Evolution of RT from 2-D to 3-D CRT and IMRT
Aim

- To introduce the concept of 3D CRT and describe the requirements for transition from 2D RT to 3D CRT and IMRT
Specific learning objectives

To identify the

- Differences between 2D and 3DCRT
- Steps involved in the 3DCRT process
- Milestones needed for implementation of 3DCRT
- Staffing, training and QA requirements for 3DCRT and IMRT
This is probably the kind of radiotherapy that you are used to delivering in your country.

This slide shows images two patients, one with a T3 N2c nasopharyngeal CA and the other with a T1/2 N1/2 lung tumor. In the early days of radiotherapy, and even today in many developing countries, radiotherapy for such tumors is planned and delivered using field shapes defined from planar radiograph. Point dose calculations are performed at various points of interest. This has been identified as “conventional radiation therapy” in IAEA TECDOC 1588.
Another example:

Beam incidence is based on experience of mentor

Roughly shaped fields related to bony anatomy, radiographical projection of contrast or tumor

High dose volume of basic shape
Differences between 2D RT and 3D CRT
• Basic radiotherapy where no attempt is made to shape the treatment fields; viz., using of the jaws to treat a rectangular field.

• Individually shaped fields can however be designed from planar radiograph or limited CT data. This level of conformal radiotherapy can be carried out in any radiotherapy dept with minimum facilities and is a useful way to begin to move towards full 3DCRT.

• This figure shows an example of basic radiotherapy or a 2D RT.
• Full 3DCRT requires a full 3D CT data set, on which the tumor volumes and Organ at risk volumes are drawn using the concepts of ICRU 50 and 62. You will learn about how to draw ICRU volumes in a different lecture.

• This figure shows an example of isodose distributions for head & neck cancer generated using a 3DCRT treatment plan.

• You will learn more about how to generate such dose distributions in this course.
• The next level is the most complex form of 3DCRT and includes IMRT and we will not discuss it today.

• This figure shows how one can use IMRT techniques to deliver a highly conformal dose to the target volume and yet at the same time avoid delivering dose to the critical structure such as the cord or the parotid.
This slide shows some of the differences between conventional RT and 3D-CRT. 3D CRT is different from traditional 2D planning and delivery.

In 2D, tumor volume and critical structures are drawn on orthogonal films or on few CT images. On the other hand for 3DCRT, design and delivery of radiotherapy treatment plans is based on full 3D data set, usually of CT images. Targets, OARs and normal structures are identified on multiple transverse images. Beams –eye-views are created from digitally reconstructed radiographs. Here you can see rectal cancer located in the middle rectum on a 2D sim film.

For 2D RT, one typically uses simple setups using 3-4 fields. For 3DCRT, one uses complex setups of 4-6 fields with precise immobilization. More on immobilization later.

For 2D broad margins are used and simple dose calculations are done on a single plane. For 3D, volumetric dose calculations are done and tight margins are used. You will learn about margins in a different lecture.

You can also see how isodose distributions are conformed to the shape of the target volume for a3DCRT as opposed to a simple 2D RT isodose calculation.
More on 3D CRT

- Field design is based on BEV projection of the target volume
- Volumetric dose calc
- Volumetric plan evaluation tools such as DVH
- Uniform radiation intensity across the field
- Conformity of dose distribution to the target volume

This slide shows some more characteristics of 3DCRT.

For 3DCRT, field design is based on beam’s eye view (BEV) projections of the target volume, dose calculations are volumetric, and one uses volumetric plan evaluation tools such as dose volume histograms (DVHs). The radiation beams normally have a uniform intensity across the field, or where appropriate, have this intensity modified by using wedges or compensating filters.

The dose distribution conforms to the shape of the target volume.
Steps in the 3D CRT process
The design and delivery of 3DCRT requires a chain of procedures all of which must be in place if the treatment is to be safe and accurate. A chain is as strong as its weakest link. If any of the links of a chain are weaker than the others, the chain will break at that point. It is therefore essential that all links have been established before embarking on a patient treatment. The links in the chain for 3DCRT are:

- Precise immobilization of patients throughout the whole Tx process;
- Use of high quality 3D /4D imaging for structure segmentation and delineation of various volumes of interest following ICRU50 and 62 recommendations;
- Use of 3D treatment planning systems for display of Beams-eye-view and 3D planning dose calculation capabilities for 3DCRT and evaluation of dose using tools such as Dose-Volume-Histograms
- Transfer of the planning data to the delivery machine;
- Verification of patient position and beam placement;
- Followed by delivery of treatment.
Ideally each cancer center will have a CT simulator housed in the radiation therapy department. If this is not possible, then the radiotherapy departments must have access to a CT scanner for planning conformal radiotherapy. Other imaging modalities such as MR, Ultrasound or PET are useful but not essential. This image shows an example of a CT simulator.

Because of the nature of the conformal radiation therapy treatment, reproducible immobilization are essential to safely use 3D CRT technique. This slide shows an example of immobilization using thermoplastic mask.

All centers should have a 3D RTPS that must have a number of particular features for satisfactory planning of conformal radiotherapy. You will learn more about it in the treatment planning lectures.

A linear accelerator fitted with MLC is ideal for delivery of the planned conformal radiotherapy. Ideally, the accelerator will also be fitted with an electronic portal imaging device (EPID) that can be used for the verification of patient setup and geometric verification of beam portals. This image shows the image of an accelerator with an EPID.

When an MLC is used a record and verification system is needed to ensure, as a minimum, that planned conformal radiation therapy is delivered as per prescription.
Immobilization:

Because of the conformal nature of 3DCRT treatment, new immobilization techniques may be necessary to safely use the technology, such as supplementing thermoplastic masks with bite block fixation. Techniques to reduce or follow internal organ motion, such as by using ultrasound localization of the prostate or respiratory gating, may be desired. All these new procedures will impose their own burdens with respect to procedure design, training, and validation.

For the treatment of a given disease site, a discussion needs to take place among the team consisting of radiation oncologist, medical physicist, dosimetrist and CT technologist on the optimum treatment position and immobilization method to be used for the treatment.

If not already known, it may be necessary to study the reproducibility that can be achieved with the immobilization system in order to establish realistic margins for planning.

Generally, the patients will be immobilized and radio-opaque markers will be placed on the patient or immobilization device to establish reference points which ideally will be at the isocenter. In some situations if this reference point is not at the isocenter, then it should be as close to the isocenter as possible.
Every department should develop protocols for image acquisition for various body sites: the goal is to determine volumes (target and organs at risk)

- Obtain high quality CT images in the treatment position
- Mark as close as possible to the anticipated treatment isocenter
- Fuse CT dataset with any other available studies such as MRI, PET etc

Every department should develop protocols for image acquisition.

As for 3D conformal treatments, a CT for treatment planning will be performed with the patient in treatment position with the immobilization device. Clinics may find that they need to obtain more slices at a finer spacing than had been the norm previously. The range of slice acquisition may also be expanded in order to permit non-coplanar beams to be used.

Image acquisition: At an early stage in the process, the goals of treatment should be discussed carefully with the planner so that a clear understanding of the imaging and planning needs is established. With the patient in the treatment position, CT images should be acquired and the isocenter position marked using the radio-opaque markers as reference points.

Optional: If MRI or PET images are available then those data sets can be fused to the CT dataset for better target delineation
In order to calculate doses to target volumes and organs at risk, it is necessary to delineate target volumes and critical structure volumes. Recommendations on how to draw such volumes are given by ICRU 50 and 62. Consistency in volume definition is critical for comparison of treatment outcomes in a multi-institutional clinical trials. You will learn more about these in a separate lecture.
This slide shows how contours for target volumes and organs at risk are drawn on different slices for a H&N patient and 3D structures are drawn for target volume and organs at risk. Identify the target volumes and critical structures.
Another example of structure segmentation and reconstruction of 3D structures. Here you can see the prostate, rectum, bladder and other organs.
3D CRT puts more responsibility on the clinician to carefully delineate what is to be treated and spared and is thus a labor-intensive for physicians and planners. For example, implementing a new parotid-sparing protocol for head and neck patients would require the parotids and at-risk nodal volumes to be defined on each axial slice, with due consideration for margins. This can be more difficult than defining conventional lateral fields on simulator films to treat the nodal volumes, hence requiring more of the physician’s time.

Another example: in conventional radiotherapy, regional treatments can be designed by drawing ports on simulation films that encompass the gross target and the draining lymph nodes. To treat the same region with 3D CRT, the clinician must contour the nodal regions explicitly as well as the gross disease so that the planner can design a treatment plan that will provide appropriate dose coverage to the various regions of interest.

So, with 3D CRT, the physician delineates all targets and other critical volumes of interest so that an appropriate plan can be generated and evaluated using different plan evaluation tools such as dose volume histograms.
Once the various volumes of interest are drawn and the required doses have been defined, treatment plans will be produced by a person trained in 3D treatment planning. The objective of the treatment planning process is to achieve the dose objectives to the target and critical structures and to produce a dose distribution that is optimal.

The treatment planning system (TPS) must have a number of features. This slide lists a few:

- The TPS ideally should have image registration and image fusion capabilities and tools to delineate anatomy and target volume in 3D.

- It should have the tools necessary to design treatment fields and treatment aids (i.e., MLC shape or shielding blocks etc).

- It should have 3D dose calculations algorithms that will permit accurate 3D dose calculations for the entire regions of interest.

- It should have the capabilities to display 3D anatomy and dose distributions.

- It should have various plan evaluation tools such as dose volume histograms.

- It should have the capabilities to generate digitally reconstructed radiographs (DRRs) and able to transfer the data electronically over a radiotherapy network to a record and verification system.
Contouring:

Highly conformal treatments require target and normal tissue structures to be identified with more care. Hence, the use of contrast agents for the CT and registration of images from other modalities, such as MRI or PET is often needed and may represent a change in typical practice.

In order to perform dose calculation, the physician will need to delineate all targets and critical structures. Skin surface and other volumes of interest can be drawn by other staff such as physicists and a dosimetrist as long as they have been trained to do so and their work is finally approved by the physician.

All structures should then be grown in 3D by adding appropriate margins. The planner then selects appropriate beam arrangements using the TPS and performs the 3D dose calculations.

The next few slides will give some examples of placement of good and bad beams.
Good beam directions
Good beam directions
Good beam directions
Good beam directions

Adding opposed beam
Good beam directions

Adding non-opposed beam
The next step is to perform an evaluation of the planned dose distribution. Evaluation of dose distribution involves evaluating many parameters and the treatment planning system provides various tools to aid in such evaluation. You will learn details of what parameters to evaluate when evaluating dose distributions. One such parameter is evaluating dose uniformity within the target volume. One also looks for hot spots and coverage of target volume with the prescription dose.

Use tools such as dose-volume-histogram to examine coverage of the target volume by the prescription dose and sparing of the critical structures from receiving unacceptable dose. It should be mentioned that DVH does not provide information of coverage of the target volume by the prescription dose on each CT slice.

3DCRT treatment plans is experience based and if the treatment plan is not optimal then one can adjust the beam weights or beam directions to generate an optimal plan.
Once the optimal treatment plan is developed, the radiation oncologist should approve the plan.

Various quality checks should be in place before the delivery of the treatment to the patient. Examples of these are:

The medical physicist should double check the plan for accuracy, check the monitor units and verify the accuracy of monitor units by using an independent calculation using a different software.
Once the treatment plan has been designed and approved by the radiation oncologist the details of the data need to be transferred to the treatment unit. If possible, a record and verification system should be used to control the treatment unit and with data transfer carried out electronically, preferable over a radiotherapy network.

File transfer to accelerator and management

- Enter or electronically transfer all treatment parameters into R&V system
Clearly, position verification is an important part of plan validation. The most critical point is to verify that the treatment isocenter matches the planned isocenter. This should be accomplished by comparing orthogonal films taken at simulation, DRRs from the planning system, and portal images from the treatment unit.

Portal images of the treatment field should be obtained for determination of accuracy of field shape and placement of fields used for treatment. It is useful to have the MLC field boundary as apertures for the ports and compare to corresponding DRRs from the planning system. The images in the slide show a DRR on the left and a portal image on the right which shows the shape of the beam. Compare the placement of the isocenter as well as placement of the beam shape anatomically.
In vivo dosimetry is a good way to compare expected and measured doses. This then is a good tool to identify any significant errors that can result from various situations such as a “gross” setup error. There are various kinds of in vivo dosimeters that are available. These are for example, TLDs, diodes, MOSFETS etc.
3D-CRT delivery techniques: blocks
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3D-CRT delivery techniques: Multileaf collimators (MLC’s)
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MLC systems

Computer-controlled MLC

Each leaf is independently driven
Leaf width: 3mm, 5mm, 10mm, . . .
Leaf Transmission: 2-3%
# pairs of leaves: 26, 29, 40, 60, . . .
There are more details of the technical capabilities of the different MLC systems in presentation ‘Treatment hardware and software for 3D CRT’.
After all verifications are done one is ready to deliver treatment.
Milestones
Milestones

- Facilities are in place for the provision of conventional radiotherapy
- Adequate diagnostic imaging facilities are in place for diagnosis and imaging
- Adequate imaging facilities are in place for planning CT scans
- There is an intention to deliver curative radiotherapy
- Demonstration by audit that satisfactory setup accuracy can be achieved
Staffing/Training
Radiation Oncologists
IMRT represents a significant departure from the current paradigm used in radiation oncology. Dose planning in conventional radiation therapy is accomplished in a very intuitive manner by optimizing the weights of strategically placed radiation portals that conform to the target volume. Planning solutions are often well understood and do not vary much from patient to patient for a particular disease site. On the other hand, IMRT planning process starts with the definition of treatment goal and constraints. The dose optimization is completely computer controlled and its success in achieving the clinical goals is very much dependent on the set of parameters used as input to the computer algorithm. Learning how to adjust the parameters to steer the results in the desired direction is complex and sometimes non-intuitive. Therefore, it is difficult to identify an optimal solution without having a complete understanding of the optimization process and its limitations. There is a significant potential of treating a patient with a sub-optimal IMRT treatment plan if the radiation oncologist lacks the training in this process.

One of the basic uses of IMRT is to treat tumors that are either in close proximity or surrounded by critical normal structures, and this presents two challenges. One is to segment the structures precisely and accurately, and the other is to choose appropriate planning margins judiciously. It is essential that the radiation oncologists are well-trained in image guided treatment planning and that they have a good understanding of treatment planning and delivery uncertainties.

Unlike conventional radiation therapy, the gross tumor and regions of sub clinical
disease are often treated concomitantly to different dose per fraction in IMRT. Moreover, the dose distribution in the target volume is often much more inhomogeneous in an IMRT plan. It is important that the radiation oncologists critically evaluate differential dose fractionation schedules for IMRT in light of their clinical experience with conventional radiation therapy. This requires an understanding of the biologically effective equivalent dose concepts and tissue tolerance doses.

Radiation oncologists who did not have chance to get training in IMRT process during their residency training should consider getting such training through special workshops conducted by academic institutions that have active clinical IMRT programs. Some private companies have also started courses in IMRT.

Radiation Oncology Physicists
IMRT is much more challenging for radiation oncology physicists than the conventional radiation therapy. Radiation oncology physicists have much more significant and direct role in IMRT planning and delivery than in conventional radiation therapy. It requires an advanced understanding of mathematical principles of dose optimization, computer-controlled delivery systems and issues that relate to the dosimetry of small and complex shaped radiation fields. They also need to have a better understanding of treatment setup, planning and delivery uncertainties and its impact on patients treated with IMRT. Treatment planning optimization for IMRT is based on dose-volume constraints and dose limits for critical structures and target tissues. Therefore, it is important that radiation oncology physicists understand these concepts and have a good familiarity with tomographic anatomy. They must understand the implications of a busy intensity patterns (with large peaks and valleys) on the treatment delivery accuracy and efficiency. The quality assurance testing for IMRT is much more complex than conventional radiation therapy. It is imperative that each physicist involved with IMRT should have special training in the whole process of IMRT.

Dosimetrists
The dosimetrists have a particularly difficult task of adjusting to IMRT planning. IMRT planning uses a paradigm that they are not used to in conventional radiation therapy planning. Compared to treatment planning for conventional radiation therapy, the emphasis in IMRT planning is more on selecting the most appropriate dose optimization constraints parameters. They do not have to worry much about beam shaping, placement and weight optimization in IMRT. Like physicists, dosimetrists must understand the implications of dose-volume constraints on optimized dose distributions. They also need to understand, at least conceptually, the implications of treatment setup, planning and delivery uncertainties in IMRT. The best source of training for a dosimetrist is the facility radiation oncologist and physicist who have special training in the use of IMRT.

Radiation Therapists
Implementing IMRT requires the active involvement of the radiation treatment therapists. They should be involved in the design and testing of treatment procedures. It is important to set aside sufficient time for that participation and the related training.

If the IMRT delivery involves specialized equipment (e.g. add-on collimating device), then
there will be the need to train the therapists in its use and storage. They may also have responsibilities for basic maintenance and quality assurance.

Therapists will need to be trained to use any new immobilization or localization systems.

However IMRT is delivered, be it with special collimators or existing MLCs, therapists will need to be trained in the new procedures. Carrying out mock procedures with phantoms needs to be part of the process of testing the new procedures. Delivery details that escape the physicist’s notice may be important to the therapists. For example, the initial field shape for an IMRT treatment may obscure the light field or the crosshair, requiring that the patient be positioned before the MLC is programmed.

Therapists need to be provided with the means of knowing that the treatment they are about to deliver is correct. For conventional treatments with blocks or static MLC shapes, they can compare the field on the patient to the simulation film, DRR, or other plan data. For IMRT, the initial field shape may show only a narrow segment or be closed entirely. For IMRT treatments, the analog to the physical block or static MLC file is the dynamic IMRT file. The physicist may well have validated the intensity map produced by each file before treatment, but on a daily basis the therapist will need to be able to verify that the appropriate file has been selected for each field or arc. (These issues were discussed above in the section on file transfer and management.) Given the complexity of IMRT treatments, it is clearly best for the treatment delivery to be fully monitored by a R/V system. Even in that case, therapists will need to be trained so they can verify for themselves that the R/V programming is correct.

Therapists will need to be shown how to respond to unplanned events. They need to know how to interrupt and restart a treatment, how to recover from a partial treatment that requires the console to be reprogrammed, how to recognize and act on new error messages and interlocks.

Therapists will need to be trained on any new procedures related to portal imaging and to daily quality assurance tests. As with any QA procedure, clear instructions and action levels need to be provided.

Service engineers
Reliable performance of all aspects of the delivery equipment used for IMRT is essential. Compared to standard treatment techniques, it is can be much more difficult to cleanly recover from an interruption in dose delivery after an intensity modulated treatment has started. Therefore, accelerators with a poor history of reliability are not suited for this type of treatment, and expanded preventive maintenance programs are extremely important. This is particularly important for the multileaf collimator component of the overall system. Intensity modulated dose delivery can place demands on the MLC that far exceed the criteria used for the design of these systems. When the standard MLC systems where designed in the late 1980s, IMRT was not anticipated as a routine treatment. It is now evident that some implementations can require several hundred field changes per patient, or many thousands of fields per treatment day. This situation can lead to component failure, and special QA procedures must be adopted to guarantee
proper calibration of leaf position and to avoid treatment interruptions. With the cooperation of the medical physicist, preventive maintenance programs must be examined to determine that they are properly designed to address the special needs of IMRT. Additionally, service engineers must have a good working knowledge of the aspects of the treatment unit that are unique to IMRT. Service engineers need to understand that small changes or adjustments to an MLC can affect the machine output for IMRT delivery and should confer with the physicist whenever changes are made.

Patient education
Patients treated with IMRT should be informed of several issues. They need to be given realistic estimates of the time required for each treatment, description of the immobilization method used, and motions and sounds they will experience. Description of the goal of treatment and potential side effects may differ from conventional radiotherapy. These will be site- and protocol-specific. If IMRT is used to escalate doses, then the potential for acute or chronic sequelae may increase. Parotid sparing protocols may decrease the incidence of xerostomia but increase acute mucositis, especially if target doses are more inhomogeneous than with conventional treatments.
Radiation Oncologists

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Guidance on staff training

**Medical oncologist**
- 3D CRT

**Radiologists**
- PET

**Additional Staffing**
- Increased time for planning and delineation of target volume (physician, planner)
- Image guidance
- Development of next generation of leaders
Guidance on staff training

- Radiation Oncologists
- Medical Physicists
- Medical Oncologists/Radiologists
- Dosimetrists
- Radiation Therapy Technologists

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Dosimetrists

- Trained and experienced in 3D-CRT
- Immobilization for 3D-CRT
- Beam shaping methodologies – leaf fitting
- Contouring target volumes and critical structures
- Image based 3D Tx planning

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Therapists need to be provided with the means of knowing that the treatment they are about to deliver is correct. For conventional treatments with blocks or static MLC shapes, they can compare the field on the patient to the simulation film, DRR, or
other plan data. For IMRT, the initial field shape may show only a narrow segment or be closed entirely. For IMRT treatments, the analog to the physical block or static MLC file is the dynamic IMRT file. The physicist may well have validated the intensity map produced by each file before treatment, but on a daily basis the therapist will need to be able to verify that the appropriate file has been selected for each field or arc. (These issues were discussed above in the section on file transfer and management.) Given the complexity of IMRT treatments, it is clearly best for the treatment delivery to be fully monitored by a R/V system. Even in that case, therapists will need to be trained so they can verify for themselves that the R/V programming is correct.

Therapists will need to be shown how to respond to unplanned events. They need to know how to interrupt and restart a treatment, how to recover from a partial treatment that requires the console to be reprogrammed, how to recognize and act on new error messages and interlocks.

Therapists will need to be trained on any new procedures related to portal imaging and to daily quality assurance tests. As with any QA procedure, clear instructions and action levels need to be provided.
Patient selection
The goal of radiation therapy is to deliver a highly conformal dose of radiation to a 3D target volume. At the same time minimize the dose to an acceptable level to surrounding healthy tissue. This should reduce both acute and late morbidity thus permitting dose escalation to the target volume with the expectation of improved local and regional control.