〈특 강〉

STEREOTACTIC RADIOSURGERY USING A LINEAR ACCELERATOR

연세대학교 원주의과대학 치료방사선과

교수 박 경 란

GOAL OF RADIOSURGICAL TECHNIQUE

to deliver a high dose of radiation in a single fraction to a well defined, small, intracranial volume without delivering significant radiation to adjacent normal tissue with great accuracy.

THE TERM RADIOSURGERY IN GENERAL SENSE

1. accurate stereotactic localization of a small intracranial target.
2. accurate dose-planning determination of three-dimensional isodose surface contours with respect to the target volume.
3. accurate, external beam, stereotactic irradiation of the target, usually in a single fraction, utilizing radiation beams distributed about the target in three dimensions.

HISTORY OF RADIOSURGERY

1951 Leksell introduced term radiosurgery and technique.
→orthovoltage(100-350kVp) X-rays.

Charged particle beam

1946 Wilson proposed the therapeutic use of charged-particle beams.

1947 Lawrence Berkeley Laboratory(LBL)-184inch synchrocyclotron.

1952 Tobias et al began to study the biologic effects of collimated beams of protons, deutrons and helium ions.

1954 First stereotactic radiosurgical procedures using charged particle were performed in clinic' patients for pituitary hormone suppression in the treatment of metastatic breast carcinoma.

Gamma unit

1951 Lars Leksell introduced radiosurgery.

1968 The first gamma knife using ^{60}Co sources was installed at Sophiahemmet hospital.

1974 The second unit was designed to produced a spherical radiation dose distribution using 179 tiny ^{60}Co sources for treatment of tumors and arteriovenous malformations(AVM).

1980s The third and forth units, which had 201 ^{60}Co sources, were established in Buenos Aires, Argentina and Sheffield, England, respectively.

1987 The fifth gamma unit(Elekta Instruments, Tucker, GA) was installed at the University of the Pittsburgh Medical Center in.

Linear accelerator

1974 Linear accelerators(LINACs) were first proposed as radiation sources for radiosurgery by Larson et al.

1984 The earliest report on clinical LINAC-based radiosurgery were published by Betti and Derechinsky 1985 by Colombo et al and Hartmann et al.

Many investigators subsequently modified LINACs in various ways to achieve the requirements of radiosurgical systems.

RADIOSURGERY DIFFERS IN SEVERAL IMPORTANT RESPECTS FROM CONVENTIONAL EXTERNAL RADIOTHERAPY

1. small volumes are treated(less than a cubic cm–tens of cubic cm)
2. usually a single fractions of radiation is used
3. extra care with target localization and treatment geometric is required : radiation dose is deposited in the target volume with great precision
4. dose gradients at field edges are high : minimize dose deposition outside the target volume
5. beam intersect at a common point within the skull after entering through points distributed over the surface of the skull : three dimensional distribution of beams reduces the volume of normal tissue receiving moderate and high doses of radiation, at the expense of increasing the volume receiving a low dose

RADIOSURGERY SYSTEM

1. stereotactic frame
   - target localization within the steretactic frame coordinate and fixation
2. imaging modality
   - information about patient's anatomic contours from CT or MR images
3. appropriate radiation source
4. three dimensional radiosurgical treatment planning system
   - dose calculation of the dose distribution

TYPICAL RADIOSURGERY PROCEDURE

1. affix stereotactic frame to patient
2. perform stereotactic imaging study
3. determine target stereotactic coordinates and dimensions
4. generate treatment plan
5. alignment procedure
6. position target with respect to radiation sources
7. irradiate target
8. remove stereotactic frame from patient

MAIN REQUIREMENT FOR RADIOSURGICAL PROCEDURES

1. accurate determination of the target's volume
2. accurate knowledge of dose required for treatment of a particular disease
3. sharp dose fall-off in regions immediately outside the target
4. calculation of three-dimensional isodose distribution inside and outside the target
5. direct superposition of isodose distributions on diagnostic images showing the anatomic location of the target
6. accurate spatial(within 1mm) and numerical(within 5%) delivery of dose to the predeterminated target
7. treatment accomplished in a reasonable amount of time
8. low skin dose(to avoid epilation) and low eye lens dose(to avoid cataract formation)
9. low or negligible scatter and leakage dose to radiosensitive organs(to avoid somatic and genetic effects of radiation)

CHARGED PARTICLE RADIOSURGERY

1. physical properties of charged particle beams
   well-defined range
   low entry dose("plateau")
   increased dose at depth("Bragg peak") – region of high dose
   adjustable width of Bragg peak
   very sharp lateral edges
   little or no exit dose
2. range
   - The specially designed particle accelerators are able to produce monoenergetic beams consisting of charged particles of very high energy and ranges in tissue up to 30cm or more.
     → range modifying absorber
   - The effective range in tissue can be modified precisely or modulated to specification by interposing absorber filters of appropriate design

or thickness in the beam path.

3. Bragg peak ionization peak
   - The unmodulated Bragg peak is extremely sharp, just a few millimeters in width in tissue, and therefore too narrow for the treatment of many intracranial lesions.
   - The width of the Bragg peak can be spread to 50mm or more in the direction of the beam path and by adding together or stacking a series of beams of slightly different ranges.
     → Bragg peak width modulator – rotating acrylic propellers
4. beam-shaping apertures
   Charged-particle beams are readily collimated by metal apertures, such as brass and certain alloys, to conform to the cross-sectional size and shape of the target volume in any projection. When more beam directions are requirement to achieve a well-localized dose distribution, their number is small, and shaped-collimators can be made for each portal.
5. radiation dose
   gray-equivalent(GyE)
   = the physical dose(in Gy) x the RBE of the charged-particle beam
6. stereotactic localization
   - four parts of stereotactic frame-mask system :
     a plastic mask prepared for each patient to immobilize the patient's head
     a Lucite-graphite mounting-frame
     a set of fiducial markers
     interfaces between the frame for immobilization and fixation to various couches for diagnostic and therapeutic radiologic procedures.

GAMMA KNIFE RADIOSURGERY

* physical description
   - Leksell stereotactic gamma knife consists of six components :
     radiation unit : 201 cylindrical ^{60}Co sources
     four interchangeable collimator(4, 8, 16, 18 mm) helmets : 201 precisely positioned collimators that align with the primary collimators
     patient-treatment table
     hydraulic system
     control consol
     treatment-planning computer system.
   - The geometry of gamma ray source is designed to minimize beam penumbra(proportional to source diameter) and maximum dose rate(approximately proportional to source length).
   - The initial dose rate in Pittsburgh gamma unit was approximately 400cGy/min to the center of a 16cm-diameter polystyrene sphere(about 1.1TBq, 30Ci).
   - Dose rate decreases over time as a result of the 5.3 year half-life of ^{60}Co, and sources therefore require periodic replacement.

LINEAR ACCELERATOR RADIOSURGERY

- A collimated x-ray beam is focused on a stereotactically identified intracranial target.
- The gantry of the Linac rotates over the patient, producing an arc of radiation focused on the target. The patient couch is then rotated in the horizontal plane and another arc performed : multiple noncoplanar intersecting arcs create a high target dose, while minimal radiation is delivered to the surrounding brain.

Mechanical stability of Linacs

- The requirements on mechanical stability of Linacs are even more stringent in radiosurgery than in routine radiotherapy.
- The isocenter of the Linac, which is the point of intersection between the gantry rotation axis and the rotation axes of the couch or chair, should be within ±1mm for any arbitrary gantry and couch or chair position.
- A better than ±1mm isocenter accuracy on a Linac has been achieved with a special colli-

mator system that rotates on its own tracks and bearings, is coupled to the Linac head, and follows the Linac gantry during the gantry rotation.

Additions and modifications

* special collimators(tertiary collimator)
  - special collimators attached to the head of the Linac.
  - circular beams are 5mm to 35mm in diameter at the Linac isocenter.
  - typically 5-to 10-cm thick lead or tungsten cylinders
  - benefits of tertiary collimator
    shaper penumbra
    circular aperture : circular radiation beams, spherical isodose contour
* floor stand
  - immobilization of stereotactic frame during treatment

Physical parameters

* The basic parameters for the stationary radiosurgical beams
  percentage depth doses(PDD)
  relative dose factors(RDF)
  off-axis ratios(beam profiles)(OAR)
  tissue-maximum ratios(TMR)
  - These are all measured in tissue-equivalent phantoms(water and polystyrene are most commonly used)
  - The beam parameters depend on the depth in phantom as well as the collimation system and the spectrum of the photon beam produced by the LINAC.

Linac-based radiosurgical techniques

- 2π geometry
  : beam-entry points are distributed essentially over a half sphere
  : all beams except those in the transverse plane enter in the upper hemisphere and exit in the lower hemisphere
- parallel-opposed beams should be avoided in radiosurgery because they degrade the fall-off outside the target in the plane containing the beams

Dose distributions in radiosurgery

- the isocenter dose is 100% and the 90% isodose curves are essentially circular, indicating that the 90% isodose surfaces are essentially spherical.
- the 50% isodose surfaces are ellipsoidal with a relatively small anisotropy, suggesting that the dose distributions for isodose surfaces above 50% are almost isotropic.
- the 10% isodose surface varies considerably from one technique to another following the irradiation scheme of the technique.

Dose fall-offs for clinical radiosurgical techniques

- the steepest and shallowest dose fall-offs for several Linac-based radiosurgical techniques and gamma unit
  : Dose fall-off curves for the dynamic rotation are similar to the corresponding curves obtained for the gamma unit and the multiple converging arcs, indicating that terms of dose distribution, both of these Linac-based techniques are viable alternatives to the gamma unit

Accuracy of dose delivery in Linac-based radiosurgery

two components : numerical and spatial

* numerical accuracy
  the requirement for the numerical accuracy
  : similar to that in standard radiotherapy
  : the International Commission on Radiation Units Measurements(ICRU) has recommended an overall accuracy in dose delivery of ±5%,

based on an analysis of dose-response data and an evaluation of errors in dose delivery

* spatial accuracy
  - three factors spatial accuracy of the clinical dose delivery
    ① accuracy of target-coordinate determination
    ② accuracy of delivery of the dose to the predetermined target
    ③ possible motion of the brain structures between the time of irradiation
  - the attainable accuracy of target localization using modern imaging equipment in conjunction with stereotactic frames is within ±1mm
  - misses as small as a few millimeters are unacceptable because of the relatively small targer volumes, the proximity or the target to sensitive structures within the brain, and the large dose given in a single session

Variability in parameters of linac based radiosurgery systems

stereotactic frame
accelerator
patient support during treatment
frame support during treatment
collimator
arc geometry
number of arc
software
dose distribution
verification
treatment time

Dose to the target relative to normal tissue

: influenced by number of arcs, arc geometry, field size, and beam energy

1. optimal energy for radiosurgery
   from 4 to 25 MV : essentially independent of beam energy
2. no. of arcs and arc geometry
   : differences between 10-arc and 5-arc plan confined to doses below 10% level (cumulative dose volume histogram)
3. field size
   : signigicant factor in the irradiation of normal tissue

New treatment strategies

conformal radiosurgery : multileaf collimator (dynamic field shaping)
fractionated stereotactic radiotherapy : relocatable frame (GTC frame)

RADIATION MODALITY-COMPARISON OF TECHNIQUES

	Charged particle	Linac	Gamma Unit
Total dose to normal brain	+++	+	+
Field edge sharpness	+++	+	+
Radiobiological effectiveness: target versus normal tissue	+++	+	+
Treatment planning flexibility	++	+++	+
Treatment planning complexity	–	++	++
Small target dosimetry	++	++	++
Large target dosimetry	+++	++	+/–
Cost to build/purchase	–	+++	+
Installation	–	++	+
Staffing requirement	–	++	+++
Cost of operation	–	++	+++
Ease of use	–	+	++

\- disadvantageous
\+ not disadvantageous
++ advantageous
+++ most advantageous

REPORTED USES OF RADIOSURGERY

acoustic neurinoma	gliblastoma
astrocytoma, anaplastic	glomus
astrocytoma, low grade	lymphoma

arterial aneurysm
arteriovenous malformation
carotid-cavernous fistula
cavernous angioma
choroid plexus papilloma
craniopharyngioma
ependymoma
functional radiosurgery
germinoma
medulloblastoma
meningioma
metastasis
oligodendroglioma
pinealoma
pineoblastoma
pineocytoma
pituitary
venous angioma