Linac Based Radiosurgery and Stereotactic Radiotherapy

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Outline

- 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

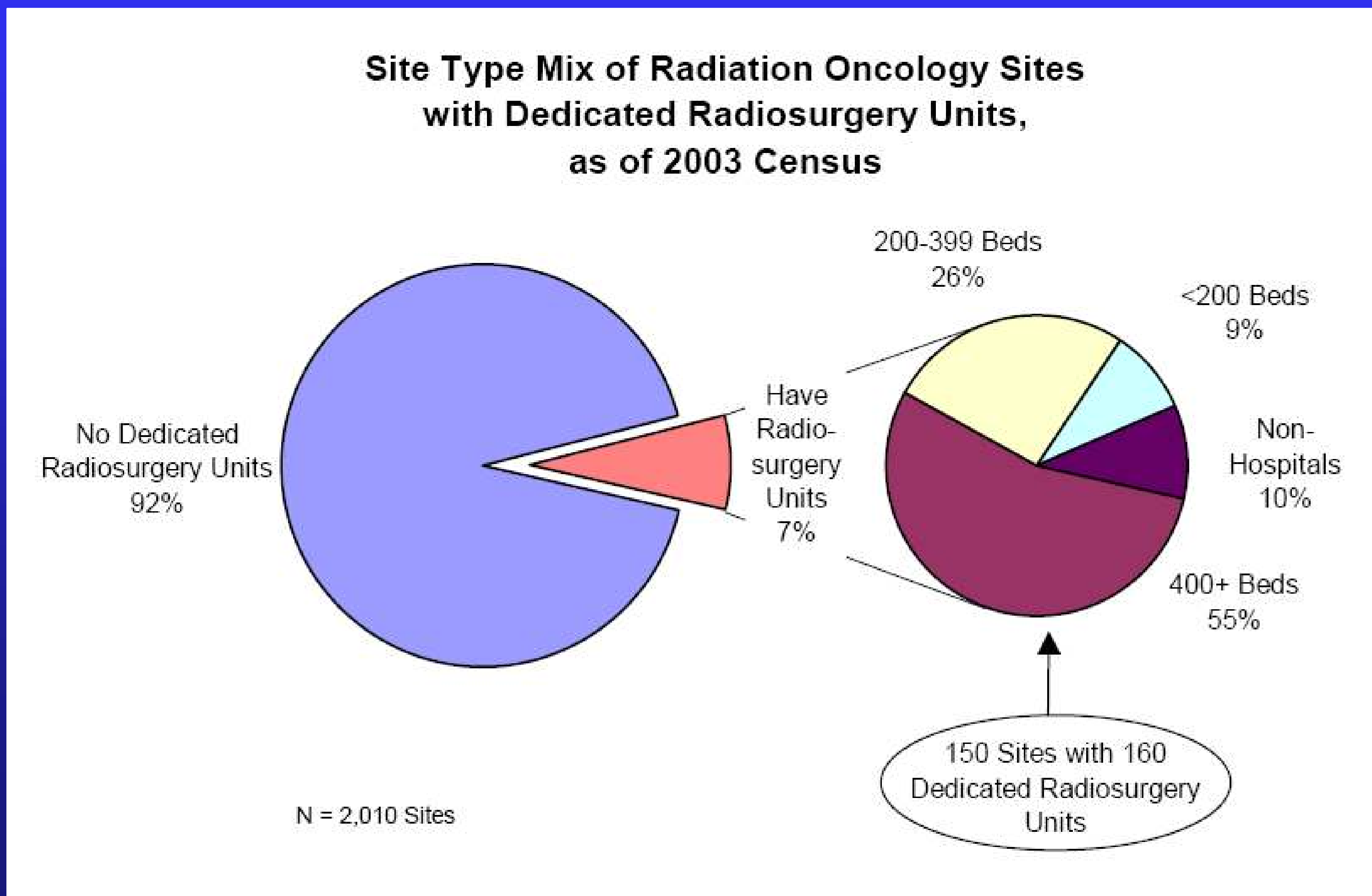
- Also multiple fraction delivery
  - » Often hypo-fractionated
    - – Small number of fractions (e.g., 5)
  - » Often called stereotactic radiotherapy (SRT) or fractionated stereotactic radiosurgery (FSRS)

US Stereotactic Market
Dedicated Machines

imv
Medical Information Division

2003 Radiation Oncology Census
Market Summary Report

February 2004



imv
Medical Information Division
2003 Radiation Oncology Census
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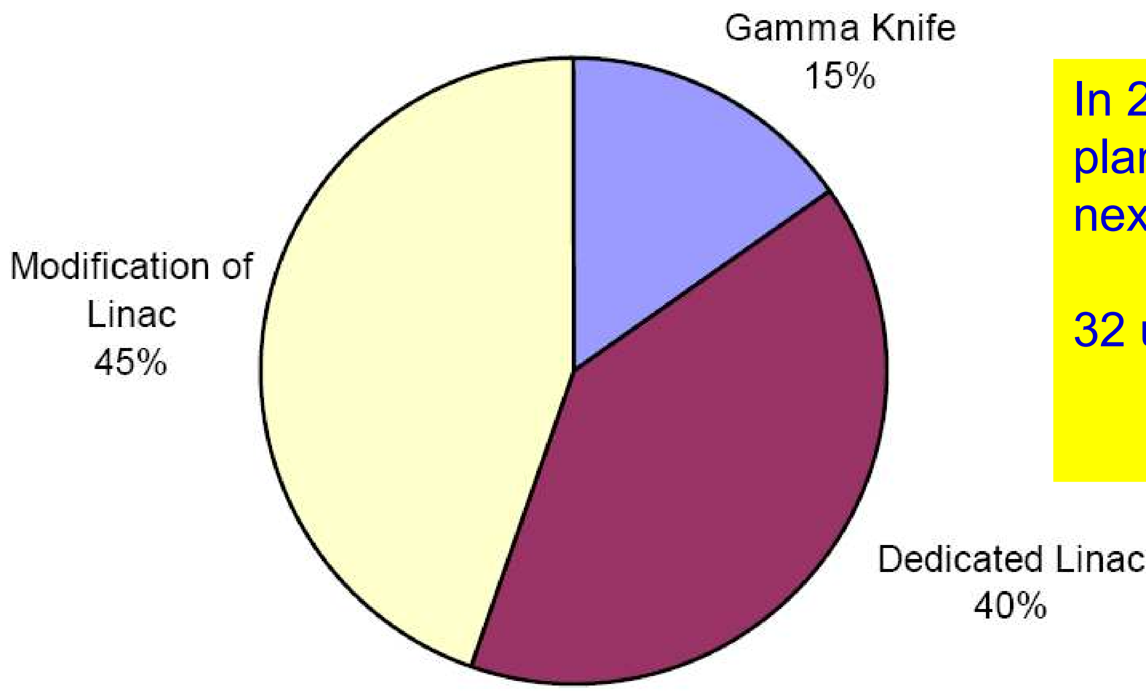
US Stereotactic Market
Dedicated Machines

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



N = 74 Units with Planned Type Specified

In 2003, 83 sites report plans to purchase in next few years

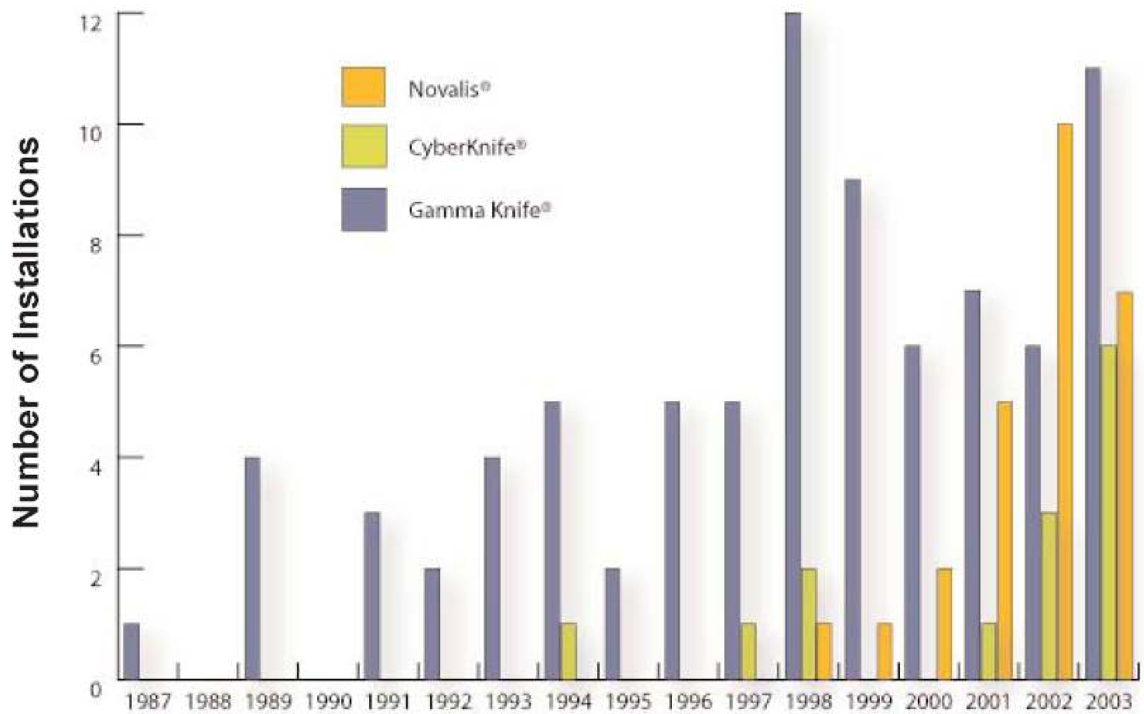
32 units in 2004
- 85% Linac based
- 15% Gamma Knife

US Stereotactic Market
Dedicated Machines

Stereotactic Radiosurgery Growth in the United States Since 1987

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)

US Stereotactic Market

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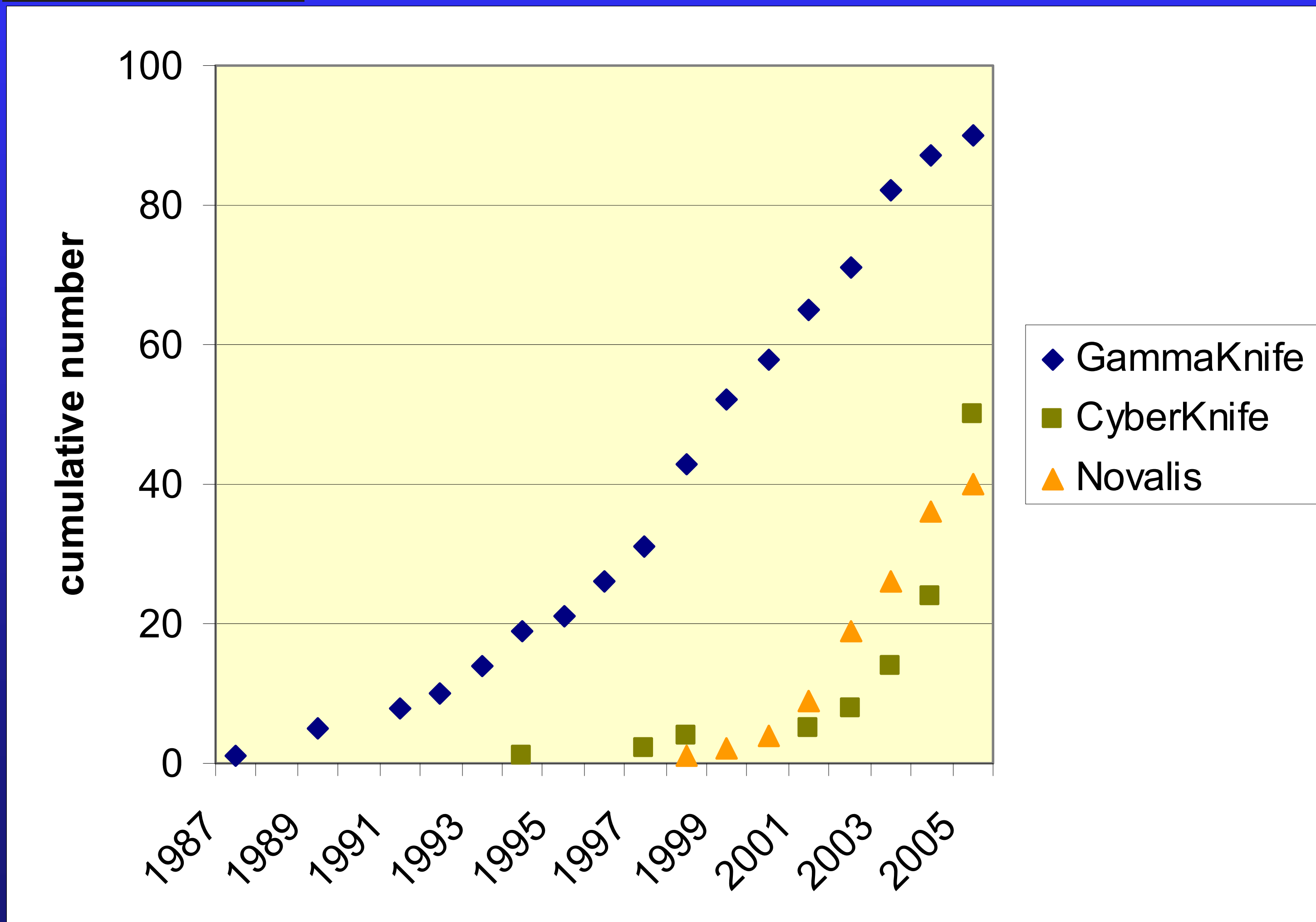
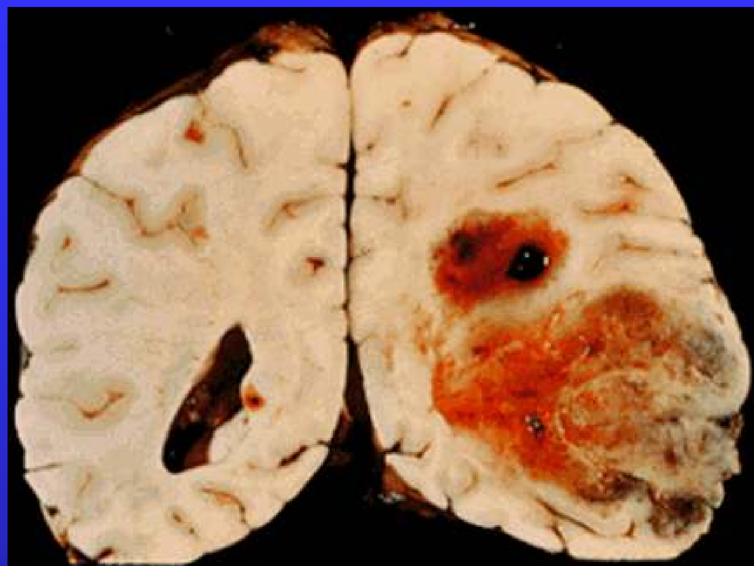
NeuroSource + imv Medical Information Division + Web Site Claims



Brain Tumors

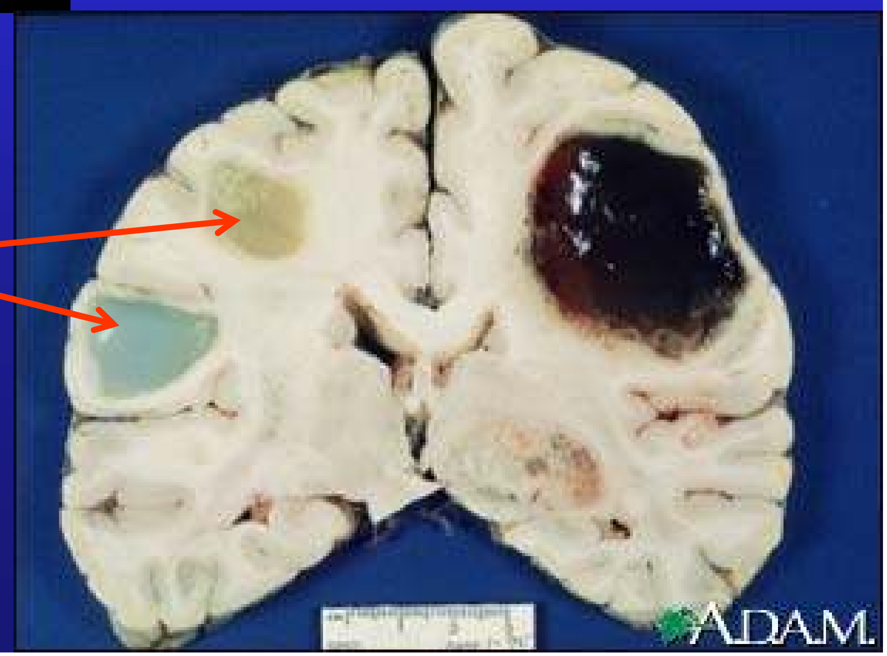
- Primary brain tumors
  - » Tumors that originate in the brain
    - – Malignant (cancerous) or benign
- Metastatic brain tumors
  - » Malignant cells have spread from elsewhere

Malignant Brain Tumors



Glioblastoma Multiforme

Large and diffuse so not very suitable for SRS

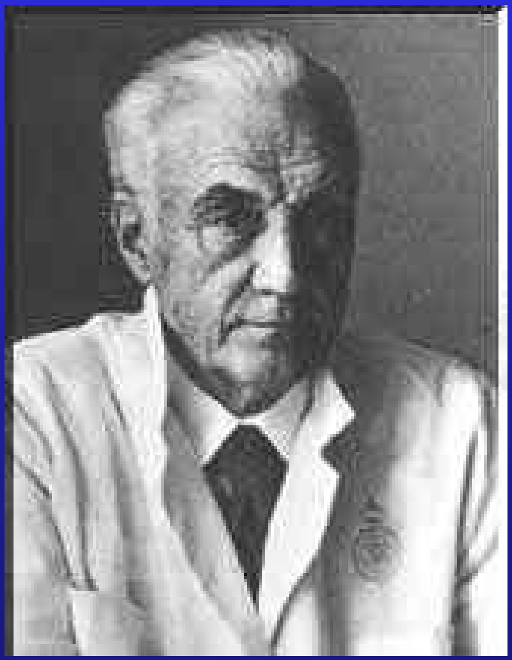


Metastases

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 w kVCT
- SRS/SRT capability

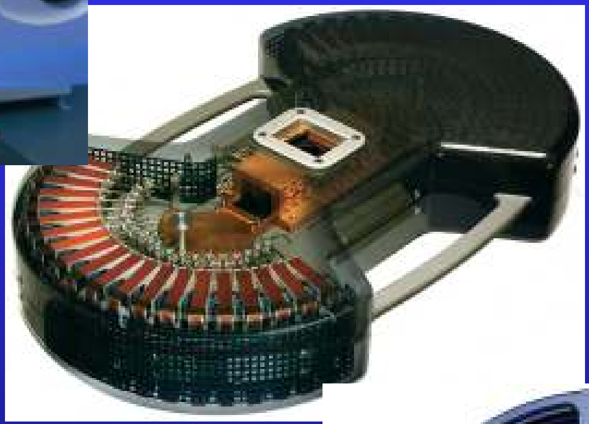
Elekta Synergy: Linac with CT

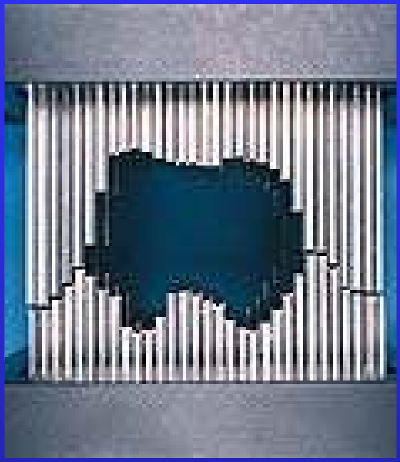
- Cone beam CT
- Pioneered at Princess Margaret Hospital in Toronto (David Jaffray)
- 4D adaptive IGRT
- SRS/SRT capability

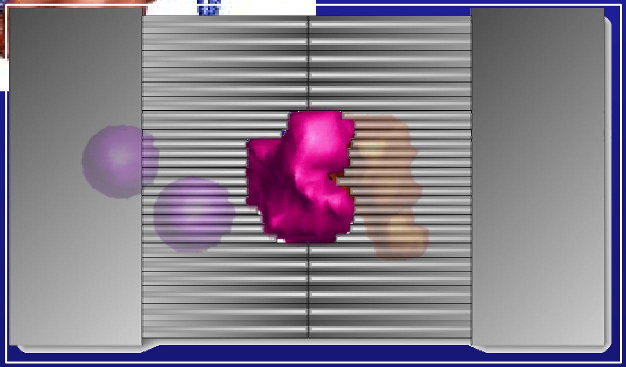
Tomotherapy Hi-ART: MVCT Scanner and Linac

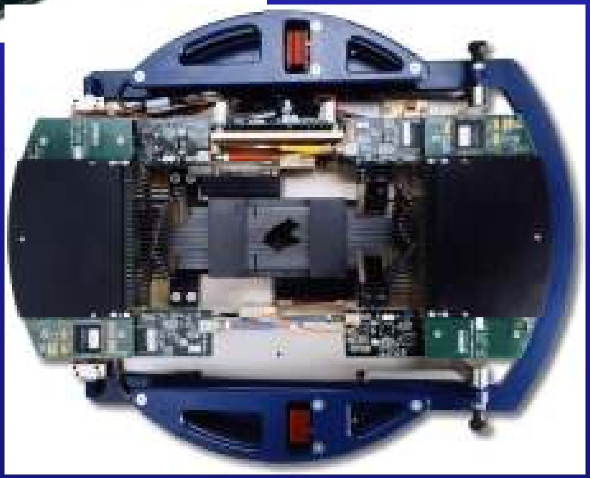
- First unit installed at University of Wisconsin
- Now 200 worldwide
- 6MV treatment unit and also MVCT imaging
- Capable of SRS and SRT treatments

Mini/Micro-MLCs









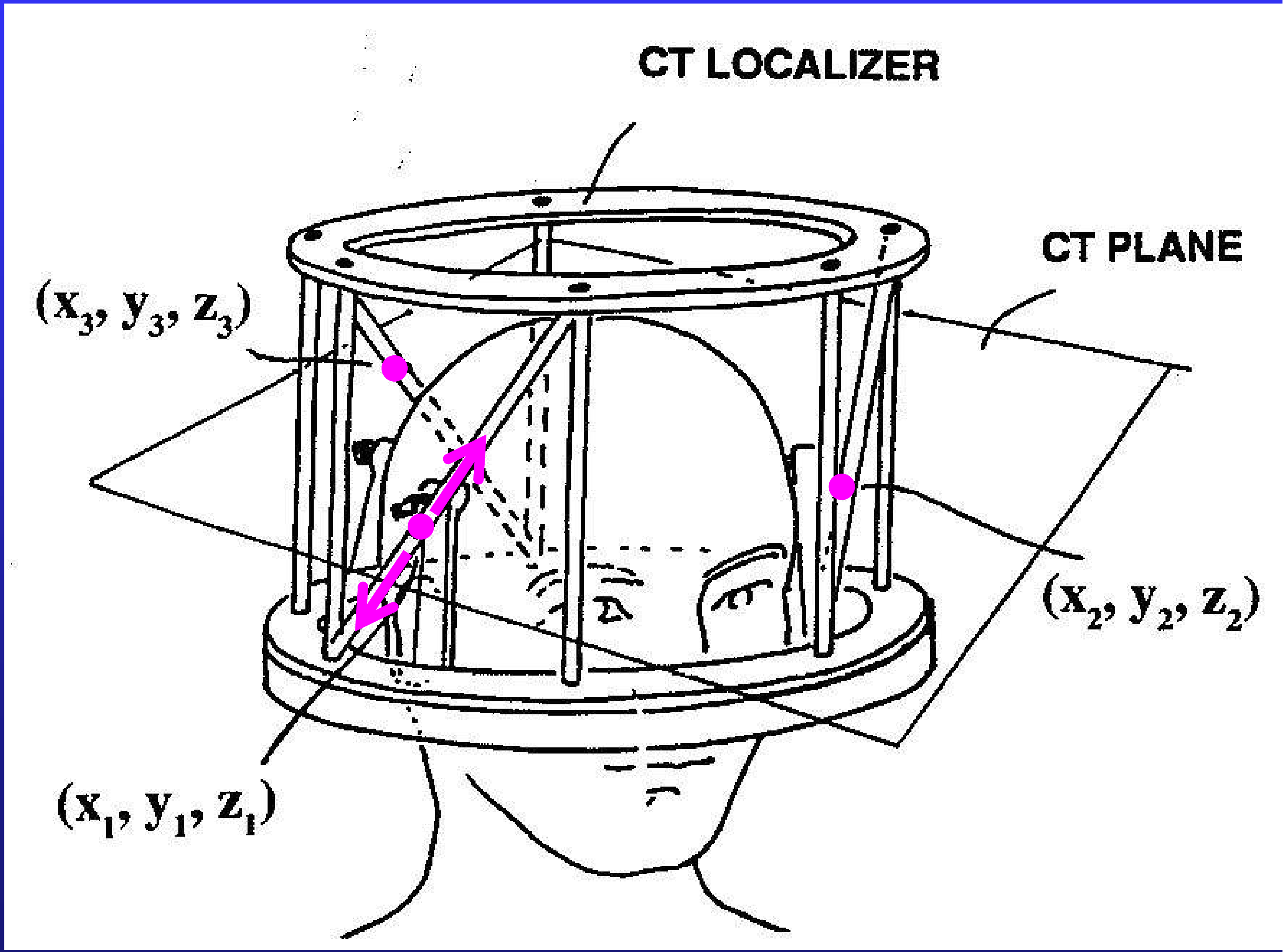
Traditional Linac Stereotactic Radiosurgery Equipment

Collimator set

Typically ~5-40mm diameter

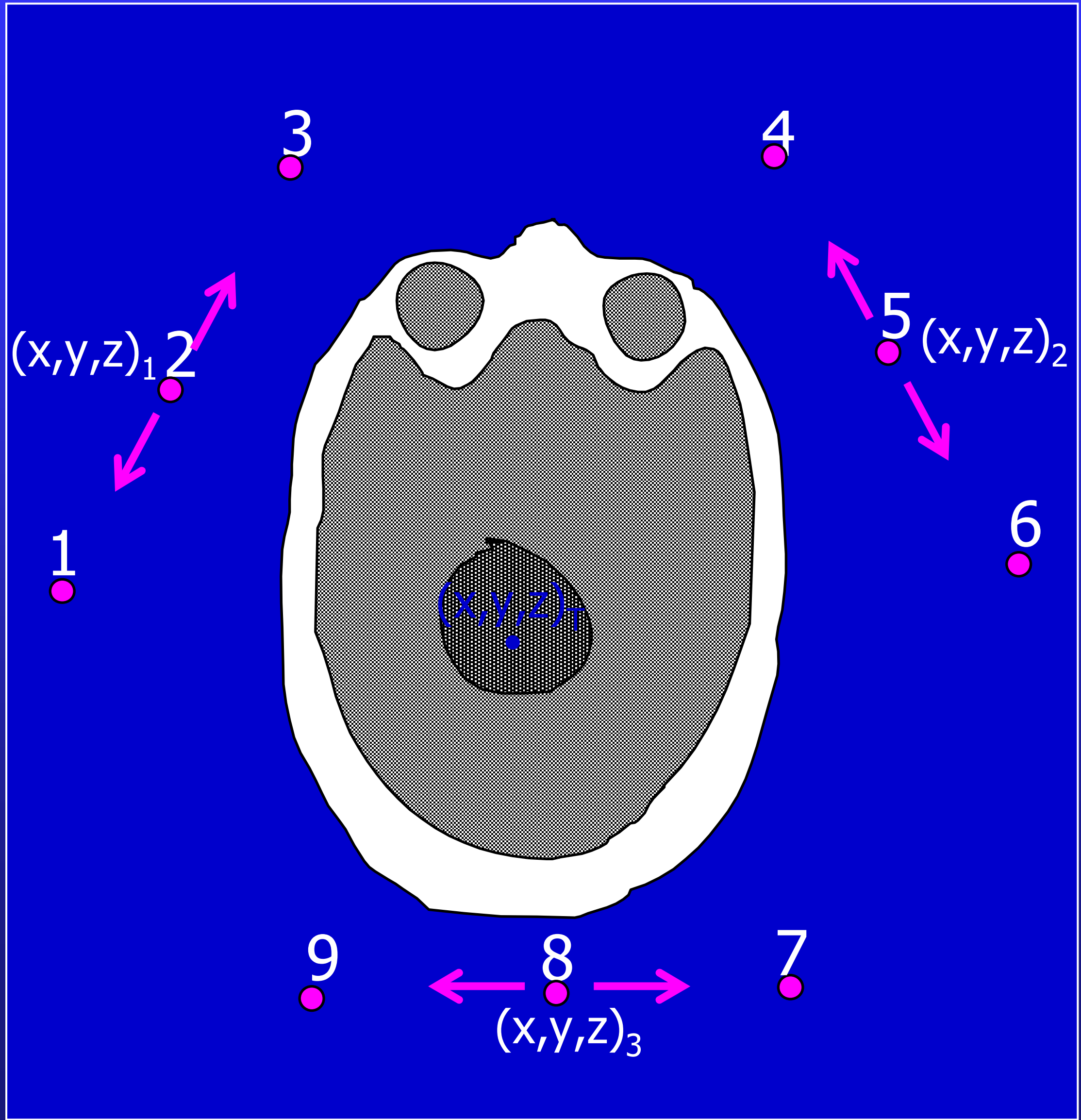
Traditional Stereotactic Localization

Rods appear on CT images



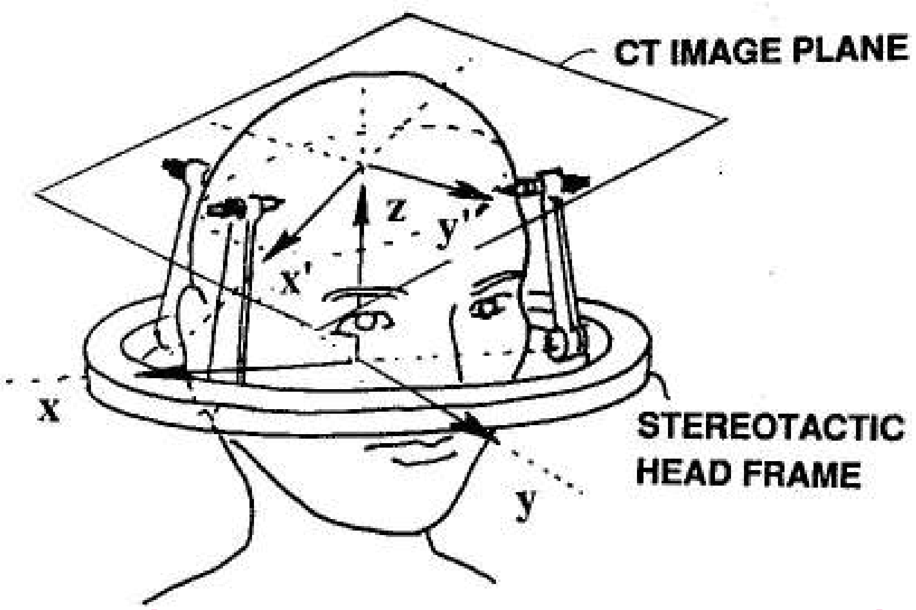
Traditional Stereotactic Localization

Frame attachment



Traditional Stereotactic Localization

CT to stereotactic coordinate transformation



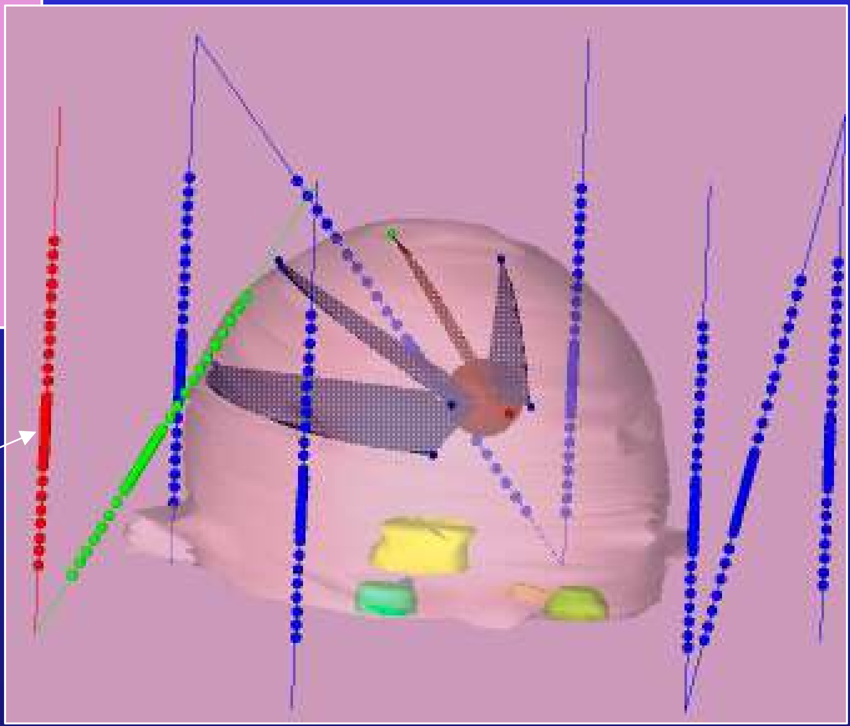
Stereo coords CT coords

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

$$C_\lambda = \sum_\mu a_{\lambda\mu} C'_\mu$$

Cranial Stereotactic Localizer

Stereotactic Arc Plans

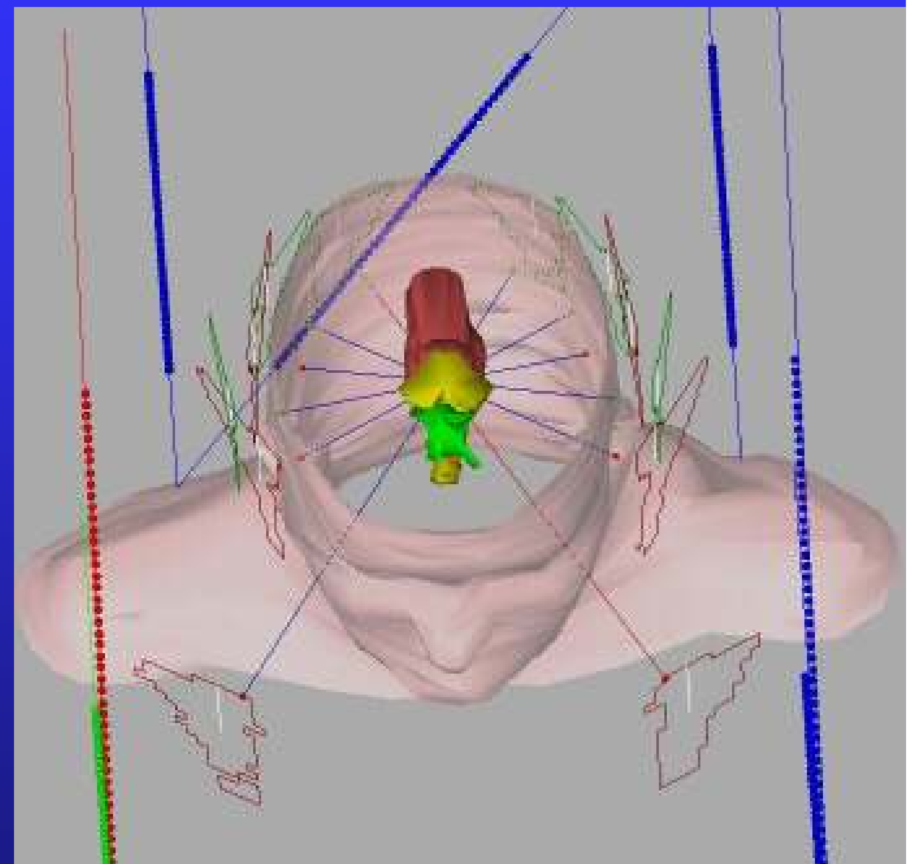


Localizer rods on 3D image

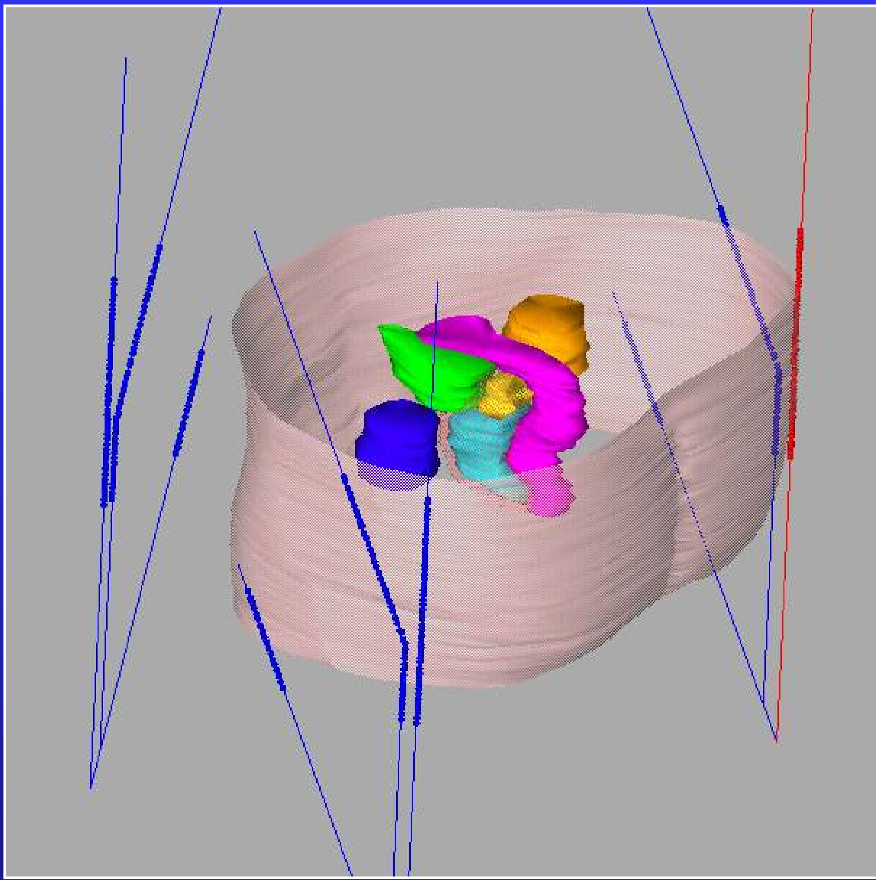
Isocenter Alignment on Linac

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

Human Factors QA/QMP

- Flickinger studied error frequency in setting coordinates (IJROBP 1993). Up to 8%, drops to less than 0.1% w 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

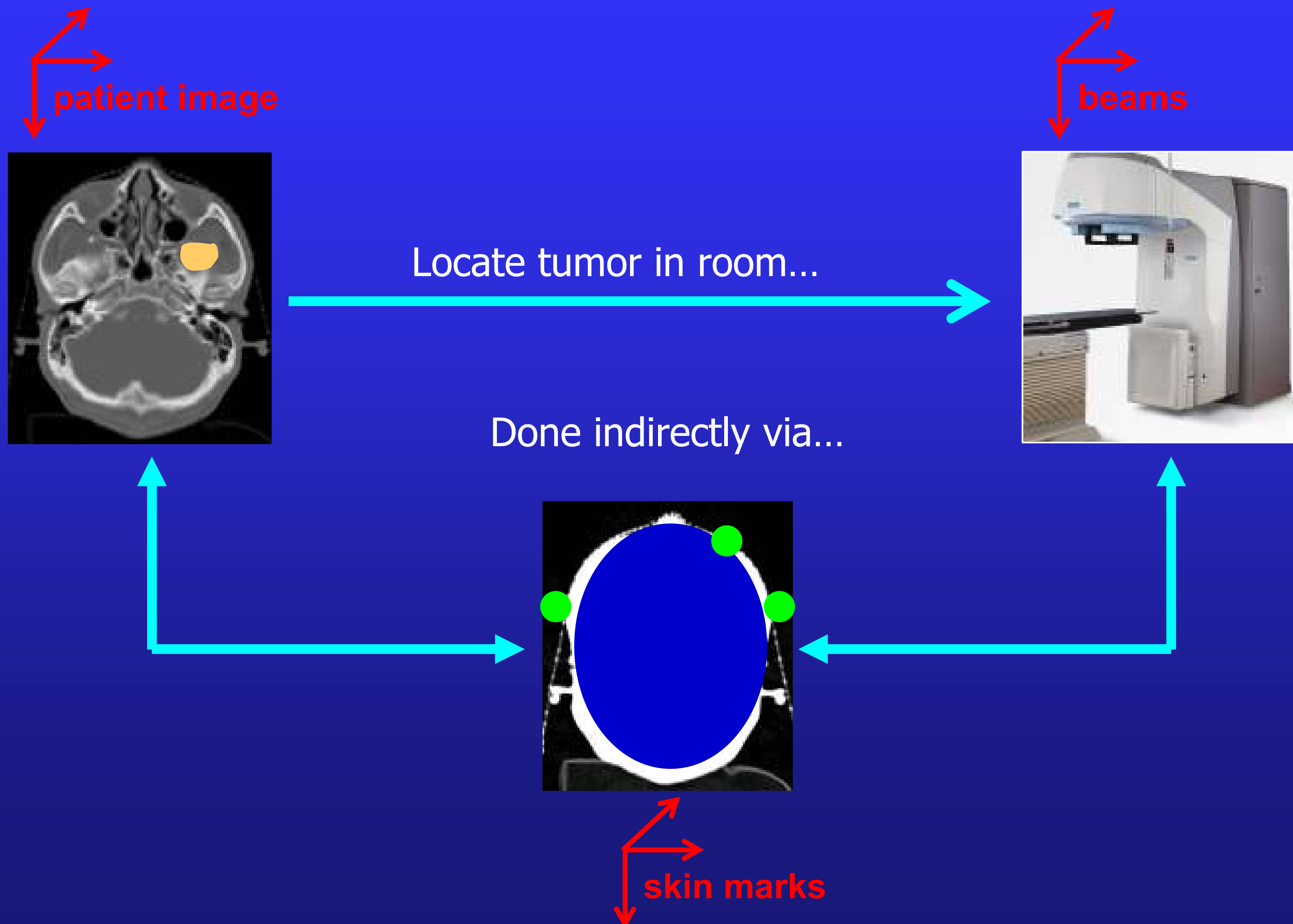
- Multiple films of test object taken from selection of couch/gantry angles each time equipment used
- Convergence should be within designated limits
- Gamma Knife claim 0.5mm, linacs attempted comparable accuracy

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 <u>can</u> 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

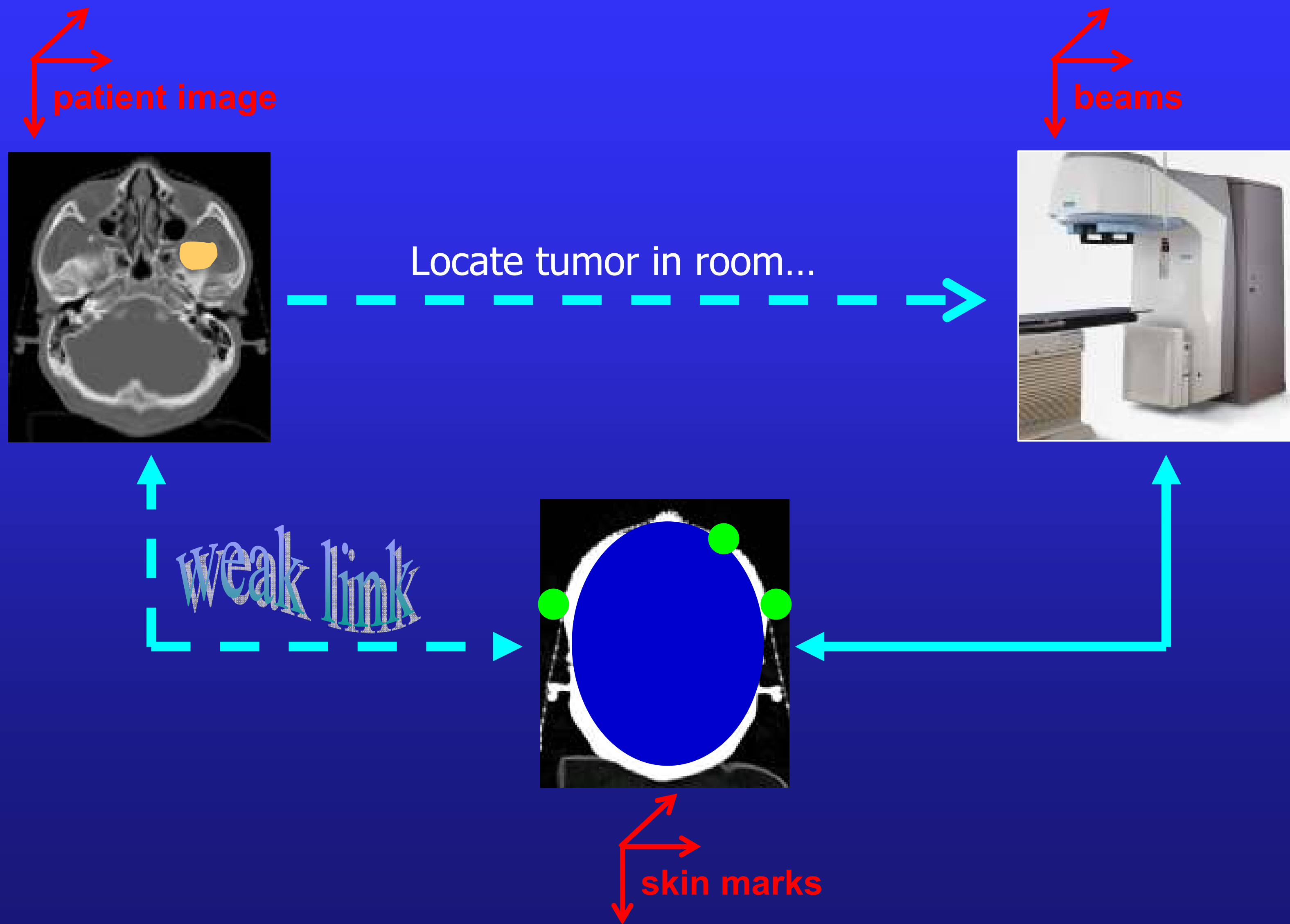
Traditional Patient Setup

Via skin marks



Traditional Patient Setup

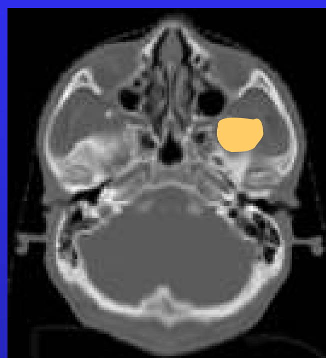
Via skin marks



Stereotactic Patient Setup

Via a stereotactic frame

patient image



Locate tumor in room…

beams

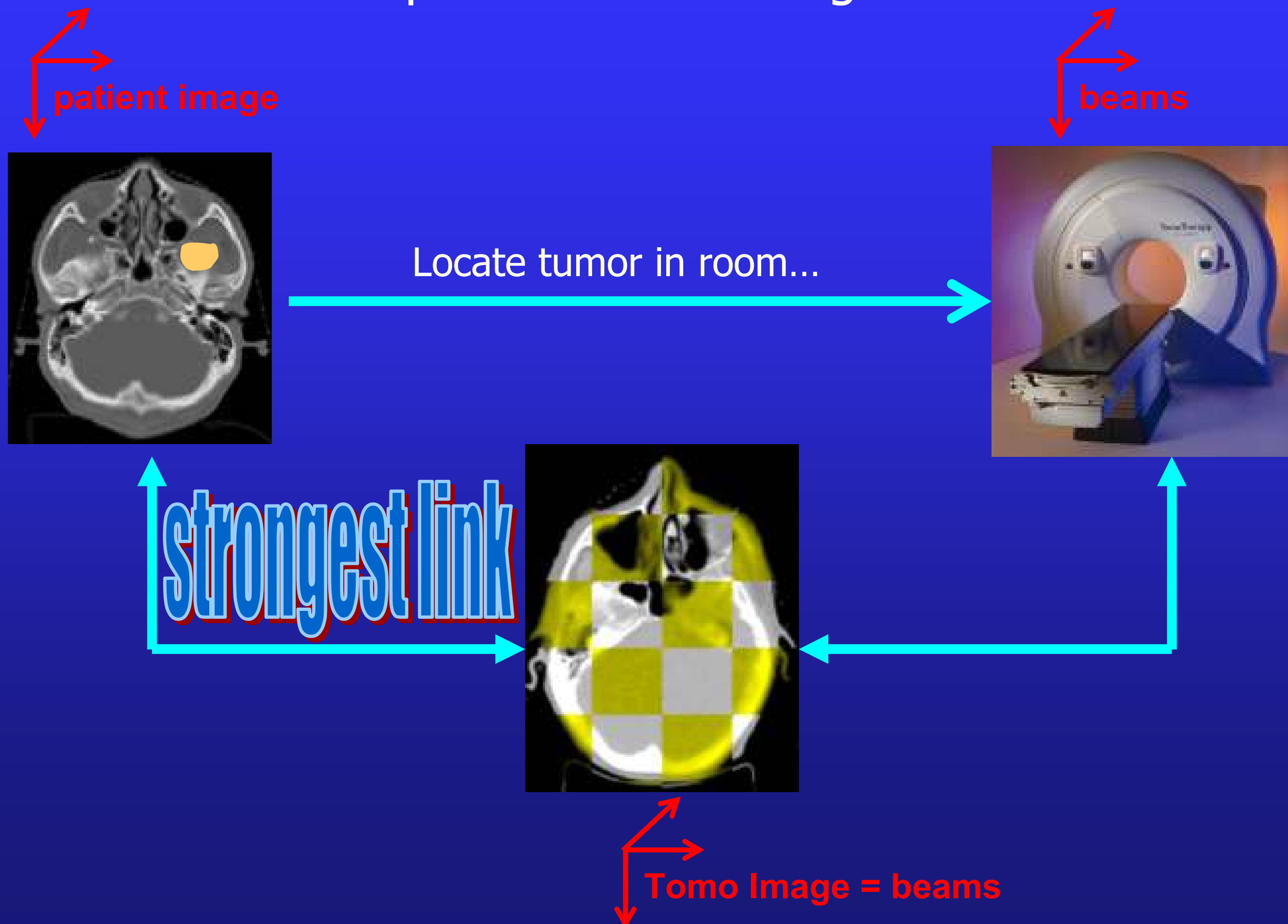
strong link

at least for the head…

stereotactic frame

Image Guided Patient Setup

Via pre-treatment images



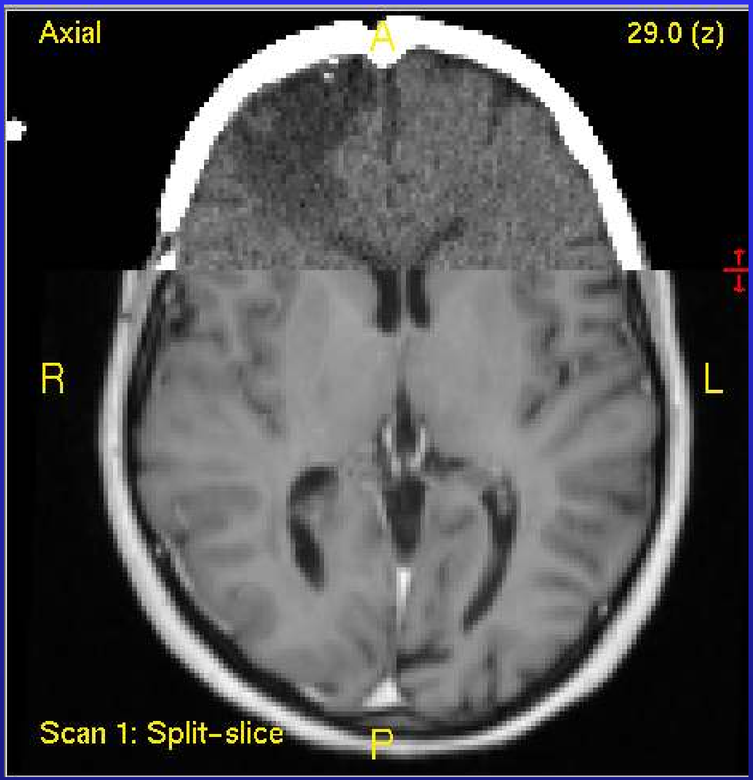
MRI Image Distortion Problems

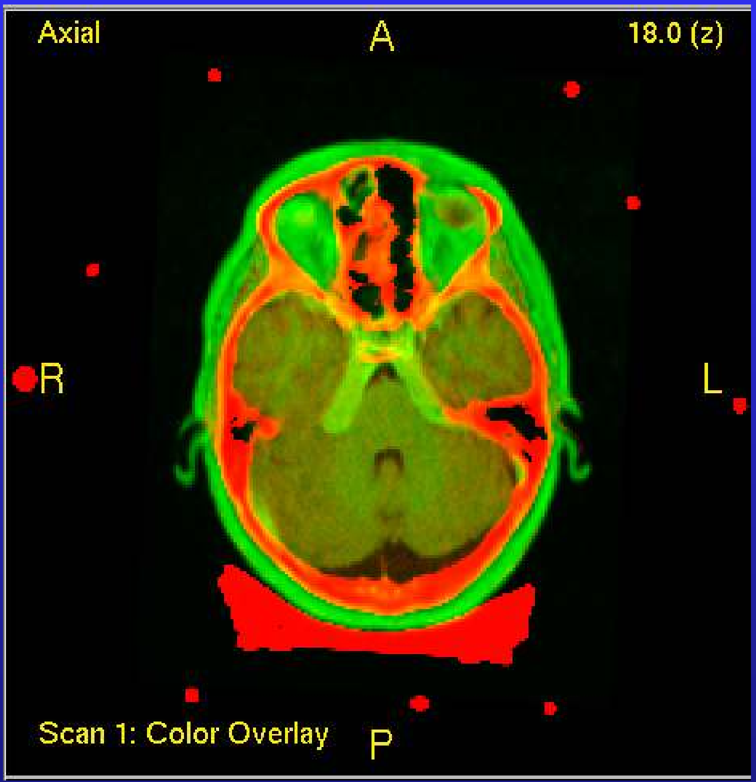
- Image distortions of up to 9mm reported
- Some sequences notorious: particularly coronal or axial acquisitions
- MRI image problems extremely scanner dependent
- Some scanners exhibit severe metal artifacts
- Vital to work with MRI expert and manufacturers engineer

Initial Acceptance of Imaging Systems

- 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


Axial
A
29.0 (z)
R
L
Scan 1: Split-slice
P


Axial
A
18.0 (z)
R
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Scan 1: Color Overlay
P

CT/MR Fusion

CT scan with frame attached

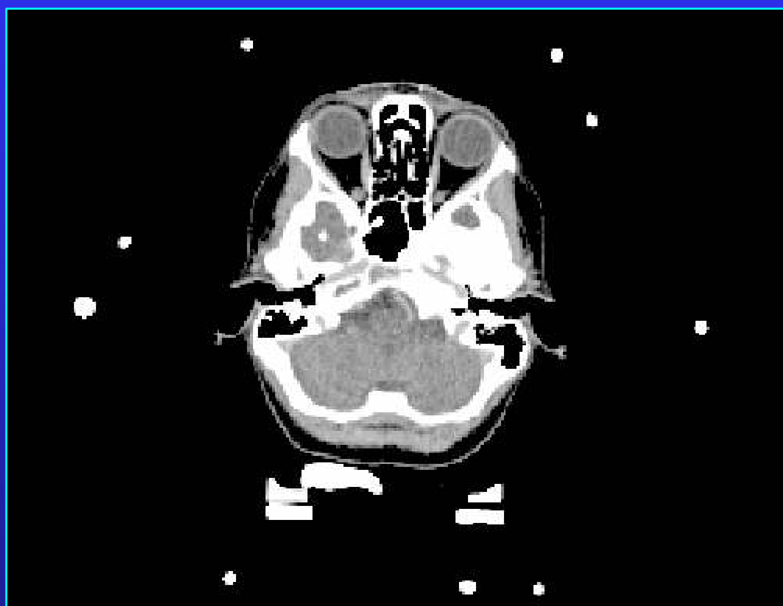


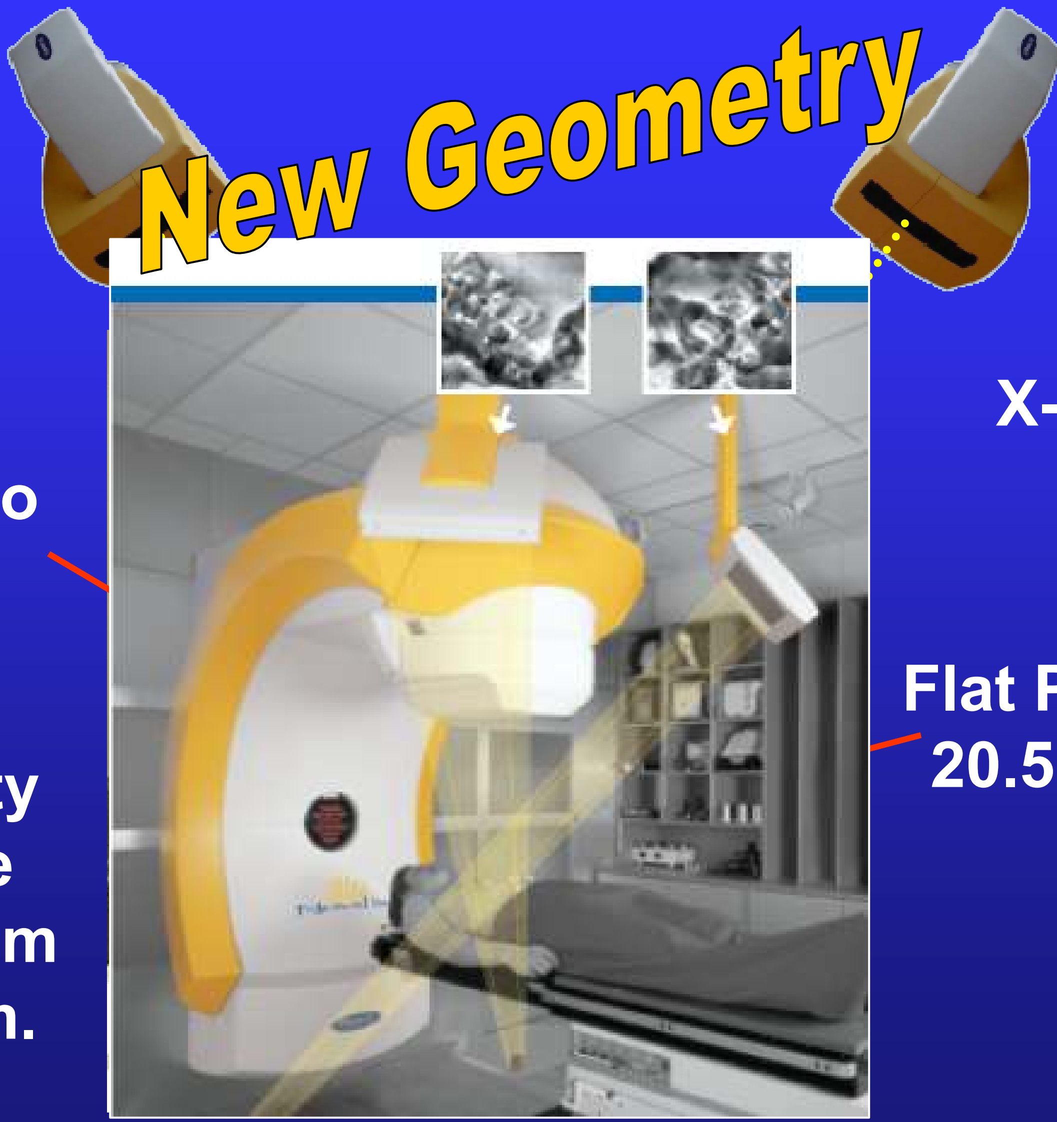
Image registration

MR with no frame

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.

Ceiling-Mounted

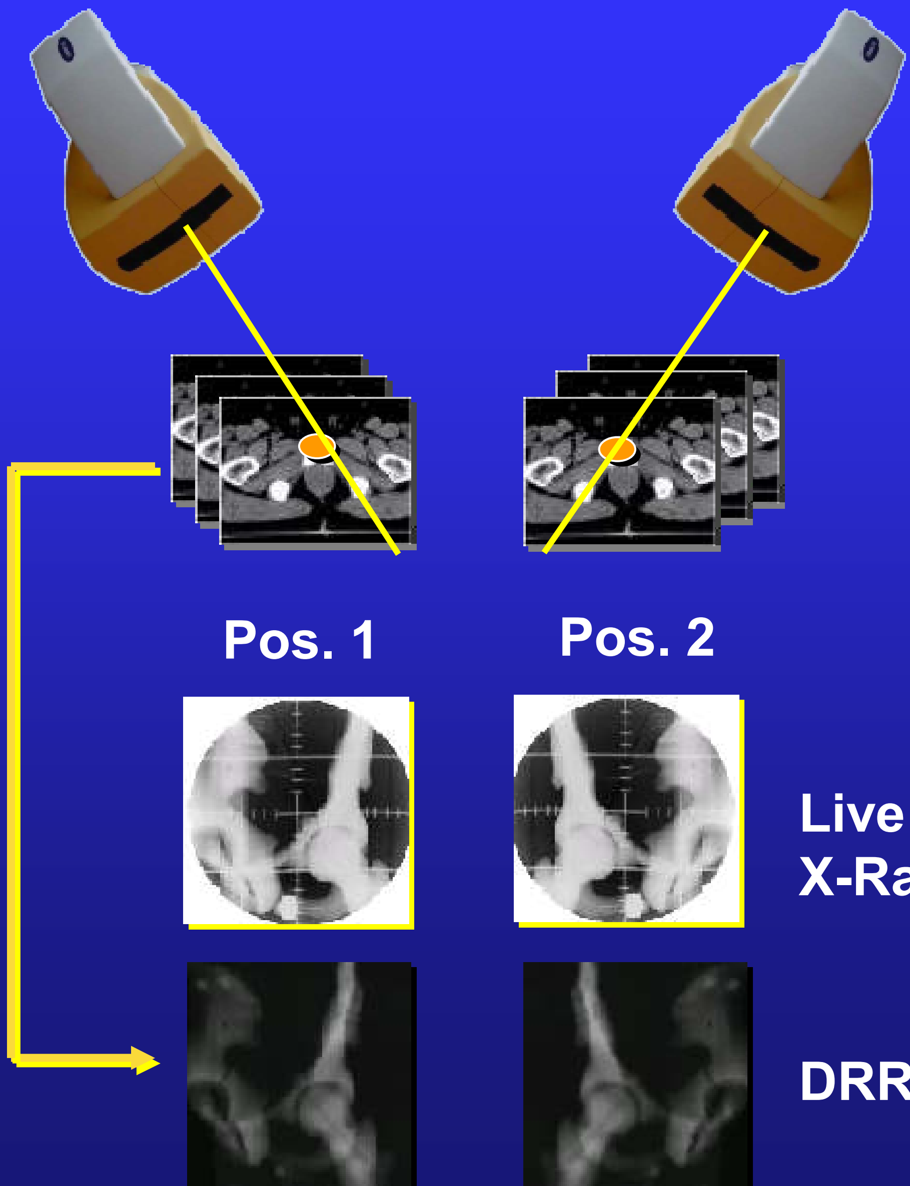
X-Ray Tubes

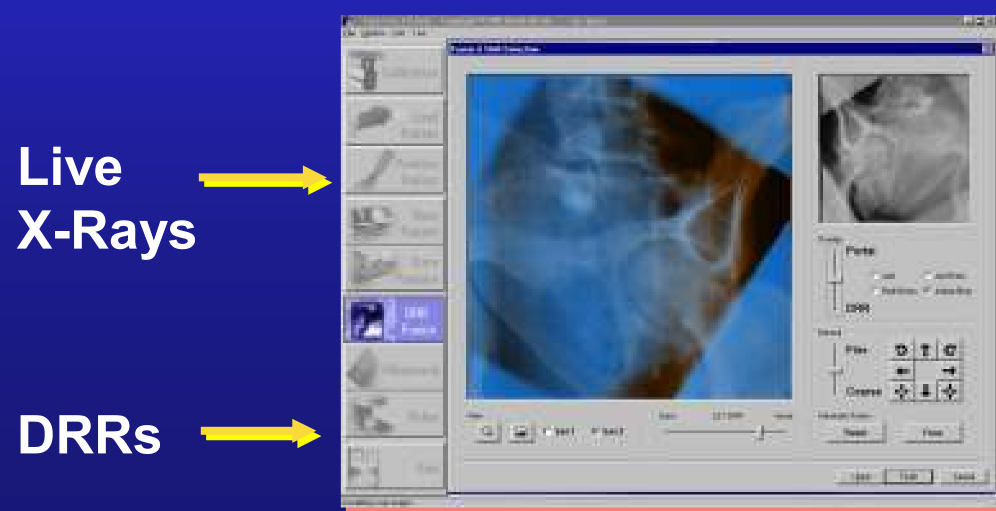
Flat Panel Imager
$20.5 \times 20.5\ cm^2$

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.

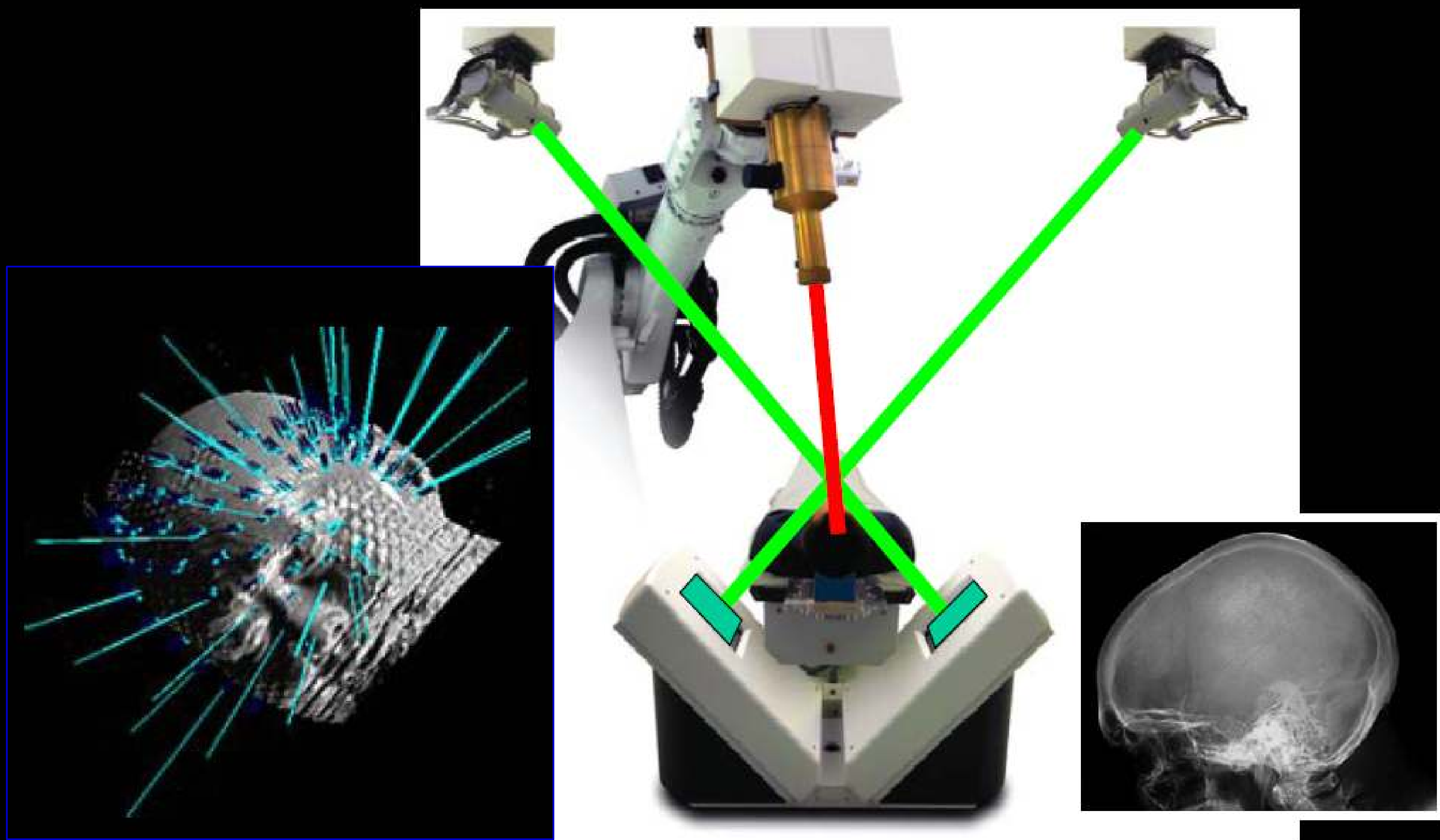




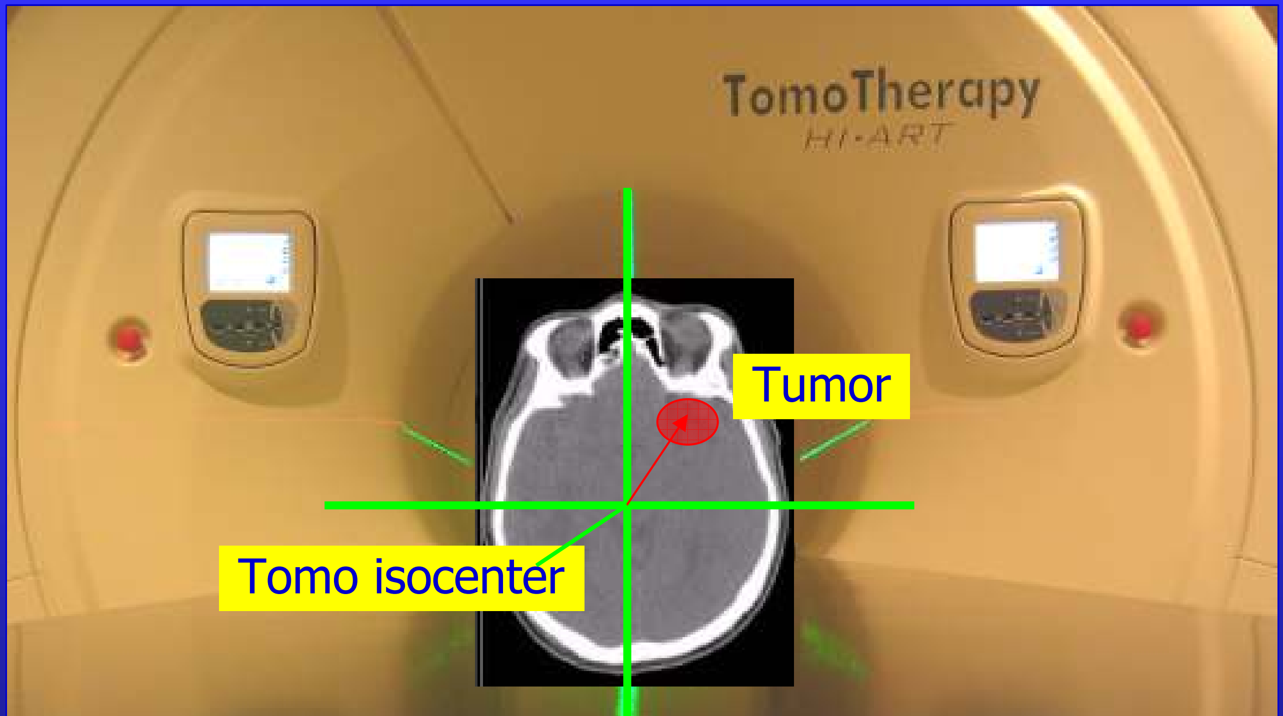
CyberKnife: Image-Guided Radiosurgery

- "Real-Time" Image Guidance
- Full-Time Robotics
- X Band Linac
- Frameless
- Full-Body Radiosurgery

CyberKnife: Image-Guided Radiosurgery



TomoTherapy Targeting

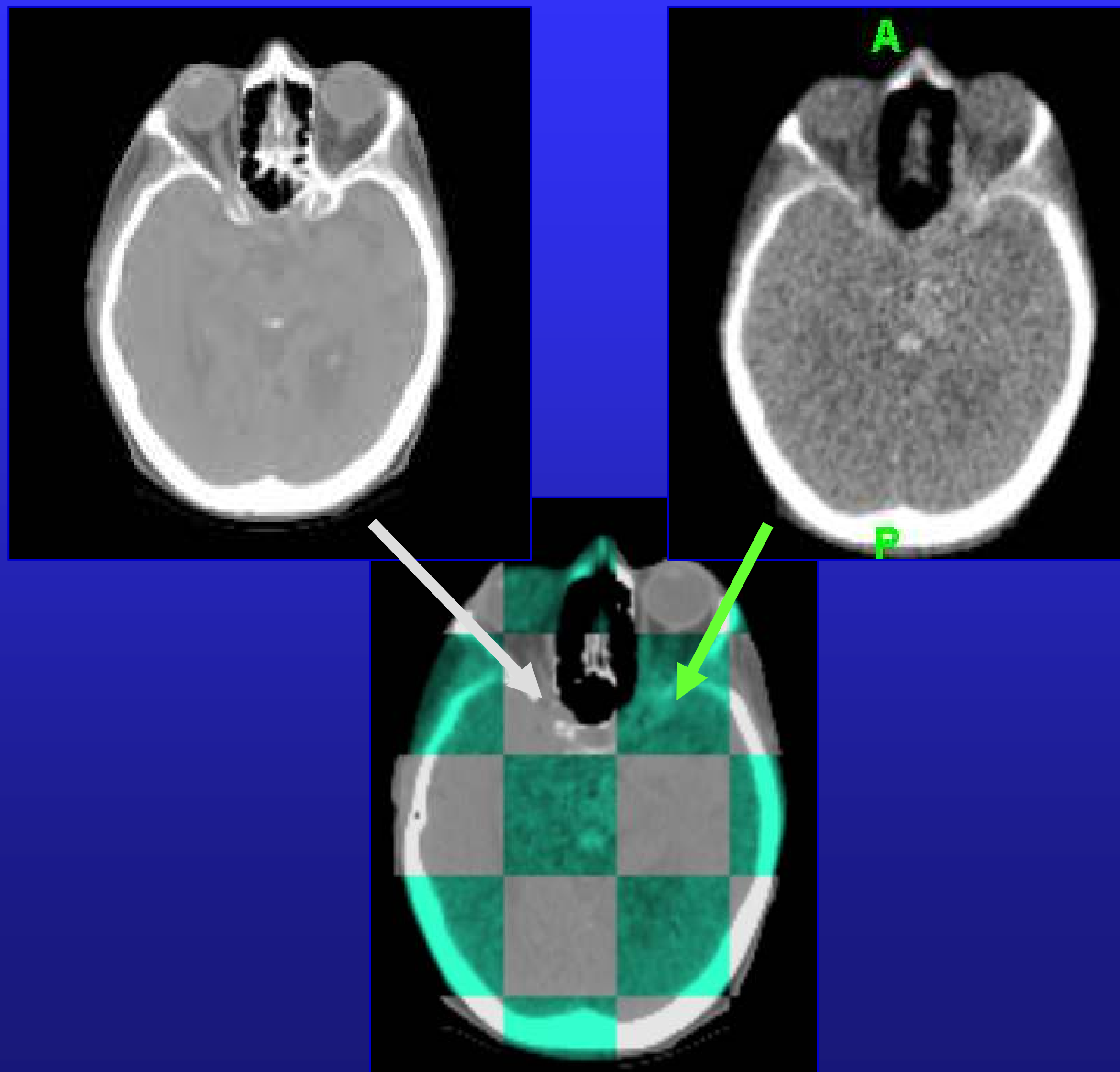


Objective:

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
- Many devices: Coffey: RSVP (1993), Ramani: LUCY (1995), Walton (1996), Goetsch: CIRS (2000)
- 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

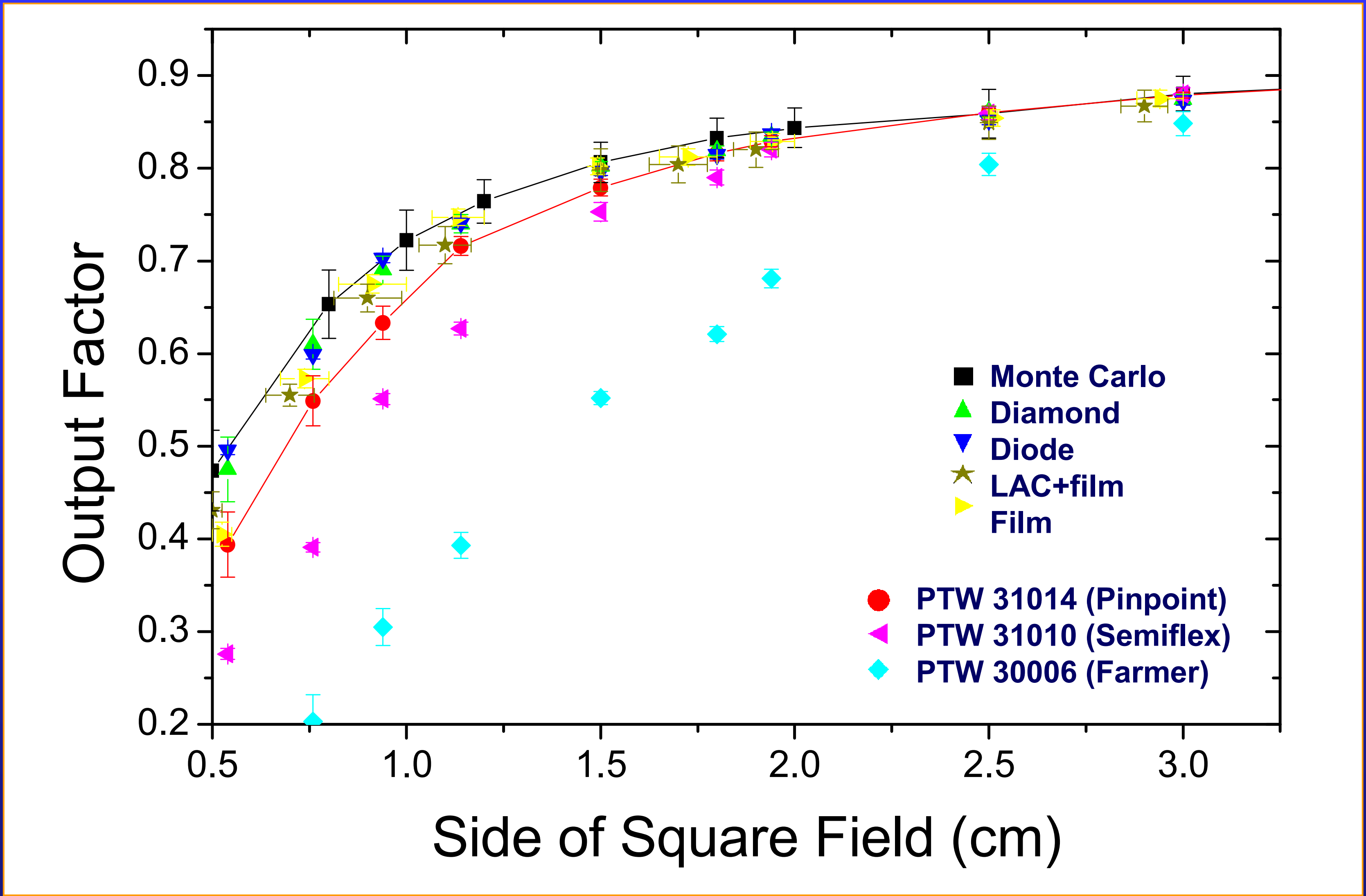
Small Field Dosimetry and Protocols

- 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

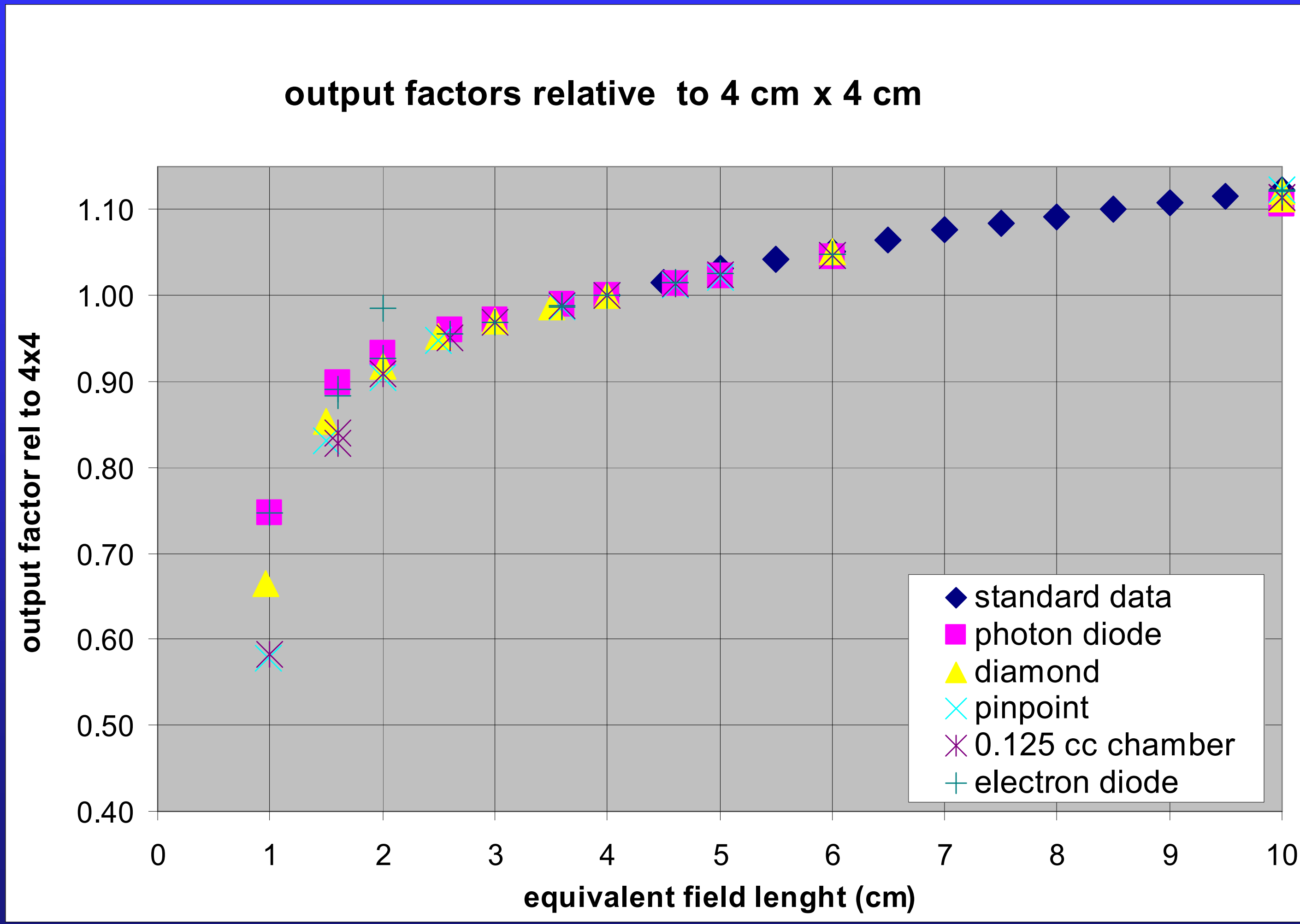
- Houdek, Med Phys (1983), Miami: used 0.02 and 0.1cm^3 ion chambers
- Rice, PMB (1987), Boston: ion chambers and film
- Kubsad, Mackie, IJROBP (2000), Wisconsin: Monte Carlo and conv./super. dosimetry
- Beddar, Med Phys (1994), Toronto: diode
- Rustgi, Med Phys (1995), Cleveland: diamond detector
-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

Dose to Water for Small Fields



From Roberto Capote, IAEA

Output Factors Measured with Different Detectors.

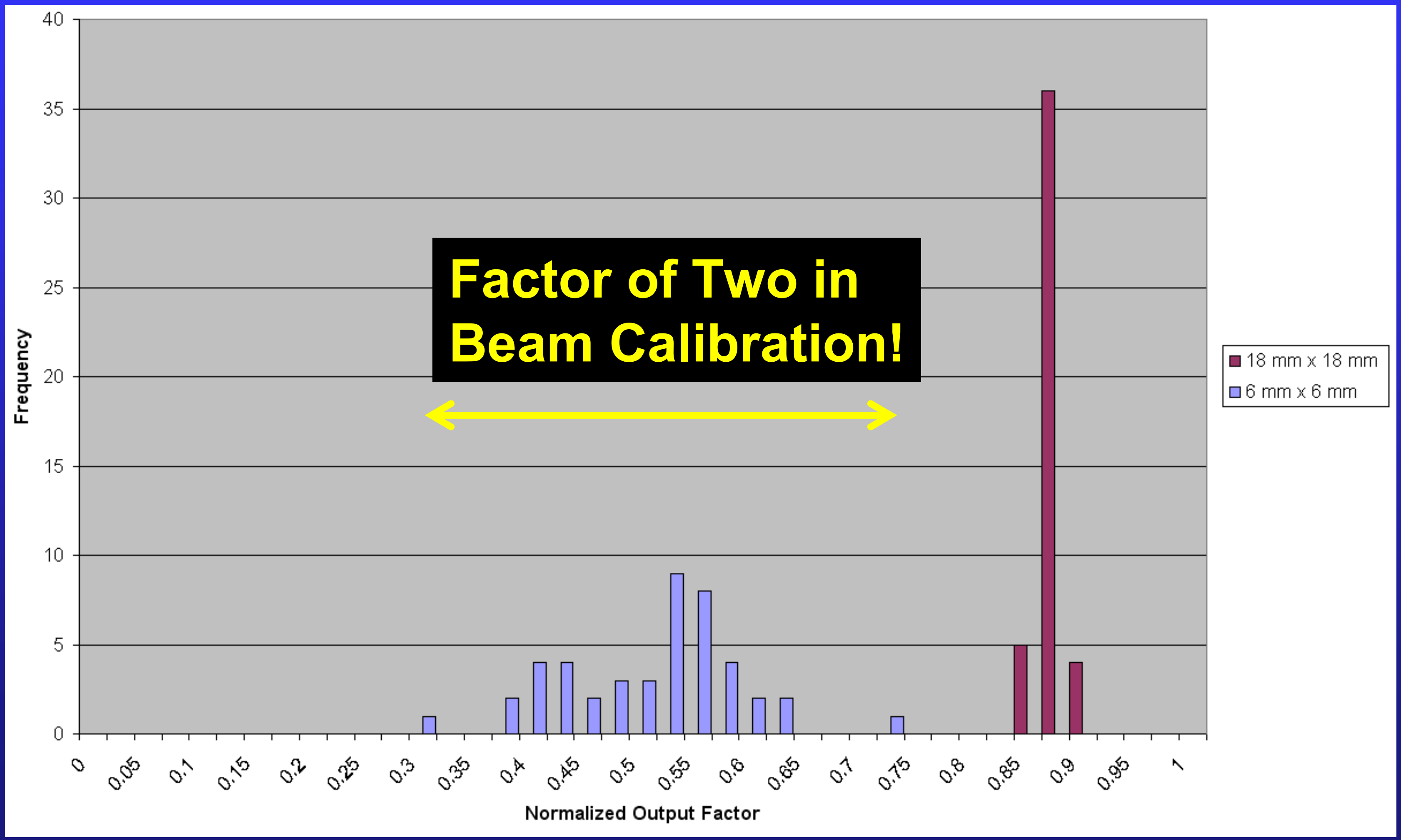


From Karen Rosser, Royal Marsden

THE 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)**



From Wolfgang Ullrich, BrainLab

Gamma Knife 4mm Output Factor

- 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 10cm^2 field size at 100cm SSD, with measurement depths of 5 or 10cm 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.