Linac Based Radiosurgery and Stereotactic Radiotherapy

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Conflict of Interest Statement: I have financial interest in TomoTherapy Inc.
Acknowledgements

Peter Hoban, TomoTherapy Inc.
Steve Goetsch, San Diego Gamma Knife Center
Fang-Fang Yin, Duke University
Chet Ramsey, Thompson Cancer Survival Center
Karen Rosser, Royal Marsden
Wolfgang Ullrich, BrainLab Inc.
Definition of SRS and SRT
Stereo Market
Indications for SRS/SRT
History of Linac-Based SRS/SRT
Variety of Systems
QA for SRS
Localization
Imaging
Small Field Dosimetry
Stereotactic Radiosurgery

- Usually single fraction delivery
  - One large dose instead of ~30 fractions as in standard radiotherapy
  - Usually called SRS

- Also multiple fraction delivery
  - Often hypo-fractionated
    - Small number of fractions (e.g., 5)
  - Often called stereotactic radiotherapy (SRT) or fractionated stereotactic radiosurgery (FSRS)
Site Type Mix of Radiation Oncology Sites with Dedicated Radiosurgery Units, as of 2003 Census

N = 2,010 Sites

No Dedicated Radiosurgery Units 92%

Have Radiosurgery Units 7%

200-399 Beds 25%

<200 Beds 9%

Non-Hospitals 10%

400+ Beds 55%

150 Sites with 160 Dedicated Radiosurgery Units
In 2003, 83 sites report plans to purchase in next few years 32 units in 2004

85% Linac based
15% Gamma Knife

Mix of Planned Acquisitions of Dedicated Radiosurgery Units, by Equipment Type, as of 2003 Census

- Gamma Knife: 15%
- Modification of Linac: 45%
- Dedicated Linac: 40%

N = 74 Units with Planned Type Specified
U.S. hospitals are adopting stereotactic radiosurgery technology at near-exponential rates.

Nearly 50 percent of all dedicated SRS technology installations have taken place within the last three years, since it was introduced to the U.S. in 1987.

Half of all dedicated SRS installations are in last 3 years (to 2003)
Brain Tumors

- Primary brain tumors
  » Tumors that originate in the brain
    – Malignant (cancerous) or benign

- Metastatic brain tumors
  » Malignant cells have spread from elsewhere
Malignant Brain Tumors

Glioblastoma Multiforme
Large and diffuse so not very suitable for SRS

Metastases
Smaller well-defined so suitable for SRS/SRT
Early SRS Developments

- 1951 – Lars Leksell, Swedish neurosurgeon, introduces the concept of radiosurgery
- 1967 – First Gamma Knife patient treated at Studsvik nuclear plant, near Stockholm
History of Linear Accelerator Based Radiosurgery

- Early reports of linac-based radiosurgery with stereotactic frames in 1980’s
- Winston and Lutz published their results from Joint Center for Radiation Therapy in Boston in 1986
- Early linac treatments required attachment of circular collimators to standard linacs
- Some relied on inherent precision of the linac, others used high precision floor mounts
- Radionics, Leibinger and Fischer, Philips, others began commercial distribution of add-on accessories in 1990s
Accuray CyberKnife: Robotic Arm and 6MV Linac

- Industrial robot arm with 6MV X-band linac
- Two orthogonal ceiling mounted X-rays with floor mounted flat panel detectors
- Infrared positioning
- Extracranial capability
BrainLAB Novalis

- Varian SRS 600 modified by adding mMLC
- First dedicated linac radiosurgery system at UCLA in 1995
- 1200 MU/min
- Shaped beam or dynamic arcs
- 84 systems worldwide plus 400 add-on systems
Varian Trilogy Linear Accelerator System

- 6MV linac
- Multileaf collimator
- X-ray head
- Silicon flat panel detector with kVCT
- SRS/SRT capability
Elekta Synergy: Linac with CT

- Cone beam CT
- Pioneered at Princess Margaret Hospital in Toronto (David Jaffray)
- 4D adaptive IGRT
- SRS/SRT capability
Tomotherapy Hi-ART: MVCT Scanner and Linac

- First unit installed at University of Wisconsin
- Now 200 worldwide
- 6MV treatment unit and also MVCT imaging
- Capable of SRS and SRT treatments
Mini/Micro-MLCs
Traditional Linac Stereotactic Radiosurgery Equipment

Collimator set
Typically ~5-40mm diameter
Traditional Stereotactic Localization

Rods appear on CT images
Traditional Stereotactic Localization

Frame attachment

(x,y,z), (x,y,z)₁, (x,y,z)₂, (x,y,z)₃
Traditional Stereotactic Localization

CT to stereotactic coordinate transformation

\[
\begin{pmatrix}
  x \\
  y \\
  z
\end{pmatrix} = 
\begin{pmatrix}
  a_{11} & a_{12} & a_{13} \\
  a_{21} & a_{22} & a_{23} \\
  a_{31} & a_{32} & a_{33}
\end{pmatrix}
\begin{pmatrix}
  x' \\
  y' \\
  1
\end{pmatrix}
\]

\[
C_\lambda = \sum_{\mu} a_{\lambda\mu} C'_\mu
\]
Cranial Stereotactic Localizer
Stereotactic Arc Plans

Localizer rods on 3D image
Isocenter Alignment on Linac

Align lasers with frame crosshairs
Head and Neck Localiser
Body Localiser
QA Reports and Recommendations

- **ASTRO/AANS** Consensus Statement on stereotactic radiosurgery quality improvement, 1993
- **RTOG** Radiosurgery QA Guidelines, 1993
- **AAPM** Task Group Report 54, 1995
- European Quality Assurance Program on Stereotactic Radiosurgery, 1995
- **DIN 6875-1** (Germany) Quality Assurance in Stereotactic Radiosurgery/Radiotherapy
- **AAPM** Task Group 68 on Intracranial stereotactic positioning systems, 2005
Recommendations for New Radiosurgery Programs:

- Rigorous acceptance testing of new equipment
- Detailed small field dosimetry by Qualified Medical Physicist
- Detailed investigation of accuracy and limitations of all imaging equipment: CT, MR, angio
- Careful examination of all systematic errors
- Rigorous training for all staff members
Flickinger studied error frequency in setting coordinates (IJROBP 1993). Up to 8%, drops to less than 0.1% with two independent observers.

U.S. NRC reported on 15 gamma stereotactic radiosurgery misadministrations over a 10 year period in the United States.

Goetsch analyzed these errors: 14 would have been prevented with the modern Gamma Knife with Automatic Positioning System (APS) and a record and verify capability (IJROBP 2002).
Failures of Quality Assurance

- U.S. NRC issued NUREG “Medical Misadministrations Caused by Human Errors in Gamma Stereotactic Radiosurgery” in 1993
- Listed 15 known misadministration reports: wrong helmet, wrong coordinates, wrong side, wrong patient, shots repeated or skipped, failure to enter intended radiation dose (treated w nominal dose)
- Gamma Knife Center reported to CDRH accidental administration up to 52% overdose to 77 patients in 2004-2005 due to miscalibration
- Linac radiosurgery center in Florida mistakenly loaded wrong factor in initial calibration, accidentally over-dosed 10 patients
- Death reported to FDA in Sep 2006 from linac radiosurgery: failure to attach accessory cone mount (field too big)
Correction Actions after Reported Incidents

- Regulatory authorities mandate that coordinates must be manually set by one person, then checked by two more staff members ("double check")
- Record and Verify systems more common now
- Elekta software now demands that a dose be entered (nominal dose of 10Gy at 100% no longer valid)
- Elekta now has password protected calibration file
- Extramural dose checks should be performed before first treatment with new system
Detailed Physics QA Recommendations

- Multiple films of test object taken from selection of couch/gantry angles each time equipment used
- Convergence should be within designated limits
- Gamma Knife claim 0.5mm, linacs attempted comparable accuracy
Localization

- The problem with radiotherapy is...
- We are treating something we can’t see with something we can’t see!
- Need to know where the target is relative to something we can see
- Stereotactic techniques utilize a visible reference frame that is fixed relative to the target
  » Traditionally a frame screwed to the head
  » Can also be an image whose location is known relative to the treatment machine
Traditional Patient Setup

Via skin marks

Locate tumor in room...

Done indirectly via...

Skin marks

Patient image

Beams
Traditional Patient Setup

Via skin marks

Locate tumor in room...

Weak link

Skin marks

Patient image

Beams
Stereotactic Patient Setup

Via a stereotactic frame

Locate tumor in room...

strong link

at least for the head...

stereotactic frame

beams

patient image
Image Guided Patient Setup

Via pre-treatment images

Locate tumor in room...

Tomo Image = beams

patient image
MRI Image Distortion Problems

- Image distortions of up to 9mm reported
- Some sequences notorious: particularly coronal or axial acquisitions
- MRI image problems extremely scanner dependent
- Some scanners exhibit severe metal artifacts
- Vital to work with MRI expert and manufacturers engineer
ACR now offers accreditation of CT programs, MRI programs; also Radiation Oncology departments

CT, MRI and Angio devices should be accepted by a Qualified Medical Physicist

Ongoing QA should be maintained in accordance with ACR standards

Each device must be qualified for use in a radiosurgery program

DICOM compatibility and rapid transmission of images is vital
CT/MR Fusion
CT/MR Fusion

CT scan with frame attached

MR with no frame

Image registration

MR in stereotactic coordinates
Artifact Caused by Metallic Dental Work
BrainLAB ExacTrac/Novalis

Calibration Phantom Referenced to Isocenter

Iso-center reproducibility based on the imaging system is within 1mm.

Yin et al., Henry Ford Hospital, Detroit, MI
Image-Guided Extracranial Target Localization

- X-Ray acquisition on treatment couch.
- Computerized generation of DRRs.
- Automatic comparison of live X-ray images with DRRs.
CyberKnife: Image-Guided Radiosurgery

- “Real-Time” Image Guidance
- Full-Time Robotics
- X Band Linac
- Frameless
- Full-Body Radiosurgery
CyberKnife: Image-Guided Radiosurgery
TomoTherapy Targeting

Objective:

Reproduce planning CT geometry on Hi-Art

Tumor stays at same location relative to isocenter
Image Guided Stereotactic TomoTherapy

Images Courtesy of Chet Ramsey, Ph.D. TCSC, Knoxville, TN
QA of Imaging Devices; Phantoms

- Numerous phantoms described over the years for QA of CT, MRI and angio
- Largest uncertainty of target determination comes from imaging
- Initial validation of imaging chain, followed by regular QA measurement
CIRS Radiosurgery Head Phantom

- Epoxy skull with MRI gel, matrix of interstitial rods with 2 cm spacing
- Now has dosimetry inserts
Small Field Dosimetry and Protocols

- Challenging physics measurement for small circular fields
- Physicist’s primary calibration tool is the ionization chamber: very difficult to use for fields less than 1cm diameter
- Extrapolations from larger fields, direct measurements with diodes, film and TLD were employed
Early Papers on Small Field Dosimetry

- Houdek, Med Phys (1983), Miami: used 0.02 and 0.1cm$^3$ ion chambers
- Rice, PMB (1987), Boston: ion chambers and film
- Kubsad, Mackie, IJROBP (2000), Wisconsin: Monte Carlo and conv./super. dosimetry
- Beddar, Med Phys (1994), Toronto: diode
- Rustgi, Med Phys (1995), Cleveland: diamond detector
- Mack, Med Phys (2002), Munich: alanine and TLD microcubes
- Perks, Med Phys (2005), UC Davis: glass rods
Dose to Water for Small Fields

Output Factor

Side of Square Field (cm)

From Roberto Capote, IAEA
Output Factors Measured with Different Detectors.

From Karen Rosser, Royal Marsden
High Uncertainty in Output Factors

- Example: Statistics of 45 Output Factors for 6 mm and 18 mm square fields (Novalis, SSD = 1000 mm, depth = 50 mm, various detectors)

Factor of Two in Beam Calibration!

From Wolfgang Ullrich, BrainLab
Elekta originally suggested output factor of 4mm helmet of 0.80 (relative to 18mm helmet) in 1987.

Based on single beam dosimetry, Monte Carlo

Later revised (1997) to 0.87 (9% increase) due to liquid ionization chamber measurements and revised Monte Carlo results (J. Arndt, AAPM Summer Meeting, 1999)

Very controversial, now well accepted
Novel Geometries for Radiosurgery

- Both accepted AAPM external beam calibration protocols: TG 21 (1983) and TG51 (1999) are written for diverging point sources with 10 by 10 cm² field size at 100 cm SSD, with measurement depths of 5 or 10 cm for photons in plastic or liquid water.
- Many dedicated radiosurgery devices cannot achieve these SSDs and/or field sizes.
- These protocols have been adopted by regulatory agencies in the United States.
- Individual physicists may interpolate and extrapolate at their own risk.
Examples of Dedicated SRS/SRT Systems

- Gamma Knife has maximum 1.8cm diameter field size at 40cm SAD, calibrated in a spherical phantom at 8cm depth
- Cyberknife has maximum 6cm diameter field size at 80cm SAD
- Tomotherapy has maximum 2.5 by 40cm field size at 85cm SAD
- CLEARLY: a new dedicated radiosurgery calibration protocol is urgently needed
Summary

- SRS/SRT has had more than its share of accidents.
- There are a wide variety of methods and techniques for linac-based SRS/SRT.
- There is no do-overs for stereotactic radiosurgery so QA is very important.
- Small field dosimetry is critical.
- SRS/SRT dosimetry protocol is required.