

Chapter 15: Special Procedures and Techniques in Radiotherapy

Set of 259 slides based on the chapter authored by
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of the IAEA publication:

*Radiation Oncology Physics:
A Handbook for Teachers and Students*

Objective:

To familiarize the student with the basic principles of special dose delivery and target localization techniques in radiotherapy.



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15.1 INTRODUCTION

- ❑ In addition to routine conventional external beam radiotherapy with photon or electron beams and brachytherapy, several **specialized radiotherapy techniques** have been developed for dose delivery or target localization.
- ❑ The special techniques are more labour intensive, require stringent quality assurance measures, and are generally practiced only in larger radiotherapy centers.



15.1 INTRODUCTION

- ❑ **The special dose delivery techniques are:**
 - Stereotactic external beam irradiation (SEBI)
 - Total body irradiation (TBI)
 - Total skin electron irradiation (TSEI)
 - Intraoperative radiotherapy (IORT)
 - Endorectal irradiation (Endocavitary rectal irradiation)
 - Conformal radiotherapy
 - Intensity modulated radiotherapy (IMRT)
 - Image guided radiotherapy (IGRT)



15.1 INTRODUCTION

☐ Special target localization techniques in radiotherapy are:

- Stereotaxy
- Image guided radiotherapy (IGRT)
- Respiratory gated radiotherapy
- Adaptive radiotherapy
- PET/CT/MRI/US fusion



15.2 STEREOTACTIC IRRADIATION

- ☐ Stereotactic irradiation comprises **focal irradiation** techniques that use multiple, non-coplanar photon radiation beams and deliver a prescribed dose of ionizing radiation to pre-selected and stereotactically localized lesions.
- ☐ The lesions are primarily in the brain; however, attempts are under way to extend the technique to other parts of the body.



15.2 STEREOTACTIC IRRADIATION

- ❑ From an obscure irradiation technique practised in the 1960s and 1970s in only a few specialized centres, **stereotactic irradiation** has during the past 20 years developed into a mainstream specialized radiotherapy technique practised in most major radiotherapy centres around the world.
- ❑ The dose in stereotactic irradiation may be delivered:
 - Through a stereotactic implantation of radioactive sources (**stereotactic brachytherapy**).
 - With one or several external radiation sources (**stereotactic external beam irradiation**).

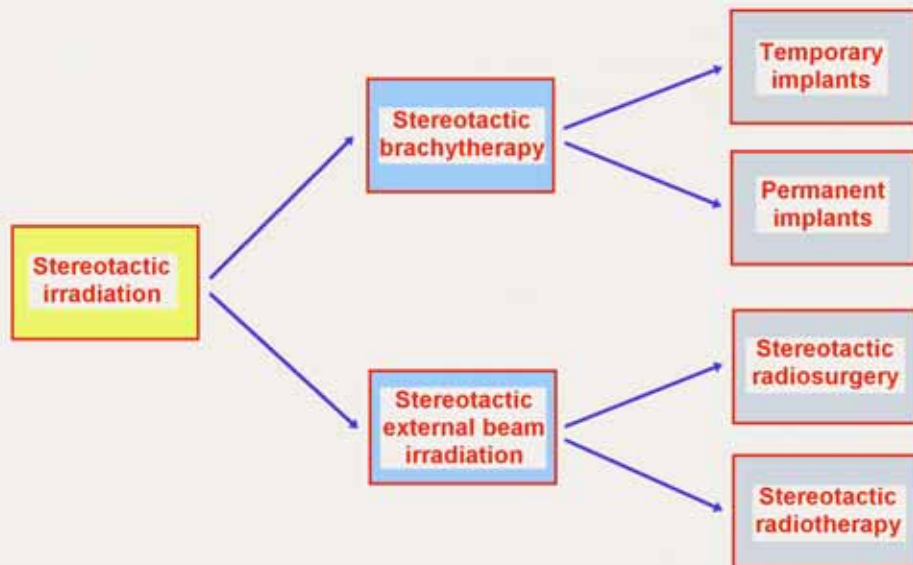


15.2 STEREOTACTIC IRRADIATION

- ❑ With regard to dose fractionation SEBI is divided into:
 - **Stereotactic radiosurgery** in which the total dose is delivered in a single treatment session.
 - **Stereotactic radiotherapy** in which the total dose is delivered in multiple fractions, similarly to standard radiotherapy.
- ❑ From a technical point of view there is essentially no difference between stereotactic radiosurgery and stereotactic radiotherapy, and often the term radiosurgery is used to describe both techniques.



15.2 STEREOTACTIC IRRADIATION



15.2 STEREOTACTIC IRRADIATION

- The main characteristics of stereotactic irradiation are:
- The total prescribed doses are of the order of 10 - 50 Gy
 - The planning targets are small, with typical volumes ranging from 1 to 35 cm³.
 - The requirements for positional and numerical accuracy in dose delivery are ± 1 mm and $\pm 5\%$, respectively.
 - Essentially any radiation beam that has been found useful for external beam radiotherapy has also found use in radiosurgery (cobalt-60 gamma rays, megavoltage x rays, proton and heavy charged particle beams, neutron beams).

15.2 STEREOTACTIC IRRADIATION

15.2.1 Physical and clinical requirements for radiosurgery

□ Physical requirements for radiosurgery are:

- Accurate determination of the target volume and its location with stereotactic techniques.
- Calculation of 3-D dose distributions inside and outside the target.
- Calculation of dose-volume histograms (DVHs) for the target and specific sensitive organs surrounding the target.
- Dose distributions that conform to target shape and give a sharp dose fall-off outside the target volume.
- Direct superposition of isodose distributions on diagnostic images, showing the anatomical location of the target.



15.2 STEREOTACTIC IRRADIATION

15.2.1 Physical and clinical requirements for radiosurgery

□ Clinical requirements for radiosurgery are:

- Accurate knowledge of the total dose and fractionation scheme required for treatment of a particular disease.
- Accurate positional (within ± 1 mm) delivery of dose to the pre-determined target.
- Accurate numerical (within $\pm 5\%$) delivery of dose to the pre-determined target.
- Low skin dose (to avoid epilation) and low eye lens dose (to avoid cataract formation).
- Low or negligible scatter and leakage dose to radiosensitive organs (to avoid subsequent somatic and genetic effects)



15.2 STEREOTACTIC IRRADIATION

15.2.2 Diseases treated with stereotactic irradiation

□ The diseases treated with stereotactic irradiation fall into one of five categories:

- **Functional disorders:** trigeminal neuralgia - Parkinson's disease -
- epilepsy - intractable pain - psychoneurosis
- **Vascular lesions:** arteriovenous malformation (AVM) -
- acoustic neuroma - cavernous angioma - arterial aneurism
- **Primary benign tumours:** pituitary adenoma - meningioma -
- chordoma - craniopharyngioma - meningioblastoma
- **Primary malignant tumours:** glioblastoma multiforme (GBM) -
- pineal tumour - medulloblastoma - lymphoma
- **Metastatic tumours**



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15.2 STEREOTACTIC IRRADIATION

15.2.2 Diseases treated with stereotactic irradiation

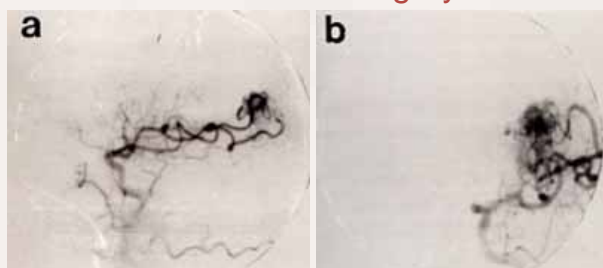
□ **Vascular lesion: Arterio-venous malformation (AVM)**

AVM is a mass of abnormal blood vessels in the brain consisting of a “nidus” through which the arteries connect directly to veins instead of through capillaries.

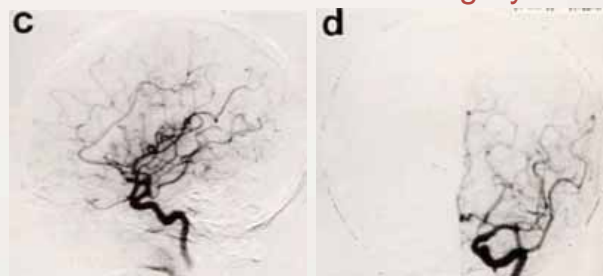
Treatment options:

- **Surgery**
- **Embolization**
- **Stereotactic radiosurgery**

Before radiosurgery



6 months after radiosurgery



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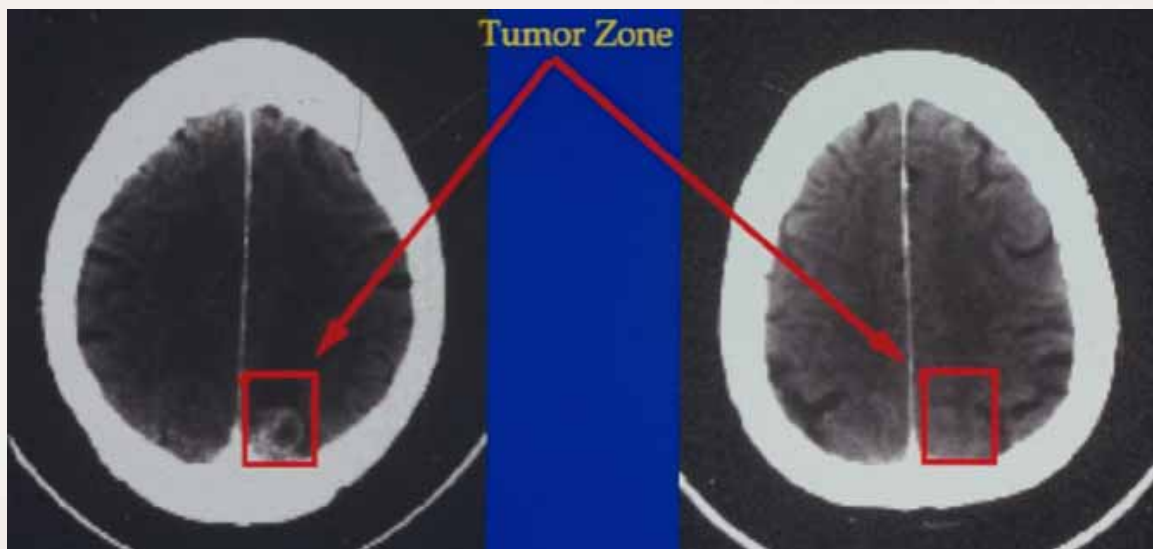
15.2 STEREOTACTIC IRRADIATION

15.2.2 Diseases treated with stereotactic irradiation

- ☐ Metastatic disease treated with stereotactic radiosurgery

Before treatment

3 months after treatment



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15.2 STEREOTACTIC IRRADIATION

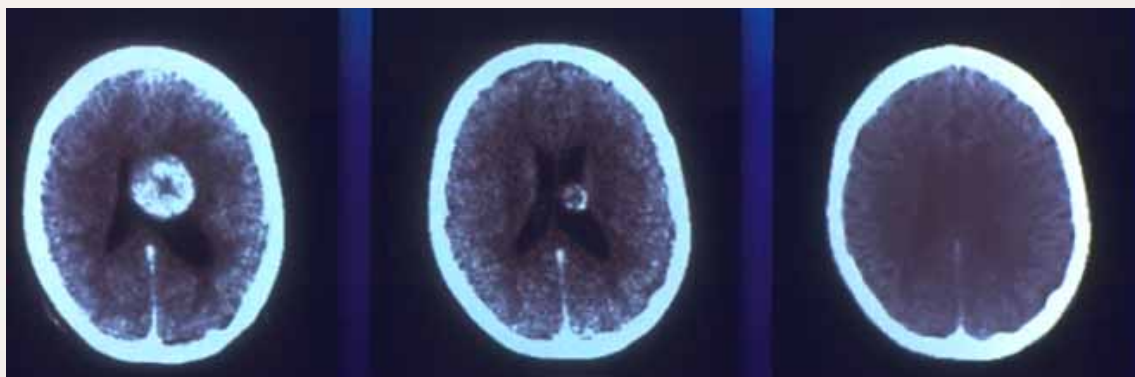
15.2.2 Diseases treated with stereotactic irradiation

- ☐ Solitary metastatic lesion treated with radiosurgery

Before treatment

One month after
treatment

Three months after
treatment



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15.2 STEREOTACTIC IRRADIATION

15.2.3 Equipment used for stereotactic radiosurgery

□ Equipment for stereotactic radiosurgery:

- **Stereotactic frame:** defines a fixed coordinate system for an accurate localization and irradiation of the planning target volume (PTV).
- **Imaging equipment** (CT, MRI and DSA) with which the structures, lesions and PTVs are visualized, defined and localized.
- **Target localization software:** used in conjunction with the stereotactic frame system and imaging equipment to determine the coordinates of the target in the stereotactic reference system.
- **Treatment planning system:** calculates the 3-D dose distribution and superimposes it onto the patient's anatomical information.
- An appropriate **radiation source** and **radiosurgical treatment technique**.



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15.2 STEREOTACTIC IRRADIATION

15.2.3 Equipment used for stereotactic radiosurgery

□ Stereotactic frame



The first human stereotactic frame
designed by Mussen and built about 1918

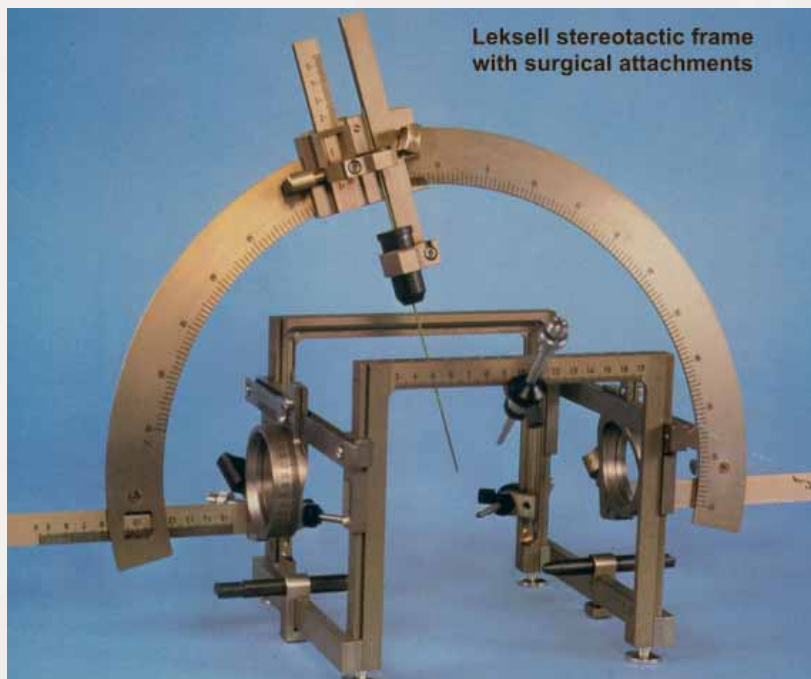


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15.2 STEREOTACTIC IRRADIATION

15.2.3 Equipment used for stereotactic radiosurgery

- Stereotactic frame

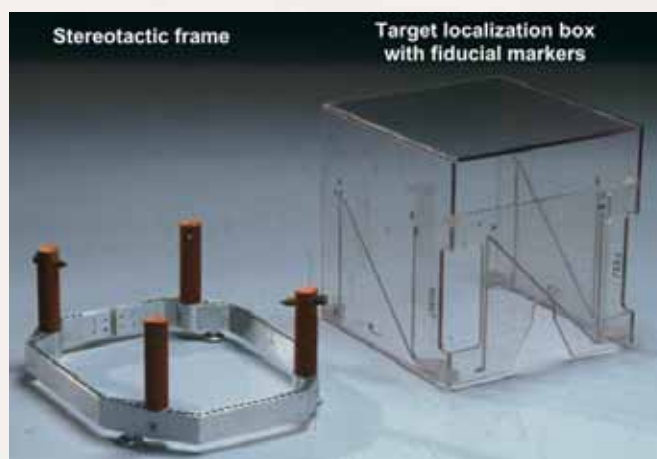


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15.2 STEREOTACTIC IRRADIATION

15.2.3 Equipment used for stereotactic radiosurgery

- Stereotactic frame



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15.2 STEREOTACTIC IRRADIATION

15.2.3 Equipment used for stereotactic radiosurgery

□ Stereotactic frame

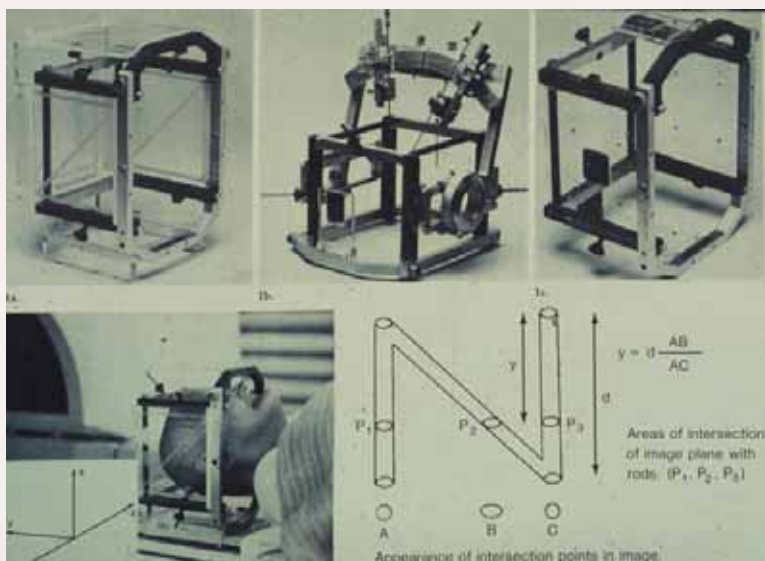


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15.2 STEREOTACTIC IRRADIATION

15.2.3 Equipment used for stereotactic radiosurgery

□ Stereotactic frame and fiducial markers

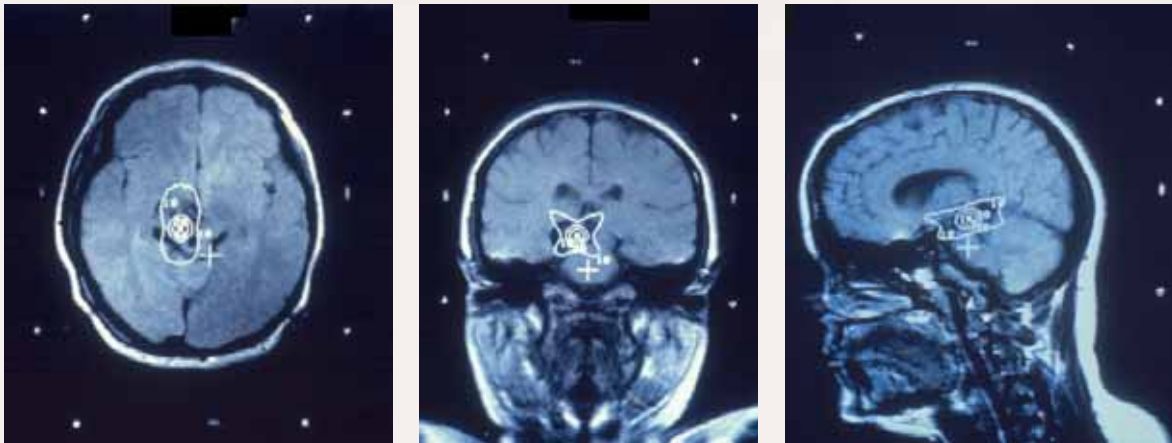


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15.2 STEREOTACTIC IRRADIATION

15.2.3 Equipment used for stereotactic radiosurgery

- Stereotactic frame, fiducial markers and dose distributions



The white dots in the images are the fiducial markers resulting from the Intercept of CT slice with the fiducial marker plates.



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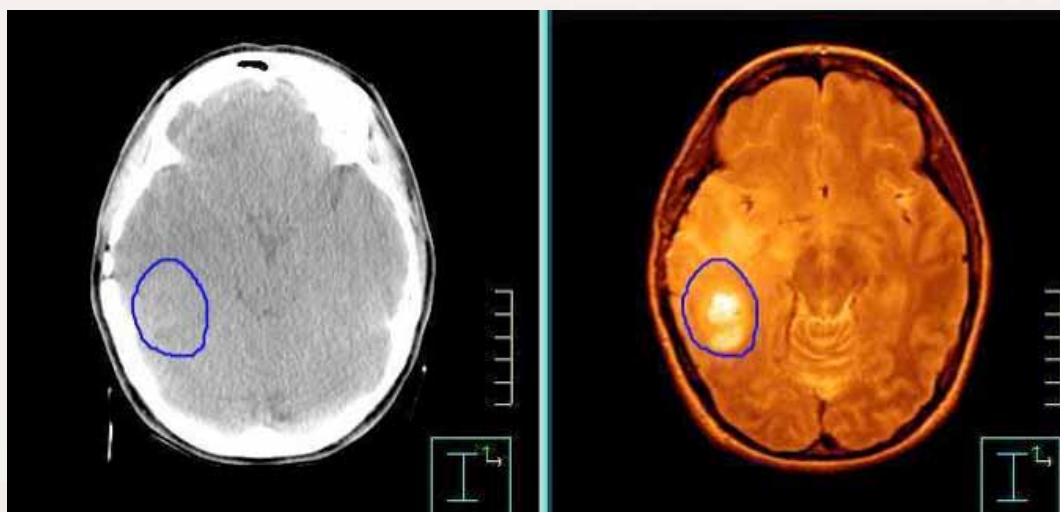
15.2 STEREOTACTIC IRRADIATION

15.2.3 Equipment used for stereotactic radiosurgery

- Imaging for target localization: CT and MRI

CT

MRI



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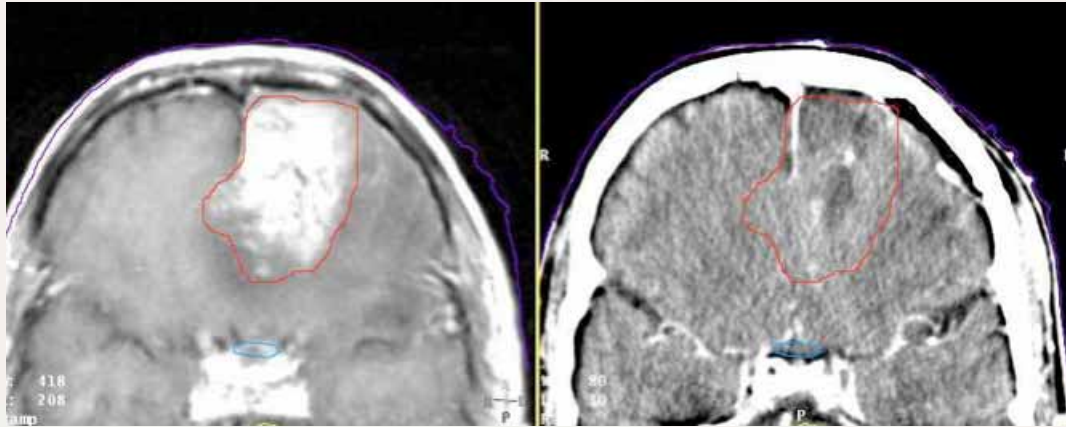
15.2 STEREOTACTIC IRRADIATION

15.2.3 Equipment used for stereotactic radiosurgery

- Imaging for target localization: CT and MRI

CT

MRI



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15.2 STEREOTACTIC IRRADIATION

15.2.4 Historical development

- Combined use of stereotaxy and irradiation was introduced by **Lars Leksell** in 1951 in Stockholm, Sweden.
- Leksell also coined the term “**radiosurgery**” to describe the technique of stereotactic irradiation with a high, single dose of radiation.



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15.2 STEREOTACTIC IRRADIATION

15.2.4 Historical development

- ❑ Acta Chir. Scand. 102, 316-319 (1951).

The Stereotaxic Method and Radiosurgery of the Brain

By

Lars Leksell

“The stereotaxic technique enables the accurate insertion of a needle electrode into any given structure of the brain and its destruction by electrolysis or electro-coagulation (HORSLEY & CLARKE, 1908; SPIEGEL *et al.*, 1947). It would therefore seem feasible to replace the needle by narrow beams of radiant energy directed at the target in the brain and thereby produce a local destruction of tissue (LEKSELL, 1951).”



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15.2 STEREOTACTIC IRRADIATION

15.2.4 Historical development

- ❑ Leksell started radiosurgery with 200 kVp x rays in the early 1950s but soon realized that orthovoltage x rays were not penetrating enough for use in intracranial radiosurgery.
- ❑ In the late 1950s Leksell moved radiosurgery to proton beams from a cyclotron. The technique is still in use today, but is not widespread because of the large installation and operating costs of cyclotrons.



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15.2 STEREOTACTIC IRRADIATION

15.2.4 Historical development

- ❑ All ionizing radiation beams used in radiotherapy were also found useful in radiosurgery with varying degrees of success:
 - Orthovoltage x rays from x-ray machines.
 - Protons and heavier ions from cyclotrons and synchrotrons.
 - Gamma rays from the Gamma Knife (201 gamma ray beams)
 - Megavoltage x rays from linacs (isocentric linacs and CyberKnife).
 - Neutron beams from cyclotrons.



15.2 STEREOTACTIC IRRADIATION

15.2.4 Historical development

- ❑ Leksell also designed and developed the Gamma Knife (1968) and the machine is still available commercially today.
- ❑ In 2005 there were over 100 Gamma Knife machines in clinical operation around the world.
- ❑ Megavoltage x ray beams from isocentric linacs are used in radiosurgery since the mid 1980s.



15.2 STEREOTACTIC IRRADIATION

15.2.4 Historical development (1950s and 1960s)

Combined use of stereotaxy and irradiation:

- ❑ 200 kVp **orthovoltage x rays**:
 - 1951 L. Leksell, Stockholm
- ❑ **Protons** from cyclotron:
 - 1958 B. Larsson, L. Leksell; Stockholm
 - 1962 J.H. Lawrence; Berkeley, CA
 - 1968 R.N. Kjellberg; Boston, MA



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15.2 STEREOTACTIC IRRADIATION

15.2.4 Historical development (1970s and 1980s)

Combined use of stereotaxy and irradiation:

- ❑ **Gamma Knife** (179 cobalt-60 sources)
 - 1968 L. Leksell; Stockholm
- ❑ **Megavoltage x rays** from isocentric linear accelerators
 - 1974 Proposed by B. Larsson; Stockholm
 - 1984 First clinical application, Betti and Derechinsky; Buenos Aires



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15.2 STEREOTACTIC IRRADIATION

15.2.4 Historical development (1980s)

Linac based stereotactic radiosurgery

❑ Multiple converging arcs

- 1984 Betti and Derechinsky; Buenos Aires
- 1985 Colombo, Benedetti et al.; Vicenza, Italy
- 1985 Hartmann, Schlegel et al.; Heidelberg, Germany
- 1988 Lutz, Winston et al.; Boston, MA

❑ Dynamic rotation

- 1987 Podgorsak, Olivier et al.; Montreal, Canada



15.2 STEREOTACTIC IRRADIATION

15.2.4 Historical development (1990s)

Linac based stereotactic radiosurgery

❑ Conical rotation (isocentric linac and special treatment chair)

- 1990 McGinley, Butker et al.: Atlanta, GA

❑ Cyberknife (miniature linac on robotic arm)

- 1995 Adler and Cox: Stanford, California

❑ Tomotherapy (miniature linac on CT gantry)

- 2000 Mackie: Madison, Wisconsin



15.2 STEREOTACTIC IRRADIATION

15.2.4 Historical development

- **Contemporary radiosurgery** is carried out mainly with Gamma Knife machines, but a significant number of radiosurgical procedures is also carried out with modified isocentric linacs and Cyberknife machines.
- CyberKnife incorporates a miniature linac mounted on a robotic arm. It is in clinical operation since the mid 1990s and in 2005 there were over 50 of these machines in clinical operation around the world.



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15.2 STEREOTACTIC IRRADIATION

15.2.4 Historical development

- Radiosurgery with 200 kVp x rays (Leksell 1950)

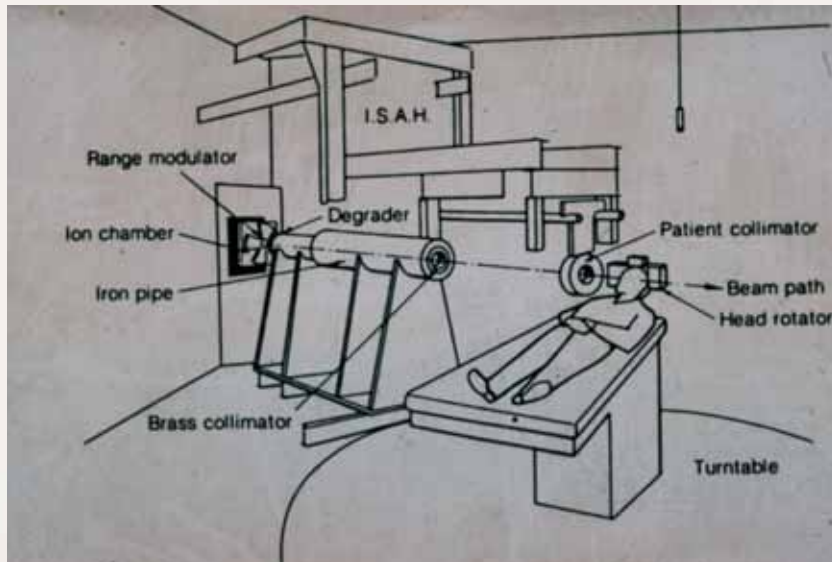


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15.2 STEREOTACTIC IRRADIATION

15.2.4 Historical development

☐ Radiosurgery with proton beams

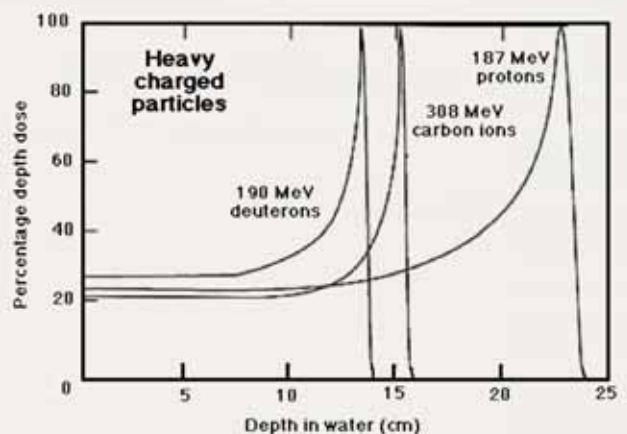
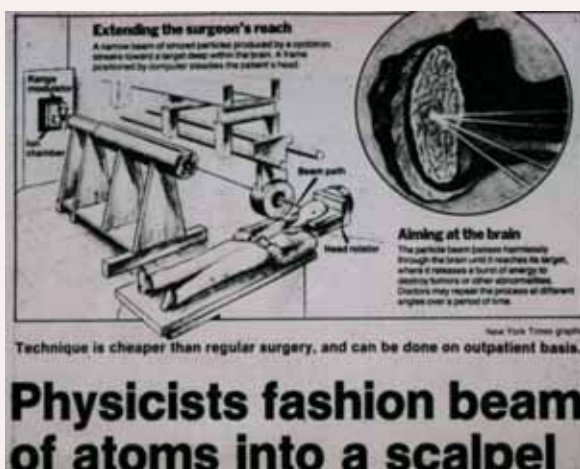


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15.2 STEREOTACTIC IRRADIATION

15.2.4 Historical development

☐ Radiosurgery with proton beams



1958 B. Larsson, L. Leksell; Stockholm

1962 J.H. Lawrence; Berkeley, CA

1968 R.N. Kjellberg; Boston, MA



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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

- ❑ **Gamma Knife (Gamma unit)** is a radiosurgical device that has been associated with, and dedicated to, radiosurgery for the past four decades.
- ❑ The fundamental design and principles of operation of the Gamma Knife have not changed much, since Leksell introduced the prototype in 1968.
- ❑ The Gamma unit incorporates 201 cobalt-60 sources, each source with an activity of 1.1 TBq (30 Ci).
- ❑ The sources produce 201 circular gamma ray beams directed to a single focal spot at an SAD of 40 cm.



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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

- ❑ Leksell Gamma Knife (older models)

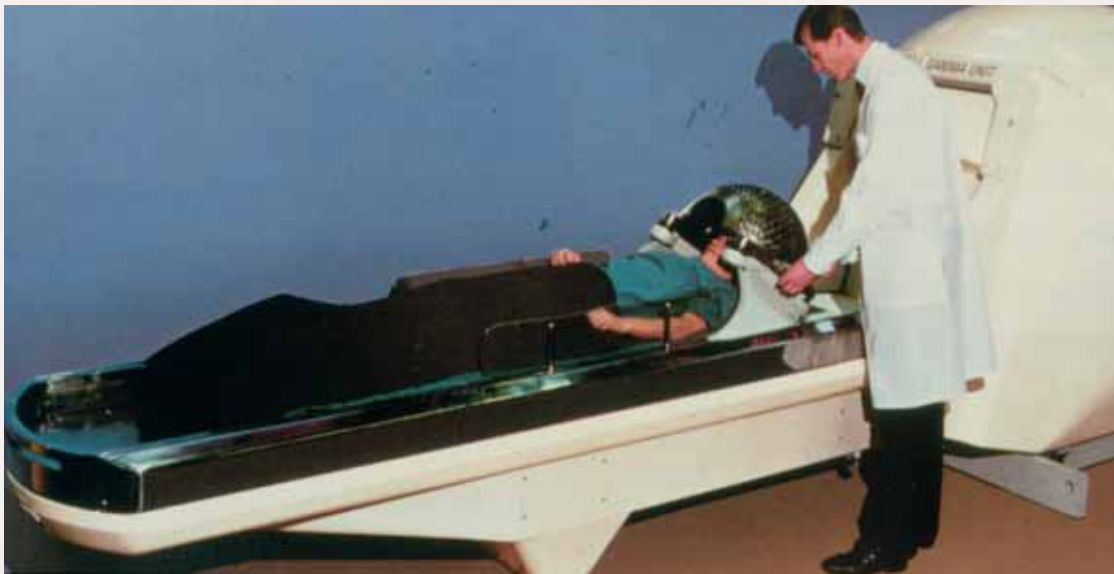


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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

□ Leksell Gamma Knife (older model)



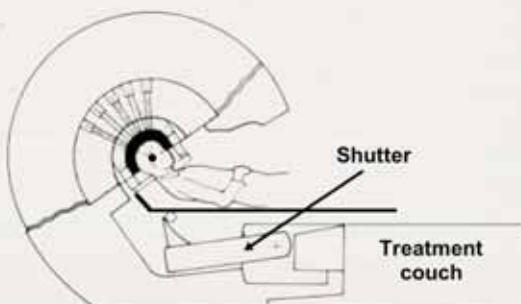
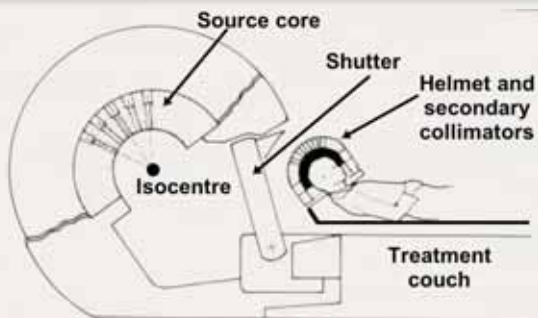
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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

□ Main components of the Gamma Knife:

- Source core
- 201 cobalt-60 sources
- Shutter mechanism
- Helmet and secondary collimators
- Treatment couch



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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques



State of the art **Gamma Knife** (Model 4C) showing:

- **Main body** of the machine containing 201 cobalt-60 sources each with a nominal activity of $30 \text{ Ci} = 1.1 \times 10^{12} \text{ Bq}$
- **Treatment table**
- **Collimator helmet** deployed for treatment.
- For collimator helmets are available producing circular fields with diameters of 4, 8, 14, and 18 mm.



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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Linac-based radiosurgery falls into three main categories:

- ☐ Radiosurgery with modified isocentric linac
 - Moving beam techniques
 - **Multiple non-coplanar converging arcs**
 - **Dynamic rotation**
 - **Conical rotation**
 - Multiple stationary beams in conjunction with miniature MLC
- ☐ Miniature linac mounted on robotic arm (CyberKnife)
- ☐ Miniature linac mounted on CT gantry (Tomotherapy)



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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Modifications to standard isocentric linacs for radiosurgery.

The **modifications** are relatively simple and consist of:

- **Supplementary collimation**
 - Either in the form of a set of collimators to define small diameter beams
 - Or with a miniature MLC to define small area irregular fields
- **Remotely controlled motorized table or treatment chair rotation.**
- **Table brackets or a floor stand** for immobilizing the stereotactic frame during treatment.
- **Special brakes** to immobilize the vertical, longitudinal and lateral table motions during treatment.
- **Interlocked readouts** for angular and height position of the couch.



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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

General aspects of radiosurgery with isocentric linacs:

- ☐ Most linac based radiosurgery procedures are carried out on modified isocentric linac used for standard radiotherapy.
- ☐ The requirements on mechanical stability of linacs are even more stringent in radiosurgery than in routine radiotherapy.
- ☐ The most important requirement of an isocentric linac used for radiosurgery is the mechanical stability and accuracy of its **isocentre**.



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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Linac isocentre

- ☐ Under ideal conditions, the linac isocentre is defined by the **fixed point of intersection** of the gantry rotation axis and the treatment couch or chair rotation axis.
- ☐ In practice, these axes do not intersect at a common point but only come closest together within a best **compromise sphere** which accounts for all possible combinations of gantry and couch or chair positions.
- ☐ The centre of this sphere is referred to as the nominal **isocentre** of the linac.



15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Linac isocentre in radiosurgery

- ☐ For linac based radiosurgery the diameter of the isocentre sphere must not exceed 1 mm.
- ☐ The uncertainty on the radiosurgical linac isocentre is of the same order of magnitude as the target localization accuracy achievable with modern imaging techniques, such as CT, MRI, and DSA.



15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Patient positioning for linac-based radiosurgery

- ☐ The stereotactically localized target is most commonly placed into the desired location with the help of treatment room laser positioning devices which, in the form of laser line cross-hairs, indicate the position of the nominal linac isocentre in the treatment room.
- ☐ The ceiling-mounted laser device indicates the couch rotation axis; the two side wall-mounted devices define the plane of gantry rotation.



15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Stereotactic frame immobilization in linac-based radiosurgery

- ☐ The immobilization of the stereotactic frame during the treatment is achieved with special brackets which attach the frame to the linac couch, chair, or a special floor stand.
- ☐ Direct couch mounting of the stereotactic frame is less expensive, safer for the patient, and more practical than mounting onto a floor stand.



15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Stereotactic frame attached
to floor stand



Stereotactic frame attached
to treatment couch



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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Collimation for linac-based radiosurgery

- ☐ Most linac based radiosurgical techniques use circular radiation beams which are produced by special collimators attached to the head of the linac.
- ☐ The circular beams are usually between 10 and 40 mm in diameter at the linac isocentre and are produced by 10 cm thick lead cylinders with appropriate circular holes drilled along their axes.
- ☐ The use of the original rectangular linac collimators for defining the small radiosurgical beams is not recommended.



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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

- Example of circular collimator attached to the linac head.



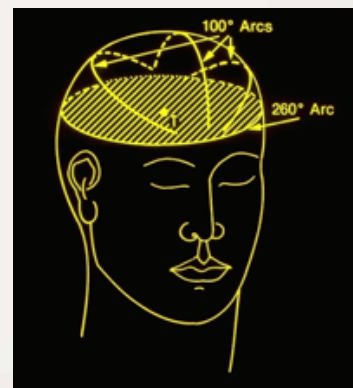
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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Multiple non-coplanar converging arcs technique:

- The target dose is delivered through a series of gantry arcs, each arc with a different stationary position of the treatment couch or chair.
- The arc angles are usually smaller than 180° to avoid parallel-opposed beams in the plane of the arc.
- Typical number of arcs used ranges from 4 to 11.

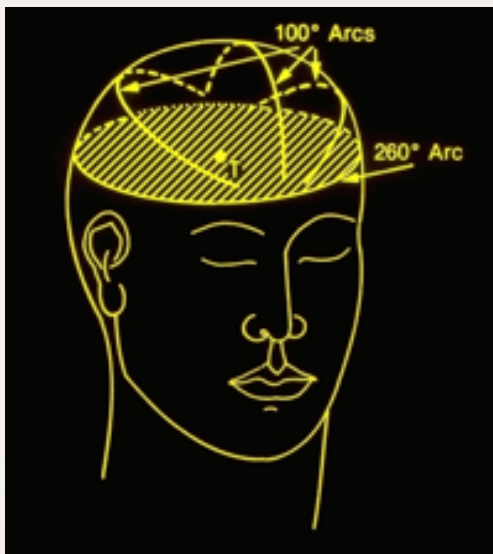


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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Multiple non-coplanar converging arcs technique:



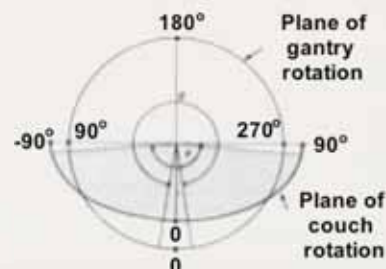
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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Dynamic stereotactic radiosurgery

- ☐ The patient is in supine position on the treatment couch.
- ☐ The main features of the dynamic rotation is the couch-mounted frame approach and the continual simultaneous rotation of the gantry and couch during treatment.
- ☐ The gantry rotates 300° from 30° to 330° and the couch 150° from 75° to -75° .

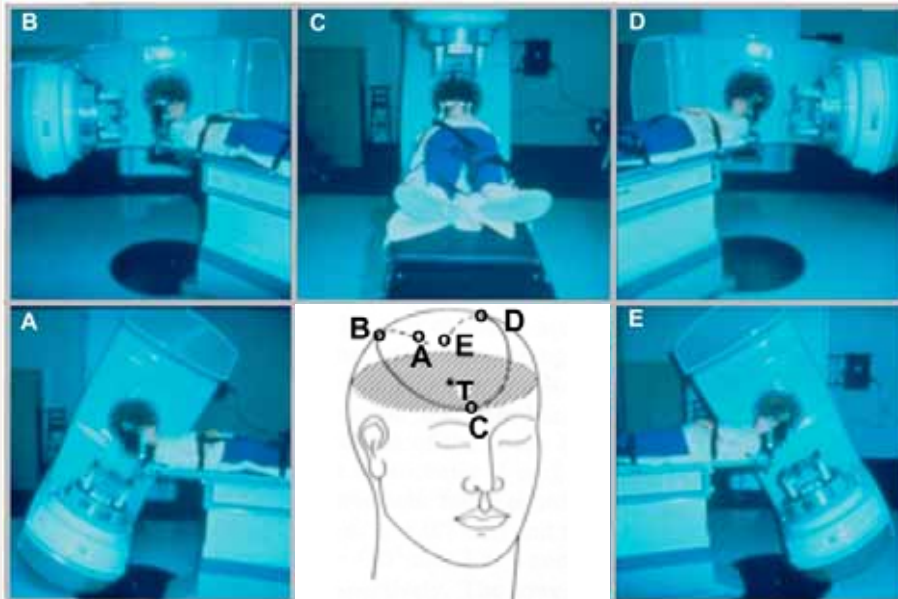


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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

□ Dynamic stereotactic radiosurgery



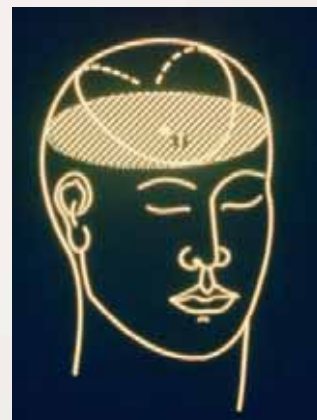
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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Dynamic stereotactic radiosurgery

- The beam entry trace on the patient's head in dynamic rotation exhibits a peculiar trace (baseball seam).
 - All points of beam entry lie in the upper hemisphere on the patient's head and all beam exit points lie in the lower hemisphere.
 - Even though all beams intersect in the target volume at the linac isocentre and the gantry travels almost a full circle (300°), there never is a parallel-opposed beam situation to degrade the steepness of the dose fall-off outside the target volume.



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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Dose fall-off outside the target:

- ❑ Dynamic rotation provides similar dose fall-offs outside the target volume as do multiple non-coplanar converging arcs techniques and the Gamma Knife.
- ❑ In comparison with multiple non-coplanar converging arcs techniques, the dynamic rotation represents a more elegant and less demanding approach to stereotactic irradiation, provided that an automated couch rotation link with the gantry rotation is available.



15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Conical rotation:

- ❑ The patient rotates on a special treatment chair while the gantry is stationary at a given angle off the vertical.
- ❑ The stereotactic frame is attached to a pedestal, which in turn is mounted to the base plate holding the linac couch.
- ❑ Up to three gantry positions are used for a typical treatment, resulting in conical circles for beam entry traces in the upper hemisphere of the patient's head and a conical irradiation pattern.



15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Beam entry traces for various linac-based techniques:

Multiple
non-coplanar
converging arcs



Dynamic
rotation



Conical
rotation



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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Miniature linac on a robotic arm (CyberKnife):

- ☐ This radiosurgical technique uses:
 - A **miniature 6 MV linac** instead of a conventional isocentric linac. The miniature linac operates in the X band and is mounted on an industrial robotic manipulator.
 - **Non-invasive image guided target localization**, instead of the conventional frame based stereotaxy.
- ☐ The image-guided frameless radiosurgery system achieves the same level of targeting precision as the frame-based radiosurgery.

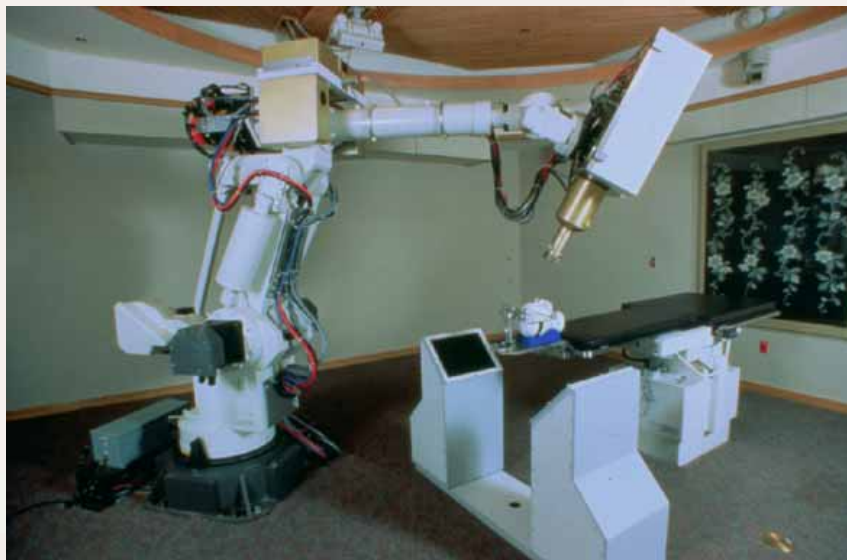


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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

- Miniature linac mounted on a robotic arm (CyberKnife)



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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

- Miniature linac mounted on a robotic arm (CyberKnife)



Courtesy of
Accuray Inc.,
Sunnyvale, CA



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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Miniature linac on a robotic arm (CyberKnife):

□ In comparison with standard radiosurgical techniques, the **CyberKnife** offers the following advantages:

- It allows frameless radiosurgery, i.e., it dispenses with the need for a rigid and invasive stereotactic frame.
- It monitors and tracks the patient's position continuously and uses on-line images for finding the exact position of the target in the treatment room coordinate system.
- It aims the radiation beam into the on-line determined target position and achieves a dose delivery accuracy of the order of 1 mm through this image-guided dose delivery method.
- It allows for frameless radiosurgical dose delivery to extracranial targets, such as the spine, lung and prostate.



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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Targets in radiosurgery:

□ **Spherical target**

- Circular field - Single isocenter
 - Possible with Gamma Knife and Linac-based radiosurgery

□ **Irregular target**

- Circular fields and Multiple isocenters - **Conformal radiosurgery**
 - Possible with Gamma Knife and Linac-based radiosurgery
- Irregular uniform intensity fields - **Conformal radiosurgery**
 - Only possible with linac equipped with micro-multileaf collimator (micro-MLC)
- Irregular intensity modulated fields - **Intensity modulated radiosurgery**
 - Only possible with linac equipped with micro-multileaf collimator (micro-MLC)



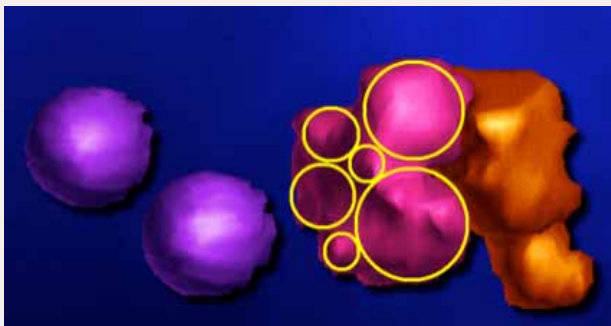
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15.2 STEREOTACTIC IRRADIATION

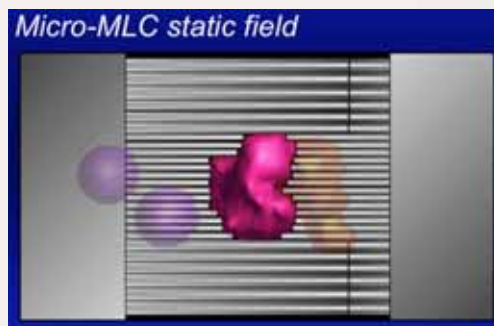
15.2.5 Radiosurgical techniques

Irregular targets in radiosurgery:

Multiple isocenters



Micro-MLC irregular fields

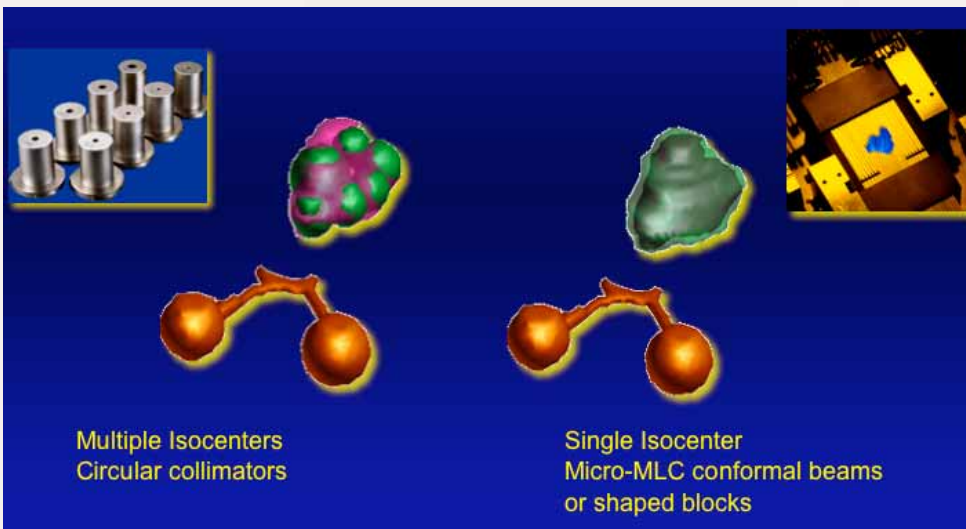


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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Irregular targets in radiosurgery:



Courtesy of:
BrainLAB
Heimstetten,
Germany



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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Micro-MLC in linac-based radiosurgery

- ❑ The treatment with micro-MLCs is achieved with multiple stationary fields that conform to the target shape.
- ❑ Advantages of the micro-MLC approach over the multiple isocentre approach:
 - Improved dose homogeneity inside the target
 - Sharper dose fall-off outside the target
 - Less time-consuming treatment planning
 - Shorter treatment time
 - Simpler treatment
 - Significantly lower scatter and leakage dose to the patient.

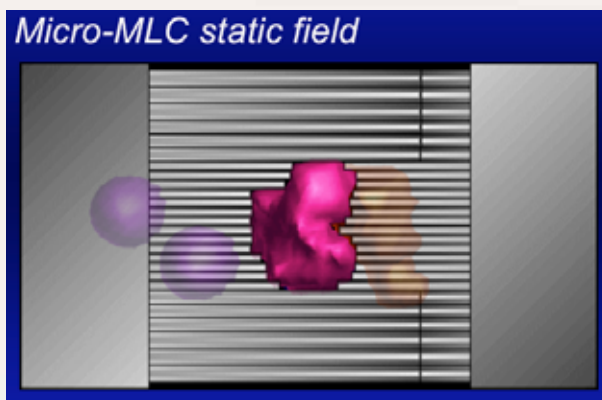


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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

Micro-MLC in linac-based radiosurgery



BrainLAB, Heimstetten, Germany



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15.2 STEREOTACTIC IRRADIATION

15.2.5 Radiosurgical techniques

MicroMLC used in linac-based radiosurgery

- ☐ The use of microMLCs in conjunction with isocentric linacs enables a simple and efficient production of small irregular fields in conformal radiosurgery.
- ☐ In contrast to the standard method used by the Gamma Knife and isocentric linacs which relies on multiple isocentres (shots) to cover the full irregular target, the microMLC approach treats the whole irregular target with a single isocentre.



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15.2 STEREOTACTIC IRRADIATION

15.2.6 Uncertainty in radiosurgical dose delivery

- ☐ The minimum uncertainty in target localization achievable with modern imaging equipment combined with stereotaxy is of the order of ± 1 mm .
- ☐ The possible motion of brain tissues when moving the patient from the imaging equipment to the therapy machine is of the order of a fraction of a millimeter.
- ☐ The measured uncertainty in radiosurgical dose delivery is:
 - Of the order of ± 0.5 mm for a linac in a superb mechanical condition.
 - Of the order of ± 0.3 mm for the Gamma Knife.



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15.2 STEREOTACTIC IRRADIATION

15.2.6 Uncertainty in radiosurgical dose delivery

- ❑ Both the Gamma Knife and an isocentric linac can provide similar overall accuracies in dose delivery.
- ❑ Achieving and maintaining the optimal accuracy with an isocentric linac in comparison with a Gamma Knife requires a much larger effort as well as very stringent and disciplined quality assurance program.
- ❑ Owing to the intricacies of the specific dose delivery methods, the potential for serious problems, like a geographic miss, is greater on a linac than on a Gamma Knife.



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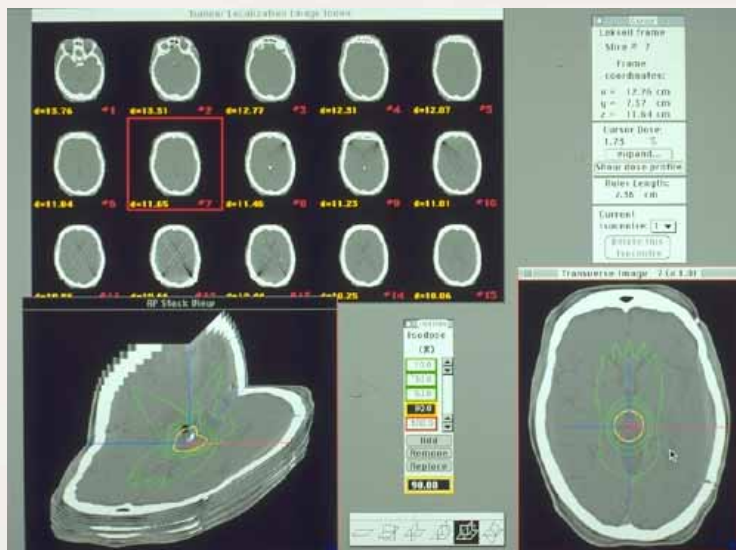
15.2 STEREOTACTIC IRRADIATION

15.2.7 Dose prescription and dose fractionation

- ❑ **Treatment planning for stereotactic radiosurgery**
Example of a 3-D treatment plan for dynamic stereotactic radiosurgery based on a series of CT transverse images.

This 3-D treatment planning system was developed at McGill University in Montreal by Conrado Pla in 1989.

Many commercial systems are currently available for planning of radiosurgical treatments.



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15.2 STEREOTACTIC IRRADIATION

15.2.7 Dose prescription and dose fractionation

- ❑ The prescribed dose and dose fractionation in stereotactic dose delivery depend upon:
 - **Volume** of the intracranial target
 - **Location** of the intracranial target
 - The **disease** treated
 - Benign and metastatic diseases are typically treated in a single session (stereotactic radiosurgery).
 - Primary malignant diseases are typically treated with fractionated regimes (stereotactic radiotherapy).
 - **Equipment and technique** used in radiosurgery
 - Treatment with Gamma Knife is traditionally carried out in a single session.
 - Treatment with linac-based techniques may be delivered in a single session or in multiple sessions.



15.2 STEREOTACTIC IRRADIATION

15.2.7 Dose prescription and dose fractionation

Stereotactic radiosurgery (single session treatment):

- ❑ Is used in treatment of functional disorders, vascular malformations, benign tumours, and metastatic lesions.
- ❑ Is occasionally used as a boost in conjunction with standard treatment of malignant intracranial lesions.
- ❑ Employs prescribed doses of 12 - 25 Gy; the larger is the target, the lower is the prescribed dose.



15.2 STEREOTACTIC IRRADIATION

15.2.7 Dose prescription and dose fractionation

Stereotactic radiotherapy (fractionated treatment):

- ☐ The stereotactic frame:
 - Is either left attached to the patient's cranium for the duration of the treatment course
 - Or a relocatable stereotactic frame is used for each individual treatment.
- ☐ For practical reasons, the dose per fraction is typically larger than that of the standard treatment.
- ☐ Typical dose fractionation regimes are:
 - 6x7 Gy (total dose: 42 Gy) with treatment given every second day.
 - 10x4 Gy (total dose: 40 Gy), with treatment given daily.



15.2 STEREOTACTIC IRRADIATION

15.2.7 Dose prescription and dose fractionation

Target dose conformity and homogeneity:

- ☐ The important parameters to be considered with regard to a radiosurgical treatment plan are:
 - Conformity of the prescribed isodose surface to the target volume.
 - Volume of healthy tissue irradiated by the prescription isodose surface.
 - Dose homogeneity inside the target volume.
- ☐ These three parameters are even more important in radiosurgery than in standard radiotherapy, but they cannot be optimized simultaneously.



15.2 STEREOTACTIC IRRADIATION

15.2.7 Dose prescription and dose fractionation

Target dose conformity and homogeneity:

- ☐ In standard radiotherapy, target dose homogeneity is very important and ideally lies within $\pm 5\%$ of the prescribed dose.
- ☐ In radiosurgery, dose conformity to the relatively small target volume is extremely important and the target dose homogeneity requirement is often relaxed to allow for optimization of the target dose conformity.
- ☐ The dose is then prescribed to the lowest isodose surface which still covers the target volume and a target dose inhomogeneity may amount to 100%.



15.2 STEREOTACTIC IRRADIATION

15.2.7 Dose prescription and dose fractionation

Evaluation of radiosurgical treatment plans:

- ☐ In the early days of linac-based radiosurgery comparisons among various radiosurgical techniques and their dose distributions were made based on the **sharpness of dose fall-offs** outside the target volume.
- ☐ Modern techniques for dose distribution comparisons are based upon:
 - **Dose - volume histogram.**
 - Ratio of maximum target dose to prescription dose (**MDPD**).
 - Ratio of prescription isodose volume to target volume (**PITV**).



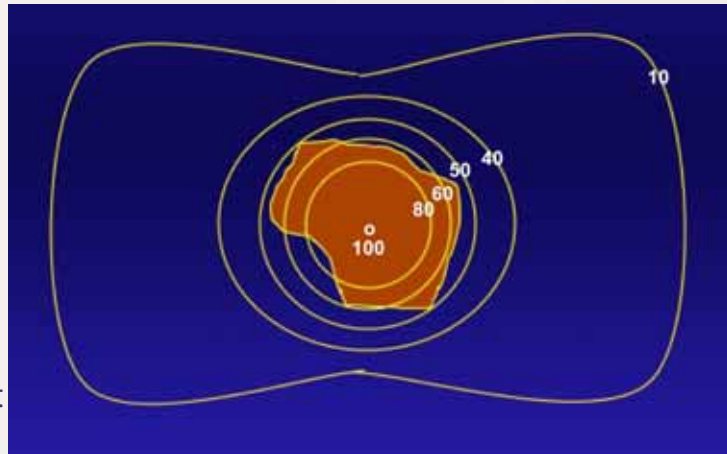
15.2 STEREOTACTIC IRRADIATION

15.2.7 Dose prescription and dose fractionation

Target coverage with various isodose surfaces:

The 50% isodose surface covers the target well but also irradiates much of healthy surrounding tissue.

If the dose is prescribed to the 50% isodose surface, the target dose inhomogeneity is very large, but the dose conformity to the target is optimized.



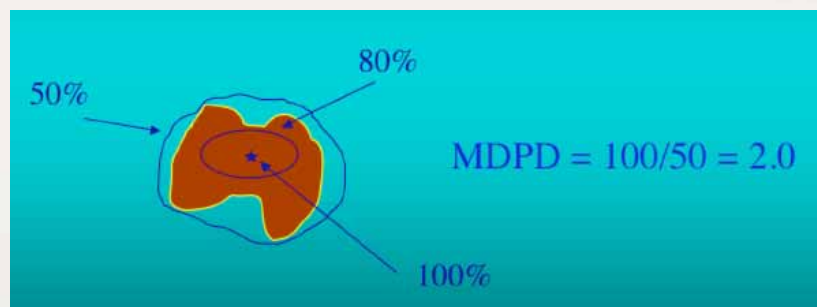
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15.2 STEREOTACTIC IRRADIATION

15.2.7 Dose prescription and dose fractionation

□ **MDPD** is defined by the RTOG (Radiotherapy Oncology Group) as the ratio of maximum dose to prescription dose inside the target volume and thus describes the dose homogeneity within the target.

- $1.0 \leq \text{MDPD} \leq 2.0$ Per protocol
- $2.0 < \text{MDPD} < 2.5$ Acceptable minor deviation
- $\text{MDPD} \geq 2.5$ Major and unacceptable deviation

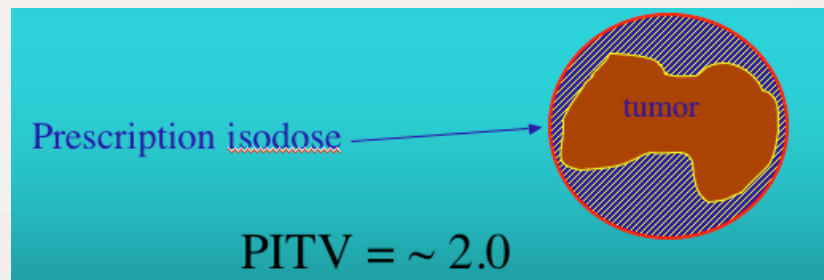


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15.2 STEREOTACTIC IRRADIATION

15.2.7 Dose prescription and dose fractionation

- ❑ **PITV** is defined by the RTOG (Radiotherapy Oncology Group) as the ratio of the prescription isodose volume to the target volume and thus describes the conformity of the prescription isodose volume to the target volume.
 - $1.0 \leq \text{PITV} \leq 2.0$ Per protocol
 - $\begin{cases} 2.0 < \text{PITV} < 2.5 \\ 0.9 < \text{PITV} < 1.0 \end{cases}$ Minor acceptable deviation
 - $\text{PITV} > 2.5$ Major and unacceptable deviation



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15.2 STEREOTACTIC IRRADIATION

15.2.7 Dose prescription and dose fractionation

- ❑ **Dose-volume histogram (DVH)** is a powerful tool used to summarize and quantify complex radiosurgical dose distributions.
- ❑ DVHs can be used for assessment of tumour volume coverage as well as for the evaluation of the dose delivered either to healthy tissue surrounding the target or to specific structures in the vicinity of the target such as the brain stem or the optic nerve.



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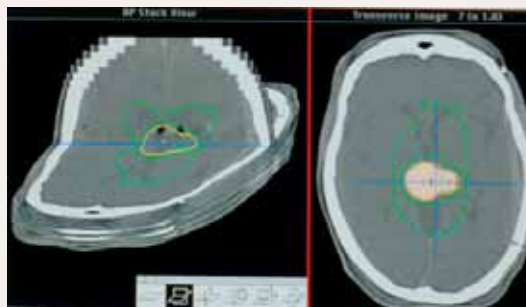
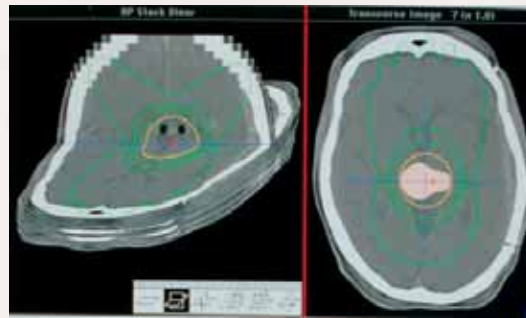
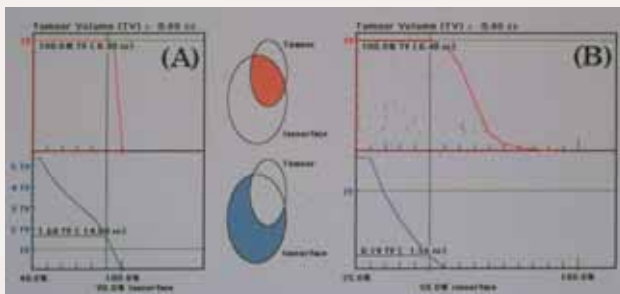
15.2 STEREOTACTIC IRRADIATION

15.2.7 Dose prescription and dose fractionation

Treatment of irregular target

using circular field and

- (A) single isocentre
- (B) two isocentres

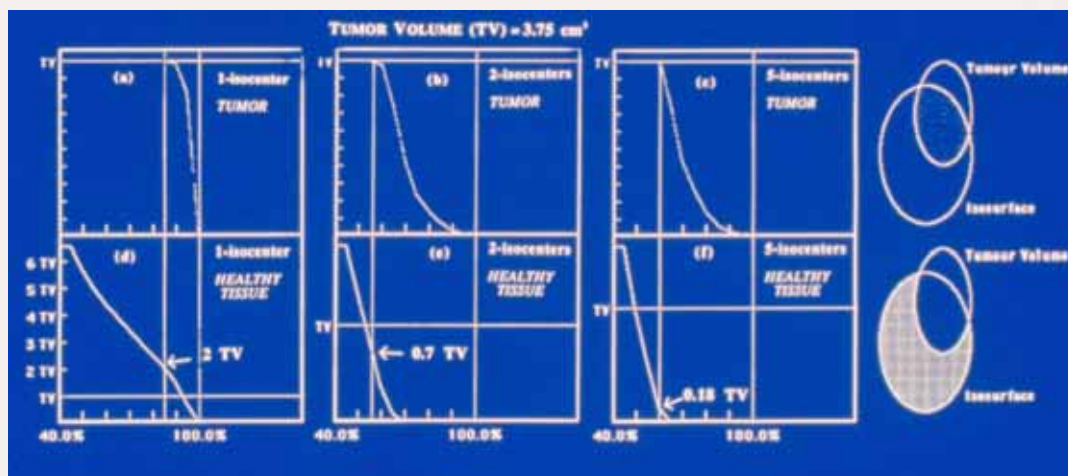


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15.2 STEREOTACTIC IRRADIATION

15.2.7 Dose prescription and dose fractionation

- Dose-volume histogram (DVH) for treatment of an irregular target volume with one, two or five isocentres.



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15.2 STEREOTACTIC IRRADIATION

15.2.8 Commissioning of radiosurgical equipment

- ❑ The basic principles involved in the **commissioning** of radiosurgical devices are similar to those used for commissioning of standard radiotherapy equipment, except that the requirements on machine integrity and performance are even more stringent in radiosurgery.
- ❑ The procedures for commissioning of all radiosurgical devices are fairly similar, despite large variations in dose delivery techniques.



15.2 STEREOTACTIC IRRADIATION

15.2.8 Commissioning of radiosurgical equipment

- ❑ The following issues should be considered before embarking on clinical use of a radiosurgery device:
 - The properties of radiation beams must be measured to ensure radiation safety of the patient and accurate treatment planning.
 - The mechanical integrity of the radiosurgical device must be within acceptable tolerances to provide reliable and accurate delivery of the dose.
 - All steps involved in the radiosurgical procedure, from the target localization, through treatment planning, to dose delivery, must be verified experimentally to ensure reliable and accurate performance of the hardware and software used in the radiosurgical procedure.



15.2 STEREOTACTIC IRRADIATION

15.2.9 Quality assurance in radiosurgery

- ❑ Stereotactic radiosurgery is a very complex treatment modality requiring not only a close collaboration among the members of the radiosurgical team but also careful target localization and treatment planning, as well as strict adherence to stringent quality assurance protocols.
- ❑ The **radiosurgical team** consists of the following members:
 - Neurosurgeon
 - Radiation oncologist
 - Medical physicist
 - Radiotherapy technologist (radiotherapist)



15.2 STEREOTACTIC IRRADIATION

15.2.9 Quality assurance in radiosurgery

- ❑ The **quality assurance protocols** for radiosurgery fall into three categories:
 - The basic quality assurance protocols covering the performance of all equipment used for:
 - Target localization
 - 3-D treatment planning
 - Radiosurgical delivery of dose
 - The treatment quality assurance protocols dealing with the calibration and preparation of equipment immediately preceding the radiosurgical treatment.
 - Treatment quality assurance protocol during the radiosurgical procedure on a patient.



15.2 STEREOTACTIC IRRADIATION

15.2.10 Gamma Knife versus linac-based radiosurgery

- ❑ The introduction of linac-based radiosurgery in radiation oncology departments during 1980s has rapidly transformed radiosurgery into a mainstream radiotherapy technique and has stimulated great advances in its technical and clinical utility.
 - **Radiation oncologists** are quite comfortable with the clinical use of isocentric linacs but have reservations about the use of single high radiation doses in radiosurgery.
 - **Neurosurgeons** had previous favourable experience with the Gamma Knife, but are concerned about the mechanical stability of linacs' isocentres.



15.2 STEREOTACTIC IRRADIATION

15.2.10 Gamma Knife versus linac-based radiosurgery

- ❑ An unstable linac isocentre can adversely affect the accuracy of dose delivery in radiosurgery and result in substandard treatment in comparison with that provided by the 201 stationary cobalt sources in the Gamma Knife.
- ❑ Clearly, not all isocentric linacs are suitable for conversion to radiosurgery; however, a well designed, well aligned and properly maintained isocentric linac will have a stable and small enough isocentre sphere for use in radiosurgery.



15.2 STEREOTACTIC IRRADIATION

15.2.10 Gamma Knife versus linac-based radiosurgery

□ Comparison: Gamma Knife versus isocentric linac

	Gamma Knife	Isocentric linac
Radiation quality	201 cobalt sources	x rays (6-18 MV)
Radiation beam	Stationary	Stationary or moving
Dose rate	Up to 350 cGy/min	Up to 600 cGy/min
Fields	Circular	Circular or irregular
Field diameters	4, 8, 14, 18 mm	5 - 40 mm
Irregular fields	Not available	Produced with microMLC
Operation	Dedicated	Used for standard RT



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15.2 STEREOTACTIC IRRADIATION

15.2.10 Gamma Knife versus linac-based radiosurgery

□ The general consensus among radiation oncologists and medical physicists is that:

- Linac-based radiosurgery with regard to treatment outcome is equivalent to that provided by a Gamma Knife
- Linac-based radiosurgery, in comparison with Gamma Knife radiosurgery, is considerably more complicated but has a much greater potential for new and exciting developments.

□ The general consensus among neurosurgeons is that Gamma Knife radiosurgery is superior to that practiced with isocentric linacs.



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15.2 STEREOTACTIC IRRADIATION

15.2.10 Gamma Knife versus linac-based radiosurgery

- ❑ New developments in linac-based radiosurgery:
 - **Fractionated radiotherapy** which in contrast to radiosurgery is better suited for treatment of malignant disease.
 - **Irregular fields** produced by microMLCs improve target dose homogeneity (i.e., decrease both the MDPD as well as the PITV) in contrast to multiple isocentre technique practiced with a Gamma Knife.
 - **Very small radiation fields** (of the order of millimetre in diameter) are available on linacs in contrast to the minimum diameter of 4 mm available from a Gamma Knife in treatment of functional disorders.
 - Radiosurgery with **relocatable frames** and **frameless radiosurgery** are available with linacs.



15.2 STEREOTACTIC IRRADIATION

15.2.11 Frameless radiosurgery

- ❑ **Frameless stereotaxy** aims to dispense with the invasiveness of the stereotactic frame fixation to the skull without losing the inherent accuracy of the frame-based stereotactic technique.
- ❑ New techniques have been developed for image guided neurosurgery and radiosurgery based:
 - either on surgical implantation of fiducial markers (gold wire or gold screws)
 - or on on-line planar imaging coupled with CT data (linac on robotic arm).



15.3 TOTAL BODY IRRADIATION

- ❑ **Total body irradiation (TBI)** is a special radiotherapeutic technique that delivers to a patient's whole body a dose uniform to within $\pm 10\%$ of the prescribed dose.
- ❑ Megavoltage photon beams, either cobalt-60 gamma rays or megavoltage x rays are used for this purpose.
- ❑ In broader sense, TBI techniques encompass:
 - Irradiation of the whole body
 - Half body irradiation
 - Total nodal irradiation



15.3 TOTAL BODY IRRADIATION

15.3.1 Clinical total body irradiation categories

- ❑ **Categories of TBI** depending on clinical situation:
 - **High dose TBI**, with dose delivery in a single session (dose: 750 to 900 cGy) or in up to six fractions of 200 cGy each in 3 days (total dose: 1200 cGy).
 - **Low dose TBI**, with dose delivery in 10 to 15 fractions of 10 to 15 cGy each.
 - **Half-body irradiation**, with a dose of 8 Gy delivered to the upper or lower half body in a single session.
 - **Total nodal irradiation**, with a typical nodal dose of 40 Gy delivered in 20 fractions.



15.3 TOTAL BODY IRRADIATION

15.3.2 Diseases treated with total body irradiation

- ❑ TBI is used primarily as part of a preparatory cytoreductive conditioning regimen prior to bone marrow transplantation (BMT).
- ❑ The source of bone marrow may be:
 - The patient (autologous transplant).
 - An identical twin (syngeneic transplant).
 - A histocompatible donor (allogeneic transplant).
- ❑ In the near future, bioengineering promises to produce a supply of stem cells originating from unrelated and unmatched donors for use in BMT.



15.3 TOTAL BODY IRRADIATION

15.3.2 Diseases treated with total body irradiation

- ❑ Before engraftment of donor bone marrow, pre-transplant conditioning is applied to eradicate the tumour cells or cells with genetic disorders.
- ❑ The conditioning regimen may be based on chemotherapy alone; however, the most common pre-transplant conditioning is a combination of high dose chemotherapy and TBI.
- ❑ TBI results in immunosuppression, which helps prevent the failure of the graft (**graft versus host disease**).



15.3 TOTAL BODY IRRADIATION

15.3.2 Diseases treated with total body irradiation

- ❑ Diseases treated with **bone marrow transplantation** are:
 - Various types of leukaemia (acute non-lymphoblastic leukaemia, acute lymphoblastic leukaemia, chronic myelogenous leukaemia)
 - Malignant lymphoma
 - Aplastic anaemia
- ❑ **High dose TBI** has been used as adjuvant therapy in treatment of: Ewing's sarcoma and non-Hodgkin's lymphoma.
- ❑ **Low dose TBI** is used in treatment of: lymphocytic leukaemia, lymphoma and neuroblastoma.
- ❑ **Total nodal irradiation** is used as adjuvant treatment of autoimmune diseases.



15.3 TOTAL BODY IRRADIATION

15.3.3 Technical aspects of total body irradiation

- ❑ All contemporary TBI techniques use megavoltage photon beams that are produced by:
 - **Cobalt-60 machines**
 - **Linear accelerators (linacs)**
- ❑ The beams are:
 - **Stationary** with field sizes of the order of 70x200 cm² encompassing the whole patient
 - **Moving**, with smaller field sizes, in some sort of translational or rotational motion to cover the whole patient with the radiation beam.
- ❑ Usually, **parallel-opposed irradiations** are used by delivering each fractional dose in two equal installments and switching the patient's position between the two installments.



15.3 TOTAL BODY IRRADIATION

15.3.4 Total body irradiation techniques

TBI treatment techniques are carried out with:

- ❑ **Dedicated irradiators**, i.e., treatment machines specially designed for total body irradiation.
- ❑ **Modified conventional megavoltage radiotherapy equipment:**
 - Treatment at extended source-surface distance (SSD)
 - Treatment at standard SSD after the cobalt-60 machine collimator is removed.
 - Treatment with a translational beam.
 - Treatment with a sweeping beam.

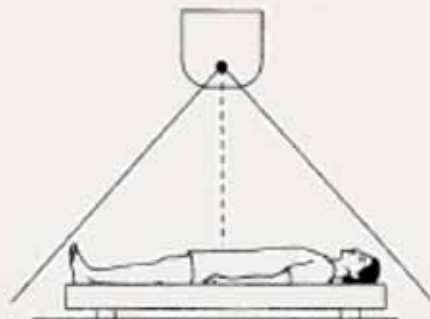


15.3 TOTAL BODY IRRADIATION

15.3.4 Total body irradiation techniques

- ❑ **Dedicated irradiators**, i.e., treatment machines specially designed for total body irradiation.

A cobalt-60 machine dedicated for TBI.
The machine collimator has been removed to obtain a large field for TBI irradiation at an SSD of 230 cm.

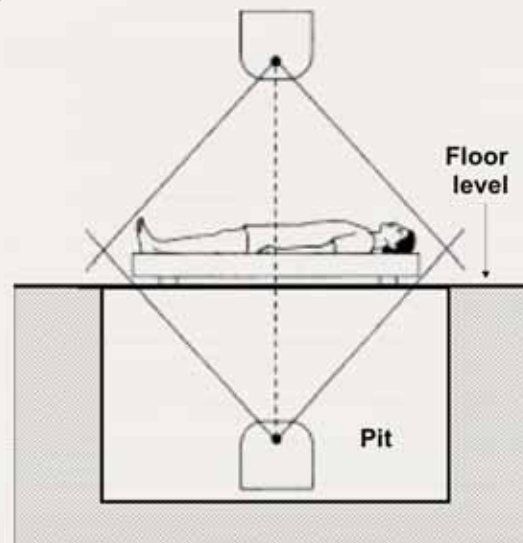


15.3 TOTAL BODY IRRADIATION

15.3.4 Total body irradiation techniques

- **Dedicated irradiators**, i.e., treatment machines specially designed for total body irradiation.

Two linear accelerators mounted in such a way that they produce two parallel-opposed beams simultaneously.

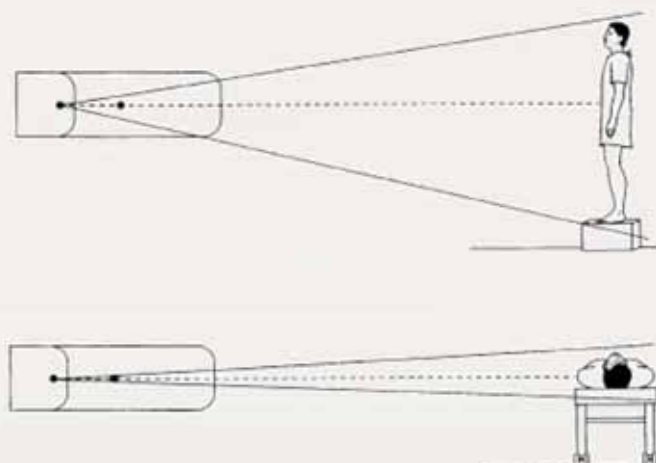


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15.3 TOTAL BODY IRRADIATION

15.3.4 Total body irradiation techniques

- **Modified conventional megavoltage radiotherapy equipment:**
Treatment at extended source-surface distance (SSD)

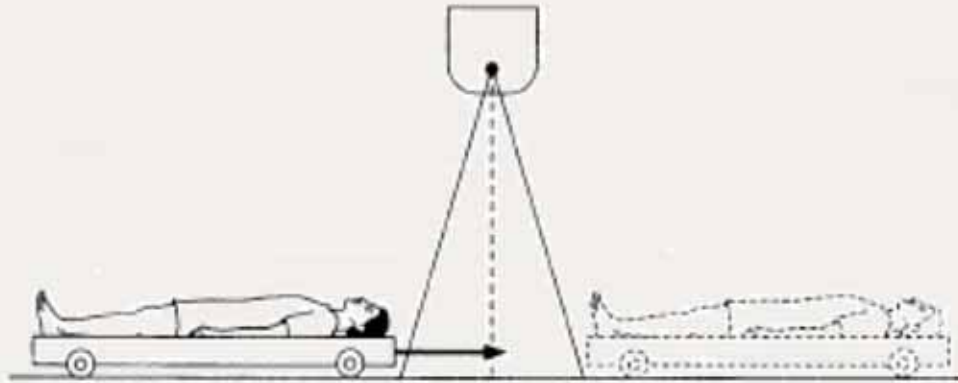


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15.3 TOTAL BODY IRRADIATION

15.3.4 Total body irradiation techniques

- ❑ Modified conventional megavoltage radiotherapy equipment:
Treatment with a translational beam.

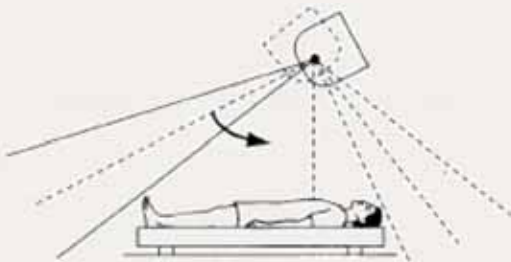


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15.3 TOTAL BODY IRRADIATION

15.3.4 Total body irradiation techniques

- ❑ Modified conventional megavoltage radiotherapy equipment:
Sweeping beam technique with a column mounted linac.



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15.3 TOTAL BODY IRRADIATION

15.3.5 Dose prescription point

- ❑ The TBI dose is prescribed to a point inside the body, referred to as the **dose prescription point** (usually at the midpoint at the level of the umbilicus).
- ❑ The TBI procedure must deliver the prescribed dose to the dose prescription point and should maintain the dose throughout the body within $\pm 10\%$ of the prescription point dose.
- ❑ Uniformity of dose throughout the body is achieved with the use of bolus, partial attenuators, and compensators.



15.3 TOTAL BODY IRRADIATION

15.3.6 Commissioning of total body irradiation procedure

- ❑ Once a particular treatment machine and TBI technique have been selected, a thorough **commissioning of the proposed TBI procedure** must be carried out.
- ❑ The basic dosimetric parameters for TBI are the same as those for standard radiotherapy, including:
 - Absolute beam calibration
 - Percentage depth doses or tissue-phantom ratios
 - Beam profiles, i.e., off-axis ratios



15.3 TOTAL BODY IRRADIATION

15.3.6 Commissioning of total body irradiation procedure

- ❑ The **dosimetric parameters** must be measured under the specific TBI conditions in order to obtain reliable data for clinical use of the TBI.
- ❑ Of special concern are:
 - Large radiation field and scattering from the treatment room floor or walls.
 - The size of the patient or calibration phantom smaller than radiation the field size.



15.3 TOTAL BODY IRRADIATION

15.3.6 Commissioning of total body procedure

- ❑ In commissioning a TBI procedure, several dosimetric problems specific to large field dosimetry must be considered. These specific problems are related to:
 - **Phantom size** is typically smaller than the field size and the patient. This causes uncertainties in scatter conditions and may lead to erroneous measured beam output and PDD or TPR.
 - The **measured ionization chamber current** may be of the order of the leakage current leading to errors in beam output determination.
 - A large portion of the **ionization chamber cable** may be irradiated with the large TBI field producing a significant non-dosimetric ionization chamber current.



15.3 TOTAL BODY IRRADIATION

15.3.7 Test of total body irradiation dosimetry protocol

- ❑ Once the basic dosimetric data for a particular TBI technique are available several irradiation “dry runs” should be carried out to verify the dosimetry protocol before clinical use of the TBI technique.
- ❑ A realistic, patient-like phantom should be irradiated and the absolute dose determined for various positions of the ionization chamber in the phantom. This verifies the beam output calibration and the whole dosimetry chain involved in the TBI procedure.
- ❑ The technique for placement of partial lung attenuators, if planned for clinical use, should also be verified.



15.3 TOTAL BODY IRRADIATION

15.3.8 Quality assurance in total body irradiation

- ❑ TBI is a complex treatment modality requiring:
 - Careful treatment planning.
 - Reliable beam output calibration.
 - Accurate localization of the organs that are to receive a partial dose or are to be shielded completely from the radiation beam.
 - Strict adherence to specific quality assurance protocols.
- ❑ The quality assurance protocols fall into three categories:
 - Basic quality assurance protocol.
 - Pre-treatment quality assurance protocol.
 - Treatment quality assurance protocol.



15.3 TOTAL BODY IRRADIATION

15.3.8 Quality assurance in total body irradiation

- ❑ The **basic quality assurance protocol** covers the performance of the equipment used for:
 - TBI treatment planning
 - Actual TBI dose delivery (cobalt unit or linac).
- ❑ In addition to the dose delivery machine, the TBI equipment may also include:
 - CT scanner or CT simulator, providing data on lung geometry and density as well as the geometry of other critical organs.
 - Treatment planning system, used in determination of lung dose.



15.3 TOTAL BODY IRRADIATION

15.3.8 Quality assurance in total body irradiation

- ❑ The **pre-treatment quality assurance protocol** deals with the calibration and preparation of equipment and the treatment room immediately preceding the TBI treatment.
- ❑ The **treatment quality assurance protocol** deals with the measurement of the dose delivered to the patient during the TBI procedure.



15.4 TOTAL SKIN ELECTRON IRRADIATION

- ❑ **Total skin electron irradiation (TSEI)** is a special radiotherapeutic technique that aims to irradiate the patient's whole skin with the prescribed radiation dose while sparing all other organs from any appreciable radiation dose.
- ❑ Since the skin is a superficial organ, the choice of electron beams for treatment of generalized skin malignancies (most often **mycosis fungoides**) is obvious, even though superficial x rays were in the past used for this purpose.



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15.4 TOTAL SKIN ELECTRON IRRADIATION

- ❑ **A patient with mycosis fungoides treated with TSEI**
Before treatment After treatment



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15.4 TOTAL SKIN ELECTRON IRRADIATION

- ❑ The patient population requiring TSEI is relatively small and the TSEI techniques are relatively complex and cumbersome, therefore **the TSEI technique is available only in major radiotherapy centres.**
- ❑ All contemporary TSEI procedures are based on electron linacs which are used for conventional radiotherapy and modified for delivery of the large and uniform electron fields required for the TSEI.



15.4 TOTAL SKIN ELECTRON IRRADIATION

- ❑ **Photon contamination** of the electron beam, a potential detriment to the patient, must be known for each TSEI technique to ensure that the total prescribed electron dose is not accompanied by an unacceptably high total body photon dose.
- ❑ Certain areas of the patient's skin as well as some organs (such as nails and eyes) may have to be shielded in order to avoid treatment morbidity.
- ❑ The typical **dose/fractionation regimen** for TSEI is 40 Gy in 20 fractions.



15.4 TOTAL SKIN ELECTRON IRRADIATION

15.4.1 Physical requirements for total skin electron irradiation

- All **clinical TSEI procedures** are governed by three categories of specification:
- Physical specification of the large stationary electron field.
 - Physical specification of the dose distribution in a water-equivalent phantom resulting from the superposition of multiple large stationary electron fields or from a rotational electron field.
 - Clinical specification of the specific patient treatment



15.4 TOTAL SKIN ELECTRON IRRADIATION

15.4.1 Physical requirements for total skin electron irradiation

- **Physical specification of the large stationary electron field:**
- Electron field size of the order of 80x200 cm².
 - Dose uniformity at z_{max} in a water equivalent phantom for at least 80% of the central nominal field area (typically $\pm 5\%$ from the dose at z_{max} in a phantom on the central ray).
 - Nominal SSD of 300 to 500 cm.
 - Beam energy at the waveguide exit window of 6 to 10 MeV.
 - Beam energy on the phantom surface of 4 to 7 MeV.
 - Dose rate on the beam central ray at z_{max} in a water phantom.
 - Photon contamination of the stationary electron beam.



15.4 TOTAL SKIN ELECTRON IRRADIATION

15.4.1 Physical requirements for total skin electron irradiation

- ❑ **Physical specification of the dose distribution** resulting from superposition of multiple stationary electron fields:
 - Dose rate at z_{\max} on the central ray (usually on the skin surface, which becomes the dose prescription point).
 - Bremsstrahlung contamination dose rate at the patient's midpoint at the level of umbilicus.
- ❑ **Clinical specifications of the specific patient treatment:**
 - Dose/fractionation regimen.
 - Actual total body photon dose received by the patient during the course of the TSEI treatment.
 - Prescription for boosts to underdosed areas.
 - Prescription for any special shielding (eyes, nails, etc.)



15.4 TOTAL SKIN ELECTRON IRRADIATION

15.4.2 Current total skin electron irradiation techniques

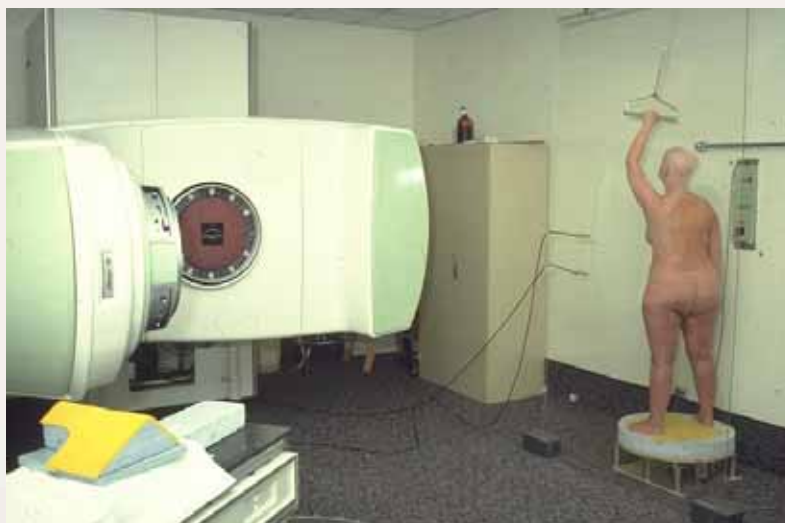
- ❑ The TSEI techniques in use today may be grouped into three main categories:
 - **Translational techniques**, in which the patient is translated on a stretcher through an electron beam of sufficient width to cover the patient's transverse dimensions.
 - **Large electron field techniques**, in which a standing stationary patient is treated at a large SSD with a single large electron beam or a combination of large electron beams.
 - **Rotational techniques**, in which the patient is standing on a rotating platform in a large electron field.



15.4 TOTAL SKIN ELECTRON IRRADIATION

15.4.2 Current total skin electron irradiation techniques

- Patient treated with rotational TSEI



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15.4 TOTAL SKIN ELECTRON IRRADIATION

15.4.3 Selection of total skin electron irradiation technique

- Once an institution decides to provide the TSEI treatment modality, an adequate TSEI technique must be chosen and commissioned, and quality assurance procedures for the clinical use of TSEI must be developed.
- The large electron field used for TSEI is produced either with single or dual large electron fields.
- The patients will be treated either with multiple large electron beams; they will be translated through a large electron field; or they will be rotated in a large electron field.



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15.4 TOTAL SKIN ELECTRON IRRADIATION

15.4.4 Dose calibration point

- ❑ The **output** of the large TSEI radiation field is specified at the **dose calibration point**, which is found on the electron beam central ray at z_{\max} in a water equivalent phantom.
- ❑ Often the beam output and flatness are monitored directly on-line with two ionization chambers, one placed on the beam central axis to monitor the beam output and the other placed off-axis to monitor the beam flatness.



15.4 TOTAL SKIN ELECTRON IRRADIATION

15.4.5 Skin dose rate at the dose prescription point

- ❑ The TSEI dose is prescribed on the patient's skin surface at the level of the umbilicus (**dose prescription point**) which is usually on the axial slice containing the central ray.
- ❑ The dose rate at the dose prescription point is the skin dose rate resulting from the particular TSEI technique used in treatment, be it with multiple stationary electron beams or with a rotational electron beam.
- ❑ The skin dose rate at the dose prescription point is related to the dose rate at the dose calibration point, but the actual relationship must be determined experimentally.



15.4 TOTAL SKIN ELECTRON IRRADIATION

15.4.6 Commissioning of the TSEI procedure

- ❑ The current TSEI standards recommend the use of a **large and uniform stationary electron field** produced by a megavoltage linac using a suitable electron beam at an extended SSD.
- ❑ The patient is irradiated either with multiple stationary fields or is standing on a rotating platform.
- ❑ Various techniques involving **beam spoilers** (to degrade the electron beam energy) or **special filters** (to improve the electron beam flatness) are used to produce the large, clinical electron beam at an extended SSD.



15.4 TOTAL SKIN ELECTRON IRRADIATION

15.4.6 Commissioning of the TSEI procedure

- ❑ The basic dosimetric parameters of the large TSEI stationary electron field are:
 - **Field flatness**, measured at z_{max} in a tissue equivalent phantom and normalized to 100 at the dose calibration point.
 - The **absolute dose rate** in cGy/MU at the dose calibration point. The MU represents the monitor units given by the monitor ionization chamber of the linac.
 - **PDDs measured to a depth of 15 cm** in a tissue equivalent phantom. The PDDs are normalized to 100 at the dose calibration point and should be measured on the beam central ray as well as on various directions parallel to the central ray.
 - **Bremsstrahlung contamination** of the electron beam.



15.4 TOTAL SKIN ELECTRON IRRADIATION

15.4.6 Commissioning of the TSEI procedure

- The basic physical parameters of the clinical TSEI beam that is produced through multiple stationary fields or through a rotational technique are:
 - The **dose maximum** occurs on patient's surface because of the superposition of various electron beams.
 - The **penetration** of the clinical beam is significantly weaker, i.e., the PDD is shallower, than that of the stationary electron beam.
 - The **bremsstrahlung contamination** of the clinical beam is roughly double that of the single stationary electron beam for the same dose at the dose prescription point.

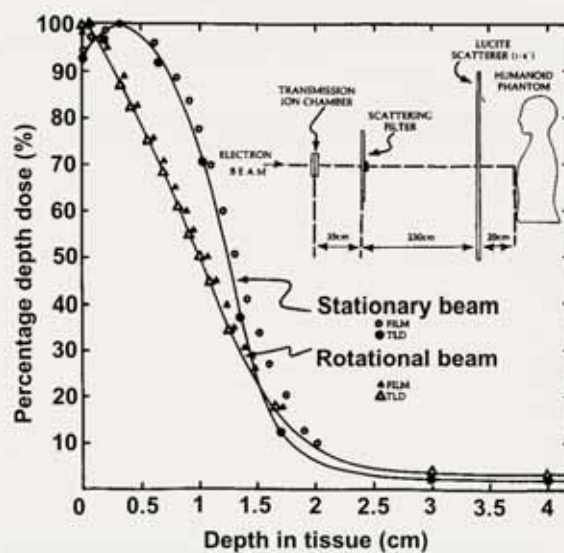


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15.4 TOTAL SKIN ELECTRON IRRADIATION

15.4.6 Commissioning of the TSEI procedure

- The PDD of the clinical beam is shallower than that of the stationary electron beam.
- The **dose maximum** occurs on patient's surface.



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15.4 TOTAL SKIN ELECTRON IRRADIATION

15.4.7 Measurement of stationary and clinical TSEI beams

Equipment required for calibration of the TSEI stationary and clinical electron beams consists of:

☐ **Various phantoms:**

- Water equivalent slab phantoms made of solid water, polystyrene or Lucite for measurement of stationary electron beams.
- Cylindrical phantoms of various diameters and made of solid water, polystyrene or Lucite for measurement of clinical beams.
- Anthropomorphic body and head phantoms for measurement of clinical beams.

☐ **Various dosimeters**, such as: cylindrical and parallel-plate ionization chambers, thermoluminescent dosimeters, radiographic films and radiochromic films.



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15.4 TOTAL SKIN ELECTRON IRRADIATION

15.4.8 Quality assurance in total skin electron irradiation

- ☐ TSEI is a special irradiation technique that, like any other irradiation technique, requires a strict adherence to quality assurance protocols.
- ☐ Quality assurance protocols in TSEI fall in three categories:
- **Basic quality assurance protocol** dealing with the equipment used for measurement of beam parameters and dose delivery.
 - **Pre-treatment quality assurance protocol** dealing with the calibration of the electron beam and preparation of equipment immediately prior to the TSEI procedure.
 - **Treatment quality assurance protocol** that deals with measurements of the actual dose delivered to a specific patient during the TSEI procedure.



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15.5 INTRAOPERATIVE RADIOTHERAPY

- ❑ **Intraoperative radiotherapy (IORT)** is a special radio-therapeutic technique that delivers in a single session a radiation dose of the order of 10 - 20 Gy to a surgically exposed internal organ, tumour or tumour bed.
- ❑ IORT combines two conventional modalities of cancer treatment: surgery and radiotherapy.
- ❑ The IORT team consists of a surgeon, radiation oncologist, medical physicist, anaesthesiologist, nurse, pathologist and radiation therapist.



15.5 INTRAOPERATIVE RADIOTHERAPY

- ❑ IORT has a long tradition, yet it is still considered a developing modality, whose role in the management of many tumour sites remains to be determined.
- ❑ Three beam modalities are used for IORT:
 - Orthovoltage x rays
 - Megavoltage electrons
 - High dose rate brachytherapy with iridium-192 source.



15.5 INTRAOPERATIVE RADIOTHERAPY

- ❑ IORT is often applied as part of a treatment protocol that includes other modalities such as chemotherapy and external beam radiotherapy. The initial treatment attempts to shrink the tumour, making the subsequent surgical resection simpler.
- ❑ When surgical resection of a residual tumour mass is finally attempted, it may happen that not all the tumour can be removed without significant morbidity.



15.5 INTRAOPERATIVE RADIOTHERAPY

- ❑ Although the largest clinical experience with IORT has been with gastrointestinal cancers in adults, any tumour site which can be exposed surgically and isolated from nearby radiation-sensitive tissues can be targeted with the IORT.
- ❑ Historically, tissues within the retroperitoneum, including the pancreas, rectum and stomach have been most commonly treated with IORT, and, on a smaller scale, bladder, breast and gynecological malignancies.



15.5 INTRAOPERATIVE RADIOTHERAPY

- ☐ To improve the local and regional control a large radiation dose is delivered during the surgical procedure.
- ☐ The main biologic advantage of the IORT is its ability to decrease normal tissue toxicity by displacing or shielding sensitive structures from the radiation beam.
- ☐ The main disadvantage of the IORT is the dose delivery in a single session.



15.5 INTRAOPERATIVE RADIOTHERAPY

15.5.1 Physical and clinical requirements for the IORT

- ☐ The IORT procedure requires an operating room for the surgical procedure and a treatment room for delivery of dose.
- ☐ Often both the operating room and the radiation treatment room are merged into one, resulting in a specially shielded operating suite in which a dedicated radiation treatment unit is installed permanently.



15.5 INTRAOPERATIVE RADIOTHERAPY

15.5.1 Physical and clinical requirements for the IORT

- ❑ Once a radiation modality and the location in which the treatment unit is to be installed are selected, an applicator system must be obtained.
- ❑ Applicators are important for three reasons:
 - To define the target area.
 - To shield tissues outside the target area from radiation.
 - To keep sensitive tissues from the target area during irradiation.
- ❑ Depending on the radiation modality applied for the IORT, there are several applicator systems available commercially. It is also possible to design and build in-house applicator systems.



15.5 INTRAOPERATIVE RADIOTHERAPY

15.5.2 Radiation modalities and techniques for the IORT

- ❑ Three different **modalities** may be used to deliver IORT:
 - Orthovoltage x rays
 - Megavoltage electron beams
 - High dose rate (HDR) iridium-192 brachytherapy sources
- ❑ Before clinical implementation of an IORT program, an extensive characterization of the radiation parameters of the radiation modality used must be carried out and documented.
- ❑ The dosimetry data must be summarized so that it can be quickly understood and readily used.



15.5 INTRAOPERATIVE RADIOTHERAPY

15.5.2 Radiation modalities and techniques in the IORT

- ❑ Most IORT programmes today are based on electron beams produced by megavoltage linacs, since electron beams provide several advantages over x rays for the purposes of IORT:
 - The electron dose is deposited over a definite range, thus sparing tissue downstream from the target volume.
 - Depending on the target volume thickness and electron energy, the dose can be deposited homogeneously throughout the target volume.
 - In contrast to low energy x rays there is not much difference between the tissue and bone absorption of megavoltage electron beams.



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15.5 INTRAOPERATIVE RADIOTHERAPY

15.5.3 Commissioning of an IORT programme

- ❑ Once a decision is made on introducing an IORT service into an institution:
 - IORT technique must be chosen.
 - IORT equipment must be ordered.
 - IORT team must be assembled.
- ❑ Upon delivery, the equipment must be installed and commissioning of the IORT procedure must be carried out.



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15.5 INTRAOPERATIVE RADIOTHERAPY

15.5.3 Commissioning of an IORT programme

- ❑ Radiation beam parameters must be measured and dosimetry data summarized so that they may be quickly understood and readily used.
- ❑ Dosimetry measurements will depend on the IORT modality chosen for clinical use and will typically include:
 - Absolute dose output at the end of each treatment applicator.
 - Central axis depth dose data.
 - Surface dose and bremsstrahlung.
 - Bremsstrahlung contamination of electron beams if electron beams are used for the IORT.
 - Dose distribution data for individual treatment applicators.



15.5 INTRAOPERATIVE RADIOTHERAPY

15.5.3 Commissioning of an IORT programme

- ❑ The transition between the surgical procedure and irradiation must be carefully planned and all steps involved properly worked out and practised as part of the commissioning procedure.
- ❑ Irrespective of the radiation modality used for the IORT, the set of dosimetry data must be documented in an easily usable format to permit quick and accurate dosimetric calculations.



15.5 INTRAOPERATIVE RADIOTHERAPY

15.5.4 Quality assurance in IORT

- ❑ **Quality assurance for IORT treatments** is at least as important as that for standard radiotherapy, since the IORT treatment are almost always given in a single session, making it essentially impossible to correct a misadministration of dose.
- ❑ The quality assurance in IORT consists of three components:
 - Basic quality assurance dealing with the IORT equipment.
 - Pre-treatment quality assurance dealing with equipment preparation and verification prior to IORT treatment.
 - Treatment quality assurance during the IORT procedure.



15.6 ENDOCAVITARY RECTAL IRRADIATION

- ❑ In recent years increasing efforts have been directed toward the development of organ saving therapeutic approaches for malignant neoplasms.
- ❑ For malignancies of the rectum and anal canal, sphincter saving procedures are successful in achieving not only a high probability of local control but also an improved quality of life by avoiding the permanent colostomy and male impotence that may result from abdominoperineal resection.



15.6 ENDOCAVITARY RECTAL IRRADIATION

- ❑ **Endocavitary rectal (endorectal) irradiation** is a sphincter saving procedure used in the treatment of selected rectal carcinomas with superficial x rays (of the order of 50 kVp).
- ❑ The technique was introduced in the 1930s by Chaoul and subsequently developed and practiced by others, most notably Papillon.



15.6 ENDOCAVITARY RECTAL IRRADIATION

15.6.1 Clinical requirements for endorectal irradiation

- ❑ **Patient selection criteria** for successful application of endocavitary irradiation are very stringent:
 - Early stage (T1) rectal cancer that is limited to submucosa.
 - Biopsy proven, well or moderately-well differentiated rectal adenocarcinoma.
 - Mobile lesion with maximum diameter of 3 cm.
 - Lesion located within 10 cm from the anal canal.
 - No evidence of lymph node involvement or distant metastases.
- ❑ **Total tumour dose** is of the order of 80 Gy, delivered in three fractions of 20 - 30 Gy in each fraction. The fractions are typically given two weeks apart.



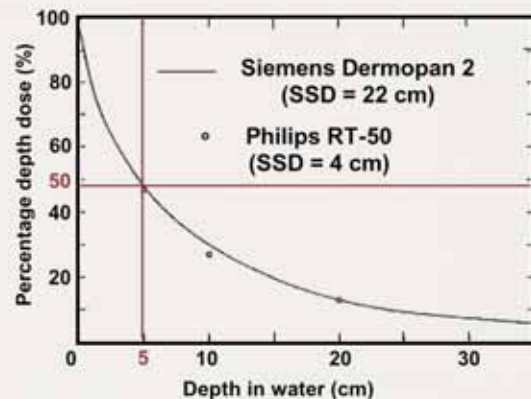
15.6 ENDOCAVITARY RECTAL IRRADIATION

15.6.1 Physical requirements for endorectal irradiation

- ❑ The **main physical requirement** for the technique to be successful is that the x ray beam should have a low effective energy with the following PDD characteristics:

- Surface 100%
- 5 mm 50%
- 10 mm 30%
- 25 mm 10%

- ❑ These PDD characteristics imply an x-ray tube potential of the order of 50 kVp and a short SSD.



15.6 ENDOCAVITARY RECTAL IRRADIATION

15.6.1 Physical requirements for endorectal irradiation

- ❑ Two techniques have been developed for endorectal irradiation:
 - The **short SSD technique**, with the SSD of the order of 4 cm and the x-ray tube inserted into the proctoscopic cone.
 - The **long SSD technique**, with the SSD of the order of 20 cm and the x-ray tube coupled to the cone externally.
- ❑ Most of the published accounts of endorectal irradiation deal with the short SSD technique, which, in honour of its main proponent, is referred to as the Papillon technique.



15.6 ENDOCAVITARY RECTAL IRRADIATION

15.6.1 Physical requirements for endorectal irradiation

Short SSD endorectal irradiation technique (SSD \approx 4 cm):

- ☐ X-ray tube is inserted into the proctoscopic cone
- ☐ Proctoscopic cone and x-ray tube are hand-held during irradiation. Two operators are required.
- ☐ Concerns
 - Possible patient or operator motion during treatment resulting in geographic miss.
 - Radiation hazard to operator during treatment.
 - Tumor dose inhomogeneity because of short SSD.



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15.6 ENDOCAVITARY RECTAL IRRADIATION

15.6.1 Physical requirements for endorectal irradiation

Short SSD endorectal irradiation technique:

- ☐ Proctoscopic cone and x-ray tube are hand-held during irradiation.



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15.6 ENDOCAVITARY RECTAL IRRADIATION

15.6.1 Physical requirements for endorectal irradiation

Long SSD endorectal irradiation technique (SSD = 22 cm):

- ❑ X-ray tube is coupled with an electromagnet to the proctoscopic cone outside the patient.
- ❑ X-ray tube and proctoscopic cone are immobilized mechanically with a clamp.
- ❑ **Advantages** over the short SSD technique:
 - Better immobilization of the x-ray tube and proctoscopic cone.
 - Lower radiation hazard to the operator.
 - Better dose uniformity in the tumor because of long SSD.
 - Proctoscopic cones with diameters smaller than 3 cm are possible.



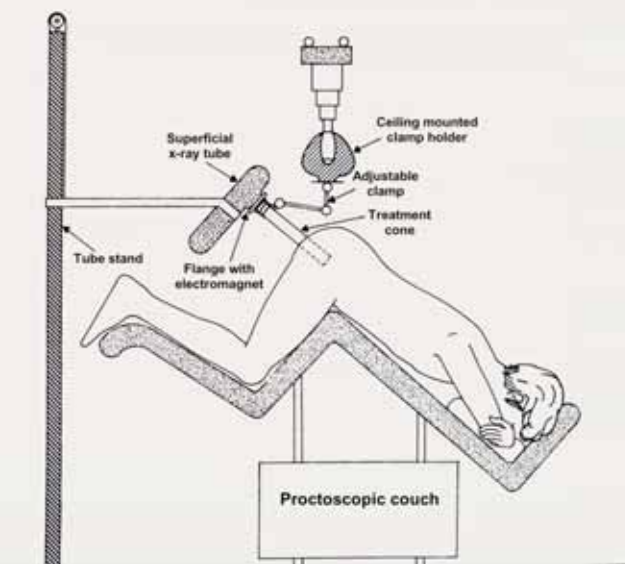
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15.6 ENDOCAVITARY RECTAL IRRADIATION

15.6.1 Physical requirements for endorectal irradiation

Long SSD endorectal irradiation technique (SSD = 22 cm):

The proctoscopic cone and the x-ray tube are coupled outside the patient with an electromagnet and immobilized mechanically with a clamp.



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15.6 ENDOCAVITARY RECTAL IRRADIATION

15.6.1 Physical requirements for endorectal irradiation

Long SSD endocavitary rectal irradiation technique



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15.6 ENDOCAVITARY RECTAL IRRADIATION

15.6.2 Endorectal treatment technique

- ☐ Patient is positioned on the proctoscopic table and the proctoscopic cone together with a plunger is inserted into the rectum.
- ☐ Plunger is removed, a proctoscopic viewing device is attached to the cone and the cone is placed over the tumor.
- ☐ The viewing device is removed, the x-ray tube is either inserted into the cone (in short SSD technique) or coupled to the cone (in long SSD technique).
- ☐ The x-ray tube is turned on and the prescribed dose is delivered to the tumor.



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15.6 ENDOCAVITARY RECTAL IRRADIATION

15.6.3 Quality assurance in endorectal irradiation

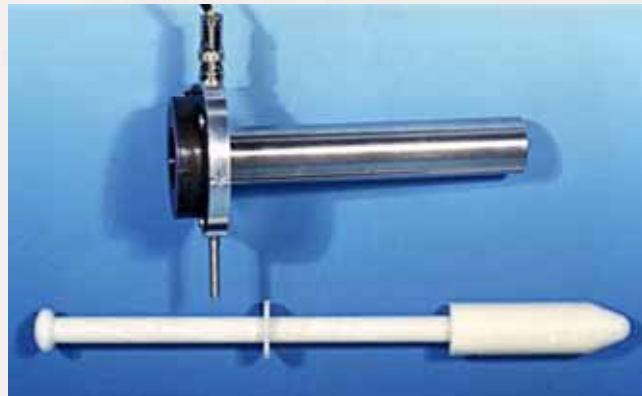
- The quality assurance of endorectal irradiation consists of three components:
 - **Basic quality assurance** dealing with the complete equipment used for endorectal irradiation procedure.
 - **Pre-treatment quality assurance** dealing with equipment preparation immediately prior to endocavitary treatment.
 - **Treatment quality assurance** during the delivery of the endorectal treatment.



15.6 ENDOCAVITARY RECTAL IRRADIATION

15.6.3 Quality assurance in endorectal irradiation

- Basic quality assurance covers the complete equipment used in endorectal treatment:
 - Superficial x-ray tube
 - Proctoscopic cone and obturator (plunger).
 - Visualization device.



15.6 ENDOCAVITARY RECTAL IRRADIATION

15.6.3 Quality assurance in endorectal treatments

- ❑ The **output of the x-ray tube** should be measured with a parallel-plate ionization chamber that is suitable for calibration of superficial x rays and has a calibration coefficient traceable to a standards laboratory.
- ❑ The **effect of the chamber body** on the chamber signal when the field size used in the calibration laboratory differs from the field size used clinically must be evaluated in order to account for the differences in backscatter.



15.7 CONFORMAL RADIOTHERAPY

- ❑ The **basic premise of conformal radiotherapy** is that, in comparison with traditional dose delivery techniques, treatment outcomes will be improved by using special techniques that allow target dose escalation (improved tumour control probability) while maintaining an acceptable level of normal tissue complications.
- ❑ **Conformal radiotherapy** conforms or shapes the prescription dose volume to the planning target volume (PTV) while at the same time keeping the dose to specified organs at risk below their tolerance dose.



15.7 CONFORMAL RADIOTHERAPY

15.7.1 Basic aspects of conformal radiotherapy

- ❑ **Three-dimensional conformal radiotherapy (3-D CRT)** is based on 3-D anatomic information and the use of dose distributions that conform tightly to the target volume.
- ❑ 3-D CRT must provide a tumouricidal dose to the tumour and a limited dose to critical organs.
- ❑ The concept of conformal dose delivery has thus two main objectives:
 - Maximized tumour control probability (TCP).
 - Minimized normal tissue complication probability (NTCP).



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15.7 CONFORMAL RADIOTHERAPY

15.7.1 Basic aspects of conformal radiotherapy



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15.7 CONFORMAL RADIOTHERAPY

15.7.1 Basic aspects of conformal radiotherapy

Target localization is achieved through:

- ❑ **Anatomical imaging** such as:
 - Computerized tomography (CT)
 - Magnetic resonance imaging (MRI)
 - Single photon emission tomography (SPECT)
 - Ultrasound (US)
- ❑ **Functional imaging** such as:
 - Positron emission tomography (PET)
 - Functional magnetic resonance imaging (fMRI)
 - Molecular imaging



15.7 CONFORMAL RADIOTHERAPY

15.7.1 Basic aspects of conformal radiotherapy

- ❑ Treatment planning is achieved through:
 - **Forward treatment planning** techniques which design uniform intensity beams shaped to the geometrical projection of the target
 - **Inverse treatment planning** techniques which, in addition to beam shaping, use intensity modulated beams to improve target dose homogeneity and to spare organs at risk.
- ❑ Modern dose delivery techniques range from the use of standard regular and uniform coplanar beams to intensity modulated non-coplanar beams produced with multileaf collimators (MLCs).



15.7 CONFORMAL RADIOTHERAPY

15.7.1 Basic aspects of conformal radiotherapy

Treatment planning process for 3-D CRT consists of 4 steps:

- ❑ Acquisition of **anatomic information** in the form of transverse (axial) images.
- ❑ Determination of the **planning target volume (PTV)** by the radiation oncologist by contouring the PTV on each individual axial image (**segmentation process**).
- ❑ Design of radiation fields using the **beam's-eye-view** option in the treatment planning software.
- ❑ **Optimization of the treatment plan** through the design of optimal field sizes, beam directions, beam energies, etc.



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15.7 CONFORMAL RADIOTHERAPY

15.7.2 Multileaf collimators

- ❑ Modern linacs are equipped with MLCs that incorporate from 20 to 60 pairs of narrow, closely abutting tungsten leaves, each leaf projecting a typical width of between 5 and 10 mm at the linac isocentre.
- ❑ MLCs projecting leaf widths less than 5 mm at the isocentre are referred to as microMLCs. They are used for:
 - Shaping irregular fields of less than 10 cm in maximal field dimension, such as head and neck fields
 - Irregular fields with less than 3 cm in largest dimension that are used in radiosurgery.



Radiation Oncology Physics: A Handbook for Teachers and Students - 15.7.2 Slide 1

15.7 CONFORMAL RADIOTHERAPY

15.7.2 Multileaf collimators

- ❑ The MLCs may be:
 - Integral part of the linac head, replacing either the upper or the lower secondary collimator jaws
 - Attached to the linac head and used in conjunction with both the upper and lower collimator jaws.
- ❑ The advantage of adding the MLC to both upper and lower collimator jaws is that, when the MLC malfunctions, the linac may still be used for traditional radiotherapy.
- ❑ The advantage of replacing either the upper or the lower jaws with an MLC is the extra space that is generated by removal of one set of jaws.



Radiation Oncology Physics: A Handbook for Teachers and Students - 15.7.2 Slide 2

15.7 CONFORMAL RADIOTHERAPY

15.7.2 Multileaf collimator

- ❑ **Multileaf collimator** with 60 pair of abutting tungsten alloy leaves (Millenium MLC; courtesy of Varian, Palo Alto, CA)



- The **density** of the tungsten alloy leaves is 17 to 18.5 g/cm³.
- The **thickness** of the leaves along the beam direction is 6 to 7.5 cm.
- The **primary transmission** through the leaves is less than 2%, in comparison with about 1% for linac jaws.



Radiation Oncology Physics: A Handbook for Teachers and Students - 15.7.2 Slide 3

15.7 CONFORMAL RADIOTHERAPY

15.7.2 Multileaf collimator

- ❑ Each leaf of a MLC is individually motorized and computer controlled, allowing positioning with an accuracy better than 1 mm and the generation of irregular radiation fields, shaped to conform to the beam's eye view (BEV) target cross section.
- ❑ Each leaf is driven by a separate, miniature DC motor.
- ❑ Positional control and verification of the leaves is achieved by a sophisticated servomechanism using electronic or optical/video techniques to sense the leaf position.



15.7 CONFORMAL RADIOTHERAPY

15.7.3 Acceptance testing of multileaf collimators

- ❑ **Acceptance testing of an MLC** must cover all aspects of the MLC clinical operation:
 - Software
 - Mechanical
 - Radiation
- ❑ **Software aspects of MLC testing** consist of:
 - Verification of the field shaper.
 - Verification of the linkage between the treatment planning system and the MLC.
 - Verification of the accuracy of field shaping.
 - Verification of functioning of the controller.



15.7 CONFORMAL RADIOTHERAPY

15.7.3 Acceptance testing of multileaf collimators

Mechanical aspects of MLC testing consist of:

- Verification of the leaf motion and their maximum travel.
- Verification of leaf abutting on and off the central axis.
- Verification of the alignment of MLC axes with the axes of the linac secondary collimators.
- Verification of the positional reproducibility of leaves.
- Verification of leaf interlocks and jaw positional tolerances.



15.7 CONFORMAL RADIOTHERAPY

15.7.3 Acceptance testing of multileaf collimators

Radiation aspects of MLC testing consist of:

- Verification of intra-leaf transmission.
- Verification of inter-leaf leakage.
- Verification of leakage in the junction of two abutting leaves both on the field axis and off the field axis.
- Verification of leaf penumbra along the leaf and perpendicularly to the leaf.



15.7 CONFORMAL RADIOTHERAPY

15.7.4 Commissioning of multileaf collimators

- ❑ The **commissioning protocol** for MLCs involves obtaining a collection of beam data for:
 - All beam energies produced by the linac
 - Various irregular fields produced by the MLC.
- ❑ The essence of the MLC commissioning is to verify that the physical characteristics of the MLC do not affect appreciably the basic dosimetric parameters of the open beams, such as:
 - Field flatness
 - Symmetry
 - Collimator factor
 - Output factor
 - Scatter factor
 - Percentage depth dose



15.7 CONFORMAL RADIOTHERAPY

15.7.4 Commissioning of multileaf collimators

- ❑ **In-phantom dosimetric parameters**, such as
 - Relative dose factor
 - Scatter factor
 - Percentage depth dose (PDD)
 - Tissue-maximum ratio (TMR)

are determined by the field shape created by the MLC collimator.



15.7 CONFORMAL RADIOTHERAPY

15.7.4 Commissioning of multileaf collimators

In-air dosimetric parameter, the collimator factor (CF):

- ☐ In linac configurations in which the MLC is essentially a tertiary collimator, is determined by the square or rectangular field shaped by the secondary linac collimator jaws and is considered independent of the MLC.
- ☐ In linac configurations in which the MLC replaces the upper or collimator jaws, the collimator factor is a function of the radiation field shaped by the MLC.



15.7 CONFORMAL RADIOTHERAPY

15.7.5 Quality assurance programme for multileaf collimators

- ☐ A **quality assurance programme** must be implemented for the clinical use of MLCs to ensure a reliable and safe operation of software and all mechanical components.
- ☐ The quality assurance programme should cover:
 - Positional accuracy of leaves
 - Leaf motion reliability
 - Leaf leakage
 - Interlocks
 - Networking
 - Data transfer



15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

- ❑ Radiation beams in standard external beam radiotherapy including 3-D conformal radiotherapy usually have a **uniform intensity across the field**, fulfilling the linac flatness and symmetry specifications.
- ❑ **Non-uniform beam intensities (intensity modulation)** can be used to improve dose distributions by:
 - Compensating for contour irregularities
 - Compensating for tissue inhomogeneities
 - Compensating for highly irregular target volumes
 - Sparing organs at risk located in the vicinity of target volume.



15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

- ❑ Physical wedges and compensators have long been used to produce **simple intensity modulation** to compensate for contour irregularities. Their effects are incorporated into a treatment plan through the use of forward planning algorithms.
- ❑ Modern radiotherapy techniques based on **computer-controlled intensity modulation systems** have been developed during the past decade and currently represent the most sophisticated 3-D conformal dose delivery process.



15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

- ❑ The 3-D CRT technique which relies on multiple beams with optimized intensity modulated fluence distributions is referred to as **intensity modulated radiotherapy (IMRT)**.
- ❑ Three techniques are currently available for IMRT dose delivery:
 - Isocentric linac in conjunction with a MIMIC collimator.
 - Tomotherapy unit.
 - Isocentric linac in conjunction with a multileaf collimator.



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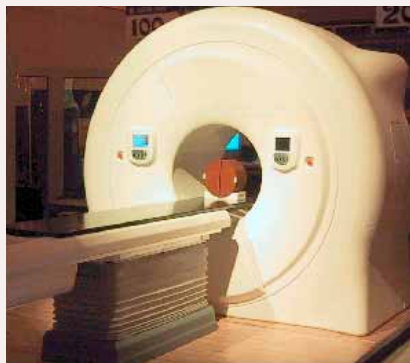
15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

MIMIC collimator
attached to linac



Tomotherapy unit



Multileaf collimator
attached to linac



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15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

- ❑ The optimal modulated intensity for each beam is determined through the dose optimization process referred to as **inverse planning** incorporating dose criteria not only for the target volume but also for the neighboring organs at risk.
- ❑ The fluence files generated by the inverse planning algorithm are transmitted electronically to the linear accelerator which by means of computer control delivers the intensity modulated beams.



15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

- ❑ The **inverse planning computational methods** for calculating the optimum modulated intensity beam distributions fall into two broad categories:
 - **Analytical methods** which use a back projection algorithm to arrive at the fluence distribution from the desired dose distribution.
 - **Iterative methods** which minimize a cost function which quantitatively represents the deviation from the desired goal.



15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

- ❑ The patient data required for inverse planning is similar to that required for 3-D forward planning.
- ❑ Planning for IMRT treatment requires the following:
 - **3-D anatomic image data** (mainly CT and MRI studies but possibly also US, SPECT and PET studies).
 - **Image registration** (fusion of image data sets obtained from different modalities).
 - **Image segmentation** (slice-by-slice delineation of anatomic regions of interest, such as the gross target volume, organs at risk, anatomic landmarks, etc.).
 - Definition of the **planning target volume (PTV)**.



15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

- ❑ For each planning target volume (PTV) the user enters the desired criteria for the plan, such as:
 - Maximum dose
 - Minimum dose
 - Dose-volume histogram
- ❑ For each critical structure (organ at risk) the user enters the following criteria:
 - Desired limiting dose
 - Dose-volume histogram.



15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

- ❑ For each IMRT plan the user may also be expected to stipulate the beam energy, number of beams, beam directions, and number of iterations before the optimization process for the dose distribution calculation is started by the inverse planning software.
- ❑ The routine clinical application of IMRT is still hindered by several **difficulties**, such as:
 - Complexity of the software used for inverse treatment planning.
 - Complexity of equipment used for IMRT dose delivery.
 - Quality assurance issues related to the dose distribution optimization process and the IMRT dose delivery process.



15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

- ❑ The inverse planning techniques for the IMRT provide several **advantages** over the standard forward planning:
 - Improved dose homogeneity inside the target volume and better potential for limited irradiation of surrounding sensitive structures.
 - Increased speed and lesser complexity in finding an optimized dose distribution.
 - A quantitative introduction of cost functions, often incorporating dose volume constraints and biological functions.
 - Adjustment of the optimal treatment planning to the actual dose delivery technique and accounting for all hardware limitations.



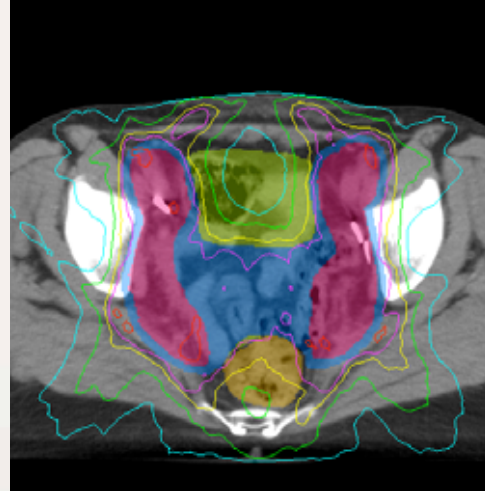
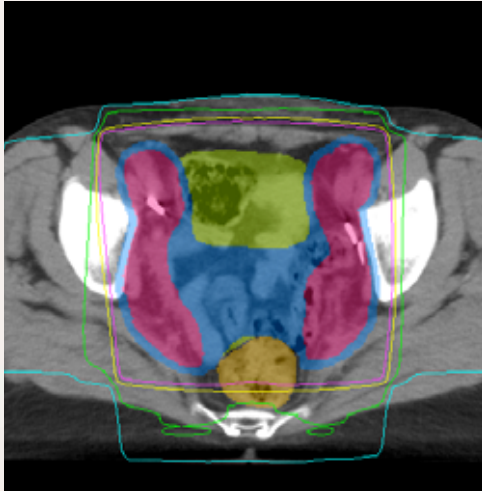
15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

- The inverse planning techniques for the IMRT provide several **advantages** over the standard forward planning:

(a) 3D conformal RT

(b) IMRT

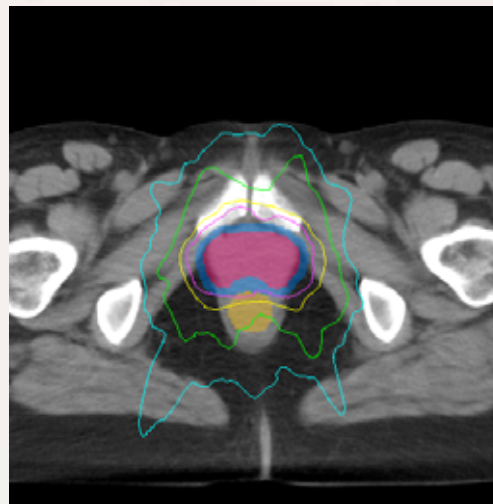
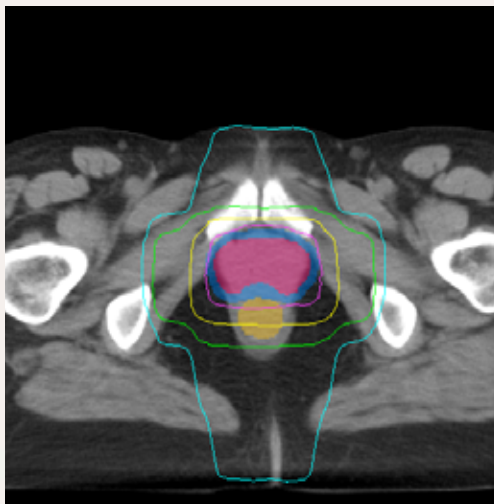


15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

(a) 3D conformal RT

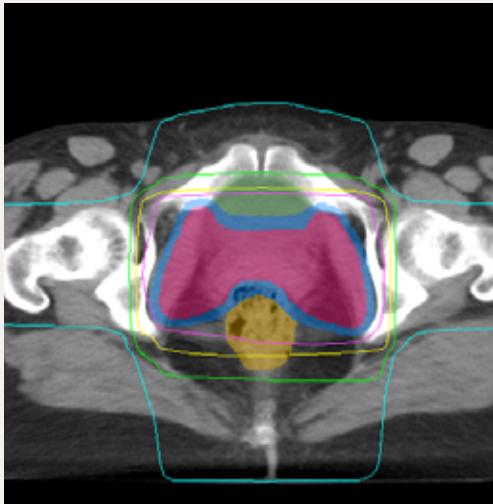
(b) IMRT



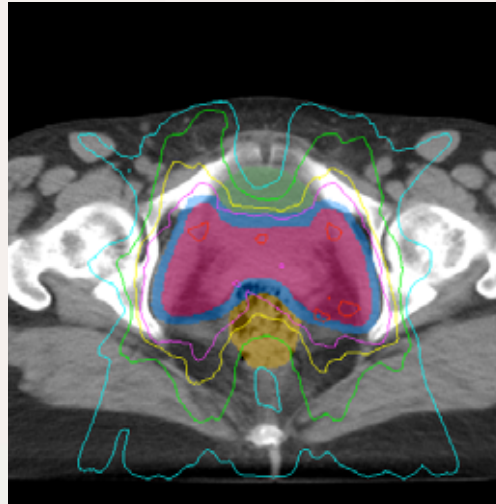
15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

(a) 3D conformal RT



(b) IMRT

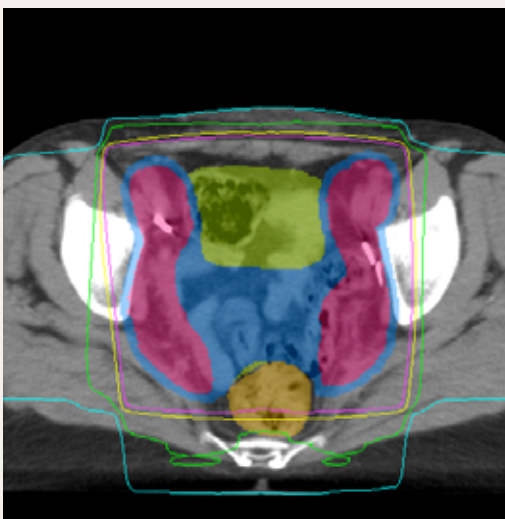


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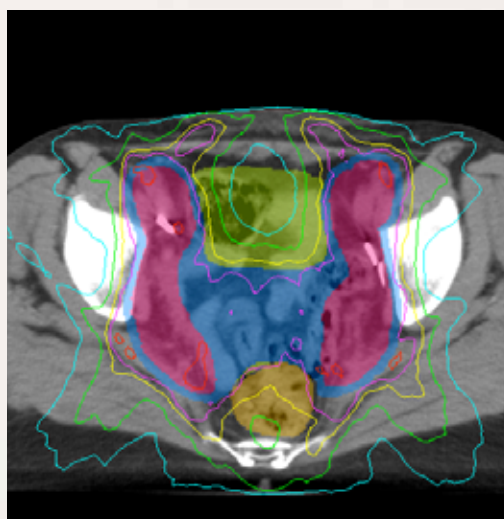
15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

(a) 3D conformal RT



(b) IMRT



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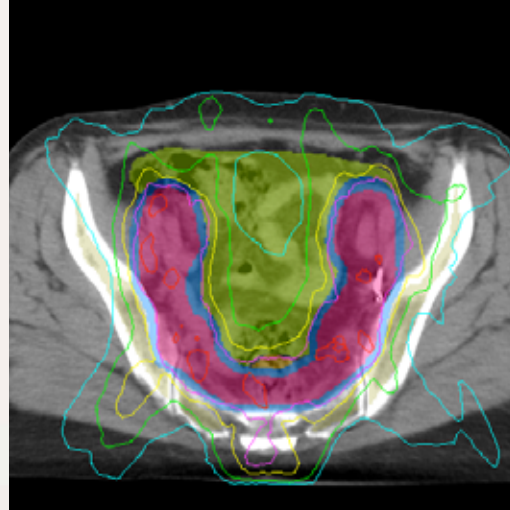
15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

(a) 3D conformal RT



(b) IMRT



15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

- ❑ Various approaches to IMRT have been developed generally falling between the two extremes:
 - Simple standard custom-made physical compensator.
 - Scanned photon pencil beam.
- ❑ Between the two extremes are the currently used IMRT techniques based on production of intensity modulated beams using MLC-equipped linear accelerators:
 - Static approach with several static intensity modulated fields.
 - Dynamic approach with intensity modulation delivered concurrently with the gantry rotation.

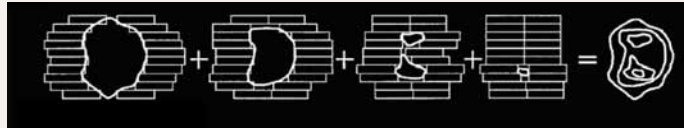
15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

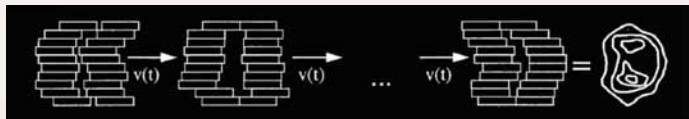
- Production of intensity modulated beams using MLC-equipped linear accelerators:



- **Static approach** with several static intensity modulated fields.



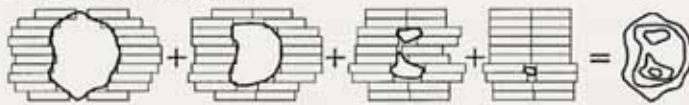
- **Dynamic approach** with intensity modulation delivered concurrently with the gantry rotation.



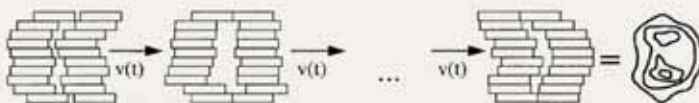
15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

Static MLC technique



Dynamic MLC technique



Static MLC

- Simple concept
- Slow dose delivery (5 min/field)
- Hard on MLC hardware

Dynamic MLC

- Not intuitive
- Fast dose delivery (1 min/field)
- Easier on MLC hardware



15.7 CONFORMAL RADIOTHERAPY

15.7.6 Intensity modulated radiotherapy

- ❑ Rudimentary IMRT treatments have been used clinically since the 1960s with wedges or custom-made physical compensators.
- ❑ **Modern IMRT** became possible during the latter part of the 1990s with the synergistic development of:
 - Sophisticated computerization of the 3-D dose distribution and dose delivery process.
 - Imaging techniques for image registration and segmentation.
 - Inverse treatment planning algorithms.
 - Quality assurance techniques for verification of dose delivery.



15.7 CONFORMAL RADIOTHERAPY

15.7.7 Commissioning of IMRT systems

- ❑ **Commissioning of an IMRT system** depends on the type of inverse planning algorithm to be used clinically.
- ❑ Some inverse planning systems consist of special modules attached to standard 3-D forward planning systems, others are stand-alone systems that require complete data measurement, entry and possibly modeling, separate from a 3-D planning system.
- ❑ Extra measurements characterizing some basic properties of the MLC to be used for the IMRT must be carried out.



15.7 CONFORMAL RADIOTHERAPY

15.7.7 Commissioning of IMRT systems

- ❑ IMRT treatments can be delivered with the MLC operating in one of three basic modes:
 - **Segmented MLC (SMLC) mode**, often referred to as the **step-and-shoot mode**, in which the intensity modulated fields are delivered in the form of a sequence of small segments or subfields, each subfield with a uniform intensity.
 - **Dynamic MLC (DMLC) mode**, also referred to as the **sliding window mode**, in which the intensity modulated fields are delivered in a dynamic fashion with the leaves of the MLC moving during the irradiation of the patient.
 - **Intensity modulated arc therapy (IMAT) mode** in which the sliding window approach is used as the gantry rotates around a patient.



15.7 CONFORMAL RADIOTHERAPY

15.7.7 Commissioning of IMRT systems

- ❑ Each method of dose delivery must be commissioned separately, since in each method the linac and the MLC are used differently.
- ❑ In dynamic MLC dose deliveries the tolerances on MLC performance are tighter than dose in static MLC applications.
- ❑ Generally, a set of quality assurance test specific to the IMRT must be developed in addition to standard MLC quality assurance procedures.



15.7 CONFORMAL RADIOTHERAPY

15.7.7 Commissioning of IMRT systems

- ❑ Usually, a clinic adopts only one IMRT method to simplify the dose delivery and minimize the possibility of errors and confusion.
- ❑ This also simplifies the commissioning process, since only one dose delivery method needs to be tested.
- ❑ In addition to the IMRT dose delivery system, the inverse planning system must also be commissioned.



15.7 CONFORMAL RADIOTHERAPY

15.7.7 Commissioning of IMRT systems

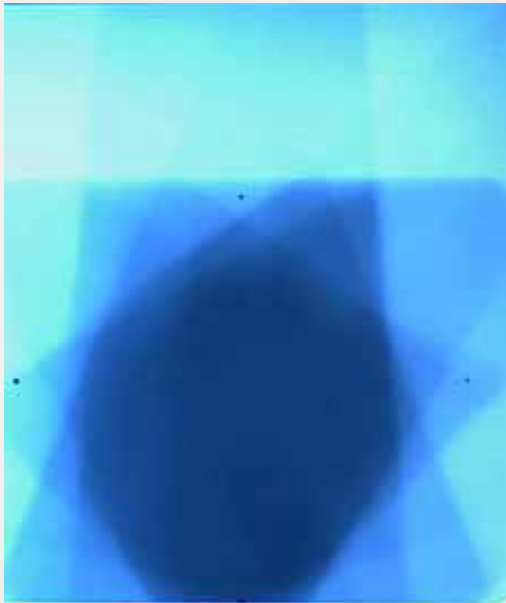
- ❑ Verification of the accuracy of the dose calculation algorithm of an inverse planning system is carried out using the standard dosimetry tools, such as radiation dosimeters in conjunction with various phantoms:
 - Ionization chamber
 - Radiographic film
 - Radiochromic film
 - Thermoluminescent dosimetry



15.7 CONFORMAL RADIOTHERAPY

15.7.7 Commissioning of IMRT systems

- ❑ Verification of the accuracy of the dose calculation algorithm of an inverse planning system using radiochromic film



15.7 CONFORMAL RADIOTHERAPY

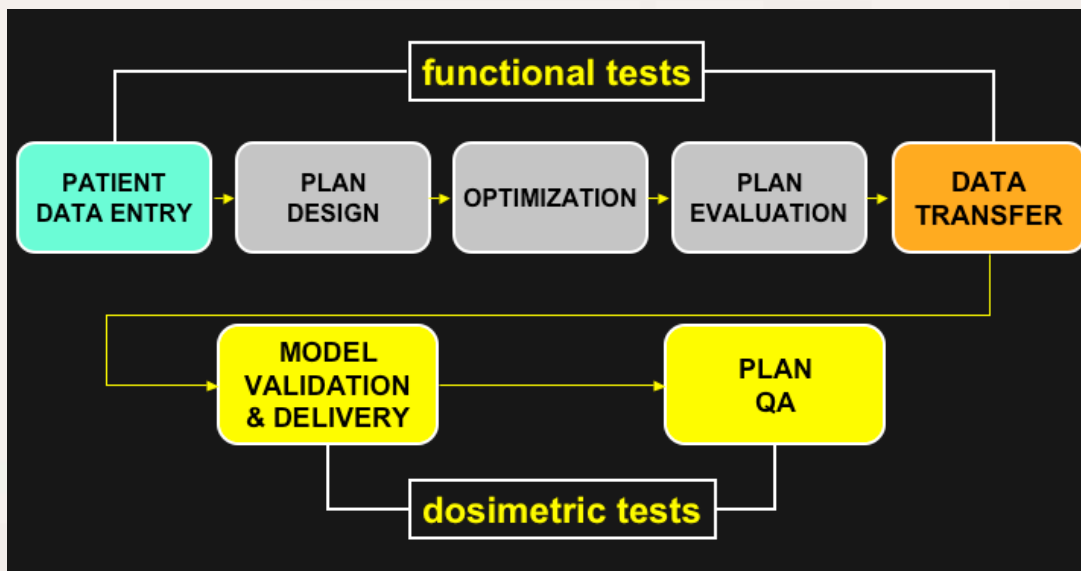
15.7.7 Commissioning of IMRT systems

- ❑ Most commercially available IMRT planning systems permit fluence maps optimized for a clinical application to be transferred to a representative phantom for calculation.
- ❑ The phantom can then be physically loaded with any one of the suitable radiation dosimeters and irradiated with the planned intensity modulated fields and the measured results compared with calculated values.

15.7 CONFORMAL RADIOTHERAPY

15.7.7 Commissioning of IMRT systems

- Summary of the IMRT commissioning process:



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15.7 CONFORMAL RADIOTHERAPY

15.7.8 Quality assurance for IMRT systems

- A **comprehensive quality assurance programme** must be in place before IMRT is used clinically to ensure accurate IMRT dose delivery.
- This programme must include standard verification of linac radiation output as well as tests of the dynamic MLC positioning and movement.
- A good approach is to perform a subset of the commissioning tests on a regular basis and to keep a record of all test results for periodic inspections.



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15.7 CONFORMAL RADIOTHERAPY

15.7.9 Dose verification for IMRT treatment plans

- ❑ It is customary to carry out an independent verification of all clinical IMRT treatment plans.
- ❑ This is done through a transfer of each IMRT plan to a representative phantom for dose calculation.
- ❑ The phantom is then loaded with suitable dosimeters and irradiated with the intensity modulated fields (static or dynamic) planned for the patient.
- ❑ The actual dose delivery can then be compared with the plan and evaluated for accuracy.



15.8 IMAGE GUIDED RADIOTHERAPY

- ❑ The recent advances in high precision radiotherapy resulted from significant advances in all three areas of importance to radiotherapy:
 - **Target localization** (image registration, image segmentation, multimodality fusion, virtual simulation)
 - **Treatment planning** (inverse treatment planning)
 - **Dose delivery** (IMRT, Tomotherapy, CyberKnife)



15.8 IMAGE GUIDED RADIOTHERAPY

- ❑ In the near future, molecular imaging will allow determination of intra-tumoural volumes that require treatment with extra high doses as a result of
 - Tumour hypoxia
 - Low intrinsic radiosensitivity
- ❑ This type of treatment will result in inhomogeneous target dose distributions and will be delivered with modern IMRT techniques.



15.8 IMAGE GUIDED RADIOTHERAPY

- ❑ The significant improvements in target localization and treatment planning resulted in smaller planning target volumes (PTVs), yet the accuracy of the actual dose delivery is still limited by the uncertainty in target position at the time of treatment as a result of:
 - Inter-fraction target movement
 - Intra-fraction target movement
 - Set-up errors



15.8 IMAGE GUIDED RADIOTHERAPY

- ❑ Imaging of patient anatomy on the treatment machine just prior to each daily dose fraction provides an accurate knowledge of the target location on a daily basis and helps with the daily patient set-up on the therapy machine.
- ❑ This technique is known as the **image guided radiotherapy (IGRT)** and has the potential of ensuring that the relative positions of the target volume and some reference marker for each fractional treatment are the same as in the treatment plan.



15.8 IMAGE GUIDED RADIOTHERAPY

- ❑ IGRT is characterized by the following features:
 - Allows reduced treatment margins in the PTV.
 - Results in fewer treatment complications.
 - Allows prescribed dose escalation.
 - Reduces the chance of geographical miss of the target.
- ❑ The ideal IGRT system will:
 - Allow the acquisition of soft tissue images at the time of each fraction of radiotherapy.
 - Have the ability to deliver a conformal dose through an IMRT technique.



15.8 IMAGE GUIDED RADIOTHERAPY

- ❑ The IGRT systems currently commercially available are based on direct integration of:
 - Kilovoltage or megavoltage imaging system and an isocentric linac (cone beam CT).
 - CT scanner and an isocentric linac.
 - Megavoltage computerized tomography (MVCT) and a Tomotherapy machine (miniature linac mounted on a CT-type gantry).
 - 2-D or 3-D ultrasound system and an isocentric linac.
 - On-line imaging with paired orthogonal planar imagers and a miniature linac mounted on a robotic arm.



15.8 IMAGE GUIDED RADIOTHERAPY

15.8.1 Cone beam computed tomography (CBCT)

- ❑ CBCT imaging enables visualization of the exact tumour location just prior to patient treatment on a linac.
- ❑ CBCT integrates CT imaging with an isocentric linac and involves an acquisition of multiple planar images about the patient in the treatment position on the linac table.



15.8 IMAGE GUIDED RADIOTHERAPY

15.8.1 Cone beam computed tomography

- ❑ In CBCT, a filtered back-projection algorithm, similar to CT scanning algorithms, is used to reconstruct the volumetric images of:
 - Target volume
 - Sensitive structures
 - Landmarks in the patient or markers on patient's skin.
- ❑ The volumetric data are then compared with the planning CT data and the associated optimized dose distribution, and the patient position is fine tuned to account for:
 - Tumour volume motion
 - Set-up error



15.8 IMAGE GUIDED RADIOTHERAPY

15.8.1 Cone beam computed tomography

- ❑ A CBCT system integrated with an isocentric linac and based on kilovoltage x-ray beams consist of:
 - Conventional x-ray tube mounted on a retractable arm at 90° to the high energy treatment beam.
 - Flat panel x-ray detector mounted on a retractable arm opposite to the x-ray tube.
- ❑ In addition to cone beam images, the x-ray system can also produce radiographic and fluoroscopic images.



15.8 IMAGE GUIDED RADIOTHERAPY

15.8.1 Cone beam computed tomography

- ❑ CBCT images can also be produced with megavoltage x-ray beams (MVCT) produced with isocentric linacs.
- ❑ The advantage of megavoltage CBCT is that no additional equipment is required for producing the cone beam since:
 - Beams come from the linac beam line.
 - MVCT systems use the detector panel that is already installed on the linac for use in electronic portal imaging.
- ❑ The disadvantage of MVCT systems is that, in comparison with KVCT systems, the MVCT systems produce an inferior tissue contrast.



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15.8 IMAGE GUIDED RADIOTHERAPY

15.8.1 Cone beam computed tomography

Integrated imaging systems based on kilovoltage cone beam CT
Elekta, Stockholm, Sweden



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15.8 IMAGE GUIDED RADIOTHERAPY

15.8.2 Computed tomography Primatom

- ❑ A system comprised of a linac and a CT unit at opposite ends of a standard radiotherapy treatment table has been developed and is marketed by Siemens.
- ❑ The main features of the system are:
 - The system allows precise CT imaging of patient anatomy prior to each fraction of radiotherapy.
 - The patient can be shifted to compensate for target motion and set-up inaccuracies.
 - The system allows clinicians to account for changes in target volume size and shape over a multifraction course of radiotherapy treatment.



15.8 IMAGE GUIDED RADIOTHERAPY

15.8.3 Tomotherapy

- ❑ The **Tomotherapy concept** for delivering image guided radiotherapy was developed by T.R. Mackie and colleagues at the University of Wisconsin in Madison.
- ❑ The commercial Tomotherapy HI ART system was released recently for clinical use and it combines the following features in one system:
 - Treatment planning
 - Patient positioning
 - Dose delivery



15.8 IMAGE GUIDED RADIOTHERAPY

15.8.3 Tomotherapy

Tomotherapy
machine



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15.8 IMAGE GUIDED RADIOTHERAPY

15.8.3 Tomotherapy

- ❑ In the tomotherapy system the IMRT is delivered with a **6 MV X-band miniature linac** mounted on a CT type gantry ring, allowing the linac to rotate around the patient.
- ❑ **Beam collimation** is accomplished with a computer controlled MLC that is also mounted on the gantry and has two sets of interlaced leaves that rapidly move in and out of the beam to constantly modulate the intensity of the radiation beam as the linac rotates around the patient.



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15.8 IMAGE GUIDED RADIOTHERAPY

15.8.3 Tomotherapy

- ❑ During treatment, the table advances the patient through the gantry bore so that the radiation beam dose is delivered in a helical geometry around the target volume.
- ❑ The system is designed to obtain an MVCT scan of the patient anatomy at any time before, during or after dose delivery.
- ❑ The MVCT image data are acquired with a 738 element xenon ionization chamber array that rotates on the gantry opposite the linac.



15.8 IMAGE GUIDED RADIOTHERAPY

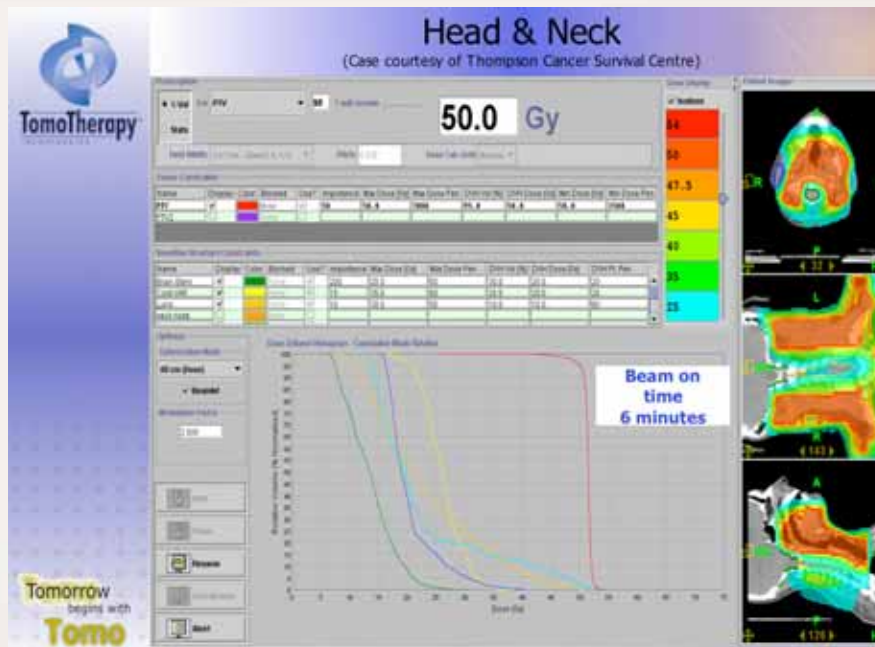
15.8.3 Tomotherapy

- ❑ The MVCT-based image guidance allows fine adjustment of the patient's position at every fraction to ensure that the dose is delivered precisely to the target volume.
- ❑ A CT scan can also be taken immediately after a fraction of therapy with the patient still in the treatment position, allowing an evaluation of the true dose distribution delivered to the patient.



15.8 IMAGE GUIDED RADIOTHERAPY

15.8.3 Tomotherapy



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15.8 IMAGE GUIDED RADIOTHERAPY

15.8.4 The BAT system

- ❑ The **B-Mode Acquisition and Targeting (BAT)** system is based on 2-D ultrasound images acquired prior to dose delivery. The images are used to realign the patient into the appropriate position on the treatment table.
- ❑ The system consists of a cart-based ultrasound unit positioned next to a linac treatment table and is used by the radiotherapist to image the target volume prior to each fraction of radiotherapy treatment.



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15.8 IMAGE GUIDED RADIOTHERAPY

15.8.4 The BAT system

- ❑ The relationship of the target volume to a reference point, usually the linac isocentre, is determined interactively by the user and compared with the target volume originally contoured in the CT data set.
- ❑ Recommendations for required patient translation to move the target volume into the same position relative to the isocentre as in the treatment plan are made by the system and the patient is moved, based on this information, to gain better treatment accuracy.



15.8 IMAGE GUIDED RADIOTHERAPY

15.8.4 The BAT system

- ❑ The BAT system has found its widest application in pelvic radiotherapy, particularly in treatment of prostate cancer, since the prostate can move significantly from one day to another within the pelvis relative to bony anatomy.
- ❑ Imaging the prostate target volume trans-abdominally with an ultrasonic probe on a daily basis and fine tuning the patient position based on system recommendation permits an accurate delivery of conformal treatment plans and allows target dose escalation without undue increase in bladder and rectal complications.

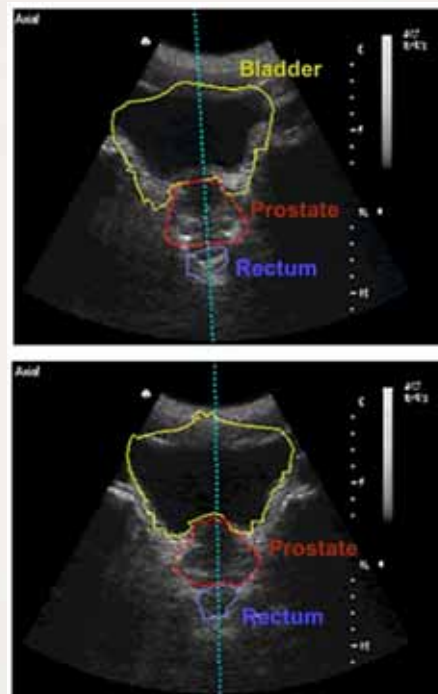


15.8 IMAGE GUIDED RADIOTHERAPY

15.8.4 The BAT system

❑ Images of a patient with prostatic adenocarcinoma captured by BAT®.

- BAT allows the determination of the degree of organ movement that has taken place since the original CT treatment planning scan (top image).
- The patient is repositioned accordingly (bottom image).
- In this case, the patient was moved 0.1 cm to the left, 0.6 cm down, and 0.9 cm away from the linac.



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15.8 IMAGE GUIDED RADIOTHERAPY

15.8.5 The ExacTrac ultrasonic and x-ray modules

- ❑ Tumour positioning conventionally relies on external skin markers that are subject to inter-fraction shifts compromising the accuracy of dose delivery.
- ❑ **ExacTrac by BrainLAB** is designed to address precise patient positioning by providing imaging of the target area around the tumour.
- ❑ Ultrasound or x-ray images are taken just before treatment and the ExacTrac system automatically compensates for any patient misalignment.



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15.8 IMAGE GUIDED RADIOTHERAPY

15.8.5 The ExacTrac ultrasonic and x-ray modules

- ❑ The **ultrasound-based ExacTrac system** can be used with any ultrasound unit and is comprised of a reflective marker array attached to an ultrasound probe. The marker array is calibrated by the ExacTrac infrared tracking system relative to reflective markers attached to patient's body.
- ❑ The system works similarly to the BAT system and allows fine adjustment of the patient's position to compensate for target motion and set-up inaccuracies.



15.8 IMAGE GUIDED RADIOTHERAPY

15.8.5 The ExacTrac ultrasonic and x-ray modules

- ❑ The **ExacTrac x-ray imaging module** provides high-resolution imaging of internal structures and organs.
- ❑ During the positioning process the system calculates the discrepancy between the actual and the planned target position and compensates for any discrepancies with automatic treatment table motions.



15.8 IMAGE GUIDED RADIOTHERAPY

15.8.6 The CyberKnife

- ❑ The **CyberKnife** was developed in the mid 1990s as an innovative tool for intracranial stereotactic radiosurgery.
- ❑ The dose is delivered with a **miniature X-band (10^4 MHz) linac** mounted on an **industrial robotic arm** in a combination that:
 - Offers excellent spatial accuracy in dose delivery
 - Allows, in comparison with isocentric linacs and tomotherapy machines, a great deal of flexibility in directing the beam toward the target.

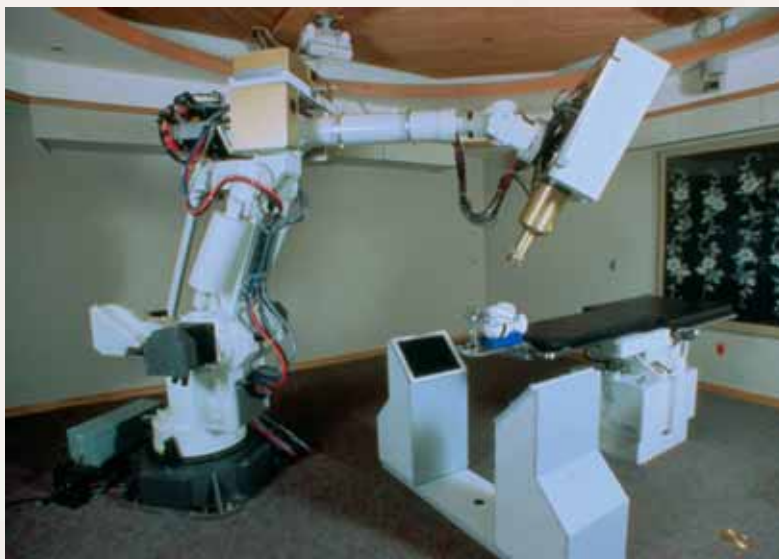


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15.8 IMAGE GUIDED RADIOTHERAPY

15.8.6 The CyberKnife

- ❑ **CyberKnife (miniature linac on robotic arm)**



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15.8 IMAGE GUIDED RADIOTHERAPY

15.8.6 The CyberKnife

Modern CyberKnife

Main components:

- 6 MV linac
- Robotic arm
- Treatment couch
- Imaging system



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15.8 IMAGE GUIDED RADIOTHERAPY

15.8.6 The CyberKnife

- ❑ The **CyberKnife radiosurgery system** provides an innovative approach to image guided dose delivery that is based on:
 - On-line orthogonal pair of digital x-ray imagers.
 - Patient axial CT data set possibly fused with MR and PET images.
 - Miniature 6 MV X-band linac.
 - Industrial robotic arm.
- ❑ This new approach to **highly accurate intracranial as well as extracranial delivery of high radiation doses** with small radiation fields opens the field of radiosurgery to exciting new IGRT techniques.



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15.8 IMAGE GUIDED RADIOTHERAPY

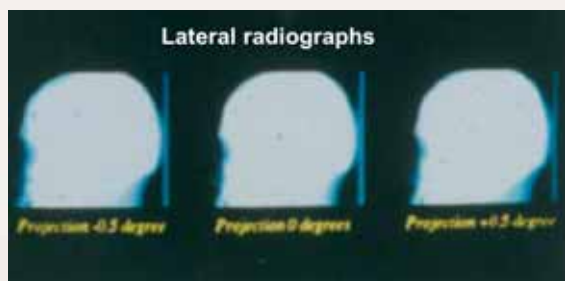
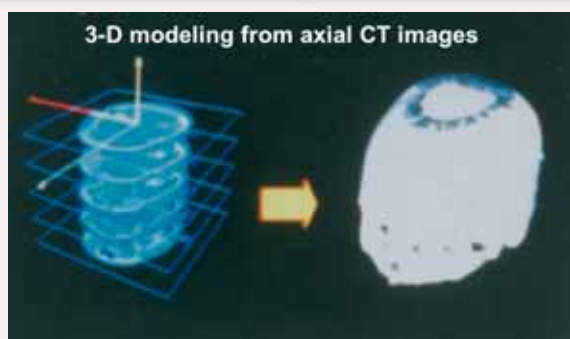
15.8.6 The CyberKnife

- ❑ **Target localization** is achieved through a family of axial CT images that serves as a base for the determination of a set of digitally-reconstructed radiograph (DRR) images.
- ❑ A set of paired orthogonal x ray imagers determines the location of the lesion in the room coordinate system and communicates these coordinates to the robotic arm, which adjusts the pointing of the linac beam to maintain alignment with the target.



15.8 IMAGE GUIDED RADIOTHERAPY

15.8.6 The CyberKnife



15.8 IMAGE GUIDED RADIOTHERAPY

15.8.6 The CyberKnife

- ❑ Owing to its on-line target imaging and automatic adjustment of the radiation beam direction to compensate for target motion, the CyberKnife provides a frameless alternative to conventional radiosurgery.
- ❑ The rigid invasive stereotactic frame which is the essential component of standard stereotactic radiosurgical treatments used for:
 - Target localization.
 - Treatment set-up.
 - Patient immobilization during treatment.is not required for treatment with the CyberKnife.



15.8 IMAGE GUIDED RADIOTHERAPY

15.8.6 The CyberKnife

- ❑ Advantages of the CyberKnife over standard stereotactic radiosurgery techniques (Gamma Knife or linac-based):
 - Dispenses with the rigid stereotactic frame.
 - Provides veritable image guided radiotherapy.
 - Allows for fractionated treatment of intracranial malignant tumours.
 - Allows treatment of extracranial lesions relying on the skeleton to provide a reference frame.
 - Allows treatment of other organs such as lung and prostate using surgically implanted fiducial markers as a reference markers.
 - Offers possibility for on-line tracking of target motion, which results either from patient motion during treatment or from organ motion within the patient during treatment.



15.9 ADAPTIVE RADIOTHERAPY

- ❑ A full implementation of image guided radiotherapy will lead to the concept of **adaptive radiotherapy (ART)**.
- ❑ In ART the dose delivery for subsequent treatment fractions of a course of radiotherapy can be modified to compensate for **inaccuracies in dose delivery** that cannot be corrected simply by adjusting the patient's positioning like in the IGRT.
- ❑ The causes of these inaccuracies may include:
 - **Tumour shrinkage** during the course of treatment.
 - Patient **loss of weight** during the course of treatment.
 - **Increased hypoxia** resulting during the course of treatment.



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15.10 RESPIRATORY GATED RADIOTHERAPY

- ❑ **Respiratory motion** has a significant effect on the dose delivery to targets in the chest and upper abdominal cavities and to compensate for these effects relatively large margins are added to clinical tumour volumes.
- ❑ The extra margin results in:
 - Compromises to prescribed tumour doses.
 - Treatment plans that adversely affect treatment outcome.
 - Increased incidence of radiation induced morbidity.



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15.10 RESPIRATORY GATED RADIOTHERAPY

- ❑ The quest for ever increasing tumour doses (dose escalation) to increase the tumour control probability (TCP) and simultaneously minimize the normal tissue complication probability (NTCP) requires a move towards smaller margins combined with an increased need to deal effectively with organ motion during treatment.
- ❑ The next big challenge in IGRT comes from the natural and unavoidable **organ motion during treatment**.



15.10 RESPIRATORY GATED RADIOTHERAPY

- ❑ To account for natural organ motion **4-D imaging** technology was developed.
- ❑ 4-D imaging technology allows viewing of volumetric CT images changing over the fourth dimension: time.
- ❑ Examples of 4-D dose delivery techniques:
 - Image guided radiosurgery, an elegant approach to dealing with organ motion.
 - **Respiratory gating system (RGS)**, a special accessory added to a linac to compensate automatically and instantly for the effects of respiratory movement on external beam radiotherapy to the chest and upper abdomen.



15.11 PET/CT SCANNER AND PET/CT IMAGE FUSION

- ❑ Both CT and PET machines have been used as imaging modalities since the 1970s.
- ❑ CT yields information on patient's anatomic structure by producing cross-sectional x ray slices of the body.
- ❑ PET provides information on the metabolic function of organs or tissues by detecting how cells metabolize certain compounds such as glucose.



15.11 PET/CT SCANNER AND PET/CT IMAGE FUSION

- ❑ Both CT and PET machines have been used independently in radiotherapy since their invention during the 1970s:
 - CT machines on a large scale not only for providing detailed high resolution images of internal anatomy including tumour volumes but also for providing electron densities for accurate treatment planning of tissues with heterogeneities.
 - PET machines only on small scale owing to relatively poor spatial resolution that precluded determination of tumour size and location with precision required for optimal diagnosis and treatment planning.



15.11 PET/CT SCANNER AND PET/CT IMAGE FUSION

- ❑ Separate CT and PET images are difficult to fuse because the patient is generally not positioned identically on both machines.
- ❑ During the past decade CT and PET machines were integrated into one machine for use in radiotherapy: a **PET/CT machine**.
- ❑ A PET/CT machine combines the strengths of two well established imaging modalities in one machine, representing the most exciting innovation in cancer diagnosis and therapy during the 1990s.



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15.11 PET/CT SCANNER AND PET/CT IMAGE FUSION

- ❑ **PET/CT machine manufactured by General Electric:**



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15.11 PET/CT SCANNER AND PET/CT IMAGE FUSION

- ❑ CT is excellent in depicting internal structures and anatomy but it may miss small or early stage tumours and does not provide any functional information on the tumours it detects (**anatomical imaging**).
- ❑ PET can identify cancerous cells by detecting increased metabolism of cancer cells with a high degree of sensitivity even at an early stage, when other imaging modalities still miss them (**functional imaging**).



15.11 PET/CT SCANNER AND PET/CT IMAGE FUSION

- ❑ **Physical characteristics of PET/CT machines:**
 - Integration of PET and CT technologies into a single device.
 - Simultaneous collection of both anatomical and biological (functional) information during a single examination.
 - Accurate acquisition of fused PET and CT images.
 - More accurate tumour detection and tumour localization for a wide variety of cancers.



15.11 PET/CT SCANNER AND PET/CT IMAGE FUSION

- ❑ Positron emission tomography (PET) imaging is based on the use of **positron-emitting radionuclides** that are administered to the patient either by injection or inhalation.
- ❑ The positron-emitting radionuclide is attached to a clinically useful **biological marker** for use in studies of various metabolic processes in cancer diagnosis and treatment.



15.11 PET/CT SCANNER AND PET/CT IMAGE FUSION

- ❑ Markers labeled with a particular radionuclide circulate through the bloodstream to reach a particular organ.
- ❑ The positrons emitted by the radionuclide have a very short range in tissue and undergo annihilation with an available electron.
- ❑ The annihilation process generally results in an emission of two gamma rays, each with an energy of 0.511 MeV, moving away from the point of production in nearly opposite directions (at 180° to each other).



15.11 PET/CT SCANNER AND PET/CT IMAGE FUSION

- ❑ The PET machine generates **transverse images** depicting the distribution of positron emitting radionuclides in the patient through the use of annihilation coincidence detection to obtain projections of the activity distribution.
- ❑ The transverse images of activity distribution are obtained through the process of filtered back-projection.



15.11 PET/CT SCANNER AND PET/CT IMAGE FUSION

- ❑ Detectors used for coincidence detection in modern PET machines are **scintillators** made of:
 - Bismuth germanate (BGO) or
 - Lutetium oxyorthosilicate doped with cerium (LSO:Ce)
- ❑ The scintillators transform the 0.511 MeV annihilation quanta into visible photons.
- ❑ The visible photons produced by the scintillators are detected by **photomultiplier tubes (PMTs)**.



15.11 PET/CT SCANNER AND PET/CT IMAGE FUSION

- ❑ The **radionuclides used in PET studies** are produced by bombardment of an appropriate stable nuclide with protons from a cyclotron, thereby producing a positron emitting radionuclide which is subsequently attached to a clinically useful biological marker.
- ❑ The F-18 radionuclide attached to the 2-fluoro-2-deoxy-D-glucose (FDG) molecule is the biological marker most commonly used in studies involving glucose metabolism in cancer diagnosis and treatment.



15.11 PET/CT SCANNER AND PET/CT IMAGE FUSION

- ❑ **Main characteristics of the four most common positron emitters produced in cyclotrons for use in medicine:**

Radionuclide	Specific activity	Target	Production reaction	Half-life (minutes)
Carbon-11	8.4×10^8	Nitrogen-14	$^{14}_7\text{N} + \text{p} \rightarrow ^{11}_6\text{C} + \alpha$	20.4
Nitrogen-13	1.4×10^9	Oxygen-16	$^{16}_8\text{O} + \text{p} \rightarrow ^{13}_7\text{N} + \alpha$	10
Oxygen-15	6.0×10^9	Nitrogen-15	$^{15}_7\text{N} + \text{p} \rightarrow ^{15}_8\text{O} + \text{n}$	2.1
Fluorine-18	9.5×10^7	Oxygen-18	$^{18}_8\text{O} + \text{p} \rightarrow ^{18}_9\text{F} + \text{n}$	110



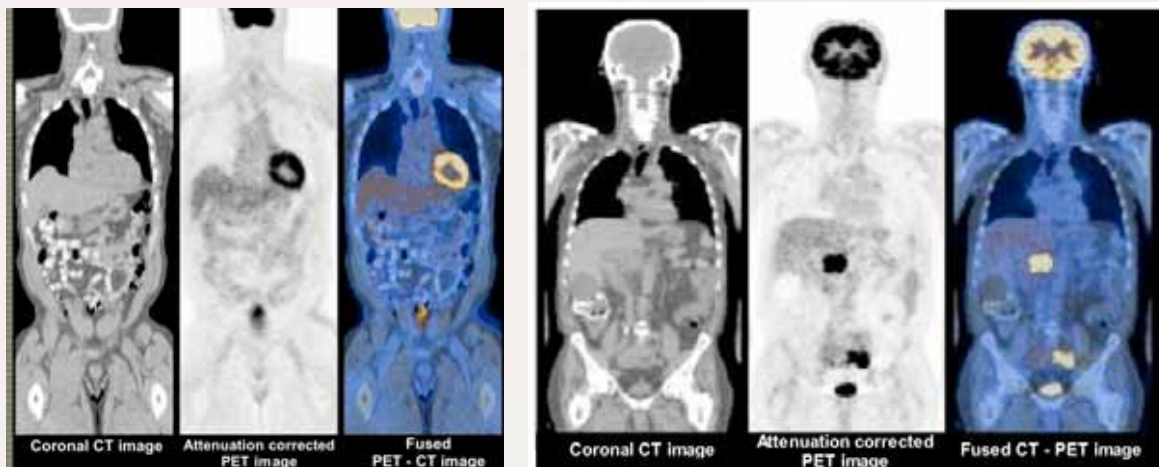
15.11 PET/CT SCANNER AND PET/CT IMAGE FUSION

- ❑ The relatively short half-life of the positron emitting radionuclides used for PET scanning requires that a cyclotron be available near the PET machine making clinical PET scanning service very costly.
- ❑ PET scanning is to a certain degree invasive, since a radionuclide is injected into a patient. The typical **equivalent dose** received by the patient from the PET study is of the order of 7 mSv in comparison with annual background equivalent dose of the order of 1.5 mSv.



15.11 PET/CT SCANNER AND PET/CT IMAGE FUSION

- ❑ **Typical images obtained from PET/CT machines:**



15.11 PET/CT SCANNER AND PET/CT IMAGE FUSION

Clinical characteristics of PET/CT machines:

- Earlier diagnosis of disease.
- Accurate staging and tumour localization.
- More precise treatment.
- Monitoring of the response to treatment.
- Early detection of recurrence.
- Reduction of biopsy sampling errors.
- Reduction of the number of invasive procedures required during follow-up.