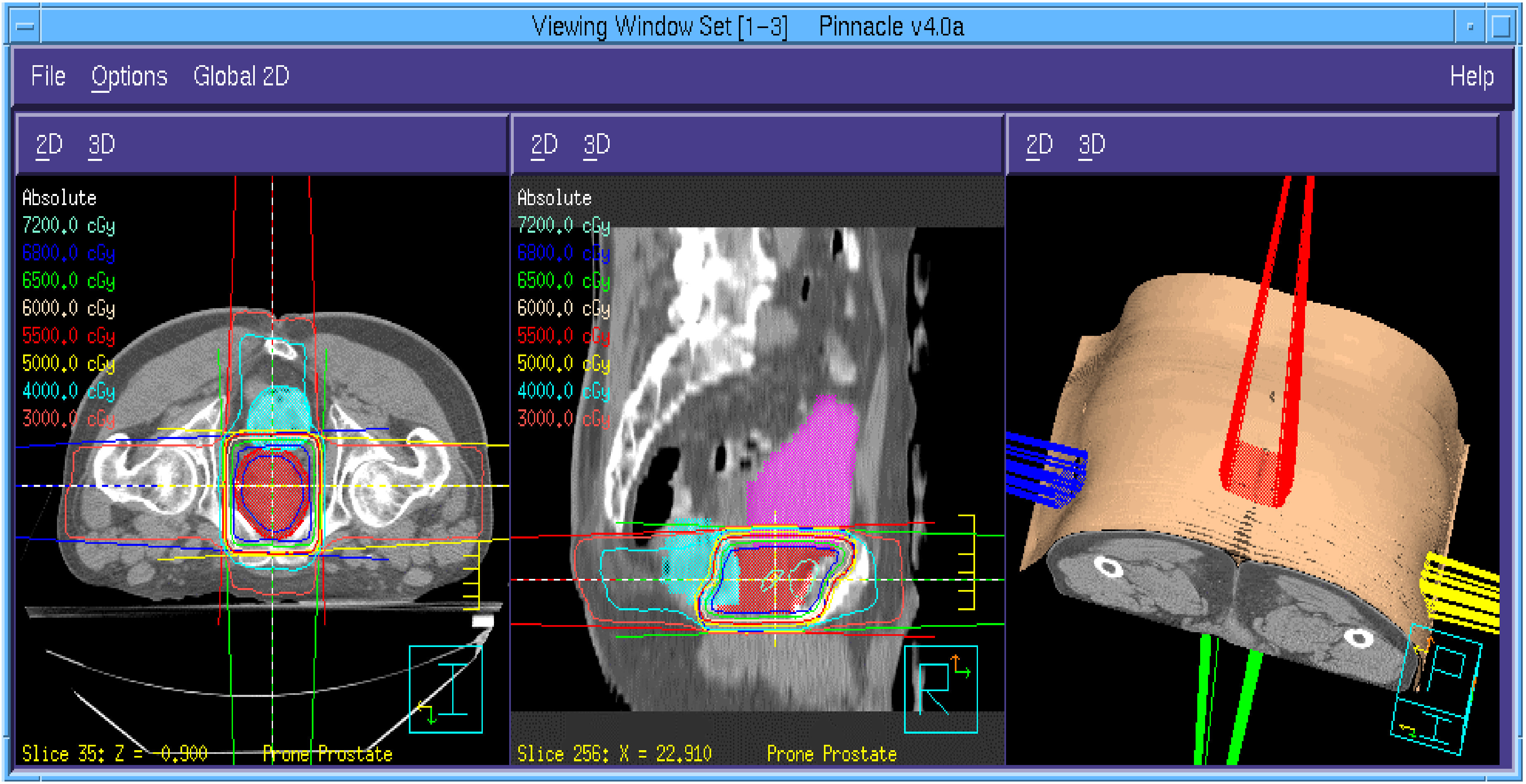
Three Beams (one with multileaf collimator)



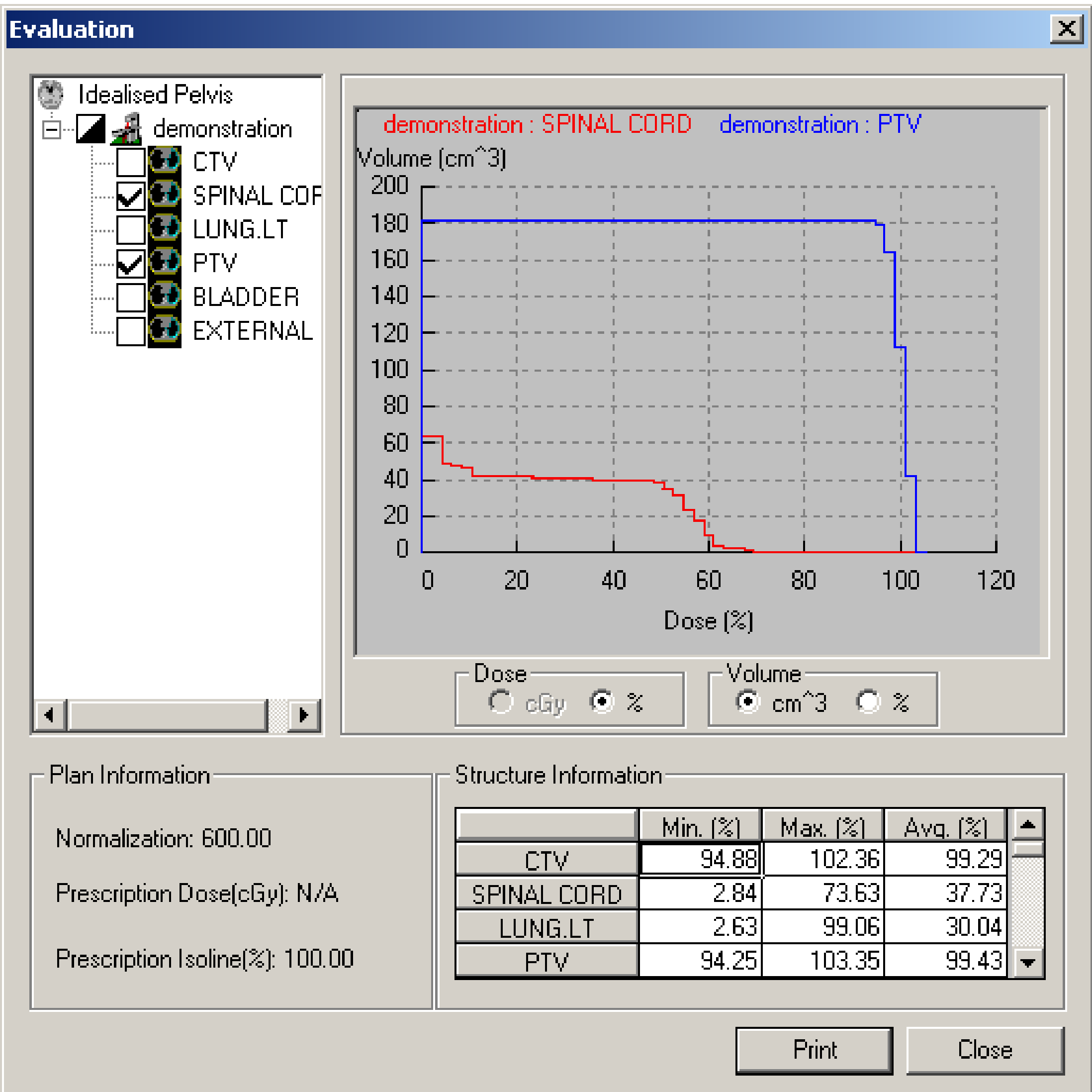
Producing a Homogeneous Treatment Plan

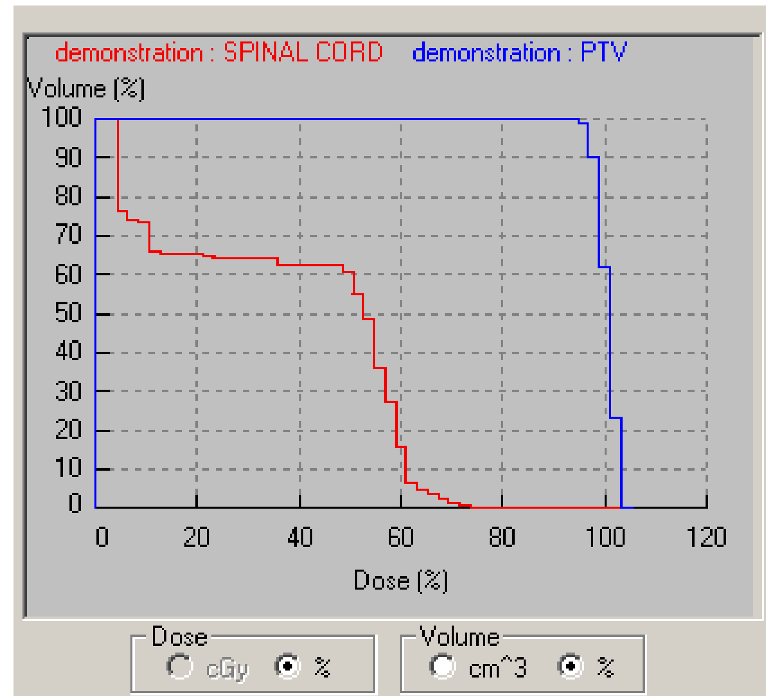


3-D Reconstruction of Isodose Curves with CT data



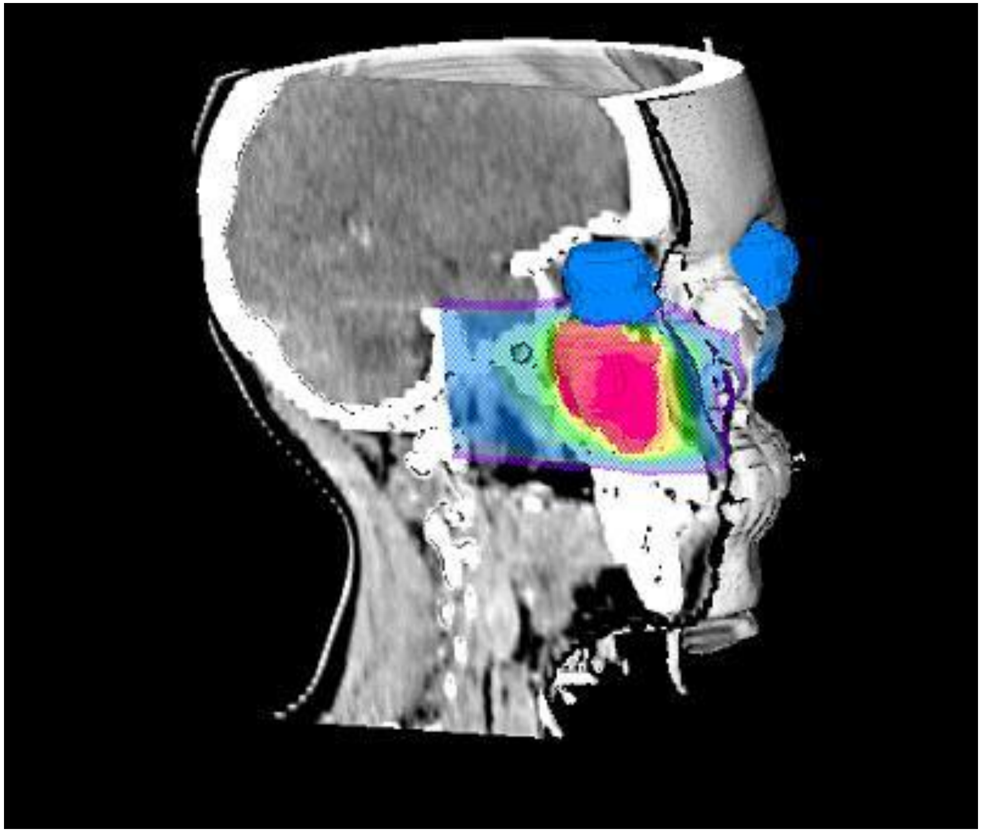
Dose Volume Histograms





3-D Virtual Simulations

- Require 3D data input.
- Produce 3D visualization.
- It is possible to address:
  - Non coplanar beam placement.
  - 3D dose computation.
- New evaluation tools.



Literature

- F.M. Khan, “The Physics of Radiation Therapy”, Lippincott, Williams & Wilkins, (4th edition, 2010)
- William R. Hendee (Ed.), “Biomedical Uses of Radiation”, Part B − Therapeutic Applications, Wiley-VCH (1999).