Overview about Stereotactic Radiosurgery (SRS) and Stereotactic Body Radiotherapy (SBRT)

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Contents

Preface:

Stereotactic/ Stereotaxy :

- Stereo-, Greek word "solid", and -taxis , New Latin , derived from Greek taxis, "arrangement", "order",
- Clinical procedure based on reference markers to precisely locate a target within 3D-boundaries.
- *Combine the use of a stereotatic apparatus & radiation beams.*

Two modalities:

1. *Stereotactic Radiosurgery - SRS*
2. *Stereotactic Radiotherapy - SRT*

STEREOTACTIC : SRS & SRT

❖ STEREOTACTIC RADIOSURGERY (SRS)

- **A “non-invasive” technique**
- **Delivers of a *single high dose of radiation***
- **Limited, well-defined small intracranial target**
- **Volumes Avoids nearby normal tissue and critical structures Minimize the dose to the adjacent brain tissue**

❖ STEREOTACTIC RADIOTHERAPY (SRT)

- **Employs same stereotactic techniques used for SRS**
- **Refers to delivering collimated beams of radiation *in multiple fractions*, to a stereotactically located target.**

Introduction

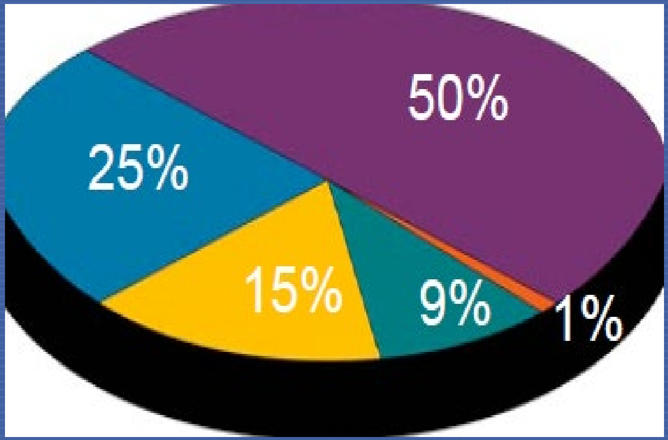
- High Doses (16 Gy to 22 Gy, generally prescribed to the 80% or 90%) , delivered in 1 fraction
- Radiosurgery uses precisely targeted radiation to destroy lesions anywhere in the body in 1-5 fractions/stages
- Alternative to surgery.
- Written detailed of QA procedures is mandatory.

INDICATIONS FOR STEREOTACTIC SRS/SRT

- Acoustic Tumors (Schwannomas, Neuromas, Neurinomas, Nerve sheath tumors, Neurilemomas)
- Arteriovenous Malformations
- Arteriovenous Malformations
- Arterial Aneurysms
- Craniopharyngiomas
- Ependymomas
- Glomus Jugulare Tumors
- Hemangioblastoma
- Medulloblastomas (Boost)
- Meningiomas
- Metastases
- Optic Gliomas
- Pinealomas
- Pituitary Adenomas
- Primary Brain Tumors (Glioblastomas, Astrocytomas, CNS Sarcoma, CNS Lymphoma)
- Retinoblastomas
- Venous Angiomas
- Functional Radiosurgery
- Clinical studies for use in Parkinson’s and Epilepsy

Clinical Indications for SRS / SRT

- Malignant Tumors, 50% - Metastatic tumors, primary and recurrent gliomas
- Benign Tumors, 25% - Meningiomas, acoustic neuromas, pituitary adenomas, craniopharyngiomas
- Vascular Disease, 15% - AVMs, cavernous angiomas
- Pediatric Tumors, 9% - Retinoblastomas
- Functional Disease, 1%



1997 Study. Courtesy Jay Loeffler, M.D., Harvard Medical School, Boston, MA

General Procedure : SRS/SRT

- Diagnostic MR images of patient
- Target/Organs contouring
- Pre-plan using MR images (whenever allowed by Tx plan software)
- Placement of Head Ring
- Stereotactic CT/Angio images
- Transfer images to Tx Plan workstation
- Fuse MR to CT images (optional)
- Treatment Planning
- QA of LINAC (previous to Tx.)
- Verify correctness of Pt. Position
- Treat patient

Uncertainties in SRS *

CT slice Thickness	1 mm	3 mm
Stereotatic Frame	1 mm	1 mm
Isocenter Alignment	1 mm	1 mm
CT Image	1.7 mm	3.2 mm
Tissue Motion	1 mm	1 mm
Angio (Pt. identification)	0.3 mm	0.3 mm
Std. Dev. of Pos. Uncertainty	2.4 mm	3.7 mm

* AAPM Report No 54:Stereotatic Radiosurgery

Delivery Modalities / Current technology

- Gamma Knife
- Linear Accelerator – Based
- Cyber Knife
- Heavy Charged particles Proton
- Tomotherapy

Stereotactic Radiosurgery (SRS)

- Also called "stereotaxy"
- Non-invasive form of "surgery"
  A type of radiation therapy
- Called surgery because the results compare to conventional surgery
- A highly precise delivery of radiation
  Accurate to within 1 to 2 mm of target

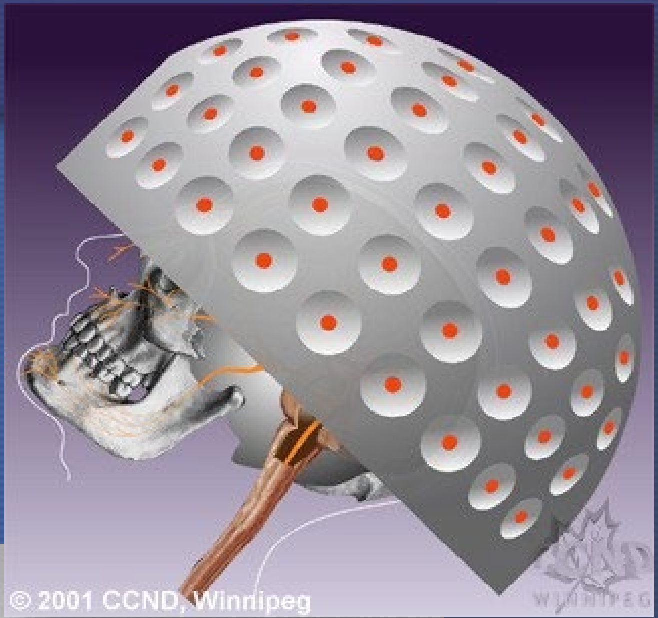
Stereo = 3-dimensional
Taxic = System (taxis)

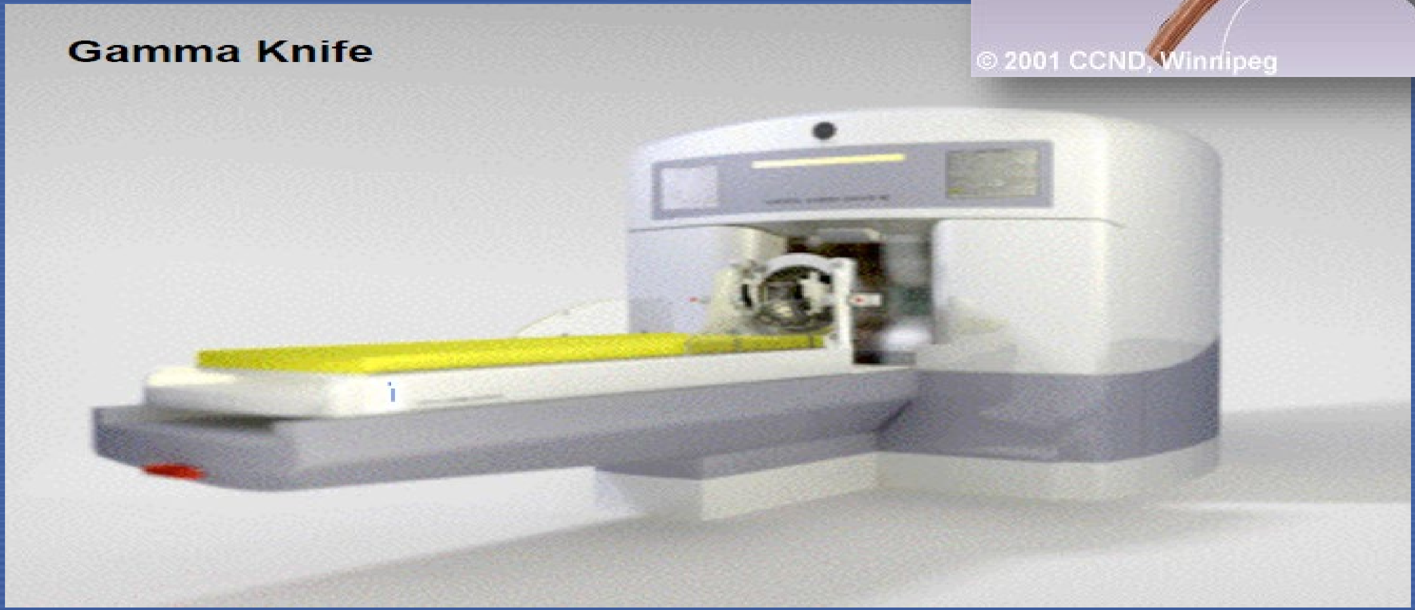
Tactic **=** to touch (tactus)

- 1908 - First stereotactic method developed in London by Sir Victor Horsley and Robert H. Clarke "Horsley-Clarke apparatus"
- 1930s - The apparatus kept receiving slight improvements
- 1947-1949 – Two stereotactic devices used for brain surgery in humans Henry T. Wycis and Ernest A. Spiegel's device (American neurosurgeons)
- Lars Leksell's device (Swedish neurosurgeon) – founded Elekta later

Gamma Knife

- Gamma Knife® by Elekta
  - Uses 192 to 201 beams of highly-focused gamma rays
  - All beams aim at target region





Process → Gamma Knife

- Injected with contrasting fluid and medicine
- Patient first gets a CT or MRI scan of the target area
- A computer takes the images created and combines them to form a 3-D map of the target area
- The head frame is then placed on the patient as the operator sees fit
- The patient then lies on a special bed that moves backward into the machine
  - While the bed moves into the machine, beams shoot from all different directions towards the target area with the guidance of the 3-D map

Gamma knife

Used for stereotactic brain irradiations 192 / 201 sources of Co-60 around a patients head - only sources which shall contribute to the irradiation are 'unplugged'

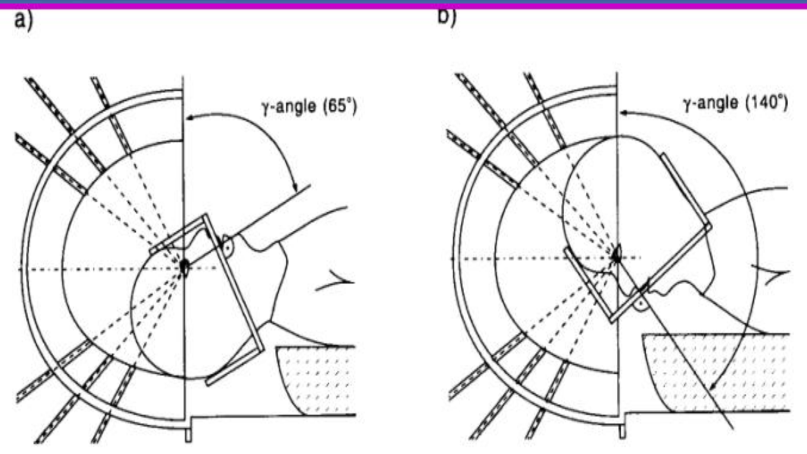
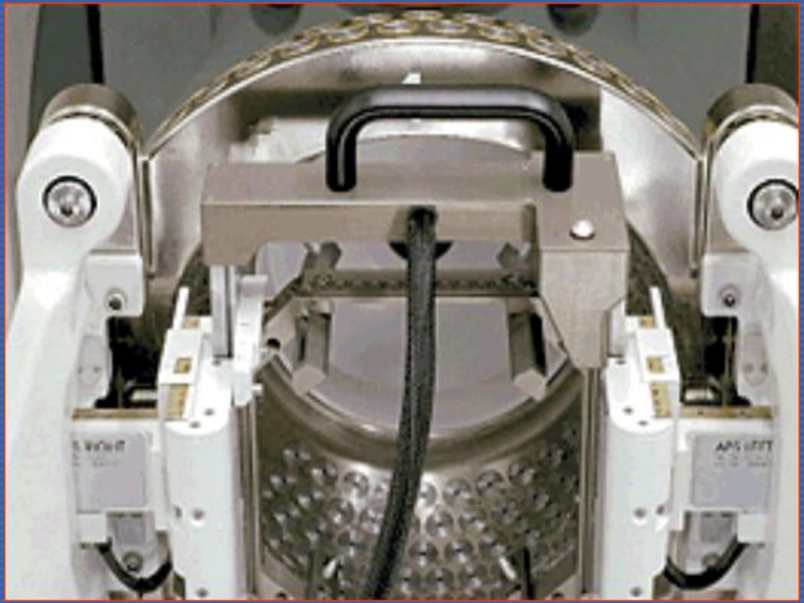
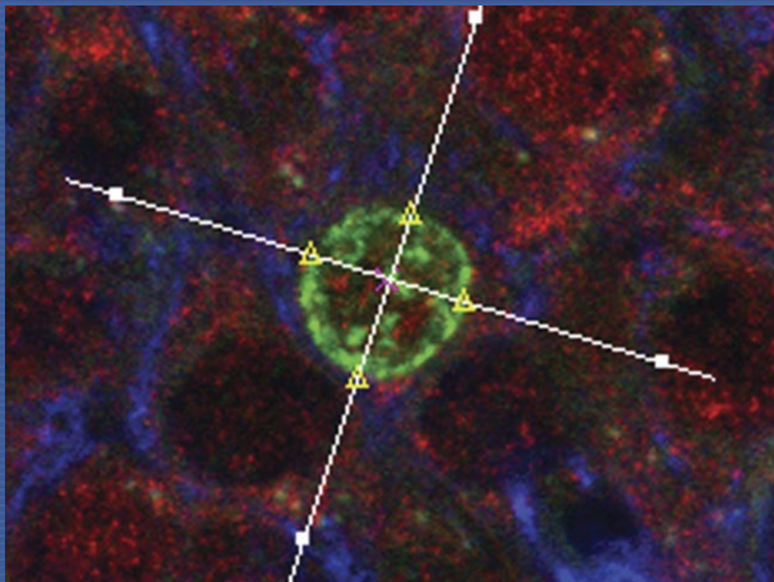


Figure 1. Diagram of a patient with an ocular target, positioned in the Gamma Knife collimator helmet: (a) supine position, γ-angle = 65°; (b) prone position, γ-angle = 140°.



Gamma knife head applicator

Gamma Knife - Process



then

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Strengths

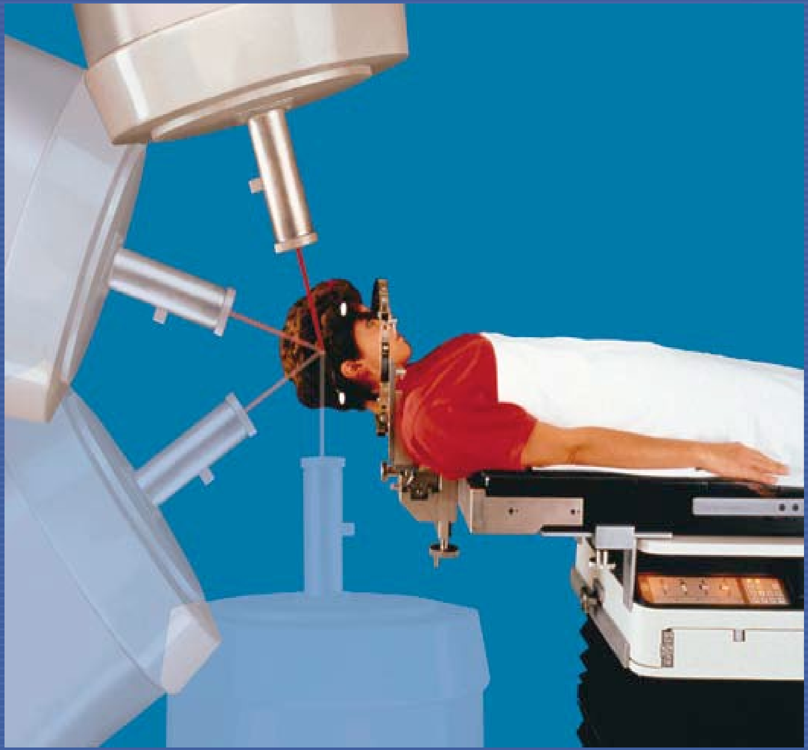
- Has been the gold standard
- Large clinical experience
- High accuracy: 0.2 mm
- Very stable mechanical attachment of patient
- Intracranial SRS is done well
  - ✓ No moving sources and patient is rigidly immobilized
- Treatment planning is relatively straightforward
- Dedicated Neurosurgery tool
  - ✓ Well accepted by the Neurosurgery community

Weaknesses

- Limited to intracranial targets.
- Bolted head frame is necessary.
- Fractionated treatments are not possible.
- Large targets with complicated shapes require treatment plans with multiple isocenters increasing complexity and treatment time.
- Co-60 sources decay, increasing treatment times, and need to be replaced.
- Radioactive source replacement is a major undertaking and expense.
- No interface to record and verify software systems.

Stereotactic Radiosurgery -Linac Based

- A “non-invasive “ technique to deliver a single high dose of radiation, to limited, well-defined target volumes, while avoiding nearby normal tissue and critical structures.



Linear accelerator (LINAC) machines

Traditional Linac Stereotactic Radiosurgery Equipment

Collimator set

Typically ~5-40mm diameter

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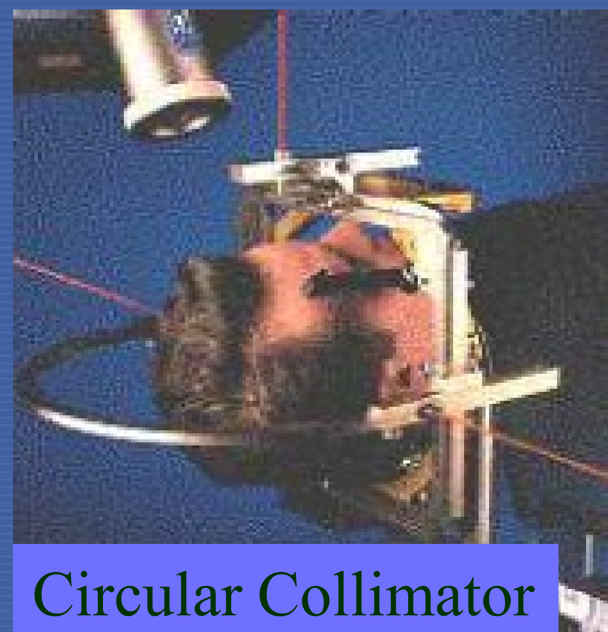
Linear accelerator (LINAC) machines

Collimation System (MMLC, MLC, circular collimators, and circular collimators with linac jaws)


MMLC

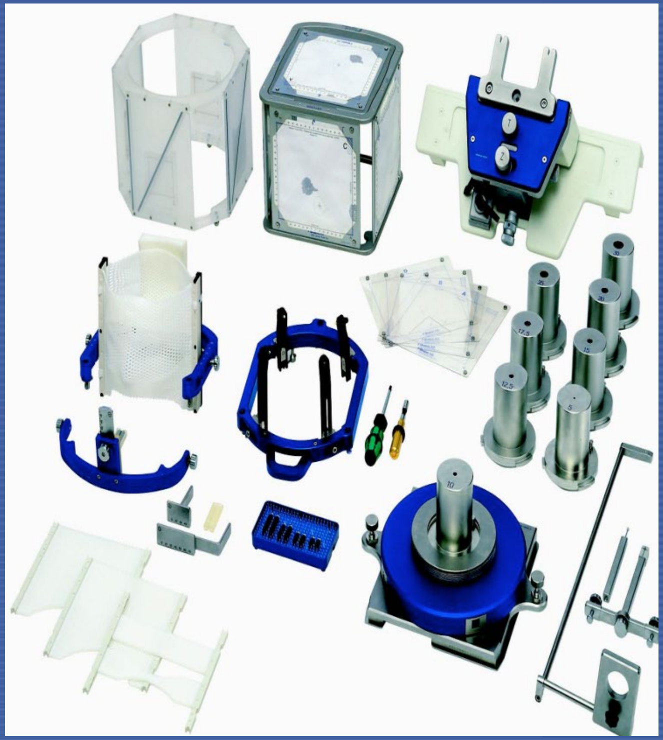

Circular Collimator

Linac Based (Xknife / Brainlab) *Vs.* Radioactive Source (Co^{60}) Gamma Knife

Linac Based (Xknife / Brainlab)	Radioactive Source (Co^{60}) Gamma Knife
• Collimator sizes: 4 to 45 mm in 2.5 mm steps • Conformal SRS: with jaws/circles or MMLC; IMRT.	• Collimator sizes: 4,8,14,18 mm • Conformality is only attained through multiple isocenters
• Extra-cranial: head and neck; body localization: spine, prostate, lung, liver	• No extra-cranial targets possible .
• Tx Room can be used for other Tx modalities.	• Requires dedicated Tx. Room.

Components of a Radiosurgery System

- Immobilization and Localization Instrumentation
  - –Cranial
  - –Head and Neck
  - –Spine and Body



- Treatment Planning Software
  - –Arcs, Conformal, IMRT, Frameless modules
  - –Image Fusion™ software

- Linac and QA instrumentation

  Collimation System (MMLC, MLC, circular collimators, and circular collimators with linac jaws)

MLC - Linac Attachment m3

- Quick and easy mounting using a dedicated storage trolley
- Gantry at 180° position
- Immediate electronic and power connection
- Full communication and safety interlocks with Varian, Elekta and Siemens Linacs for IMRT and dynamic conformal arc treatment

VARIAN SIEMENS ELEKTA

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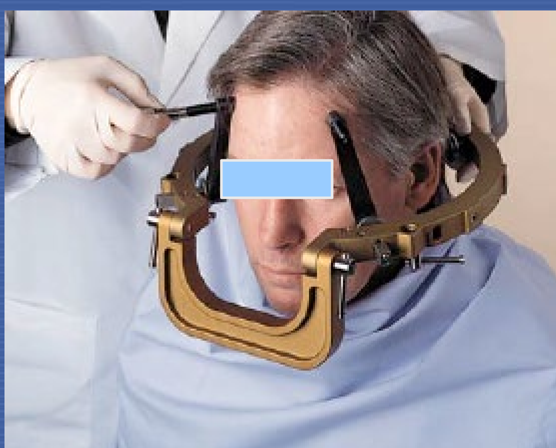
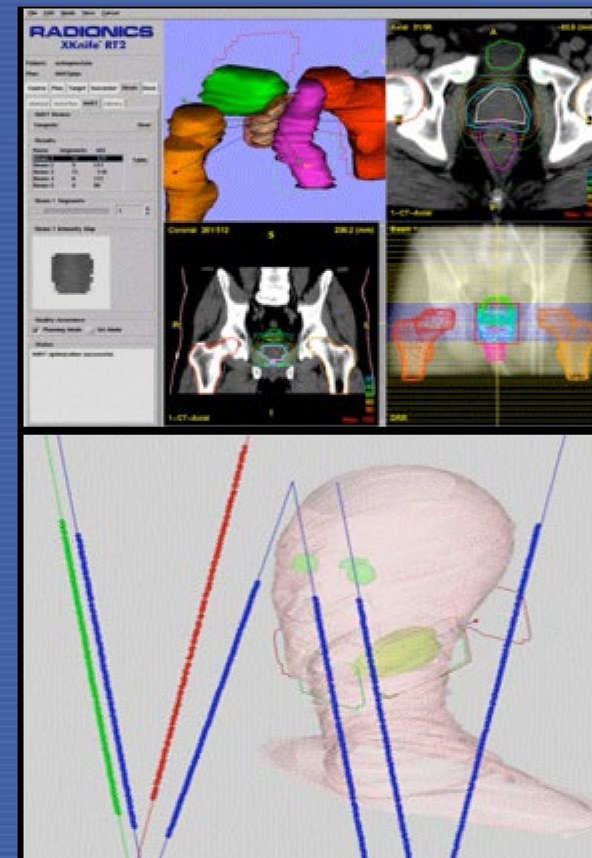
Micro - MLCs add-on

- **1992 - First mMLC collimators for SRS developed in DKFZ (Heidelberg)**
  – 3mm wide leaves
  – Motorized
- **1997 – XKnife system**
  – 15 pairs
  – 4mm (max field size: 6x6cm2)
  – v2.0: 27 leaf pair (13.4x10.8cm2)
- **1997 – BrainLAB**
  – 52 leaf
  – 3mm (14 pairs) / 4.5mm (6pairs)

Stereotactic Radiotherapy

- A hybrid technique that combines the benefits of conventional radiotherapy with the benefits of stereotaxy.



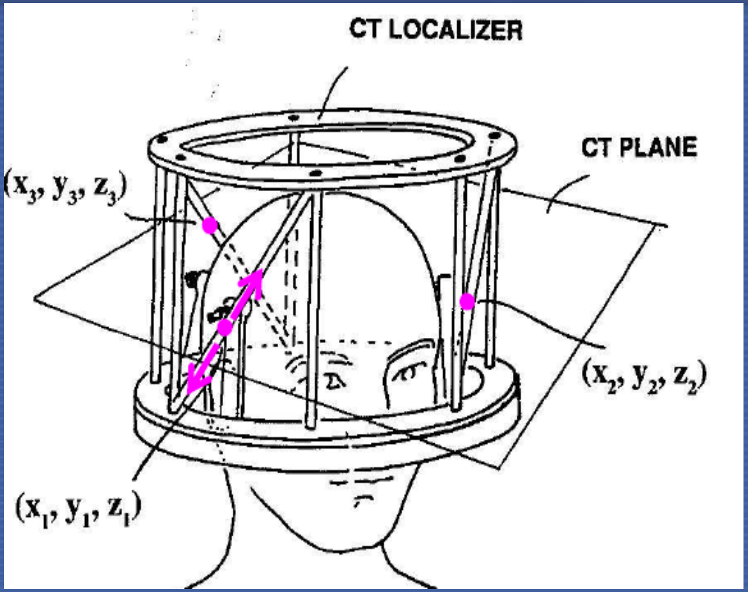


Stereotactic Patient Set-up

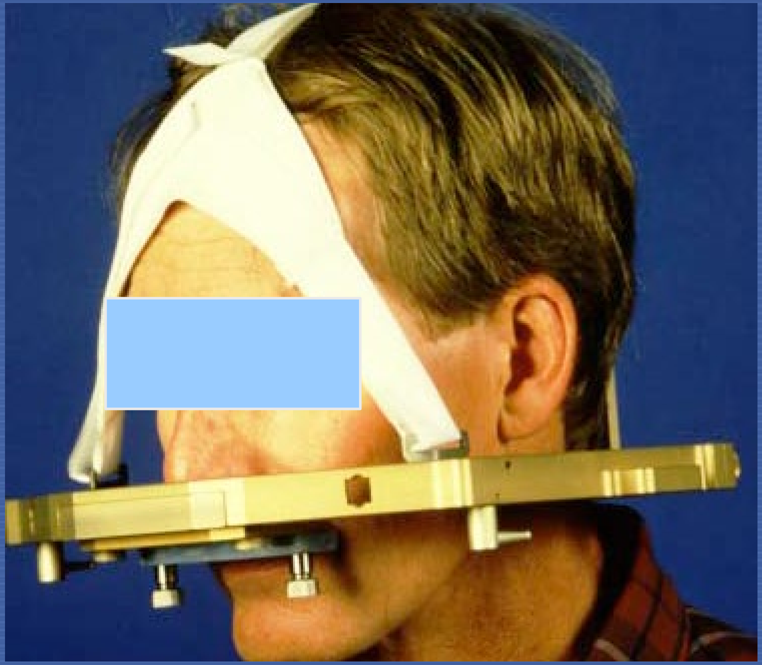
CT Localizer

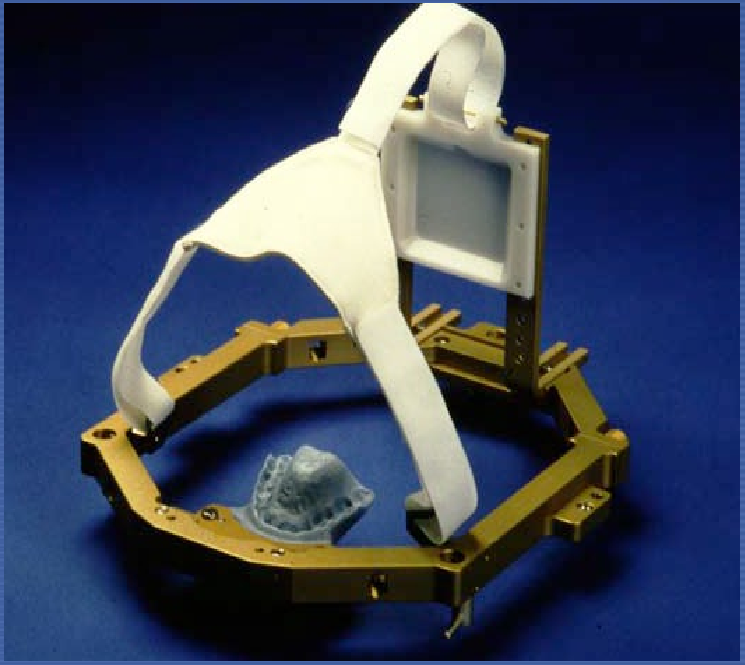
- For CT / X-Ray localization
- Links Angio Images to CT
- Creates stereotactic coordinate system
- Large scan range (185 mm)
- No fixation to CT couch
- Not required in MR

Stereotactic CT scan for SRS

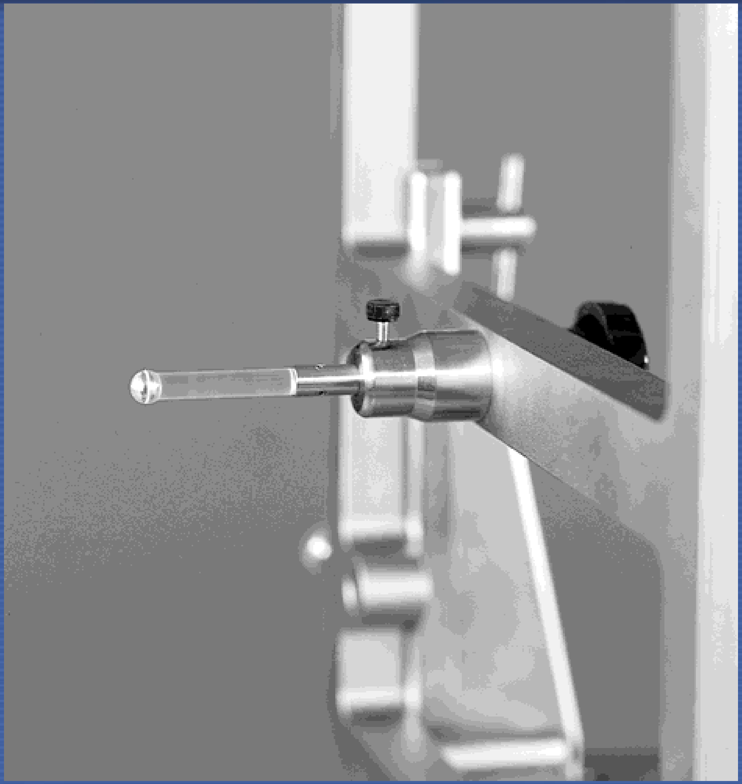


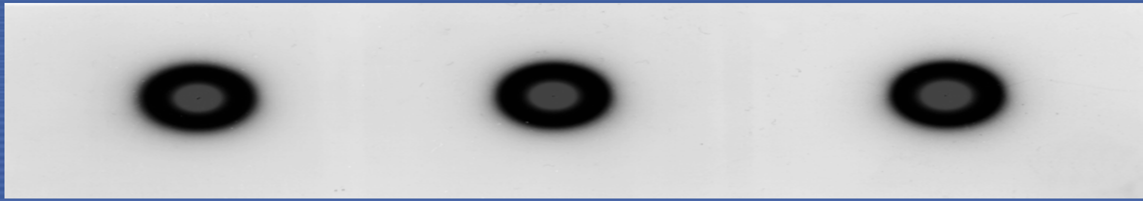
Relocatable Head Frame



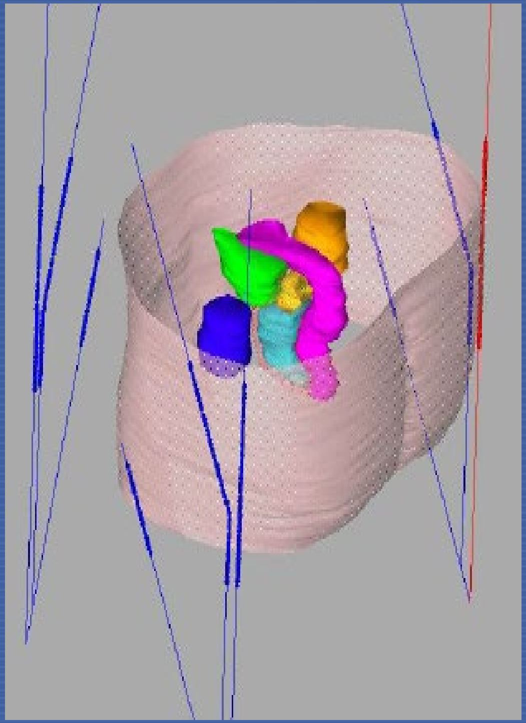


QA of Isocenter





Body Localizer



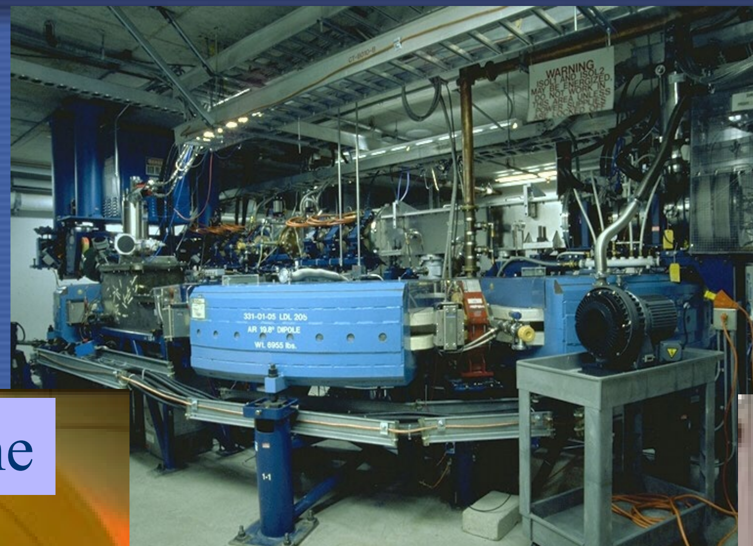
History of Proton Beam Therapy

- 1946 R. Wilson suggests use of protons
- 1954 First treatment of pituitary tumors
- 1958 First use of protons as a neurosurgical tool
- 1967 First large-field proton treatments in Sweden
- 1974 Large-field fractionated proton treatments program begins at HCL, Cambridge, MA
- 1990 First hospital-based proton treatment center opens at Loma Linda University Medical Center

Protons

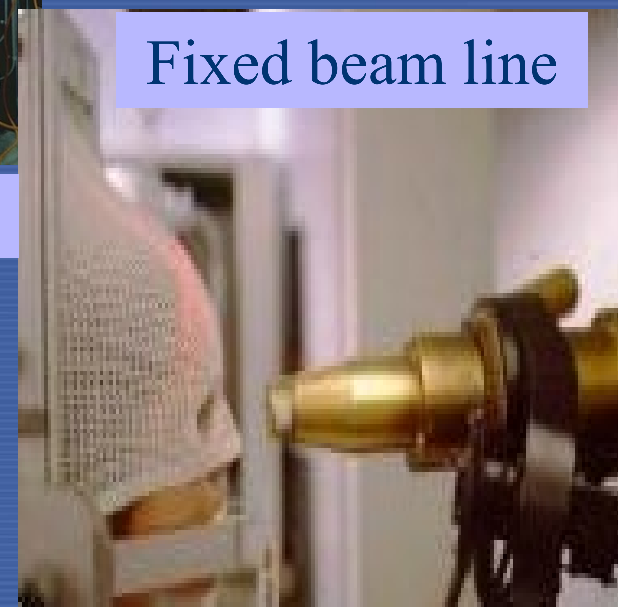
- Positively charged particles - directly ionizing radiation
- About 2000 times heavier than electrons
  - less angular struggling
  - more difficult to steer
- The lightest of heavy charged particles (such as C, Ne, Si, Ar) used for radiotherapy

Proton Treatment



40-250 MeV Synchrotron

Gantry beam line



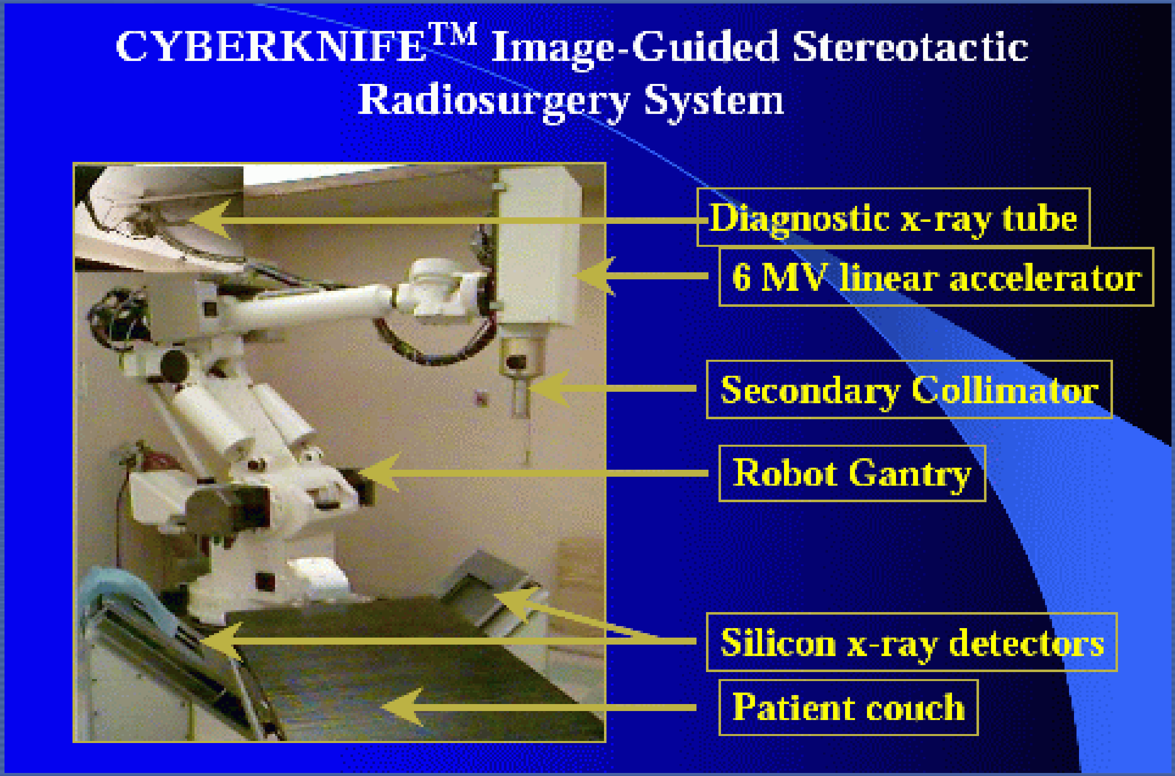
Fixed beam line

Beam-Delivery Systems

- Although the weight of a proton gantry is around 100 tons and has a diameter of 10 meters.
- The size and weight of such a gantry together with the high spatial accuracy required for the beam position at the isocenter is probably the reason why no such gantry has been built up to now.
- Beams with 45° inclination are available together with horizontal beams.
- Another possibility is to move the patient rather than the beam. At some proton, treatment chairs and molds that can be rotated around the patient's longitudinal axis by about 15° are available.

CyberKnife

- The CyberKnife is a frameless robotic radiosurgery system invented by John R. Adler of Stanford University.
- It is used for treating benign tumors, malignant tumors and other medical conditions.



Two Main Elements:

(1) the radiation produced from a small linear particle accelerator

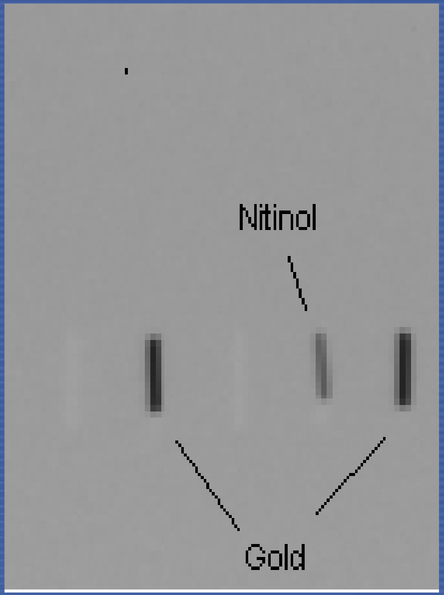
(2) a robotic arm which allows the energy to be directed at any part of the body from any direction.

Cyber knife

- Used for cranial and extracranial stereotactic radiosurgery (SRS)
- Lightweight linac mounted on robotic arm
- Image guidance tracks position during treatment
- 6 MV, 800 mu/min, compact linac
- Aperture sizes: 5, 7.5, 10, 12.5, 15, 20, 25, 30, 35, 40, 50, 60 mm
- Fixed cones or adjustable iris collimator
- diagnostic x-ray sources :
- Patient imaged at 45^{o} orthogonal angles
- 2 amorphous silicon detectors, During treatment robot adjusts position
- based on comparison of live images with DRRs
- Sub-millimeter targeting accuracy

Fiducial Tracking with CyberKnife

- Implant Fiducials in the patient
- Identify fiducials in the CT Study during treatment planning
- Generate DRR's
- Identify and track fiducials during treatment delivery
- Translation and rotation can be tracked
- 1 fiducial needed to track translations
- 3 fiducials needed to track rotation
- 50% increase in targeting accuracy in going from 3 4 fiducials; small increase in accuracy between 4-6 fiducials



Synchrony Tracking

- Hardware and software components work with Cyberknife to dynamically track tumors that move with respiration
- Establishes a path of motion in real time based on breathing pattern of patient
- Eliminates need for gating or breath hold

- Synchrony camera
- Synchrony tracking markers
- Fiber optic sensing technology
- Tracks patient's respiratory motion

Strengths

1. Intracranial and extracranial tumors can be treated
2. Large number of beam angles are available
3. Frameless immobilization (more comfortable and allows fractionated treatment)
4. Monitors and tracks patient position during treatment

Weaknesses

1. No posterior beams (below couch) are possible
2. Treatment times are long
   - 3-4 hours to deliver single-shot SRS
   - 60-90 minutes per session to deliver fractionated treatment
3. Significant quality assurance (QA) is required prior to treatment to ensure that the robotic arm performs as expected
4. No interface to record and verify systems

Tomotherapy

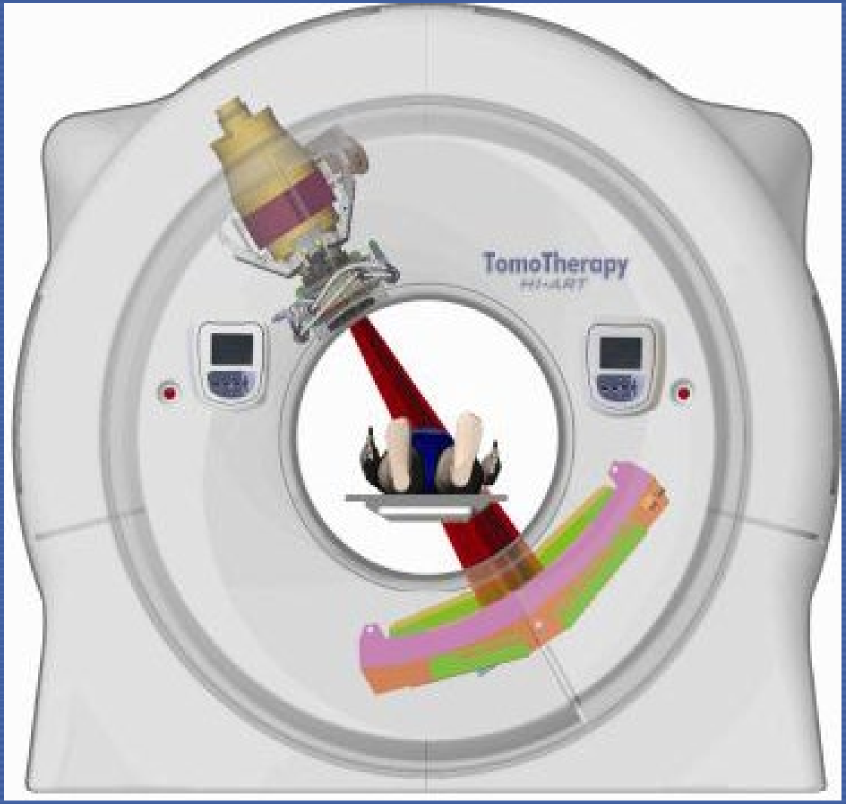
- Tomotherapy is rotational IMRT.
- Compared to conventional linac- based IMRT it has one possible advantage and one disadvantage.
- Advantage:

  Delivers radiation from all 360° of the axial plane.
- Disadvantage:

  deliveryisexclusivelycoplanar;currentlynoncoplanarfieldscannotb edelivered.

Main features

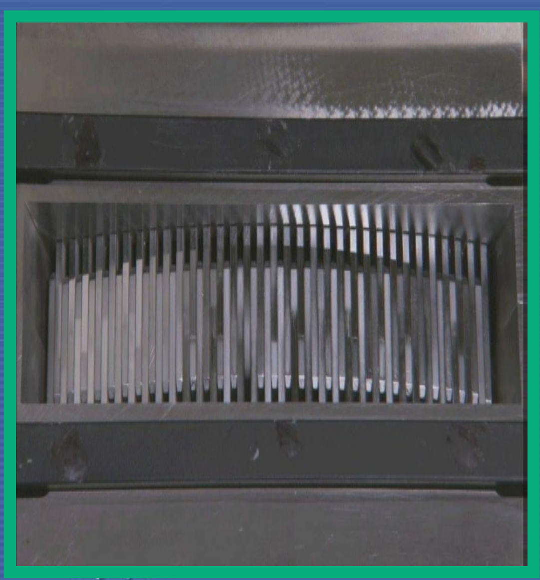
- Integrated, stand-alone system.
- Linac mounted on CT gantry.
- 6MV helical IMRT.
- Constant gantry rotation rate and couch velocity.
- Field size 40 cm x {1 cm, 2.5 cm, or 5 cm}.
- Dose rate 850cGy/min at 85 cm SSD, 40 x 5 cm^2 field, 1.5 cm depth.
- Binary MLC´s.
- Increased shielding for highly modulated delivery.



Helical Tomotherapy

- MLC leaves that move at 250 cm/s to open or shut in milliseconds
- Thousands of beamlets throughout multiple 360 degree rotations
- Coverage of a target extent up to 160 cm in length with no matching

Fast Binary MLC



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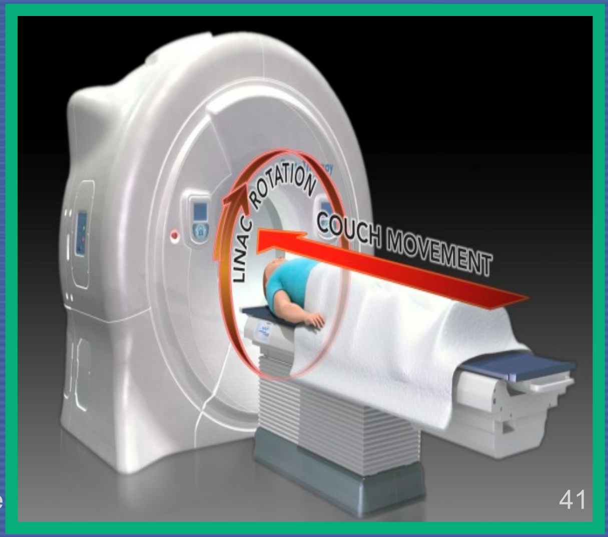
Continuous Gantry Rotation

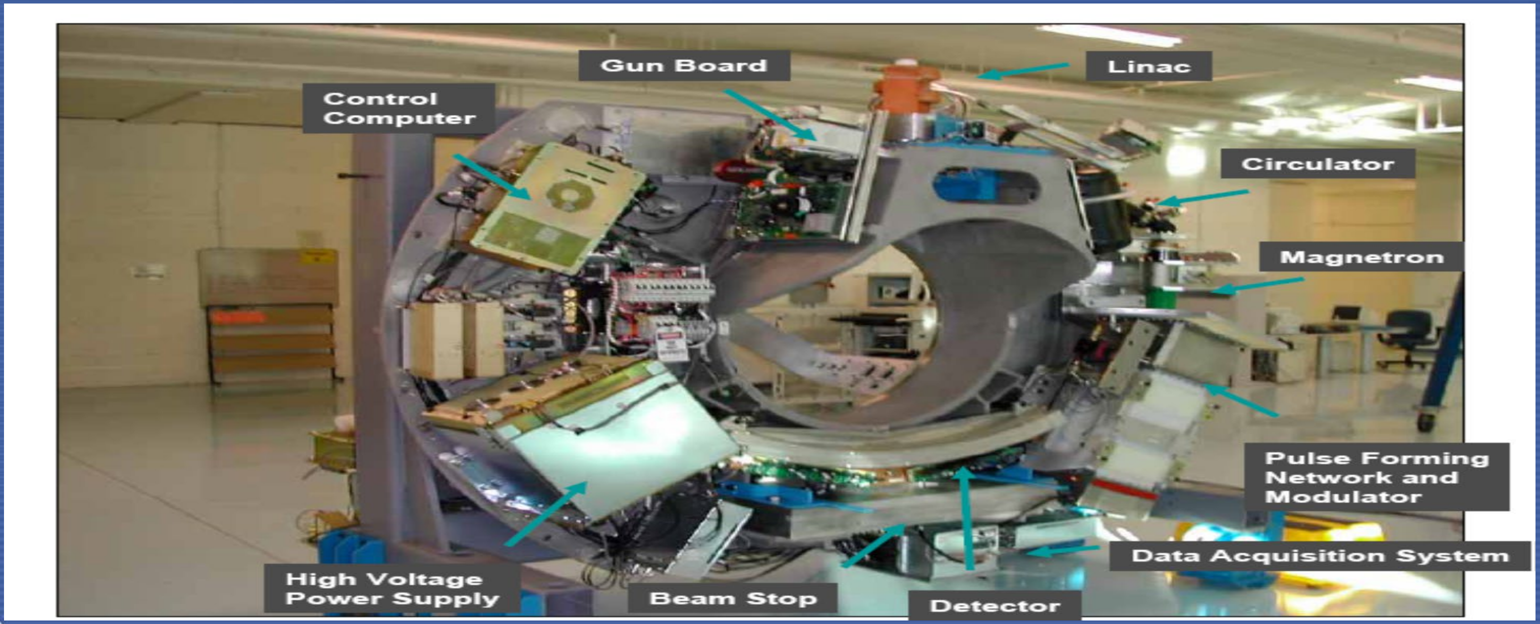
+

Simultaneous Couch Movement



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.
- System is designed to obtain an MVCT scan of the patient anatomy at any time before, during or after dose delivery.
- MVCT image data are acquired with a 738 element xenon ionization chamber array that rotates on the gantry opposite the linac.



How to Choose?

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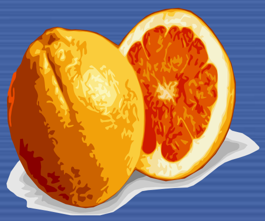


How to Choose?

Because there is no data supporting outcome differences, the choice is based on various factors such as:

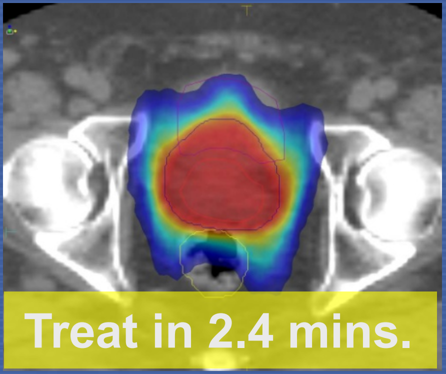
1. Planning and treatment delivery time
2. Machine cost and reimbursement
3. Immobilization techniques
4. Machine flexibility
5. Patient convenience and satisfaction
6. etc.

Gamma Knife, CyberKnife , Tomotherapy , Protons, Neutrons and Linac-Based Technologies (Rapid Arc/ VMAT).

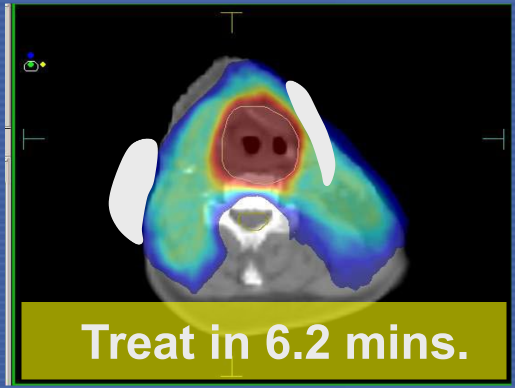
Consistent Quality

Quality of treatment delivery

Mod. factor 1.3



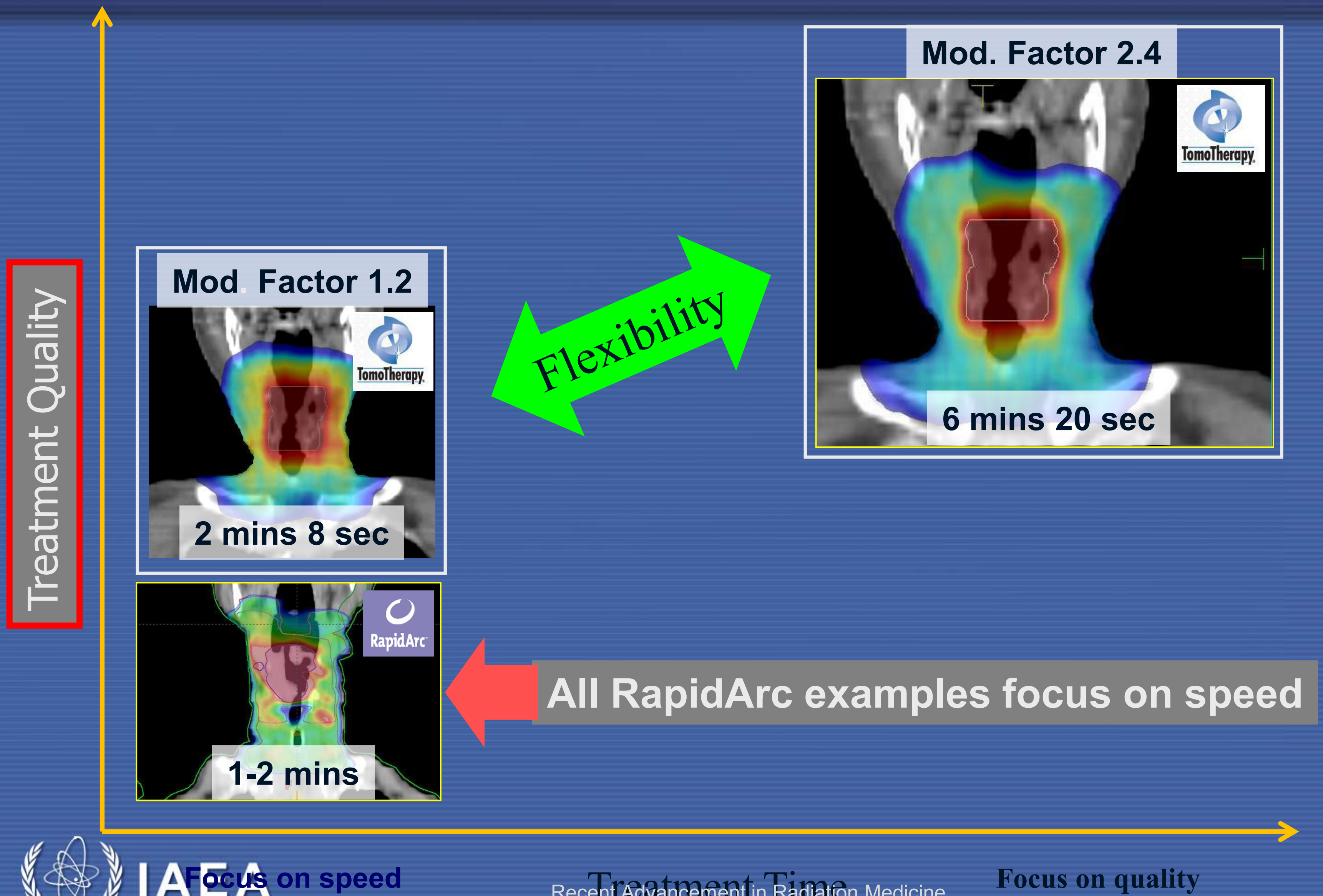
Mod. factor 2.4



Modulation factor set higher

Case complexity

Optimal Quality Versus Time



Hsu et al. Radiation Oncology (2017) 12:155
DOI 10.1186/s13014-017-0890-0

Radiation Oncology

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Dosimetric comparison of different treatment modalities for stereotactic radiotherapy

Shih-Ming Hsu[1,2,3*], Yuan-Chun Lai[1,4,5], Chien-Chung Jeng[4] and Chia-Ying Tseng[1,2]

Results: The dose homogeneity indices of all the treatment modalities were lower than 1.25. The cone-based linac had the best conformity for all tumors, regardless of the tumor location and size, followed by the FFF-VMAT linac; tomography was the worst-performing treatment modality in this regard. The cone-based linac had the best gradient, regardless of the tumor location and size, whereas the FFF-VMAT linac had a better gradient than tomotherapy for a large tumor diameter (28 mm). The TLD and EBT3 measurements of the dose at the center of tumors indicated that the average difference between the measurements and the calculated dose was generally less than 4%. When the 3% 3-mm gamma passing rate metric was used, the average passing rates of all three treatment modalities exceeded 98%.

Conclusions: Regarding the dose, the cone-based linac had the best conformity and steepest dose gradient for tumors of different sizes and distances from the brainstem. The results of this study suggest that SRT should be performed using the cone-based linac on tumors that require treatment plans with a steep dose gradient, even as the tumor is slightly irregular, we should also consider using a high dose gradient of the cone base to treat and protect the normal tissue. If normal tissues require special protection exist at positions that are superior or inferior to the tumor, we can consider using tomotherapy or Cone base with couch at 0° for treatment.

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Table 1 HI, CGI, and Paddick indices calculated by the treatment planning system using the cone-based linac, FFF-VMAT linac, and tomotherapy treatment modalities

Tumor Diameter	8 mm						18 mm						28 mm					
Distance from brainstem	1 mm			6 mm			1 mm			6 mm			1 mm			6 mm		
Modality	Cone-based	FFF-VMAT	Tomo	Cone-based	FFF-VMAT	Tomo	Cone-based	FFF-VMAT	Tomo	Cone-based	FFF-VMAT	Tomo	Cone-based	FFF-VMAT	Tomo	Cone-based	FFF-VMAT	Tomo
HI	1.24	1.25	1.20	1.23	1.25	1.23	1.20	1.19	1.25	1.20	1.17	1.24	1.17	1.23	1.21	1.16	1.19	1.23
CGI_c	84.59	48.89	47.96	86.25	67.93	46.79	92.02	75.66	69.75	95.35	73.99	67.76	98.99	95.44	86.04	99.84	92.27	86.68
CGI_g	103.25	66.45	74.39	103.15	74.30	75.96	88.43	60.53	60.61	89.33	59.71	62.68	74.02	52.79	48.02	75.26	61.62	50.49
CGI	93.92	57.67	61.18	94.71	71.11	61.38	90.23	68.10	65.18	92.34	66.85	62.22	86.50	74.11	67.03	87.55	76.95	68.58
$CI_{Paddick}$	0.82	0.48	0.47	0.84	0.66	0.45	0.90	0.73	0.68	0.92	0.72	0.66	0.94	0.92	0.84	0.95	0.88	0.81
$GI_{Paddick}$	4.23	10.97	9.07	4.28	10.58	8.57	3.02	4.90	4.83	3.00	4.93	4.62	2.73	3.67	4.14	2.69	3.21	3.90

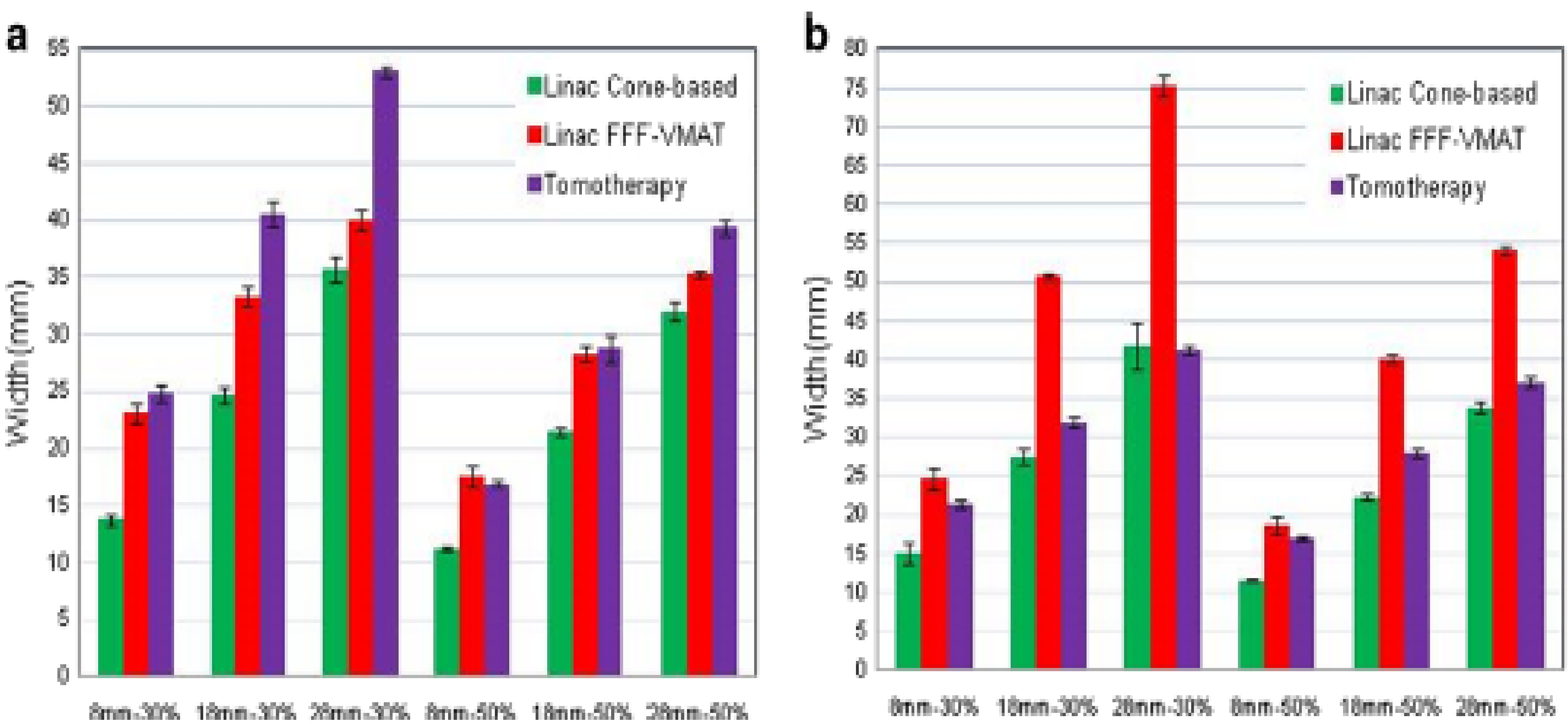

Fig. 6 Average dose profile widths of doses that are 50% and 30% of the dose at the center of the tumor, measured using EBT3 films, in the (**a**) R–L direction and (**b**) S–I direction

Thanks for your attention