Tools in Planning & Plan Evaluation Evolution Through the Years

36th ICRO-SUN PG WEBINAR ON PLAN EVALUATION

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HELLO!

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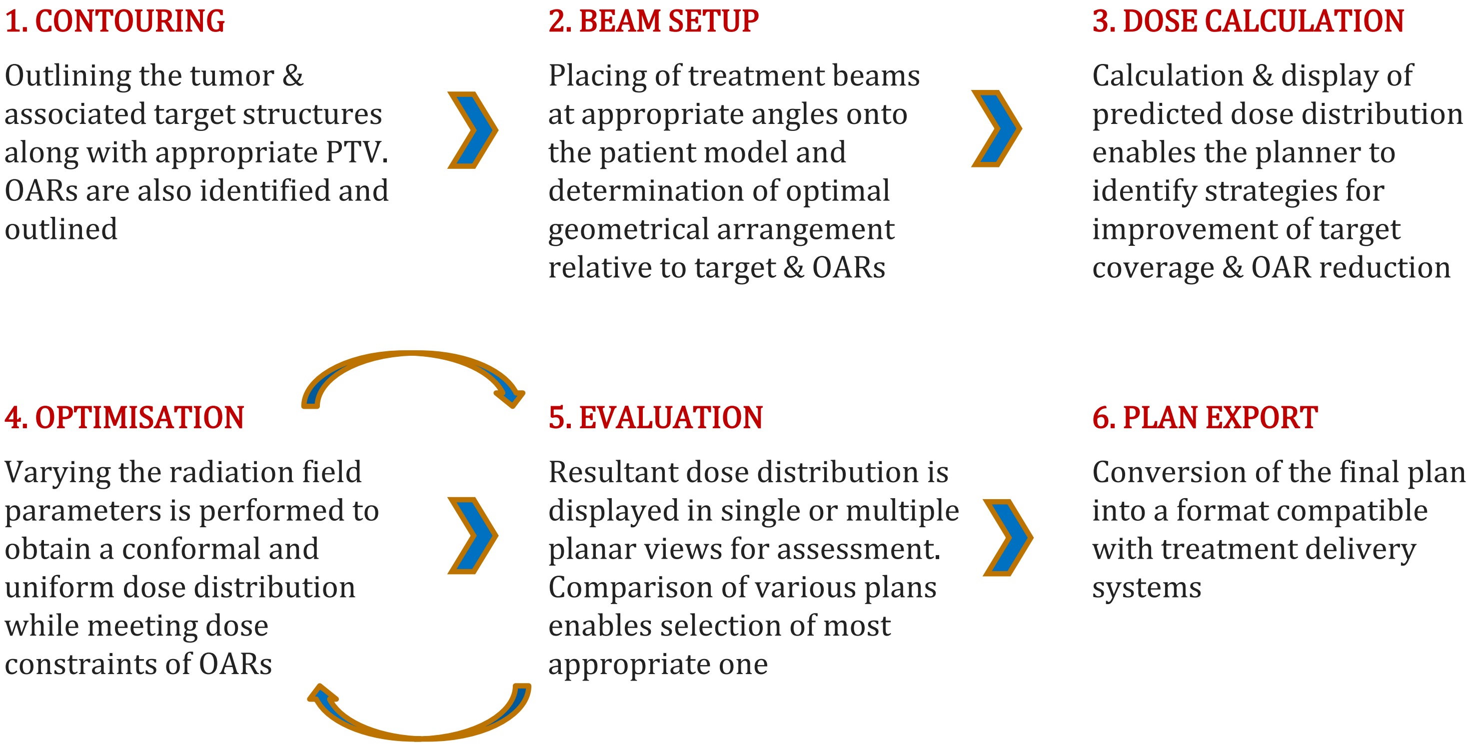
What is Treatment Planning?

- Decisions and processes required to design radiotherapy treatment
- Complexity depends on treatment intent & techniques
- Basic elements are common
- Early: Distribution of radioactive sources determined by set of rules
- Now: Complex computer modelling
- AIM: Translation of therapeutic requirements into a set of treatment instructions

Objectives of Treatment Planning

- Achieve a uniformity of dose in the target volume
- Reduce doses to critical structures as far below specific limits as possible
- Minimise the volume of normal tissue that is irradiated
- Ensure that the volume of the target that is underdosed is within the tolerances specified



1. CONTOURING

Outlining the tumor & associated target structures along with appropriate PTV. OARs are also identified and outlined

2. BEAM SETUP

Placing of treatment beams at appropriate angles onto the patient model and determination of optimal geometrical arrangement relative to target & OARs

3. DOSE CALCULATION

Calculation & display of predicted dose distribution enables the planner to identify strategies for improvement of target coverage & OAR reduction

4. OPTIMISATION

Varying the radiation field parameters is performed to obtain a conformal and uniform dose distribution while meeting dose constraints of OARs

5. EVALUATION

Resultant dose distribution is displayed in single or multiple planar views for assessment. Comparison of various plans enables selection of most appropriate one

6. PLAN EXPORT

Conversion of the final plan into a format compatible with treatment delivery systems

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Treatment Planning Process

Contouring

- Purpose of contouring is inform the planning process as well as provide volumes for dose evaluation

- Target volume delineation
- Organs of Risk
- Inaccurate contouring: Systematic errors

Patient CT Model

- Accurate 3D model of patient: visualization of target & critical structures, provides necessary tissue attenuation data for accurate dose calculation
- Also provides a geometric framework to enable delivery of plan to correct site
- Most common modality for patient modelling is CT
- Main limitation of CT is poor soft tissue definition
- Overcome by incorporating data from MRI & PET images
- Accurate planning proceeds on assumption that the images used for planning are true and reproducible depiction of patient's daily positioning.

Patient CT Model

The following are useful:

1. Flat top couch inserts
2. Immobilisation devices and patient alignment as used for treatment
3. Marking of reference points on the patient's skin using radio-opaque markers
4. Minimal distortion of image

- Images produced for treatment planning may be transferred directly by computer network or via the *digital imaging and communications in medicine format for radiotherapy* (DICOM-RT): common framework for data generation and exchange between radiotherapy systems

Contouring Tools & Features

- TPS offers a range of tools to assist in the contouring process
- Simple manual drawing tools to automatic & semiautomatic ’intelligent’ algorithms
- Simplest: freehand contouring (retains clinical control)
- Interpolate between contours delineated on nonconsecutive slices/ copy contours: Shortens the process for relatively regular structures
- TPS has windows (display of three orthogonal views): helpful in checking the continuity of structures
- Boundary detection tools: helpful in contour structures that provide high contrast with surrounding structures, e.g., lungs

Contouring Tools & Features

- Predefined ATLAS models: automatic segmentation tool
- Aim to reduce the time taken to contour OARs
- Fused with patient model and adapted to fit
- Others use predefined settings for typical CT numbers of organs (brain, bladder etc) with knowledge of organs' typical size and shape to delineate the structures with minimal user input
- Unsuitable for structures that vary considerably from 'normal' appearance like target volumes and require manual editing most of the times

Artificial Intelligence (AI) in Radiotherapy

- **Machine learning** (**ML**) is the study of computer algorithms that improve automatically through experience. It is a subset of artificial intelligence (AI)
- **Artificial Neural Networks (ANN)** are a subfield of ML that mimic the organization of the brain and use several layers of so-called neurons, where each neuron has a weight and a bias that determines its importance. Each layer receives variables, calculates a score and passes the output to the next layer. In radiation oncology, ANNs have been used to predict different outcomes: survival in advanced carcinoma of the head and neck treated with radio(chemo)therapy, PSA-level response and toxicity after radiotherapy for prostate cancer, pneumonitis in radiotherapy for lung cancer, or even survival in uterine cervical cancer treated with irradiation

Deep Learning in Radiation Oncology

- **Deep Learning (DL)** is a new term for ANN arising from advances in the ANN architectures and algorithms since 2006, referring especially to ANN with many hidden layers
- **The application areas of deep learning in radiation oncology include:**

1. Image segmentation and detection,
2. Image phenotyping, and radiomic signature discovery,
3. Clinical outcome prediction,
4. Image dose quantification, dose-response modeling,
5. Radiation adaptation, and image generation

- Deep Learning techniques to auto-segmentation for radiotherapy planning could represent a significant innovation in daily practice workflow, decreasing the time required for segmentation and the variability of the contours and also increasing the adherence to delineation guidelines

Contouring Tools & Features

- Tools for manipulation and editing: improves quality
- Simple adjustment of contours on a slice by slice basis
- **Boolean operators**: combination or subtraction of structures; particularly useful in IMRT for creating ‘tuning structures’
- **Post processing algorithms**: filling cavities, removing extraneous contours, smoothing structures
- Automatic edition of user specified margins to contoured GTV, CTV, or OAR volumes

Radiotherapy Simulator

- The radiotherapy simulator is an X-ray generator designed to simulate the treatment beam of a linear accelerator in terms of size and direction, but not the energy.
- It has the same mobility and accuracy as the linear accelerator, and is capable of producing radiographic images of the treatment area for use in the treatment planning process.
- The requirement for simulators developed primarily from the development of the linear accelerator, with its ability to deliver X-ray beams with significantly greater percentage depth doses, which resulted in an awareness of the need to avoid radiosensitive areas and the long-term effects of poorly planned therapy.
- The need for simulators has been increased by advances in conformational radiotherapy techniques.

Radiotherapy Simulator

- It should be mechanically and geometrically as compatible with as many of the department's treatment units as possible.
- It should be well constructed so that the manufacturer's tolerances are maintained for long periods during routine use.
- The variable focus to film distance (FFD) should match the focus to skin distance (FSD) range of the treatment equipment and techniques available.
- As some treatment techniques use very large treatment fields, the image intensifier should have provision to accept or support cassettes of size that will record these fields.
- It should be Digital Imaging and Communications in Medicine (DICOM) compatible to permit digital communication between it and other imaging equipment in the department.

CT Simulator

Dedicated CT simulators are based on diagnostic CT scanners, with a few modification

1. laser alignment system as a reference for patient positioning
2. 3-D imaging workstation for image visualization and manipulation
3. larger bore size to accommodate patient immobilization devices, and a flat tabletop to replicate the radiotherapy treatment unit couch.
4. CT data sets can be reconstructed in any orientation to provide coronal or sagittal slices of the anatomy, and digitally reconstructed radiographs can be created from CT data sets to resemble planar x-ray images from any angle or orientation. These characteristics allow for treatment geometries to be visualized that are possible on the treatment unit, but not possible on a conventional 2-D simulator.
5. Four-dimensional CT simulation allows for the tumor to be evaluated at multiple time points in the respiratory cycle and for the most beneficial respiratory phase to be selected for treatment planning and delivery

V-Sim Software and Approaches

- Virtual simulation
- CT scan imported to V-Sim software
- V-Sim software mimics linac and allows to change all relevant linac parameters: Gantry, collimator, couch angle, field size, MLC position etc
- Generates a virtual treatment beam
- Change in various parameters: updated Beam’s Eye View (BEV) and DRRs
- Snapshot of patients anatomy with NO MOVEMENT
- Rise of V-Sim: decrease in the need for a simulator

Fixed Focus to Skin Distance (FSD) & Isocentric Planning

- Isocentric planning a preferred approach: patient need be setup once only

1. Stable patient position
2. Reduced treatment time
3. More reliable field matching
4. Option for rotational therapy

Advantages of Fixed FSD Treatment

- More flexibility in positioning the treatment head allowing a greater range of beam entry positions
- Lower scatter dose from the treatment head
- Higher relative depth dose within the beam reduces entry dose
- Larger treatment fields are possible

Coplanar vs Non-coplanar Planning

- Coplanar: central axes of all beams lie within the same plane

1. Manual methods for external contours in pre-CT era
2. Time consuming and difficult to perform accurately
3. Hence a single representative contour used

- 3D model: greater flexibility in the choice of gantry/ couch/ collimation: Improved dose distribution

ICRU

- International Commission on Radiation Units
- Conceived in 1925
- International volunteers
- Propose an internationally agreed upon unit for measurement of radiation as applied to medicine
- Publish guidance on a wide range of radiation issues including volumes

ICRU: Basic Concepts

Malignant Diseases

- Gross Tumor Volume, GTV
- Clinical Target volume, CTV
- Planning Target Volume, PTV
- Treated Volume
- Irradiated Volume
- Organs at Risk, OAR

ICRU: Basic Concepts

Planning Organ at Risk Volume (PRV)

- OAR move with the patient and subjected to the same random and systematic errors as CTV
- Grow the OAR volumes by a set amount to create PRV (consider it a safety margin around sensitive structures)
- What if PTV and PRV overlaps: Clinicians judgement

ICRU: Basic Concepts

Dose Prescription

- Purpose of dose prescription is to turn relative dose (in percentage) shown on the treatment plan into absolute dose in Gray (Gy).
- Enables calculation of monitor units
- A single point in the relative (percentage) distribution is chosen (usually on the 100% isodose) and this is assigned to the prescribed dose: **ICRU reference point**
- ICRU recommends that the PTV be covered by the 95% isodose, with the maximum less than 107%

ICRU: Basic Concepts

ICRU Reference Point (50/62): CASE

- The dose at the point should be **Clinically relevant**
- Point should be selected so that the dose can be **Accurately determined**
- Point should be in a region where there is **no Steep dose gradient**
- Point should be **Easy to define** in a clear and unambiguous way

- Ideally ICRU reference point should be on the isocentre which should be in the centre of PTV.
- Not possible always: at least the reference point should be in the PTV and conform to the four criteria above

ICRU: Basic Concepts

Dose Reporting

- Tumor control depends on CTV dose: dose to CTV can only be estimated with regards to PTV dose, hence the dose to the PTV are commonly reported
- Modified PTV for reporting: if the PTV is close or outside the body
- **Level I**: Minimum requirement: ICRU reference point, Max dose to PTV, Min dose to PTV
- **Level II**: assumes that computerized planning is in use (GTV, CTV, OR, PTV, PRV)
- **Level III**: Developmental techniques
- More advanced plan (IMRT): more information is desired, DVH are produced

Simple Monitor Unit Calculation: Basics

- **Monitor Unit**: Measure of amount of radiation passing out of linac head
- **Prescribed Dose**: Amount of radiation dose (Gy) to be delivered to a point
- The part of the patient that should receive this dose: where this point is located dictates how many MU per Gray are required

- **REMEMBER**: Photons transfer energy to the patient but it's the electrons that deliver the dose!
- Dose delivered to tissue is dependent on the energy a photon has (to liberate an electron) and how tightly the electron is bound to the atom
- More photons= more scattered electrons= more dose

- MU= Dose per fraction (Gy)/ Output dose (Gy per MU)

Principles of CT Treatment Planning

- **Accurate spatial information**
- **Electron density information**

- Image manipulation and image Fusion: MRI/CT/PET
- Defining the volume, growing tools: GTV, CTV generation
- Beams eye view: vision from treatment machine head: helpful for shaping MLC and jaws
- Margins: How large must a treatment field be to give adequate dose coverage to PTV

- Common Mistake: Fit the MLC or jaws upto the edge of PTV in the BEV (Remember that the beam edge is defined by 50% isodose: coverage at the edge will be cold)
- Dose profile of 6 MV field: you achieve 95% dose about 6 mm inside the field (MARGIN)

Advanced concepts: Plan Verification & Evaluation

- **Isodose display**: TPS will link together regions of equal dose (isodose), it actually calculates to a 3D series of points (Dose Grid)
- **Dose Volume Histograms (DVH)**
- 2D graphical representation of 3D dose distribution for individual organs, useful for evaluating and comparing treatment plans
- Do not replace full isodose distribution as they do not contain geometric information
- Differential (frequency) DVH: fractional volume of organ receiving a dose (show homogeneity of dose to a structure, not so useful for OAR)
- Integral (cumulative) DVH: fractional volume of organ receiving a dose or greater (most commonly used to give PTV and OAR data

1. Global maximum received by an organ (serial organ, spinal cord maximum)
2. Dose received by a certain volume of an organ (parallel organs, V20 of lung)

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Advanced concepts: DRR

- **Digitally Reconstructed Radiographs**

- CT data used for generating image to mimic plain X-ray radiographs
- For each treatment field, option to generate a DRR: this DRR can be used to compare against X-ray images taken on the treatment unit to verify the accuracy of the patient setup
- DRRs are used to replace simulator images in virtual simulation

Advanced concepts: Inverse Planning

- **3D conformal treatments are forward planned**

1. Planner decides treatment parameters (field size, beam weight, gantry angle etc)
2. Calculates the plan to see what the dose distribution looks like
3. If they don’t like the result, can change something (eg beam weightage) and try again
4. Works well with simple beam modulation options (field size/ field weight/ wedges)

- Iterative process by planner
- Iteration: Repetition of a process

Advanced concepts: Inverse Planning

- **Inverse planning: computer program makes the iterative changes**
- **Non-uniform intensity of the radiation beams.**

- Inverse planning is less dependent on the geometric parameters but more on specification of volumes of tumor targets & sensitive structures, as well as their dose constraints

- *Inverse planning is less forgiving*

1. Only treat contoured targets
2. Only spare contoured critical structures

IMRT Treatment Delivery

- No. of diverse techniques: most common are segmental IMRT and Dynamic IMRT
- Both use multi-leaf collimators (MLCs)

- First MLC developed in 1948, now standard of modern linacs
- Movable tungsten leaves that can block part of the radiation field
- Normally 5-10 mm wide, arranged in opposing pairs, positioned under computer control
- Creates irregular field that confirms to tumor shape, and shields normal tissues

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Segmental MLC IMRT

- Evolved directly from conformal radiotherapy
- For each beam orientation, several different MLC-shaped fields (segments) created
- Modulated field intensity is achieved by summing all segments
- Radiation only turned on when the segments are in position (step and shoot)

Dynamic MLC IMRT

- MLC leaves are in continuous motion during treatment of each field
- At a fixed beam angle, each pair of opposing MLC leaves are swept across the target under computer control to produce the desired fluence profile
- Variation of the speed and distance between leaves delivers the desired intensity of radiation to the specified point
- More conformal dose distribution than segmental IMRT
- Continue to deliver radiation while the MLC is in the beam: more leakage and integral dose

TOMOTHERAPY

- Based on the design of CT scanners
- Short 6 MV waveguide spinning around the patient which produces a fan beam of 6 MV photons
- Beam modulated by a mini MLC
- The beam is collimated to a narrow slit and then modified with moving leaves as the gantry rotates around the patient
- Dose is built up in a helix as the patient moves through the gantry on the couch
- Complex dose distributions to large volumes

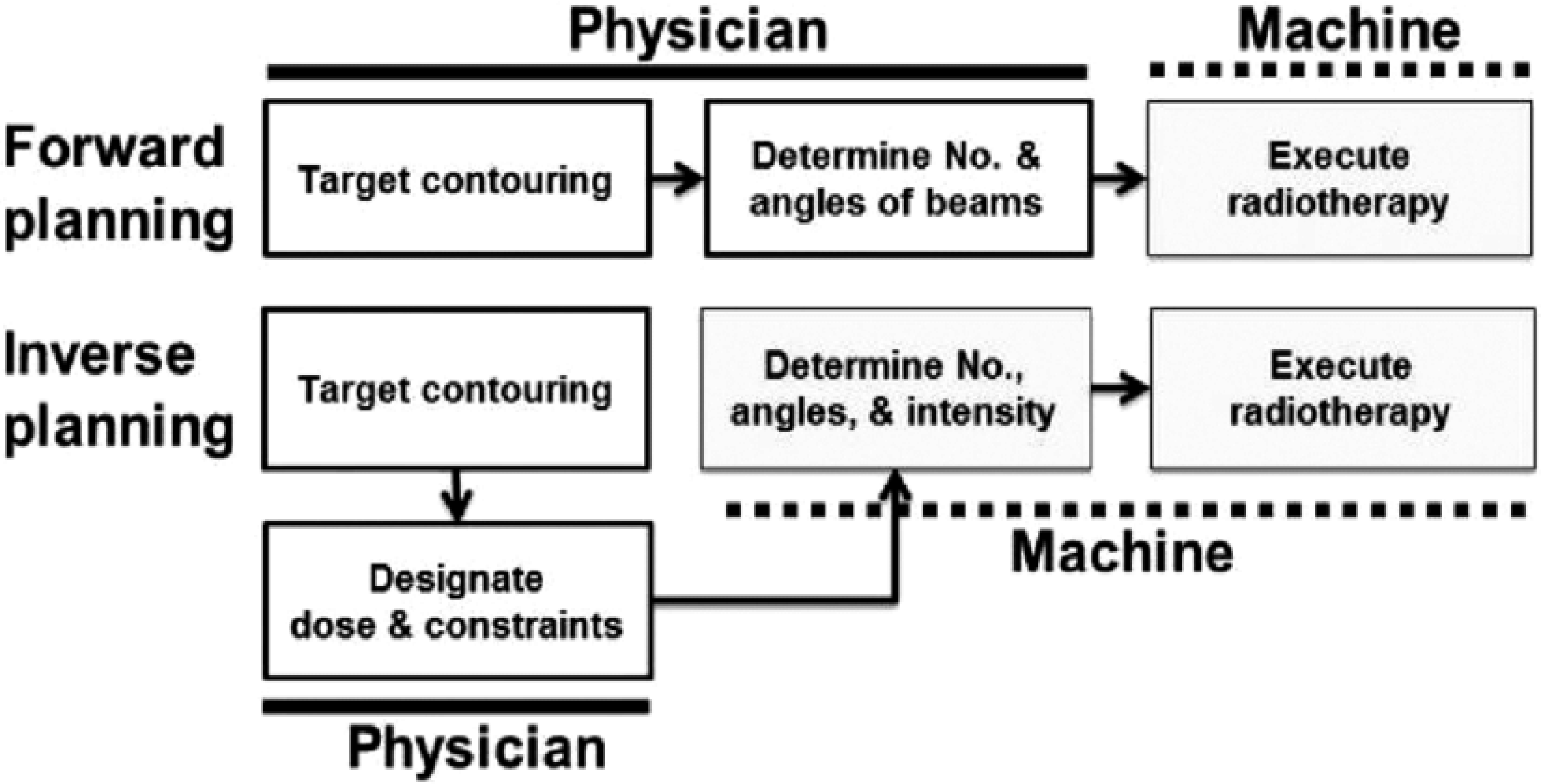
VMAT

- Volume Modulated Arc Therapy
- Uses same concepts as of IMRT with extra variables

- While the beam is on, the gantry rotates, we can vary

1. Gantry rotation speed
2. Dose rate (certain vendors)
3. MLC position

- Delivers dose distribution similar to IMRT plans but in a significant shorter time


Physician
Machine
Forward planning
Target contouring
Determine No. & angles of beams
Execute radiotherapy
Inverse planning
Target contouring
Determine No., angles, & intensity
Execute radiotherapy
Designate dose & constraints
Machine
Physician

Advantages of IMRT

- Improved target conformity, particularly for concave target volumes
- Can produce intentional dose inhomogeneity—dose-painting
- Increases normal tissue sparing
- Enables dose escalation
- Can compensate for missing tissue

Disadvantages of IMRT

- Increased clinician time for target and organ outlining
- Needs extensive quality assurance programme
- Increased machine treatment time
- Increased planning time (initially)
- Increased total body irradiation dose

Stereotactic Radiotherapy

- Process largely same as rest of radiotherapy
- Radiation is inherently the same
- Used to treat small volumes to very high doses in a small number of fractions (1-5)
- **Two objectives**

1. Tumor ablation with minimum dose to surrounding tissues (requires highly collimated beams to achieve sharp dose fall off at the edges)
2. Very precise patient positioning (sub millimetre accuracy)

- Originally for brain lesions now branched out to treat other parts of body (SBRT)
- Organ motion management must for SBRT

Reasons for Efficacy of High Dose per Fraction RT

- Advances in image guidance and dose delivery enable the delivery of large doses to tumors with much smaller volumes of normal tissue irradiated, thus overcoming the need in some situations to be concerned with normal tissue injury
- The LQ model may not accurately predict cell killing at high doses. It might be suggested that the model may over predict cell killing at high doses so the damage to late responding normal tissues (which have smaller α/β values and therefore a more "curvy" dose response curve) may be less than predicted by the model, thereby allowing bigger doses than predicted by the model to be used in practice
- There are anti-tumor effects of high radiation fractions that are not predicted by classical radiobiology including enhanced anti-tumor immunity and secondary effects deriving from injured vasculature
- Many tumors may not be hypoxic so there would be no benefit of reoxygenation between doses in a multi-fraction regime

Adaptive Radiotherapy (ART)

- When plans are changed after treatment has started in response to changes to the geometric configuration of patient
- Due to tumor response or growth/ change in tumor position as in IGRT
- **IGRT: patient position is changed**
- **ART: treatment plan is changed to reflect the new situation**
- Methods: Proactive or Reactive
- **Proactive**: **Plan of the day**: range of plans are produced prior to treatment commencement (cervix, bladder)
- **Reactive:** New treatment plan is generated from a prebooked CT scan or from daily CBCT data

Calculation Algorithms

Manual planning

- Upto early 1980s
- Target volumes were localized from Orthogonal radiographs (radiographic projections obtained at 90 degree to original view)
- Transferred to single patient contour (acquired using thick wire)
- Measured or calculated single isodose beams were selected to cover the target and combined together by copying into tracing paper and then adding manually

Calculation Algorithms

First planning systems

- Came in early 1980s
- Computers did the same thing as hand planning but lot quicker
- The type of dose calculation method was **Beam Library Model**
- Contour correction was taken into account but not missing tissue
- Density correction was possible but crude (without CT!)

Calculation Algorithms

Simple planning systems

- Scatter Integration model
- Unlike beam library, they differentiate between primary radiation (treatment head) and scattered radiation (generated within the patient)
- Able to take account of missing tissue: accuracy improved
- Ideal dose calculation model: represents the true nature of dose deposition (photons interact but electron give dose)

What Are We Trying To Model?

- All current algorithms are an approximation of what is happening in the patient
- Photons interact with matter -> slightly lower energy photon (scatter) and a moving electron -> photon goes on to liberate more electrons
- All these electrons move through the tissue losing energy or to other electrons
- Interaction is random, not a certainty
- Every photon (millions) must be tracked through every interaction and the product of every interaction must be tracked too: time consuming
- Best technique: **Monte Carlo modelling:** lengthy but accurate

Pencil Beam Algorithm

- Convolution or **Pencil Beam convolution (PBC)** type models (mid 1990s)
- Start off along the lines of Monte Carlo but use much quicker methods to get a result of dose deposited
- Based on **Kernels** (map of the dose that will occur for the energy of radiation beam hitting a small volume of water)
- Created in advance: during commissioning of planning system
- Time consuming calculations are shortened
- Works well with water, cant scale the kernels laterally on change in density **(1D model)**

Superposition Algorithms

- Next level of algorithm
- **Collapsed cone** and **AAA** algorithm (vendor specific)
- Can correct inhomogeneity in all directions **(3D model)**
- Most accurate type of dose calculation model

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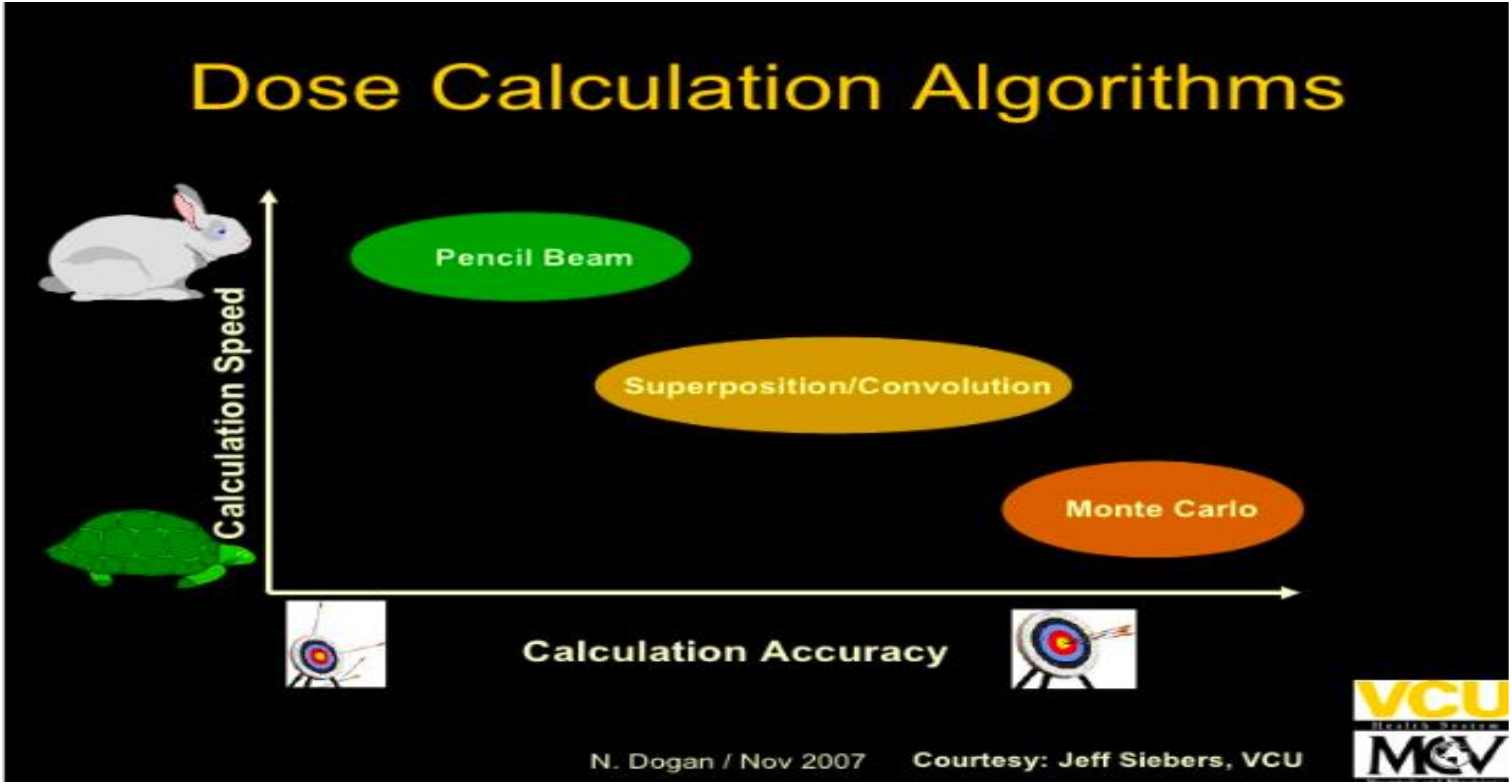

Dose Calculation Algorithms

N. Dogan / Nov 2007 Courtesy: Jeff Siebers, VCU

Treatment Planning Systems

Last updated on July 09, 2020

☐	Company	Product
☐	Accuray,Incorporated	Radixact Precision Planning System
☐	Accuray,Incorporated	CyberKnife Precision Planning System
☐	Brainlab	RT Elements
☐	Elekta	Monaco
☐	Philips Healthcare	Pinnacle Therapy Planning System
☐	RaySearch Laboratories AB	RayStation
☐	Varian Medical Systems,Inc.	Eclipse Treatment Planning System

THANKS!

Any questions?

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