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A virtual radiation therapy workflow training simulation

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ABSTRACT

Aim: Simulation forms an increasingly vital component of clinical skills development in a wide range of professional disciplines. Simulation of clinical techniques and equipment is designed to better prepare students for placement by providing an opportunity to learn technical skills in a "safe" academic environment. In radiotherapy training over the last decade or so this has predominantly comprised treatment planning software and small ancillary equipment such as mould room apparatus. Recent virtual reality developments have dramatically changed this approach. Innovative new simulation applications and file processing and interrogation software have helped to fill in the gaps to provide a streamlined virtual workflow solution. This paper outlines the innovations that have enabled this, along with an evaluation of the impact on students and educators.

Method: Virtual reality software and workflow applications have been developed to enable the following steps of radiation therapy to be simulated in an academic environment: CT scanning using a 3D virtual CT scanner simulation; batch CT duplication; treatment planning; 3D plan evaluation using a virtual linear accelerator; quantitative plan assessment, patient setup with lasers; and image guided radiotherapy software.

Results: Evaluation of the impact of the virtual reality workflow system highlighted substantial time saving for academic staff as well as positive feedback from students relating to preparation for clinical placements. Students valued practice in the "safe" environment and the opportunity to understand the clinical workflow ahead of clinical department experience.

Conclusion: Simulation of most of the radiation therapy workflow and tasks is feasible using a raft of virtual reality simulation applications and supporting software. Benefits of this approach include time-saving, embedding of a case-study based approach, increased student confidence, and optimal use of the clinical environment. Ongoing work seeks to determine the impact of simulation on clinical skills.

Introduction

Radiotherapy education, as in other health professions, aims to equip students with a combination of essential knowledge and understanding, clinical professional skills and clinical technical competencies. Traditionally, academic teaching blocks have provided the underpinning theoretical understanding while clinical placements have facilitated integration of theory into clinical skills development. At Queensland University of Technology students undertake 6 separate placements at a variety of clinical sites spending a total of 32 weeks in radiotherapy departments over the 3 year Course. During these placements students are expected to develop a wide range of technical and interpersonal skills. The variety of sites provides students with exposure to a range of equipment and techniques. While this has great value in terms of providing a wide educational experience, it can lead to challenges when students are faced with learning to handle different situations. Students also need to maximize their patient-care skills, and concentrating on equipment skills can distract them from this.

Simulation forms an increasingly vital component of clinical skills development in a wide range of professional disciplines including medicine,[2] surgery,[1] physiotherapy,[3] podiatry,[4] pharmacy,[5] chiropractice,[6] paramedicine,[7] psychiatry[8] and nursing.[9] Simulation of clinical techniques and equipment is designed to better prepare students for clinical placement by providing an opportunity to learn technical skills in a "safe" academic environment. Fear of making an error or inconveniencing clinical staff and patients

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is removed, allowing students to learn at their own pace. By familiarising students with complex equipment or processes before arrival in clinical departments, students are able to make optimal use of this valuable time and concentrate their efforts on patient care and applying their technical skills in a professional manner.

In radiotherapy training over the last decade or so, clinical simulation has predominantly comprised treatment planning software and small ancillary equipment such as mould room apparatus. The large and expensive nature of treatment delivery systems has until recently made their use in an academic training environment unfeasible. With the advent of the Virtual Environment for Radiotherapy Training (VERT), however, the potential for treatment simulation has increased. Published studies highlight the value of VERT for pre-clinical skills development[10,11] although it is only capable of simulating a couple of components of the radiotherapy workflow. Over the past 12 months at Queensland University of Technology, an initiative to develop and integrate new simulation applications, Digital Imaging and Communications in Medicine (DICOM)[12] processing, and interrogation software has aimed to fill in the gaps left in the existing simulation solutions to provide a streamlined virtual workflow solution. This paper outlines the innovations that have enabled this, along with an evaluation of the potential benefits for students, educators and patients.

Materials and methods

A series of new simulation applications and software solutions were developed to link existing simulation equipment and provide students with a continuous patient journey simulation. Table 1 illustrates how the various stages of a patient's radiotherapy course can be simulated using these tools. Although space prevents a detailed description of each tool an overview of each follows.

Virtual CT-scanner

With support from a Health Workforce Australia grant, a 3D virtual environment was developed to simulate a CT-scanner. Although primarily developed as a medical imaging simulation, it has demonstrated clear value for radiation therapy teaching. Students are able to “position” a patient on the couch and use the CT controls to set the correct parameters for their chosen radiotherapy planning scan. The application reinforces the importance of selecting correct scan limits, scan thickness and patient position. A gaming environment and realistic patient and equipment visualization along with 3D glasses engenders a genuine and high fidelity experience. Full class teaching using a PC laboratory can enable 40 students to undertake a rudimentary CT experience concurrently.

Batch CT handler

The planning of multiple treatments on copies of a single CT dataset is an ideal teaching opportunity as students' solutions and skills can be directly compared. This can be problematic since clinical DICOM systems do not allow simultaneous user access, there is greater potential for data loss through human error, and file access can be slower. To overcome these problems a new tool was developed, the DICOM CT Duplicator, allowing the automated production of duplicate CT datasets with unique identifiers. The user is able to specify override values for the Study ID, Patient ID and Patient Name DICOM attributes, such that files can be more easily organised in the planning system and beyond. This enables multiple students to plan the same dataset while retaining individual identification for each plan and thus allowing plan export and evaluation in all DICOM environments. The software was developed in the C# programming language and uses the Fellow Oak DICOM for .NET library.

Table 1
Virtual radiotherapy workflow solutions.

Workflow stage	Simulation/Solution
Patient imaging	Virtual CT-scanner
Image transfer	Batch CT anonymisation, copying and labelling
Patient database preparation	Verification system
Radiotherapy planning	Treatment planning system
Plan evaluation	Virtual environment for radiotherapy training
Plan assessment	Batch plan comparison system
Patient setup	Patient alignment lasers
Room setup	Virtual environment for radiotherapy training
Treatment verification	Image-guided RT software

Radiotherapy information management system

The MOSAIQ patient management software is used clinically to administrate patient schedules, connect planning and treatment software, and record and verify treatment-unit parameters. The system allows for easy transfer of data between the planning system and the VERT virtual linear accelerator, while students can gain valuable and clinically relevant experience with data input and checking procedures.

Treatment planning system

The Pinnacle planning system (Philips Healthcare, Fitchburg) is used at Queensland University of Technology to provide students with a range of planning opportunities from simple phantom dosimetry to IMRT using clinical software. Teaching is conducted in a specialist simulation IT lab to enable whole-class teaching, tutoring input from multiple clinical experts and proximity to additional simulation equipment. Broadcast software allows students' work to be shared with the class and for live plan evaluations to be conducted. Although Pinnacle is tolerant of duplicate DICOM headers, other planning systems and DICOM tools refuse to distinguish between different copies of the same CT datasets. A case-study based approach provides students with genuine clinical details including diagnostic, IGRT and follow-up information to engender a holistic approach to each patient's radiation therapy workflow.

VERT plan evaluation

VERT is a radiotherapy-specific virtual reality application utilising a large-screen and 3D shutter glasses to provide a high level of realism and presence.[13] It offers the user the opportunity to control a virtual linear accelerator with a genuine hand control system, displays CT and plan data in 3D and is rapidly becoming an integral component of radiotherapy training globally. Since VERT's implementation in Australia in 2011 it has been mainly used for pre-clinical skills practice, demonstration of techniques and 3D plan evaluation. The latter facility allows student-created dosimetry plans to be imported and displayed in immersive 3D using 3D shutter glasses and large screen rear projection. At Queensland University of Technology all students have an opportunity to view their plans in 3D with at-elbow evaluation from a clinical tutor. With the ability to view the relative dose to target and critical structures; students can be informed of their plan development and provided with guidance as to how improvements may be made.

Batch plan comparison

The Treatment and Dose Assessor (TADA) software allows the batch analysis of dosimetric quality for treatment plans exported as

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DICOM files. Data exported to spreadsheets include student identification information (via the study ID), planning parameters and dose volume metrics. The software allows the specification of planning objectives and reports on whether they have been successfully met. These features can allow efficient evaluation of student performance with respect to assessment criteria. The software has previously been used for retrospective dose quality evaluations in a clinical environment[14] and the study of the relationship between plan complexity and treatment deliverability.[15]

Lasers

The recent acquisition of a laser positioning system further enhances the student's ability to practice core clinical tasks. The set up incorporates a ceiling mounted fixed sagittal laser in conjunction with two side-mounted lateral lasers, simulating the configuration of a standard radiotherapy bunker. This allows students to straighten and level within the scope of patient case studies, making the current VERT environment more clinically realistic to clinical practice. These clinical skills form the foundation of radiotherapy practice and it is of pivotal importance to provide students with the facilities and the time to become proficient at these central tasks outside the scope of a busy, rushed and often intimidating clinical setting.

VERT room setup

VERT's primary function is to prepare students for clinical practice in a safe environment. Students are able to use the hand pendant to control the various parameters as they would prior to a real patient treatment. They are not only able to gain experience at using the complex control systems but also understanding of treatment fundamentals and techniques. Furthermore, in the training of students VERT provides the flexibility to enhance learning or address 'at-risk' students where tailored instruction on techniques and processes can be delivered without calling on already pressured clinical resources.

IGRT software

With the advent of electronic portal imaging in the 1990s, and even more so with the more recent development of Intensity Modulated Radiation Therapy (IMRT) and Image Guided Radiation Therapy (IGRT), treatment field verification using imaging prior to beaming on has taken a prominent place in the routine delivery of radiation. Whether by the use of electronically captured MV portal images, orthogonal kV iso-check films, or the ever-increasing application of Cone Beam Computed Tomography (CBCT), daily treatment field verification prior to beaming on is now more often performed than not in a growing number of departments.

Equipping students for this task involves not only instruction on the use of equipment for acquiring and assessing images, but also in the often subtle art of making 'on the spot' clinical decisions based on their assessment. As for any art, this latter skill is best developed with experience; in this case in the busy clinical environment. Unfortunately, acute time constraints during real world treatment delivery mean that the procedures of IGRT are often denied the student on clinical placement, leading to a shortfall in an essential clinical skill. Clinically relevant IGRT software is used in conjunction with case-studies created from real de-identified patients to provide a set of simulated situations in which students are introduced to the challenge of evaluating images and making treatment decisions. This can be done with a gradual increase of time pressure to practice decision making under gradually more realistic circumstances.

Workflow evaluation

Student feedback was gathered from all students across all 3 years relating to several key aspects of the workflow simulation as part of an ongoing Course Development and Evaluation project. Different aspects of the workflow were used by different year groups as seen in Table 2. All feedback was anonymous and provided voluntarily via a simple tool utilizing both Likert-style and open question formats. Ethical approval for data collection was provided by the University Human Research Ethics Committee. Descriptive statistical analysis of the Likert responses and thematic analysis of the open questions was performed.

Results and discussion

Time saving

Tutorials using the virtual CT scanner and VERT for pre-clinical preparation have replaced previous introductory visits to a clinical department. This was traditionally run in small groups and demanded hours of clinical resource and personnel time. Replacing this initial experience with virtual simulation aims to reduce this burden on clinical resources. Fig. 1 shows the substantial time-reduction that whole-class simulation-based teaching can facilitate. It should be acknowledged that virtual simulations only aim to replace the introductory group teaching, and are not seen as a replacement for clinical experience gained on individual placements.

In addition to savings on clinical time the workflow tools have enabled additional administrative time-saving. Copying of identical CT datasets can now be performed with automatic generation of user-determined identification codes including Unit Code, tumour site and student ID codes that overwrite even to "StudyID" level. This enables batch upload of multiple copies of the same patient with different IDs. For academic purposes this is very useful as it provides good parity for assessment as well as facilitating whole class teaching. Previously, anonymisation and plan copying was performed manually in a laborious and time-consuming manner as seen in Fig. 1. Since the deep anonymisation allows multiple copies to be uniquely identified in patient information systems, automated transfer between the planning system and VERT can be facilitated. Previously plans had to be transferred via USB, as batch export failed when identical Study UIDs were picked up by DICOM servers.

This means that students can evaluate plans in VERT to identify potential improvements and then action the changes immediately. An advantage of whole-class planning of identical patient datasets is that students can be assessed with parity. A software tool has been created that provides quantitative assessment of student performance against PTV and OAR doses. Although this is only 1 component of plan assessment, it does provide a useful indication of the extent to which individual students have achieved their targets compared to class performance. Fig. 2 illustrates typical results from this with comparative PTV coverage statistics for a Year 2 cohort of 29 students; it can be seen that Students 2, 20 and 25

Table 2
Teaching resource use and data collection.

Resource	Student numbers	Evaluation method
Virtual CT Scanner	Year 1 (n = 58)	Dedicated questionnaire
VERT plan evaluation	Year 2 (n = 29)	Module feedback questionnaire
Lasers	Year 1 (n = 58)	Module feedback questionnaire
VERT room setup	Year 1 (n = 58)	Module feedback questionnaire
IGRT Software	Year 3 (n = 24)	Module feedback questionnaire

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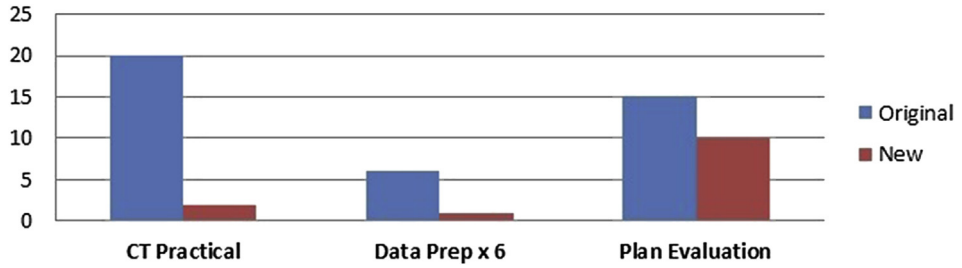

Figure 1. Time taken for tasks (hours for 40 students).

have under-dosed their target volumes compared to the rest of the class.

When combined with whole class teaching and practice on the same patient dataset, this allows students to gauge their performance against the "gold standard" generated from their peers. Although existing software allows generation of contouring gold standards for teaching purposes,[16] these have yet to extend to plan evaluation. This has great formative value as optimal solutions can be rapidly identified and used to illustrate possible solutions to the rest of the class.

Improved pre-clinical preparation

One of the criticisms of simulation-based education is that it usually focuses on a single "high-stakes" procedure and fails to replicate the full workflow of processes. This has led to the concept of integrated simulation[17] where radiotherapy students have the opportunity to "scan", plan, evaluate, QA check, "treat" and verify their own patient in a simulated yet integrated manner. The software solutions offer students the closest experience possible to clinical practice in a virtual environment. This has the benefit of not only better preparing students for clinical practice but also integrating it more completely and closing the theory-practice gap.[18]

Students can be made aware of the cumulative effect of errors as well as the importance of viewing each step of the patient journey as part of an interlinked continuum. Table 3 contains typical comments related to the benefits of simulation reported by Year 1 students. The comments highlight the value of their prior exposure to the simulated radiation therapy environment. It can be seen that students felt better prepared for placement and in particular understood the workflow processes. This should allow students to concentrate more on patient interaction skills, and ongoing evaluation seeks to determine the extent to which this was achieved. It was particularly interesting to see students citing a firmer link between academic theory and clinical practice.

Safe learning environment

The major advantage of simulating the whole RT workflow is that students can be allowed to experiment and start to gain valuable clinical skills that only come with hard earned experience. While the best forum for this is the clinical environment, the provision of a safe environment for learning purports to promote a range of skills stemming from simple motor control to high-level clinical decision making but with reduced pressure and risk. Table 3 highlights typical feedback comments concerning the benefits of learning in a safe environment. The introduction of VERT for pre-clinical skills training has already been demonstrated[10] to relieve the heavy burden that exists in meeting teaching and training needs of students whilst still doing the best by an unyielding patient waiting list. This is reflected in positive informal feedback from clinical educators and students in their identification of being 'better prepared' for clinic.

With the integration of additional software solutions, simulation of the radiation therapy workflow in a safe learning environment not only equips students for clinical placement but also frees up valuable clinical resources and time and allows students to make the most of the rich clinical learning environment.

Simulation limitations

It was reassuring to see that the students identified the key limitation of the workflow simulation as being the lack of patient interaction. Comments acknowledged that real patients would move, would be more challenging to position and would require constant use of interpersonal skills. This is unsurprising as the stated aim of the simulation was to provide foundation technical skills in order to help students focus more on patient skills when out on clinical placement. Some of the students also reported limitations from the hardware requirements and difficulty with the control systems.

Resource implications

Clearly some of these resources required substantial initial development while some draw on existing commercial products. Ongoing use of these innovations, however, promises to bring significant efficiency gains to the academic workload. Batch processing software reduces time taken to prepare a class (n = 40) CT datasets by around 80%. Use of a virtual reality CT environment

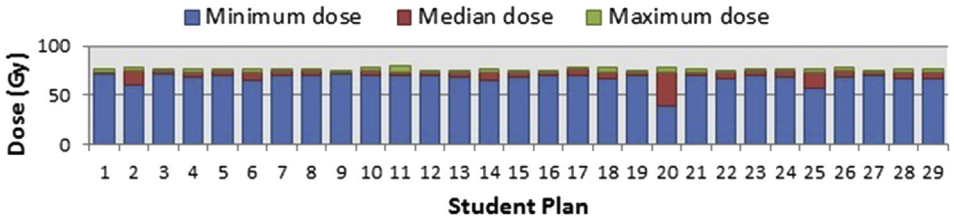

Figure 2. Cohort PTV dose comparison using TADA.

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Table 3
Benefits of simulating workflow.

Theory-practical link
"Helped me link theory to practical to develop understanding."
"It allows you to learn practically as well as theoretically."
"Apply theoretical knowledge into practical situations"
Preparation
"Will know how to use machine for placement"
"Getting to have hands-on experience during semester made me more confident when attending placement and I felt I got the hang of the real life situations easier."
"You were able to put into practice what you had learnt straight away rather than waiting for placement."
"It was very useful to gain more knowledge on how to set up patients and the use of pendants."
"It will help us to be more prepared towards future practicals"
"Allow to build knowledge before placement"
Workflow understanding
" we could understand the relations between imaging and planning departments"
"It provided me with a better understanding of clinical treatment prior to my placement."
"Experience in practical application before placement made me more aware of procedures."
"It was good for placement as I was more aware of procedures."
"Helpful to see and walk through the process"
"Provides run through of steps in process"
"Increasing familiarity with procedures"
Safe environment
"Can be useful to make mistakes"
"You can't kill the patient"
"You can fiddle around and have a go with the buttons … without the patient being there"
"Similar to actual set-ups without the pressure."
"I was able to practice moving the bed without the pressure of a real patient set-up."
"It was a good way to learn without the time constraint of a real patient scenario."

enables whole class experience that would require multiple consecutive small group bookings in a real imaging suite. For a class size of 40 this would replace 10 h of clinical seminars with a single hour in a PC lab. Investment In staff training with software is important to ensure efficient and effective use of resources but overall the time gains outweigh this initial outlay.

Future directions

It is hoped to further develop the plan assessment tool to generate a quantitative "score" for plans to complement qualitative plan feedback and assessment. In addition, the ability to quickly compare treatment plan "quality" for different students could enable the construction of a database of results for experience-based course design. This in turn would enable identification of areas of systematic deficiency in the plans that could inform future teaching.

More longitudinal evaluation will seek to determine student perspectives on the workflow simulation initiative. Additionally, in-depth and ongoing evaluation of the individual components of the workflow simulation is necessary to determine the value in practical skills preparation for students and impact on clinical performance. As with so many clinical skills training projects, however, the multitude of factors impacting on student performance in the clinical environment threatens to frustrate attempts to quantify the specific impact of a single intervention.

Conclusions

A series of existing and newly developed simulation applications have been integrated to successfully and efficiently simulate the workflow of a radiation therapy department in an academic environment. Student feedback suggests that this better prepares them for clinical placement, ensures that they understand the relevant processes and allows them to learn in a safe environment with minimal impact on clinical resources. Additionally, developed DICOM software tools allow for substantial time-saving while facilitating whole class teaching, comparative automated assessment and streamlined case preparation. The virtual workflow simulation supports a clinical case-study based approach to radiotherapy education. Ongoing evaluation seeks to determine the specific impact of simulation on students' clinical skills.

Conflict of interest statement

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On the use of virtual simulation in radiotherapy of the intact breast

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In this paper a method of breast cancer treatment planning using virtual simulation implemented at the Department of Human Oncology at the University of Wisconsin is described. All patients in this procedure are placed in a custom vacuum mold in treatment position with both arms up to avoid collision with the CT scanner aperture. For all patients a CT scan of 5-mm-slice thickness is acquired. The ipsilateral and contralateral breast, the ipsilateral lung and the heart are delineated and a three-dimensional plan is generated that tries to minimize the dose to the ipsilateral lung and heart while ensuring adequate coverage of the affected breast. Digitally reconstructed radiographs are used to verify the patient setup on the treatment machine.

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I. INTRODUCTION

In 1997, approximately 181,600 new cases of breast cancer were diagnosed in the United States. There were only 43,900 deaths that year, indicating that the majority of patients with breast cancer are treated successfully with long-term survival. This high survival rate may be attributed in part to annual mammography as a screening tool for middle-aged and elderly women. This has led to the more frequent diagnosis of breast cancer at earlier stages, including breast cancer *in situ*. Therefore, it has become feasible to utilize breast-conserving treatment for most breast cancer patients. In 1992, the American College of Surgeons, the American College of Radiology, and the American Cancer Society agreed that it would be appropriate to apply breast-conserving therapy for most breast cancer patients who had tumors less than 5 cm in diameter and affected breasts large enough to allow lumpectomy with a good cosmetic result. The only contra-indications for breast-conserving therapy were prior radiotherapy to the same breast, pregnancy, collagen vascular disease, or a high probability of gross multicentric breast cancer or extensive *in situ* carcinoma.

The goals of breast irradiation are to eradicate microscopic foci of multicentric cancer that might be present after lumpectomy, by using moderate doses of radiation. Theoretically, 50 Gy to the breast should minimize the probability of local recurrence at the primary site from approximately 20% (in unirradiated patients) to 5–7 % over a five-year observation period. Breast conservation is associated with better self-image (i.e., quality of life), but should be delivered so that the risk of complications is low and the cosmetic outcome should be acceptable (cf. Refs. 1 and 2)

In this paper we describe a technique for virtual simulation and three-dimensional (3D) treatment planning, that employs the PINNACLE^3 3D Treatment Planning System (ADAC Laboratories, Milpitas, CA), used in our clinic for breast-conserving radiotherapy. Virtual simulation may not be

needed for breast radiotherapy since it is by its nature regional therapy, and is therefore not target driven (cf. Ref. 3). However, even though the whole breast is the target, virtual simulation enables the planner to avoid critical organs such as the lung and heart. Hence, the value of virtual simulation in breast therapy does not lie in the ability to conform as best as possible to a target, but as best as possible to avoid critical structures while ensuring adequate coverage of the breast.

Image segmentation allows the planner to take critical anatomical structures explicitly into account through volume rendering in the 3D beam's-eye-view display, and therefore shape the blocks such that the critical organs are avoided as far as possible, while ensuring adequate coverage of the breast. This is in contrast to conventional simulation, where the blocks are shaped by either following the chest wall as imaged on the simulation film or using a rotatable half beam block to approximate the chest wall (see, for example, Refs. 4–7). Lind *et al.*[8] have concluded that there is a clinically important reduction in pulmonary function in a subset of patients following locoregional radiotherapy for breast cancer and point out that attention should be paid to individual lung dose-volume histograms. Furthermore, Das *et al.*[9] have concluded in a retrospective study of 108 patients receiving breast radiotherapy that virtual simulation provides accurate information of the percent of irradiated volume of lung and heart, and point out that this information, together with dose-volume histograms, is essential in reducing pulmonary and cardiac complications. In addition, the planner can easily determine if the lateral beam will diverge into the contralateral breast, and can choose the gantry angle accordingly. Last, but not least, it should be pointed out that virtual simulation allows this to be done without the physical presence of the patient, hence sparing the patient a sometimes lengthy and uncomfortable simulation procedure.

In the next section we describe a technique of virtual simulation as implemented at the University of Wisconsin. For ease of setup and to avoid match-line issues we treat our intact breast using a mono-isocentric technique (see, for example, Refs. 10–12). In the technique we employ the breast lies in the inferior half of the treatment field and a supraclavicular field can be easily matched in the superior half of the treatment field if therapeutically indicated.

II. CT PROTOCOL FOR 3D PLANNING

When the patient arrives at the CT scanner she is placed supine in a halfbody Vac-Lok bag (Med-Tec, Orange City, IO) on the scanner table. The patient is then positioned with both arms up and the scanner couch is driven through the scanner aperture to determine if the patient will collide with the CT scanner aperture. If the patient does not clear the scanner aperture we adjust the arm position so that the patient will clear the scanner aperture. If the arm position has been adjusted as much as possible and the patient still does not clear the scanner aperture, then the patient is scheduled for a regular simulation. If the patient clears the scanner aperture without problems we proceed with making the custom mold.

We pay particular attention to the reproducibility of shoulder and arm positions and that they are comfortable for the patient. Hence, we make sure that both arms and the shoulders are well outlined in the mold. We found that reproducibility of arm and shoulder position is one of the most important factors that determines the day-to-day reproducibility of the setup on the treatment machine. For this reason we have moved away from the use of a breast board, which did not provide a reproducible patient position on a day-to-day basis. The affected breast then is palpated and the breast parenchyma is outlined with a radio-opaque tube having an outer diameter of 2.7 mm and an inner diameter of 1.5 mm (Cook, Bloomington, IN). Three fiducial markers are placed in anatomically stable regions. We have chosen these points to be the anterior midline over the sternum, a point on the skin near the ipsilateral lower axilla, and a point on the skin near the contralateral lower axilla. Of these three points the anterior midline sternum point is the anatomically most stable, and we make all our shifts from this point. It is important to realize that these fiducial points are the only link between the real and virtual patient. It should be emphasized, however, that this link is only as good as the reproducibility of the positioning of the patient with respect to the custom mold (see comments above) and the positioning of the vacuum mold with

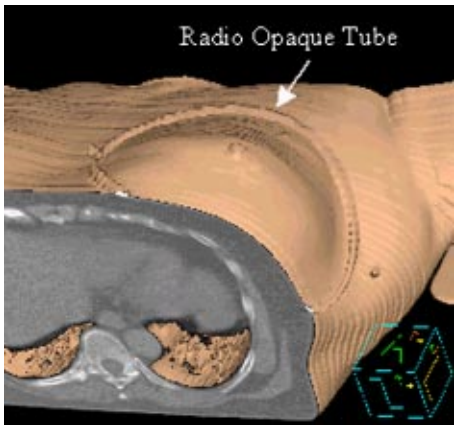

FIG. 1. (Color) Three-dimensional reconstruction of patient illustrating the placement of the radio-opaque tube.

respect to the patient support system (treatment machine couch). If either of these fail to be reproducible, then the link between the real patient and virtual model is broken. Hence, particular attention is paid to these aspects. For this reason the points are marked with lead BBs during the CT scan and are tattooed afterwards. Once the fiducial points are marked the upper and lower limits of CT scans are set. The upper limit is chosen such that the first CT slice starts just below the mandible and the lower limit is chosen such that the entire breast and the BBs marking the points on the skin near the ipsilateral and contralateral lower axilla are included in the scan volume. CT images are acquired with 5 mm spacing. Figure 1 shows a surface rendering of a patient on the treatment planning system. One can clearly observe the radio-opaque tube, which outlines the extent of the breast parenchyma as determined by the physician's palpation.

III. VIRTUAL SIMULATION/PLANNING

A. Registration of the patient in the treatment planning system

After the CT scans have been acquired they are transferred over the network to the treatment planning system and a treatment plan is generated. First, we place a point of interest (POI) called the ''CT Isocenter'' at the intersection of the perpendicular through the anterior midsternum BB and the coronal plane passing through the BBs placed on the skin in the region of the lower axilla as is illustrated in Fig. 2. Once the CT Isocenter has been identified, the laser localization point is set to the CT Isocenter so that the correct shifts (that yield the patient's beam isocenter) are obtained at the end of treatment planning.

The laser localization tool in the treatment planning system allows the user to select a POI with respect to which all other POIs are referenced; i.e., the user chooses the origin to which everything else is referenced. It is, therefore natural to choose the CT Isocenter since everything has to be referenced with respect to this point when one translates the treatment plan into reality. In fact, the patient has now been registered in the treatment planning system and the link between the virtual and real patient has been established.

The PINNACLE^3 treatment planning system employs the following coordinate system. The origin of an image set lies in the lower left-hand corner of the first transverse CT slice in an image set. The positive x axis points from right to left, the positive y axis points from the posterior to the anterior, and the positive z axis points from the superior to the inferior direction.

We take care that the z coordinate of the CT Isocenter coincides with the z coordinate of the CT slice that contains the midsternum fiducial mark. Next, an anterior beam and a right or left lateral beam (depending on which breast is treated) is added having the CT Isocenter as their isocenter. This is done to determine the AP and lateral setup SSDs (Fig. 3).

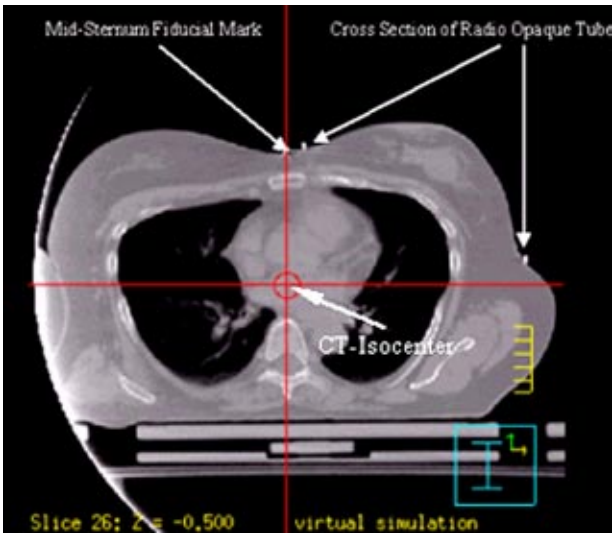

FIG. 2. (Color) The CT-isocenter is placed at the intersection of the perpendicular through the anterior midsternum BB and the coronal plane passing through the BBs placed on the skin in the region of the lower axilla.

This information is used at the treatment start to double-check the initial setup to the CT Isocenter before the shifts to the beam isocenter are made. This is done since the tattoos placed on the patient at the time of CT do not lie in the same transverse plane. For convenience we then add another set of anterior and lateral beams. These beams are later set to the beam isocenter to

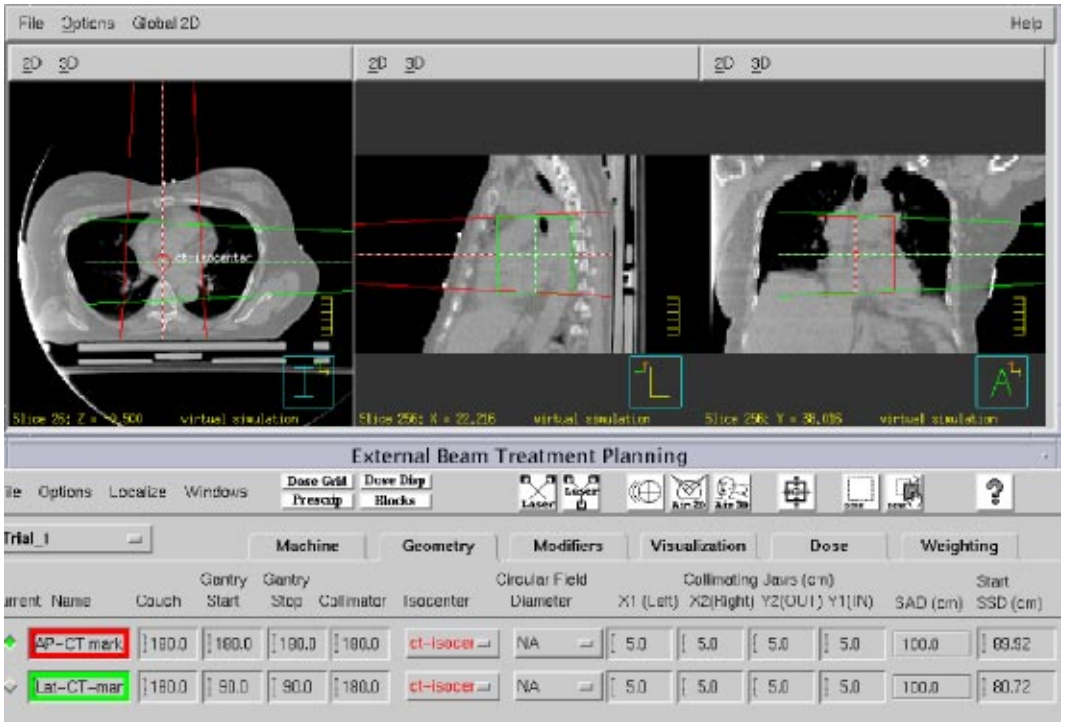

FIG. 3. (Color) Placement of anterior and left lateral setup beams having the 'CT Isocenter' as their isocenter for a left breast. The anterior setup beam has an SSD=89.9 cm and the left lateral setup beam has an SSD=80.7 cm.

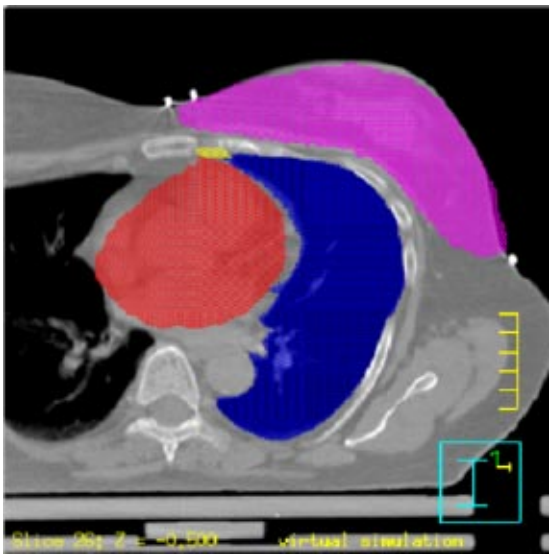

FIG. 4. (Color) Typical image segmentation generated during the process of virtual simulation. The breast parenchyma, ipsilateral lung, heart, and (IM) nodes are shown.

determine the AP and lateral setup SSDs for the beam isocenter, once it has been determined (see below) and the treatment plan has been generated. After this initial phase, we outline the ipsilateral and contralateral breast parenchyma [as well as the ipsilateral lung, heart, and internal mammary (IM) nodes] and define the superior and inferior borders by indicating the most superior and most inferior CT slice to be irradiated. Figure 4 shows the typical image segmentation obtained in this process. We use the radio-opaque tube as a visual guide to relate the impression of the breast exam with the anatomical information contained in each of the transverse slices. It should be pointed out that there is no special reason other than convenience of illustration to follow the sequence of events outlined above. One could just as well start with outlining the anatomical structures and then proceed with the patient registration.

B. Determining the isocenter and generating the treatment plan

The next step is to determine the beam isocenter. Using the software utility ''Auto place POI'' in the treatment planning system, we place a POI in the center of the breast parenchyma. Next, on the CT slice closest to the z coordinate of this POI, the physician draws a line that represents the intended posterior (deep) field edge (Fig. 5). We use this line as a starting point for the selection of gantry angle. We then manually place a POI at the center of this line. Next we add the medial tangent beam and choose this POI as its provisionary isocenter. We then determine the gantry angle such that the central axis coincides with the drawn line. At this point we make sure that the medial tangent does not pass through the contralateral breast, that there is at least 2 cm of flash above the breast parenchyma, and that no more than 2–3 cm of lung are included in the treatment field by scanning through the CT slices above and below. If we find that the medial tangent passes through the contralateral breast, then the lateral point of the drawn line is moved posterior until the medial tangent does no longer pass through the contralateral breast. In case there is inadequate flash (Fig. 6), we move the manually placed POI anterior. To ensure adequate coverage of the breast the posterior jaw of the medial tangent beam is then opened by the amount the manually placed POI is moved anterior, and the gantry angle is changed so that the beam edge coincides with the line drawn (Fig. 7). We now set the true beam isocenter such that the breast will lie in the inferior half of the treatment field. On the most superior CT slice that defines the upper border of

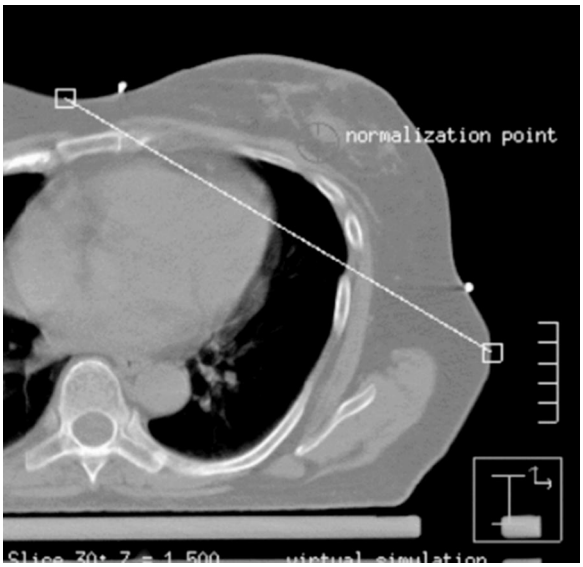

FIG. 5. Placement of line that represents the intended posterior (deep) filed edge.

the treatment fields, the entrance and exit points of the central axis (CAX) of the medial tangent beam are marked by adding two points of interest. Note that the exit point of the medial tangent beam CAX is the entrance point of the lateral tangent beam CAX. The beam isocenter is then chosen as the midpoint of the line connecting the lateral and medial entrance points (Fig. 8).

This procedure ensures that the line drawn by the physician is the posterior field edge for the tangent fields. However, when the field size necessary to cover the breast exceeds 20 cm the above procedure is applied to the CT slice containing the manually placed POI. The x and y coordinates of the POI are modified such that the POI becomes the midpoint of the line connecting the entrance and exit points of CAX of medial tangent beam. The modified POI then becomes our beam isocenter and we follow the Siddon technique.[4,7]

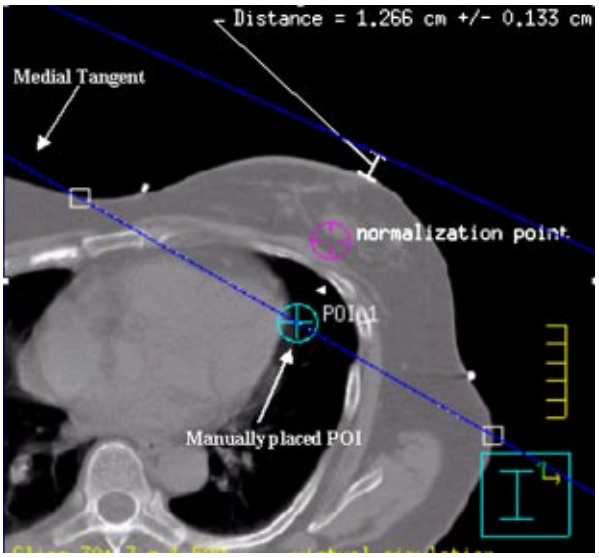

FIG. 6. (Color) Shows an example of inadequate filed flash above the breast. The anterior field flash is less than 2 cm.

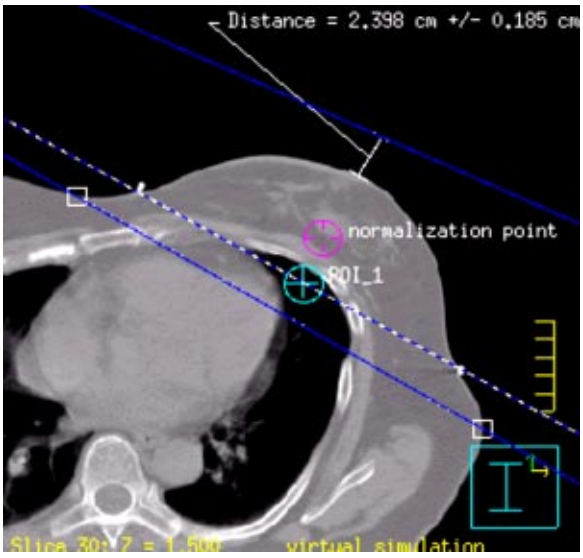

FIG. 7. (Color) Shows an example of adequate anterior field flash after adjustments have been made. The anterior field flash is larger than 2 cm.

The medial tangent beam is then copied and opposed to create the lateral tangent beam. If the isocenter has been moved anteriorly, then the gantry angle is changed so that the lateral tangent beam edge aligns with the line drawn by the physician. A 45° wedge is added to the lateral tangent beam, and, if needed, a 15° to 30° wedge may later be added to the medial tangent beam to improve dose homogeneity.[13] The physician draws the blocks for both the medial and lateral tangent fields so that the treatment portals follow the outlined breast parenchyma (Fig. 9).

If the mono-isocentric technique is used, the POI placed in the center of the breast parenchyma becomes the dose prescription point. We normalize the dose to this point, since it lies approximately in the center of the treatment field. This minimizes the dose inhomogeneity across the treatment volume. Doses are calculated using heterogeneity corrections and the beams are

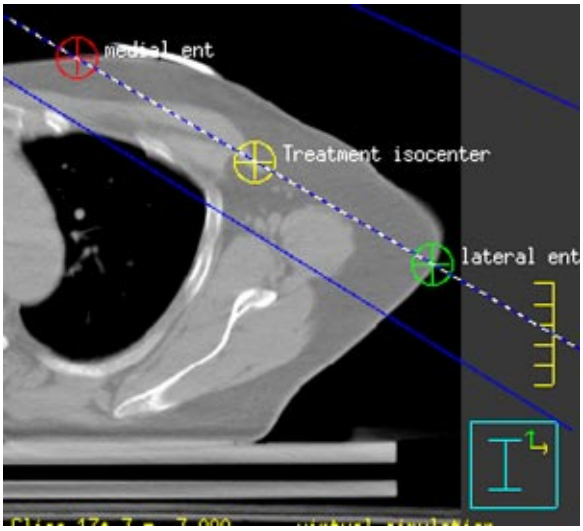

FIG. 8. (Color) Treatment Isocenter is chosen as the midpoint of the line connecting the lateral and medial entrance points.

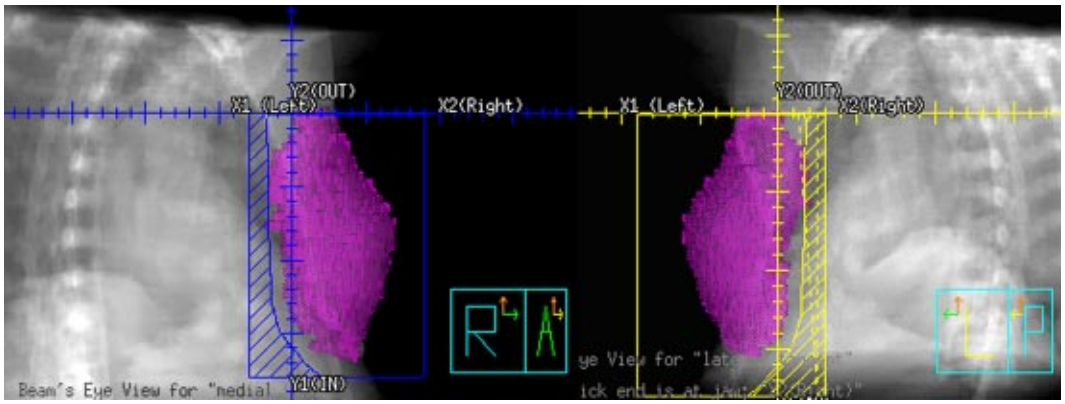

FIG. 9. (Color) Beams-eye-view of the blocks for the lateral and medical tangent fields, which follows the outlined breast parenchyma.

weighted so that the prescription isodose line encircles most of the drawn-in breast parenchyma (see discussion below). Figure 10 shows a typical dose-volume histogram (DVH) for an acceptable treatment plan.

As can be seen from Fig. 10 it seems that only 50% of the target volume receives the prescribed dose of 1.8 Gy per fraction. As can be seen from Fig. 4 the breast extends all the way to the skin surface. Hence, some of the target volume lies in the build region, and will therefore receive a dose less than the prescribed dose. That this effect is quite significant can be seen from the following example. Approximate the breast by a semicircle of a radius of 6 cm, then a 1.0-cm-thick rim between 5 and 6 cm corresponds to 42% of the total volume. Therefore, it is not surprising that we have only 50% coverage of the target volume.

Once the treatment plan is deemed acceptable, we generate digitally reconstructed radiographs (DRRs) for AP and lateral setup beams to verify the beam isocenter as well as tangential treatment fields. We make sure that if there is a wedge in the beam, the wedged beam is printed so that the wedge direction can be verified (Figs. 11 and 12).

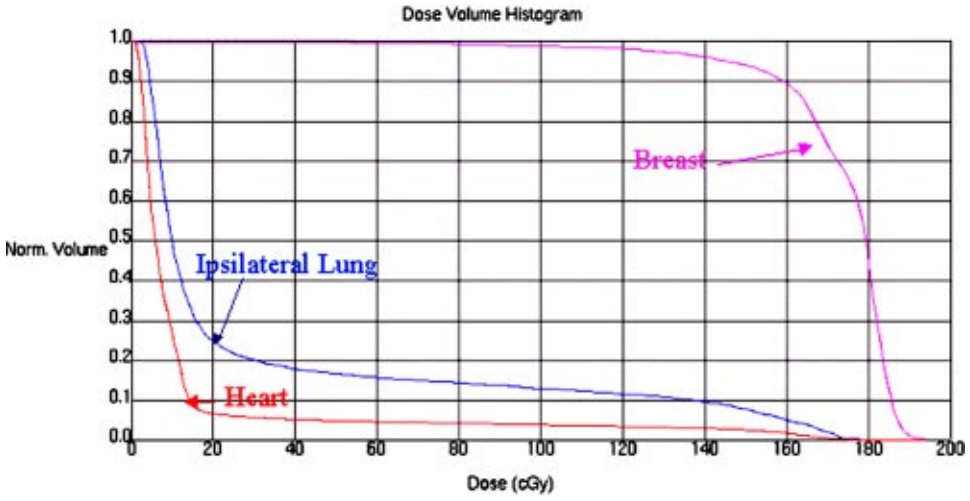

FIG. 10. (Color) Dose volume histogram for an acceptable treatment plan. Cumulative dose volume Histograms for the breast parenchyma, lung, and heart are shown.

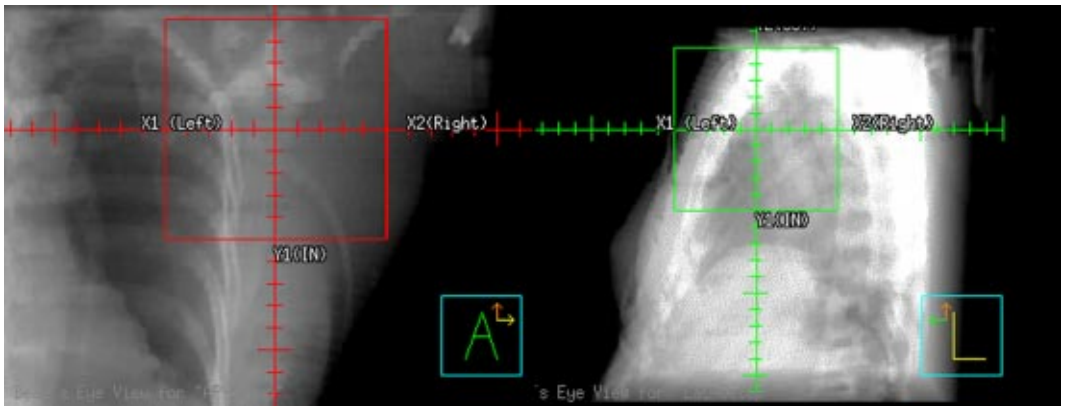

FIG. 11. (Color) AP and left lateral digitally reconstructed radiographs for setup verification of the treatment isocenter (true beam isocenter).

C. Initial treatment setup

On the first day of treatment the patient is placed supine in the custom-made mold that was manufactured at the time of the CT scan. The patient is then realigned to the CT marks and the AP and lateral SSDs are verified. We use the shifts that were determined at the time of virtual simulation to move the patient to the intended beam isocenter, and the AP and lateral SSDs for the beam isocenter are verified. Once it has been determined that the SSDs are correct, AP and lateral port films are obtained which are then compared to the AP and lateral isocenter DDRs, respectively. If the physician deems the setup satisfactory, we set the medial tangent field and a port film is obtained, and compared to the medial tangent field DRR. Once approved, the medial tangent field is treated, and one proceeds to the lateral tangent field for which we again obtain a port film. After the physician has approved the lateral tangent field port film, the wedge is inserted, the wedge direction is visually verified by the DDR indicating the wedge direction, and treatment is initiated. It typically takes between 25 and 35 min to execute a new start.

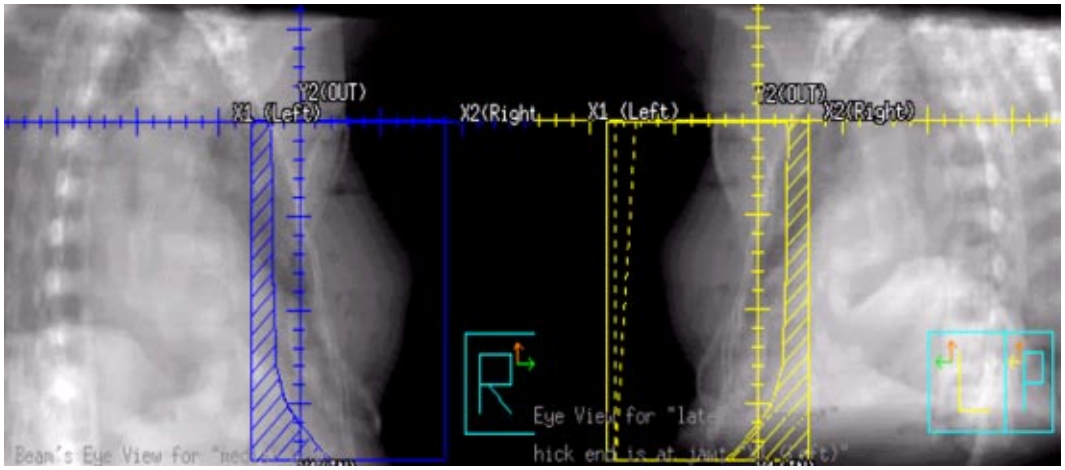

FIG. 12. (Color) Lateral and medical tangent digitally reconstructed radiographs for setup verification of the lateral and medial tangent treatment field. The heel of lthe wedge is towards the X_1 (left) yaw as indicated in the DDR of the lateral tangent field on the right.

IV. DISCUSSION

Besides making conventional simulation unnecessary, the application of 3D treatment planning allows us to be more precise about including within the treatment beams all tissues at risk for cancer recurrence. It also allows one to define treatment fields based on segmented images, i.e., based on a CT anatomy of the breast, lung, and heart. Since the planner can see each of these structures, treatment fields can be designed that balance the need for adequate coverage of the target volume with conformal avoidance of the lung and heart. This latter benefit is one of the major advantages of virtual simulation over conventional simulation. The radiation oncology team (physician, physicist, and dosimetrist) can generate a treatment plan based on quantitative data (cf. Ref. 9) instead of relying on radiological/anatomical landmarks. It is hoped that this will lead to fewer side effects (cf. Refs. 8 and 9) at equal tumor control rates. In addition, virtual simulation also opens the door to advanced treatment techniques such as the use of custom compensators (cf. Ref. 14) and IMRT (cf. Ref. 15).

DEDICATION

This paper is dedicated to the memory of Judith Stitt, M.D., who has been an advocate for women's health issues and has been an avid supporter in the implementation of virtual simulation for treatment of breast cancer in our clinic.

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REVIEW ARTICLE

Simulation-based education for medical radiation students: A scoping review

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Education, medical radiation, radiography, simulation

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Abstract

Simulation-based education is a significant aspect of teaching clinical skills in tertiary medical radiation science programmes, allowing students to experience the clinical setting in a safe environment. As an educational tool, simulation exists in many valid forms including role play, interprofessional simulation and virtual reality simulation. This scoping review looks at the current literature in this field to identify the evidence surrounding simulation-based education for medical radiation students. The purpose of this review is to provide an evidence-based guide for educators, identify gaps in the literature and suggest areas of future research. Data extraction was performed on 33 articles where the interventions could be categorised into either role play simulation, virtual simulation, simulation videos or online learning environments. Most studies demonstrated that simulation could improve clinical competence and increase preparedness and confidence for clinical placement. Student satisfaction remained high throughout the studies; however, it is the view of many that although simulation-based education is a valid and effective tool, it is complementary to and not a replacement for clinical placement.

Introduction

Clinical education is a core component of medical radiation university programmes (Medical Imaging/ Diagnostic Radiography, Radiation Therapy and Nuclear Medicine) with simulation recognised as an essential preparatory tool for work-integrated learning and clinical practice. Over the course of their undergraduate studies, students are required to develop a solid grounding in academic knowledge together with the associated technical and patient-centred capabilities to facilitate a holistic approach in their own discipline. Globally, there is increasing pressure for training institutions to develop the competency of their students without the negative impacts that may be associated with clinical placements. This has resulted in university educators reassessing how to best facilitate the development of practical clinical skills in effective, safe and supported learning environments. Students not only need to be academically prepared for placement, but also need opportunities to develop technical skills outside the clinical learning environment.

Simulation-based education is a highly effective tool for mimicking the clinical environment to teach skills to students and practitioners in healthcare.[1] Founded on educational theories, a simulation program can provide training and professional development as well as opportunities for student assessment.[2] All phases of the simulation, from preparation, pre-briefing, the simulation activity, feedback, debriefing, to evaluation and reflection, play significant roles in the individuals' learning.[3] Of particular importance is the reflection process, with Levett-Jones and Lapkin[4] suggesting that the advantages of the debrief phase outweigh the actual simulation activity.

While virtual simulation has been successfully embedded within radiation therapy programs in Australia, the use of virtual simulation within diagnostic radiography has not been widely adopted despite some promising recent studies.[5,6] An Australian study confirmed the effectiveness of simulating clinical practice using anthropomorphic phantoms to develop patient positioning and communication skills.[7] Another

Australian study, Gunn and colleagues,[8] demonstrated that virtual reality simulation is more effective at improving clinical skills than conventional teaching methods. In addition, other studies have shown that medical radiation students benefit from simulation in an interprofessional context, resulting in improved confidence, teamwork and preparedness.[9–11] A systematic review concluded that simulation training increased students' knowledge, confidence and satisfaction.[12] Students value simulation training because they can see, practise and perform techniques/skills that may not be possible while on placement.

Despite the recent studies conducted in this field, many educators continue to use conventional teaching methods rather than seeking the potential benefits that simulation has to offer. Student preparation for clinical practice is essential and should be conducted with the most appropriate teaching methods to achieve the best results. Several scoping reviews and meta-analyses have been performed in the field of nursing and medicine. There is, however, a scarcity of comprehensive literature review on this contemporary pedagogical approach. It is also unknown if medical radiation simulation curricula have been designed according to current best practice guidelines incorporating the cycle of simulation phases. The aim of this scoping review is to provide a contemporary evidenced-based guide to simulation-based education in medical radiation programs.

Materials and Methods

A scoping review was performed to assess the current literature on the use of simulation for medical radiation students in an academic setting. Our existing knowledgebase and initial literature review of this topic have discovered a wide variety of alternate approaches to simulation education in medical radiation science. These aspects differ particularly in terms of the setting, duration and technology utilised by educators. Scoping reviews are particularly useful in this case, especially as our topic exhibits a complex and heterogeneous nature not amenable to a more precise form of review.[14] Overall, this review was intended to 'map out' the current literature, attempting to explore the conceptual boundaries of the topic and provide a clear indication of the volume of literature and an overview of its focus.

The organisational framework described by Arksey and O'Malley[13] was chosen as the preferred method in evaluating the extent of available evidence for this mapping overview. Specifically, this method entails: (1) identifying the research question, (2) identifying relevant studies, (3) study selection, (4) charting the data and (5) collating, summarising and reporting the results. These stages form the basis of the methods and results section of this review.

Research question

The intention of this scoping review is to answer the question, 'What is the current literature on simulation-based education for medical radiation students'? For this review, we refined our search strategy based on a PICO approach, where P (population) is the medical radiation student/curriculum, I (intervention) is simulation-based education, C (comparator) is other forms of learning and O (outcome) is knowledge retention/satisfaction/perceptions/experiences.

Search strategy

A scoping search was performed on three databases: PubMed, Scopus and Medline from 2010 to 2021. These databases were selected to capture the existing literature in allied health and higher education. To identify the search terms, a preliminary search was conducted in the Scopus and Medline databases. The following terms were entered: 'simulation', 'simulated learning', 'computed tomography', 'medical radiation', 'medical imaging', 'radiation therapy', 'nuclear medicine', 'radiologic technology' and 'radiography'. Later, synonyms for each search term were used and applied with the Boolean operators 'AND' and 'OR' to capture all possible relevant articles (see Table 1). Although no relevant MeSH terms

Table 1. Databases, search terms and number of hits.

Database	Search terms	Number of hits
PubMed	((radiography[Title]) OR (computed tomography[Title]) OR (medical imaging [Title]) OR (radiation therapy[Title]) OR (nuclear medicine[Title]) OR (radiologic technology[Title]) OR (medical radiation [Title])) AND ((simulation[Title]) OR (simulated learning[Title]))	233
Scopus	TITLE(((radiography) OR (computed tomography) OR (medical imaging) OR (radiation therapy) OR (nuclear medicine) OR (radiologic technology) OR (medical radiation)) AND ((simulation) OR (simulated learning))) PUBYEAR AFT 2010	586
Medline	((radiography) OR (computed tomography) OR (medical imaging) OR (radiation therapy) OR (nuclear medicine) OR (radiologic technology) OR (medical radiation)) AND ((simulation) OR (simulated learning))	232

exist for such keywords, these were deemed relevant to the research aims. The search included all peer-reviewed primary research studies using qualitative and quantitative designs that have been published in English between 2010 and 2021. The timeframe was selected in accordance to the recommendation by Joanna Briggs Institute,[14] as a narrow timeframe might severely limit the number of eligible studies.

Following the addition of studies identified through snowballing and reference list searching, duplicate studies were removed by a single researcher and titles and abstracts were screened according to the inclusion and exclusion criteria (see Table 2). The independent screening and reviewing of eligible studies was consistent with the 2005 scoping review framework by Arksey and O'Malley,[13] as well as the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines.[15] This process has been visually represented using the 2020 PRISMA flow diagram template in Figure 1. Any disagreement was discussed and resolved by consensus among the team members. The research team also had extensive experience conducting scoping reviews, systematic reviews and meta-analyses, which they used to inform their practice on this reviewing literature.

Results

Table 3 summarises the characteristics of all included studies. Publication dates span from 2010 until the four most recent studies in 2021, highlighting the contemporary nature of simulation. The majority of studies were conducted in developed English-speaking nations (AUS = 12, UK = 9, IRE = 2, NZ = 2 and USA = 1), with the remaining conducted in the UAE, Finland, Sweden, Norway, France/Switzerland and Portugal. Twelve studies presented quantitative findings, while seven adopted a wholly qualitative approach. Another 14 studies adopted an approach combining both paradigms. Outcomes were most commonly measured based purely from the self-reported perception of participants (n = 30), with Likert scale questionnaires being the most popular tool (n = 21). Only seven studies incorporated performance-based measures to assess skills or knowledge in their data collection. In two of these studies, however, performance-based assessments were not a prominent feature. Six studies also employed a control group which did not experience the simulation intervention, while one additional study utilised a crossover study approach. None of the studies with a control group employed blinding, though it is noted that effective blinding is largely inconceivable. The total sample size of participants across the studies was 2343, with individual sample sizes ranging from five to 293. 'Radiography' was the sole focus for 20 articles, while seven had an interprofessional focus. The remainder focused on a combination of 'radiation therapy' (n = 5) or 'sonography' (n = 1). Role play simulation was the most common intervention (n = 16) followed by virtual/digital simulation (n = 13). Two studies each used simulation video clips or online learning environments as interventions.

Table 2. Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
• Peer-reviewed papers using simulation education. • Reported the use of simulation learning in medical radiations. • Published in English between 2010 and 2021.	• Only evaluated the software/equipment/ instruments. • Conference abstracts, case–control studies or case series. • Outside the scope of the medical radiation curriculum. • Narrative/systematic/scoping reviews or meta-analysis.

The use of performance-based outcome measures, as adjudicated by external observers or questionnaires was only a major part of the data collection in five studies.[8,9,16–18] Each of these five studies featured a control group which received either conventional educational interventions or no intervention. All studies using performance-based outcome measures reported significant improvement in favour of simulation other than Lee, Baird,[17] where no significant difference was found. In this study, the control group received conventional teaching methods, with both groups significantly improving in their core CT knowledge.

Seventeen of the nineteen studies analysing self-reported quantitative data, demonstrated an increase in competence after completing the simulation intervention. Students reported benefits in areas including empathy, attitudes towards patients, preparedness, confidence, content knowledge, reflection and technical skills. A control group was not utilised in 95% of studies, with Shiner[19] being the outlier. Leong, Herst[20] however, employed a crossover study design contrasting conventional teaching methods to VERT, finding that an integrated teaching approach may be of most benefit to the students. Only Jimenez, Thwaites[21] and Liley, Ryan[22] identified either no significant difference or decreased perceived competence post-intervention. Liley, Ryan[22] reported a significant decrease in the students' perception of confidence in their clinical skills after the intervention with 68% indicating that simulation did not help them to prepare for their clinical placements.

The studies including qualitative findings used many methods during data collection, namely open-ended

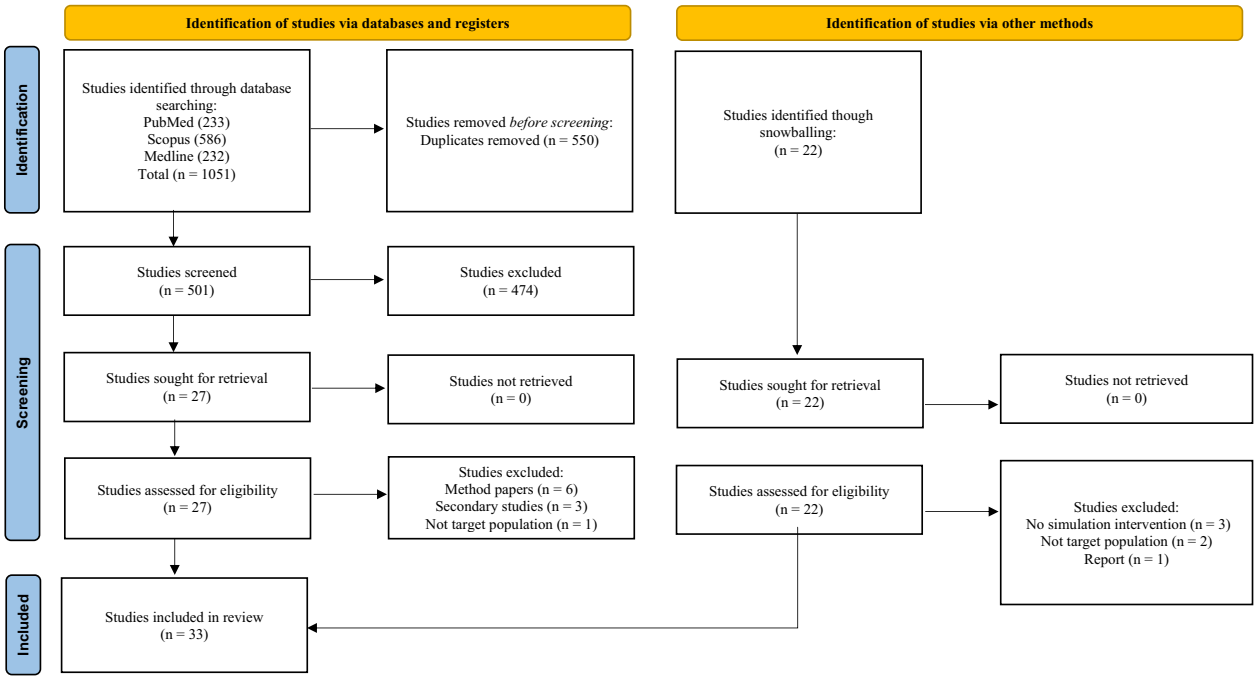

Figure 1. 2020 PRISMA flow diagram.

questions ($n = 10$), interviews ($n = 8$), focus groups ($n = 7$), observations ($n = 1$), with five studies employing a combination of methods. Their findings were supportive of the use of simulation, citing enhanced student knowledge, confidence, clinical competence and collaboration with others as positive outcomes. Students mentioned that the opportunity to perform activities relating to positioning, visualisation, communication, clinical preparation, patient care, collaborative learning and relationship-building were particularly beneficial.[19–21,23–30]

The use of simulation as an intervention was received positively by the students in 16 of the 17 studies reporting on satisfaction levels, with only Liley, Ryan[22] receiving substantial negative feedback. The students in studies by Carramate, Rodrigues,[31] Elshami and Abuzaid[32] and Halkett, McKay[33] agreed that simulation was able to positively impact on their learning and is an important educational tool, endorsing its use into the future.

Discussion

The review of the literature highlighted key aspects of simulation education, being the influence of type (e.g. roleplay and digital simulation); the capacity of simulation to achieve a variety of outcomes (e.g. clinical skills and preparedness); the mode of delivery (e.g. self-directed and teacher-led) and student satisfaction.

All studies included in this review explored simulation as a means for education in a tertiary setting for medical radiation sciences; however, two primary subgroups emerged with regard to the intervention used; role play simulations and virtual/digital simulation. Bleiker, Knapp[23] and Williams, Brown[34] both used video clips while Mc Inerney and Baird[35] and Paalimäki-Paakki, Virtanen[36] employed an online learning environment as a means to simulate the clinical setting.

The role play simulation studies can be broken down into further subgroups; practical targeted simulation and interprofessional simulation. For the purpose of this study, 'practical targeted simulation' will refer to any simulation-based teaching approach that was given to a specific population of students, whereas 'interprofessional simulation' will refer to any simulation-based teaching approach given to students as part of a multidisciplinary team. Practical targeted simulation was the intervention of choice for eleven studies, eight of which were specific to radiography participants. The other three studies included participants from radiation therapy[30,31] and sonography programs.[27] Six studies simply simulated the clinical environment with the use of role play, three of which incorporated actors to enhance realism.[26,30,33] Four studies used practical effects such as masks, suits and

Table 3. Data extraction table.

Author	Journal	Location	Design	Field	Intervention	Time frame	Outcome(s)	Instrument(s)	Key Finding(s)
Ahlqvist et al. 2013[16]	*Simulation In Healthcare*	SWE	Quant.	MI	Virtual radiography simulator	60 mins (one session/day)	Virtual sim. is effective for teaching image quality assessment.	Knowledge-based MCQ survey	The interv. group had significantly ↑ scores post-interv. The control group had no significant change after conventional teaching.
Alinier et al. 2014[9]	*Clinical Simulation In Nursing*	UK	Quant.	MI, RT, physiotherapy, nursing, midwifery, paramedic science, social work, pharmacy	IP sim.	4-h session (over 3 years)	The interv. enabled students to gain knowledge of professions outside of their own and appreciate IP learning.	Likert Scale questionnaire, knowledge questionnaire	The interv. group reported ↑ perceived knowledge and confidence in working in a team compared to the control group ($P < 0.05$). The interv. group scored 3.23% ↑ than the control group in the discipline knowledge questionnaire ($P < 0.05$).
Bleiker, Knapp & Frampton 2011[23]	*Radiography*	UK	Both	MI	Sim. videos	Unspecified (self-directed)	The interv. is a useful edu. tool in teaching MI students.	Likert Scale questionnaire, interviews	The interv. gave students insight into patients' feelings through observation and reflection. Helped students visualise situations they have not experienced yet. Helped relate patient care theory to their clinical practice.
Booth & Kada 2014[38]	*Radiography*	NOR	Quant.	MI	Edu. sessions, role play sim.	2 days of workshops	The interv. can significantly impact the attitudes of student radiographers towards the older population.	Likert scale questionnaire	Attitudes of students were + towards older patients before the interv. Students had a significantly ↑ + attitude towards the elderly after interv. Only a few students (5/38) reported ↑ negative scores post-interv. (still were overall +).
Bridge et al. 2015[5]	*Radiography*	AUS	Both	RT	VERT	Unspecified	Sim. of the RT workflow and its tasks are feasible using VR sim. applications and software.	Likert scale questionnaire, open-ended questions	The interv. saved substantial time for academic staff. Students had + feedback regarding its ability to prepare them for clinical placements. A 'safe' environment and opportunity to understand clinical workflow before actual clinical experience were important to students.

(*Continued*)

Table 3. Continued.

Author	Journal	Location	Design	Field	Intervention	Time frame	Outcome(s)	Instrument(s)	Key Finding(s)
Brown, Howard & Morse 2016[10]	*Journal of Interprofessional Care*	UK	Quant.	MI, nursing, medicine	IP sim.	Unspecified (over 3 weeks)	The interv. is an effective at preparing students to understand the roles of themselves and others in the trauma team.	Likert scale questionnaire	Students ↑ in preparedness to perform their role and had ↑ understanding of the roles in a trauma setting ($P < 0.01$).
Buckley et al. 2012[11]	*Journal of Interprofessional Care*	UK	Quant.	Medicine, nursing, physiotherapy, MI	IP sim.	Half-day sessions	The interv. improved understanding of roles and responsibilities, enhancing teamwork and communication.	Likert scale questionnaire, open-ended questions	Students ↑ in experience, knowledge of other professional roles and the patient's condition. Students ↑ confidence in interacting with other professional groups.
Carramate et al. 2020[31]	*JMIRS*	POR	Quant.	MI, RT	Role play sim.	One session/day	The interv. enabled acquisition and consolidation of content, highlighting the importance of engaging in their edu.	Likert scale questionnaire	Students valued the learning experience. Students strongly agreed that the interv. aided their learning and helped them acquire, consolidate and deepen their knowledge.
Dungey & Neser 2016[30]	*JMRS*	NZ	Both	RT	Role play sim.	One session/day	The use of high-fidelity sim. can help develop communication skills and prepare RT students for the clinical environment.	Likert scale questionnaire, open-ended questions, interviews	Students benefitted from active discussions with peers, actors and staff post-interv. The realistic sim. scenarios (due to trained actors) helped prepare students for clinical environment. Students demonstrated self-awareness but not high levels of self-reflection. Students viewed the interv. as effective, useful and engaging, but were less comfortable receiving feedback from peers. Creating a safe learning environment is important in each sim.
Elshami & Abuzaid 2017[32]	*JMIRS*	UAE	Both	MI	Virtual MRI Simulator	6 × 1-h sessions	The study supports sim. in MRI edu. and shows that the simulated sessions can be received well by MI students.	Likert scale questionnaire, focus groups	The interv. was effective at providing a comfortable environment for learning. 69% of students used the skills learnt during sim. in their clinical practice. Sim. training aided identification of areas of improvement and helped them learn from mistakes (60%).

(*Continued*)

Table 3. Continued.

Author	Journal	Location	Design	Field	Intervention	Time frame	Outcome(s)	Instrument(s)	Key Finding(s)
Gunn et al. 2018[8]	*Interactive Learning Environments*	AUS	Quant.	MI	Virtual radiography simulator	Unspecified (self-directed).	VR sim. can enhance the acquisition technical skills of MI students.	Assessor rubric	Mean role play score was significantly ↑ in the interv. group compared to the control ($P < 0.017$). These results translate to a 4.75% improved skill level in favour of the interv.
Gunn et al. 2021[24]	*JMRS*	AUS	Both	MI, RT	Virtual CT simulator	Unspecified	Use of virtual CT sim. does not provide a disadvantage to the students' confidence.	Likert scale survey, open-ended questions	93% MI students found the interv. easy to use. 75% MI students enjoyed the interv. The perceived usefulness was + for 57% of the MI students, 36% neutral. 46% were negative/neutral to one of the three categories of usefulness, enjoyment and/or ease of use. 68% of RT students found the inclusion of VR CT sim. helpful. Access to this sim. was beneficial to the student's clinical CT confidence.
Halkett, Mckay & Shaw 2010[33]	*Radiography*	AUS	Quant.	MI	Edu. sessions, role play sim.	Weekly sessions (3 weeks)	The interv. is an effective method of developing students' communication and history taking skills.	Likert scale questionnaire	Students were highly satisfied with the workshops. 7/15 items relating to confidence and patient communication had statistically significant increases ($P < 0.05$).
Holmstrom 2019[25]	*JMIRS*	FIN	Qual.	MI	Role play sim. (manikin)	38-h total	The interv. was a useful learning method in teaching students to perform plain X-ray examinations.	Observations & interviews	Themes included: ↑ theory-practice connection, guiding students to follow instructions and strengthening collaboration between students.
Jimenez et al. 2018[21]	*JMRS*	AUS	Both	RT, medical physics	VERT	4-h (one session/day)	The interv. is an appropriate edu. tool at promoting IP collaboration between RT and MP students.	Likert scale questionnaire, open-ended questions	Scores showed an insignificant difference in mean scores post-interv. Satisfaction with VERT was high in both the interv. and control groups.

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Table 3. Continued.

Author	Journal	Location	Design	Field	Intervention	Time frame	Outcome(s)	Instrument(s)	Key Finding(s)
Lee et al. 2020[17]	*Radiography*	AUS	Both	MI	Virtual CT simulator	1.5 h (self-directed)	CT knowledge acquisition via remote access with peer-assisted learning is comparable to local access with facilitation.	MCQ & short-answer knowledge assessment tests, Likert scale & open-ended survey	There was no significant difference in CT knowledge between the interv. and control groups. Significant ↑ was seen in assessment scores from the pre- and post-clinical period in both groups.
Leong, Herst & Kane 2018[20]	*JMRS*	NZ	Both	RT	VERT	Two teaching periods	VERT is able to help RT students visualise and connect concepts to the clinical context, giving merit to integrated teaching approaches.	Likert scale questionnaire, open-ended questions, interviews	Students generally found VERT relatable and beneficial to their learning (93% interested in more VERT sessions). VERT had more benefits to connecting theory to practice through visualisation, standard teaching methods were more valuable for core content. VERT seemed to promote student engagement more than standard teaching. Neither teaching approach was superior, rather they complimented each other.
Liley et al. 2020[22]	*Interactive Learning Environments*	AUS	Both	MI	Virtual CT simulator	2-h (self-directed)	CT sim. can not only be engaging but also present challenges, despite still being perceived as inferior to real clinical experience.	Likert scale questionnaire, open-ended questions	Students had mixed satisfaction. There was a significant ↓ in students' confidence in their skills after clinical placement. There was ↓ satisfaction from remote learning. There was ↑ preference for hands-on experiences. Sim. did not help prepare them for clinical practice in terms of CT skills (68% disagreed/strongly disagreed).
Mc Inerney & Baird 2015[35]	*Radiography*	AUS	Both	MI	Online clinical sim. environment	Unspecified	The interv. facilitated acquisition of evidence-based skills and established reflective practice in students.	Likert scale questionnaire, open-ended & yes/no survey	57.5% of students found the interv. useful when formulating action plans from clinical situations. 52.55% reported the interv. was effective in bridging theory and practice. The interv. promoted aiming for best practice in a clinical setting. 70% agreed that the interv. ↑ confidence in making professional decisions in clinical situations. 60% felt in charge of their learning.

(*Continued*)

Table 3. Continued.

Author	Journal	Location	Design	Field	Intervention	Time frame	Outcome(s)	Instrument(s)	Key Finding(s)
Naylor, Harcus & Elkington 2015[26]	*Radiography*	UK	Qual.	MI	Role play sim.	One session/day	Use of a service user as a patient in a sim. exercise for student assessment was successful in this setting.	Focus groups	The interv. was valuable for developing and assessing positioning skills, patient care and communication.
Naylor & Foulkes 2018[39]	*Radiography*	UK	Qual.	MI	Role play sim	Two sessions	Sim. is useful for preparing students to work in an operating theatre.	Focus group	Issues in identification and lack of clarity in communication were important in the operating theatre. Lack of preparation of the working environment was also highlighted.
O'Connor et al. 2021[37]	*Radiography*	IRE	Both	MI	Virtual radiography simulator	4 x 30min sessions (self-directed)	The interv. is a valuable teaching tool in MI edu.	Likert scale questionnaire, open-ended questions	58% of students enjoyed VR sim. Students ↑ confidence in anatomical marker placement (63%), beam collimation (75%), exposure parameter selection (56%) and centring the X-ray tube (64%). 55% of students advocated for the use of VR in formative assessments.
Paalimaki-Paakki et al. 2021[36]	*Radiography*	FIN	Qual.	MI	Virtual coronary CTA sim. environment.	Self-directed (2 weeks)	The interv. can usefully complement the current counselling practices.	Face-to-face & phone interviews	Students felt the interv. provided useful information and familiarisation with the cCTA unit, particularly regarding the department, examination room and scanner.
Reid-Searl et al. 2014[27]	*JMRS*	AUS	Qual.	MI, sonography	Role play sim.	2 days (40-min sessions)	The interv. contributed to the clinical communication skills of students.	Focus group	Key themes included: benefits of interacting with someone other than a student, awareness of empathy, engaged problem solving, learning made fun, therapeutic communication skills and purposeful reflection.
Roberts & Goodhand 2018[28]	*Nursing & Health Sciences*	UK	Qual.	MI, nursing, dietetics, occupational therapy, pharmacy, physiotherapy.	IP sim.	45 min (one session/day)	The interv. could be an engaging and useful IP learning activity.	Focus group	Students learnt important ideas central to the IP edu. curricula such as working together as an IP team. This learning is partly from sim. allowing things to go wrong.
Sapkaroski et al. 2018[40]	*JMRS*	AUS	Quant.	MI	Virtual radiography simulator	45 min (one session/day)	Clinical and technical skills is better developed in sim. with dynamic patient interaction than without dynamic interaction.	Likert scale questionnaire	Student perception scores indicated a significant ↑ favouring the VR sim.

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Table 3. Continued.

Author	Journal	Location	Design	Field	Intervention	Time frame	Outcome(s)	Instrument(s)	Key Finding(s)
Shanahan 2016[7]	*Radiography*	AUS	Quant.	MI	Virtual radiography simulator	Weekly sessions (one semester)	Virtual radiography sim. is valuable in developing technical and cognitive skills.	Likert scale & open-ended survey	83% found the interv. easy to use. 89% were able to control the equipment as needed. 95% of students benefited from repeating activities until satisfied. 94% benefited from being able to quickly see images and understand if changes needed to be made. 78% reported the sim. developed their technical skills. 85% reported it improving their image evaluation. 85% improved their problem solving. 88% improved self-evaluation abilities.
Shiner & Howard 2019[41]	*Radiography*	UK	Both	MI	Role play sim.	One session/day	The interv. was effective in preparing students to understand their role within the complex care setting.	Questionnaire with VAS, focus group	Students significantly ↑ in perception of preparedness. Students felt better prepared to perform their role in the imaging of complex care patients.
Shiner 2019[19]	*Radiography*	UK	Both	MI	Role play sim.	One session/day	The interv. provided an opportunity for the students to explore and reflect on initial reactions to new experiences.	Questionnaire with VAS, interview, focus group	The sim. ↓ negative feelings. Emotional preparedness, excitement and distraction ↑. Themes included: building relationships, emotional engagement, developing professional, self-engagement with wound and sim. impact.
Stowe et al. 2021[18]	*Radiography*	IRE	Quant.	MI	Virtual CT simulator	One session/day	The interv. improved student learning when used as a component in CT edu.	Knowledge-based multiple choice questionnaire	Mean scores for understanding image quality and dose ↑ after the interv. The interv. proved to be beneficial (although not as significant) when part of a larger CT module.
Titzer, Swenty & Hoehn 2012[29]	*Clinical Simulation In Nursing*	USA	Both	MI, nursing, occupational therapy, respiratory therapy.	IP sim.	One session/day (over 16 weeks)	The interv. provided an environment supporting interdisciplinary teamwork and working in a clinical situation with peers.	Likert scale questionnaire, open-ended questions	The interv. supported interdisciplinary team work. Independent problem solving was facilitated by allowing students to explore various paths of delivering patient care.

(*Continued*)

Table 3. Continued.

Author	Journal	Location	Design	Field	Intervention	Time frame	Outcome(s)	Instrument(s)	Key Finding(s)
Williams et al. 2015[34]	*Journal of Compassionate Health Care*	AUS	Quant.	Allied Health	Sim. videos	2-h session	Self-reported empathy levels can be improved after attending DVD sim. workshops.	Likert scale questionnaire	Mean empathy levels significantly ↑ after interv. MI had the second lowest mean pre-test empathy score (104) but ↑ post-interv. by the most (14). No students had a ↓ in empathy scores post-interv.
Zorn et al. 2019[42]	*Radiography*	FRA/ CHE	Qual.	MI	Role play sim.	Three sessions	The interv. had a + impact on the motivation of the students.	Interviews & observations	Sim. sessions were effective in developing high motivational dynamics for students.

+ – positive.
↑ – increase/higher.
↓ – decrease/lower.
AUS, Australia; Edu., education; FIN, Finland; FRA, France; Interv., intervention; IP, interprofessional; IRE, Ireland; JMIRS, Journal of Medical Imaging and Radiation Sciences; JMRS, Journal of Medical Radiation Sciences; MI, medical imaging; NOR, Norway; NZ, New Zealand; POR, Portugal; Qual., qualitative; Quant., quantitative; RT, radiation therapy; Sim., Simulation; SWE, Sweden; CHE, Switzerland; UAE, United Arab Emirates; UK, United Kingdom; USA, United States of America; VAS, Visual Analogue Scales; VERT, Virtual Environment for Radiation Therapy; VR, virtual reality.

moulage in order to increase realism in the simulation, with Holmstrom[25] the only study to use a manikin. These practical targeted simulations proved capable of changing perceived attitudes towards the ageing population and helped to consolidate and deepen knowledge. Further to this, the interventions enhanced student communication, preparedness, clinical skills and promoted self-reflection. It is noteworthy that the use of actors and practical effects was received well by the students, assisting them to suspend disbelief and fully engage in the activity.[30] Interprofessional role play accounted for five of the studies, in which participants were involved in a multidisciplinary, situational simulation. This intervention was met with positive feedback from the participants, citing increased levels of confidence, teamwork and better understanding of roles as its benefits. Alinier, Harwood[9] was the only study to incorporate a control group and measure outcomes based on knowledge gained, finding that the intervention group scored 3.23% higher in the knowledge-based questionnaire post-intervention. Students often have their first exposure to interprofessional environments such as trauma or ward radiography during clinical placement and are likely to feel unprepared in the absence of formal training.[10] Overall, studies which offered interprofessional simulation were seen to be beneficial for preparing students, which could have potential future implications for graduates as they enter the workforce and must work collaboratively with other professions to provide higher quality care.

The intervention that was most common among the virtual simulation studies was virtual radiography software ($n = 5$), allowing the students to position patients and operate an X-ray tube in a digitally simulated clinical environment. Similarly, four studies used virtual Computed Tomography (CT) software, three used VERT[5,20,21] while Elshami and Abuzaid[32] used virtual Magnetic Resonance Imaging (MRI) software. These studies viewed virtual simulation as an effective educational tool. Many noted that it provided the students with a safe environment to make mistakes and learn while also preparing the students for their clinical placements. Leong, Herst[20] reported increased engagement when contrasted to conventional teaching methods; however, they did not identify any significant benefits to achieving learning outcomes. Rather, its real benefit lies in integrating the two learning models. Student satisfaction remained positive throughout these studies with common responses indicating that the experience was beneficial to their education. Self-reported improvement was seen in many categories including understanding of image quality, dose, critical thinking, image evaluation and clinical skills. Students enjoyed having free access to the software to work at their own pace with less stress while developing familiarity in a clinical context. Having a safe environment to repeat examinations and learn from their mistakes were also positive outcomes. Conversely, confusing software, technical difficulties and lack of support led to some negative experiences. One study by Liley, Ryan[22] noted mixed results among the students with a decrease in their perceived clinical skill levels. The participants expressed a desire for 'hands-on' experience in preference to remote access learning.

Simulation video clips were found in one study to significantly increase empathy levels in an interprofessional context.[34] Although radiography students exhibited the second lowest empathy levels in the pre-test measurement, medical radiation students (radiography and radiation therapy) benefitted the most from the intervention. Similarly, Bleiker, Knapp[23] also noted themes of increased empathy as well as linking theory to practice, demonstrating that simulation videos can be an effective tool in medical radiation.

Although quite different in execution, both studies involving online learning environment simulations allowed the students to experience the clinical environment and learn remotely. Mc Inerney and Baird[35] demonstrated that most students (70%) believed the simulation to be beneficial to their professional judgement and clinical decision making; however, only 52.55% reported that the simulation was an effective link between theory and practice. The students participating in the study by Paalimäki-Paakki, Virtanen[36] found the interactive environment was suitable for familiarisation of the department and equipment in the clinical context, but did not explore this in great detail. As only two studies were found utilising this intervention, it makes it difficult to draw conclusions. Further studies with similar methodologies and interventions are warranted.

Student outcomes across all studies were generally positive towards simulation. The studies using performance-based outcome measures demonstrate its capability to achieve a variety of outcomes ranging from theoretical knowledge to clinical skills. Each of these studies reported statistical significance in the improvements over the control group, highlighting the advantages of simulation over conventional teaching methods. The favourable results from Alinier, Harwood[9] and Stowe, O'Halloran[18] reflect well on their respective interventions; however, their control groups received no intervention. This fails to address the question regarding the effectiveness of simulation compared with conventional teaching methods.

Similarly, the self-reported benefits from the students demonstrate the versatility of simulation to achieve a desired outcome. While only a few studies employed

control groups, the results show that most students are able to reflect on the intervention and identify benefits to their learning. Although this is less rigorous than other methodologies, outcomes such as preparedness and confidence are difficult to assess via alternate means without participant bias. Of the two studies receiving mixed qualitative responses, both used CT virtual simulation as the intervention. These responses were primarily due to the unfamiliar systems and lack of support but were also influenced by the lack of interaction with a physical CT environment.[17,22] It is important to note that although the benefit of simulation is clear, most studies are of the opinion that it should complement clinical placement rather than replace it.[5,22,27,37] This is in accordance with Thoirs, Giles[6] where it was the view of tertiary educators, accrediting bodies and clinicians that simulation should not replace clinical placement.

Students commonly reported that they enjoyed the simulation and that similar experiences should be incorporated into their respective courses. A large factor for this was the capacity for self-directed learning for online simulations whereby the students could complete the tasks in their own time. The high-fidelity nature of many simulations was also a contributor to the satisfaction levels.[26,30,38] The lack of control groups in these studies may again skew the results in favour of the intervention as the students had no comparative teaching method. Liley, Ryan[22] was the only study to report mixed satisfaction levels within the students. This was primarily due to the remote-access nature of the intervention leading to frustration within the participants and was also seen to a lesser extent in other virtual interventions.[37] However, it is important to note that this was a pilot study with a relatively small sample size.

Limitations

The studies comprising this review primarily relied upon self-reported outcome measures which are considered much less reliable than objective measures. Quantitatively determining the effect of simulation interventions should be prioritised by employing objective outcome measures in future research. Control arms should also be included in future research where possible to improve methodological quality. It should be noted that many institutions would employ simulation but may not publish their practices. Additionally, publication bias may have impacted the results as there was no active search of grey literature (e.g. unpublished theses and conference proceedings), and this review only included English-language studies. Publication of studies with more favourable results are more likely to be published than those with contrary findings, meaning that the literature available may overestimate the true value of simulation interventions. Real-world outcomes such as cost were not reported in any included study. Data regarding costs of implementation and qualitative discussion concerning accessibility of resources would be advantageous in enabling financial and resource analysis of given interventions.

Conclusion

It is evident that the use of simulation-based education can have significant effects on the learning of students in medical radiation. Almost all studies included in this review viewed the use of simulation in Medical Radiation education positively. If implemented appropriately, simulation can provide students with opportunities to experience the clinical environment in a safe context and learn at their own pace. Both practical and virtual simulation have shown their potential in a variety of contexts in this review, with many students endorsing its use in medical radiation courses as a complementary learning tool rather than a replacement for clinical practice. Due to the small number of studies with objective performance-based outcome measures and control arms, it is difficult to arrive at a reliable comparative evaluation of the relative benefits of simulation versus traditional teaching methods. Nevertheless, this review highlights the benefits of simulation in medical radiation education and outlines the shortcomings in recent literature. There is a need for further research into simulation using objective outcome measures and control arms, particularly concerning modalities such as CT and MRI.

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Conflict of interest

The authors declare no conflict of interest.

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CHAPTER 7.

CLINICAL TREATMENT PLANNING IN EXTERNAL PHOTON BEAM RADIOTHERAPY

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7.1. INTRODUCTION

External photon beam radiotherapy is usually carried out with more than one radiation beam in order to achieve a uniform dose distribution inside the target volume and as low as possible a dose in healthy tissues surrounding the target. The ICRU report 50 recommends a target dose uniformity within +7% and –5% of the dose delivered to a well defined prescription point within the target. Modern photon beam radiotherapy is carried out with a variety of beam energies and field sizes under one of two setup conventions: constant source-surface distance (SSD) for all beams or isocentric setup with a constant source-axis distance (SAD).

- In an SSD setup, the distance from the source to the surface of the patient is kept constant for all beams, while for an SAD setup the center of the target volume is placed at the machine isocenter.

- Clinical photon beam energies range from superficial (30 kVp to 80 kVp) through orthovoltage (100 kVp to 300 kVp) to megavoltage energies (Co-60 to 25 MV).

- Field sizes range from small circular fields used in radiosurgery through standard rectangular and irregular fields to very large fields used for total body irradiations.

7.2. VOLUME DEFINITION

Volume definition is a prerequisite for meaningful 3D treatment planning and for accurate dose reporting. The ICRU 50 and 62 reports define and describe several target and critical structure volumes that aid in the treatment planning process and that provide a basis for comparison of treatment outcomes. The following volumes have been defined as principal volumes related to 3D treatment planning: gross tumour volume, clinical target volume, internal target volume, and planning target volume. Figure 7.1 shows how the different volumes are related to each other.

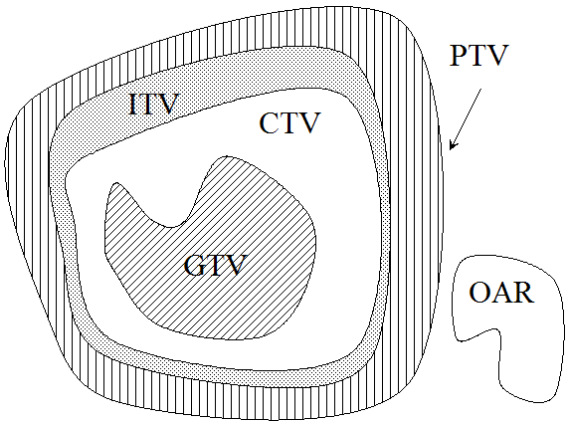

FIG. 7.1.Graphical representation of the volumes-of-interest, as defined by the ICRU 50 and 62 reports.

7.2.1. Gross Tumour Volume (GTV)

- *"The Gross Tumour Volume (GTV) is the gross palpable or visible/demonstrable extent and location of malignant growth*" (ICRU 50).

- The GTV is usually based on information obtained from a combination of imaging modalities (CT, MRI, ultrasound, etc.), diagnostic modalities (pathology and histological reports, etc.) and clinical examination.

7.2.2. Clinical Target Volume (CTV)

- "*The clinical target volume (CTV) is the tissue volume that contains a demonstrable GTV and/or sub-clinical microscopic malignant disease, which has to be eliminated. This volume thus has to be treated adequately in order to achieve the aim of therapy, cure or palliation*" (ICRU 50).

- The CTV often includes the area directly surrounding the GTV that may contain microscopic disease and other areas considered to be at risk and require treatment (e.g., positive lymph nodes).

- The CTV is an anatomical-clinical volume and is usually determined by the radiation oncologist, often after other relevant specialists such as pathologists or radiologists have been consulted.

- The CTV is usually stated as a fixed or variable margin around the GTV (*e.g.*, CTV = GTV + 1 cm margin), but in some cases it is the same as GTV (*e.g.*, prostate boost to the gland only).

- There can be several non-contiguous CTVs that may require different total doses to achieve treatment goals.

7.2.3. Internal Target Volume (ITV)

- Consists of the CTV plus an internal margin.
- The internal margin is designed to take into account the variations in the size and position of the CTV relative to the patient's reference frame (usually defined by the bony anatomy), *i.e*., variations due to organ motions such as breathing, bladder or rectal contents, etc. (ICRU 62).

7.2.4. Planning Target Volume (PTV)

- "*The planning target volume is a geometrical concept, and it is defined to select appropriate beam arrangements, taking into consideration the net effect of all possible geometrical variations, in order to ensure that the prescribed dose is actually absorbed in the CTV*" (ICRU 50).
- Includes the internal target margin (ICRU 62) and an additional margin for set-up uncertainties, machine tolerances and intra-treatment variations.
- The PTV is linked to the reference frame of the treatment machine.
- It is often described as the CTV plus a fixed or variable margin (*e.g*., PTV = CTV + 1 cm).
- Usually a single PTV is used to encompass one or several CTVs to be targeted by a group of fields.
- The PTV depends on the precision of such tools as immobilization devices and lasers, but does NOT include a margin for dosimetric characteristics of the radiation beam (*i.e.*, penumbral areas and build-up region) as these will require an additional margin during treatment planning and shielding design.

7.2.5. Organ at Risk (OAR)

- Organ at risk is an organ whose sensitivity to radiation is such that the dose received from a treatment plan may be significant compared to its tolerance, possibly requiring a change in the beam arrangement or a change in the dose.
- Specific attention should be paid to organs that, although not immediately adjacent to the CTV, have a very low tolerance dose (*e.g*., eye lens during naso-pharyngeal or brain tumour treatments).
- Organs with a radiation tolerance that depends on the fractionation scheme should be outlined completely to prevent biasing during treatment plan evaluation.

7.3. DOSE SPECIFICATION

A clearly defined prescription or reporting point along with detailed information regarding total dose, fractional dose and total elapsed treatment days allows for proper comparison of outcome results. Several dosimetric end-points have been defined in the ICRU 23 and 50 reports for this purpose:

- Minimum target dose – from a distribution or a dose-volume histogram (DVH).
- Maximum target dose – from a distribution or a DVH.
- Mean target dose – the mean dose of all calculated target points (difficult to obtain without computerized planning).
- The ICRU reference point dose is located at a point chosen to represent the delivered dose using the following criteria:
  - Point should be located in a region where the dose can be calculated accurately (*i.e.,* no build-up or steep gradients)
  - Point should be in the central part of the PTV.
  - Isocentre (or beam intersection point) is recommended as the ICRU reference point.
- Specific recommendations are made with regard to the position of the ICRU reference point for particular beam combinations:
  - For single beam: the point on central axis at the centre of the target volume.
  - For parallel-opposed equally weighted beams: the point on the central axis midway between the beam entrance points.
  - For parallel-opposed unequally weighted beams: the point on the central axis at the centre of the target volume.
  - For other combinations of intersecting beams: the point at the intersection of the central axes (insofar as there is no dose gradient at this point).

7.4. PATIENT DATA ACQUISITION AND SIMULATION

7.4.1. Need for patient data

Patient data acquisition is an important part of the simulation process, since reliable data is required for treatment planning purposes and allows for a treatment plan to be properly carried out. The type of gathered data varies greatly depending on the type of treatment plan to be generated (*e.g.*, manual calculation of parallel-opposed beams versus a complex 3D treatment plan with image fusion). General considerations include:

- Patient dimensions are almost always required for treatment time or monitor unit calculations, whether read with a caliper, from CT slices or by other means.
- Type of dose evaluation dictates the amount of patient data required (*e.g.*, DVHs require more patient information than point dose calculation of organ dose).

- Landmarks such as bony or fiducial marks are required to match positions in the treatment plan with positions on the patient.

7.4.2. Nature of patient data

The patient information required for treatment planning varies from rudimentary to very complex ranging from distances read on the skin, through manual determination of contours, to acquisition of CT information over a large volume, or even image fusion using various imaging modalities.

2D treatment planning

- A single patient contour, acquired using lead wire or plaster strips, is transcribed onto a sheet of graph paper, with reference points identified.
- Simulation radiographs are taken for comparison with port films during treatment.
- For irregular field calculations, points of interest can be identified on a simulation radiograph, and *SSD*s and depths of interest can be determined at simulation.
- Organs at risk can be identified and their depths determined on simulator radiographs.

3D treatment planning

- CT dataset of the region to be treated is required with a suitable slice spacing (typically 0.5 - 1 cm for thorax, 0.5 cm for pelvis, 0.3 cm for head and neck).
- An external contour (representative of the skin or immobilization mask) must be drawn on every CT slice used for treatment planning.
- Tumour and target volumes are usually drawn on CT slices by the radiation oncologist.
- Organs at risk and other structures should be drawn in their entirety, if DVHs are to be calculated.
- Fig. 7.2 shows the typical outlining of target volume and organs at risk for a prostate treatment plan on one CT slice.
- MRI or other studies are required for image fusion.
- With many contemporary treatment planning systems, the user can choose to ignore inhomogeneities (often referred to as heterogeneities), perform bulk corrections on outlined organs, or use the CT data itself (with an appropriate conversion to electron density) for point-to-point correction.
- Simulator radiographs or digitally reconstructed radiographs (DRRs) are used for comparison with portal films.

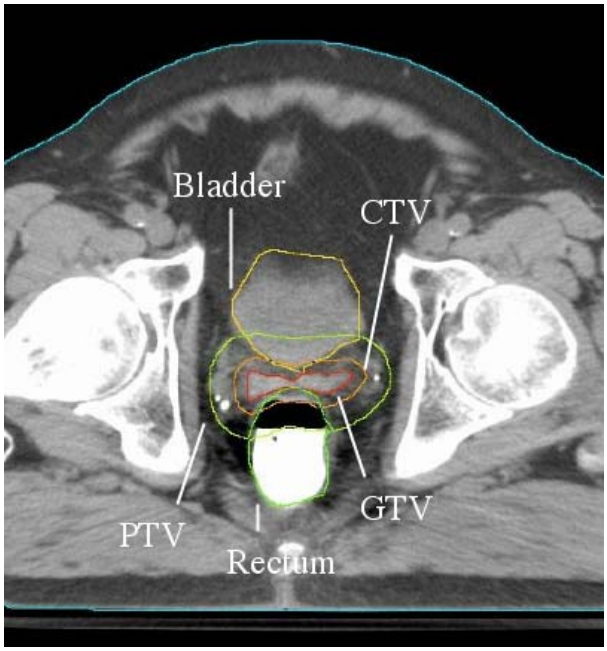

FIG. 7.2. Contours of GTV, CTV, PTV and organs at risk (bladder and rectum) have been drawn on this CT slice for a prostate treatment plan.

7.4.3. Treatment simulation

- Patient simulation was initially developed to ensure that the beams used for treatment were correctly chosen and properly aimed at the intended target.

- Presently, treatment simulation has a more expanded role in the treatment of patients consisting of:

  - Determination of patient treatment position.
  - Identification of the target volumes and organs at risk.
  - Determination and verification of treatment field geometry.
  - Generation of simulation radiographs for each treatment beam for comparison with treatment port films.
  - Acquisition of patient data for treatment planning.

- The simplest form of simulation involves the use of port films obtained on the treatment machines prior to treatment in order to establish the treatment beam geometry. However, it is neither efficient nor practical to perform simulations on treatment units. Firstly, these machines operate in the megavoltage range of energies and therefore do not provide adequate quality radiographs for a proper treatment simulation, and secondly, there is a heavy demand for the use of these machines for actual patient treatment, so using them for simulation is often considered an inefficient use of resources.

- There are several reasons for the poor quality of port films obtained on treatment machines, such as:

  - Most photon interactions with biological material in the megavoltage energy range are Compton interactions that are independent of atomic number and that produce scattered photons that reduce contrast and blur the image.

  - The large size of the radiation source (either focal spot for a linear accelerator or the diameter of radioactive source in an isotope unit) increases the detrimental effects of beam penumbra on the image quality.

  - Patient motion during the relatively long exposures required and the limitations on radiographic technique also contribute to poor image quality.

- For the above reasons, dedicated equipment for radiotherapy simulation has been developed. Conventional simulation systems are based on treatment unit geometry in conjunction with diagnostic radiography and fluoroscopy systems. Modern simulation systems are based on computed tomography (CT) or magnetic resonance (MR) imagers and are referred to as CT-simulators or MR-simulators.

- The clinical aspects of treatment simulation, be it with a conventional or CT-simulator rely on the positioning and immobilization of the patient as well as on the data acquisition and beam geometry determination.

7.4.4. Patient treatment position and immobilization devices

- Depending on the patient treatment position or the precision required for beam delivery, patients may or may not require an external immobilisation device for their treatment.

- Immobilisation devices have two fundamental roles:

  – To immobilise the patient during treatment.
  – To provide a reliable means of reproducing the patient position from simulation to treatment, and from one treatment to another.

- The simplest immobilisation means include masking tape, velcro belts, or elastic bands.

- The basic immobilisation device used in radiotherapy is the head rest, shaped to fit snugly under the patient's head and neck area, allowing the patient to lie comfortably on the treatment couch.

- Figure 7.3 shows common headrests used for patient comfort and immobilization during treatment.

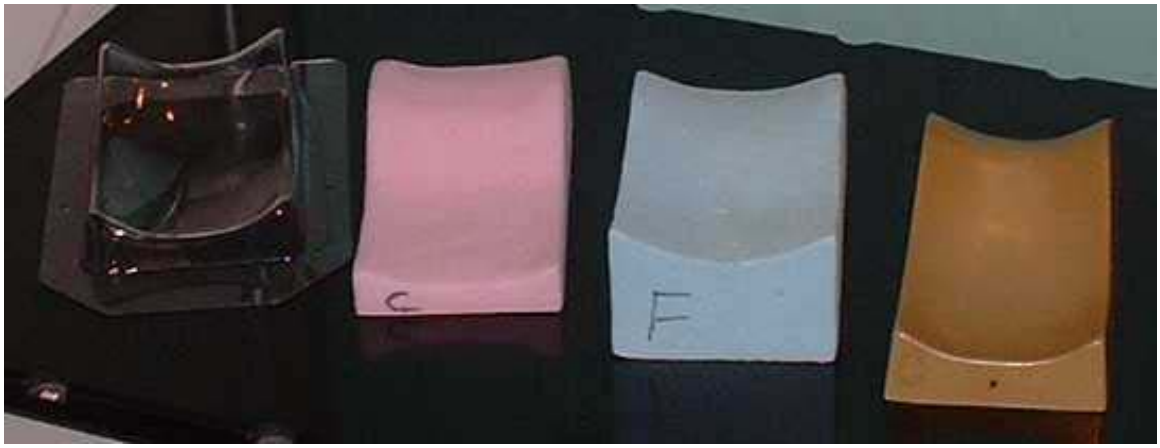

FIG. 7.3. Headrests used for patient positioning and immobilization in external beam radiotherapy.

- Modern radiotherapy generally requires additional immobilisation accessories during the treatment of patients.

- Patients to be treated in the head and neck or brain areas are usually immobilised with a plastic mask which, when heated, can be moulded to the patient's contour. The mask is affixed directly onto the treatment couch or to a plastic plate that lies under the patient thereby preventing movement. A custom immobilization mask is shown in Fig. 7.4.

- For treatments to the thoracic or pelvic area, a variety of immobilisation devices are available. Vacuum-based devices are popular because of their reusablility. Basically, a pillow filled with tiny styrofoam balls is placed around the treatment area, a vacuum pump evacuates the pillow leaving the patient's form as an imprint in the pillow. The result is that the patient can be positioned snugly and precisely in the pillow prior to every treatment. Another system, similar in concept, uses a chemical reaction between reagents in the pillow to form a rigid mould of the patient.

- Special techniques, such as stereotactic radiosurgery, require such high precision that conventional immobilization techniques are inadequate. In radiosurgery, a stereotactic frame is attached to the patient's skull by means of screws and is used for target localization, patient setup on the treatment machine, and patient immobilization during the entire treatment procedure. The frame is bolted to the treatment couch thereby providing complete immobilization during the treatment.

7.4.5. Patient data requirements

- In cases where only the dose along the central axis of the beam is sought (e.g. treatment with a direct field, or parallel and opposed fields, and a flat beam incidence), only the source-surface distance is required, since a simple hand calculation for beam-on time or linac monitor units may suffice.

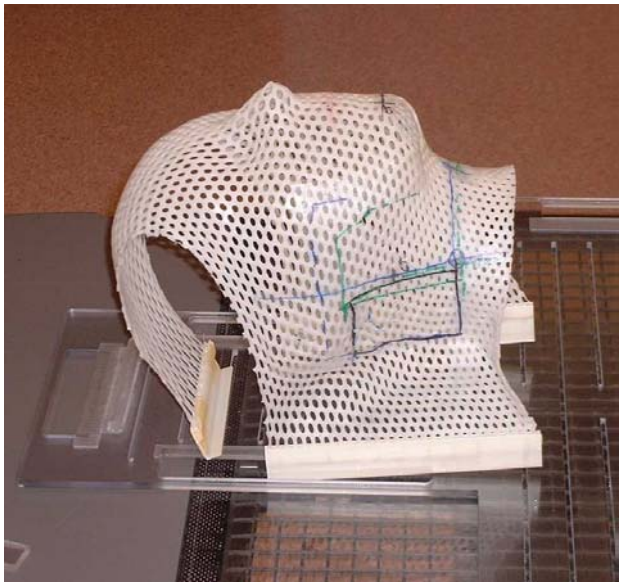

FIG. 7.4. Plastic mask used for immobilization of brain or head and neck patients.

- Simple algorithms, such as Clarkson integration, may be used to determine the dosimetric effects of having blocks in the fields, and calculate dose to off-axis points if their coordinates and source to surface distance is measured. Since only point doses are calculated, the patient shape or contour off-axis is not required.

- For simple computerized 2D treatment planning, the patient's shape is represented by a single transverse skin contour through the central axis of the beams. This contour may be acquired using lead wire or plaster cast at the time of simulation.

- The patient data requirements for more sophisticated treatment planning systems such as those used in conformal treatment planning are more elaborate than those for 2D treatment planning. They include the following:

  - The external shape of the patient must be outlined for all areas where the beams enter and exit (for contour corrections) and in the adjacent areas (to account for scattered radiation).
  - Targets and internal structures must be outlined in order to determine their shape and volume for dose calculation.
  - Electron densities for each volume element in the dose calculation matrix must be determined if a correction for heterogeneities is to be applied.

- Attenuation characteristics of each volume element are required for image processing.

- The nature and complexity of data required for sophisticated treatment planning limits the use of manual contour acquisition. At the very best, patient external contour information can be obtained through this method.

- Transverse CT scans contain all information required for complex treatment planning and form the basis of CT-simulation in modern radiotherapy treatment.

7.4.6. Conventional treatment simulation

Simulators

- Simulators provide the ability to mimic most treatment geometries attainable on megavoltage treatment units, and to visualize the resulting treatment fields on radiographs or under fluoroscopic examination of the patient. They consist of a gantry and couch arrangement similar to that found on isocentric megavoltage treatment units, with the exception that the radiation source in a simulator is a diagnostic quality x-ray tube rather than a high-energy linac or a cobalt source. Some simulators have a special attachment that allows them to collect patient cross-sectional information similarly to a CT scanner, hence, the combination is referred to as a simulator-CT.

- Figure 7.5 shows a photograph of a conventional treatment simulator.

- The photons produced by the x-ray tube are in the kilovoltage range and are preferentially attenuated by higher Z materials such as bone through photoelectric interactions. The result is a high quality diagnostic radiograph with limited soft-tissue contrast, but with excellent visualization of bony landmarks and high Z contrast agents.

- A fluoroscopic imaging system may also be included and would be used from a remote console to view patient anatomy and to modify beam placement in real time.

FIG. 7.5. A Conventional treatment simulator has capability to reproduce most treatment geometries available on radiotherapy treatment units. Simulators use a diagnostic X-ray tube and fluoroscopic system to image the patient.

Localization of target volume and organs at risk

- For the vast majority of sites, the disease is not visible on the simulator radiographs, therefore the block positions can be determined only with respect to anatomical landmarks visible on the radiographs (usually bony structures or lead wire clinically placed on the surface of the patient).

Determination of treatment beam geometry

- Typically, the patient is placed on the simulator couch, and the final treatment position of the patient is verified using the fluoroscopic capabilities of the simulator (*e.g.*, patient is straight on the table, etc.).

- The position of the treatment isocenter, beam geometry (*i.e.*, gantry, couch angles, etc.) and field limits are determined with respect to the anatomical landmarks visible under fluoroscopic conditions.

- Once the final treatment geometry has been established, radiographs are taken as a matter of record, and are also used to determine shielding requirements for the treatment. Shielding can be drawn directly on the films, which may then be used as the blueprint for the construction of the blocks. A typical simulator radiograph is shown in Fig. 7.6.

- Treatment time port films are compared to these radiographs periodically to ensure the correct set up of the patient during the treatments.

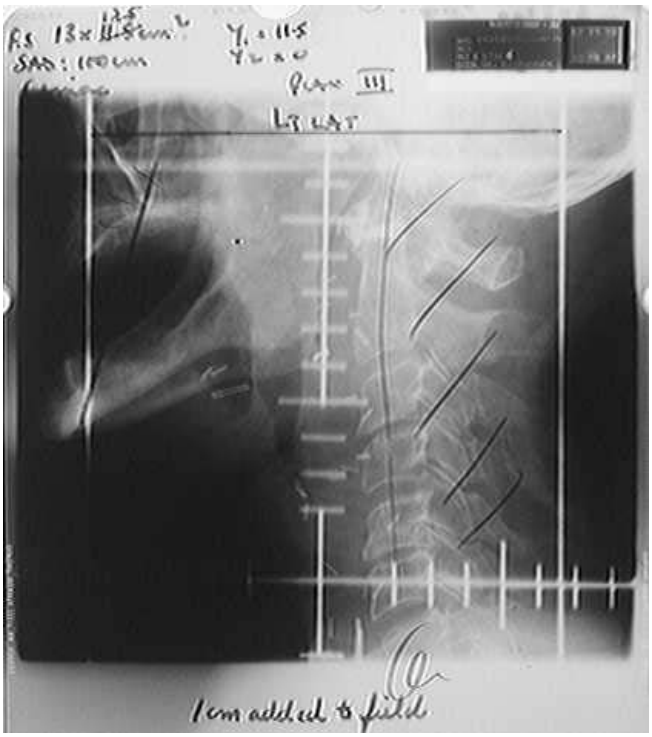

FIG. 7.6. A typical simulator radiograph for a head and neck patient. The field limits and shielding are clearly indicated on the radiograph.

Acquisition of patient data

- After the proper determination of beam geometry, patient contours may be taken at any plane of interest to be used for treatment planning.

- Although more sophisticated devices exist, the simplest and most widely available method for obtaining a patient contour is though the use of lead wire.

- Typically, the wire is placed on a transverse plane parallel to the isocenter plane. The wire is shaped to the patient's contour, and the shape is then transferred to a sheet of graph paper.

- Some reference to the room coordinate system must be marked on the contour (*e.g.*, laser position) in order to relate the position of the beam geometry to the patient.

7.4.7. Computed tomography-based conventional treatment simulation

Computed tomography-based patient data acquisition

With the growing popularity of computed tomography (CT) in the 1990s, the use of CT scanners in radiotherapy became widespread. Anatomical information on CT scans is presented in the form of transverse slices, which contain anatomical images of very high resolution and contrast, based on the electron density.

- CT images provide excellent soft tissue contrast allowing for greatly improved tumour localization and definition in comparison to conventional simulation.

- Patient contours can be obtained easily from the CT data; in particular, the patient's skin contour, target, and any organs of interest.

- Electron density information, useful in the calculation of dose inhomogeneities due to the differing composition of human tissues, can also be extracted from the CT dataset.

- The target volume and its position are identified with relative ease on each transverse CT slice. The position of each slice and therefore the target can be related to bony anatomical landmarks through the use of scout or pilot images obtained at the time of scanning. Shown in Fig. 7.7 is a CT slice through a patient's neck used in CT-based conventional simulation.

- Pilot or scout films relate CT slice position to anterior-posterior and lateral radiographic views of the patient at the time of scanning (see Fig. 7.8). They are obtained by keeping the x-ray source in a fixed position and moving the patient (translational motion) through the stationary slit beam. The result is a high definition radiograph which is divergent on the transverse axis, but non-divergent on the longitudinal axis.

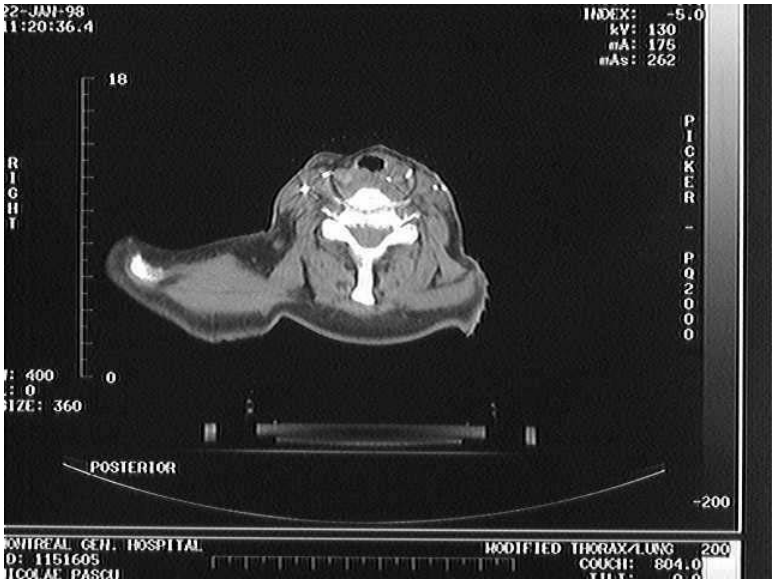

FIG. 7.7. A CT image through a patient's neck. The target volume has been marked on the film by the physician.

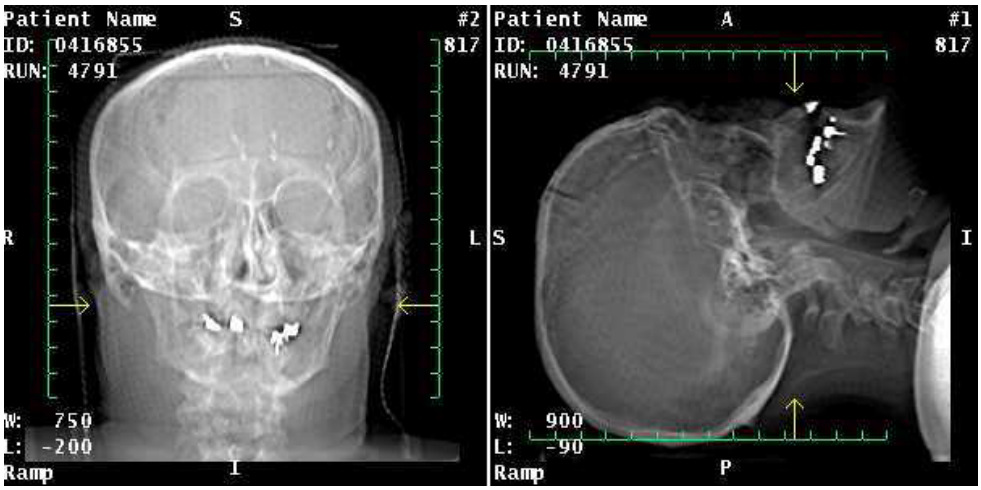

FIG. 7.8. Pilot or scout images relate slice position to radiographic landmarks.

- The target position relative to the bony anatomy on the simulator radiographs may then be determined through comparison with the CT scout or pilot films keeping in mind the different magnifications between the simulator films and scout films.

- This procedure allows for a more accurate determination of tumour extent and therefore more precise field definition at the time of simulation.

- If the patient is CT scanned in the desired treatment position prior to simulation, the treatment field limits and shielding parameters may be set with respect to the target position, as determined from the CT slices.

Determination of treatment beam geometry

- The treatment beam geometry, and any shielding required can now be determined indirectly from the CT data.

- The result is that the treatment port more closely conforms to the target volume, reducing treatment margins around the target and increasing healthy tissue sparing.

7.4.8. Computed tomography-based virtual simulation

CT-Simulator

- Dedicated CT scanners for use in radiotherapy treatment simulation and planning are known as CT-simulators.

- The components of a CT-simulator include: a large bore CT scanner (with an opening of up to 85 cm to allow for a larger variety of patient positions and the placement of treatment accessories during CT scanning); room lasers allowing for patient positioning and marking; a flat table top to more closely match radiotherapy treatment positions; and a powerful graphics workstation, allowing for image manipulation and formation. An example of a modern CT-simulator is shown in Fig. 7.9.

FIG. 7.9. A dedicated radiotherapy CT simulator. Note the flat table top and the large bore (85 cm diameter). The machine was manufactured by Marconi, now Philips.

Virtual Simulation

- Virtual simulation is the treatment simulation of patients based solely on CT information.
- The premise of virtual simulation is that the CT data can be manipulated to render synthetic radiographs of the patient for arbitrary geometries.
- These radiographs, known as digitally reconstructed radiographs (DRRs), can be used in place of simulator radiographs to determine the appropriate beam parameters for treatment.
- The advantage of virtual simulation is that anatomical information may be used directly in the determination of treatment field parameters.

Digitally reconstructed radiographs (DRRs)

- DRRs are produced by tracing ray-lines from a virtual source position through the CT data of the patient to a virtual film plane.
- The sum of the attenuation coefficients along any one ray-line gives a quantity analogous to optical density on a radiographic film. If the sums along all ray-lines from a single virtual source position are then displayed onto their appropriate positions on the virtual film plane, the result is a synthetic radiographic image based wholly on the 3-D CT data set that can be used for treatment planning.
- Figure 7.10 provides an example of a typical DRR.

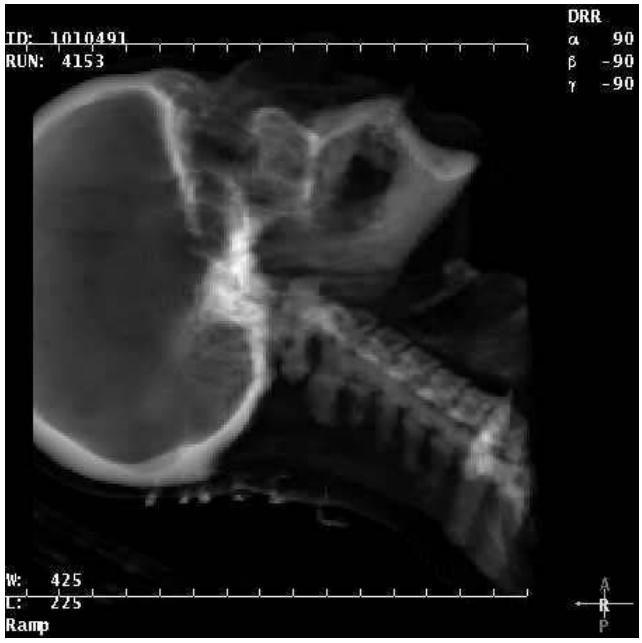

FIG. 7.10. A digitally reconstructed radiograph (DRR). Note that gray levels, brightness, and contrast can be adjusted to provide an optimal image.

Beam's eye view (BEV)

- Beam's eye views (BEV) are projections of the treatment beam axes, field limits, and outlined structures through the patient onto the corresponding virtual film plane.

- BEVs are frequently superimposed onto the corresponding DRRs resulting in a synthetic representation of a simulation radiograph.

- Field shaping is determined with respect to both anatomy visible on the DRR, and outlined structures projected by the BEVs (see Fig. 7.11).

- Multi-planar reconstructions (MPR) are images formed from reformatted CT data. They are effectively CT images through arbitrary planes of the patient. Although typically sagittal or coronal MPR cuts are used for planning and simulation, MPR images through any arbitrary plane may be obtained.

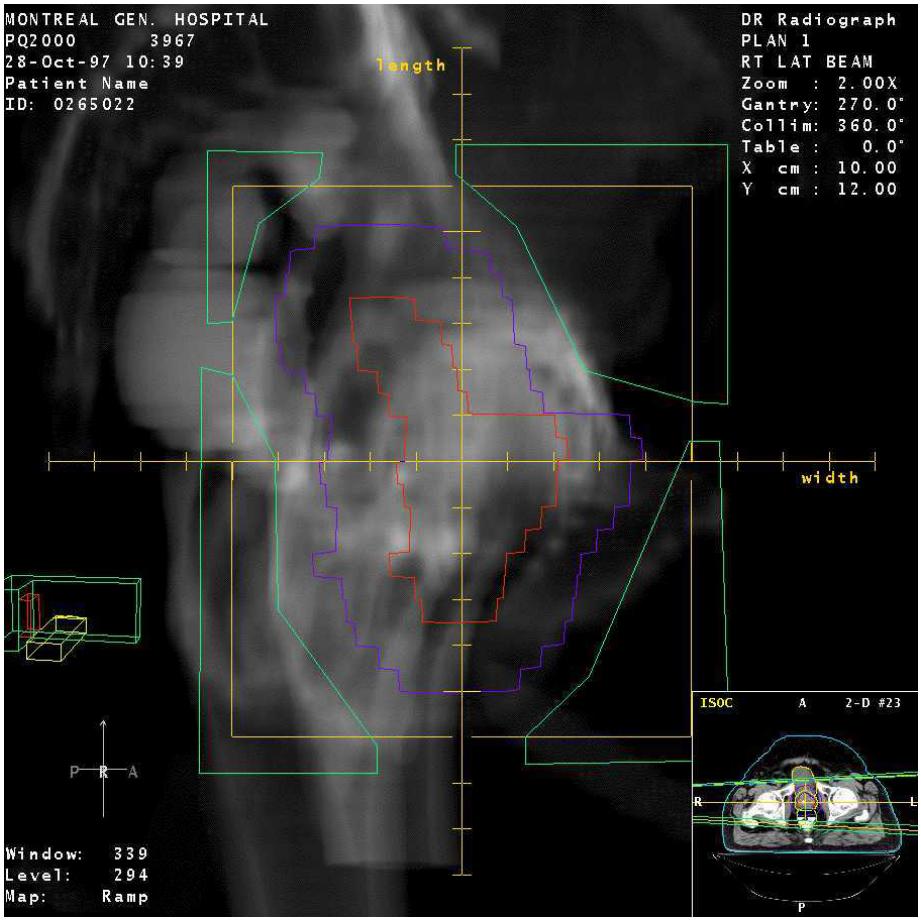

FIG. 7.11. A digitally reconstructed radiograph (DRR) with superimposed beam's eye view for a lateral field of a prostate patient.

Virtual simulation procedure

- The CT simulation commences by placing the patient on the CT-simulator table in the treatment position. The patient position is verified on the CT pilot or scout scans.

- Prior to being scanned, it is imperative that patients be marked with a reference isocenter. Typically, a position near the center of the proposed scan volume is chosen, radio-opaque fiducial markers are placed on the anterior and lateral aspects of the patient (with the help of the positioning lasers to ensure proper alignment), and the patient is tattooed to record the position of the patient's fiducial markers to help with the subsequent patient setup on the treatment machine.

- This "reference" isocenter position can be used as the origin for a reference coordinate system from which our actual "treatment" isocenter position can be determined through tranlational motions of the couch.

- Target structures and organs of interest can be outlined directly on the CT images using tools available in the virtual simulation software.

- DRRs and BEVs created from the CT information and outlined data are used to simulate the treatment.

- The determination of treatment beam geometry and shielding is carried out with respect to target position and critical organ location. Standard beam geometries (*e.g.*, 4 field box, parallel opposed pair, lateral oblique beams, etc.) can be used together with conformal shielding to increase the healthy tissue sparing.

- Alternatively, more unorthodox beam combinations can be used to maximize healthy tissue sparing in the event that a critical organ or structure is in the path of a beam.

- It is imperative that when choosing beam geometries, consideration be given to the prospective dose distributions. Additionally, the physical limitations of the treatment unit and its accessories with respect to patient position must be considered. For example, care must be taken that the gantry position does not conflict with the patient position.

- Once a reasonable beam arrangement has been found, the field limits and shielding design may be obtained.

- Since the precise target location is known, the determination of shielding design and treatment field limits becomes a matter of choosing an appropriate margin to account for physical and geometric beam effects, such as beam penumbra.

- Once the relevant treatment parameters have been obtained, the treatment beam geometry, the CT data including contours and electron density information are transferred to the treatment planning system for the calculation of the dose distribution.

7.4.9. Conventional simulator vs. CT simulator

- The increased soft tissue contrast, in combination with the axial anatomical information available from CT scans, provides the ability to localize very precisely the target volumes and critical structures.

- The CT-simulation phase allows for accurate identification and delineation of these structures directly onto the CT data set. This ability, in conjunction with the formation of DRRs and BEVs on which organs and targets are projected onto synthetic representations of simulator radiographs, allow the user to define treatment fields with respect to target volume and critical structure location.

- By contrast, conventional simulation requires knowledge of tumour position with respect to the visible landmarks on the diagnostic quality simulator radiographs. Since these radiographs provide limited soft tissue contrast, the user is restricted to setting field limits with respect to either the bony landmarks evident on the radiographs or anatomical structures visible with the aid of contrast agents such as barium.

- Another important advantage of the CT-simulation process over the conventional simulation process is the fact that the patient is not required to stay after the scanning has taken place. The patient only stays the minimum time necessary to acquire the CT data set and this provides the obvious advantage in that the radiotherapy staff may take their time in planning the patient as well as try different beam configurations without the patient having to wait on the simulator couch.

- A CT-simulator allows the user to generate DRRs and BEVs even for beam geometries which were previously impossible to simulate conventionally. Vertex fields, for instance, obviously are impossible to plan on a conventional simulator because the film plane is in the patient (see Fig. 7.12).

- There is some debate whether there is a place in the radiotherapy clinic for a conventional simulator, if a CT-simulator is in place. Aside from the logistics and economics of having to CT scan every patient, there are certain sites where the use of CT-simulation is not necessary (*e.g.*, cord compression, bone and brain metastases).

- Additionally, it is useful to perform a fluoroscopic simulation of patients after CT-simulation in order to verify isocenter position and field limits as well as to mark the patient for treatment.

7.4.10. Magnetic resonance imaging for treatment planning

- The soft tissue contrast offered by magnetic resonance imaging (MRI) in some areas, such as the brain, is superior to that of CT, allowing small lesions to be seen with greater ease.

- MRI alone, however, cannot be used for radiotherapy simulation and planning for several reasons:

  - The physical dimensions of the MRI and its accessories limit the use of immobilization devices and compromise treatment positions.
  - Bone signal is absent and therefore digitally reconstructed radiographs cannot be generated for comparison to portal films.
  - There is no electron density information available for heterogeneity corrections on the dose calculations.
  - MRI is prone to geometrical artifacts and distortions that may affect the accuracy of the treatment.

- Many modern virtual simulation and treatment planning systems have the ability to combine the information from different imaging studies using the process of image fusion or registration.

- CT-MR image registration or fusion combines the accurate volume definition from MR with electron density information available from CT.

- The MR dataset is superimposed on the CT dataset through a series of translations, rotations, and scaling.

- This process allows the visualization of both studies side by side in the same imaging plane even if the patient has been scanned in a completely different treatment position. An example of CT-MR image fusion is presented in Fig. 7.13.

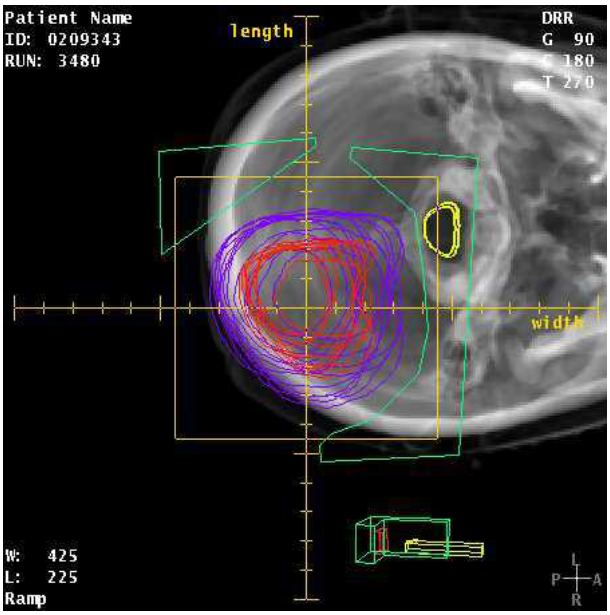

FIG. 7.12. A digitally reconstructed radiograph (DRR) with superimposed beam's eye view for a vertex field of a brain patient. This treatment geometry would be impossible to simulate on a conventional simulator.

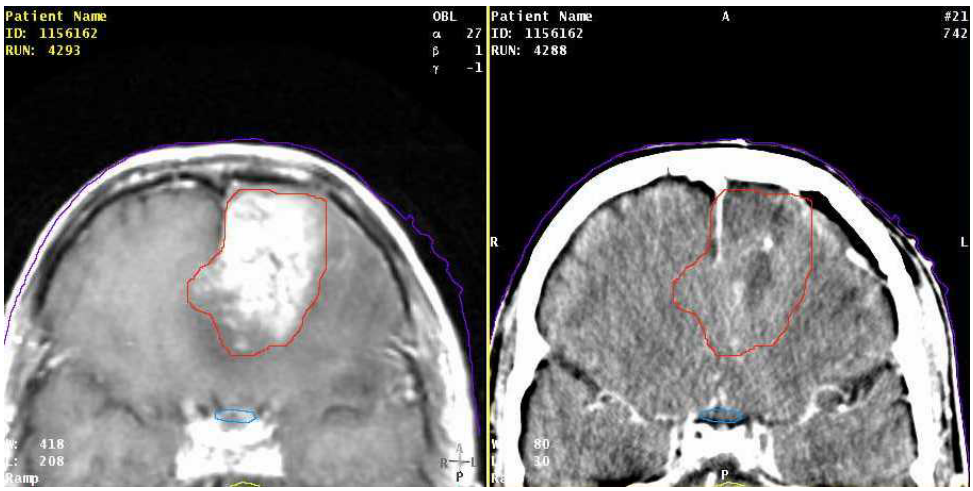

FIG. 7.13. On the left is an MR image of a patient with a brain tumour. The target has been outlined and the result was superimposed on the patient's CT scan. Note that the particular target is clearly seen on the MR image but only portions of it are observed on the CT scan.

7.4.11. Summary of simulation procedures

Tables 7.I., 7.II., 7.III. summarize the conventional and virtual simulation processes.

TABLE 7.I. SUMMARY OF THE CONVENTIONAL SIMULATION PROCEDURE FOR A TYPICAL PATIENT (6 STEPS).

	Conventional Simulation Procedure
1	Determination of patient treatment position with flouroscopy
2	Determination of beam geometry
3	Determination field limits and isocenter
4	Acquisition of contour
5	Acquisition of beam's eye view and set-up radiographs
6	Marking of patient

TABLE 7.II. SUMMARY OF THE PROCEDURE FOR A TYPICAL PATIENT CT-SIMULATION (9 STEPS)

	CT Simulation Procedure
1	Determination of patient treatment position with pilot/scout films
2	Determination and marking of reference isocenter
3	Acquisition of CT data and transfer to virtual simulation workstation
4	Localization and contouring of targets and critical structures
5	Determination treatment isocenter with respect to target and reference isocenter.
6	Determination of beam geometry
7	Determination of field limits and shielding
8	Transfer of CT and beam data to treatment planning system
9	Acquisition of beam's eye view and setup DRRs

TABLE 7.III. GOALS OF PATIENT TREATMENT SIMULATION, AND THE TOOLS AVAILABLE FOR ACHIEVING THE GOALS IN CONVENTIONAL AND CT SIMULATION.

Goals of patient simulation	Conventional	CT simulation
Treatment position	fluoroscopy	pilot/scout views
Identification of target volume	bony landmarks	from CT data
Determination of beam geometry	fluoroscopy	BEV/DRR
Shielding design	bony landmarks	conformal to target
Contour acquisition	manual	from CT data

7.5. CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.1. Isodose curves

Isodose curves are lines that join points of equal dose. They offer a planar representation of the dose distribution and easily show the behavior of one beam or a combination of beams with different shielding, wedges, bolus, etc.

- Isodose curves can be measured in water directly, or can be calculated from *PDD* and beam profile data.

- A set of isodose curves is valid for a given treatment machine, beam energy, *SSD*, and field size.

- While isodose curves can be made to display the actual dose in Gy, it is more common to present them normalized to 100% at a fixed point. Two such common point normalizations are as follows:

  - Normalization to 100% at the depth of dose maximum on the central axis.
  - Normalization at the isocentre.

Figure 7.14 shows isodose curves superimposed on a transverse contour of a patient for the same beam. The left figure illustrates a distribution normalized at the depth of dose maximum z_{max}, the distribution on the right figure is normalized at isocentre.

7.5.2. Wedge filters

Three types of wedge filters are currently in use: manual, motorized, and dynamic. Physical wedges are angled pieces of lead or steel that are placed in the beam to produce a gradient in radiation intensity. Manual intervention is required to place the physical wedges on the treatment unit's collimator assembly. A motorized wedge is a similar device, a physical wedge integrated into the head of the unit and controlled remotely. A dynamic wedge produces the same wedged intensity gradient by having one jaw close gradually while the beam is on. A typical isodose distribution for a wedged beam is shown is Fig. 7.15.

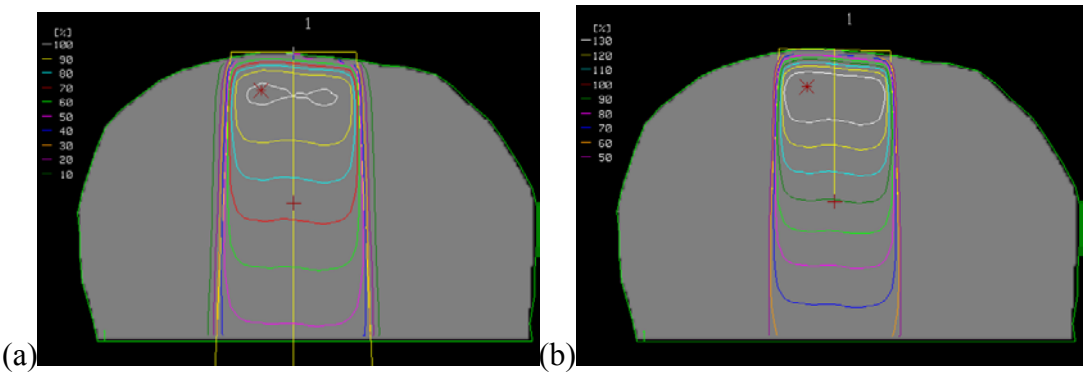

FIG. 7.14. A single 18 MV photon beam incident on a patient contour. Isodose curves are for (a) a fixed SSD beam normalized at depth of dose maximum and (b) an isocentric beam normalized at the isocenter.

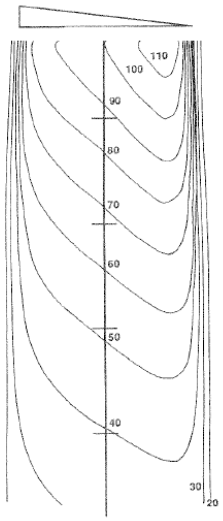

FIG. 7.15. Isodose curves for a wedged 6 MV photon beam. The isodoses have been normalized to z_{max} with the wedge in place.

The following applies to all wedges:

- The thick end of the wedge is called the heel; the dose is lowest underneath this end. The other end is called the toe.

- Wedge angle is defined as the angle between the 50% isodose line and the perpendicular to the beam central axis. Wedge angles in the range from 10˚ to 60˚ are commonly available.

There are two main uses of wedges:

- Wedges can be used to compensate for a sloping surface, as for example, in nasopharyngeal treatments where wedges are used to compensate for decreased thickness anteriorly, as shown in Fig. 7.16. Part (a) shows two wedged beams in a parallel-opposed configuration with the wedges used to compensate for missing tissue. Part (b) shows two wedged beams at 90^{o} to one another with the wedges compensating for the hot-spot near the surface.

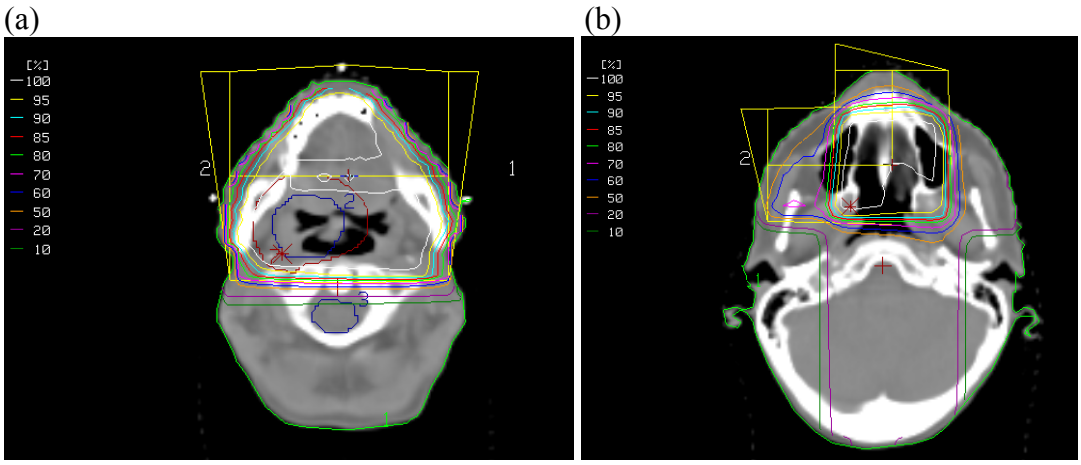

FIG. 7.16. Treatment plans illustrating two uses of wedge filters. In (a) two 15° wedges are used to compensate for the decreased thickness anteriorly. In (b) a wedged pair of beams is used to compensate for the hot spot that would be produced,with a pair of open beams at 90° to each other.

- A pair wedged of beams is also useful in the treatment of relatively low lying lesions where two beams are placed at an angle (less than 180˚) called the hinge angle (see Fig. 7.17). The optimal wedge angle (assuming a flat patient surface) may be estimated from: 90˚ - 1/2 (hinge angle)

- The wedge factor is defined as the ratio of dose at a specified depth (usually z_{max}) on the central axis with the wedge in the beam to the dose under the same conditions without the wedge. This factor is used in monitor unit calculations to compensate for the reduction in beam transmission produced by the wedge. The wedge factor depends on depth and field size.

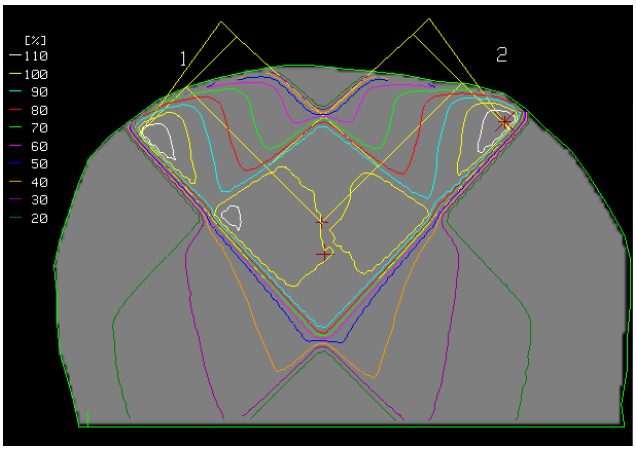

FIG. 7.17. A wedge pair of 6 MV beams incident on a patient. The hinge angle is 90° (orthogonal beams) for which the optimal wedge angle would be 45°. However, the additional obliquity of the surface requires the use of a higher wedge angle of 60°.

7.5.3. Bolus

Bolus is a tissue-equivalent material placed in contact with the skin to achieve one or both of the following: (a) to increase the surface dose and (b) to compensate for missing tissue.

- To increase the surface dose, a layer of uniform thickness bolus is often used (0.5 –1.5 cm), since it does not significantly change the shape of the isodose curves at depth. Several flab-like materials were developed commercially for this purpose; however, cellophane wrapped wet towels or gauze offer a low cost substitute.

- To compensate for missing tissue or sloping surface, a custom made bolus can be built that conforms to the patient skin on one side and yields a flat perpendicular incidence to the beam (see Fig. 7.18).

- The result is an isodose distribution that is identical to that produced on a flat phantom, however, skin sparing is not maintained. A common material used for this kind of bolus is wax, that is essentially tissue-equivalent, and when heated is malleable and can be fitted precisely to the patient's contour.

Bolus can also be used to compensate for lack of scatter, such as near the extremities or the head during total-body irradiation. Saline or rice bags can be used as bolus in these treatments.

7.5.4. Compensating filters

A compensating filter or compensator achieves the same effect on the dose distribution as a shaped bolus but does not cause a loss of skin sparing.

- Compensating filters can be made of almost any material, but metals such as lead are the most practical and compact. They are usually placed in a shielding slot on the treatment unit head and can produce a gradient in two dimensions (such compensators are more difficult to make and are best suited for a computer-controlled milling machine).

- The closer to the radiation source the compensator is placed, the smaller the compensator. It is a simple case of de-magnification with respect to the patient and source position to compensate for beam divergence. The dimensions of the compensator are simply scaled in length and width by the ratio of *SSD* to the distance from the source to the compensator, as shown schematically in Fig. 8.18.

- Thickness of the compensator is determined on a point-by-point basis depending on the fraction I/I_o of the dose without a compensator which is required at a certain depth in the patient. The thickness of compensator x along the ray line above that point can be solved from the attenuation law, $I/I_o = exp(-\mu x)$, where μ is the linear attenuation coefficient for the radiation beam and material used to construct the compensator.

- The reduction in beam output through a custom compensator at z_{max} on the central axis, needs to be measured and accounted for in MU/time calculations.

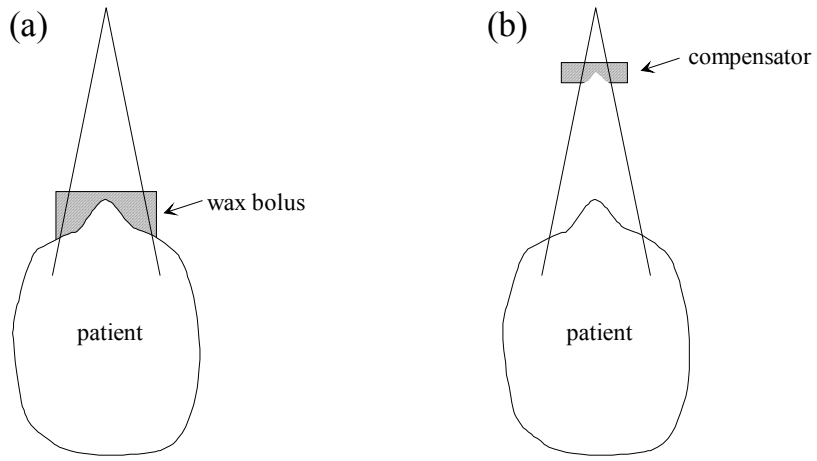

FIG. 7.18. This simple diagram illustrates the difference between a bolus and a compensating filter. In (a) a wax bolus is placed on the skin producing a flat radiation distribution. Skin sparing is lost with bolus. In (b) a compensator achieving the same dose distribution as in (a) is constructed and attached to the treatment unit. Due to the large air gap skin sparing is maintained.

- The use compensating filters instead of bolus is generally more laborious and time consuming. Additionally, the resulting dose distribution cannot be readily calculated on most treatment planning systems without measurement of the beam profile under the compensator and additional beam data entry into the treatment planning system. Bolus on the other hand can be considered part of the patient contour thus eliminating the need for measurement. The major advantage of a compensating filter over bolus is the preservation of the skin sparing effect.

7.5.5. Corrections for contour irregularities

Measured dose distributions apply to a flat radiation beam incident on a flat homogeneous water phantom. To relate such measurements to the actual dose distribution in a patient, corrections for irregular surface and tissue inhomogeneities have to be applied. Three methods for contour correction are used: the *isodose shift method*, the *effective attenuation coefficient method,* and the *TAR method*.

Isodose shift method

- A simple method, called the isodose shift method, can be used in the absence of computerized approaches, for planning on a manual contour. The method is illustrated in Fig. 7.19.

  - Grid lines are drawn parallel to beam the central axis all across the field.
  - The tissue deficit (or excess) *h* is the difference between the *SSD* along a gridline and the *SSD* on the central axis.
  - *k* is an energy dependent parameter given in Table 7.IV. for various photon beam energies.
  - The isodose distribution for a flat phantom is aligned with the *SSD* central axis on the patient contour.

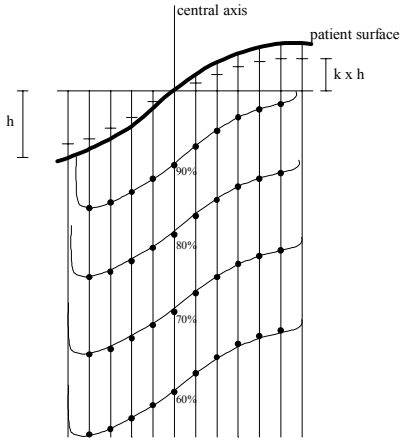

FIG. 7.19. Schematic diagram showing the application of the isodose shift method for contour irregularity correction. The isodoses shown join the dose points calculated by the method (shown as solid black circles).

- For each gridline, the overlaid isodose distribution is shifted up (or down) such that the overlaid *SSD* is at a point $k \times h$ above (or below) the central axis *SSD*.
- The depth dose along the given gridline in the patient can now read directly from the overlaid distribution.

Effective attenuation coefficient method

A second method uses a correction factor known as the effective attenuation coefficient. The correction factor is determined from the attenuation factor $\exp(-\mu x)$, where x is the depth of missing tissue above the calculation point, and μ is the linear attenuation coefficient of tissue for a given energy. For simplicity the factors are usually pre-calculated and supplied in graphical or tabular form.

TAR method

The tissue-air ratio (*TAR*) correction method is also based on the attenuation law, but takes the depth of the calculation point and the field size into account. Generally, the correction factor C_F as a function of depth d, thickness of missing tissue h, and field size f, is given by:

$$C_F = \frac{TAR(z-h, f)}{TAR(z, f)} \tag{7.1}$$

TABLE 7.IV. PARAMETER *k* USED IN THE ISODOSE SHIFT METHOD FOR CORRECTING ISODOSE DISTRIBUTIONS FOR IRREGULAR SURFACE.

Photon energy (MV)	*k* (approximate)
< 1	0.8
^{60}Co - 5	0.7
5 – 15	0.6
15 – 30	0.5
> 30	0.4

7.5.6. Corrections for tissue inhomogeneities

In the most rudimentary treatment planning process, isodose charts and *PDD* tables are applied under the assumption that all tissues are water-equivalent. In the actual patients, however, the photon beam traverses tissues with varying densities and atomic numbers such as fat, muscle, lung, air, and bone. Tissues with densities and atomic numbers different from those of water are referred to as tissue inhomogeneities or heterogeneities. Inhomogeneities in the patient result in:

- Changes in the absorption of the primary beam and associated scattered photons.
- Changes in electron fluence.

The importance of each effect depends on the position of the point of interest relative to the inhomogeneity. In the megavoltage range the Compton interaction dominates and its cross-section depends on the electron density (in electrons per cm^3). The following four methods correct for the presence of inhomogeneities within certain limitations: the *TAR* method; the Batho power law method; the equivalent *TAR* method and the isodose shift method. A sample situation is shown in Fig. 7.20 where a layer of tissue of electronic density ρ_e is located between two layers of water-equivalent tissue.

TAR method

- The dose at each point is corrected by:

$$CF = \frac{TAR(z', r_d)}{TAR(z, r_d)} \tag{7.2}$$

where

$z' = z_1 + \rho_e z_2 + z_3$ and
$z = z_1 + z_2 + z_3$.

- This method does not account for the position relative to the inhomogeneity. It also assumes that the homogeneity is infinite in lateral extent.

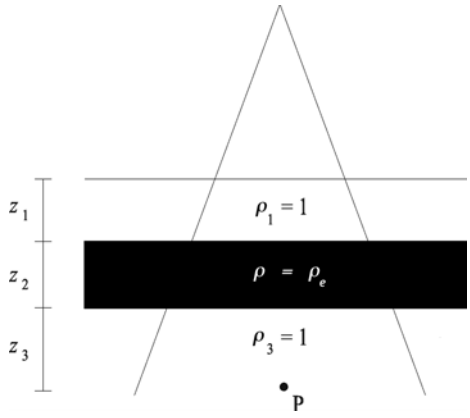

FIG. 7.20. Schematic diagram showing an inhomogeneity nested between two layers of water-equivalent tissue.

Batho Power-law method

- Method initially developed by Batho, later generalized by Sontag and Cunningham.

- The dose at each point is corrected by

$$CF = \frac{TAR\left(z_3, r_d\right)^{\rho_3 - \rho_2}}{TAR\left(z, r_d\right)^{1-\rho_2}} \tag{7.3}$$

where, similarly to Eq. (7.2),

$z' = z_1 + \rho_2 z_2 + z_3$ and
$z = z_1 + z_2 + z_3$.

- This method accounts for the position relative to the inhomogeneity. It still assumes that the homogeneity is infinite in lateral extent.

Equivalent TAR method

Similar to the TAR method outlined above with the exception that the field size parameter r_d' is modified as a function of density to correct for the geometrical position of the inhomogeneity with respect to the calculation point. The new dose at each point is corrected by:

$$CF = \frac{TAR(z', r_d')}{TAR(z, r_d)} \tag{7.4}$$

where

$z' = z_1 + \rho_e z_2 + z_3$ and
$z = z_1 + z_2 + z_3$.

Isodose shift method

- The isodose shift method for the dose correction due to the presence of inhomogeneities is essentially identical to the isodose shift method outlined in the previous section for contour irregularities.

- Isodose shift factors for several types of tissue have been determined for isodose points beyond the inhomogeneity.

- The factors are energy dependent but do not vary significantly with field size.

- The factors for the most common tissue types in a 4 MV photon beam are: air cavity: -0.6; lung: -0.4; and hard bone: 0.5. The total isodose shift is the thickness of inhomogeneity multiplied by the factor for a given tissue. Isodose curves are shifted away from the surface when the factor is negative.

7.5.7. Beam combinations and clinical application

Single photon beams are of limited use in the treatment of deep-seated tumours, since they give a higher dose near the entrance at the depth of dose maximum than at depth. The guidelines for use of a single photon beam in radiotherapy are as follows:

- Reasonably uniform dose to the target ($\pm 5\%$),
- Low maximum dose outside the target (<110%) and
- No organs exceeding their tolerance dose.

Single fields are often used for palliative treatments or for relatively superficial lesions (depth < 5-10 cm, depending on the beam energy). For deeper lesions, a combination of two or more photon beams is usually required to concentrate the dose in the target volume and spare the tissues surrounding the target as much as possible.

Weighting and normalization

- Dose distributions for multiple beams can be normalized to 100% just as for single beams: at z_{max} for each beam, or at isocentre for each beam. This implies that each beam is equally weighted.

- A beam weighting is applied at the normalization point for the given beam. A wedged pair with z_{max} normalization weighted 100:50% will show one beam with the 100% isodose at z_{max} and the other one with 50% at z_{max}. A similar isocentric weighted beam pair would show the 150% isodose at the isocentre.

Fixed SSD vs. isocentric techniques

- Fixed *SSD* techniques require moving the patient such that the skin is at the correct distance (nominal *SSD*) for each beam orientation.

- Isocentric techniques require placing the patient such that the target (usually) is at the isocentre. The machine gantry is then rotated around the patient for each treatment field.

- Dosimetrically, there is little difference between these two techniques: Fixed *SSD* arrangements are usually at a greater *SSD* (*i.e.*, machine isocentre is on the patient skin) than isocentric beams and therefore have a slightly higher *PDD* at depth. Additionally, beam divergence is smaller with *SSD* due to the larger distance.

- These advantages are small and, with the exception of very large fields exceeding 40x40 cm^2, the advantages of a single set-up point (*i.e.*, the isocentre) greatly outweigh the dosimetric advantage of *SSD* beams.

Parallel opposed beams

Parallel-opposed beams overcome the difficulty of a decreasing dose gradient due to each individual beam. Decrease in depth dose of one beam is partially compensated by increase in the other. The resulting distribution has relatively uniform distribution along the central axis. Figure 7.21 shows a distribution for parallel-opposed beams normalized to the isocentre.

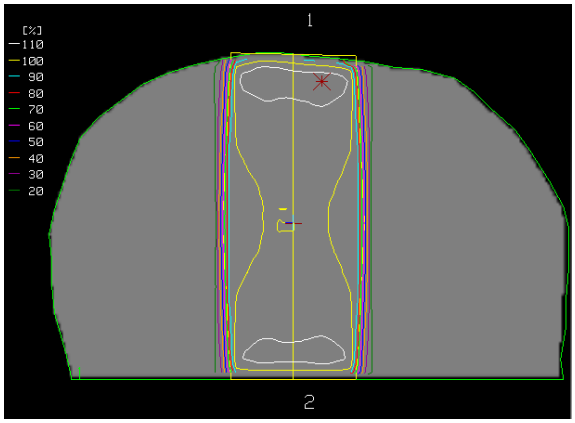

FIG .7.21. A parallel-opposed beam pair is incident on a patient. Note the large rectangular area of relatively uniform dose (<15% variation). The isodoses have been normalized to 100% at the isocentre. This beam combination is well suited to a large variety of treatment sites (e.g., lung, brain, head and neck).

- For small separations (<10 cm), low energy beams are well suited, since they have a sharp rise to a maximum dose and a relatively flat dose plateau in the region between both maximums.

- For large separations (>15 cm), higher energy beams provide a more homogeneous distribution whereas low energy beams can produce significant hot-spots at the z_{max} locations of the two beams (>30%).

Many anatomical sites, such as lung lesions and head and neck lesions, can adequately be treated with parallel-opposed beams.

Multiple co-planar beams

Multiple coplanar beams can still be planned using a 2-D approach on a single plane, but their use allows for a higher dose in the beam intersection region. Common field arrangements include (see two examples in Fig. 7.22):

- Wedge pair. Two beams with wedges (often orthogonal) are used to achieve a trapezoid shaped high dose region. This technique is useful in relatively low-lying lesions (*e.g.*, maxillary sinus and thyroid lesions).

- 4-field box. A technique of four beams (two opposing pairs at right angles) producing a relatively high dose box shaped region. The region of highest dose now occurs in the volume portion that is irradiated by all four fields. This arrangement is used most often for treatments in the pelvis, where most lesions are central (*e.g.*, prostate, bladder, uterus).

- Opposing pairs at angles other than 90^o also result in the highest dose around the intersection of the four beams, however, the high dose area here has a rhombic shape.

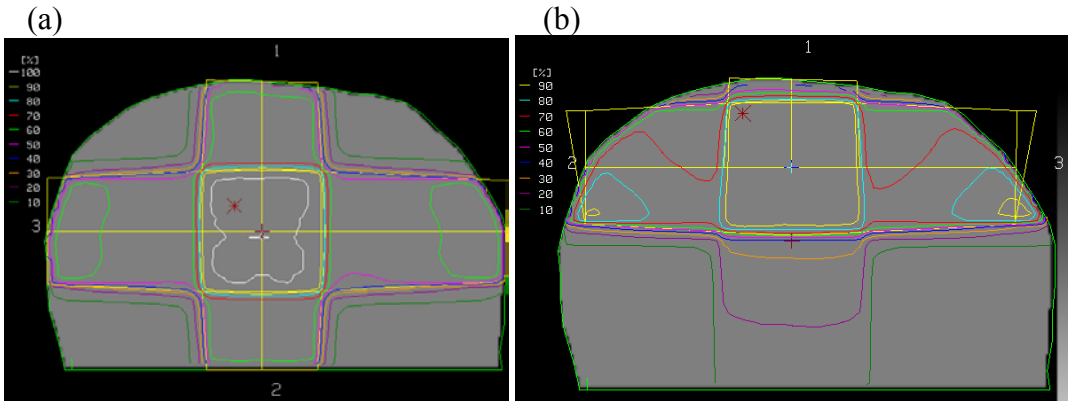

FIG. 7.22. Comparison of different beam geometries. A 4-field box (a) allows for a very high dose to be delivered at the intersection of the beams. A 3-field technique (b), however, requires the use of wedges to achieve a similar result. Note that the latter can produce significant hot spots near the entrance of the wedged beams and well outside the targeted area.

- Occasionally, three sets of opposing pairs are used, resulting in a more complicated dose distribution, but also in a spread of the dose outside the target over a larger volume, *i.e.,* in more sparing of tissues surrounding the target volume.

- 3-field box. A technique similar to a 4-field box for lesions that are closer to the surface (*e.g.*, rectum). Wedges are used in the two opposed beams to compensate for the dose gradient in the third beam.

Rotational techniques

Rotational techniques produce a relatively concentrated region of high dose near the isocentre, but also irradiate a greater amount of normal tissue to lower doses than fixed-field techniques. The target is placed at the isocentre, and the machine gantry is rotated about the patient in one or more arcs while the beam is on. A typical distribution achieved with two rotational arcs is shown in Fig. 7.23.

- Useful technique used mainly for prostate, bladder, cervix and pituitary lesions, particularly boost volumes.

- The dose gradient at the edge of the field is not as sharp as for multiple fixed field treatments.

- Skipping an angular region during the rotation allows the dose distribution to be pushed away from the region; however, this often requires that the isocentre be moved closer to this skipped area so that the resulting high-dose region is centred on the target .

- The MU/time calculation uses the average *TMR* or *TAR* for the entire range of angles that the gantry covers during each arc.

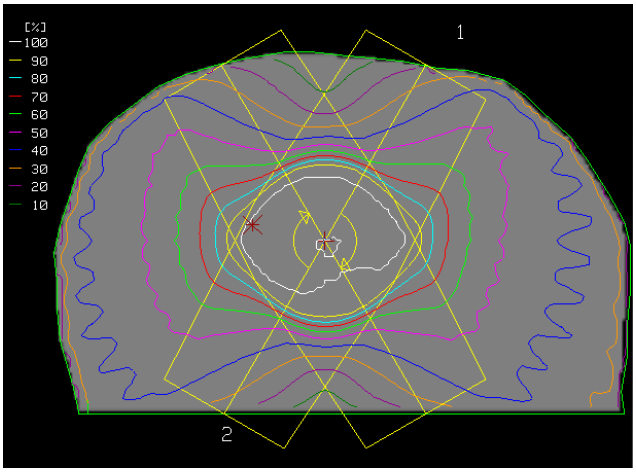

FIG. 7.23. Isodose curves for two bilateral arcs of 120° each. The isodoses are tighter along the angles avoided by the arcs (anterior and posterior). The isodoses are normalized at the isocentre. Pelvic lesions such as prostate have been popular sites for the application of arc techniques.

Multiple non-coplanar beams

- Non-coplanar beams arise from non-standard couch angles coupled with gantry angulations.
- Non-coplanar beams may be useful when there is inadequate critical structure sparing from a conventional co-planar beam arrangement.
- Dose distributions from non-coplanar beam combinations yield similar dose distributions to conventional multiple field arrangements.
- Care must be taken when planning the use of non-coplanar beams to ensure no collisions occur between the gantry and patient or couch.
- Non-coplanar beams are most often used for treatments of brain as well as head and neck disease where the target volume is frequently surrounded by critical structures.
- Non-coplanar arcs are also used, the best-known example being the multiple non-coplanar converging arcs technique used in radiosurgery.

Field matching

Field matching at the skin is the easiest field junctioning technique. However, due to beam divergence, this will lead to significant overdosing of tissues at depth and is only used in regions where tissue tolerance is not compromised. For most clinical situations field matching is performed at depth.

- To produce a junction dose similar to that in the centre of the open fields, beams must be junctioned such that their diverging edges match at the desired depth (*i.e.*, their respective 50% isodose levels add up at that depth).

- For two adjacent fixed *SSD* fields of different lengths L_1 and L_2, the surface gap g required to match the two fields at a depth z is (see Fig. 7.24):

$$GAP = 0.5 \cdot L_1 \cdot \left(\frac{z}{SSD}\right) + 0.5 \cdot L_2 \cdot \left(\frac{z}{SSD}\right) \tag{7.5}$$

- For adjacent fields with isocentric beams and a sloping surface, a similar expression can be developed using similar triangle arguments.

7.6. TREATMENT PLAN EVALUATION

After the dose calculations are performed by dosimetrists or medical physicists on computer or by hand, a radiation oncologist evalutes the plan. The dose distribution may be obtained for:

(1) A few significant points within the target volume
(2) A grid of points over a 2-D contour or image
(3) A 3-D array of points that cover the patient's anatomy.

The treatment plan evaluation consists of verifying the treatment portals and the isodose distribution for a particular treatment:

- The treatment portals (usually through simulation radiographs or DRRs) are verified to ensure that the desired PTV is targeted adequately.

- The isodose distribution (or the other dose tools discussed in this section) is verified to ensure that target coverage is adequate and that critical structures surrounding the PTV are spared as necessary.

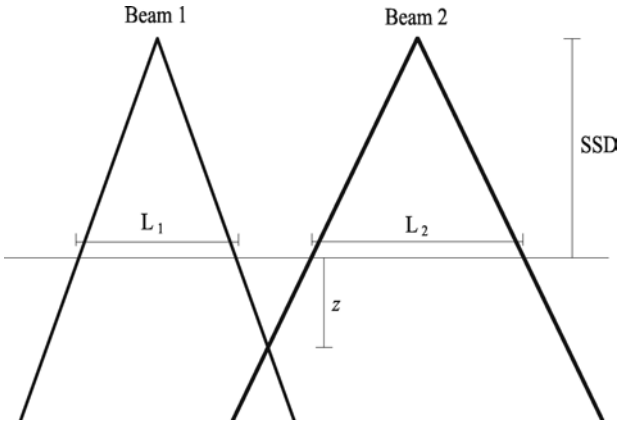

FIG. 7.24. Schematic diagram of two adjacent fields matched at a depth d.

The following tools are used in the evaluation of the planned dose distribution:

- *Isodose curves*
- *Orthogonal planes and isodose surfaces*
- *Dose distribution statistics*
- *Differential Dose Volume Histogram*
- *Cumulative Dose Volume Histogram*

7.6.1. Isodose curves

Isodose curves, of which several examples were given in section 7.5, are used to evaluate treatment plans along a single plane or over several planes in the patient. The isodose covering the periphery of the target is compared to the isodose at the isocentre. If the ratio is within a desired range (*e.g.*, 95-100%) then the plan may be acceptable provided critical organ doses are not exceeded. This approach is ideal if the number of transverse slices is small.

7.6.2. Orthogonal planes and isodose surfaces

When a larger number of transverse planes are used for calculation (such as with a CT scan) it may be impractical to evaluate the plan on the basis of axial slice isodose distributions alone. In such cases, isodose distributions can also be generated on orthogonal CT planes, reconstructed from the original axial data. Sagittal and coronal plane isodose distributions are usually available on most 3D treatment planning systems and displays on arbitrary oblique planes are becoming increasingly common.

An alternative way to display isodoses is to map them in three dimensions and overlay the resulting isosurface on a 3D display featuring surface renderings of the target and or/other organs. An example of such a display is shown in Fig. 7.25. While such displays can be used to assess target coverage, they do not convey a sense of distance between the isosurface and the anatomical volumes and give not quantitative volume information.

7.6.3 Dose statistics

In contrast to the previous tools, the plan evaluation tools described here do not show the spatial distribution of dose superimposed on CT slices or anatomy that has been outlined based on CT slices. Instead, they provide quantitative information on the volume of the target or critical structure, and on the dose received by that volume. From the matrix of doses to each volume element within an organ, key statistics can be calculated. These include:

- *Minimum dose to the volume*
- *Maximum dose to the volume*
- *Mean dose to the volume*
- *Dose received by at least 95% of the volume*
- *Volume irradiated to at least 95% of the prescribed dose.*

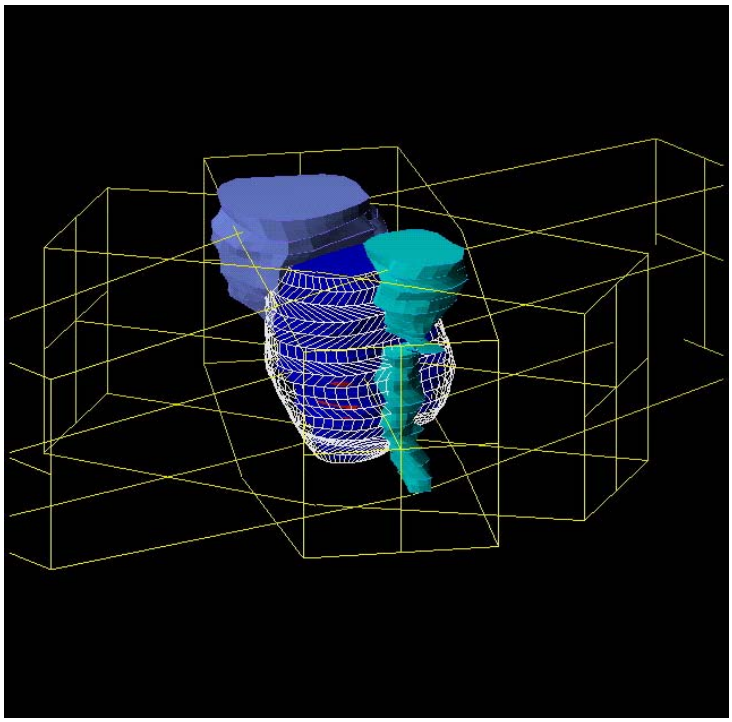

FIG. 7.25. A 3-D plot of the prescription isodose (white wireframe) is superimposed on the target volume with the bladder and the rectum also shown. The individual beams are also shown.

The final two statistics are only relevant for a target volume. Organ dose statistics such as these are especially useful in dose reporting, since they are simpler to include in a patient chart than the dose-volume histograms that are described below.

7.6.4. Dose-volume histograms

A 3-D treatment plan consists of dose distribution information over a 3-D matrix of points over the patient's anatomy. Dose volume histograms (DVHs) summarize the information contained in the 3-D dose distribution and are extremely powerful tools for quantitative evaluation of treatment plans.

In its simplest form a DVH represents a frequency distribution of dose values within a defined volume that may be the PTV itself or a specific organ in the vicinity of the PTV. Rather than displaying the frequency, DVHs are usually displayed in the form of "per cent volume of total volume" on the ordinate against the dose on the abscissa.

Two types of DVHs are in use:

- *Direct* (or differential) DVH
- *Cumulative* (or integral) DVH

The main drawback of the DVHs is the loss of spatial information that results from the condensation of data when DVHs are calculated.

Direct Dose Volume Histogram

To create a *direct* DVH, the computer sums the number of voxels with an average dose within a given range and plots the resulting volume (or more frequently the percentage of the total organ volume) as a function of dose. An example of a direct DVH for a target is shown in Fig. 7.26(a). The ideal DVH for a target volume would be a single column indicating that 100% of the volume receives the prescribed dose. For a critical structure, the DVH may contain several peaks indicating that different parts of the organ receive different doses. In Figure 7.26(b), an example of a DVH for a rectum in the treatment of the prostate using a four-field box technique is sketched.

Cumulative Dose Volume Histogram

Traditionally, physicians have sought to answer questions such as: "How much of the target is covered by the 95% isodose line?" In 3-D treatment planning this question is equally relevant and the answer cannot be extracted directly from the direct DVH, since it would be necessary to determine the area under the curve for all dose levels above 95% of the prescription dose. For this reason, *cumulative DVH* displays are more popular.

- The computer calculates the volume of the target (or critical structure) that receives at least the given dose and plots this volume (or percentage volume) versus dose.

- All cumulative DVH plots start at 100% of the volume for 0 Gy, since all of the volume receives at least no dose.

For the same organs as indicated in the example of Fig. 7.26, Fig. 7.27 shows the corresponding cumulative DVH (both structures are now shown on the same plot). While displaying the percent volume versus dose is more popular, it is useful in some circumstances to plot the absolute volume versus dose. For example, if a CT scan does not cover the entire volume of an organ such as the lung and the un-scanned volume receives very little dose, then a DVH showing percentage volume versus dose for that organ will be biased, indicating that a larger percentage of the volume receives dose. Furthermore, in the case of some critical structures, tolerances are known for irradiation of fixed volumes specified in cm^3.

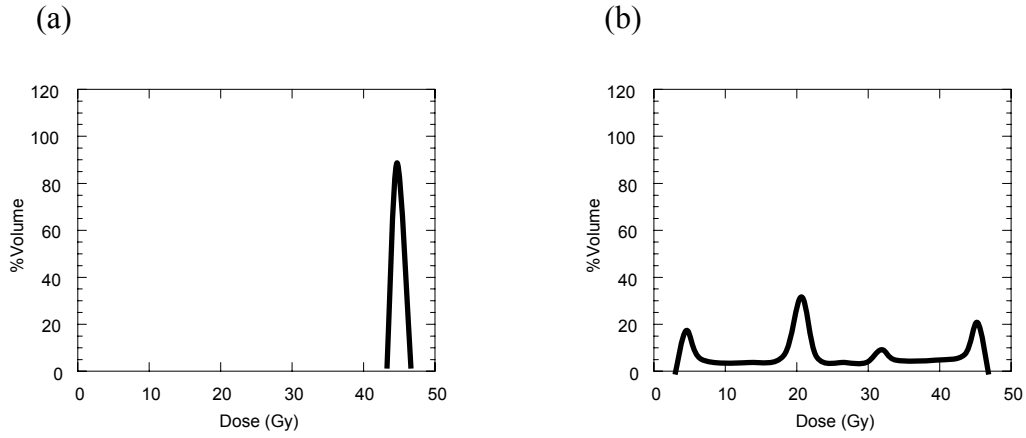

FIG. 7.26. Differential dose volume histograms for a four field prostate treatment plan for (a) the target volume and (b) the rectum are shown. The ideal target differential DVHs would be infinitely narrow peaks at the target dose for the PTV and at 0 Gy for the critical structure.

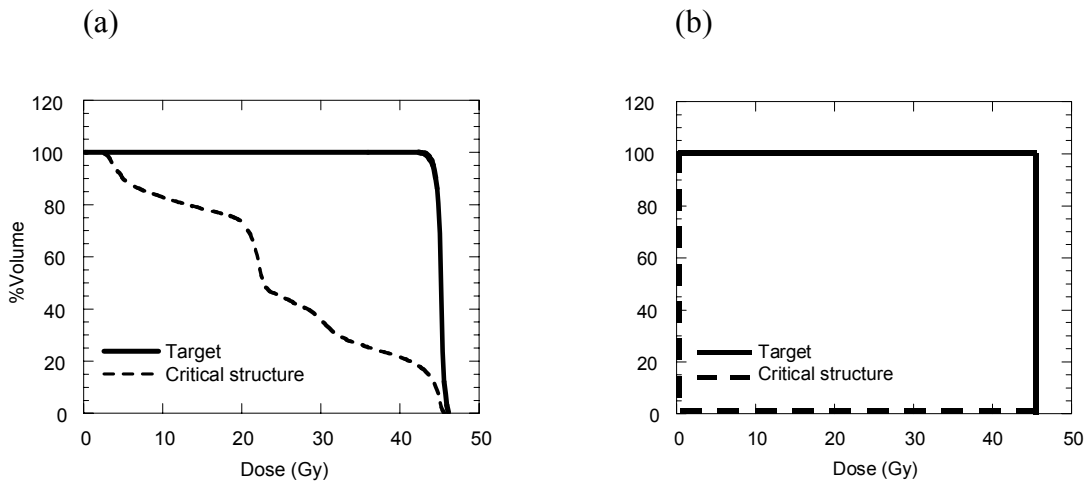

FIG. 7.27. Cumulative dose volume histograms for the same four field prostate treatment plan used in Figure 7.26. The ideal cumulative DVHs are shown on the right.

7.6.5. Treatment evaluation

Treatment evaluation consists of:

- Verifying the treatment portals (through port films or online portal imaging methods) and comparing these with simulator radiographs or DRRs.
- Performing in-vivo dosimetry through the use of diodes, thermoluminescent dosimeters and other detectors.

The latter methods are complex, often difficult to use in-vivo and are beyond the scope of this section. Portal imaging, either through port films or online systems provides relatively simpler ways of ensuring that the treatment has been successfully delivered.

Port films

A port film is usually an emulsion-type film, often still in its light-tight paper envelope, that is placed in the radiation beam beyond the patient. Depending on the sensitivity to radiation (or speed) port films can be used in one of two ways:

- *Localization*: a fast film (requiring only a few cGy to expose) is placed in each beam at the beginning or end of the treatment to verify that the patient installation is correct for the given beam.
- *Verification*: a slow film is placed in each beam and left there for the duration of the treatment. In this case any patient or organ movement during treatment will most likely affect the quality of the film.

Fast films generally produce a better image and are recommended for verifying small or complex beam arrangements. Slow films are recommended for larger fields for example where as many as 4 films may be required to verify the treatment delivery.

Localization films used in radiotherapy do not require intensifying screens such as those used in diagnostic radiology. Instead, a single thin layer of a suitable metal (such as copper or aluminum) is used in front of the film (beam entry side) to provide for electronic buildup that will increase the efficiency of the film. A backing layer is sometimes used with double emulsion films to provide backscatter electrons. Since there is no conversion of x rays to light photons as in diagnostic films, the films need not be removed from its envelope.

Port films can be taken either in single or double exposure techniques.

- *Single exposure*: The film is irradiated with the treatment field alone. This technique is well suited to areas where the anatomical features can clearly be seen inside the treated field. Practically all verification films are single exposure.

- *Double exposure*: The film is irradiated with the treatment field first, then the collimators are opened to a wider setting (usually 5-10 cm beyond each field limit) and all shielding is removed. A second exposure of typically 1-2 monitor units then is given to the film. The resulting image not only shows the treated field but also some of the surrounding anatomy that may be useful in verifying the beam position. Figure 7.28 shows a typical double exposure port film.

Online portal imaging

Online portal imaging systems consist of a suitable radiation detector, usually attached through a manual or semi-robotic arm to the linac, and capable of transferring the detector information to a computer that will process it and convert it to an image. These systems use a variety of detectors, all producing computer based images of varying degrees of quality.

Currently these systems include:

(1) *Fluoroscopic detectors*
(2) *Ionisation chamber detectors*
(3) *Amorphous silicon detectors*

- Fluoroscopic portal imaging detectors:

  - Work on the same principle as a simulator image intensifier system.
  - The detector consists of a combination of a metal plate and fluorescent phosphor screen, a 45° mirror and a television camera.
  - The metal plate converts incident x-rays to electrons and the fluorescent screen converts electrons to light photons.
  - The mirror deflects light to the TV camera, reducing the length of the imager, and the TV camera captures a small fraction (<0.1%) of the deflected light photons to produce an image.
  - Good spatial resolution (depends on phosphor thickness).
  - Only a few MU are required to produce an image.
  - Uses technology that has been used in many other fields.

- Matrix ionisation chamber detectors:

  - are based on grid of ion chamber-type electrodes that measure ionisation from point to point
  - The detector consists of two metal plates, 1 mm apart with the gap filled with isobutene. Each plate is divided into 256 electrodes and the plates are oriented such that the electrodes in one plate are at 90° to the electrodes in the other.
  - A voltage is applied between two electrodes across the gap and the ionisation at the intersection is measured. By selecting each electrode on each plate in turn, a 2D ionisation map is obtained and converted to a grayscale image of 256 x 256 pixels.
  - The maximum image size is usually smaller than for fluoroscopic systems.

- Amorphous silicon detectors:

  - Solid-state detector array consisting of amorphous silicon photodiodes and field-effect transistors arranged in a large rectangular matrix
  - Uses metal plate/fluorescent phosphor screen combination like the fluoroscopic systems. Light photons produce electron-hole pairs in the photodiodes whose quantity is proportional to the intensity allowing an image to be obtained
  - Produces an image with a greater resolution and contrast than the other systems.

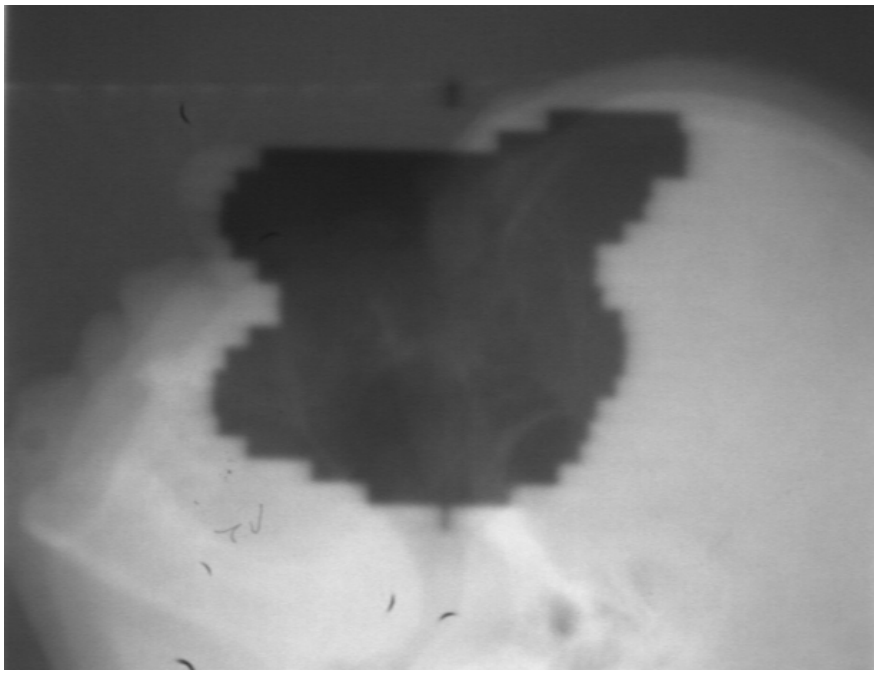

FIG. 7.28. Port film for lateral field used in a treatment of the maxillary sinus. This double exposure radiograph allows the physician to visualize both the treatment field and the surrounding anatomy.

7.7. TREATMENT TIME AND MONITOR UNIT CALCULATIONS

Treatment time and monitor unit calculations are an important component of the dose delivery process, since they determine the number of monitor units (for linacs) and time (for isotope teletherapy and orthovoltage machines) of beam-on for each individual beam of the treatment plan.

The patient treatments are carried out either with a fixed SSD or isocentric technique. Each of the two techniques is characterized with a specific dose distribution and treatment time or monitor unit calculation. The fixed SSD technique results in an isodose distribution that is governed by percentage depth doses resulting from a well defined dose delivery to points *P* at the depth of dose maximum for each of the beams in the treatment plan. The weight *W* ranging from 0 to 1.0 applied for a given beam actually determines the dose delivered to point *P* for the particular beam. Weight *W*=1 implies a dose of 100 cGy to point *P*, weight *W*=0.65 implies a dose of 65 cGy to point *P*, etc.

The isocentric technique, on the other hand, results in the dose distribution that is most often governed by tissue-maximum ratios normalized in such a way that each beam of the treatment plan delivers a prescribed fraction of the total dose at the isocenter. Other functions such as tissue-air ratios or tissue-phantom ratios are also sometimes used in isocentric dose distribution calculations.

Calculations of treatment time or monitor units for both the fixed SSD as well as the isocentric technique depend on the basic treatment machine output calibration that are discussed in Chapter 9. For megavoltage photon machines, the output is most commonly stipulated in cGy/MU for linacs and in cGy/min for cobalt units under conditions that may be summarized as follows:

(1) Measured in a water phantom,
(2) Measured on the central axis of the radiation beam,
(3) Stated for point *P* at the depth of maximum dose,
(4) Measured with a field size of 10×10 cm^2,
(5) Measured at the nominal $SSD = f$ of the unit (most commonly 100 cm).

The output may be designated by $\dot{D}(z_{\max}, 10, f, hv)$ and is used directly in meter-set calculations involving fixed *SSD* techniques.

- For cobalt units the output $\dot{D}(z_{\max}, 10, f, \mathrm{Co})$ is measured and quoted as the dose rate in cGy/min.

- The sensitivity of linac monitor chambers, on the other hand, is usually adjusted in such a way that $\dot{D}(z_{\max}, 10, f, hv) = 1$ cGy/MU .

- When used in isocentric calculations, $\dot{D}(z_{\max}, 10, f, hv)$ must be corrected by the inverse-square factor *ISF* unless the machine is actually calibrated at the isocenter.

$$ISF = \left[\frac{f + z_{\max}}{f} \right]^2 . \tag{7.6}$$

7.7.1. Treatment time and monitor unit calculations for fixed *SSD* set-up

Figure 7.29 shows a typical dose distribution obtained for a 3-field prostate boost treatment with a fixed *SSD* (100 cm) technique on a 6 MV linac.

The three treatment fields have the following characteristics:

- Anterior field: 7.5×7.5 cm^2 open field with a weight W = 1.0.
- Left posterior oblique (LPO) field: 6.5×7.5 cm^2 wedged field with weight W=0.8 and wedge factor WF = 0.53.
- Right posterior oblique (RPO) field: 6.5×7.5 cm^2 wedged field with weight W=0.8 and wedge factor WF = 0.53.

Dose *D(Q)* of 200 cGy is prescribed at the *ICRU reference point* located at the intersection of the three fields.

- As shown in Fig. 7.29, the isodose line (*IL*) through the ICRU reference point is 152%, the maximum dose 154%, and the 150% isodose curve completely covers the PTV.
- The PTV dose is thus between +2% and –2% of the *D(Q)* dose fulfilling well the recommendation which stipulates target doses should lie between +7% and –5% of the dose prescribed at the ICRU reference point.

The dose distribution of Fig. 7.29 delivers a dose of 152 cGy to the ICRU reference point *Q* under the following conditions:

(1) Dose of 100 cGy is delivered at a point P_A (W=1 for anterior field)
(2) Dose of 80 cGy is delivered at a point P_{LPO} (W=0.8 for left posterior oblique field)
(3) Dose of 80 cGy is delivered at a point P_{RPO} (W=0.8 for right posterior oblique field)

Thus, to obtain the prescribed dose of 200 cGy rather than 152 cGy at point *Q*, doses of $D(P_A)$ = 131.6 cGy, $D(P_{LPO})$ = 105.3 cGy, and $D(P_{RPO})$ = 105.3 cGy should be delivered to points P_A, P_{LPO}, and P_{RPO}., respectively. The doses at points *P* for individual beams are often referred to as the *given doses* for a particular field in the fixed *SSD* treatment plan and are determined as follows:

$$D(P_A) = \frac{D(Q) \times 100 \times W_A}{IL} = \frac{200 \text{ cGy} \times 100 \times 1.0}{152} = 131.6 \text{ cGy} \tag{7.7}$$

$$D(P_{LPO}) = \frac{D(Q) \times 100 \times W_{LPO}}{IL} = \frac{200 \text{ cGy} \times 100 \times 0.8}{152} = 105.3 \text{ cGy} \tag{7.8}$$

$$D(P_{RPO}) = \frac{D(Q) \times 100 \times W_{RPO}}{IL} = \frac{200 \text{ cGy} \times 100 \times 0.8}{152} = 105.3 \text{ cGy} \tag{7.9}$$

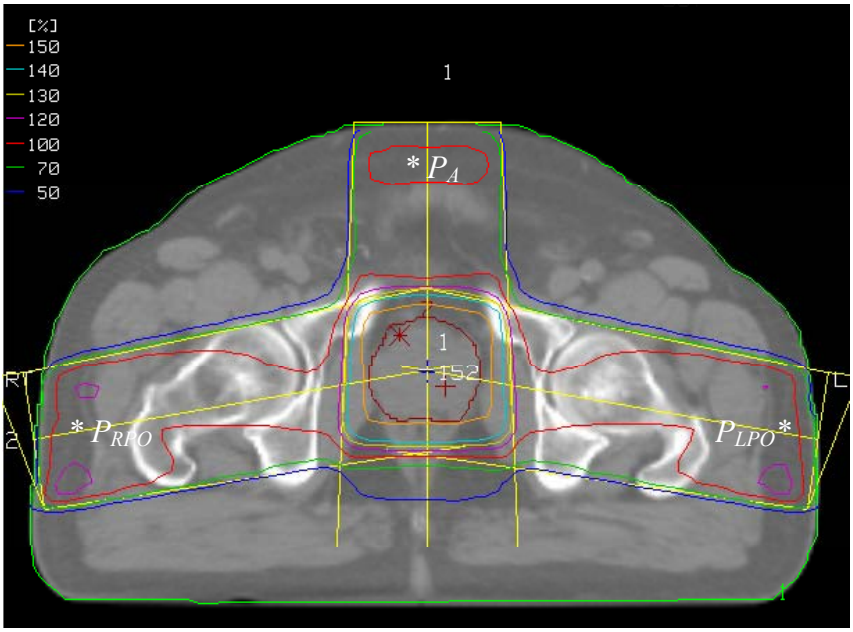

FIG. 7.29. Fixed SSD isodose distribution for a three field treatment of the prostate.

The next step is to calculate the linac monitor chamber setting in MUs required for delivery of the given doses for each of the three fields constituting the fixed SSD treatment plan. The given dose rates for points P_A, P_{LPO}, *and* P_{RPO} are obtained by multiplying the basic linac output $\dot{D}(z_{\max}, 10, f, h\nu)$ with the relative dose factor *RDF(A)* where *A* refers to the appropriate field size (see Sec. 6.6.4.), and any other applicable transmission factors (such as the wedge factor or the tray factor).

The *monitor settings* $\mathcal{MU}$ for points P_{A}, P_{LPO}, and P_{RPO} are calculated as follows:

$$\mathcal{MU}(A) = \frac{D(P_{\mathrm{A}})}{\dot{D}(z_{\max}, 10, 100, h\nu) \times RDF(A, h\nu)} =$$

$$= \frac{131.6 \text{ cGy}}{1.0 \text{ cGy/MU} \times 0.98} = 134 \text{ MU} \tag{7.10}$$

$$\mathcal{MU}(\mathrm{LPO}) = \frac{D(P_{\mathrm{LPO}})}{\dot{D}(z_{\max}, 10, 100, h\nu) \times RDF(A, h\nu) \times WF} =$$

$$= \frac{105.3 \text{ cGy}}{1.0 \text{ cGy/MU} \times 0.97 \times 0.53} = 205 \text{ MU} \tag{7.11}$$

$$\mathcal{MU}(\mathrm{RPO}) = \frac{D(P_{\mathrm{RPO}})}{\dot{D}(z_{\max}, 10, 100, h\nu) \times RDF(A, h\nu) \times WF} =$$

$$= \frac{105.3 \text{ cGy}}{1.0 \text{ cGy/MU} \times 0.97 \times 0.53} = 205 \text{ MU} \tag{7.12}$$

7.7.2. Monitor units and treatment time calculations for isocentric set-ups

Figure 7.30 shows a typical isodose distribution obtained for a 3 field prostate boost treatment with an isocentric (100 cm) technique on a 6 MV linac.

For the isocentric distribution, all field sizes (A_Q) are defined at the isocenter, and wedges are used for the two oblique fields as in the fixed SSD example:

- Anterior 8×8 cm^2 open field with weight W = 1.0.
- Left and right posterior oblique 7×8 cm^2 fields both with weight W of 0.7, and a wedge factor WF of 0.53.

A dose D_Q of 200 cGy is prescribed at the ICRU reference point that is located at the treatment isocenter. The IL at this point is 240% (sum of the weights in %), the maximum dose in the distribution is 242%, and the 235% isodose completely covers the PTV.

The dose distribution of Fig. 7.30 that delivers a dose of 240 cGy to the ICRU reference point Q is achieved under the following conditions:

(a) 100 cGy is delivered by the anterior field at the isocenter (W=1)
(b) 70 cGy is delivered by the left posterior oblique field at the isocenter (W=0.7)
(c) 70 cGy is delivered by the right posterior oblique field at the isocenter (W=0.7)

Thus, to obtain the prescribed dose of 200 cGy at point Q, doses of 83.4 cGy, 58.3 cGy, and 58.3 cGy should be delivered by the respective beams at the isocenter. These doses are obtained by considering the relative weight of each beam, such that:

$$D(Q)_A = \frac{D(Q)\times 100\times W_{\mathrm{A}}}{IL} = \frac{200\ \mathrm{cGy}\times 100\times 1.0}{240} = 83.4\ \mathrm{cGy} \tag{7.13}$$

$$D(Q)_{LPO} = \frac{D(Q)\times 100\times W_{\mathrm{LPO}}}{IL} = \frac{200\ \mathrm{cGy}\times 100\times 0.7}{240} = 58.3\ \mathrm{cGy} \tag{7.14}$$

$$D(Q)_{RPO} = \frac{D(Q)\times 100\times W_{\mathrm{RPO}}}{IL} = \frac{200\ \mathrm{cGy}\times 100\times 0.7}{240} = 58.3\ \mathrm{cGy} \tag{7.15}$$

To calculate the linac monitor chamber setting in MU, it is first necessary to calculate the doses from each beam at the isocenter at a depth of maximum dose $D(Q_{\max})$ where $SSD=SAD-z_{\max}$. The tissue maximum ratio (TMR) is obtained for each field and used in the calculation as follows:

$$D(Q_{\max})_{\mathrm{A}} = \frac{D(Q)_{\mathrm{A}}}{TMR(8\times 8, 11.5)} = \frac{83.4\ \mathrm{cGy}}{0.72} = 97.2\ \mathrm{cGy} \tag{7.16}$$

$$D(Q_{\max})_{\mathrm{LPO}} = \frac{D(Q)_{\mathrm{LPO}}}{TMR(7\times 8, 18.5)} = \frac{58.3\ \mathrm{cGy}}{0.54} = 108.3\ \mathrm{cGy} \tag{7.17}$$

$$D(Q_{\max})_{\mathrm{RPO}} = \frac{D(Q)_{\mathrm{RPO}}}{TMR(7\times 8, 18.5)} = \frac{58.3\ \mathrm{cGy}}{0.54} = 108.3\ \mathrm{cGy} \tag{7.18}$$

Once the dose at $D(Q_{\max})$ is known for each beam it is possible to calculate MU setting *(MU)* from the basic linac output $\dot{D}(d_{\max},10,f,h\nu)$ multiplied by the *RDF(A$_Q$)*, the *ISF*, and other transmission factors as applicable, such that:

$$\mathcal{MU}(\mathrm{A}) = \frac{D(Q_{\max})_{\mathrm{A}}}{\dot{D}(z_{\max},10,100,h\nu)\times ISF\times RDF(8\times 8)}$$

$$= \frac{97.2\ \mathrm{cGy}}{1.0\ \mathrm{cGy/MU}\times\left(\frac{101.5}{100}\right)^2\times 0.982} = 96\ \mathrm{MU} \qquad (7.19)$$

$$\mathcal{MU}(\mathrm{LPO}) = \frac{D(Q_{\max})_{\mathrm{LPO}}}{\dot{D}(z_{\max},10,100,h\nu)\times ISF\times RDF(7\times 8)\times WF}$$

$$= \frac{108.3\ \mathrm{cGy}}{1.0\ \mathrm{cGy/MU}\times\left(\frac{101.5}{100}\right)^2\times 0.975\times 0.53} = 203\ \mathrm{MU} \qquad (7.20)$$

$$\mathcal{MU}(\mathrm{RPO}) = \frac{D(Q_{\max})_{\mathrm{RPO}}}{\dot{D}(z_{\max},10,100,h\nu)\times ISF\times RDF(7\times 8)\times WF}$$

$$= \frac{108.3\ \mathrm{cGy}}{1.0\ \mathrm{cGy/MU}\times\left(\frac{101.5}{100}\right)^2\times 0.975\times 0.53} = 203\ \mathrm{MU} \qquad (7.21)$$

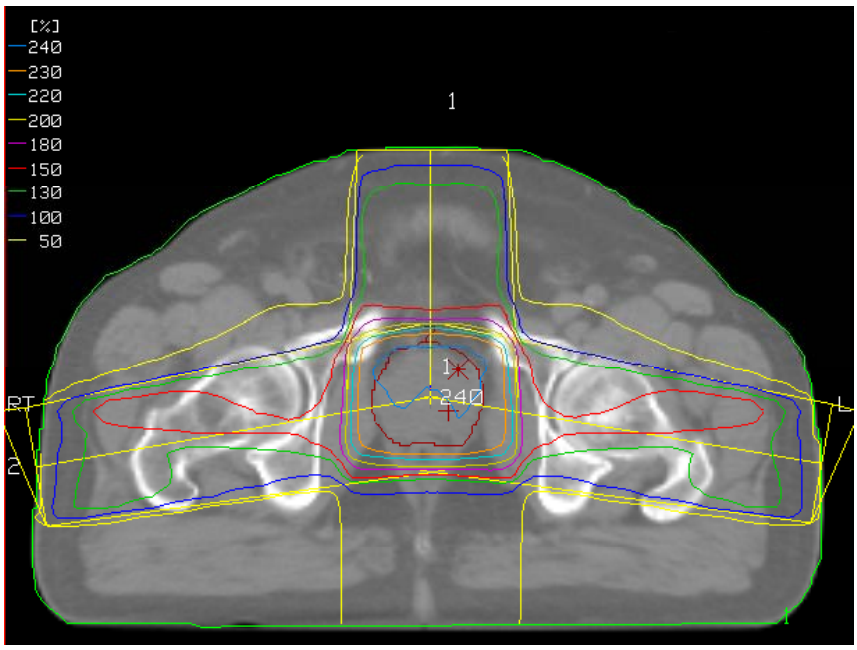

FIG. 7.30. Isocentric isodose distribution for a three-field treatment of the prostate.

7.7.3. Normalization of dose distributions

It is important to note that dose distributions can be normalized in a variety of different ways. The ICRU recommends normalization of the dose distribution to 100% at the prescription point *Q*. Clearly, the calculation of monitor units must reflect the normalization technique employed for each particular case.

- If the dose distribution is normalized to 100% at the isocenter then an adjustment must be made to the calculation when calculating the relative dose contribution to the isocenter from each beam.

- For the isocentric example above, the isodose value at the isocenter is simply the sum of the absolute weights of each beam. If the dose distribution was normalized to 100% at the isocenter, with *D(Q)* = 200 cGy and a prescription isodose value (IL) of 100%, the relative contribution for beam A would amount to:

$$D(Q)_{\mathrm{A}} = \frac{D(Q)\times 100}{IL}\times\left(\frac{W_{\mathrm{A}}}{W_{\mathrm{A}}+W_{\mathrm{LPO}}+W_{\mathrm{RPO}}}\right) = \frac{200\ \mathrm{cGy}\times 100}{100}\times\left(\frac{1.0}{1.0+0.7+0.7}\right) = 83.4\ \mathrm{cGy} \tag{7.22}$$

  The remainder of the calculation remains the same.

7.7.4. Inclusion of output parameters in dose distribution

Modern treatment planning systems give the user the ability to take into account several dosimetric parameters in the dose distribution affecting the beam output, thereby relieving the need for correcting the beam output when performing the monitor setting calculation. Obviously large errors in monitor calculations could occur if the outputs were corrected without need. Frequently, for example, the isodose values in a dose distribution may already include:

(1) *inverse square law factors* for extended distance treatments,
(2) effects on dose outputs from *blocks* in the field, or
(3) *tray* and *wedge factors.*

It is of utmost importance to know exactly what the isodose lines mean on a dose distribution obtained from a given treatment planning system.

7.7.5. Treatment time calculation for orthovoltage and cobalt-60 units

Treatment time calculations for orthovoltage units and cobalt-60 teletherapy units are carried out similarly to the above examples except that machine outputs are stated in cGy/min and the treatment timer setting in minutes replaces the monitor setting in MU. A correction for shutter error should be included in the time set.

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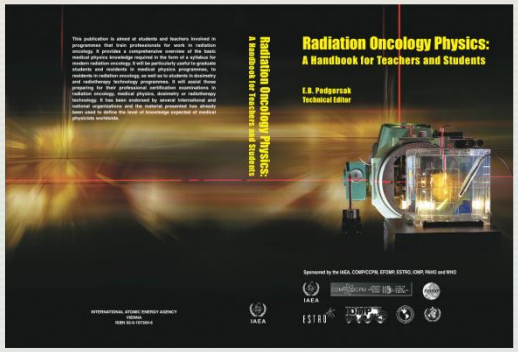
Chapter 7: Clinical Treatment Planning in External Photon Beam Radiotherapy

Set of 232 slides based on the chapter authored by
W. Parker, H. Patrocinio
of the IAEA publication (ISBN 92-0-107304-6):
Review of Radiation Oncology Physics:
A Handbook for Teachers and Students

Objective:

To familiarize the student with a variety of modern photon beam radiotherapy techniques to achieve a uniform dose distribution inside the target volume and a dose as low as possible in the healthy tissues surrounding the target.



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International Atomic Energy Agency

Slide set prepared in 2006
by G.H. Hartmann (Heidelberg, DKFZ)
Comments to S. Vatnitsky:
dosimetry@iaea.org

Version 2012

CHAPTER 7. TABLE OF CONTENTS

7.1 INTRODUCTION

General considerations for photon beams

- Almost a dogma in external beam radiotherapy:

Successful radiotherapy requires a uniform dose distribution within the target (tumor).

→ External photon beam radiotherapy is usually carried out with **multiple radiation beams** in order to achieve a **uniform dose distribution** inside the target volume and a dose as low as possible in healthy tissues surrounding the target.

7.1 INTRODUCTION

Criteria of a uniform dose distribution within the target

- Recommendations regarding dose uniformity, prescribing, recording, and reporting photon beam therapy are set forth by the International Commission on Radiation Units and Measurements (ICRU).

- The ICRU report 50 recommends a target dose uniformity **within +7 % and –5 %** relative to the dose delivered to a well defined prescription point within the target.

7.1 INTRODUCTION

To achieve this goal, modern beam radiotherapy is carried out with a variety of:

- **Beam energies**

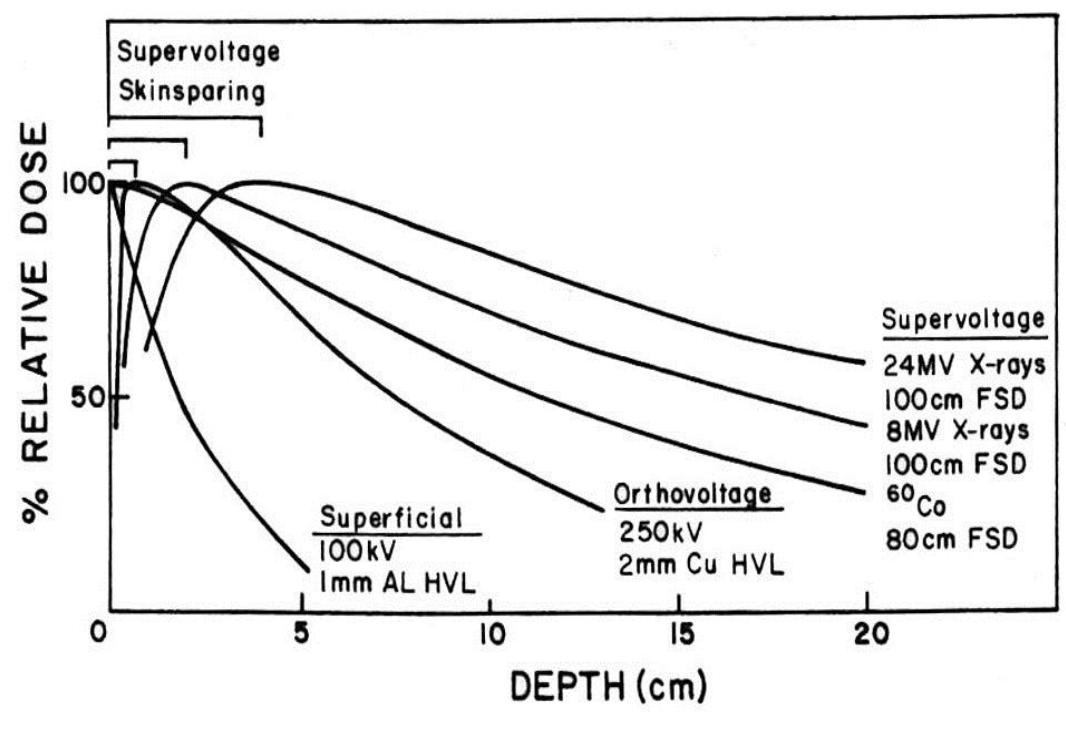
  and

- **Field sizes**

7.1 INTRODUCTION

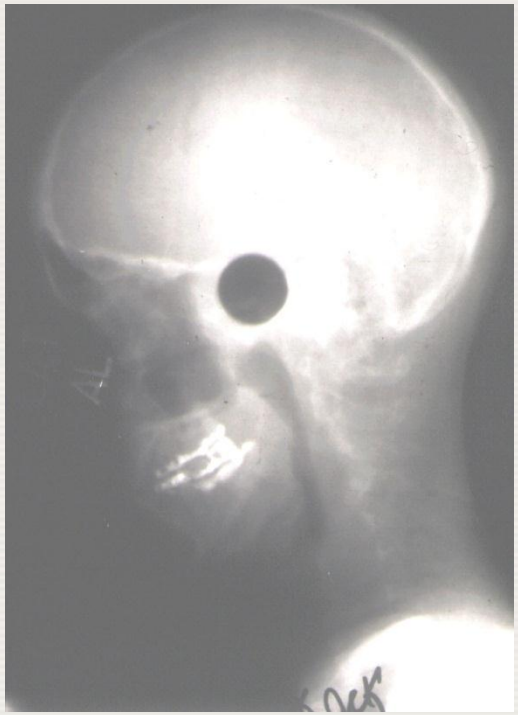
Beam energies used:

- Superficial (30 kV to 80 kV)
- Orthovoltage (100 kV to 300 kV)
- Megavoltage or supervoltage energies (Co-60 to 25 MV)

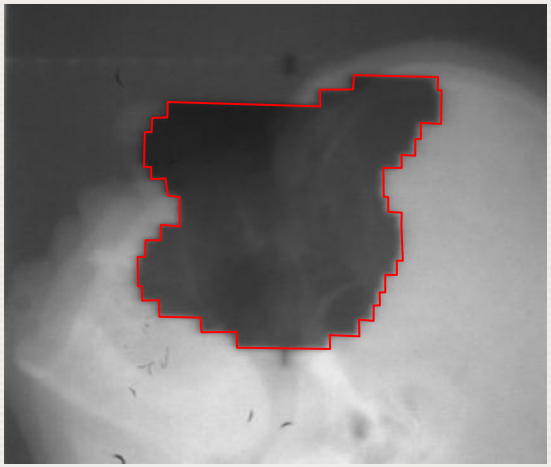


7.1 INTRODUCTION

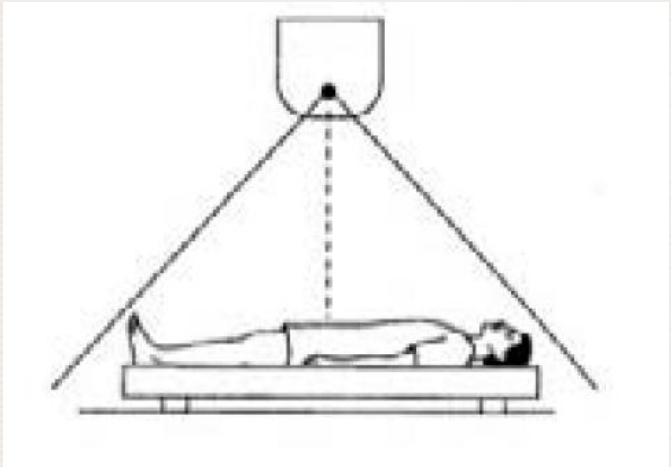
- **Field sizes** range from:



Small **circular** fields used in radiosurgery



Standard rectangular and **irregular** fields



Very **large** fields used for total body irradiations

7.1 INTRODUCTION

Methods of Patient setup:

- Photon beam radiotherapy is carried out under two setup conventions

constant Source-Surface Distance

(SSD technique)

isocentric setup with a constant Source-Axis Distance

(SAD technique).

7.1 INTRODUCTION

SSD technique

- The distance from the source to the **surface** of the patient is kept **constant** for all beams.

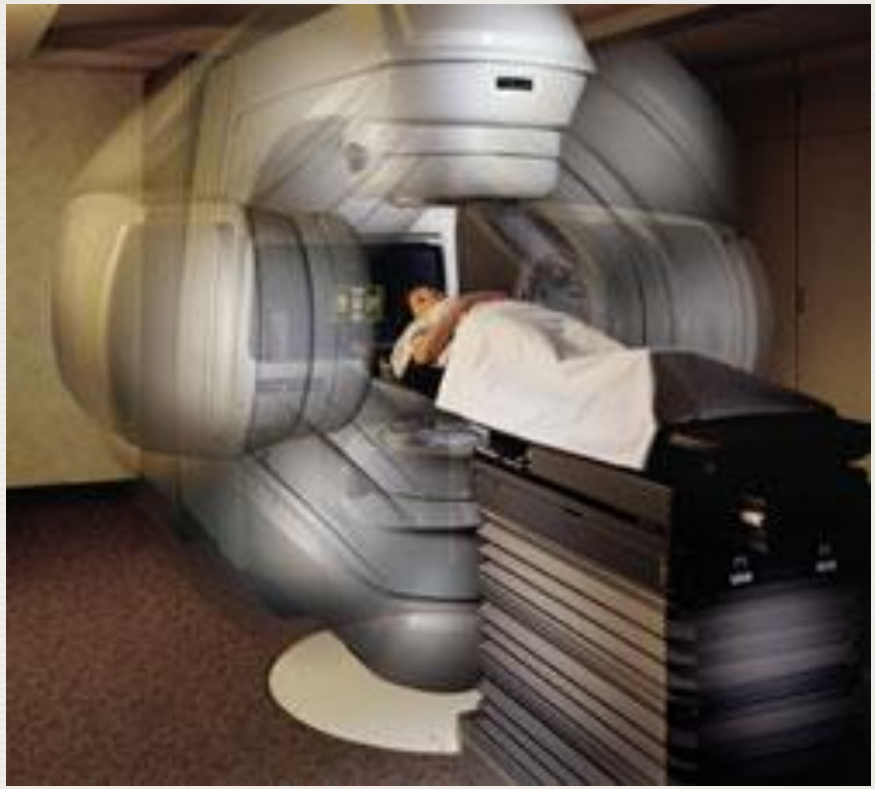
SAD technique

- The center of the target volume is placed at the machine isocenter, i.e. the **distance to the target point** is kept constant for all beams.

7.1 INTRODUCTION

***Note*:**

In contrast to SSD technique, the **SAD technique** requires **no** adjustment of the patient setup when turning the gantry to the next field.



7.2 VOLUME DEFINITION

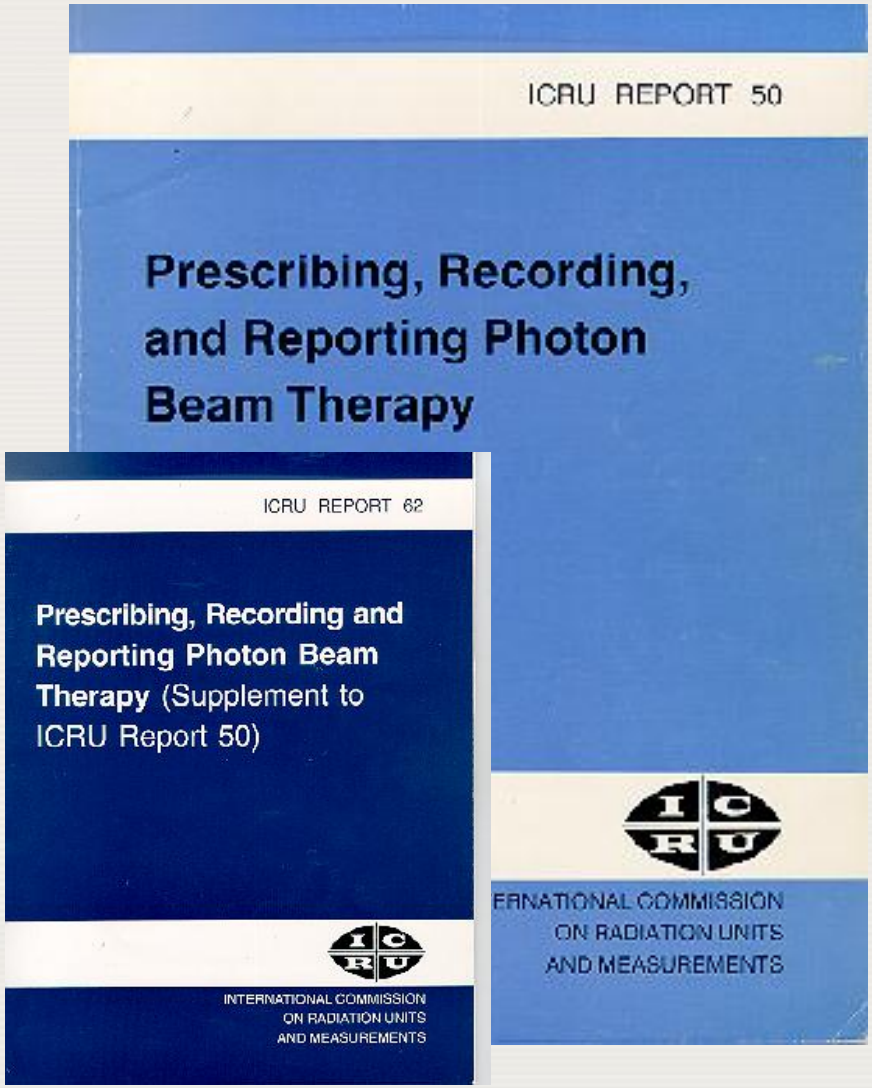
- The process of determining the **volume for the treatment** of a malignant disease consists of several distinct steps.

- In this process, **different volumes** may be defined, e.g. due to:
  - Varying concentrations of malignant cells.
  - Probable changes in the spatial relationship between volume and beam during therapy.
  - Movement of patient.
  - Possible inaccuracies in the treatment setup.

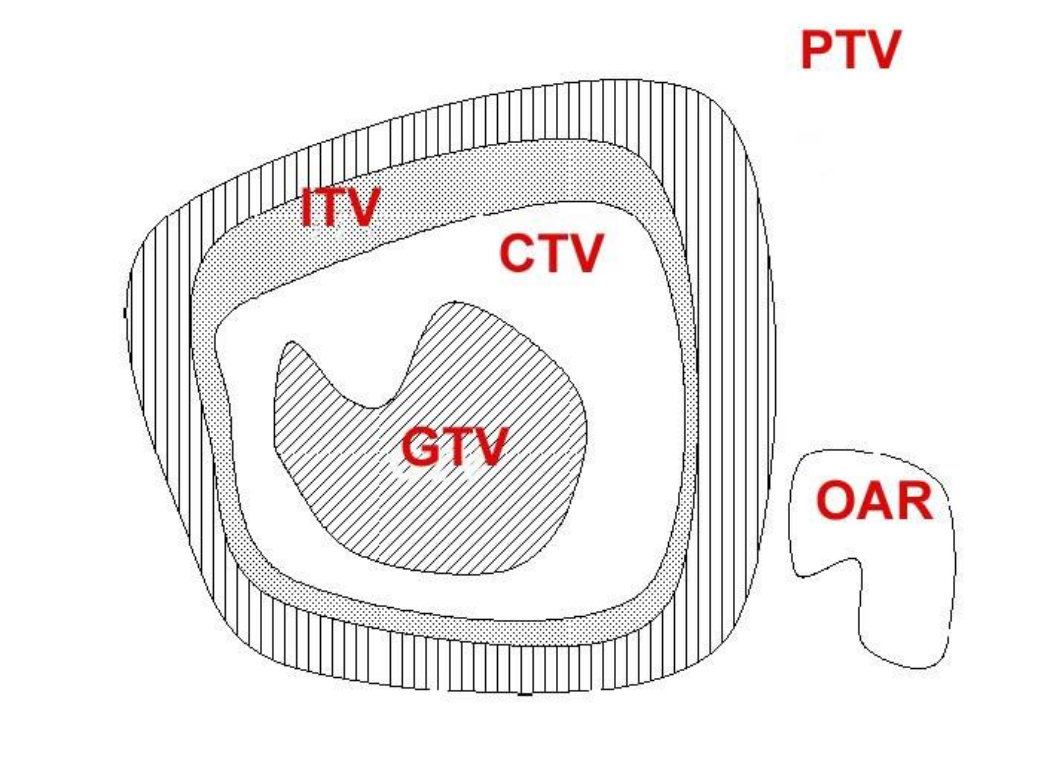
7.2 VOLUME DEFINITION

The **ICRU 50 and 62 Reports** define and describe several target and critical structure volumes that:

- Aid in the treatment planning process
- Provide a basis for comparison of treat-ment outcomes.



7.2 VOLUME DEFINITION



The following slides describe these **"ICRU volumes"** that have been defined as **principal volumes** related to three-dimensional treatment planning.

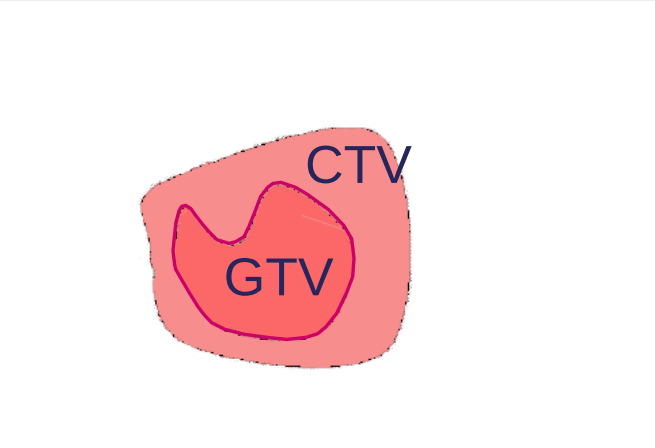
7.2 VOLUME DEFINITION

7.2.1 Gross Tumor Volume (GTV)

- The **Gross Tumor Volume** (GTV) is the gross palpable or visible/demonstrable extent and location of malignant growth.
- The GTV is usually based on information obtained from a combination of **imaging modalities** (CT, MRI, ultrasound, etc.), **diagnostic modalities** (pathology and histological reports, etc.) and **clinical examination**.

7.2 VOLUME DEFINITION

7.2.2 Clinical Target Volume (CTV)



- The **Clinical Target Volume** (CTV) is the tissue volume that contains a **demonstrable** GTV and/or **sub-clinical microscopic malignant disease**, which has to be eliminated.
- This volume thus has to be treated adequately in order to achieve the aim of therapy, cure or palliation.

7.2 VOLUME DEFINITION

7.2.2 Clinical Target Volume (CTV)

- The CTV often includes the area **directly surrounding the GTV** that may contain microscopic disease and other areas considered to be at risk and require treatment.

  Example: positive lymph nodes.

- The CTV is an **anatomical-clinical volume.**

- It is usually determined by the **radiation oncologist**, often after other relevant specialists such as pathologists or radiologists have been consulted.

7.2 VOLUME DEFINITION

7.2.2 Clinical Target Volume (CTV)

- The CTV is usually stated as a fixed or variable margin around the GTV.
  Example:
  CTV = GTV **+ 1 cm margin**

- In some cases the CTV is the same as the GTV.
  Example:
  prostate boost to the gland only

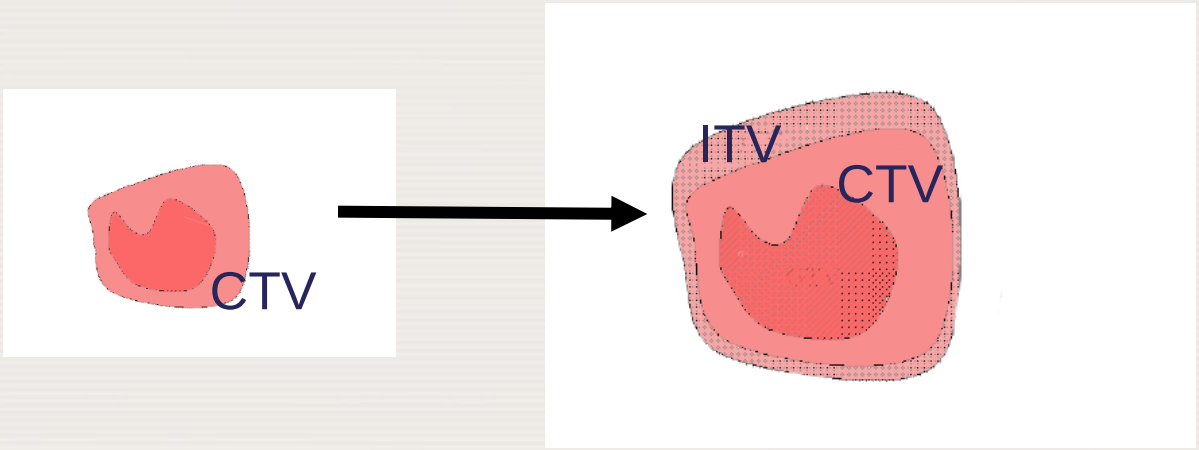
- There can be several non-contiguous CTVs that may require different total doses to achieve treatment goals.

General consideration on margins:

- Margins are most important for clinical radiotherapy. They depend on:
  - organ motion ⇒ internal margins
  - patient set-up and beam alignment ⇒ external margins
- Margins can be non-uniform but should be three dimensional.
- A reasonable way of thinking would be: “Choose margins so that the target is in the treated field at least 95 % of the time.”

7.2 VOLUME DEFINITION

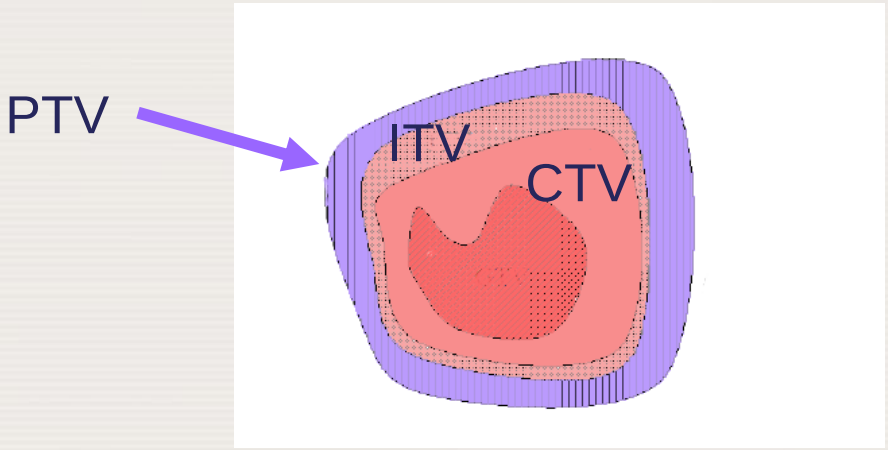
7.2.3 Internal Target Volume (ITV)



- The **Internal Target Volume** (ITV) consists of the CTV **plus** an internal margin.
- The internal margin is designed to take into account the variations in the size and position of the CTV relative to the patient's reference frame (usually defined by the bony anatomy), i.e., variations due to organ motions such as breathing, bladder or rectal contents, etc.

7.2 VOLUME DEFINITION

7.2.4 Planning Target Volume (PTV)

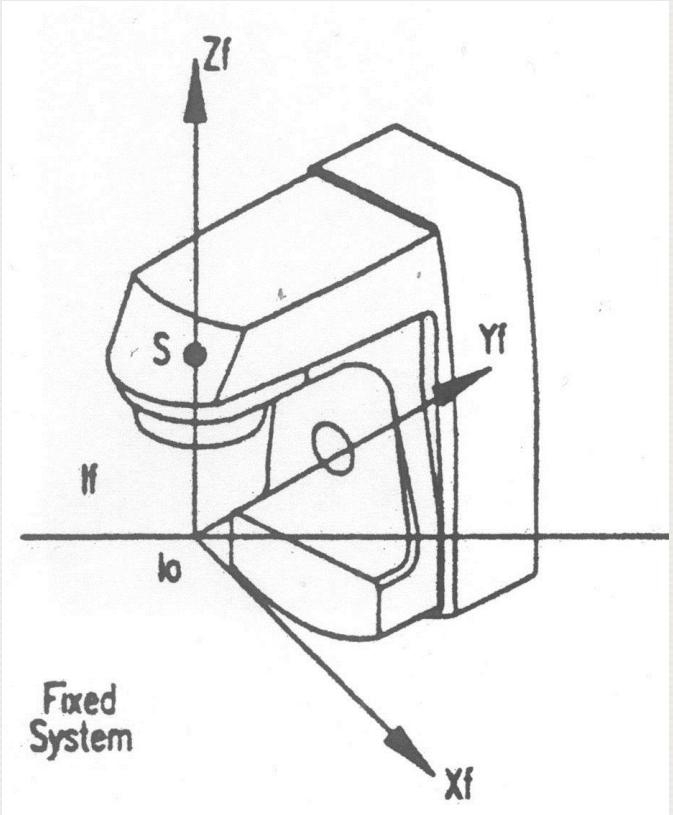


- In contrast to the CTV, the **Planning Target Volume** (PTV) is a **geometrical concept.**
- It is defined to select appropriate beam arrangements, taking into consideration the net effect of all possible geometrical variations, in order to ensure that the prescribed dose is actually absorbed in the CTV.

7.2 VOLUME DEFINITION

7.2.4 Planning Target Volume (PTV)

- The PTV includes the **internal target** margin and an **additional margin** for:
  - set-up uncertainties
  - machine tolerances
  - and intra-treatment variations.
- The PTV is linked to the reference frame of the treatment machine (IEC 1217: "Fixed System").



7.2 VOLUME DEFINITION

7.2.4 Planning Target Volume (PTV)

- The PTV is often described as the CTV plus a fixed or variable margin.
  Example:

  PTV = CTV **+ 1 cm**

- Usually a single PTV is used to encompass one or several CTVs to be targeted by a group of fields.

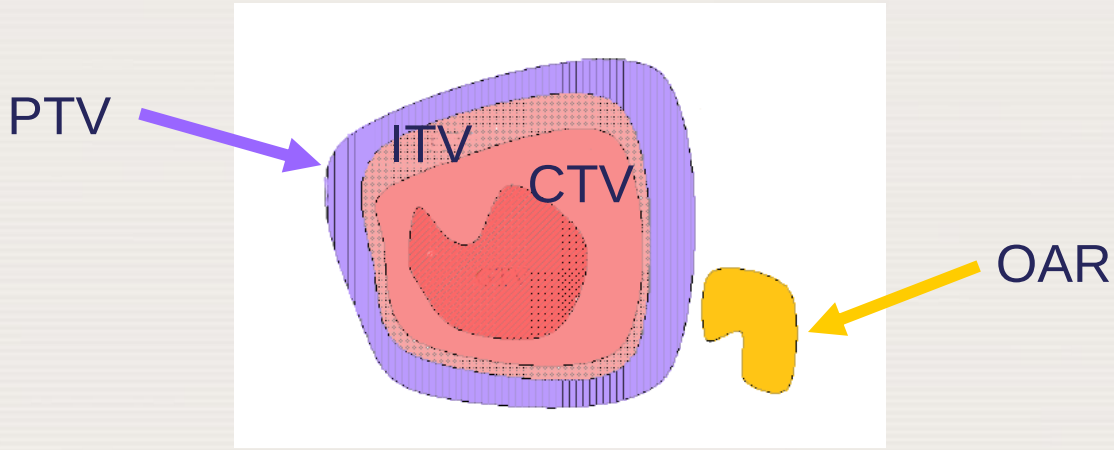
7.2 VOLUME DEFINITION

7.2.4 Planning Target Volume (PTV)

- The PTV depends on the precision of such tools such as:
  - Immobilization devices
  - Lasers
- The PTV does **NOT** include a margin for dosimetric characteristics of the radiation beam as these will require an additional margin during treatment planning and shielding design.
  Examples not included:
  - Penumbral areas
  - Build-up region

7.2 VOLUME DEFINITION

7.2.5 Organ at Risk (OAR)



- **Organ At Risk** is an organ whose sensitivity to radiation is such that the dose received from a treatment plan may be significant compared to its tolerance, possibly requiring a change in the beam arrangement or a change in the dose.

7.2 VOLUME DEFINITION

7.2.5 Organ at Risk (OAR)

- Specific attention should be paid to organs that, although not immediately adjacent to the CTV, have a very low tolerance dose.
  Example for such OARs:
  - Eye lens during nasopharyngeal or brain tumor treatments
- Organs with a radiation tolerance that depends on the fractionation scheme should be outlined completely to prevent biasing during treatment plan evaluation.

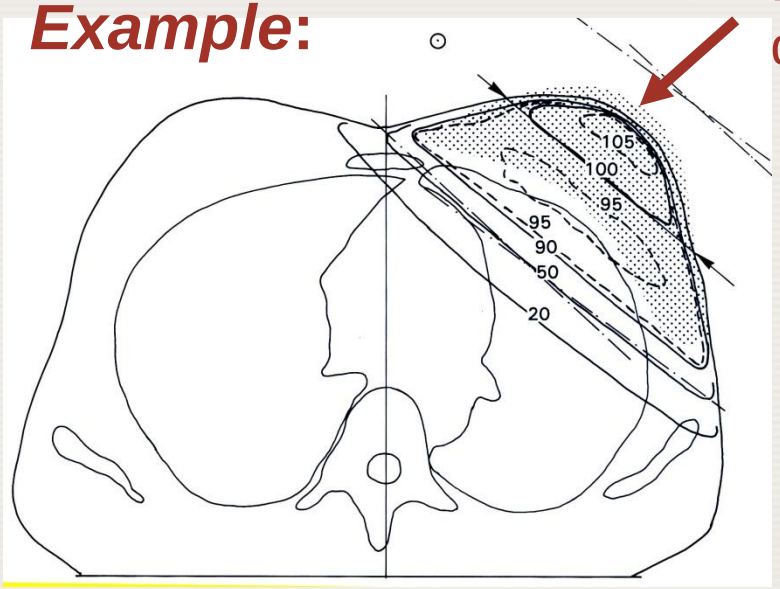
7.3 DOSE SPECIFICATION

- The **complete prescription** of radiation treatment must include:
  - Definition of the **aim** of therapy
  - **Volumes** to be considered
  - **Prescription** of **dose** and **fractionation.**
- Only detailed information regarding total dose, fractional dose and total elapsed treatment days allows for proper comparison of outcome results.
- Different concepts have been developed for this requirement.

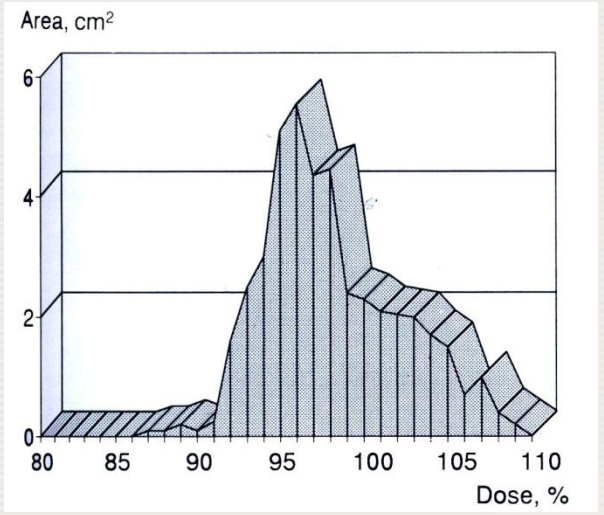
7.3 DOSE SPECIFICATION

- When the dose to a given volume is prescribed, the corresponding delivered dose should be as homogeneous as possible.
- Due to technical reasons, some heterogeneity has to be accepted.

***Example*:**



PTV = dotted area



frequency dose-area histogram for the PTV

7.3 DOSE SPECIFICATION

- The ICRU report 50 recommends a target dose uniformity **within +7 % and –5 %** relative to the dose delivered to a well defined prescription point within the target.
- Since some dose heterogeneity is always present, a method to describe this dose heterogeneity within the defined volumes is required.
- ICRU Report 50 is suggesting several methods for the **representation** of a spatial dose distribution.

7.3 DOSE SPECIFICATION

- Parameters to characterize the dose distribution within a volume and to specify the dose are:
  - Minimum target dose
  - Maximum target dose
  - Mean target dose
  - A **reference dose** at a **representative point** within the volume
- The ICRU has given recommendations for the selection of a representative point (the so-called **ICRU reference point**).

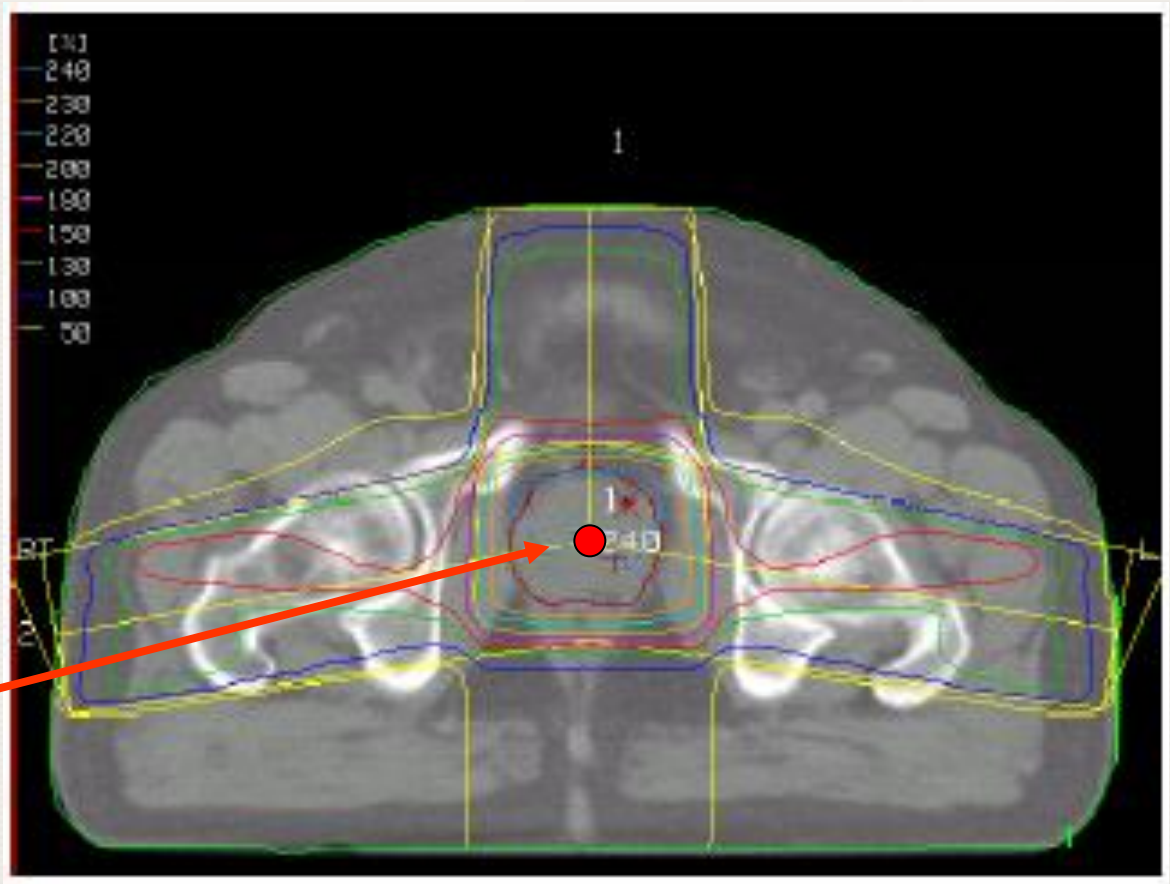
7.3 DOSE SPECIFICATION

- The **ICRU reference dose point** is located at a point chosen to represent the delivered dose using the following criteria:
  - The point should be located in a region where the dose can be calculated accurately (i.e., no build-up or steep gradients).
  - The point should be in the central part of the PTV.
  - For multiple fields, the isocenter (or beam intersection point) is recommended as the ICRU reference point.

7.3 DOSE SPECIFICATION

ICRU reference point for multiple fields

Example for a 3 field prostate boost treatment with an isocentric technique



The ICRU (reference) point is located at the isocenter

7.3 DOSE SPECIFICATION

- Specific recommendations are made with regard to the position of the ICRU (reference) point for particular beam combinations:
  - **For single beam:**
    the point on central axis at the center of the target volume.
  - **For parallel-opposed equally weighted beams:**
    the point on the central axis midway between the beam entrance points.
  - **For parallel-opposed unequally weighted beams:**
    the point on the central axis at the centre of the target volume.
  - **For other combinations of intersecting beams:**
    the point at the intersection of the central axes (insofar as there is no dose gradient at this point).

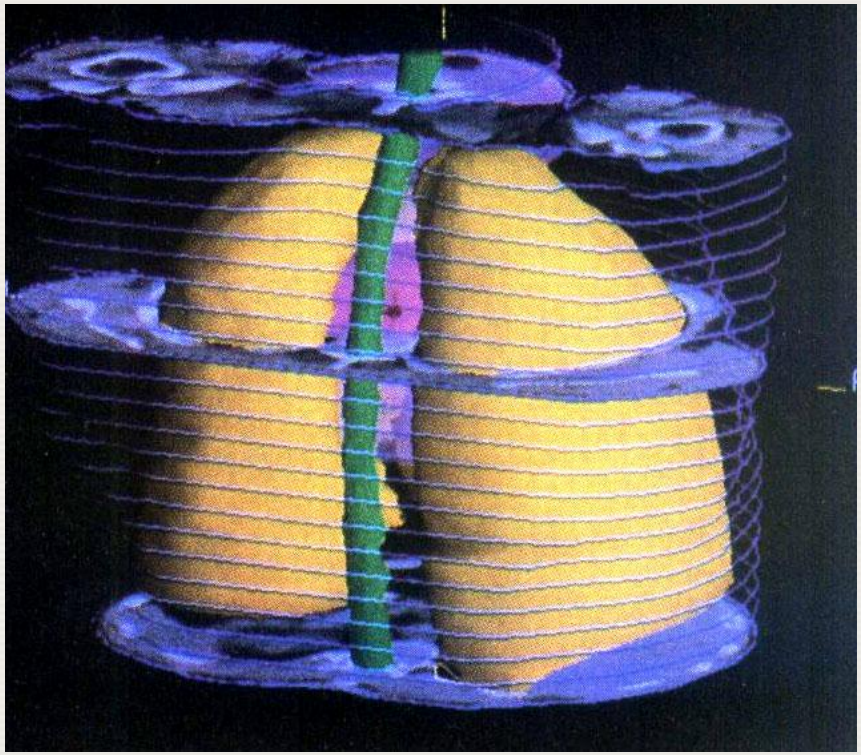
7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.1 Need for patient data

- Within the simulation process of the entire treatment using the computerized treatment planning system, the patient anatomy and tumor targets can be represented as three-dimensional models.

Example:

- CTV: mediastinum (violet)
- OAR:
  - Both lungs (yellow)
  - Spinal cord (green)



7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.1 Need for patient data

- Patient data acquisition to create the patient model is the initial part of this simulation process.

- The type of gathered data varies greatly depending on the type of treatment plan to be generated.

  Examples:

  - manual calculation of parallel-opposed beams

    ⇒ requires less effort

  - complex 3D treatment plan with image fusion

    ⇒ requires large effort

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.1 Need for patient data

General considerations on patient data acquisition:

- **Patient dimensions** are always required for treatment time or monitor unit calculations, whether read with a caliper, from CT slices or by other means.
- Type of dose evaluation also dictates the amount of patient data required (e.g., DVHs require more patient information than point dose calculation of organ dose).
- Landmarks such as bony or fiducial marks are required to match positions in the treatment plan with positions on the patient.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.2 Nature of patient data

- The patient information required for treatment planning varies from rudimentary to very complex data acquisition:

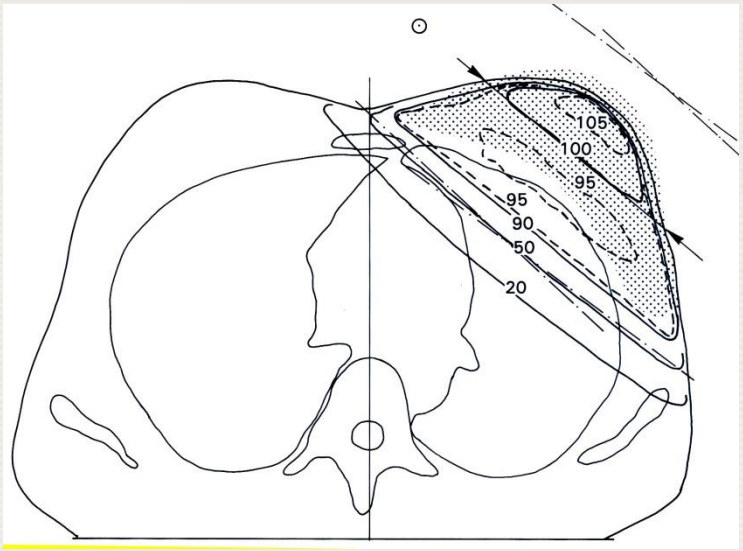
- Distances read on the skin.
- Manual determination of contours.
- Acquisition of CT information over a large volume.
- Image fusion using various imaging modalities.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

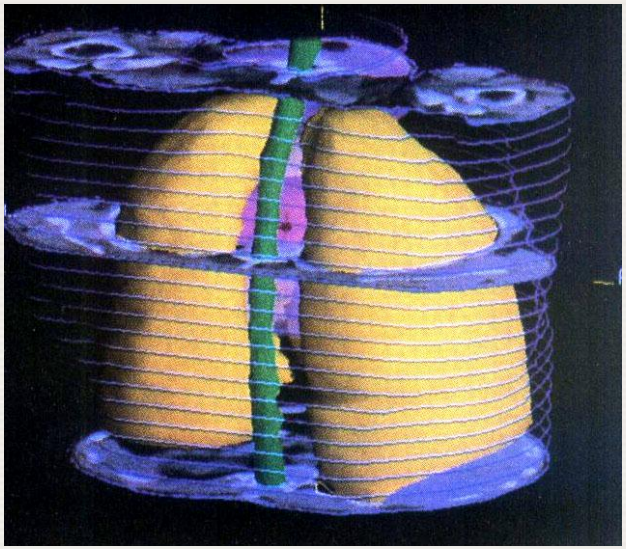
7.4.2 Nature of patient data

- The patient information required for treatment planning in particular depends on which system is used:

Two-dimensional system



Three-dimensional system



2D treatment planning

- A single patient contour, acquired using lead wire or plaster strips, is transcribed onto a sheet of graph paper, with reference points identified.
- Simulation radiographs are taken for comparison with port films during treatment.
- For irregular field calculations, points of interest can be identified on a simulation radiograph, and SSDs and depths of interest can be determined at simulation.
- Organs at risk can be identified and their depths determined on simulator radiographs.

3D treatment planning

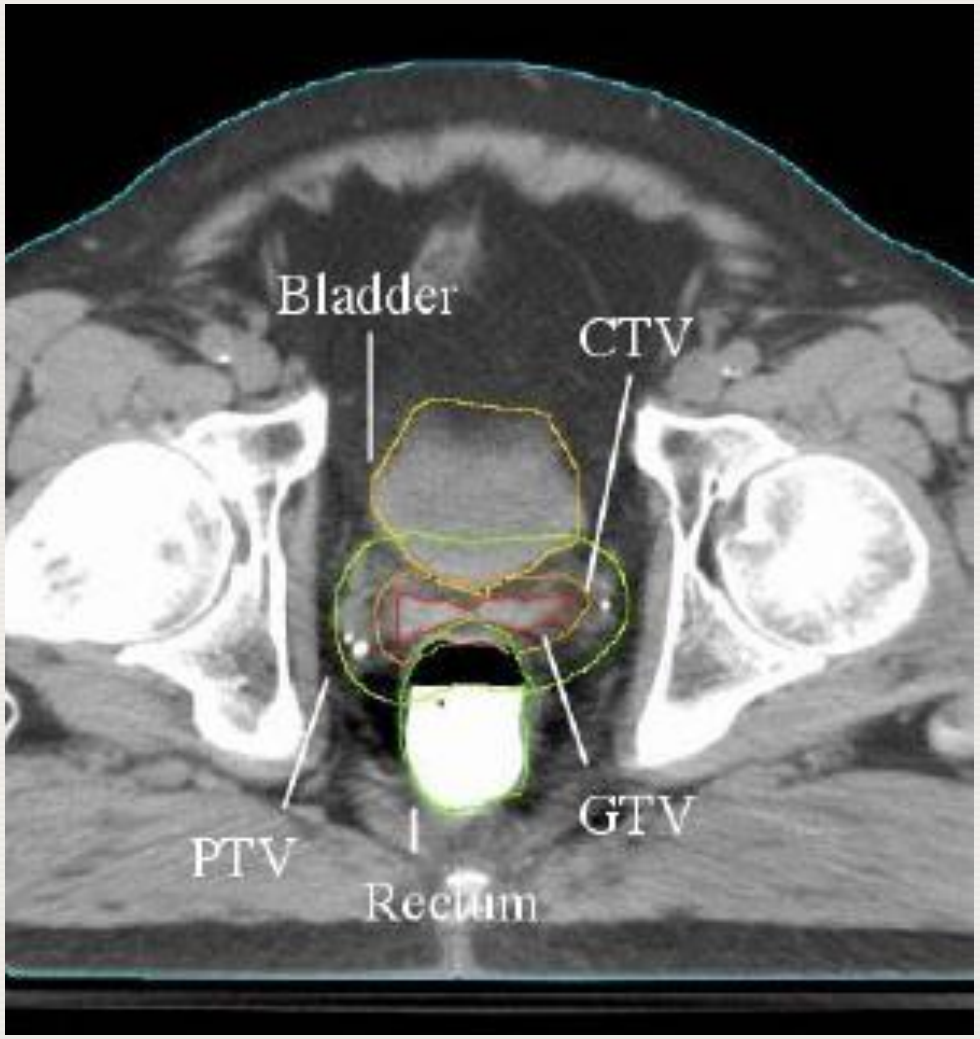
- CT dataset of the region to be treated is required with a **suitable slice spacing** (typically 0.5 - 1 cm for thorax, 0.5 cm for pelvis, 0.3 cm for head and neck).
- An external contour (representative of the skin or immobilization mask) must be drawn **on every CT slice** used for treatment planning.
- Tumor and target volumes are usually drawn on CT slices.
- Organs at risk and other structures should be drawn in their **entirety**, if dose-volume histograms are to be calculated.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.2 Nature of patient data

Contours for different volumes have been drawn on this CT slice for a prostate treatment plan:

- GTV
- CTV
- PTV
- Organs at risk (OAR) (bladder and rectum).

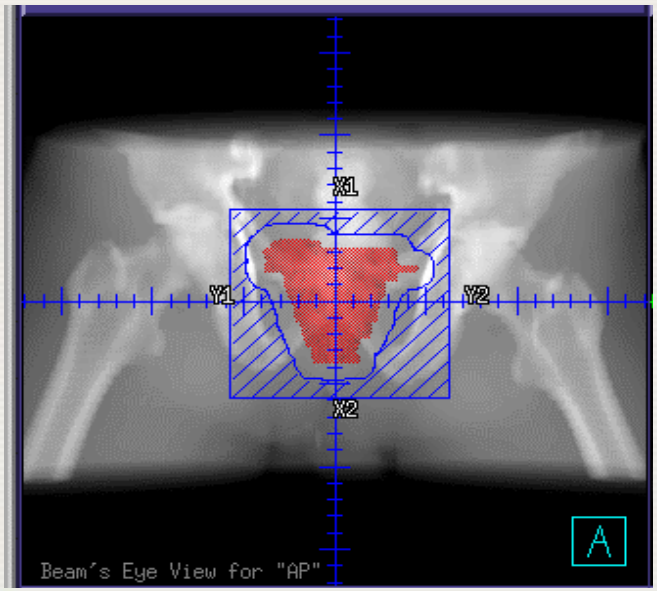


3D treatment planning (cont.)

- MRI or other studies (PET) are required for image fusion.
- With many treatment planning systems, the user can choose:
  - To **ignore inhomogeneities** (often referred to as heterogeneities).
  - To **perform bulk corrections** on outlined organs.
  - To **use the CT data itself** (with an appropriate conversion to electron density) for point-to-point correction.

3D treatment planning (cont.)

- CT images can be used to produce digitally reconstructed radiographs (DRRs)
- DRRs are used for comparison with portal films or beam's eye view to verify patient set up and beam arrangement

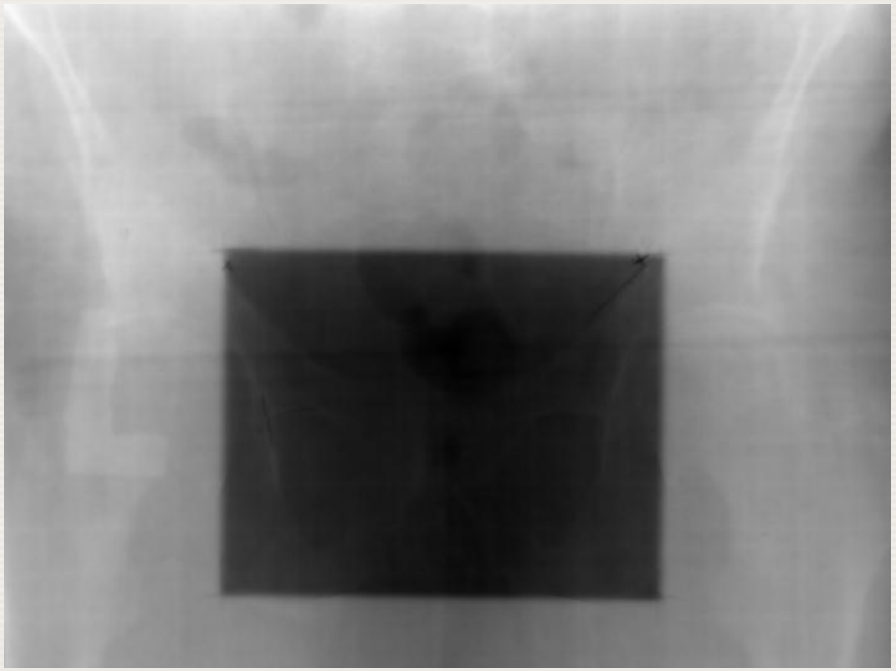


A digitally reconstructed radiograph with super-imposed beam's eye view for an irregular field

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.3 Treatment simulation

- Patient simulation was initially developed to ensure that the beams used for treatment were correctly chosen and properly aimed at the intended target.



Example: **The double exposure technique**

Film is irradiated with the treatment field first, then the collimators are opened to a wider setting and a second exposure is given to film.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.3 Treatment simulation

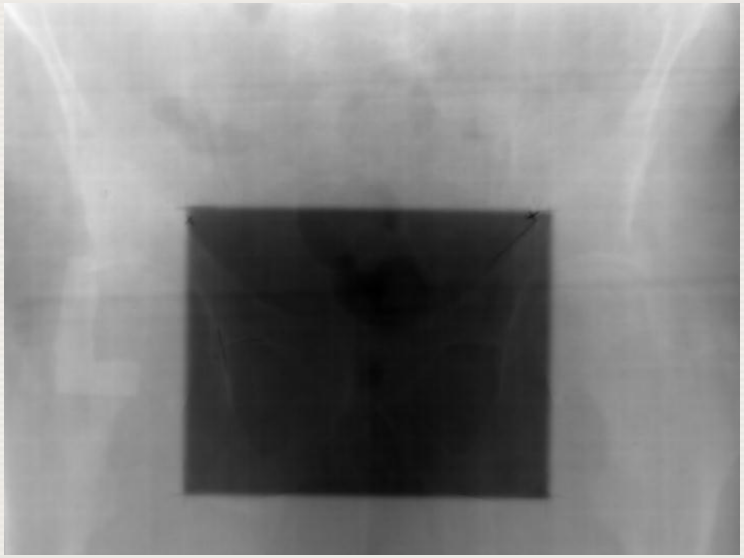
- Presently, treatment simulation has a more expanded role in the treatment of patients consisting of:
  - Determination of **patient treatment position**
  - Identification of the **target volumes** and **OARs**
  - Determination and verification of treatment **field geometry**
  - Generation of **simulation radiographs** for each treatment beam for comparison with treatment port films
  - **Acquisition of patient data** for treatment planning.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

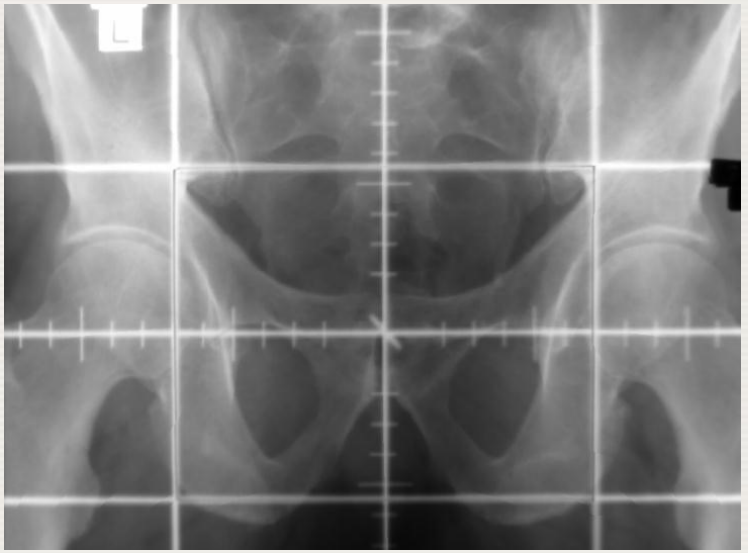
7.4.3 Treatment simulation

Comparison of simple simulation with portal image (MV) and conventional simulation with diagnostic radiography (kV) of the same anatomical site (prostate) demonstrates the higher quality of information on anatomical structures.

Check portal film (MV)



Reference simulator film (kV)



- It is neither efficient nor practical to perform simulations with portal imaging on treatment units.

  - There is always heavy demand for the use of treatment units for actual patient treatment.
  - Using them for simulation is therefore considered an inefficient use of resources.
  - These machines operate in the megavoltage range of energies and therefore do not provide adequate quality radiographs for a proper treatment simulation.

→ poor image quality!

- Reasons for the poor quality of port films:
  - Most photon interactions with biological material in the megavoltage energy range are Compton interactions that produce scattered photons that reduce contrast and blur the image.
  - The large size of the radiation source (either focal spot for a linear accelerator or the diameter of radioactive source in an isotope unit) increases the detrimental effects of beam penumbra on the image quality.
  - Patient motion during the relatively long exposures required and the limitations on radiographic technique also contribute to poor image quality.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.3 Treatment simulation

Therefore, **dedicated equipment** – fluoroscopic simulator - has been developed and was widely used for radiotherapy simulation.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.3 Treatment simulation

Modern simulation systems are based on computed tomography (CT) or magnetic resonance (MR) imagers and are referred to as CT-simulators or MR-simulators.

A dedicated radiotherapy CT simulator

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.4 Patient treatment position and immobilization devices

Patients may require an external immobilization device for their treatment, depending upon:

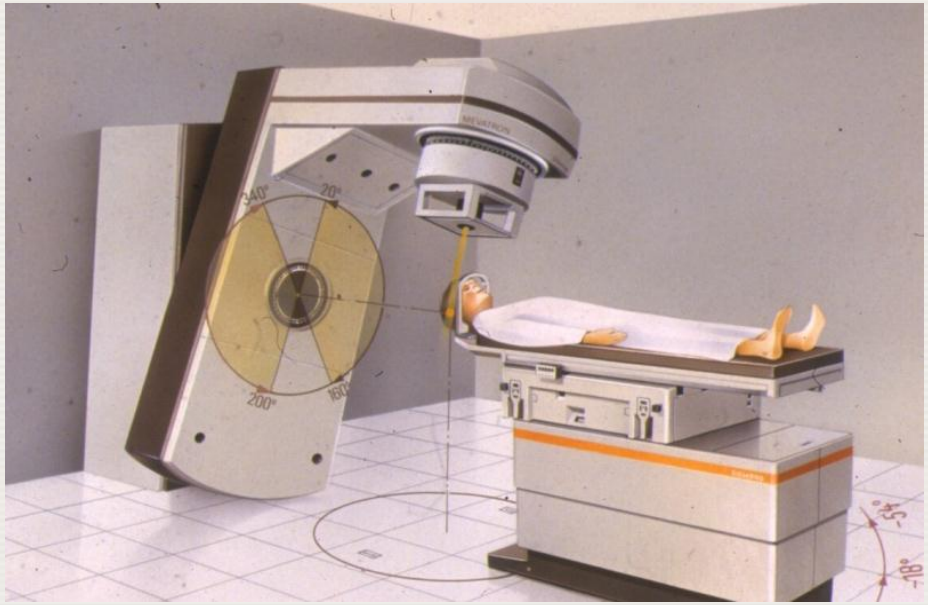
- Patient treatment position

or

- Precision required for beam delivery.

Example:

Precision required in radiosurgery



7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.4 Patient treatment position and immobilization devices

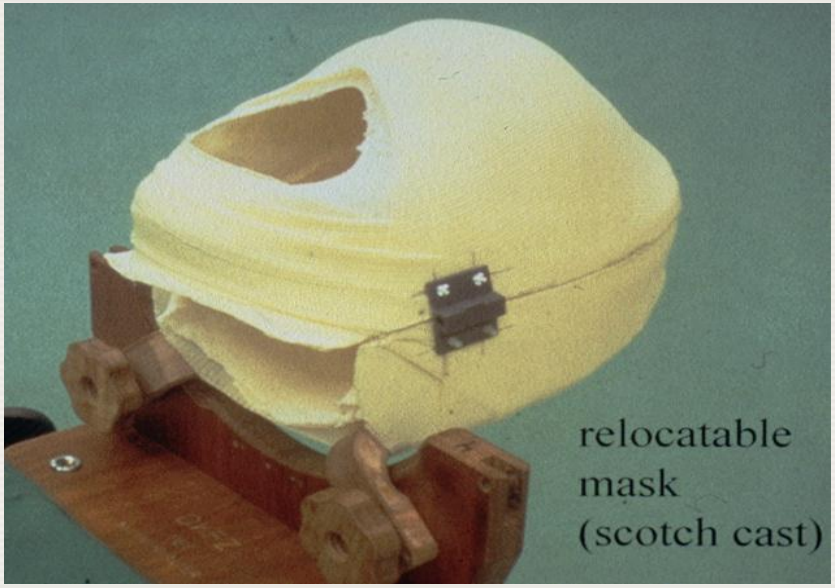
Immobilization devices have two fundamental roles:

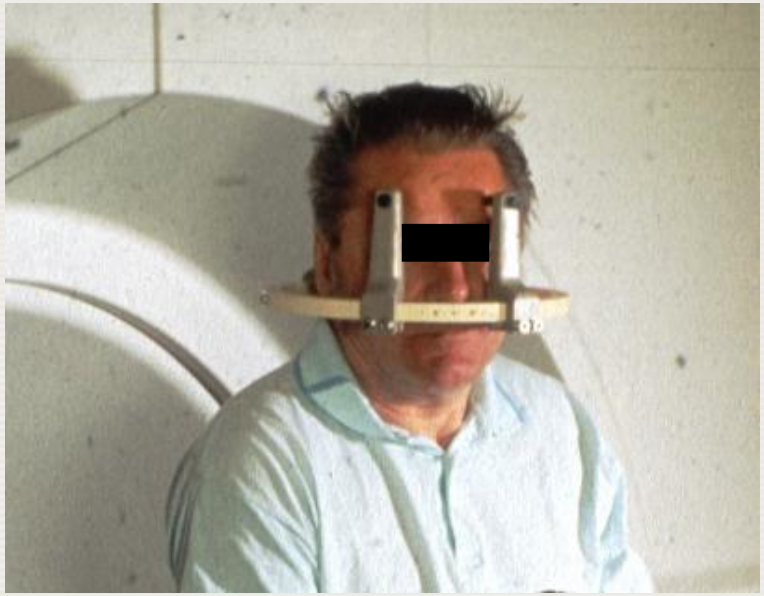
- To **immobilize** the patient during treatment;
- To provide a reliable means of **reproducing the patient position** from treatment planning and simulation to treatment, and from one treatment to another.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.4 Patient treatment position and immobilization devices

- The immobilization means include masking tape, velcro belts, or elastic bands, or even a sharp fixation system attached to the bone.





7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.4 Patient treatment position and immobilization devices

- The simplest immobilization device used in radiotherapy is the **head rest**, shaped to fit snugly under the patient's head and neck area, allowing the patient to lie comfortably on the treatment couch.

Headrests used for patient positioning and immobilization in external beam radiotherapy

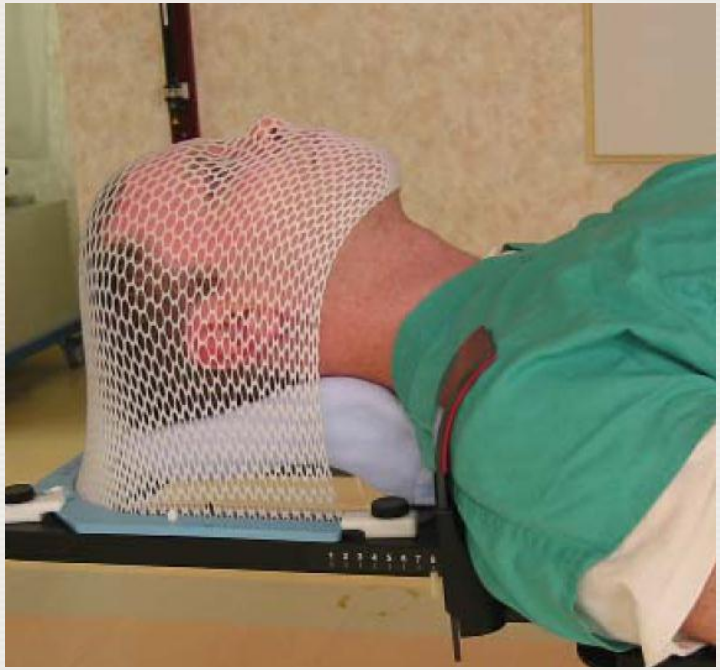
7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.4 Patient treatment position and immobilization devices

Other immobilization accessories:

- Patients to be treated in the head and neck or brain areas are usually immobilized with a plastic mask which, when heated, can be moulded to the patient's contour.

- The mask is affixed directly onto the treatment couch or to a plastic plate that lies under the patient thereby preventing movement.

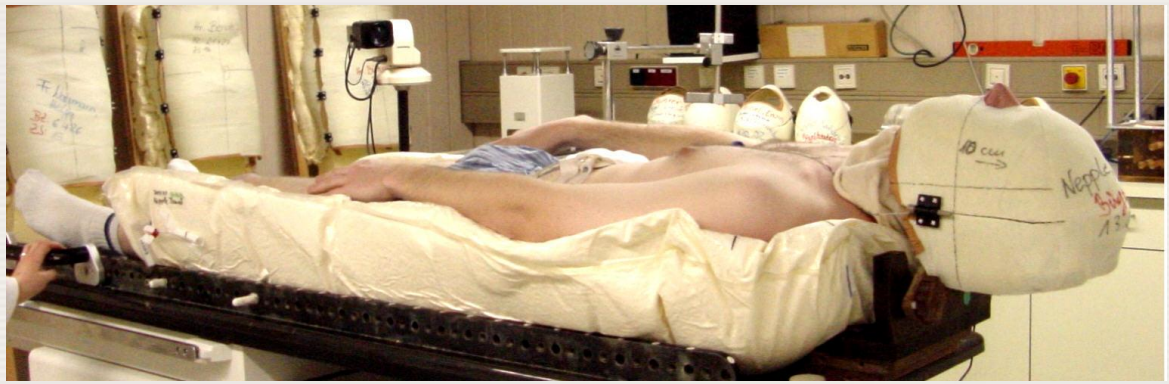


7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.4 Patient treatment position and immobilization devices

For **extra-cranial** treatments (such as to the thoracic or pelvic area), a variety of immobilization devices are available.

Vacuum-based devices are popular because of their re-usability.



A pillow filled with tiny styrofoam balls is placed around the treatment area, a vacuum pump evacuates the pillow leaving the patient's form as an imprint in the pillow.

Another system, similar in concept, uses a chemical reaction between two reagents to form a rigid mould of the patient.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

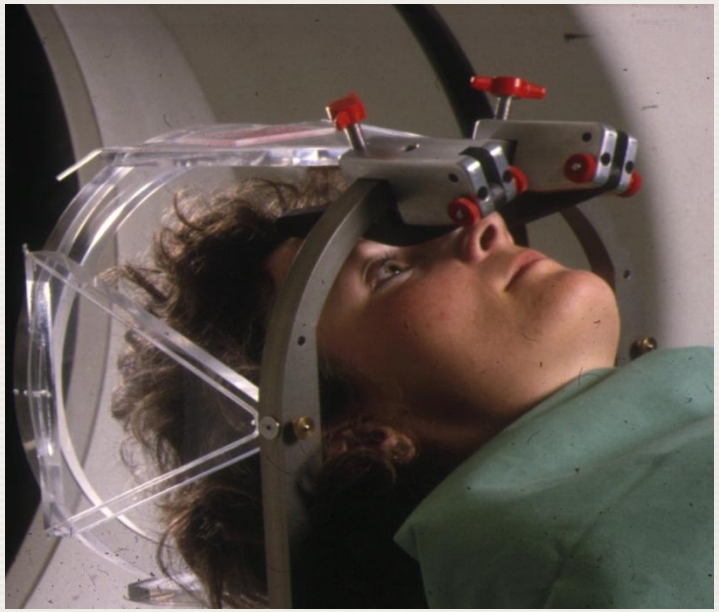
7.4.4 Patient treatment position and immobilization devices

Another system uses the mask method adopted to the body.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.4 Patient treatment position and immobilization devices

- Special techniques, such as **stereotactic radiosurgery**, require such high precision that conventional immobilization techniques are inadequate.
- In radiosurgery, a **stereotactic frame** is attached to the patient's skull by means of screws and is used for target localization, patient setup, and patient immobilization during the entire treatment procedure.



7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.5 Patient data requirements

- For simple hand calculations of the dose along the central axis of the beam and the beam-on time or linac monitor units, the source-surface distance along the central ray only is required.

  Examples:

  - Treatment with a direct field.
  - Parallel and opposed fields.

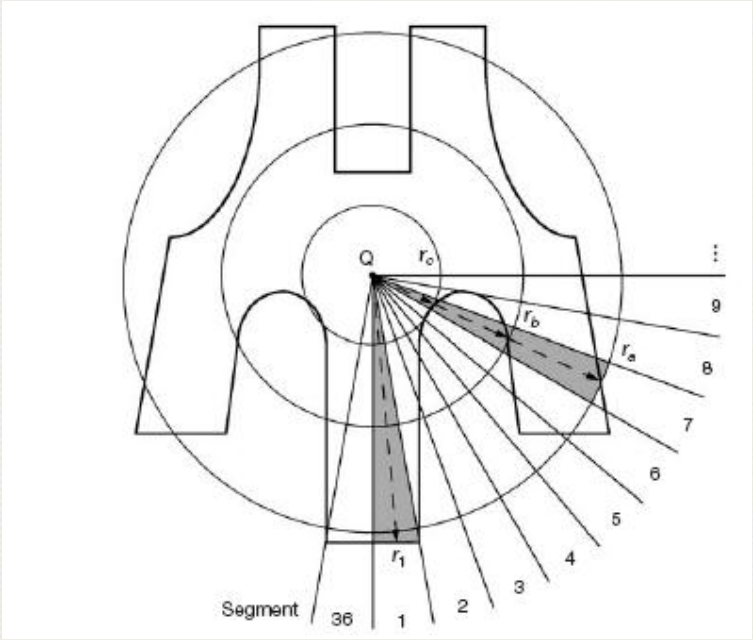
  Requirement: a flat beam incidence.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.5 Patient data requirements

- If simple algorithms, such as Clarkson integration, are used to determine the dosimetric effects of having blocks in the fields or to calculate the dose to off-axis points, their coordinates and source to surface distance must be measured.

The Clarkson integration method (for details see chapter 6)



7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.5 Patient data requirements

- For simple computerized **2D treatment planning**, the patient's shape is represented by a single transverse skin contour through the central axis of the beams.
- This contour may be acquired using lead wire or plaster cast at the time of simulation.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.5 Patient data requirements

- The patient data requirements for modern **3D treatment planning** systems are more elaborate than those for 2D treatment planning.
- The nature and complexity of data required limits the use of manual contour acquisition.
- **Transverse CT scans contain all information** required for complex treatment planning and form the basis of CT-simulation in modern radiotherapy treatment.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.5 Patient data requirements

The patient data requirements for 3D treatment planning include the following:

- The external shape of the patient must be outlined **for all areas** where the beams enter and exit (for contour corrections) and in the adjacent areas (to account for scattered radiation).
- **Targets and internal structures must be outlined** in order to determine their shape and volume for dose calculation.
- **Electron densities for each volume** element in the dose calculation matrix must be determined if a correction for heterogeneities is to be applied.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.6 Conventional treatment simulation

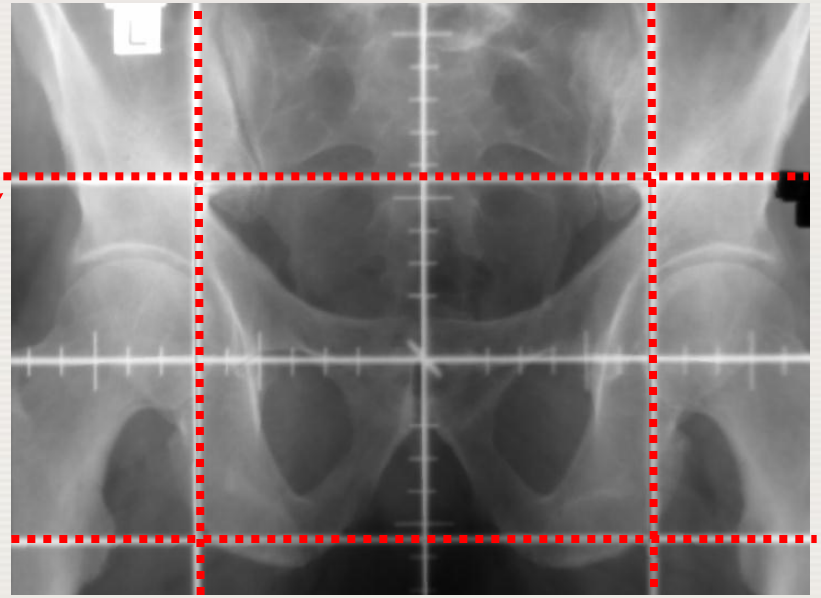
- A fluoroscopic simulator consists of a gantry and couch arrangement similar to that on a isocentric megavoltage treatment unit.
- The radiation source is a diagnostic quality x-ray tube rather than a high-energy linac or a cobalt source.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.6 Conventional treatment simulation

- Modern simulators provide the ability to mimic most treatment geometries attainable on megavoltage treatment units, and to visualize the resulting treatment fields on radiographs or under fluoroscopic examination of the patient.

Adjustable bars made of tungsten can mimic the planned field size superimposed to the anatomical structures.



7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.6 Conventional treatment simulation

- Photons produced by the x-ray tube are in the kilovoltage range and are preferentially attenuated by higher *Z* materials such as bone through photoelectric interactions.
- The result is a high quality diagnostic radiograph with limited soft tissue contrast, but with excellent visualization of bony landmarks and high *Z* contrast agents.
- A fluoroscopic imaging system may also be included and would be used from a remote console to view patient anatomy and to modify beam placement in **real time**.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.6 Conventional treatment simulation

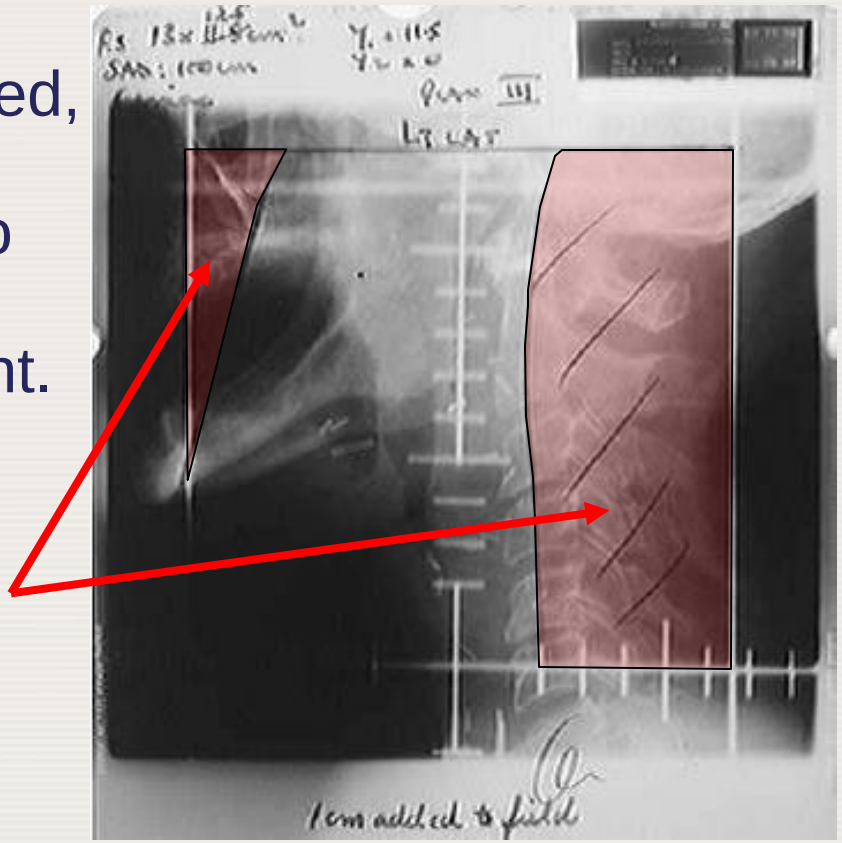
- For the vast majority of sites, the disease is not visible on the simulator radiographs
- Therefore the block positions can be determined only with respect to anatomical landmarks visible on the radiographs (usually bony structures or lead wire clinically placed on the surface of the patient).

Determination of treatment beam geometry

- Typically, the patient is placed on the simulator couch, and the final treatment position of the patient is verified using the fluoroscopic capabilities of the simulator (e.g., patient is straight on the table, etc.).
- The position of the treatment isocenter, beam geometry (i.e., gantry, couch angles, etc.) and field limits are determined with respect to the anatomical landmarks visible under fluoroscopic conditions.

Determination of treatment beam geometry

- Once the final treatment geometry has been established, radiographs are taken as a matter of record, and are also used to determine shielding requirements for the treatment.
- Shielding can be drawn directly on the films, which may then be used as the blueprint for the construction of the blocks.



Acquisition of patient data

- After the proper determination of beam geometry, **patient contours** may be taken at any plane of interest to be used for treatment planning.
- Although more sophisticated devices exist, the simplest and most widely available method for obtaining a patient contour is through the use of lead wire.

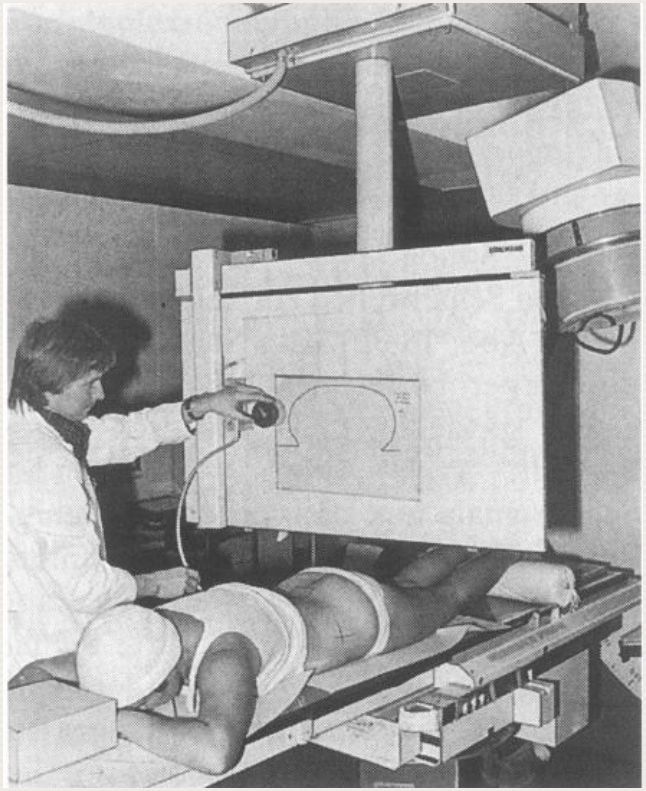
Acquisition of patient data (cont.)

The lead wire method:

- The wire is placed on a transverse plane parallel to the isocenter plane.
- Next, the wire is shaped to the patient's contour.
- The shape of the wire is then transferred to a sheet of graph paper.

Acquisition of patient data (cont.)

- Use of a special drawing instrument.



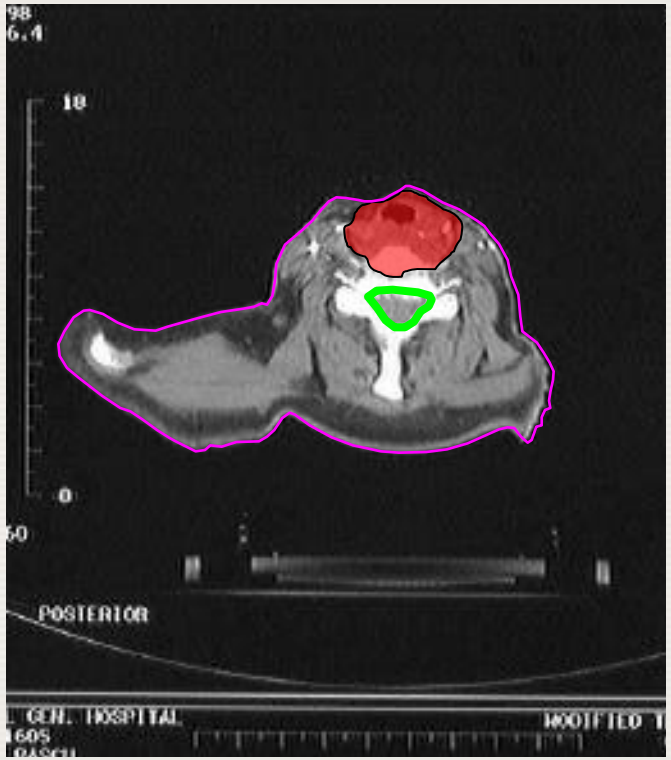
Data acquisition with Computed Tomography

- With the growing popularity of computed tomography (CT) in the 1990s, the use of CT scanners in radiotherapy became widespread.
- Anatomical information on CT scans is presented in the form of transverse slices, which contain anatomical images of very high resolution and contrast.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.7 Computed tomography-based conventional simulation

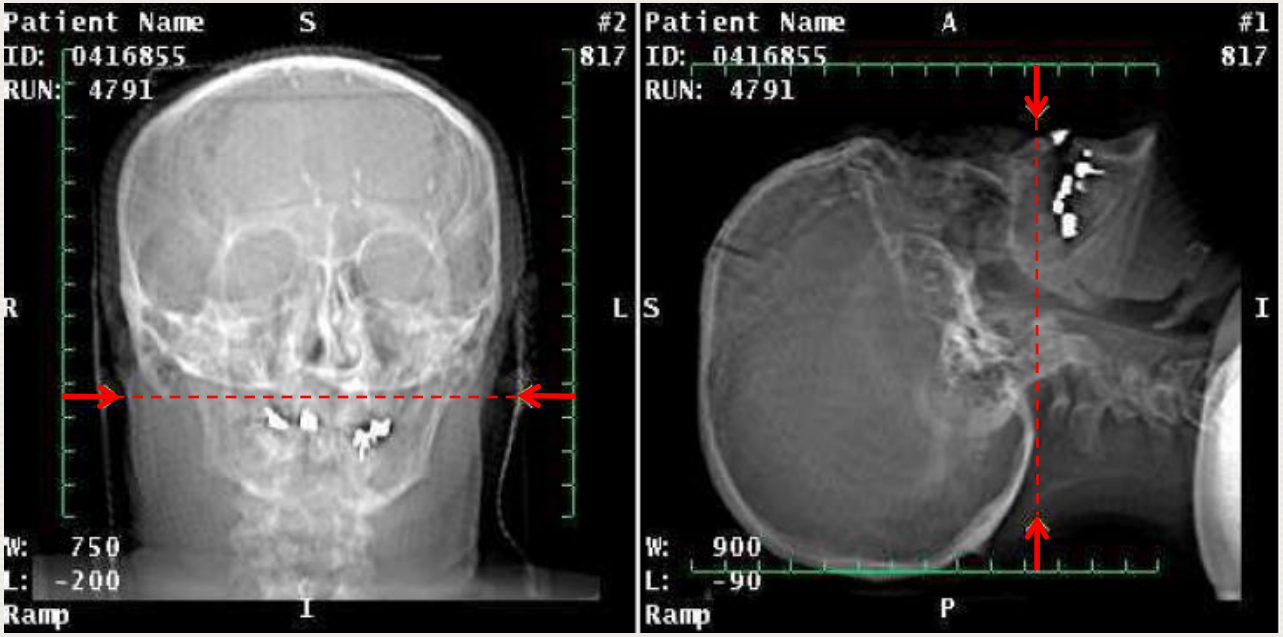
- CT images provide excellent soft tissue contrast allowing for greatly improved tumor localization and definition in comparison to conventional simulation.
- Patient contours can be obtained easily from the CT data:
  - Patient's skin contour
  - Target
  - Any organs of interest



7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.7 Computed tomography-based conventional simulation

- The position of each slice and therefore the target can be related to bony anatomical landmarks through the use of **scout or pilot images** obtained at the time of scanning.



Scout films

- Pilot or scout films are obtained by keeping the x-ray source in a fixed position and moving the patient (translational motion) through the stationary slit beam.
- The result is a **high definition radiograph** which is divergent on the transverse axis, but non-divergent on the longitudinal axis.

Scout films

- The target position can also be determined through **comparison between the CT scout and pilot films**.
- *Note*: A different magnification between simulator film and scout film must be taken into account.
- This procedure allows for a more accurate determination of tumor extent and therefore more precise field definition at the time of simulation.

Scout films

- If scanned in treatment position, **field limits and shielding parameters** can be directly set with respect to the target position, similar to conventional treatment simulation.
- The result is that the treatment port more closely conforms to the target volume, reducing treatment margins around the target and increasing healthy tissue sparing.

Virtual Simulation

- Virtual simulation is the treatment simulation of patients based **solely on CT information**.
- The premise of virtual simulation is that the CT data can be manipulated to render **synthetic** radiographs of the patient for arbitrary geometries.

CT-Simulator

- Dedicated CT scanners for use in radiotherapy treatment simulation and planning have been developed.
- They are known as CT-simulators.

Example of a modern CT-simulator

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.8 Computed tomography-based virtual simulation

components of a CT-simulator include:

- CT scanner, including scanners with a large bore (with an opening of up to 85 cm to allow for a larger variety of patient positions and the placement of treatment accessories during CT scanning);
- Movable lasers for patient positioning and marking;
- Flat table top to more closely match radiotherapy treatment positions;
- Powerful graphics workstation, allowing for image manipulation and formation.

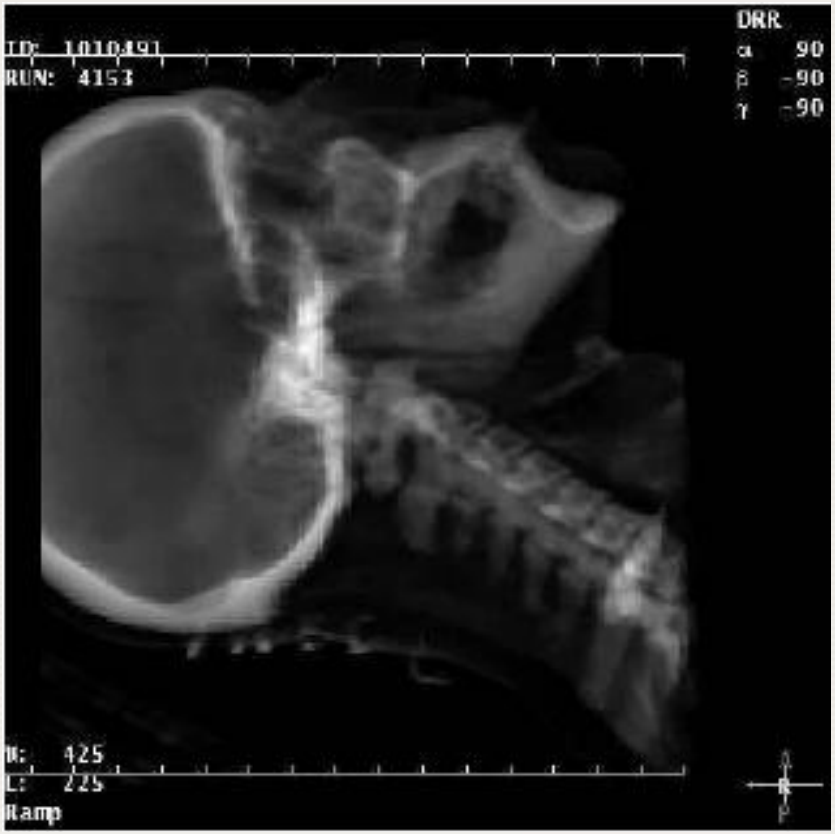
Virtual Simulation

- **Synthetic** radiographs can be produced by tracing ray-lines from a virtual source position through the CT data of the patient to a **virtual film plane** and simulating the attenuation of x-rays.
- Synthetic radiographs are called **Digitally Reconstructed Radiographs** (DRRs).
- Advantage of DRRs is that anatomical information may be used directly in the determination of treatment field parameters.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.8 Computed tomography-based virtual simulation

***Example* of a DRR**



Note: gray levels, brightness, and contrast can be **adjusted** to provide an optimal image.

Beam's eye view (BEV)

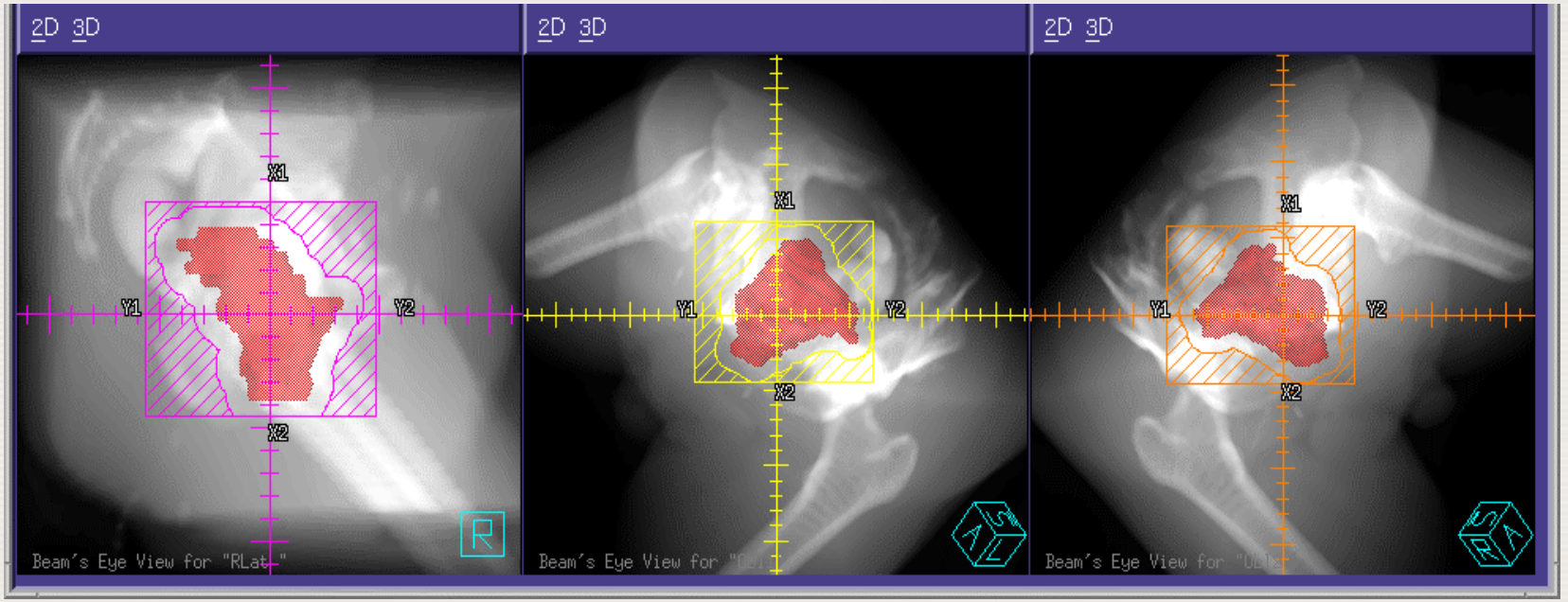
Beam's eye views (BEV) are **projections** through the patient onto a **virtual film plane perpendicular** to the beam direction.

Projections include:

- Treatment beam axes
- Field limits
- Outlined structures

Beam's eye view (BEV)

- BEVs are frequently superimposed onto the corresponding DRRs resulting in a synthetic representation of a simulation radiograph.



Multiplanar reconstructions (MPR)

- Multiplanar reconstructions (MPR) are images formed from reformatted CT data.
- They are effectively CT images through **arbitrary planes** of the patient.
- Although typically sagittal or coronal MPR cuts are used for planning and simulation, MPR images **through any arbitrary plane** may be obtained.

Conventional simulator

Advantage

- Useful to perform a fluoroscopic simulation in order to verify isocenter position and field limits as well as to mark the patient for treatment.

Disadvantages

- Limited soft tissue contrast.
- Tumour mostly not visible.
- Requires knowledge of tumor position with respect to visible landmarks.
- Restricted to setting field limits with respect to bony landmarks or anatomical structures visible with the aid of contrast.

CT simulator

Advantages	Disadvantages
❑ Increased soft tissue contrast. ❑ Axial anatomical information available. ❑ Delineation of target and OARs directly on CT slices. ❑ Allows DRRs. ❑ Allows BEV.	❑ Limitation in use for some treatment setups where patient motion effects are involved. ❑ Require additional training and qualification in 3D planning.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.9 Conventional simulator vs. CT simulator

- Another important advantage of the CT-simulation process over the conventional simulation process is the fact that the patient is not required to **stay after the scanning has taken place**.
- Patient only stays the minimum time necessary to acquire the CT data set and mark the position of reference isocentre; this provides the obvious advantage as the radiotherapy staff may take their time in planning the patient as well as try different beam configurations without the patient having to wait on the simulator couch.

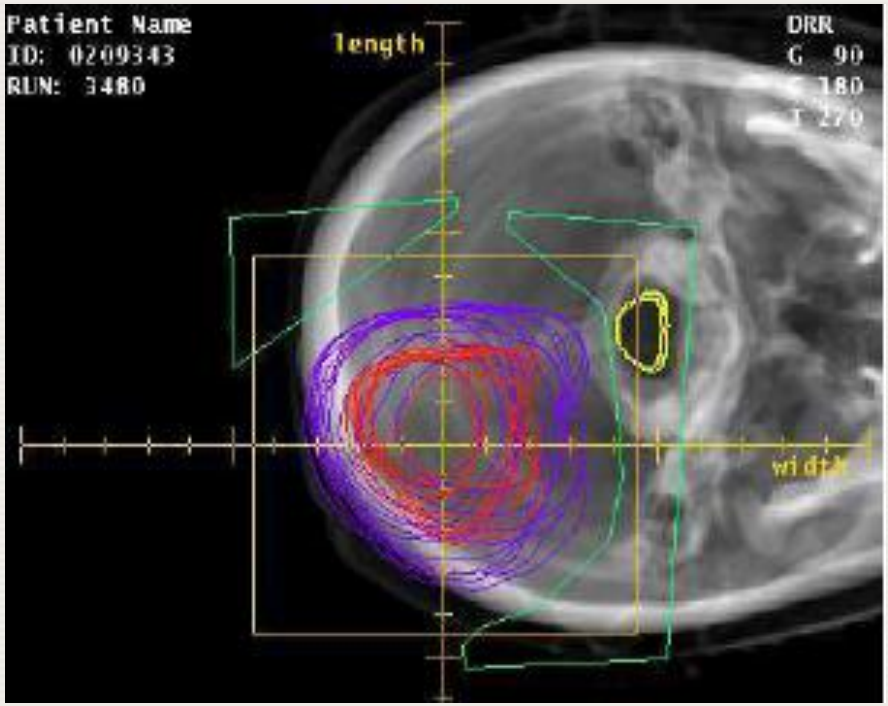
7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.9 Conventional simulator vs. CT simulator

- Another important advantage : CT-simulator allows the user to generate DRRs and BEVs even for beam geometries which were previously impossible to simulate conventionally.
- *Example*:

  A DRR with superimposed beam's eye view for a **vertex field** of a brain patient.

  This treatment geometry would be impossible to simulate on a conventional simulator because the film plane is in the patient.



7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.10 Magnetic resonance imaging for treatment planning

- MR imaging plays an increasing role in treatment planning.
- **Soft tissue contrast** offered by magnetic resonance imaging (MRI) in some areas, such as the brain, is **superior to that of CT**, allowing small lesions to be seen with greater ease.

Disadvantage of MRI

It cannot be used for radiotherapy simulation and planning for several reasons:

- The physical dimensions of the MRI and its accessories limit the use of immobilization devices and compromise treatment positions.
- Bone signal is absent and therefore digitally reconstructed radiographs cannot be generated for comparison to portal films.
- There is no electron density information available for heterogeneity corrections on the dose calculations.
- MRI is prone to geometrical artifacts and distortions that may affect the accuracy of the treatment.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

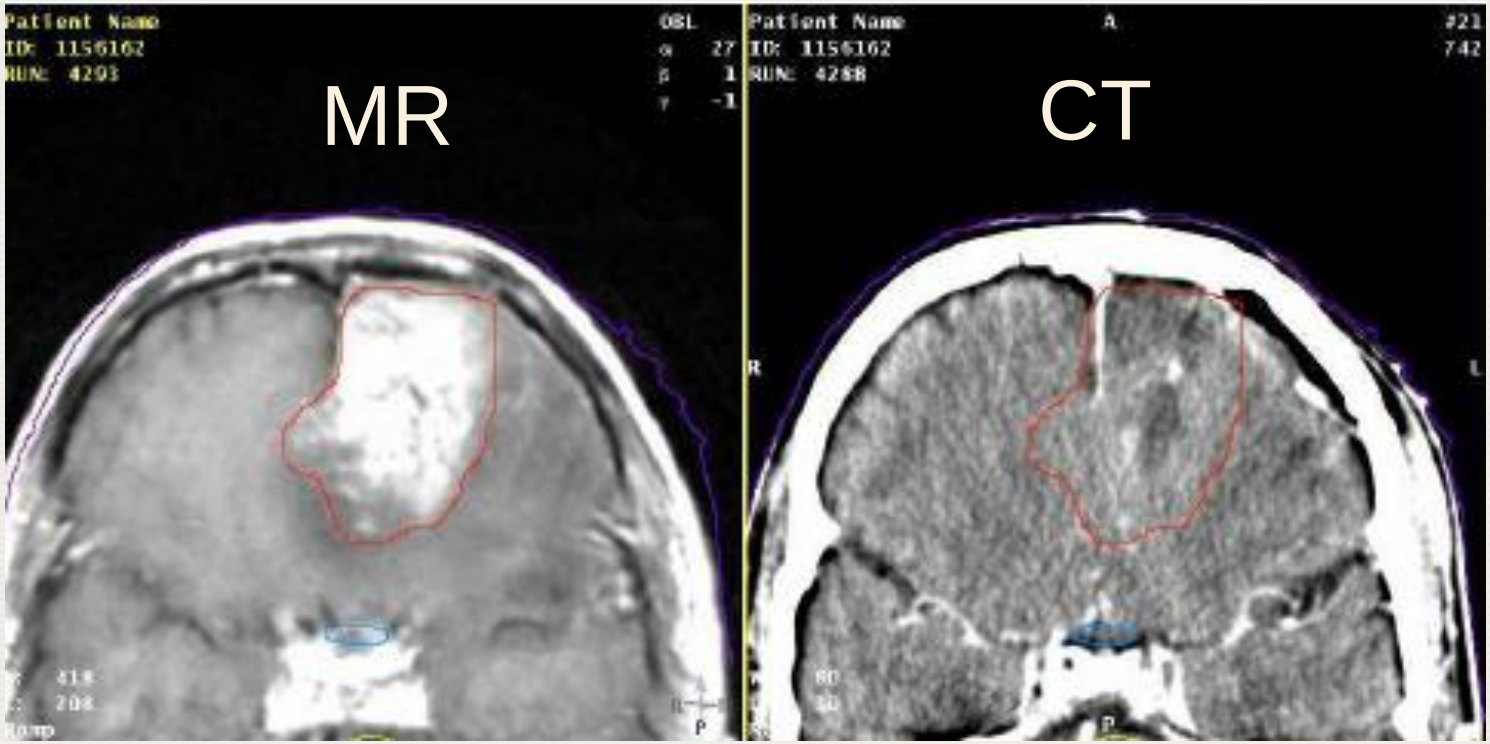
7.4.10 Magnetic resonance imaging for treatment planning

- To overcome this problem, many modern virtual simulation and treatment planning systems have the ability to **combine** the information from different imaging studies using the process of **image fusion** or **registration**.
- CT-MR image registration or fusion combines the
  - **Accurate volume definition** from MR

    with
  - **Electron density information** available from CT.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.10 Magnetic resonance imaging for treatment planning



On the left is an MR image of a patient with a brain tumour. The target has been outlined and the result was superimposed on the patient's CT scan. Note that the particular target is clearly seen on the MR image but only portions of it are observed on the CT scan.

Goals and tools in conventional and CT simulation

Goals	Conventional	CT simulation
Treatment position:	fluoroscopy	pilot/scout views
Identification of target volume:	bony landmarks	from CT data
Determination of beam geometry:	fluoroscopy	BEV/DRR
Shielding design:	bony landmarks	conformal to target
Contour acquisition:	manual	from CT data

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.11 Summary of simulation procedures

The following six steps are typically involved in **conventional** simulation procedures:

1. Determination of patient **treatment position** with fluoroscopy.
2. Determination of **beam geometry.**
3. Determination **field limits and isocentre.**
4. Acquisition of **contour.**
5. Acquisition of **beam's eye view** and **set-up radiographs.**
6. **Marking** of patient.

7.4 PATIENT DATA ACQUISITION AND SIMULATION

7.4.11 Summary of simulation procedures

The following nine steps are typically involved in **CT simulation:**

1. Determination of patient treatment position with pilot/scout films.
2. Determination and marking of reference isocentre.
3. Acquisition of CT data and transfer to virtual simulation workstation.
4. Localization and contouring of targets and critical structures.
5. Determination treatment isocentre with respect to target and reference isocentre.
6. Determination of beam geometry.
7. Determination of field limits and shielding.
8. Transfer of CT and beam data to treatment planning system.
9. Acquisition of beam's eye view and setup DRRs.

7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

Clinical considerations for photon beams include the following items:

- Isodose curves
- Wedge filters
- Bolus
- Compensating filters
- Corrections for contour irregularities
- Corrections for tissue inhomogeneities
- Beam combinations and clinical application

7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.1 Isodose curves

- Isodose curves are defined as lines that join points of equal dose.
- They offer a **planar representation** of the dose distribution.
- Isodose curves are useful to characterize the behavior of
  - One beam
  - Combination of beams
  - Beams with different shielding
  - Wedges
  - Bolus, etc.

How are isodose curves obtained?

- They are measured directly using a beam scanning device in a water phantom.
- They are calculated from percentage depth dose and beam profile data.
- They are adopted from an atlas for isodose curves.

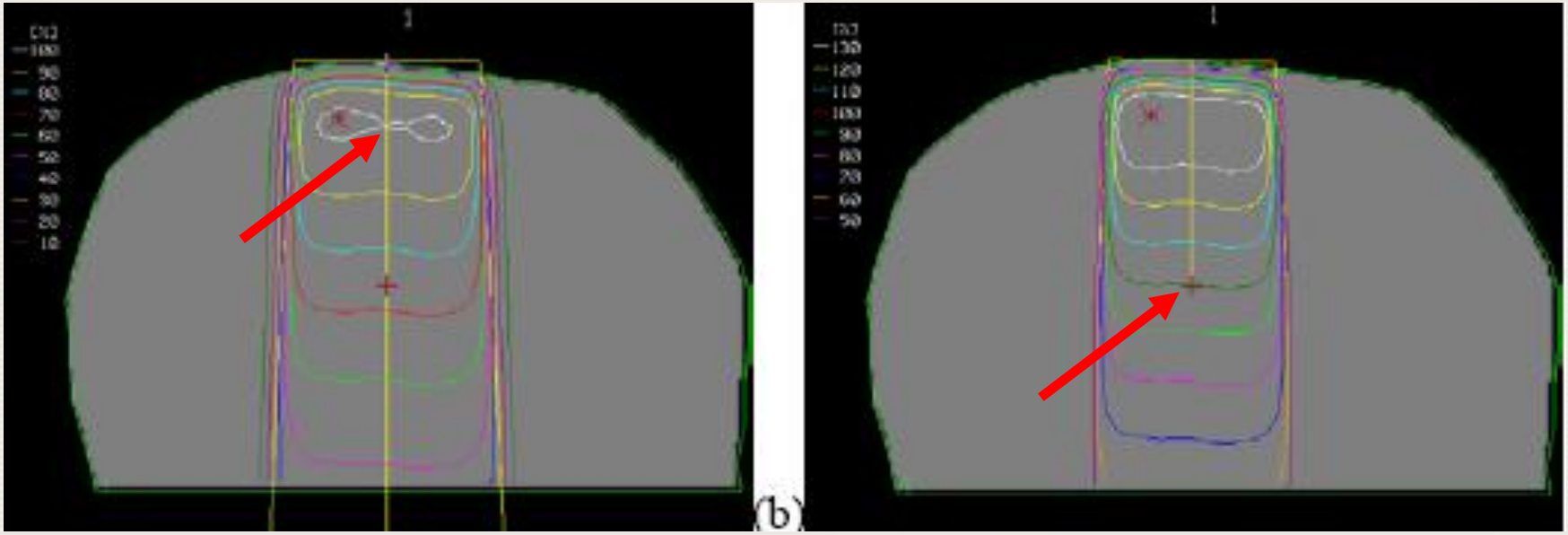
To which dose values do isodose curves refer?

- While isodose curves can be made to display the actual dose in Gy (per fraction or total dose), it is more common to present them normalized to 100 % at a fixed point.
- Possible point normalizations are:
  - Normalization to 100 % at the depth of **dose maximum** on the central axis.
  - Normalization at the **isocenter**.
  - Normalization at the **point of dose prescription**.

7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.1 Isodose curves

Different normalizations for a single 18 MV photon beam incident on a patient contour



Isodose curves for a fixed SSD beam normalized at depth of **dose maximum**

Isodose curves for an isocentric beam normalized at the **isocenter**

7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.2 Wedge filters

Three types of wedge filters are currently in use:

1. Physical (requiring manual intervention)
2. Motorized
3. Dynamic

- **Physical wedge:**
  It is an angled piece of lead or steel that is placed in the beam to produce a gradient in radiation intensity.
- **Motorized wedge:**
  It is a similar physical device, integrated into the head of the unit and controlled remotely.

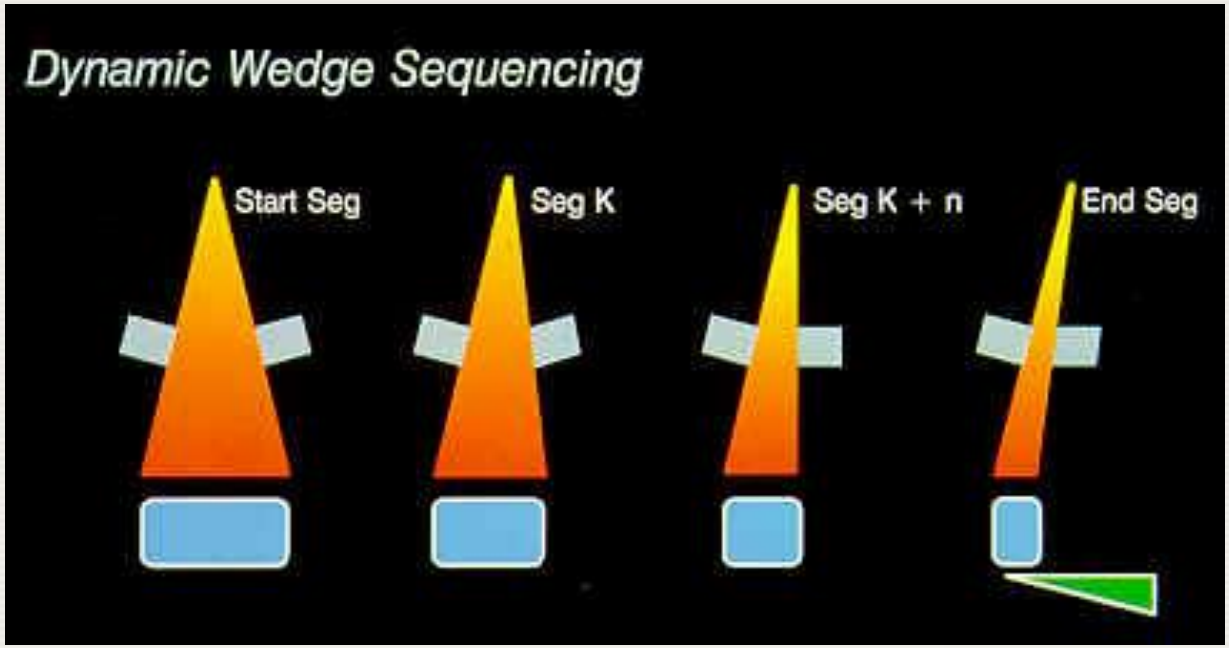
7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.2 Wedge filters

- **Physical wedge:**
  A set of wedges (15°, 30°, 45°, and 60°) is usually provided with the treatment machine.

Dynamic wedge:

Produces the same wedged intensity gradient by having one jaw close gradually while the beam is on.

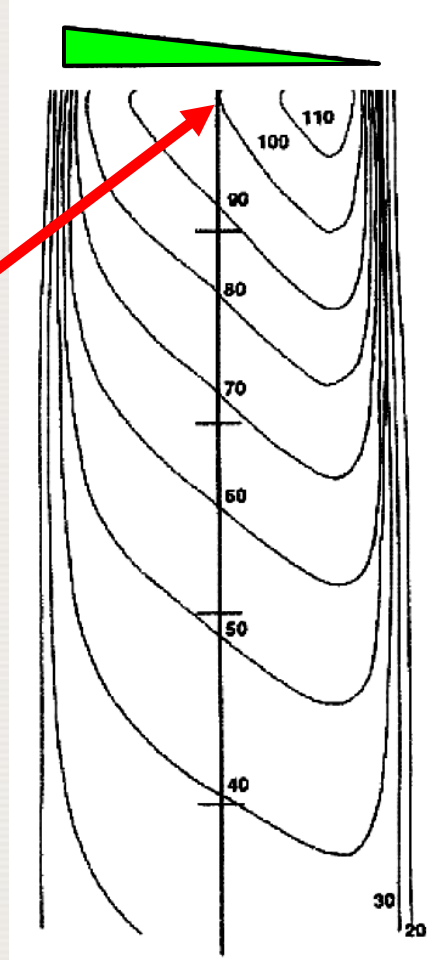


7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.2 Wedge filters

Isodose curves obtained for a wedged 6 MV photon beam.

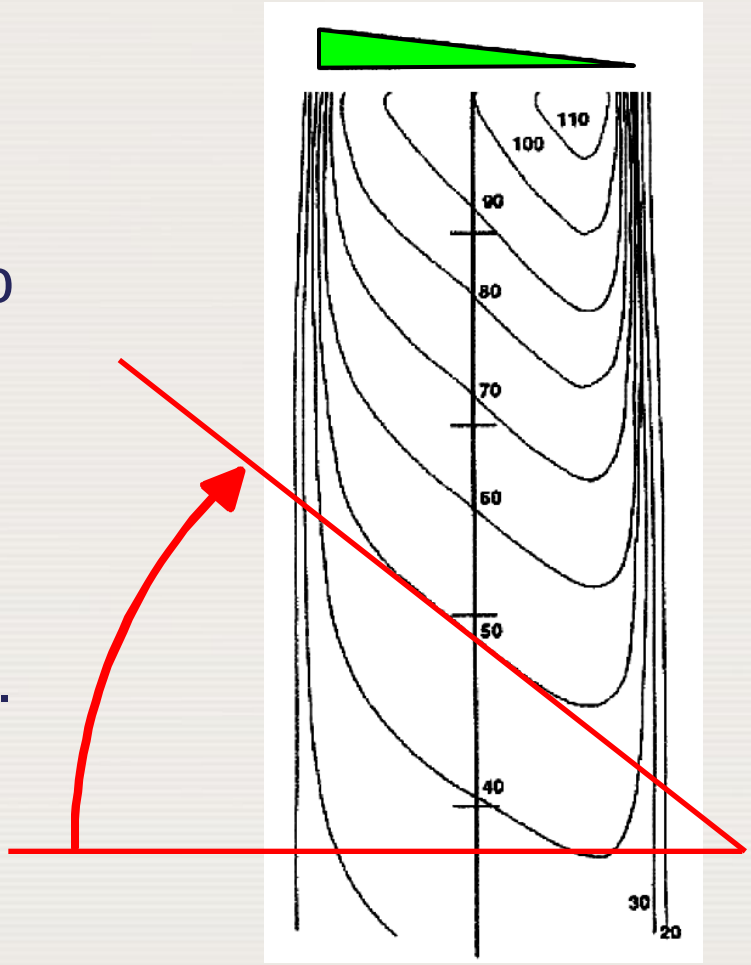
Isodose curves have been normalized to z_{max} with the wedge in place.



7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.2 Wedge filters

- Wedge angle is defined as the angle between the 50 % isodose line and the perpendicular to the beam central axis.
- Wedge angles in the range from 10° to 60° are commonly available.

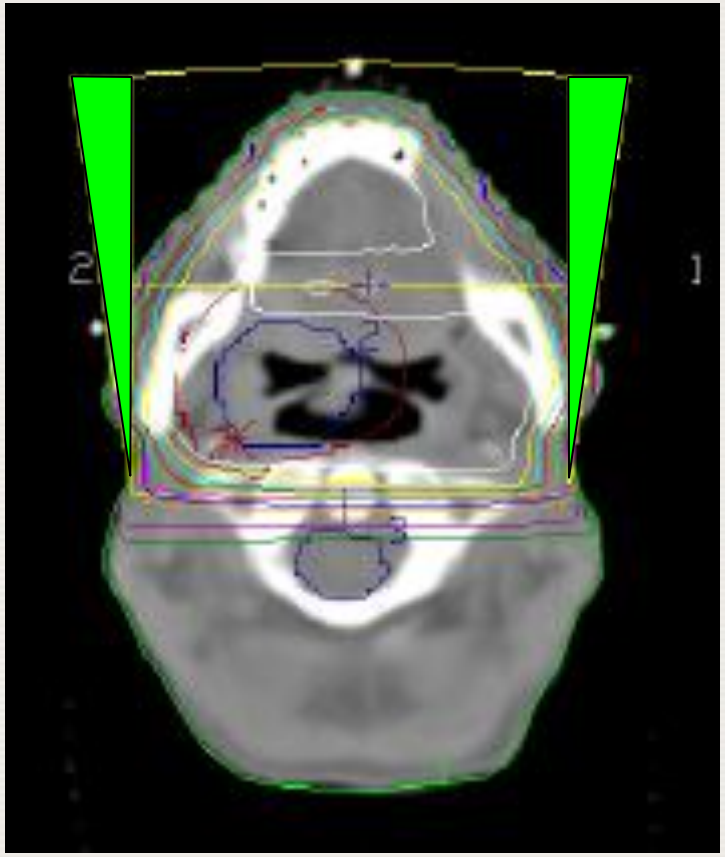


7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.2 Wedge filters

There are two main uses of wedges

1. Wedges can be used to **compensate for a sloping surface.**



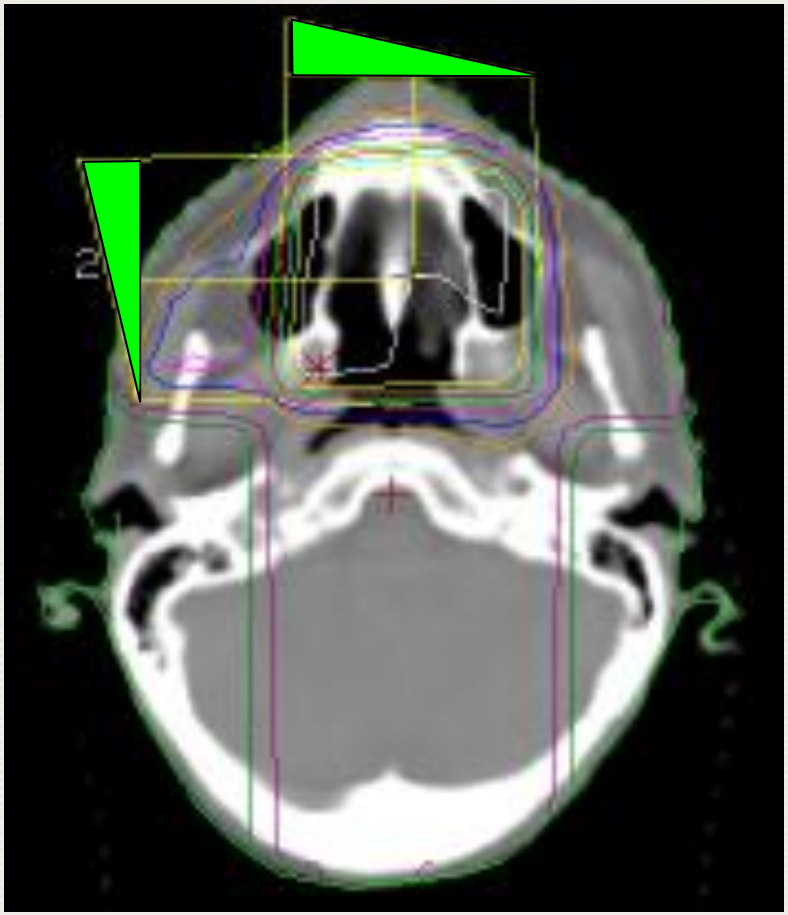
***Example* 1:**

Two 15° wedges are used in a nasopharyngeal treatments to compensate for the decreased thickness anteriorly.

7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.2 Wedge filters

2. Wedges can be used to compensate for a sloping surface.



***Example 2*:**

A wedged pair of beams is used to compensate for the hot spot that would be produced with a pair of open beams at 90° to each other.

There are two main uses of wedges (cont.)

3. Wedges can also be used in the treatment of relatively low lying lesions where two beams are placed at an angle (less than 180°) called the **hinge angle**.

   The optimal wedge angle (assuming a flat patient surface) may be estimated from:

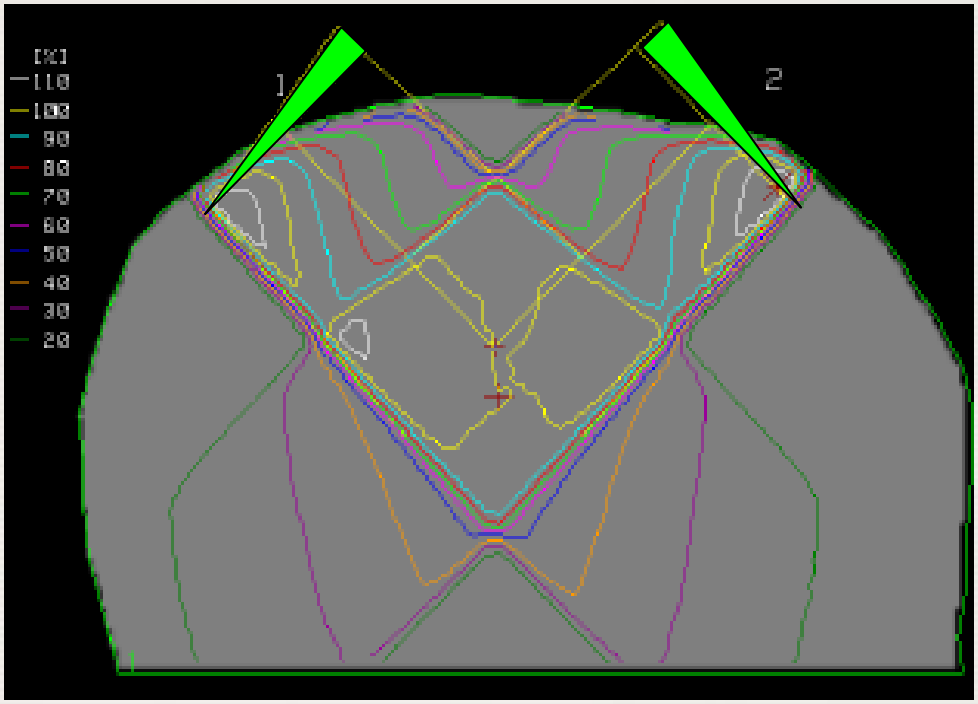
$$\text{wedge angle} = 90° - \text{hinge angle}$$

7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.2 Wedge filters

Example:

- A wedge pair of 6 MV beams incident on a patient.
- The hinge angle is 90° (orthogonal beams) for which the optimal wedge angle would be 45°.
- However, in this case the additional obliquity of the surface requires the use of a higher wedge angle of 60°.



Wedge factor:

- Wedge factor is defined as the ratio of dose at a specified depth (usually z_{max}) on the central axis **with the wedge** in the beam to the dose under the same conditions **without the wedge**.
- This factor is used in monitor unit calculations to compensate for the reduction in beam transmission produced by the wedge.
- Wedge factor depends on depth and field size.

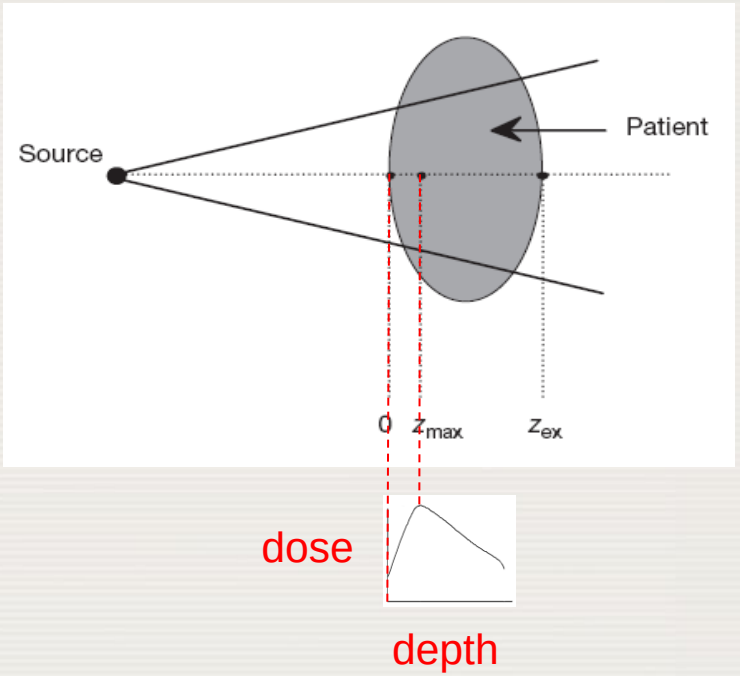
7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.3 Bolus

Bolus is a tissue-equivalent material placed in contact with the skin to achieve one or both of the following:

1. Increase of surface dose

Because of the dose buildup in megavoltage beams between the **surface** and **the dose maximum** (at a certain depth z_{max}), the dose may not be sufficient for superficial targets.



7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

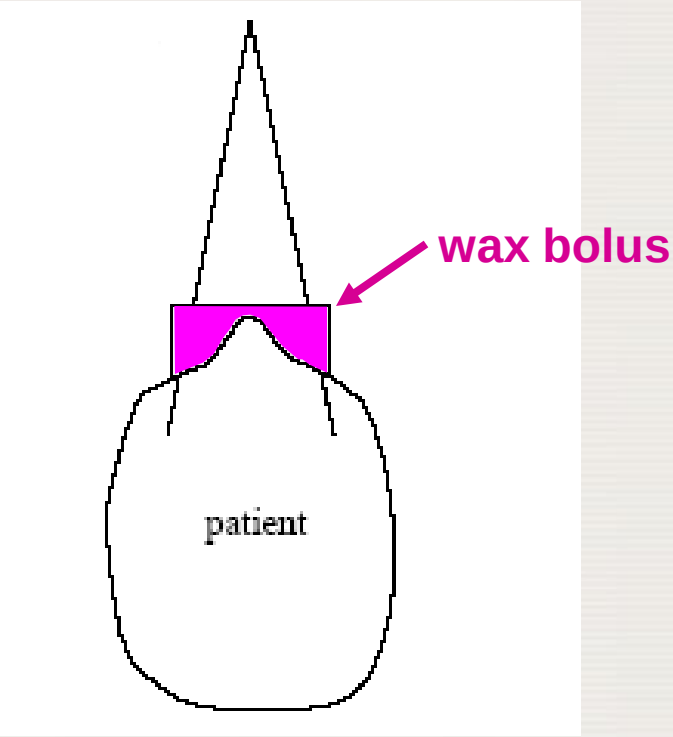
7.5.3 Bolus

- **To increase the surface dose**, a layer of uniform thickness bolus is often used (0.5 cm – 1.5 cm), since it does not significantly change the shape of the isodose curves at depth.
- Several flab-like materials were developed commercially for this purpose.
- Cellophane wrapped wet towels or gauze offer a low cost substitute.

Bolus is also used to achieve:

2. Compensation for missing tissue

Custom made bolus can be built such that it conforms to the patient skin on one side and yields a flat perpendicular incidence to the beam.



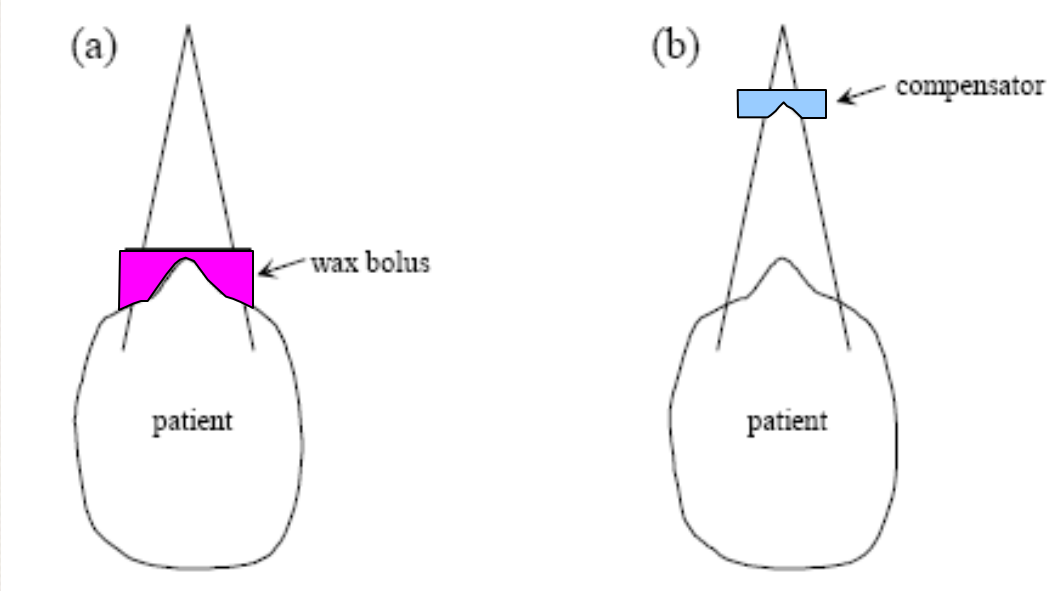
7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.3 Bolus

- The result is an isodose distribution that is identical to that produced on a flat phantom.
- **However, skin sparing is not maintained with a bolus, in contrast to the use of a compensator.**

7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.3 Bolus



Difference between a bolus and a compensating filter:

a) A wax bolus is used. Skin sparing is lost with bolus.

b) A compensator achieving the same dose distribution as in (a) is constructed and attached to the treatment unit. Due to the **large air gap** skin sparing is maintained.

7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.4 Compensating filters

- A compensating filter achieves the same effect on the dose distribution as a shaped bolus but does not cause a loss of skin sparing.
- Compensating filters can be made of almost any material, but metals such as lead are the most practical and compact.
- Compensating filters can produce a gradient in two dimensions.
- They are usually placed in a shielding slot on the treatment unit head.

- Thickness of the compensator is determined on a point-by-point basis depending on the fraction I/I_0 of the dose without a compensator which is required at a certain depth in the patient.
- Thickness of compensator x along the ray line above that point can be solved from the attenuation law:

$$\frac{I}{I_0} = e^{-\mu x}$$

where μ is the linear attenuation coefficient for the radiation beam and material used to construct the compensator.

Use of Compensating Filters

Advantage:	Disadvantages:
❑ Preservation of the skin sparing effect	❑ Generally more laborious and time consuming ❑ Difficult to calculate resulting dose distribution ❑ Additional measurements may be required

7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.5 Corrections for contour irregularities

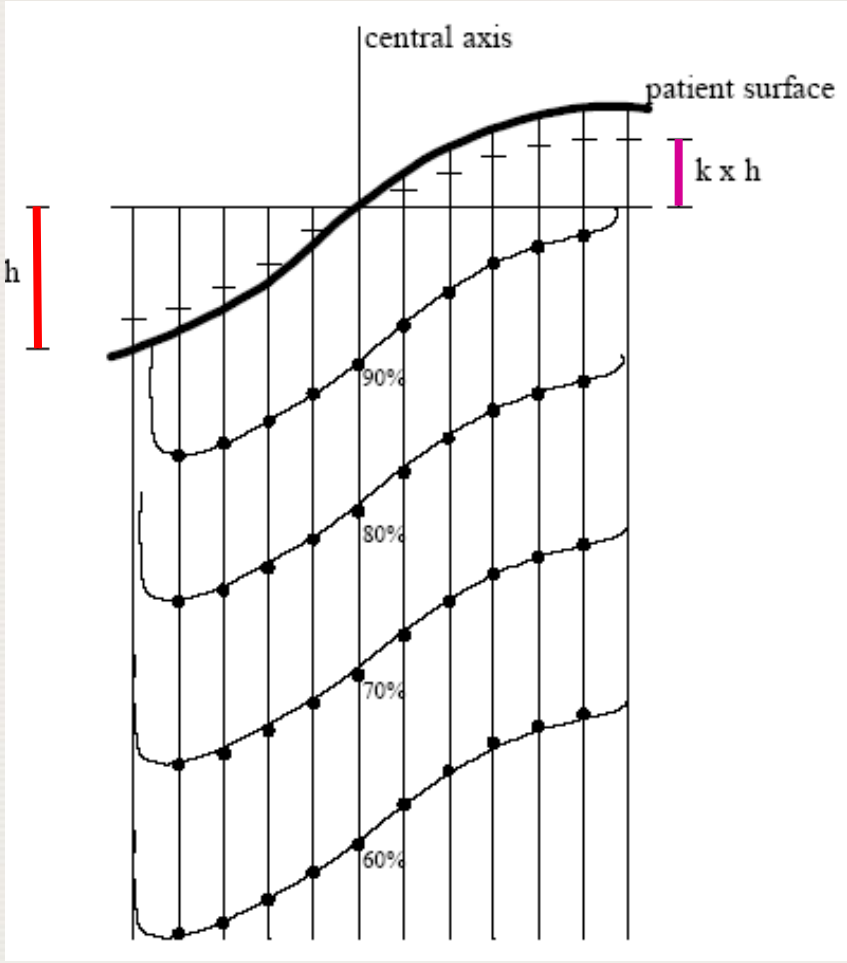
- Measured dose distributions apply to a **flat radiation beam** incident on a flat homogeneous water phantom.
- To relate such measurements to the actual dose distribution in a patient, **corrections** for irregular surface and tissue inhomogeneities have to be applied.
- Three methods for contour correction are used:
  1. Manual isodose shift method.
  2. Effective attenuation coefficient method.
  3. TAR method.

7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.5 Corrections for contour irregularities

- Grid lines are drawn parallel to the central beam axis all across the field.
- The tissue deficit (or excess) ***h*** is the difference between the SSD along a gridline and the SSD on the central axis.
- *k* is an energy dependent parameter given in the next slide.
- Isodose distribution for a flat phantom is aligned with the SSD central axis on the patient contour.
- For each gridline, the overlaid isodose distribution is shifted up (or down) such that the overlaid SSD is at a point ***k×h*** above (or below) the central axis SSD.

1. Manual isodose shift method



Parameter *k* used in the isodose shift method

Photon energy (MV)	*k* (approximate)
< 1	0.8
^{60}Co – 5	0.7
5 – 15	0.6
15 – 30	0.5
> 30	0.4

2. Effective attenuation coefficient method

- Correction factor is determined from the attenuation factor $\exp(-\mu x)$, where x is the depth of missing tissue above the calculation point, and μ is the linear attenuation coefficient of tissue for a given energy.
- For simplicity the factors are usually pre-calculated and supplied in graphical or tabular form.

3. TAR method

- Tissue-air ratio (TAR) correction method is also based on the attenuation law, but takes the depth of the calculation point and the field size into account.
- Generally, the correction factor C_F as a function of depth z, thickness of missing tissue h, and field size f, is given by:

$$C_F = \frac{\mathrm{TAR}(z-h,f)}{\mathrm{TAR}(z,f)}$$

7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.6 Corrections for tissue inhomogeneities

- In a simple approach to calculate the dose and its distribution in a patient, one may assume that all tissues are water-equivalent.
- However, in the actual patient the photon beam traverses tissues with varying densities and atomic numbers such as fat, muscle, lung, air, and bone.
- This will influence the attenuation and scatter of photons beam such that the depth dose curve will deviate from that in water.

7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.6 Corrections for tissue inhomogeneities

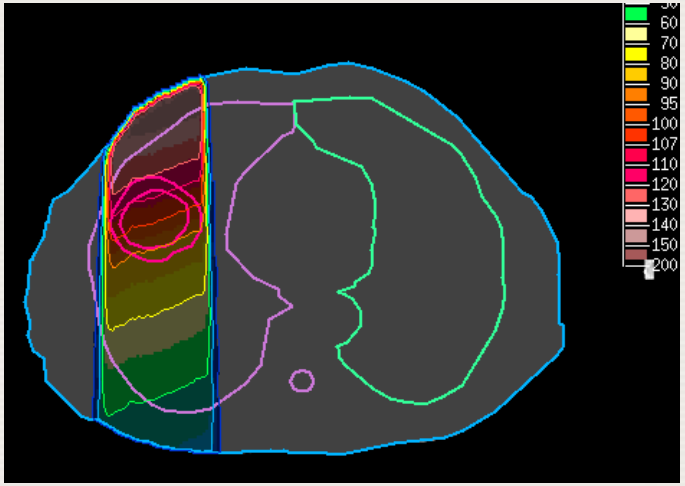
- Tissues with densities and atomic numbers different from those of water are referred to as **tissue inhomogeneities** or **heterogeneities**.
- Inhomogeneities in the patient result in:
  - Changes in the absorption of the primary beam and associated scattered photons
  - Changes in electron fluence.
- The importance of each effect depends on the position of the point of interest relative to the inhomogeneity.

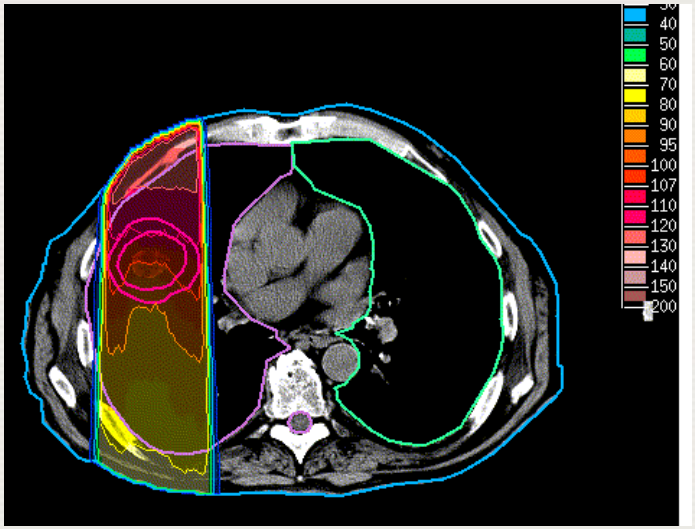
7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.6 Corrections for tissue inhomogeneities

Difference in isodose curves obtained using a single vertical 7×7cm^2 field.

- Top:
  Assuming that all tissues (including the lung) have water-equivalent density
- Bottom:
  Taking into account the real tissue density





7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

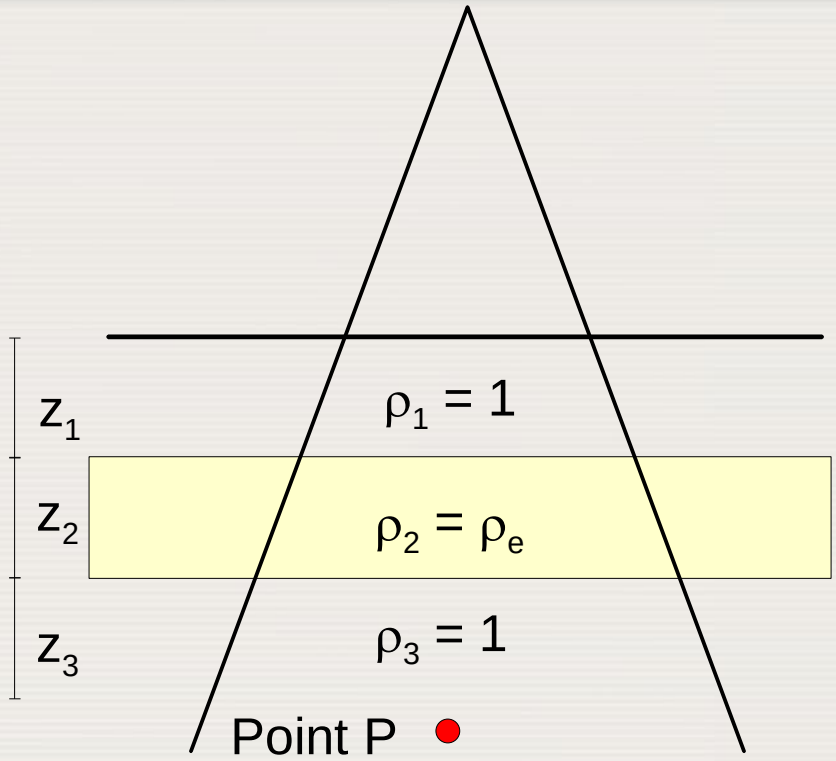
7.5.6 Corrections for tissue inhomogeneities

- In the megavoltage range the Compton interaction dominates and its cross-section depends on the **electron density** (in electrons per cm^3).
- The following four methods correct for the presence of inhomogeneities within certain limitations:
  - TAR method.
  - Batho power law method.
  - Equivalent TAR method.
  - Isodose shift method.

7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.6 Corrections for tissue inhomogeneities

- The four methods are presented using the schematic diagram which shows an inhomogeneity with an electron density ρ_e nested between two layers of water-equivalent tissue.



TAR method

Dose at each point is corrected by the factor C_F:

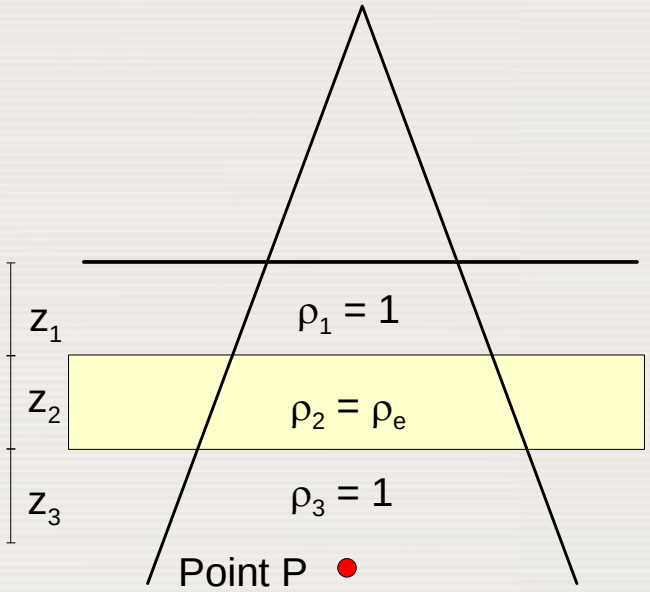
$$C_F = \frac{TAR(z', r_d)}{TAR(z, r_d)}$$

where

$z' = z_1 + \rho_e z_2 + z_3$

and

$z = z_1 + z_2 + z_3$



Batho Power-law method

Dose at each point is corrected by:

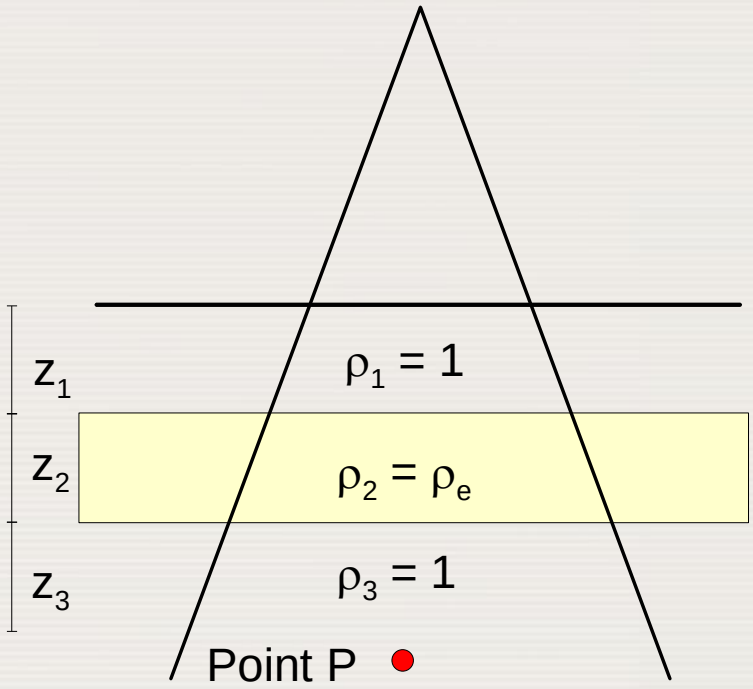
$$C_F = \frac{TAR(z', r_d)^{\rho_3 - \rho_2}}{TAR(z, r_d)^{1-\rho_2}}$$

where

$z' = z_1 + \rho_2 z_2 + z_3$

and

$z = z_1 + z_2 + z_3$



Equivalent TAR method

Method is similar to the TAR method. The field size parameter r_d is now modified into r'_d as a function of density

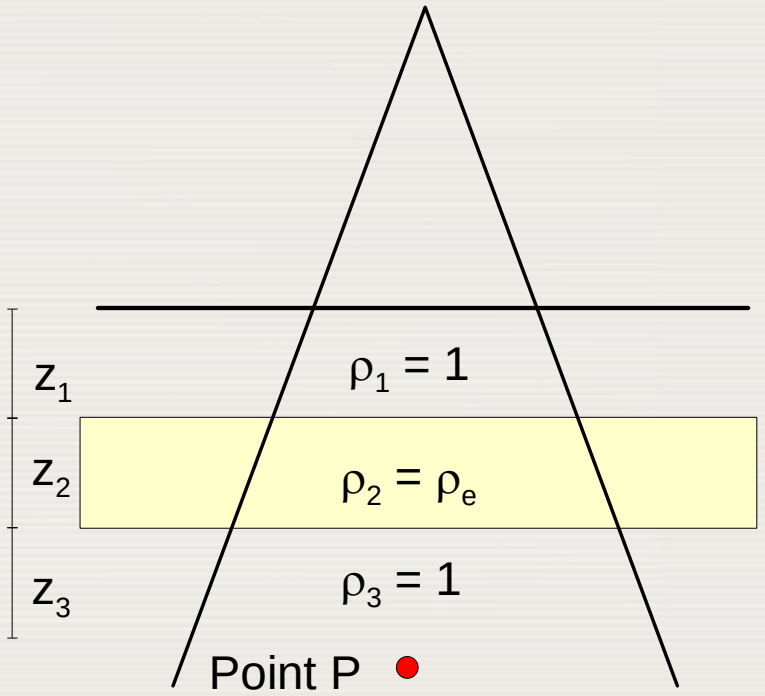
$$C_F = \frac{\mathrm{TAR}(z', r'_d)}{\mathrm{TAR}(z, r_d)}$$

where

$z' = z_1 + \rho_2 z_2 + z_3$

and

$z = z_1 + z_2 + z_3$



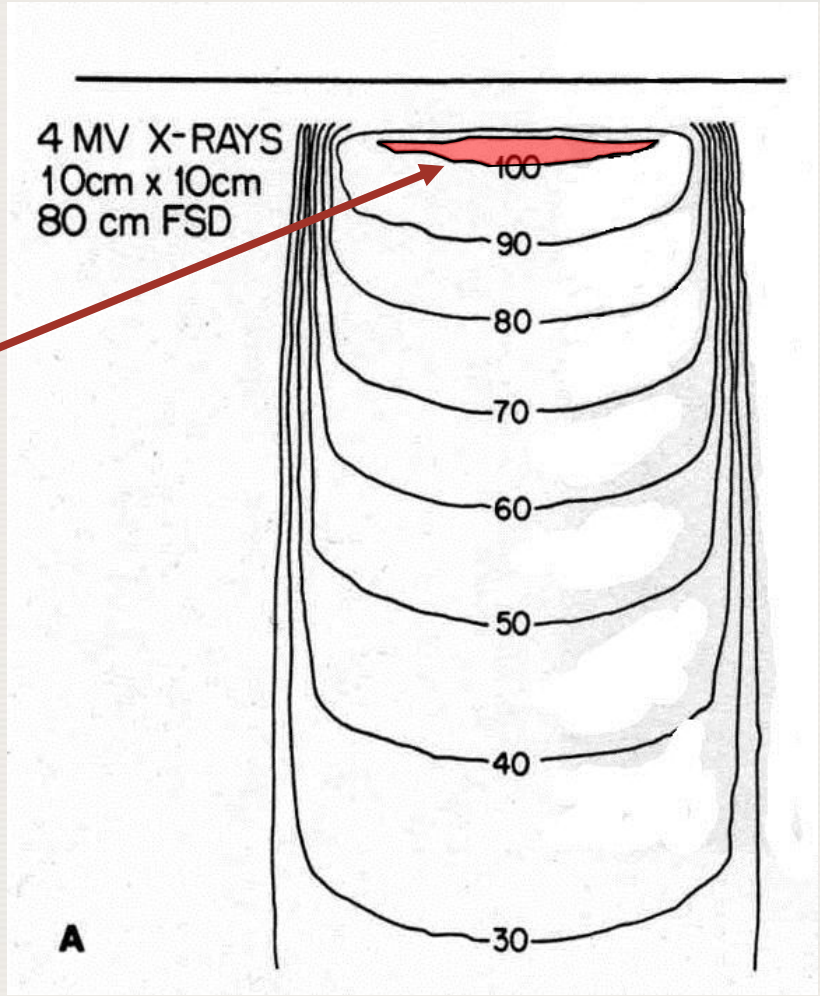
Isodose shift method

- The isodose shift method for the dose correction due to the presence of inhomogeneities is essentially identical to the isodose shift method outlined in the previous section for contour irregularities.
- Isodose shift factors for several types of tissue have been determined for isodose points beyond the inhomogeneity.
- The factors are energy dependent but do not vary significantly with field size.
- The factors for the most common tissue types in a 4 MV photon beam are: air cavity: – 0.6; lung: – 0.4; and hard bone: + 0.5. The total isodose shift is the thickness of inhomogeneity multiplied by the factor for a given tissue. Isodose curves are shifted away from the surface when the factor is negative.

7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.7 Beam combinations and clinical application

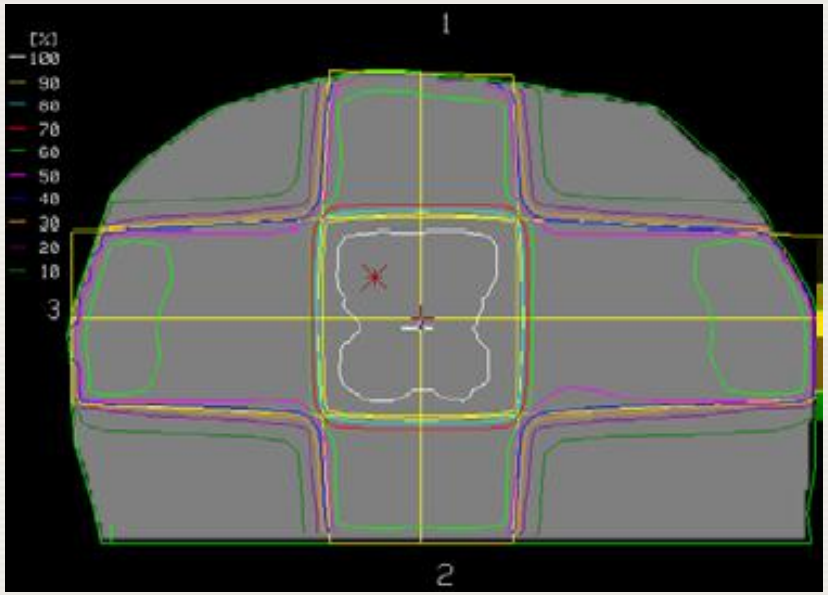
- Single photon beams are of limited use in the treatment of deep-seated tumors, since they give a **higher dose** near the entrance at the depth of dose maximum than at depth.



7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.7 Beam combinations and clinical application

- Single fields are often used for **palliative treatments** or for relatively **superficial lesions** (depth < 5 cm – 10 cm, depending on the beam energy).
- For deeper lesions, a **combination** of two or more photon beams is usually required to concentrate the dose in the target volume and spare the tissues surrounding the target as much as possible.



Weighting and normalization

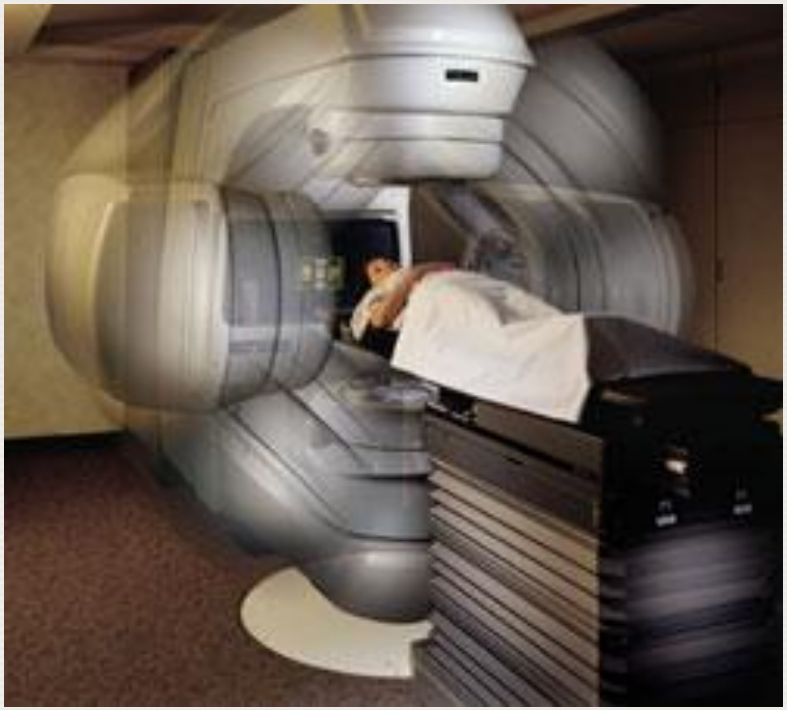
- Dose distributions for multiple beams can be normalized to 100 % just as for single beams:
  - at z_{max} for each beam,
  - at isocenter for each beam.
- This implies that each beam is equally weighted.

Weighting and normalization

- **Beam weighting** may additionally applied at the normalization point for the given beam.
- *Example*:
  Wedged pair with z_{max} normalization weighted as 100 % : 50 % will show one beam with the 100 % isodose at z_{max} and the other one with 50 % at z_{max}.
- A similar isocentric weighted beam pair would show the 150 % isodose at the isocenter.

Fixed SSD vs. isocentric techniques

- Fixed SSD techniques require adjusting the patient such that the skin is at the correct distance (nominal SSD) for each beam orientation.
- Isocentric techniques require placing the patient such that the target (usually) is at the isocentre.
- Machine gantry is then rotated around the patient for each treatment field.



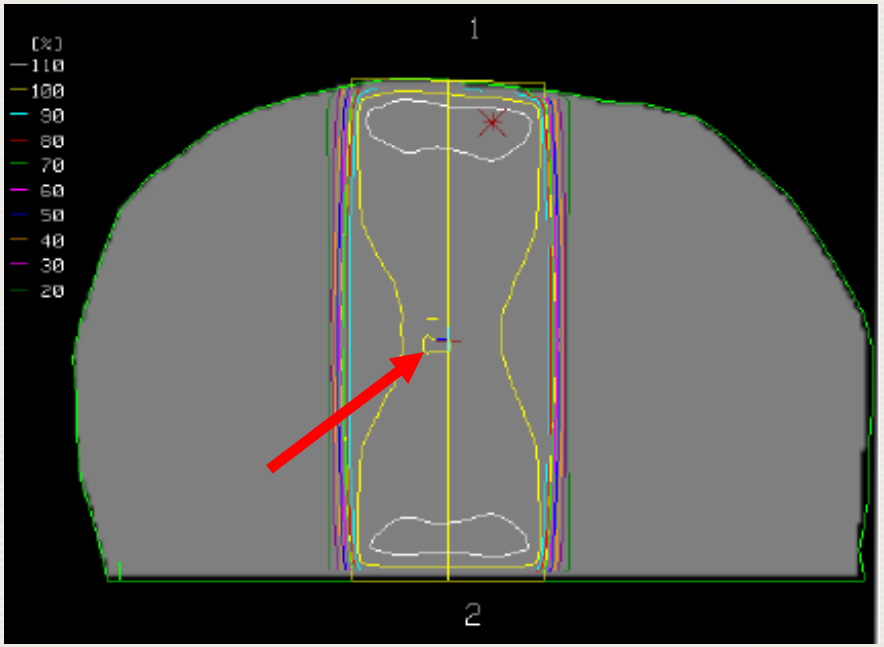
Fixed SSD vs. isocentric techniques

- There is little difference between fixed SSD techniques and isocentric techniques with respect to the dose:
  - Fixed SSD arrangements are usually at a **greater SSD** than isocentric beams because the machine isocenter is on the patient skin.
  - They have therefore a slightly **higher PDD** at depth.
  - Additionally, beam **divergence is smaller** with SSD due to the larger distance.

Fixed SSD vs. isocentric techniques

- Dosimetric advantages of SSD techniques are small.
- With the exception of very large fields exceeding 40×40 cm^2, **advantages of using a single set-up point** (i.e., isocentre) greatly outweigh the dosimetric advantage of SSD beams.

Parallel opposed beams



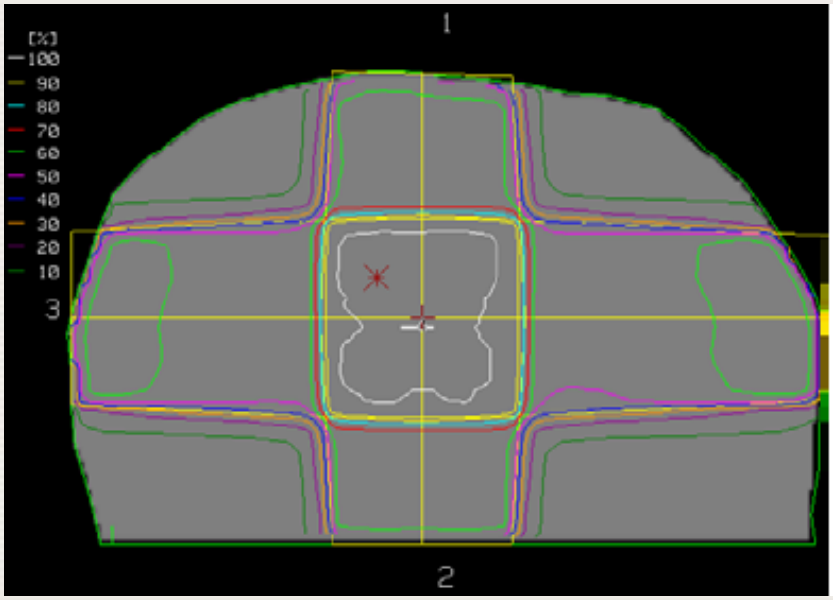
- *Example*:
  A parallel-opposed beam pair is incident on a patient.
- *Note* the large rectangular area of relatively uniform dose (<15 % variation).
- Isodose curves have been normalized to 100 % at the isocentre.
- This beam combination is well suited to a large variety of treatment sites (e.g., lung, brain, head and neck).

Multiple coplanar beams:

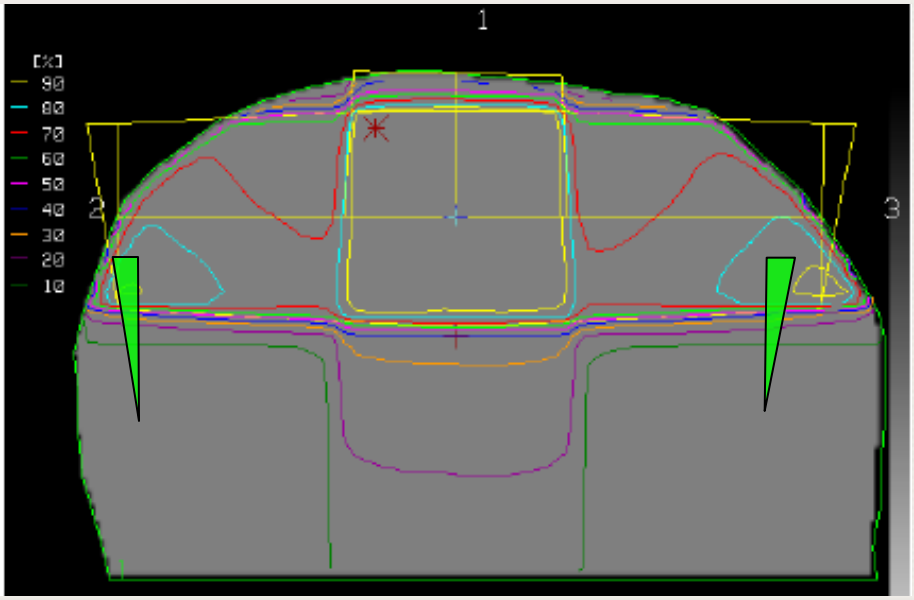
- Allow for a higher dose in the beam intersection region.

Two examples:

4-field box



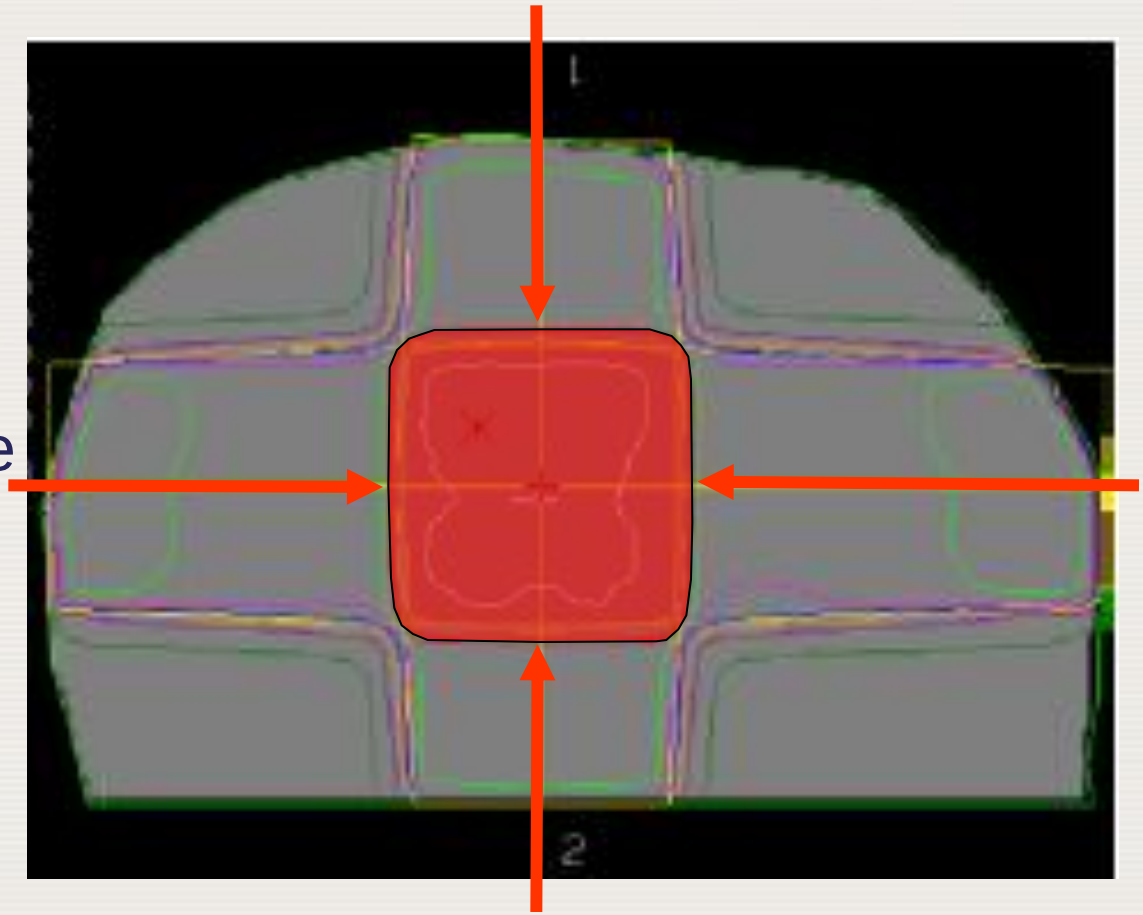
3-field technique using wedges



Multiple co-planar beams

4-field box

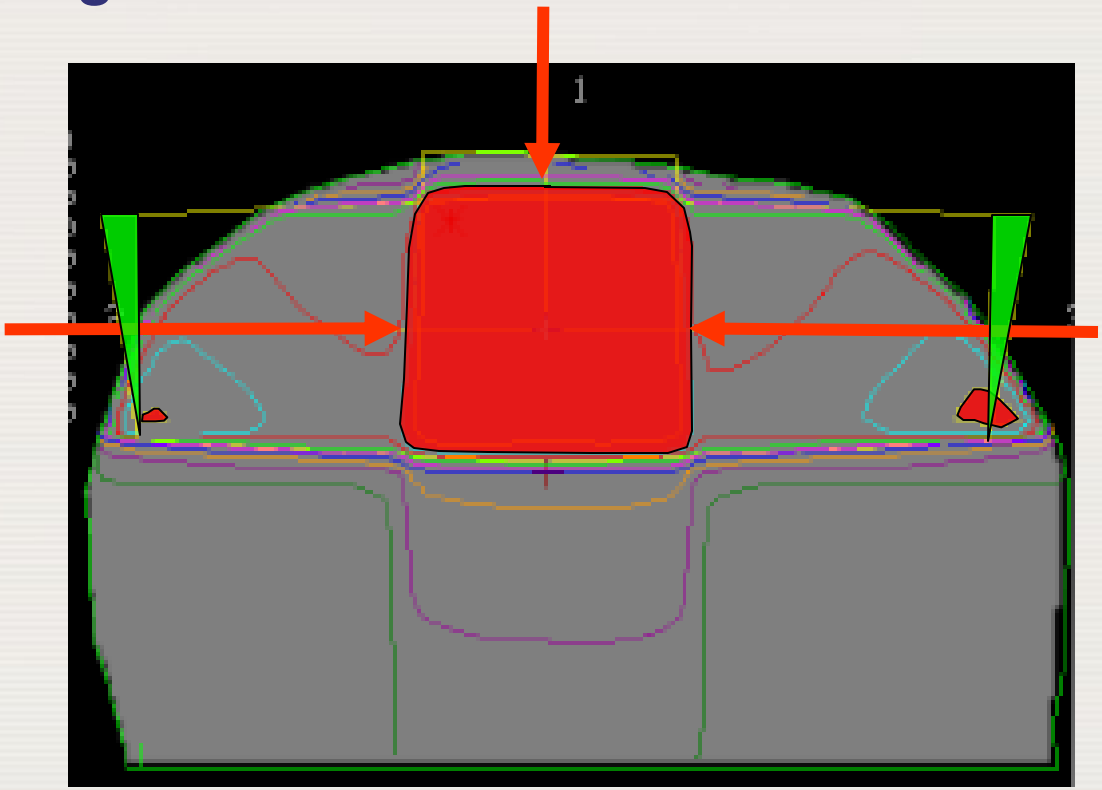
- A 4-field box allows for a very high dose to be delivered at the **intersection** of the beams.



Multiple co-planar beams

3-field technique using wedges

- A 3-field technique requires the use of wedges to achieve a **similar result**.
- *Note* that the latter can produce significant **hot spots** near the entrance of the wedged beams and well outside the targeted area.



Multiple coplanar beams: General characteristics

Type	Characteristics	Used for:
Wedge pairs	Used to achieve a trapezoid shaped high dose region	Low-lying lesions (e.g., maxillary sinus and thyroid lesions).
4-field box	Produces a relatively high dose box shaped region	Treatments in the pelvis, where most lesions are central (e.g., prostate, bladder, uterus).
Opposing pairs at angles other than 90°	High dose area has a rhombic shape	Similar indications

Multiple coplanar beams: General characteristics

- Wedge pair:
  Two beams with wedges (often orthogonal) are used to achieve a trapezoid shaped high dose region. This technique is useful in relatively low-lying lesions (e.g., maxillary sinus and thyroid lesions).

- 4-field box:
  A technique of four beams (two opposing pairs at right angles) producing a relatively high dose box shaped region. The region of highest dose now occurs in the volume portion that is irradiated by all four fields. This arrangement is used most often for treatments in the pelvis, where most lesions are central (e.g., prostate, bladder, uterus).

- Opposing pairs at angles other than 90°:
  also result in the highest dose around the intersection of the four beams, however, the high dose area here has a rhombic shape.

Multiple coplanar beams: General characteristics

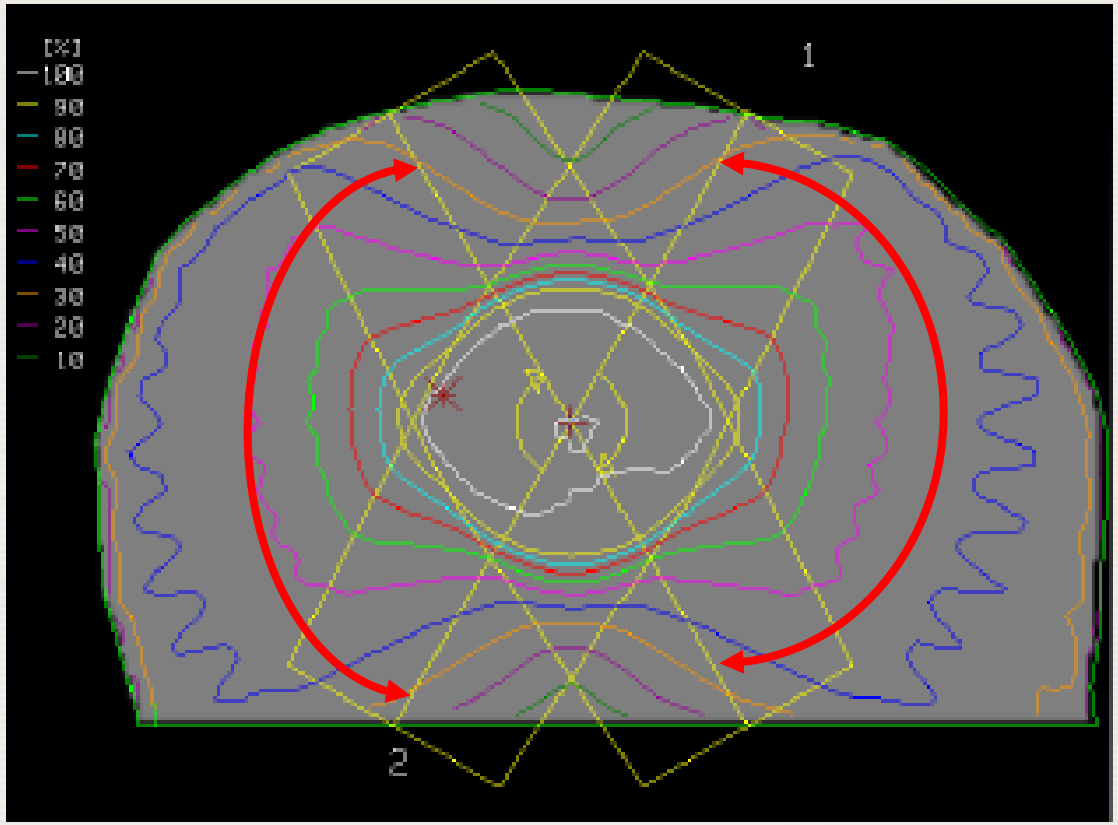
- Occasionally, three sets of opposing pairs are used, resulting in a more complicated dose distribution, but also in a spread of the dose outside the target over a larger volume, i.e., in more sparing of tissues surrounding the target volume.
- The 3-field box technique is similar to a 4-field box technique. It is used for lesions that are closer to the surface (e.g., rectum). Wedges are used in the two opposed beams to compensate for the dose gradient in the third beam.

7.5 CLINICAL CONSIDERATIONS FOR PHOTON BEAMS

7.5.7 Beam combinations and clinical application

Rotational techniques

- Isodose curves for two bilateral arcs of 120° each.
- *Note*:
  Isodose curves are tighter along the angles avoided by the arcs (anterior and posterior).



Rotational techniques: General characteristics

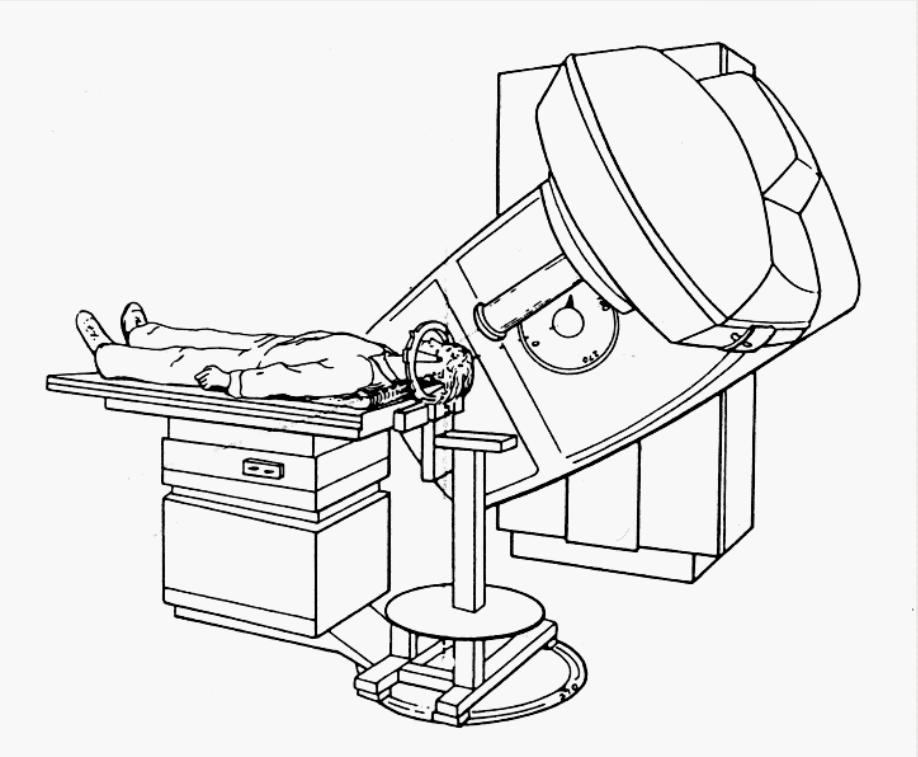
- Target is placed at the isocentre, and the machine gantry is rotated about the patient in one or more arcs while the beam is on.
- Rotational techniques produce a relatively concentrated region of high dose near the isocentre.
- But they also irradiate a greater amount of normal tissue to lower doses than fixed-field techniques.

Rotational techniques: General characteristics

- Useful technique used mainly for prostate, bladder, cervix and pituitary lesions, particularly boost volumes.
- Dose gradient at the edge of the field is not as sharp as for multiple fixed field treatments.
- Skipping an angular region during the rotation allows the dose distribution to be pushed away from the region; however, this often requires that the isocentre be moved closer to this skipped area so that the resulting high-dose region is centered on the target .

Multiple non-coplanar beams: General characteristics

- Non-coplanar beams arise from non-standard couch angles coupled with gantry angulations.



Multiple non-coplanar beams: General characteristics

- Non-coplanar beams may be useful to get more adequate critical structure sparing compared to conventional co-planar beam arrangement.
- Dose distributions from non-coplanar beam combinations yield similar dose distributions to conventional multiple field arrangements.

Multiple non-coplanar beams: General characteristics

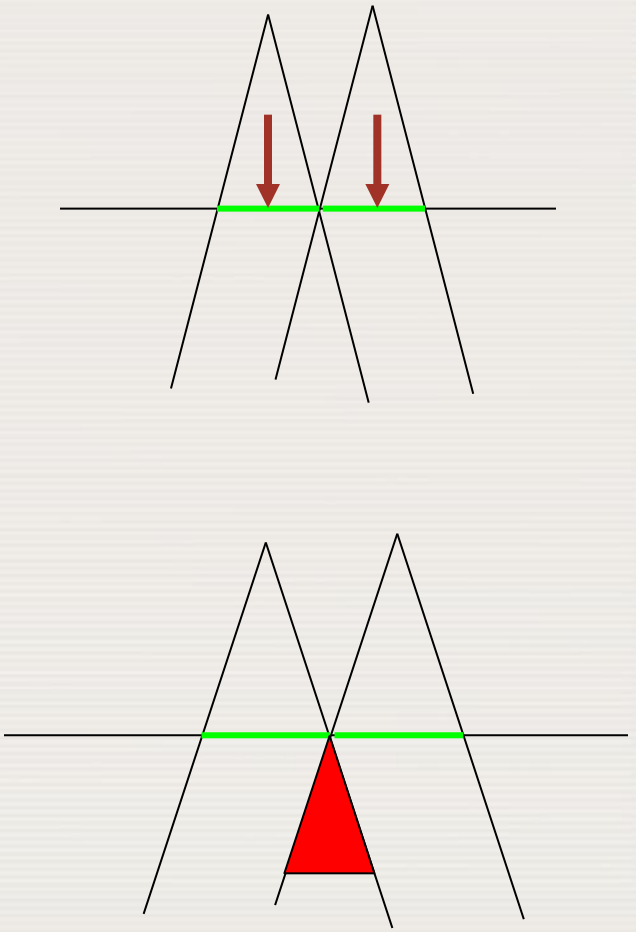
- Care must be taken when planning the use of non-coplanar beams to ensure no collisions occur between the gantry and patient or couch.
- Non-coplanar beams are most often used for treatments of brain as well as head and neck disease where the target volume is frequently surrounded by critical structures.

Multiple non-coplanar beams: General characteristics

- **Non-coplanar arcs** are also used.
- The best-known example is the multiple non-coplanar converging arcs technique used in radiosurgery.

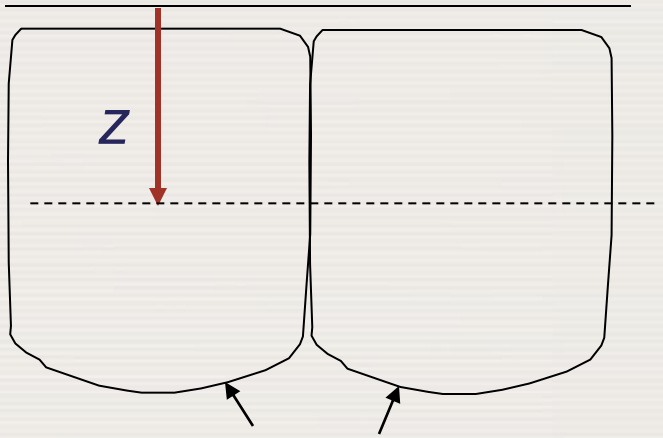
Field matching

- Field matching at the skin is the easiest field matching technique.
- However, due to beam divergence, this will lead to significant overdosing of tissues at depth and is only used in regions where tissue tolerance is not compromised.



Field matching

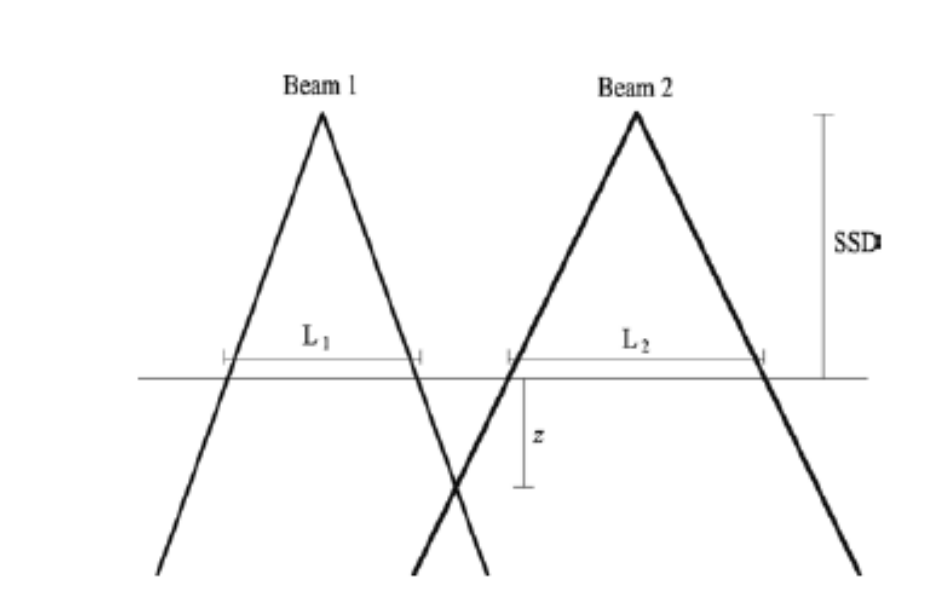
- For most clinical situations field matching is performed **at depth** rather than at the skin.
- To produce a junction dose similar to that in the center of the open fields, beams must be matched such that their diverging edges **match at the desired depth *z***.



Field matching

- For two adjacent fixed SSD fields of different lengths L_1 and L_2, the surface gap g required to match the two fields at a depth z is:

$$g = 0.5L_1 \times \left(\frac{z}{SSD}\right) + 0.5L_2 \times \left(\frac{z}{SSD}\right)$$



7.6 TREATMENT PLAN EVALUATION

- It is essential to assess the "quality" of a treatment plan regardless whether the dose calculations are performed
  - On computer.
  - Or by hand.
- Good "quality" means that the calculated dose distribution of the treatment plan complies with he clinical aim of the treatment.
- A radiation oncologist must therefore evaluate the result of the treatment plan.

7.6 TREATMENT PLAN EVALUATION

- Depending on the method of calculation, the dose distribution may be obtained:

  1. Only for a **few significant points** within the target volume.
  2. For a **two-dimensional grid** of points over a contour or an image.
  3. For a **full three-dimensional array** of points that cover the patient's anatomy.

7.6 TREATMENT PLAN EVALUATION

- Treatment plan evaluation generally consists of verifying:
  - **Treatment portals**
    They are verified to ensure that the desired PTV is covered adequately.
  - **Isodose distribution**
    It is verified to ensure that target coverage is adequate and that critical structures surrounding the PTV are spared as necessary.

7.6 TREATMENT PLAN EVALUATION

The following tools are used in the evaluation of the planned dose distribution:

- Isodose curves.
- Orthogonal planes and isodose surfaces.
- Dose distribution statistics.
- Differential Dose Volume Histogram.
- Cumulative Dose Volume Histogram.

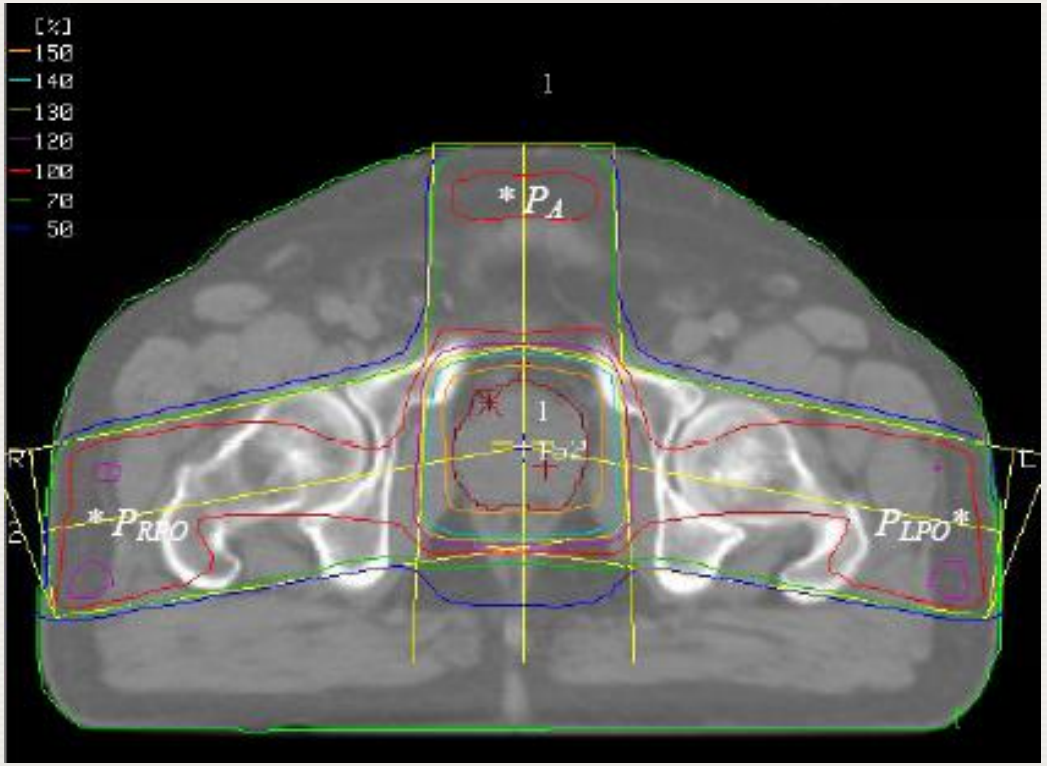
7.6 TREATMENT PLAN EVALUATION

7.6.1 Isodose curves

- Isodose curves are used to evaluate treatment plans along a single plane or over several planes in the patient.

Example:

Isodose curve covering the periphery of the target is compared to the isodose curve through isocentre.



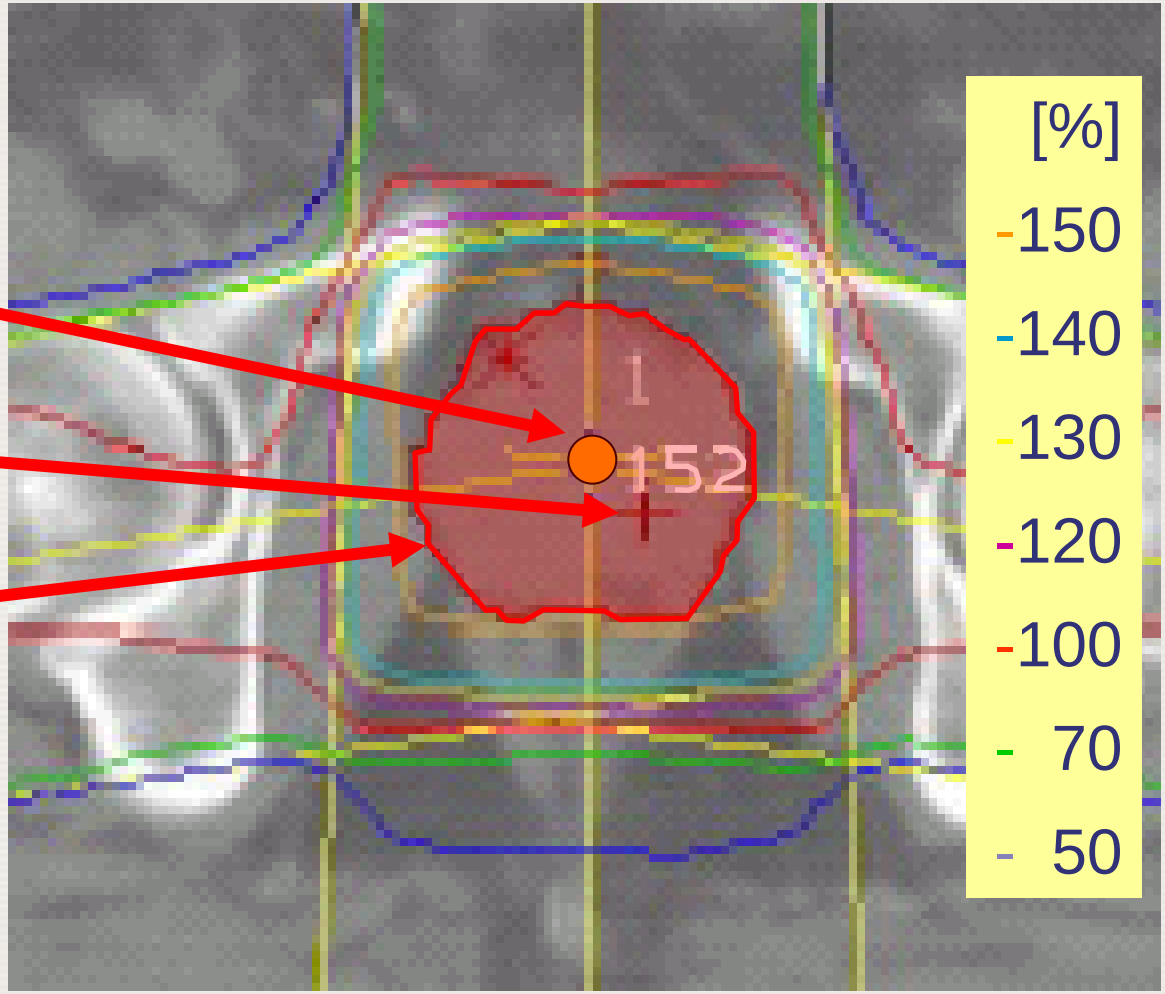
7.6 TREATMENT PLAN EVALUATION

7.6.1 Isodose curves

***Same example*:**
Isodose line through the ICRU reference point is 152 %.

Maximum dose 154 %.

The 150 % isodose curve completely covers the PTV.



7.6 TREATMENT PLAN EVALUATION

7.6.1 Isodose curves

- If the ratio of isodoses covering the periphery of the target to that at the isocentere is within a desired range (e.g., 95 % - 100 %) then the plan may be acceptable provided critical organ doses are not exceeded.
- This approach is ideal **if the number of transverse slices is small**.

7.6 TREATMENT PLAN EVALUATION

7.6.2 Orthogonal planes and isodose surfaces

- When a larger number of transverse planes are used for calculation it may be impractical to evaluate the plan on the basis of axial slice isodose distributions alone.
- In such cases, isodose distributions can also be generated on **orthogonal CT planes**, reconstructed from the original axial data.
- *For example*, **sagittal and coronal** plane isodose distributions are usually available on most 3D treatment planning systems.
- Displays on **arbitrary oblique planes** are also becoming increasingly common.

7.6 TREATMENT PLAN EVALUATION

7.6.2 Orthogonal planes and isodose surfaces

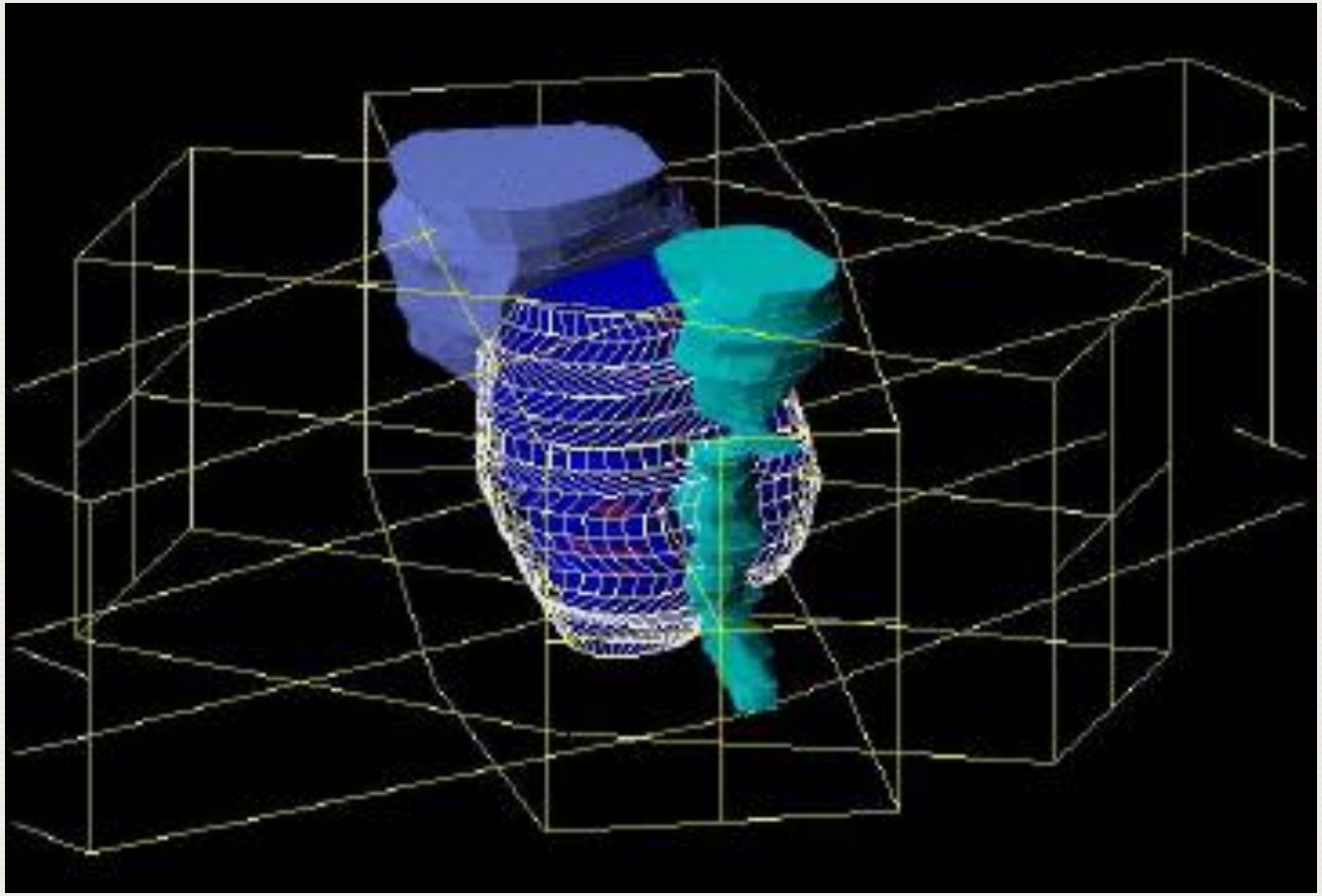
- An alternative way to display isodoses is to map them in three dimensions and overlay the resulting isosurface on a 3D display featuring surface renderings of the target and or/other organs.

Example: Prostate cancer

Target volume: blue

Prescription isodose: white wireframe

Bladder and rectum are also shown.



Such displays are useful to assess target coverage in a qualitative manner.

Disadvantages:

- They do not convey a sense of distance between the isosurface and the anatomical volumes.
- They do not give a quantitative volume information.

7.6 TREATMENT PLAN EVALUATION

7.6.3 Dose statistics

- In order to get more quantitative information, statistics tools have been introduced.
- In contrast to the isodose tools, the dose statistics tools cannot show the spatial distribution of dose superimposed on CT slices or anatomy that has been outlined based on CT slices.
- Instead, they can provide quantitative information on the **volume** of the target or critical structure, and on the **dose received by that volume**.

7.6 TREATMENT PLAN EVALUATION

7.6.3 Dose statistics

From the location of matrix points within an organ and the calculated doses at these points, a series of statistical characteristics can be obtained.

These include:

- Minimum dose to the volume.
- Maximum dose to the volume.
- Mean dose to the volume.
- Dose received by at least 95% of the volume.
- Volume irradiated to at least 95% of the prescribed dose.

7.6 TREATMENT PLAN EVALUATION

7.6.3 Dose statistics

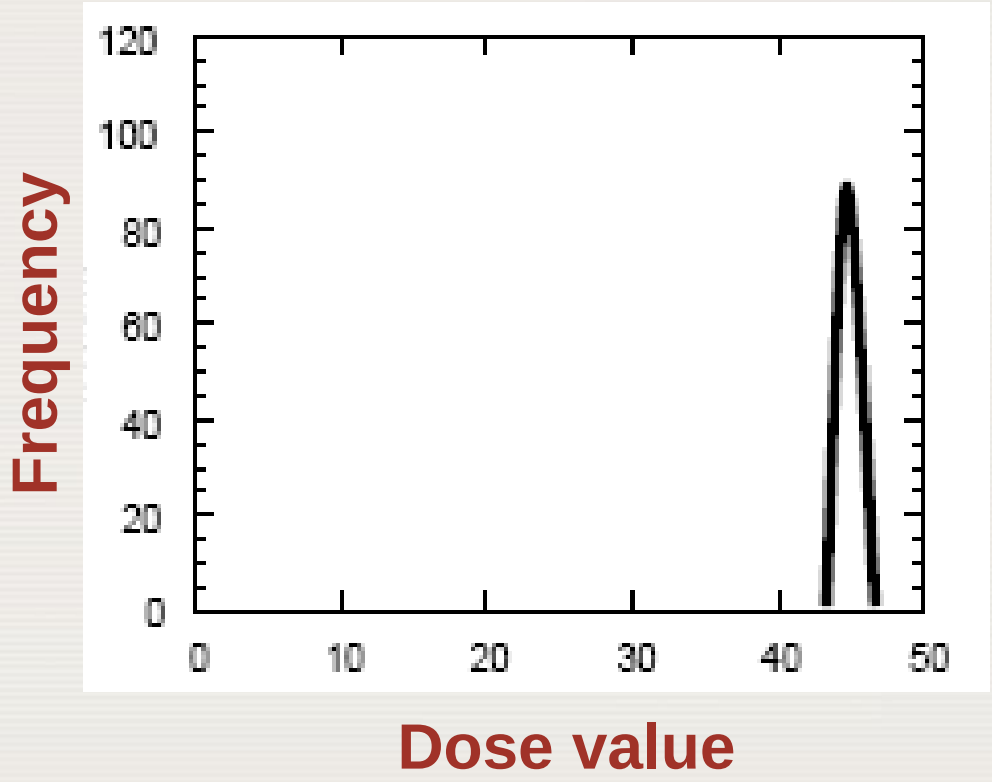
- Target dose statistics as well as organ dose statistics can be performed.
- "**Dose received by at least 95 % of the volume**" and the "**Volume irradiated to at least 95 % of the prescribed dose**" are only relevant for the target volume.
- Organ dose statistics are especially useful in dose reporting, since they are simpler to include in a patient chart than dose-volume histograms that are described in the next slides.

7.6 TREATMENT PLAN EVALUATION

7.6.4 Dose-volume histograms

- Dose volume histograms (DVHs) summarize the information contained in a three-dimensional treatment plan.
- This information consists of dose distribution data over a three-dimensional matrix of points over the patient's anatomy.
- DVHs are extremely powerful tools for quantitative evaluation of treatment plans.

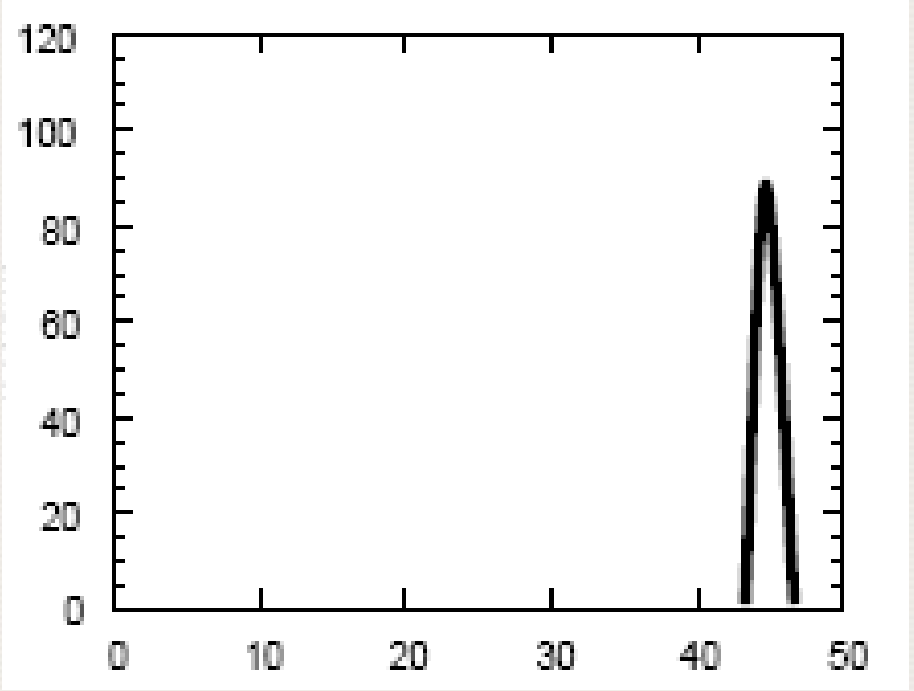
- In its simplest form a DVH represents a **frequency distribution** of **dose values** within a defined volumes such as:
  - PTV itself
  - Specific organ in the vicinity of the PTV.



7.6 TREATMENT PLAN EVALUATION

7.6.4 Dose-volume histograms

- Rather than displaying the frequency, DVHs are usually displayed in the form of "**per cent volume of total volume**" on the ordinate against the dose on the abscissa.

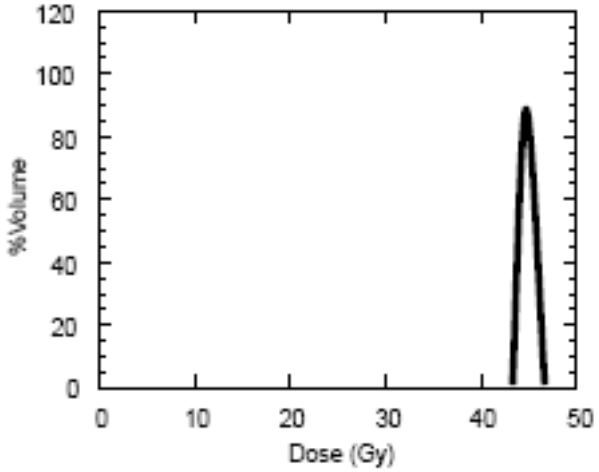


7.6 TREATMENT PLAN EVALUATION

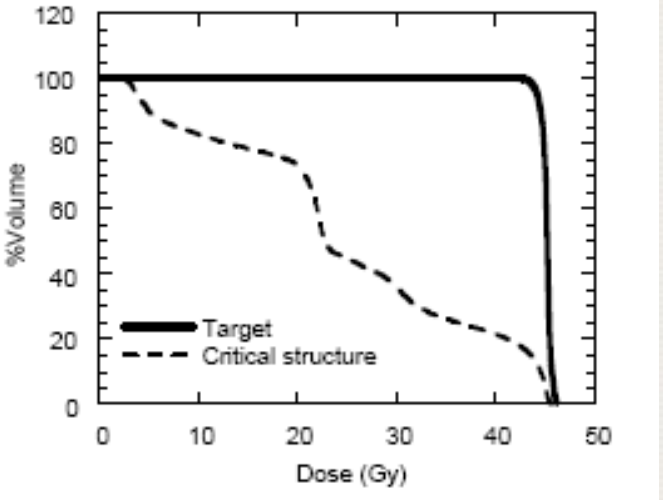
7.6.4 Dose-volume histograms

Two types of DVHs are in use:

- Direct (or differential) DVH



- Cumulative (or integral) DVH
  Definition: Volume that receives **at least** the given dose and plotted versus dose.

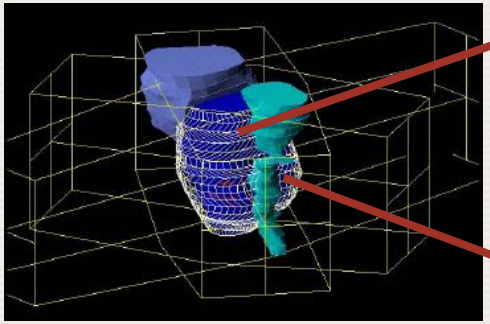


Direct Dose Volume Histogram

- To create a direct DVH, the computer sums the number of voxels which have a specified dose range and plots the resulting volume (or the percentage of the total organ volume) as a function of dose.
- Ideal DVH for a **target volume** would be a single column indicating that 100% of the volume receives the prescribed dose.
- For a critical structure, the DVH may contain several peaks indicating that different parts of the organ receive different doses.

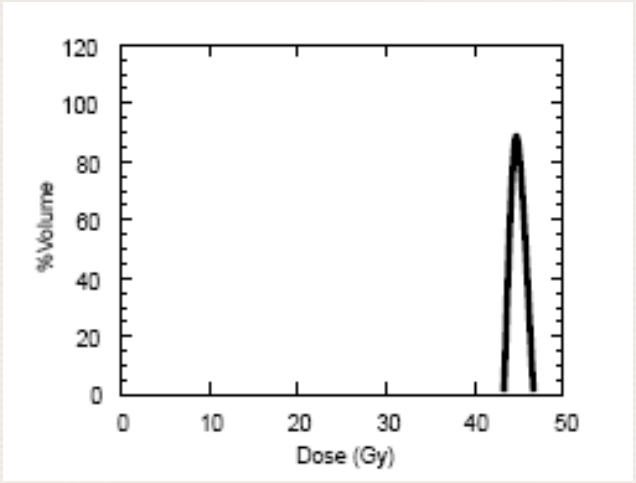
Differential DVHs

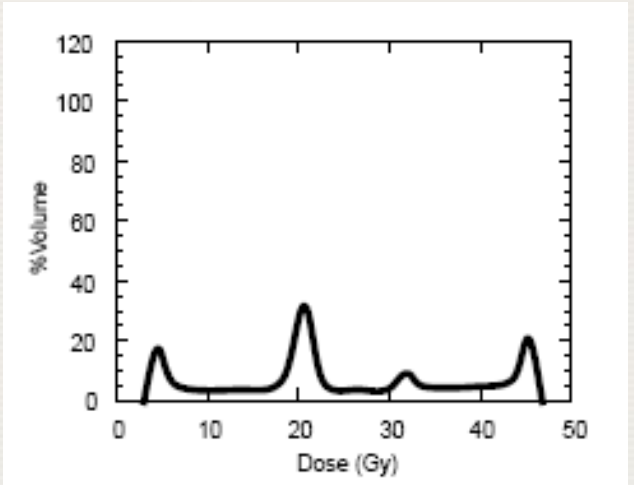
Example: Prostate cancer



Target

Rectum



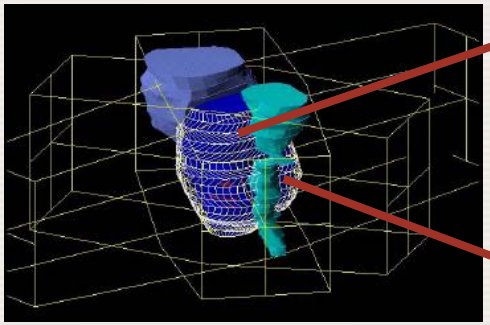


Cumulative Dose Volume Histogram

- Traditionally, physicians have sought to answer questions such as: "*How much of the target is covered by the 95 % isodose line?*"
- In 3-D treatment planning this question is equally relevant and the answer cannot be extracted directly from the direct DVH, since it would be necessary to determine the area under the curve for all dose levels above 95 % of the prescription dose.

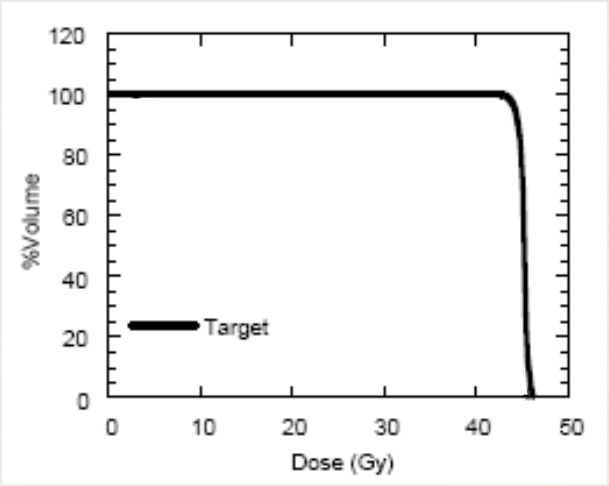
Integral DVHs

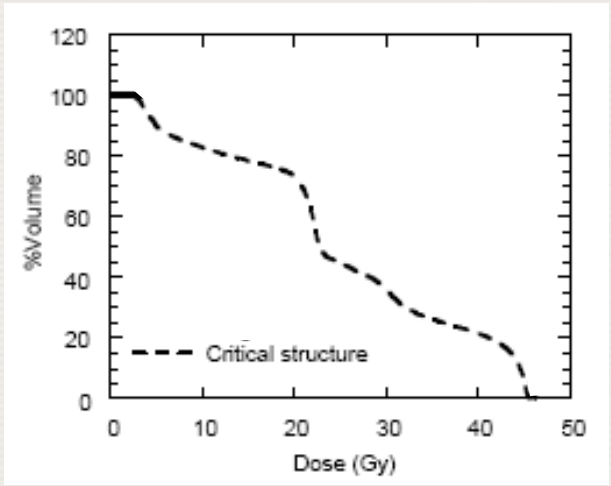
Example: Prostate cancer



Target

Critical structure: rectum





For this reason, cumulative DVH displays are more popular.

- Computer calculates the volume of the target (or critical structure) that receives at least the given dose and plots this volume (or percentage volume) versus dose.
- All cumulative DVH plots start at 100 % of the volume for zero dose, since all of the volume receives at least no dose.

7.6 TREATMENT PLAN EVALUATION

7.6.4 Dose-volume histograms

- While displaying the **percent volume** versus dose is more popular, it is also useful in some circumstances to plot the **absolute volume** versus dose.
- *For example*, if a CT scan does not cover the entire volume of an organ such as the lung and the un-scanned volume receives very little dose, then a DVH showing percentage volume versus dose for that organ will be biased, indicating that a larger percentage of the volume receives dose.
- Furthermore, in the case of some critical structures, tolerances are known for irradiation of fixed volumes specified in cm^3.

7.6 TREATMENT PLAN EVALUATION

7.6.4 Dose-volume histograms

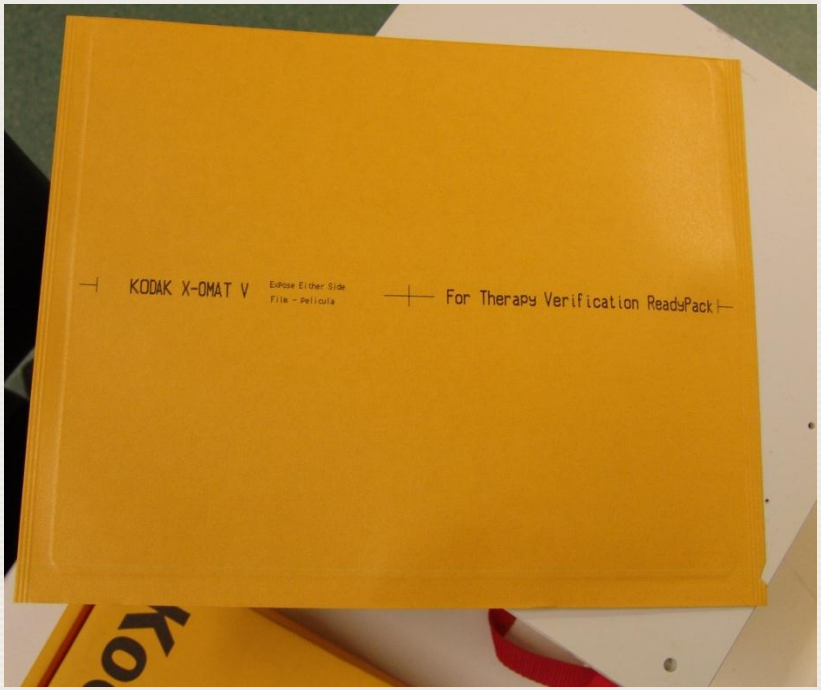
- The main drawback of the DVHs is the **loss of spatial information** that results from the condensation of data when DVHs are calculated.

7.6 TREATMENT PLAN EVALUATION

7.6.5 Treatment evaluation

Port films

- A port film is usually an emulsion-type film, often still in its light-tight paper envelope, that is placed in the radiation beam beyond the patient.



Since there is no conversion of x rays to light photons as in diagnostic films, the films need not be removed from its envelope.

Port films

- Two port films are available.
- Depending on their sensitivity (or speed) port films can be used for:
  - **Localization:**
    A fast film is placed in each beam at the beginning or end of the treatment to verify that the patient installation is correct for the given beam.
  - **Verification:**
    A slow film is placed in each beam and left there for the duration of the treatment.

Localization (fast) vs. verification (slow) films

Advantages:	Disadvantage:
❑ Fast films generally produce a better image. ❑ Recommended for verifying small or complex beam arrangements. ❑ Patient or organ movement during treatment will not affect the quality of the film.	❑ Not recommended for larger fields for example where as many as 4 films may be required to verify the treatment delivery.

7.6 TREATMENT PLAN EVALUATION

7.6.5 Treatment evaluation

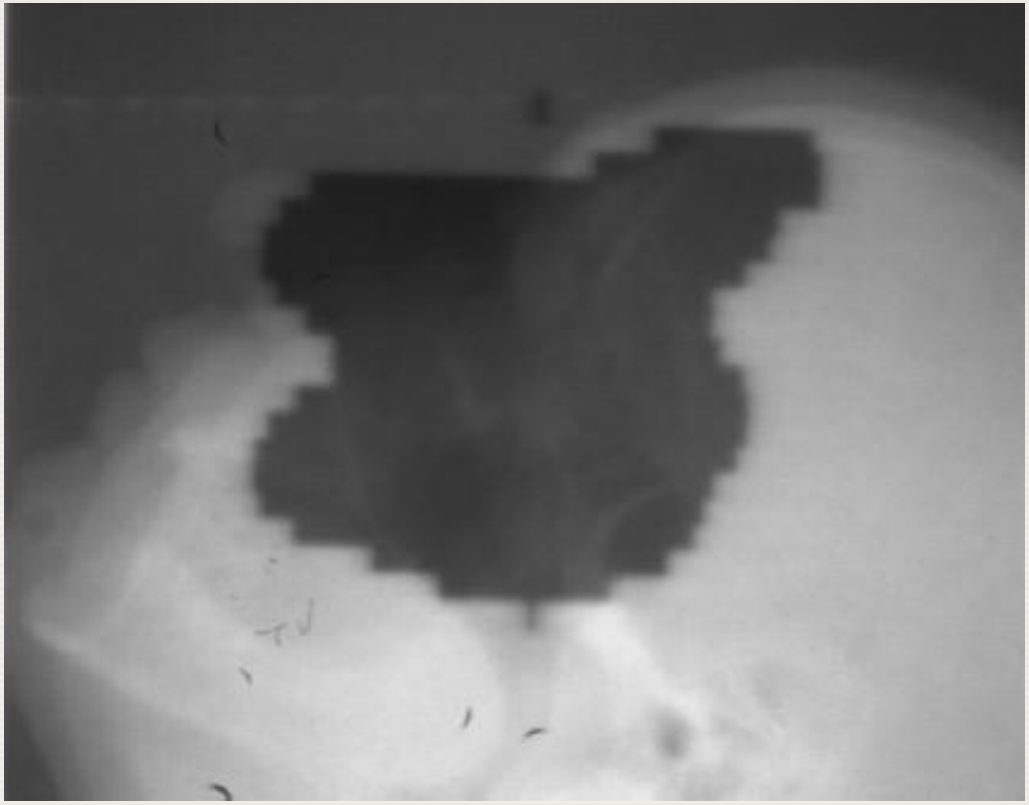
- Localization films used in radiotherapy do not require intensifying screens such as those used in diagnostic radiology.
- Instead, a single thin layer of a suitable metal (such as copper or aluminum) is used in front of the film (beam entry side) to provide for electronic buildup that will increase the efficiency of the film.
- A backing layer is sometimes used with double emulsion films to provide backscatter electrons.

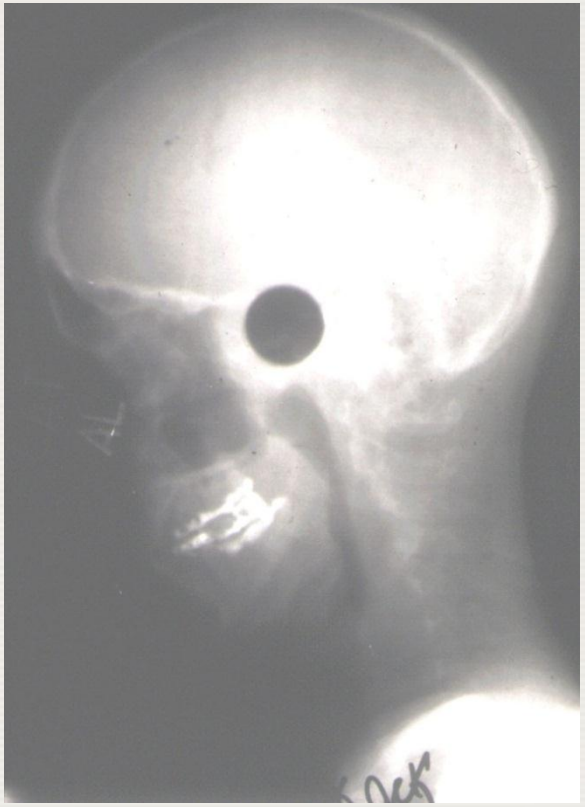
Port films are taken either in single or double exposure technique.

- **Single exposure:**
  Film is irradiated with the treatment field alone. This technique is well suited to areas where the anatomical features can clearly be seen inside the treated field. Practically all verification films are single exposure.

- **Double exposure:**
  - Film is irradiated with the treatment field first.
  - Then the collimators are opened to a wider setting, all shielding is removed, and a second exposure is given to the film.
  - The resulting image shows the treated field **and** the surrounding anatomy that may be useful in verifying the beam position.

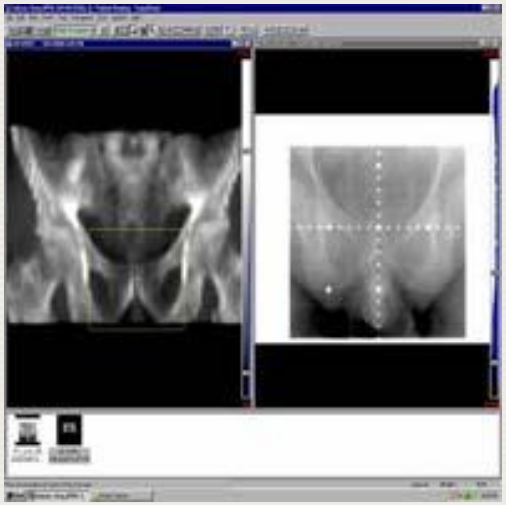
Double exposure technique: *Two examples*





Online portal imaging

- Online portal imaging systems consist of:
  - Suitable radiation detector, usually attached through a manual or semi-robotic arm to the linac.
  - Data acquisition system capable of transferring the detector information to a computer.
  - Software that will process it and convert it to an image.
- These systems use a variety of detectors, all producing computer based images of varying degrees of quality.



Online portal imaging systems currently include:

1. Fluoroscopic detectors.
2. Ionisation chamber detectors.
3. Amorphous silicon detectors.

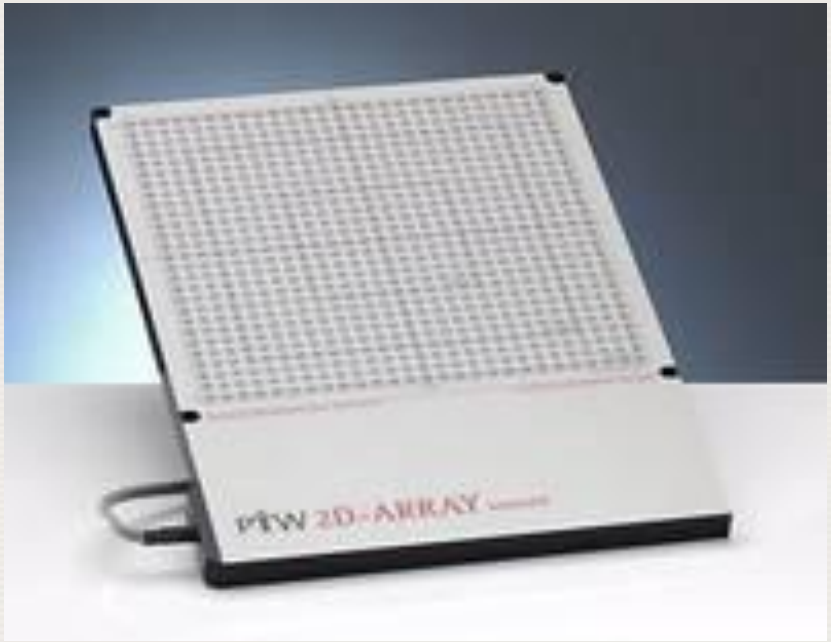
Fluoroscopic portal imaging detectors:

- Work on the same principle as a simulator image intensifier system.
- Detector consists of a combination of a metal plate and fluorescent phosphor screen, a 45° mirror and a television camera.
- Metal plate converts incident x-rays to electrons and the fluorescent screen converts electrons to light photons.
- Mirror deflects light to the TV camera, reducing the length of the imager, and the TV camera captures a small fraction (<0.1 %) of the deflected light photons to produce an image.
- Good spatial resolution (depends on phosphor thickness).
- Only a few MU are required to produce an image.
- Uses technology that has been used in many other fields.

7.6 TREATMENT PLAN EVALUATION

7.6.5 Treatment evaluation

- **Matrix ionisation chamber detectors:**



Matrix ionisation chamber detectors:

- Are based on grid of ion chamber-type electrodes that measure ionisation from point to point.
- Detector consists of two metal plates, 1 mm apart with the gap filled with isobutene. Each plate is divided into 256 electrodes and the plates are oriented such that the electrodes in one plate are at 90° to the electrodes in the other.
- Voltage is applied between two electrodes across the gap and the ionisation at the intersection is measured. By selecting each electrode on each plate in turn, a 2D ionisation map is obtained and converted to a gray-scale image of 256×256 pixels.
- Maximum image size is usually smaller than for fluoroscopic systems.

Amorphous silicon detectors:

- Solid-state detector array consisting of amorphous silicon photodiodes and field-effect transistors arranged in a large rectangular matrix.
- Uses metal plate/fluorescent phosphor screen combination like the fluoroscopic systems. Light photons produce electron-hole pairs in the photodiodes whose quantity is proportional to the intensity allowing an image to be obtained.
- Produces an image with a greater resolution and contrast than the other systems.

7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

Introductory remark:

The process of treatment planning and optimization may be considered as completed if the calculated **relative** dose distribution shows an acceptable agreement with the PTV.

By way of example, the 80 % isodose curve may well encompasses the PTV.

It remains to determine the most important final parameter which controls the **absolute** dose delivery, that is:

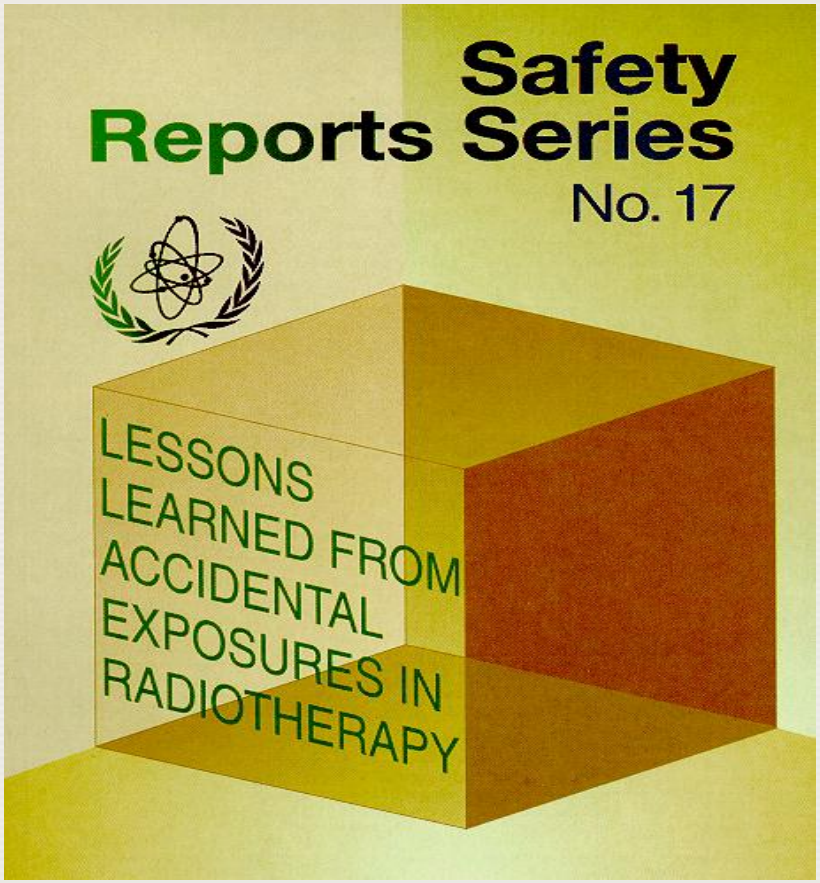
- **Treatment time** (for radiation sources).
  or
- **Monitor units** (for linacs).

7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

Data on treatment time and/or monitor units are usually provided by modern TPS after having passed the "dose prescription" procedure.

However, a **manual calculation** method to obtain such data **independent from the TPS** is of highest importance.

- Accidents in radiotherapy can and do happen.



7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

Before going into the details of manual calculation methods for an individual plan, a clear understanding of the following associated issues is required:

- Techniques used for **patient setup**:
  - Fixed SSD setup.
  - Isocentric setup.
- Methods used for :
  - **Dose prescription**
  - **Addition of dose** from multiple fields.
- Formulas used for **central axis dose calculations.**

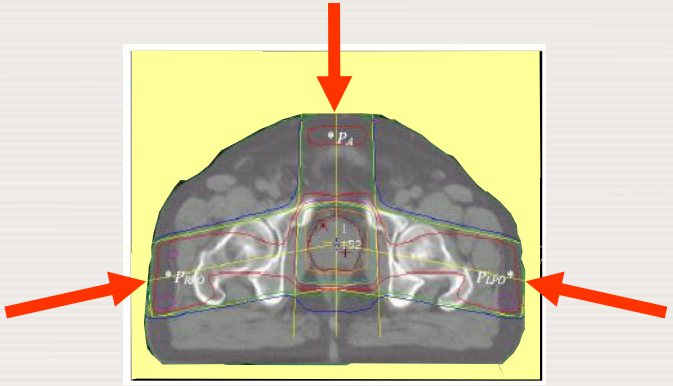
7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

Methods used for patient setup: (already shown previously)

- Patient treatments are carried out either with a fixed SSD or isocentric technique.
- Each of the two techniques is characterized with a specific dose distribution and treatment time or monitor unit calculation.

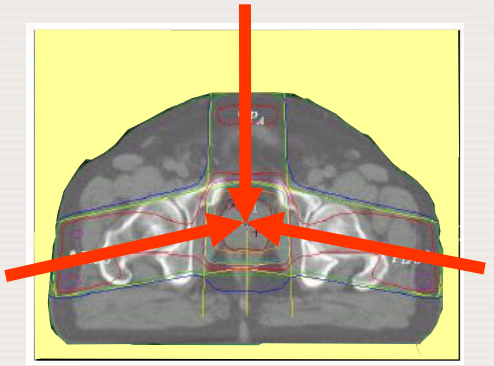
7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

Fixed SSD technique



Fixed SSD technique results in an isodose distribution that is typically governed by **percentage depth dose data**.

Isocentric technique



Isocentric technique results in an dose distribution that is typically governed by **tissue-maximum ratios** (or **tissue-phantom ratios**).

Methods used for dose prescription

Determination of treatment time or monitor units (whether by the treatment planning system or manually)
is directly related to the two following actions:

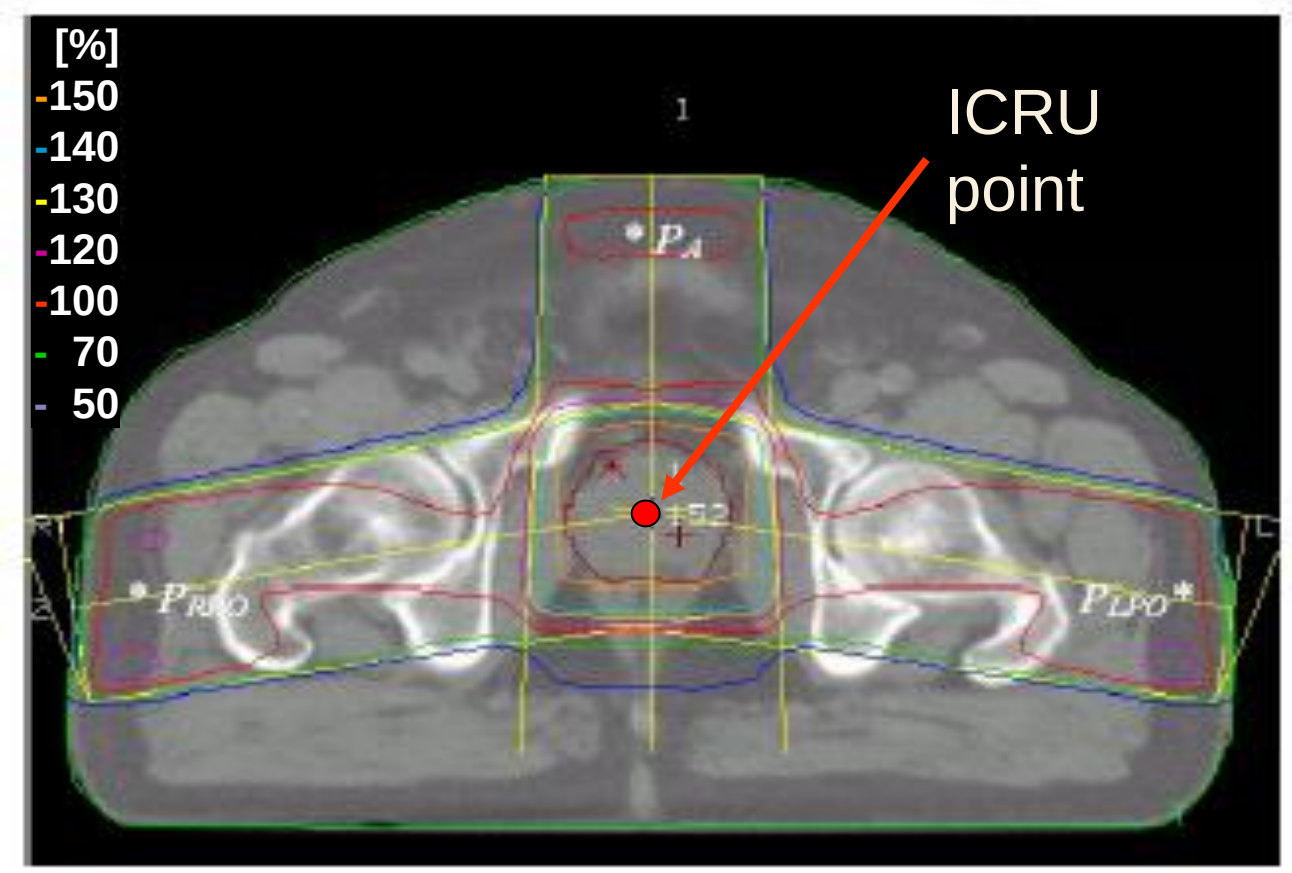
- Selection of an appropriate point for dose prescription (recommended by ICRU: the ICRU reference point).
- Prescription of an absolute dose at this point.

7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

Example:

- The ICRU point is located at the intersection of three fields.
- A dose of 200 cGy per fraction is prescribed at the ICRU point.

Isodose distributions of a three field treatment of the prostate using fixed SSD on a 6 MV linac



Methods used for dose prescription (continued)

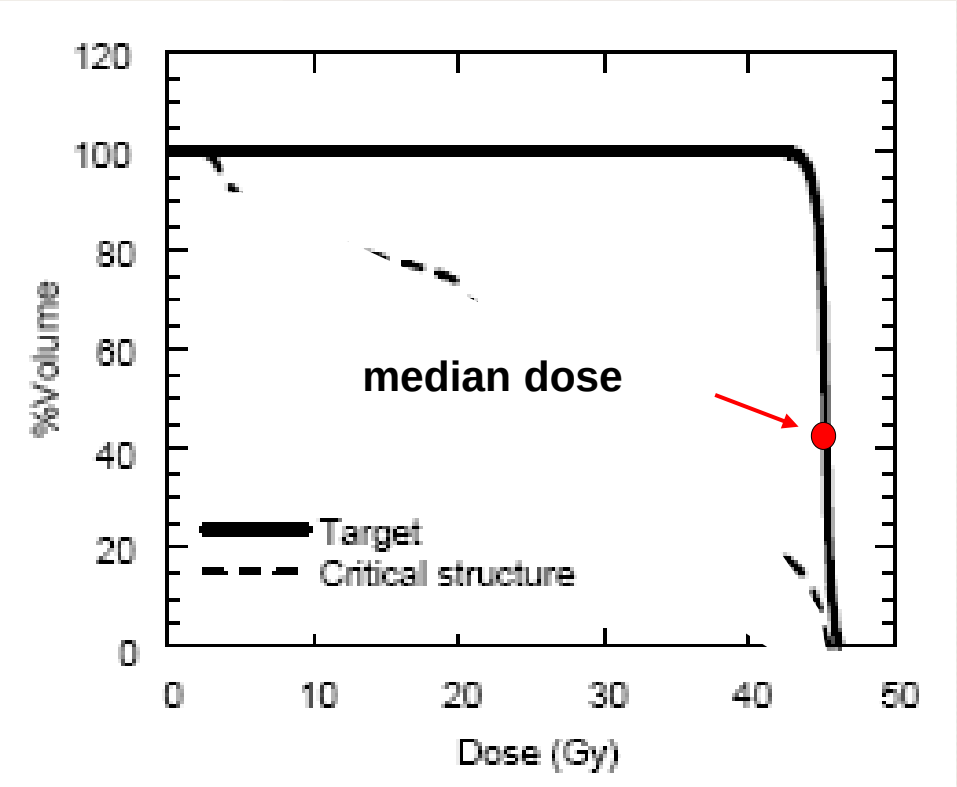
- There are also other methods such as using a **dose volume histogram** (DVH).
- This method is particular useful for IMRT when the evaluation of a treatment plan is based on the DVH of the target.
- Method consists of assigning the prescribe dose to the **median dose** in the target volume.

Methods used for dose prescription (continued)

- *Example* is shown in the DVH:

  Median dose is the dose at the 50 % volume level.

- Since this method is not applicable in manual dose calculations, it is not further explained in the following slides.



7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

Methods used for adding the dose at the ICRU point from multiple fields:

1. The simplest method (usually not used):

   Each field contributes to the total prescribed dose at the ICRU point using an **equal number** of MU (or equal treatment time).

2. Each field contributes to the total prescribed dose at the ICRU point with **different weights**.
   Prescribed weights for individual fields may refer to:

   - ICRU point IP (used for the isocentric techniques).
   - Point of maximum dose D_{max} of each field (used for fixed SSD techniques).

7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

- In the following slides two examples are shown to calculate treatment time or monitor units when using different weights at the ICRU point.
- The method used is divided into 5 steps and is based on well known central axis formulas for the dose calculation (at the ICRU point).
- ***Note*: This method deviates slightly from that given in the Handbook.**

7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

The five steps are:

1. Get calibrated output of the machine at the calibration reference point.
2. Determine the dose at the ICRU point (IP) from each beam, initially for an arbitrary value of 100 MU.
3. Rescale the MUs such that the dose contributions (at IP or D_{max}) are proportional to the pre-defined weights and sum up the total resultant dose using the rescaled MUs.
4. Determine the ratio between the prescribed dose and the sum dose at IP obtained in step 3.
5. Rescale again the MUs (from step 3) by the ratio obtained in step 4 to get finally the required MU.

7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

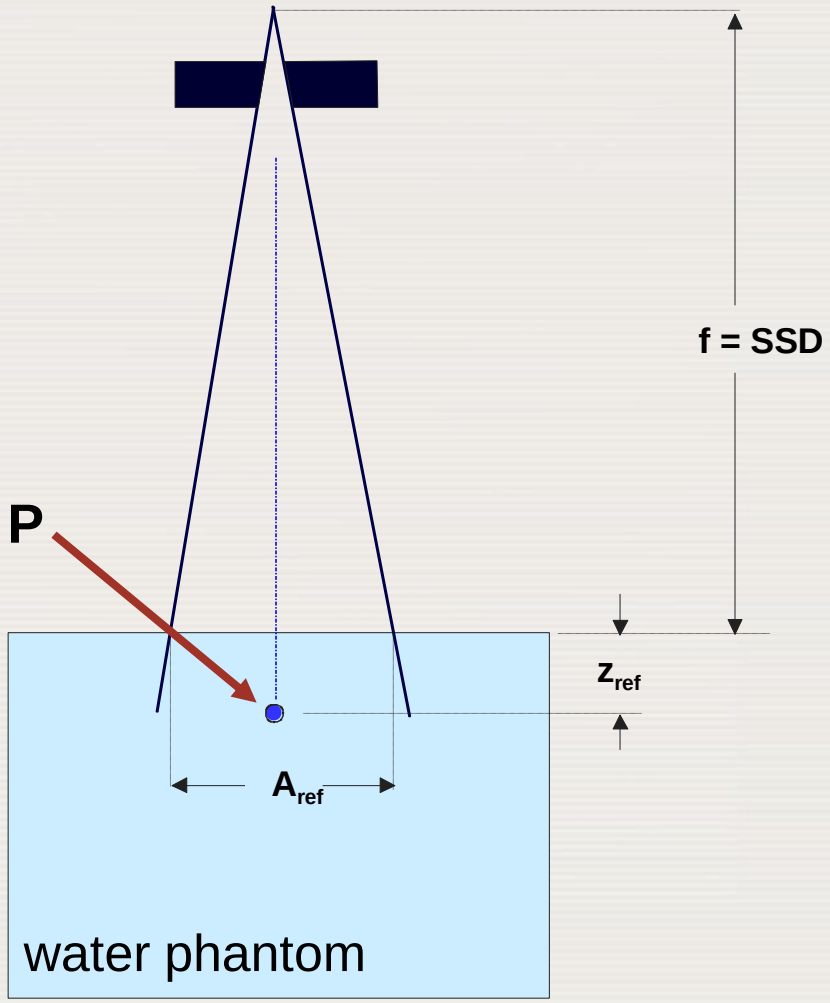
Step 1: **Calibrated output of the machine**

- For kilovoltage X ray generators and teletherapy units the output is usually given in Gy/min.
- For clinical accelerators the output is given in Gy/MU.
- For superficial and orthovoltage beams and occasionally for beams produced by teletherapy radionuclide machines, the basic beam output may also be stated as the air kerma rate in air (Gy/min) at a given distance from the source and for a given nominal collimator or applicator setting.

7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

Output for a radiotherapy machine is usually stated:

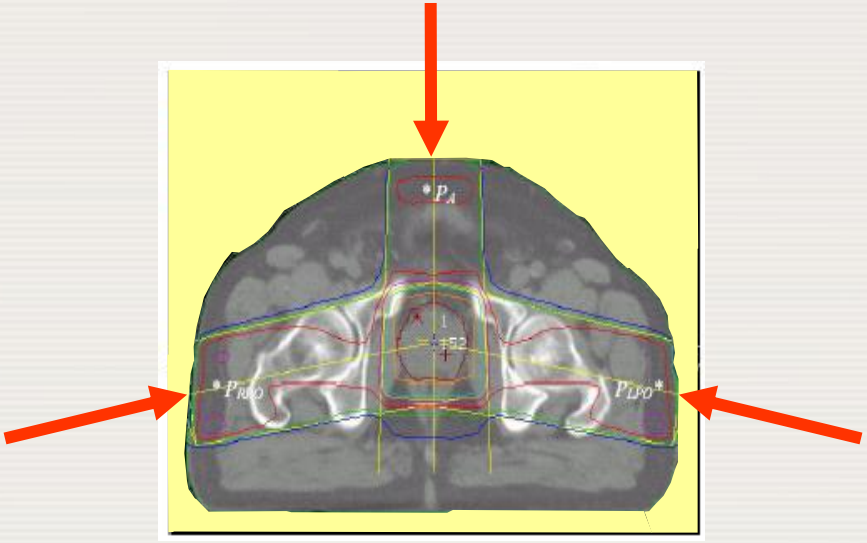
- In water phantom.
- As the dose rate for a point P at a reference depth z_{ref} (often the depth of maximum dose z_{max}).
- For a nominal source - surface distance (SSD) or source - axis distance (SAD)
- Reference field size A_{ref} (often 10×10 cm^2) on the phantom surface or the isocenter.



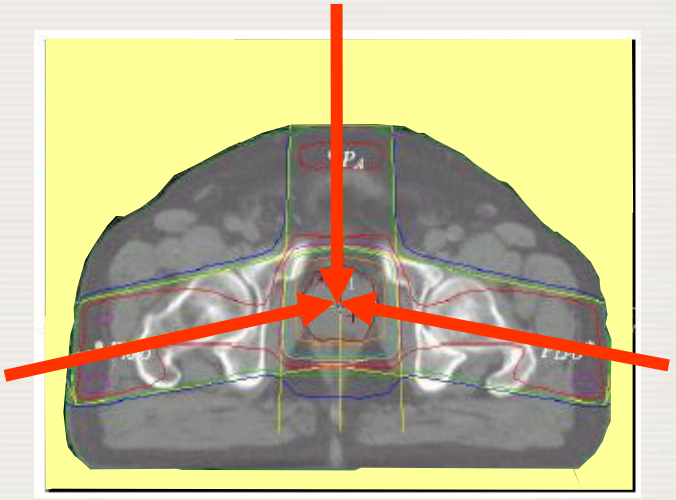
7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

- Second step is performed differently depending on whether the **fixed SSD set-up** or the **isocentric set-up** is used.

Fixed SSD



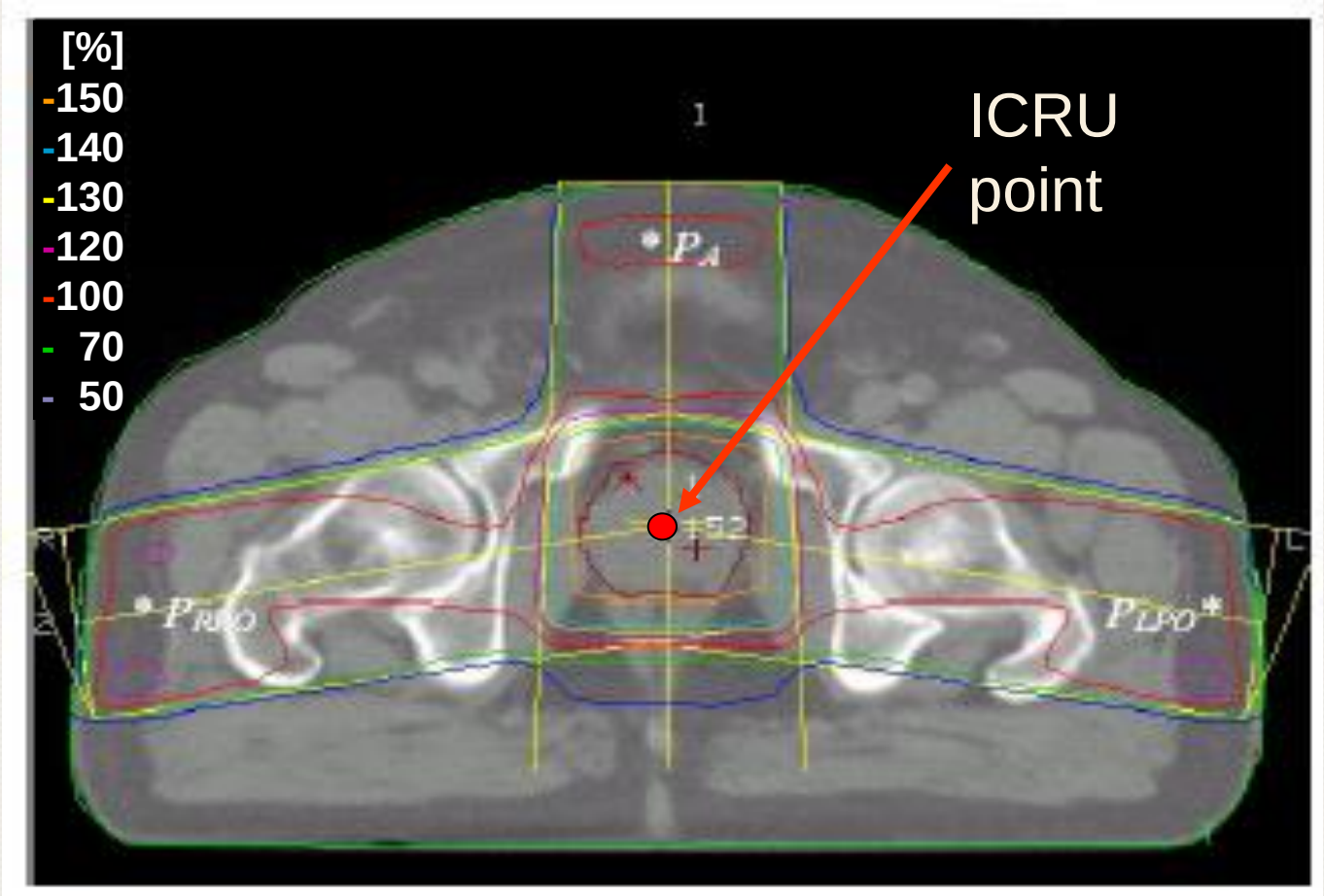
Isocentric technique



7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

7.7.1 Calculations for fixed SSD set-up

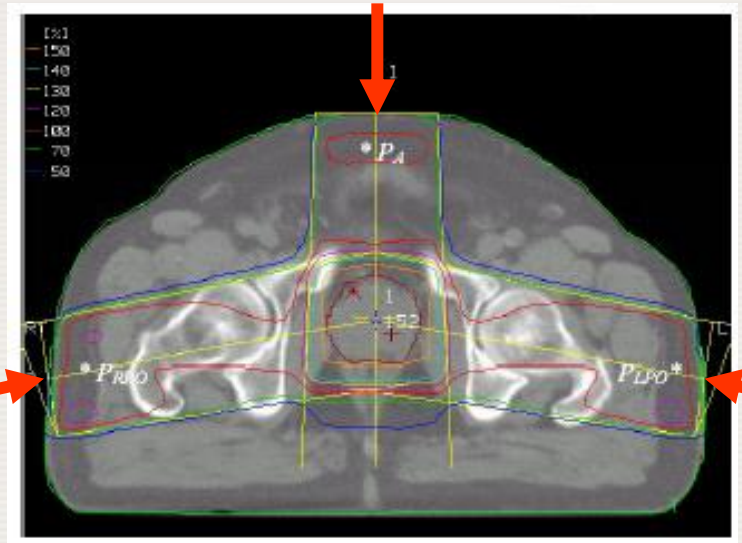
Example of isodose distributions of a three field treatment of the prostate using fixed SSD on a 6 MV linac



Field parameters as obtained from the treatment planning:

Anterior field:
7.5×7.5 cm^2 open field
weight *W* = 1.0

Right posterior field:
6.5×7.5 cm^2 wedge field
weight *W* = 0.8
wedge factor WF =0.53



Left posterior field:
6.5×7.5 cm^2 wedge field
weight *W* = 0.8
wedge factor WF =0.53

7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

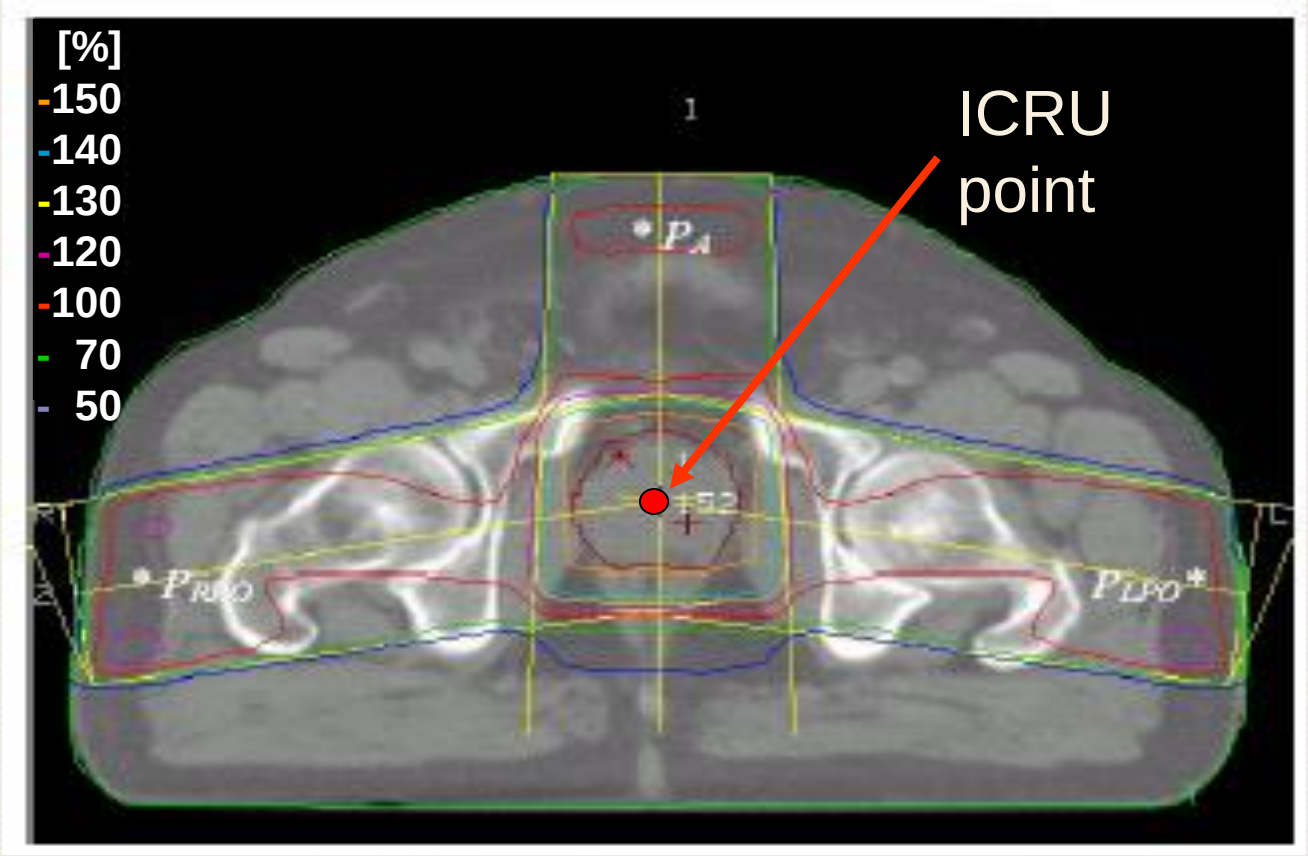
7.7.1 Calculations for fixed SSD set-up

Note:
Prescribed weights refer to the point of maximum dose in each field:

P_A $W = 1.0$

P_{RPO} $W = 0.8$

P_{RPO} $W = 0.8$



7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

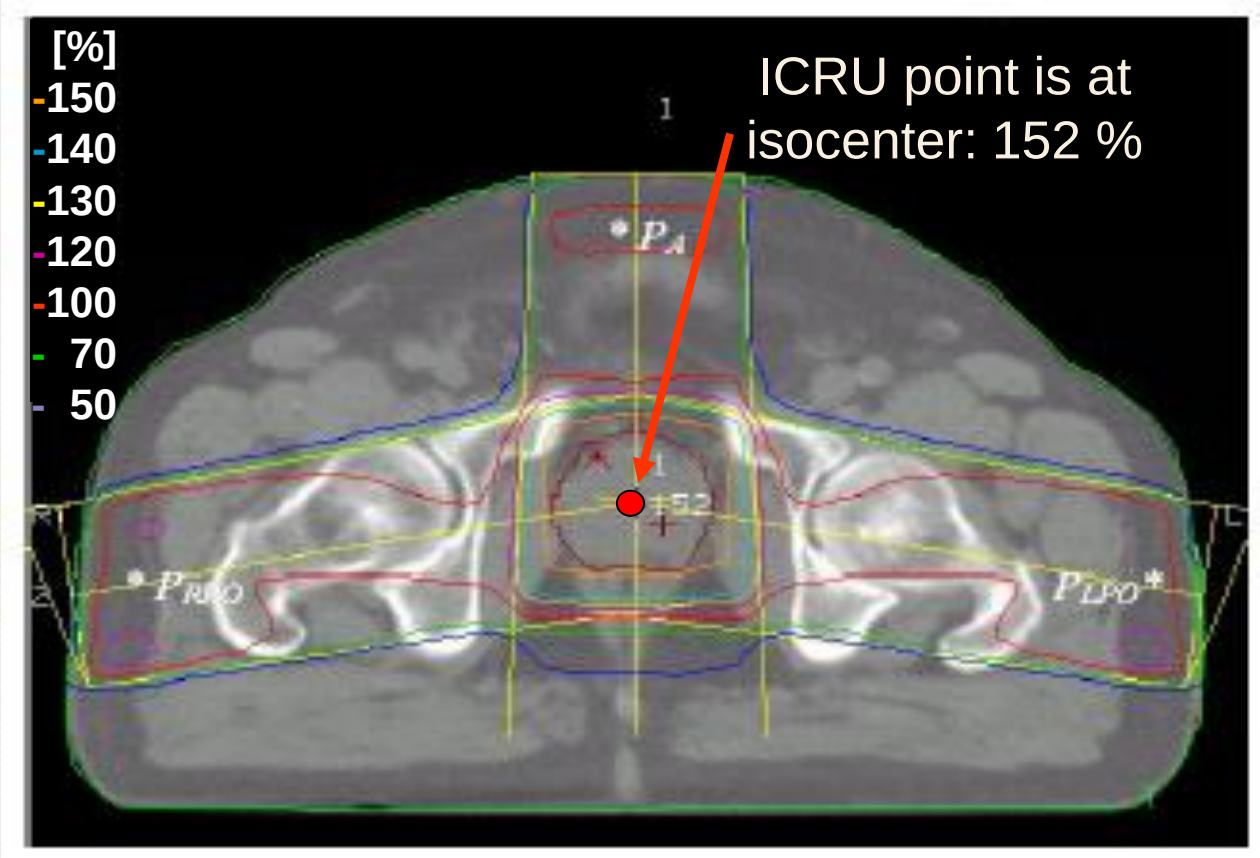
7.7.1 Calculations for fixed SSD set-up

Normalization was first performed for each field individually:

Anterior field:
D_{max} *refers to* 100 %
Right posterior field:
D_{max} *refers to* 80 %
Left posterior field:
D_{max} *refers* to 80 %

Isodose lines are then obtained by summing up the individual %-values.

Method of normalization:



Step 2: For each field i, the dose at the ICRU point, $D_i(\mathrm{IP})$, is calculated by (using 100 MU):

$$D_i(\mathrm{IP}) = \dot{D}(z_{max}, A_{ref}, f, E) \times \frac{PDD(z, A, f, E)}{100} \times \mathrm{RDF}(A, E) \times \mathrm{WF} \times 100$$

where

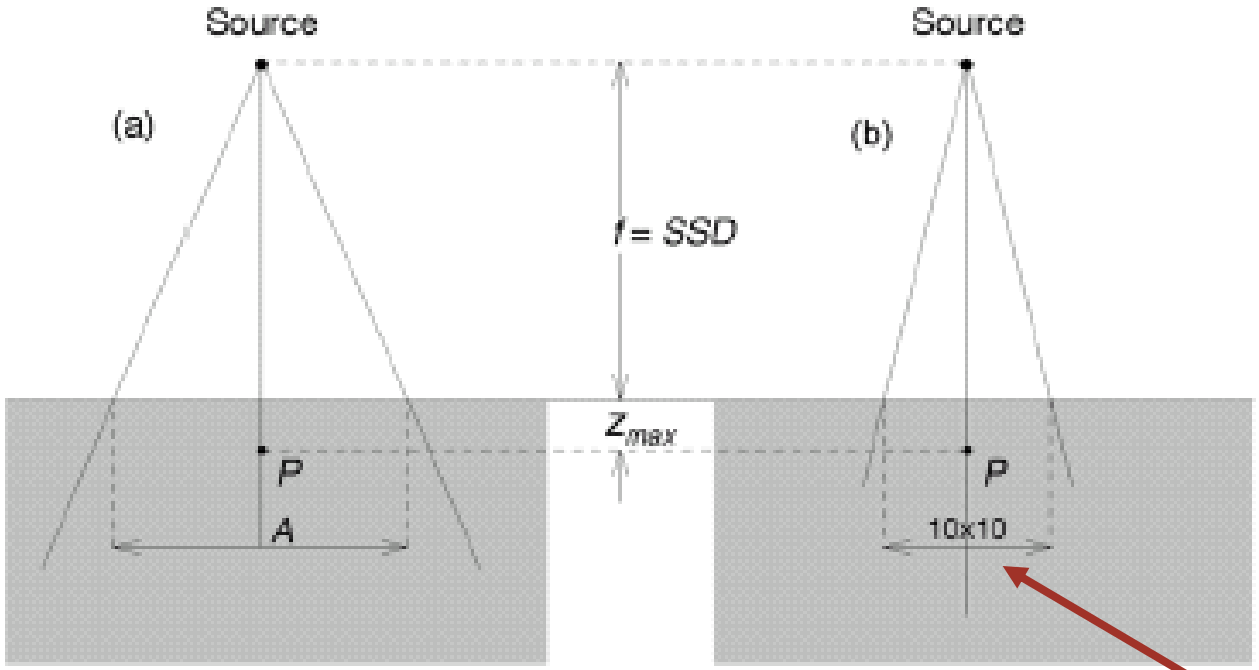
$\dot{D}(z_{max}, A_{ref}, f, E)$	is the calibrated output of the machine
$\mathrm{PDD}(z, A, f, E)$	is the percentage depth dose value
WF	is the wedge factor
RDF(A,E)	is the relative dose factor (see next slide)

Relative dose factor RDF describes the field size dependence:

- For a given beam energy *E*, the dose at the calibration point P (at depth z_{ref}) depends on the field size *A*.
- The ratio of dose to that of reference field size A_{ref} is called the **output factor**, also known as **total scatter factor**.
- The IAEA Handbook is using the expression: **relative dose factor (RDF)**:

7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

7.7.1 Calculations for fixed SSD set-up



- RDF is defined as:

$$\mathrm{RDF}(A,E) = \frac{D_P(z_{ref}, A, \mathrm{SSD}, E)}{D_P(z_{ref}, A_{ref}, \mathrm{SSD}, E)}$$

Step 3: Rescale the MUs such that the dose contributions at D_{max} are proportional to the pre-defined weights and sum up the total resultant dose using the rescaled MUs.

Field	Starting MU	Dose at D_{max}	Weight	Weighted dose at D_{max}	Rescaled MU	Dose at IP
Anterior	100	98.0	1.0	100 %=98.0	100	69.5
Left post.	100	51.4	0.8	80 % =78.4	152	39.7
Right post.	100	51.4	0.8	80 % =78.4	152	39.7

Σ(dose) = 148.96

Step 4: Determine the ratio between the prescribed dose and the sum dose at IP obtained in step 3.

Prescribed dose = 200 cGy

Calculated dose = 148.96 cGy

$$\text{Ratio} = \frac{200}{148.96} = 1.343$$

Step 5: Rescale again the MUs (from step 3) by the ratio obtained in step 4 to get finally the required MU.

- Anterior field: 100 MU × 1.343 = **134 MU**
- Left posterior field: 152 MU × 1.343 = **205 MU**
- Right posterior field: 152 MU × 1.343 = **205 MU**

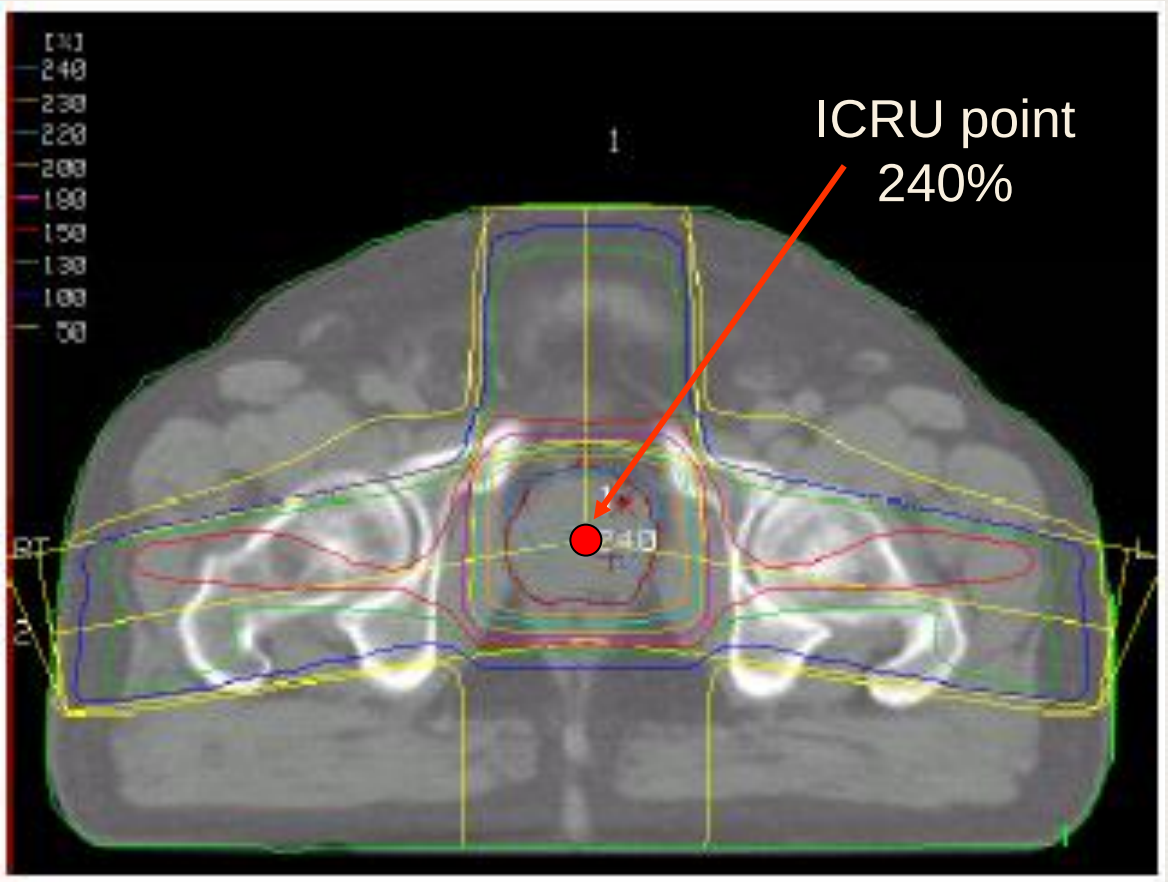
7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

7.7.2 Calculations for isocentric set-ups

Example for an isodose distribution obtained for a 3 field prostate boost treatment with an isocentric technique

In this *example*, the normalization was performed for each beam individually such that $D_{\text{isocenter}}$ is 100 % times the beam weight.

Isodose lines are then obtained by summing up the individual %-values.

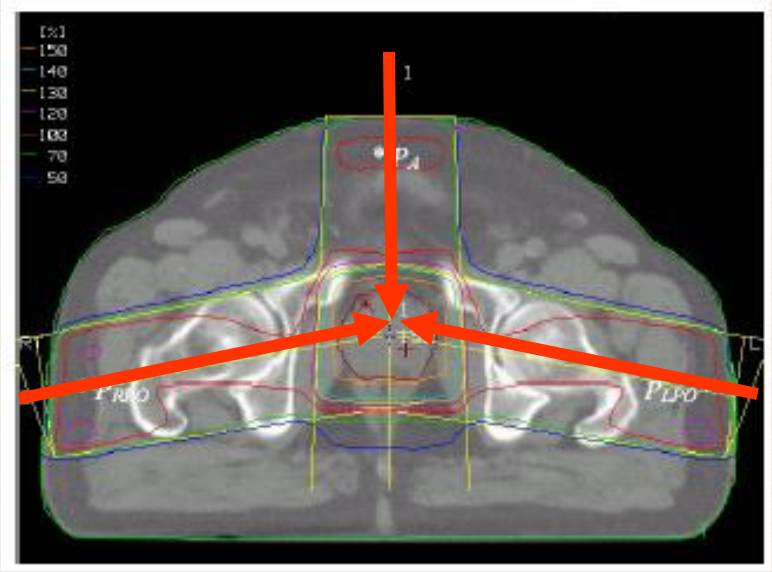


7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

7.7.2 Calculations for isocentric set-ups

Field parameters as obtained from the treatment planning:

Anterior field:
8×8 cm^2 open field
PDD = 70.9, W = 1.0



Right posterior field:
7×8 cm^2 wedge field
PDD = 50.7, *W* = 0.7
wedge factor WF =0.53

Left posterior field:
7×8 cm^2 wedge field
PDD = 50.7, *W* = 0.7
wedge factor WF =0.53

Step 2: For each field i, the dose at the ICRU point, $D_i(\mathrm{IC})$, is calculated by (using 100 MU):

$$D_i(\mathrm{IC}) = \dot{D}(z_{max}, A_{ref}, f, E) \times \mathrm{TMR}(A,z) \times \mathrm{ISF} \times \mathrm{RDF}(A,E) \times \mathrm{WF} \times 100$$

where:

$\dot{D}(z_{max}, A_{ref}, f, E)$	is the calibrated output of the machine.
TMR(A,z)	is the tissue-maximum-ratio at depth z.
WF	is the wedge factor.
RDF(A,E)	is the relative dose factor.
ISF	is the inverse-square factor (see next slide).

When the calibrated output factor $\dot{D}(z_{max}, A_{ref}, f, E)$ is used in isocentric calculations, it must be corrected by the inverse-square factor ISF unless the machine is actually calibrated at the isocentre:

$$ISF = \left[\frac{SSD + z_{max}}{SSD}\right]^2$$

Step 3: Rescale the MUs such that the dose contributions at the IP are proportional to the pre-defined weights and sum up the total resultant dose using the rescaled MUs.

Field	Starting MU	Dose at IP	Weight	Weighted dose at IP	Rescaled MU
Anterior	100	73.1	1.0	100 %= 73.1	100
Left post.	100	28.7	0.7	70 % = 51.2	178
Right post.	100	28.7	0.7	70 % = 51.2	178

↓

Σ(dose) = 175.44

Step 4: Determine the ratio between the prescribed dose and the sum dose at IP obtained in step 3.

- Prescribed dose = 200 cGy
- Calculated dose = 175.44 cGy

$$\text{Ratio} = \frac{200}{175.44} = 1.140$$

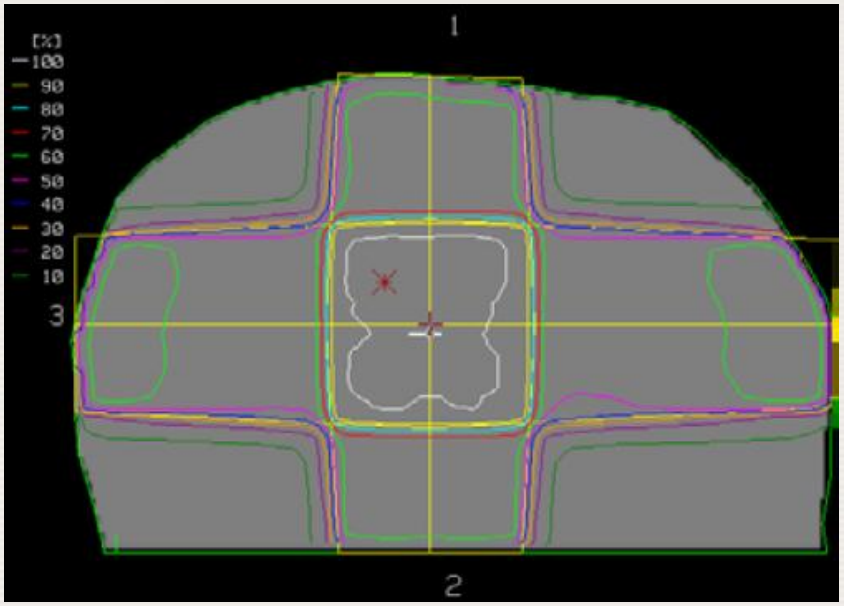
Step 5: Rescale again the MUs (from step 3) by the ratio obtained in step 4 to get finally the required MU.

- Anterior field: 100 MU x 1.14 = **114 MU**
- Left posterior field: 178 MU x 1.14 = **203 MU**
- Right posterior field: 178 MU x 1.14 = **203 MU**

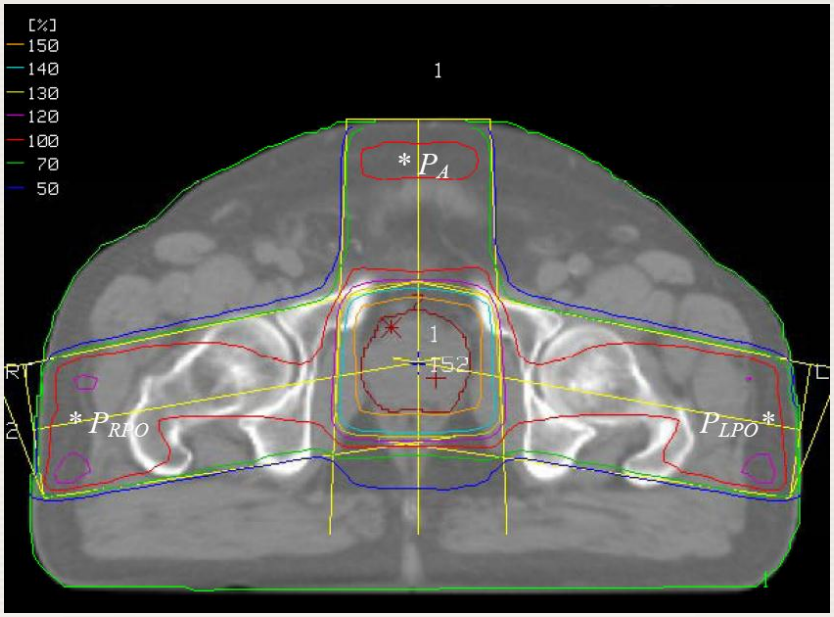
7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

7.7.3 Normalization of dose distributions

Important: Dose distributions can be normalized in different ways:



Normalized to maximum dose



Normalized such that 100 % = 100cGy

7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

7.7.3 Normalization of dose distributions

- Frequently the dose distribution is normalized to the maximum dose.
- The ICRU recommends normalization of the dose distribution to 100 % at the prescription point.
- As a consequence, values of the dose distribution larger than 100 % will be obtained if the prescription point is not located at the point of maximum dose.
- If the isodose values generated by the TPS itself are used for the monitor calculations, the **method of normalization used in the TPS must be taken into account**.

7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

7.7.4 Inclusion of output parameters in dose distribution

- Modern treatment planning systems give the user the ability to take into account several dosimetric parameters in the dose distribution affecting the beam output.
- *For example*, the isodose values in a dose distribution may already include:
  - Inverse square law factors for extended distance treatments.
  - Effects on dose outputs from blocks in the field.
  - Tray and wedge factors.
- If the isodose values generated by the TPS are used for the monitor calculations, **it is of utmost importance to know exactly what the isodose lines mean**.

7.7 TREATMENT TIME AND MONITOR UNIT CALCULATIONS

7.7.5 Orthovoltage and cobalt-60 units

- Treatment time calculations for orthovoltage units and cobalt-60 teletherapy units are carried out similarly to the above examples except that machine outputs are stated in cGy/min and the treatment timer setting in minutes replaces the monitor setting in MU.
- Shutter correction should be included in the time set.