Gamma Knife and CyberKnife: Physics and Quality Assurance

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SWEDISH

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- Michelle Lee, Elekta

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Objectives

1) To provide an overview of the physics of Gamma Knife and CyberKnife radiosurgery.
2) To review the quality assurance procedures for the Gamma Knife and CyberKnife.

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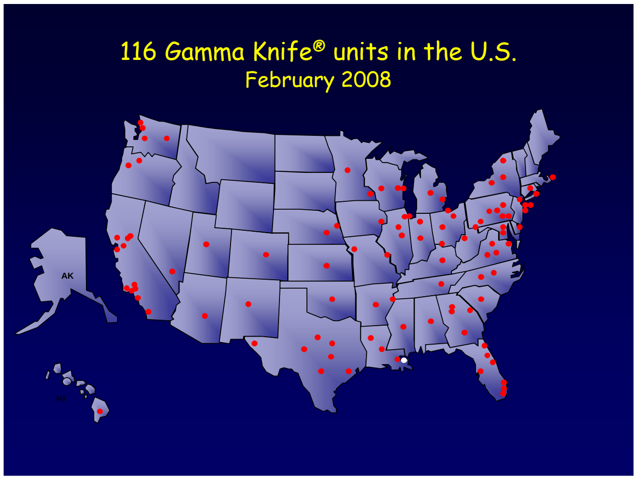
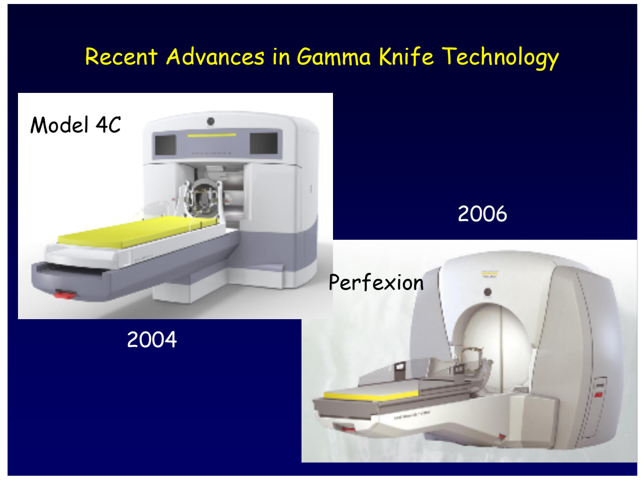
Gamma Knife - Basics

- A treatment unit designed specifically for intracranial radiosurgery.
- First Gamma Knife built in 1967 under direction of Lars Leksell in Stockholm, Sweden.


116 Gamma Knife® units in the U.S.
February 2008
AK


Recent Advances in Gamma Knife Technology
Model 4C
2004
2006
Perfexion


Model 4C

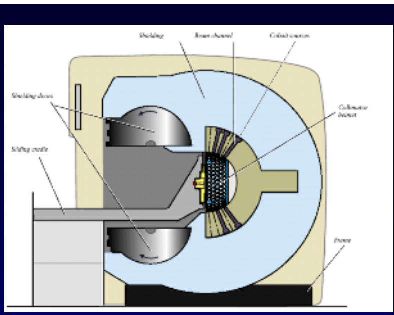

Gamma Knife Procedure
Step 1: A stereotactic head frame is attached to the patient's head under local anesthesia.

Step 2: The patient is imaged using either MRI or CT with a fiducial box attached to the patient's stereotactic frame.

Step 3: A treatment plan is developed.

Step 4: The patient's stereotactic head frame is affixed to the Gamma Knife's automatic positioning system.

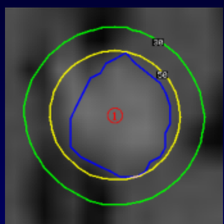
Step 5: The doors to the treatment unit open. The patient is advanced into the shielded treatment vault.



- Inside the shielded vault, the beams from 201 Co-60 sources are focused so that they intersect at a single location.
- An elliptical region of high dose is produced with a rapid falloff in dose outside the boundary of the ellipse.
- Each exposure is referred to as a shot of radiation.

- Four focusing helmets are available.
- Each focusing helmet includes 201 collimators that dictate the size of the shot of radiation (4, 8, 14, or 18 mm).

Creating the Treatment Plan (1)

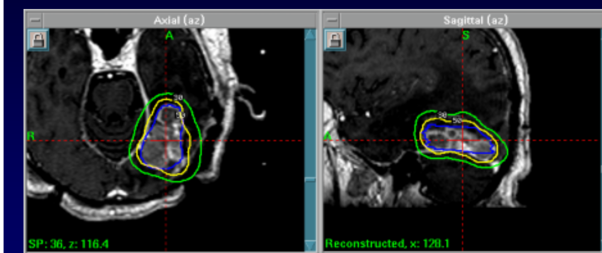


- For small spherical lesions, the planning is straightforward.
- For example, here a single 8mm shot covered the target (6mm in diameter).

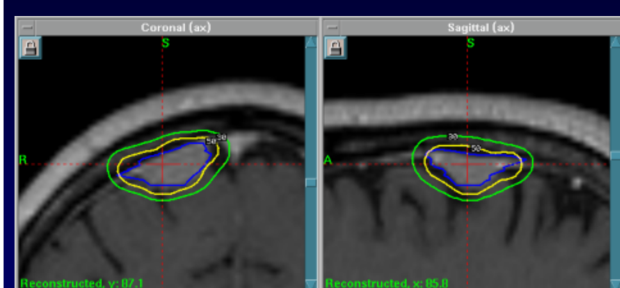
Creating the Treatment Plan (2)

- For tumors that are large or irregularly shaped, the planning process becomes more complex.
- These cases typically require several shots of radiation.
- Through an iterative trial-and-error approach, the user must determine how many shots to use along with their sizes, locations and weights.

Met – 8 shots (18mm)



Meningioma – 12 shots (8mm)



Leksell Gamma Knife® Perfexion™

19 Leksell Gamma Knife® Perfexion™ units
June 2008

Gamma Knife Perfexion

- Major redesign of the Gamma Knife.
- July 2006 – 1st system became operational at Timone University Hospital of Marseille France.
- August 2006 - FDA issued a 510(k) pre-market clearance for the Perfexion.

Gamma Knife Perfexion
Beam Collimation (1)

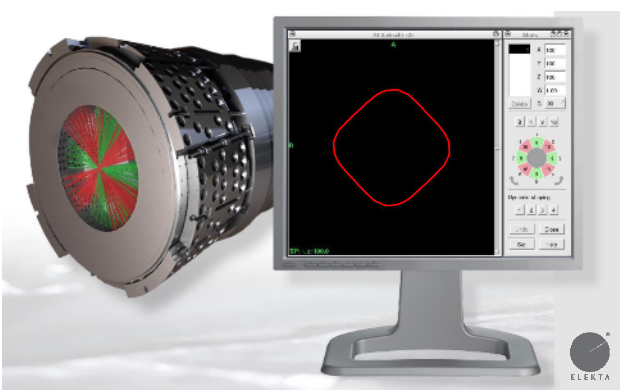
- The most critical change in the Perfexion is the new collimator system.
- The new system replaces the multi-helmet collimator setup with a single integrated permanent collimator system that incorporates openings for 4mm, 8mm, and 16mm treatment beams.

Gamma Knife Perfexion
Beam Collimation (2)

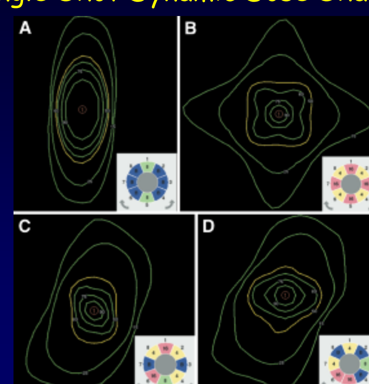
- The collimator is partitioned into 8 independently moveable sectors each delivering 24 beams of radiation (192 total sources).
- Beam size can be changed dynamically by sector.
- Individual sectors can be blocked to provide further shaping of each shot of radiation.

Collimator system 16-16-16-16-16-16-16-16

Collimator system 8-16-8-16-8-16-8-16



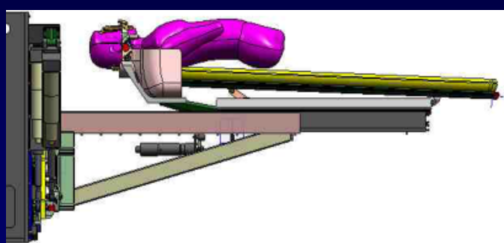
Single Shot Dynamic Dose Shaping



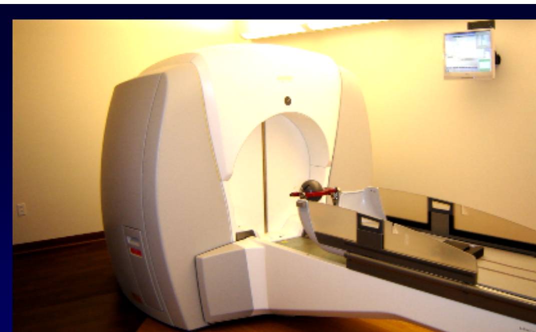
Courtesy of David Larson

Positioning System Design

- The GK Perfexion positions the patient by moving the couch rather than moving the patient's head within an APS.
- The transition between shot locations is typically under 3 seconds



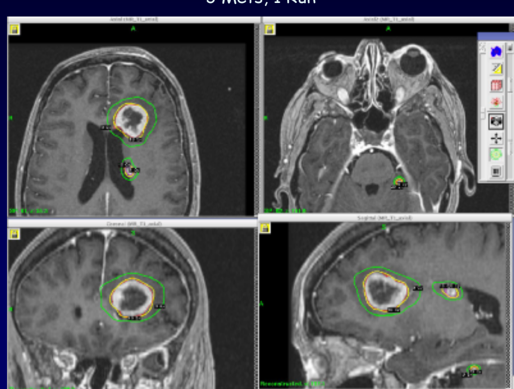
Courtesy of David Larson



- First Perfexion in US installed at Washington Hospital, Fremont, CA.
- First patient treated June 2007

First Perfexion™ Patient at WHHS

3 Mets, 1 Run



Perfexion – Key Advantages

1. Improved patient throughput.
2. Improved patient comfort.
3. Extended anatomical reach.

Improved Patient Throughput

- No helmet changes.
- The patient no longer needs to moved out of the unit between shots because the beams can be moved to the off position.

Courtesy of Jean Régis

Improved Patient Comfort

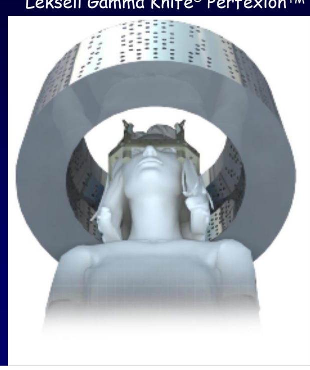
- Increased space inside collimator body leads to reduced patient anxiety.
- The need for eccentric frame positioning is eliminated.

Courtesy of Jean Régis

Larger Collimator Size

Leksell Gamma Knife® C

Leksell Gamma Knife® Perfexion™



Extended Anatomical Reach

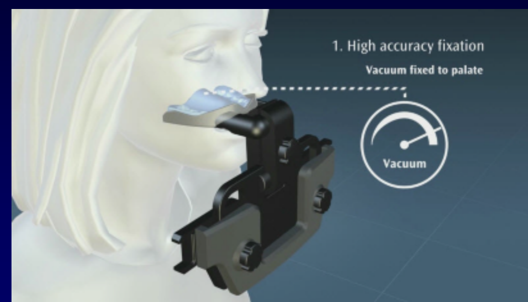
- Most peripheral lesions can now be treated.
- Lesions in and around the paranasal sinuses, the orbits, and the cervical spine are now accessible.
- Elekta is developing a fixation device for cervical spine lesions as well as a repositionable frame for fractionated radiosurgery.

Courtesy of Jean Régis

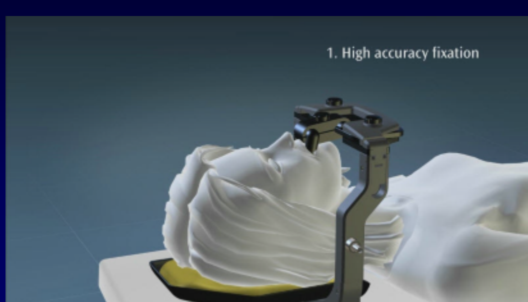
Gamma Knife eXtend™

- Starting May 2009, Elekta will offer a toolkit for fractionated treatments in the head and upper neck region.
- The system will use a stereotactic frame with a vacuum assisted bite block.

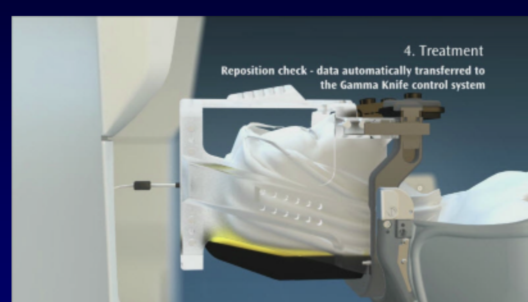
Gamma Knife eXtend™



Gamma Knife eXtend™



Gamma Knife eXtend™



Gamma Knife eXtend™

Gamma Knife

Routine Quality Assurance

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Gamma Knife Routine QA Procedures

Daily QA

- Warmup
- Door interlock
- Emergency off
- AV communications
- Radiation monitor

Weekly QA

- Couch release handle
- Helmet microswitches
- Helmet trunions
- Automatic positioning system

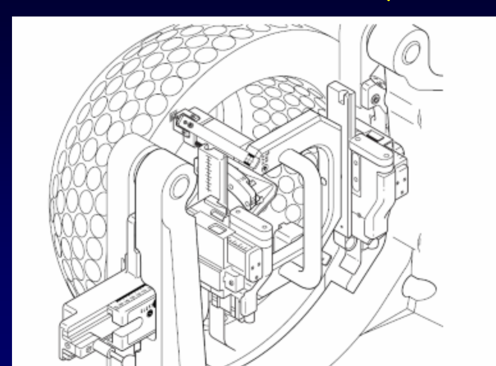
Monthly QA

- Radiation output
- Computer output vs. measured
- Emergency rod release
- Medical UPS battery check
- Timer constancy, linearity, and accuracy

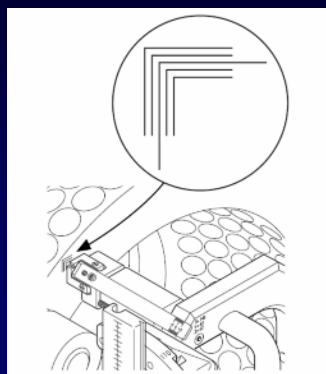
Annual QA

- Relative helmet factors
- Isocenter coincidence
- Film measurements

Gamma Knife – APS QA



Gamma Knife – APS QA



Gamma Knife - Summary

- Radiosurgery delivery technique using beams from Co-60 sources to deliver highly conformal dose distributions.
- Well established technology used for treating patients since 1967.
- More than 250 units installed worldwide with over 350,000 patients treated.

CyberKnife

134 CyberKnife Units Installed Worldwide

CyberKnife - Basics

- A treatment unit designed for both intracranial and extracranial radiosurgery.
- CyberKnife uses a compact linear accelerator mounted on a robotic arm, which has 6-degrees of freedom.
- Pencil beams of radiation are delivered sequentially as the robot moves around patient.

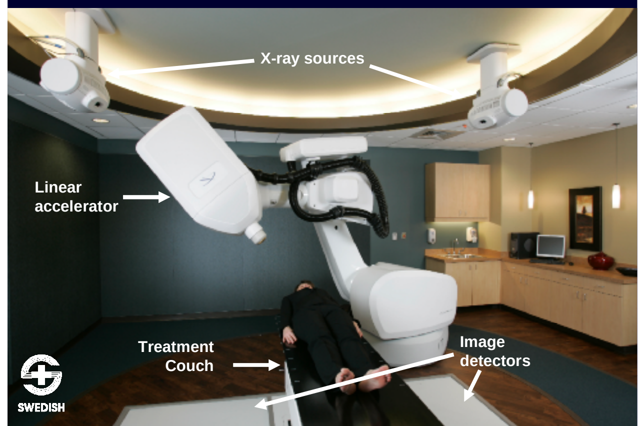


Image Guidance

- The CyberKnife delivers frameless radiosurgery.
- During delivery, the patient position is monitored and the delivery is modified to correct for patient movement.
- Orthogonal kilvoltage (kV) x-ray sources are mounted to the ceiling and directed at amorphous silicon detectors on either side of the table.
- kV images are obtained before and during the treatment to monitor the alignment of the patient.

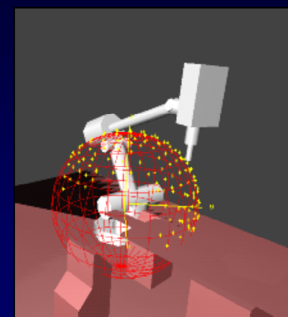
CyberKnife – Treatment Delivery

CyberKnife – Beam Characteristics

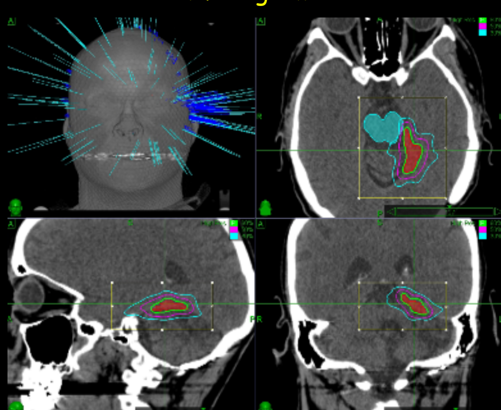
- 6 MV accelerator
- 12 interchangeable circular collimators
- At an SSD of 80cm, collimators provide a beam diameter from 5 to 60 mm
- SSD can be varied from 65 to 100 cm

CyberKnife – Delivery

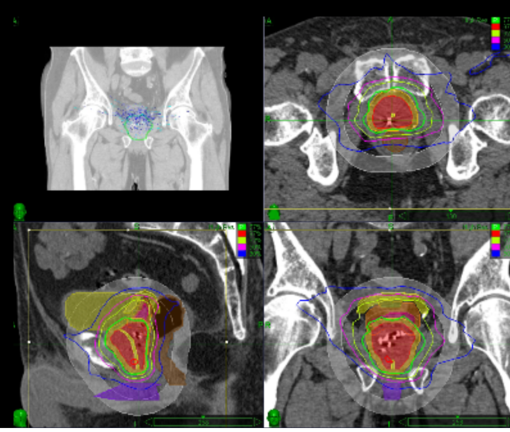
- Radiation is delivered at a discrete set of linac positions (called nodes).
- A typical treatment plan will use 110 nodes distributed approximately uniformly over about one half of a sphere centered on the treatment site.



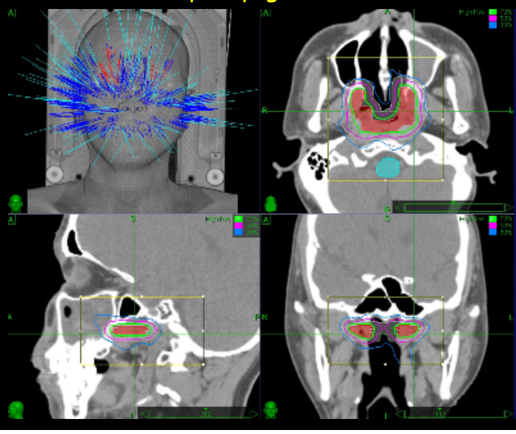
Meningioma



Prostate



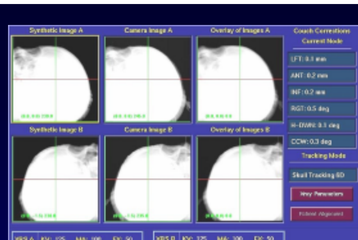
Nasopharyngeal Tumor



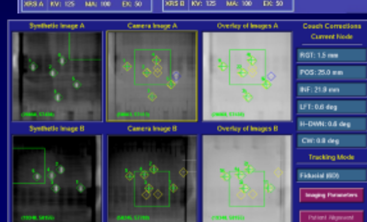
Frameless Radiosurgery

- Intracranial lesions:
  - Immobilization with aquaplast mask
  - Patient positioning is monitored using bony landmarks
- Extracranial lesions:
  - Immobilization with vacuum bag
  - Patient positioning is monitored using either:
    1) implanted fiducial markers
    2) spine tracking (Xsight spine)
    3) synchrony lung tracking
    4) soft tissue lung tracking (Xsight lung)

Skull tracking window:



Fiducial tracking window:



Synchrony™ Respiratory Tracking System

- Patient wears a vest with optical markers that serve as a surrogate for tumor position.
- Camera system monitors position of markers.

Synchrony™ Respiratory Tracking System

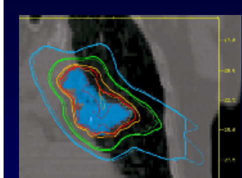
- Before the treatment, a correspondence model between the markers and the tumor position is constructed using the camera and multiple orthogonal x-rays.
- Model is updated continuously during treatment by further x-ray imaging.
- During delivery, the tumor position is tracked using the live camera signal and the correspondence model.
- The robot is moved in real-time to maintain alignment with the tumor.

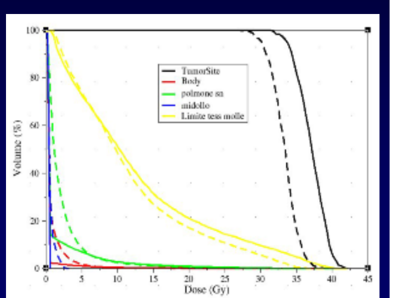
New CyberKnife Features

- Sequential Optimization
- 800 MU/min accelerator
- RoboCouch
- Monte Carlo Dose Calculation
- Iris Variable Aperture Collimator

Monte Carlo Dose Calculation

Comparison with Ray Tracing

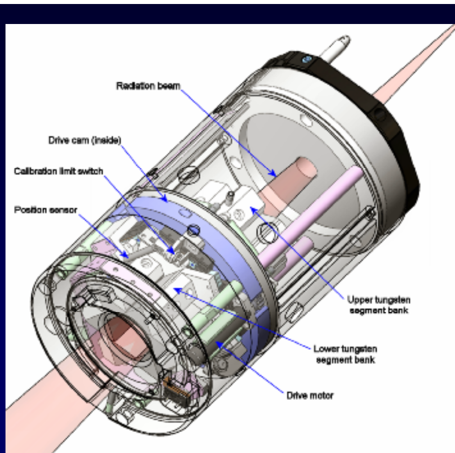




Courtesy of Charlie Ma

Iris™ Variable Aperture Collimator

- Description
  - 2 stacked banks of 6 tungsten segments creates a 12-sided variable aperture
  - Variable aperture automatically replicates sizes of the existing 12 fixed collimators (5 to 60 mm)
  - All segment are driven by a single motor



Iris™ Variable Aperture Collimator

- Benefits
  - Reduces treatment time by consolidating multiple-path sets and multiple-collimators into a single path set
  - Improved plan quality
  - Automatically changes the size of the variable aperture without having to re-enter the treatment suite

CK - G4 with 8.0 Delivery Software

- Hillcrest Medical Center (Tulsa, OK) became 1st center to treat with Iris Collimator on 7/10/2008.

CyberKnife Routine QA Procedures

Daily QA

- Linac Output
- Various voltages and currents
- Robot perch position
- Safety interlocks
- Test coincidence of treatment beam with imaging center (AQA)

Quarterly QA

- Laser/radiation coincidence
- Imaging system alignment

Monthly QA

- Beam Energy
- Flatness/symmetry/penumbra
- Robot pointing
- End-to-end test

Annual QA

- Spot check beam data
- Treatment planning system beam data and calculation checks.

Daily QA – Linac Output Constancy

- In air measurement using "birdcage" phantom.
- CyberKnife's ion chambers are vented to the atmosphere.

Monthly QA - End-to-end Test

- QA test designed to measure total accuracy of the system including localization, mechanical targeting, and planning errors.
- Measurements are performed using an anthropomorphic head phantom loaded with a target ball and orthogonal pieces of gafchromic film.

Anthropomorphic Head/Neck phantom

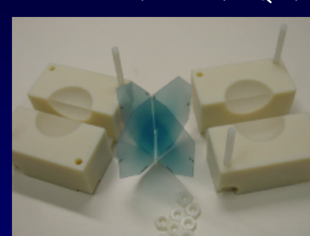
2.5" Ball Cube in cranium for fiducial and skull tracking QA

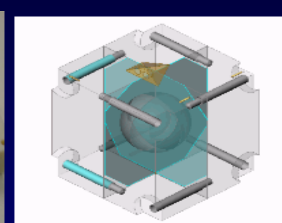
1.25" Ball Cube in neck for Xsight Spine QA

Courtesy of Accuray Inc.

Ball-Cube Film Cassette

- Allows accuracy measurements using only two films
- Contains fiducials for QA for extracranial treatments.



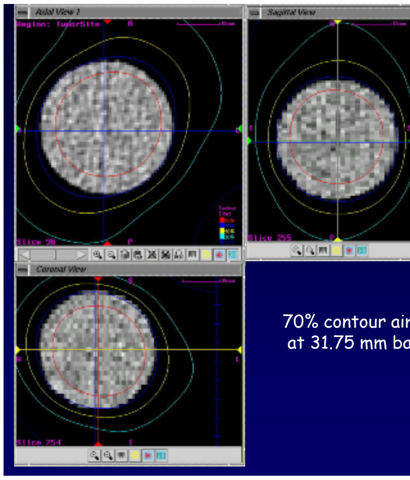


Courtesy of Accuray Inc.

End-to-end Test

- The head phantom is imaged using CT.
- A treatment plan is developed with the goal of conforming the 70% isodose line to the target ball.
- After the delivery, the orthogonal films are scanned and analyzed using software from Accuray that determines the shift between the centroid of the 70% isodose curve and the center of the film.
- Test is repeated for each tracking technique: skull tracking, fiducial tracking, spine tracking, and synchrony based tracking.

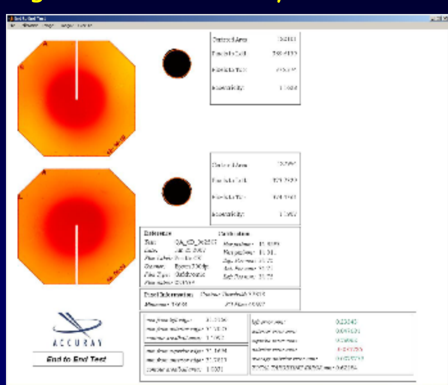
TPS Images



70% contour aiming at 31.75 mm ball target.

Courtesy of Accuray Inc.

Digital Centroid Analysis Software



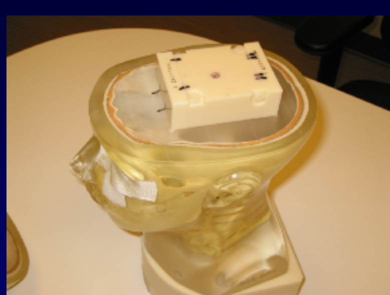
left error mm:	0.23343
anterior error mm:	0.047681
superior error mm:	0.58062
anterior error mm:	-0.031725
average anterior error mm:	0.0079779
TOTAL TARGETING ERROR mm:	0.62584

- The total error should be below 0.9mm for skull tracking, fiducial tracking, and X-sight spine tracking.
- The total error should be less than 1.5mm for tracking using Synchrony.

CyberKnife - Summary

- Radiosurgery delivered using an x-band linear accelerator mounted on a robotic arm.
- Uses a frameless approach and is capable of intracranial and extracranial radiosurgery.
- Real time image-guidance is accomplished using 2 kilovoltage imagers.

Anthropomorphic Head Phantom



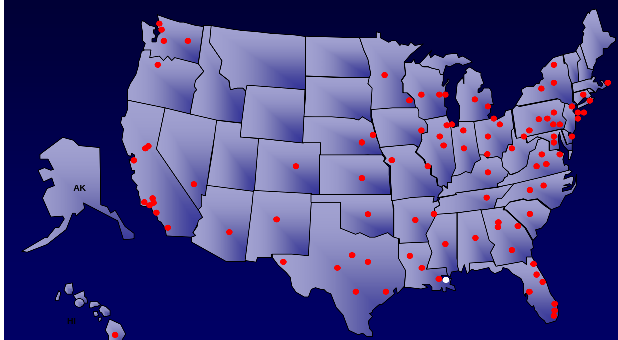
QA Reports and Recommendations

1. ASTRO/AANS Consensus Statement on stereotactic radiosurgery quality improvement, 1993
2. RTOG Radiosurgery QA Guidelines, 1993
3. AAPM Task Group Report 54, 1995
4. European Quality Assurance Program on Stereotactic Radiosurgery, 1995
5. DIN 6875-1 (Germany) Quality Assurance in Stereotactic Radiosurgery/Radiotherapy
6. AAPM Task Group 68 on Intracranial stereotactic positioning systems, 2005

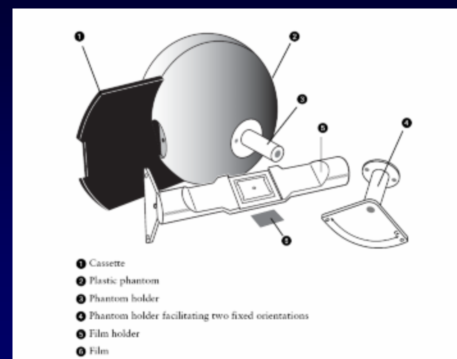
Courtesy of Steven Goetsch

111 Leksell Gamma Knife® units installed U.S.

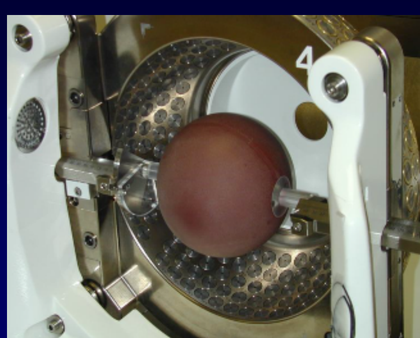
November 2006

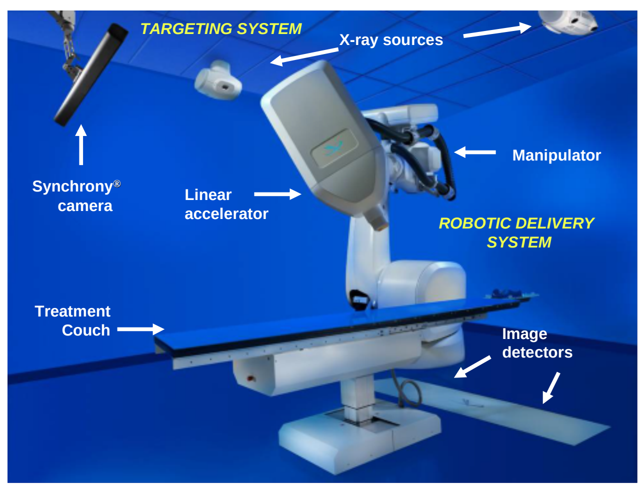


Gamma Knife – Spherical Phantom



Gamma Knife – Spherical Phantom





800 MU/min. LINAC

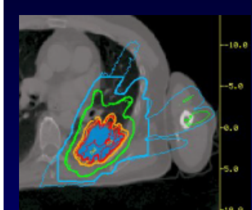
- Provides reduced treatment times relative to existing 600 MU/min design.
- More compact

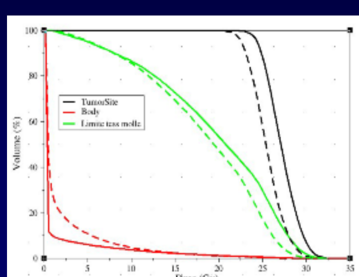
Monte Carlo Dose Calculation

- Accuray is now offering a Monte Carlo dose engine.
- This provides a significant improvement in dose accuracy relative to their current ray-tracing algorithm.

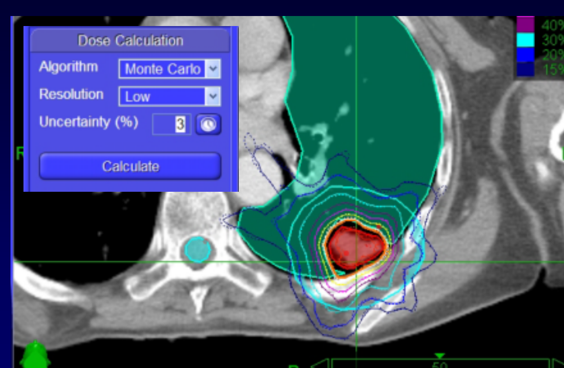
Monte Carlo Dose Calculation

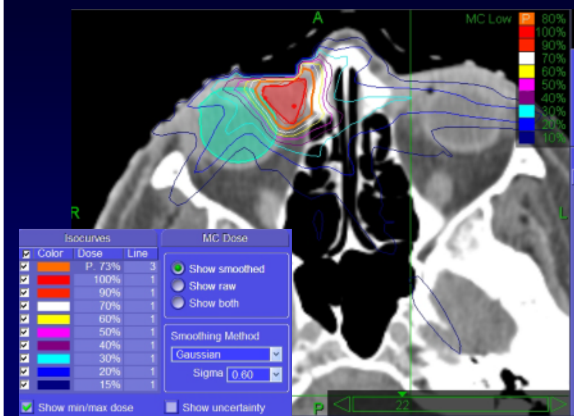
Comparison with Ray Tracing





Courtesy of Charlie Ma





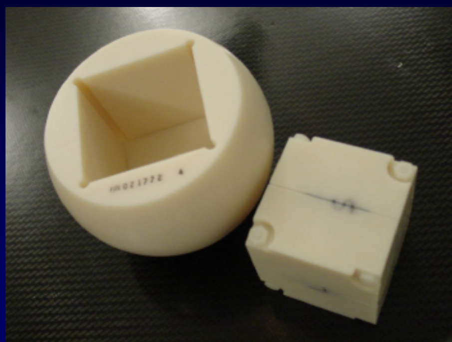
RoboCouch®

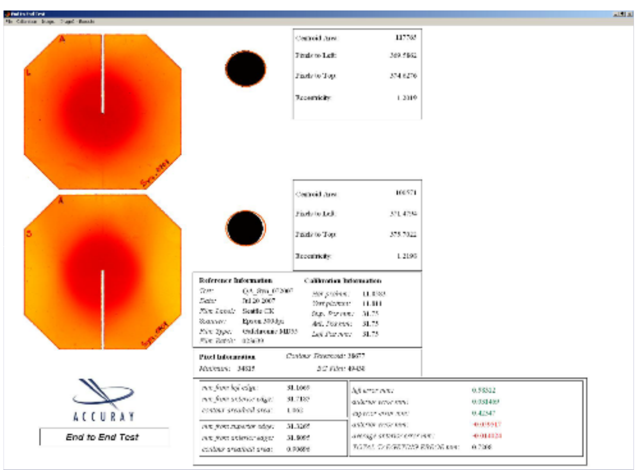
RoboCouch®

- 6D robotic couch
- Converts between seated and flat positions
- 500lb weight capacity

Synchrony End-to-end Test

Ball Phantom and Ball Cube





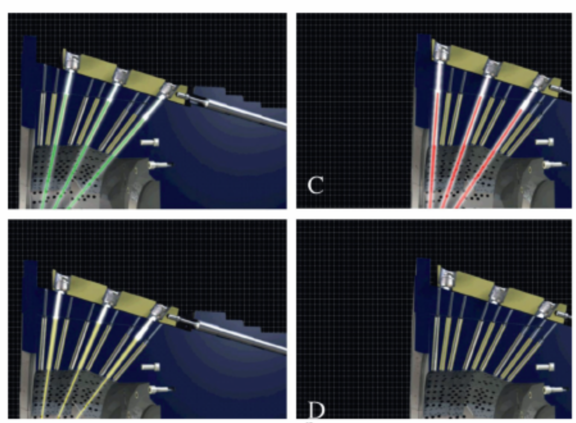
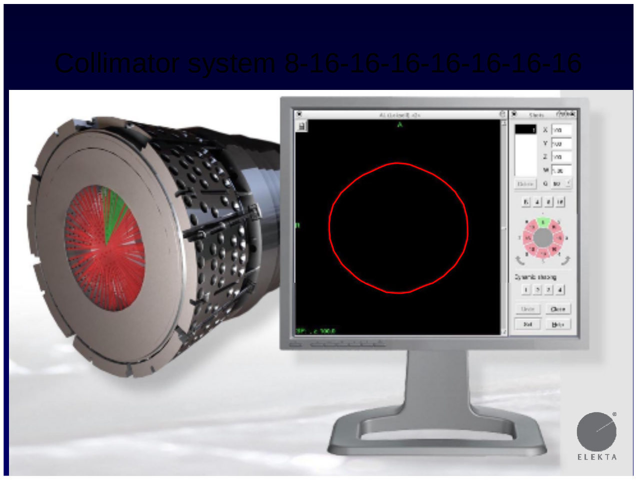
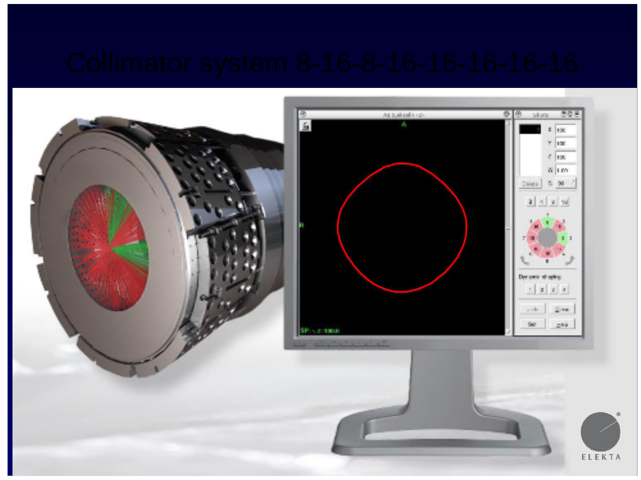


FIG 4: The original design of the Perfexion. Eight sectors, containing 24 Co^{60} sources each, are moved by 8 servo drives (see Fig. 6). Depending on the sector position the collimator size can be 4 (A), 8 (B) and 16 mm (C) or Blocked/off (D).


Collimator system 8-16-16-16-16-16-16-16
ELEKTA


Collimator system 8-16-8-16-16-16-16-16
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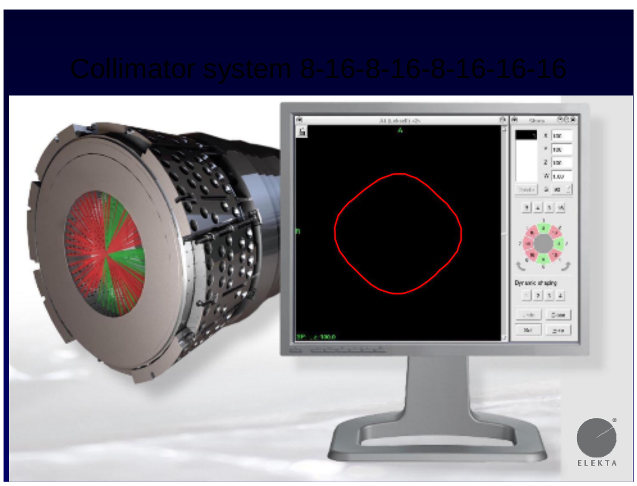
Collimator system 8-16-8-16-8-16-16-16
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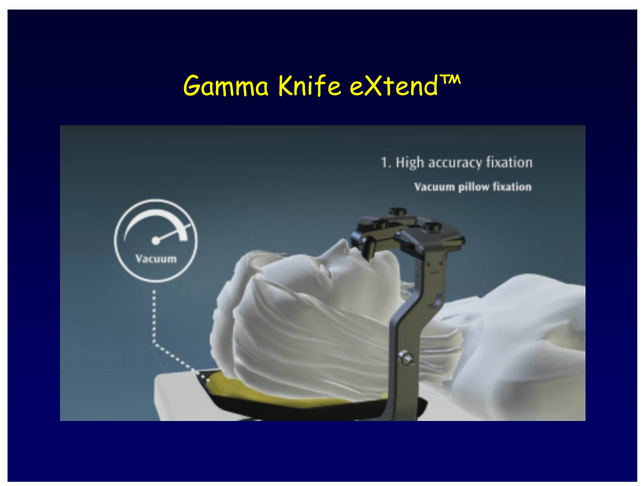
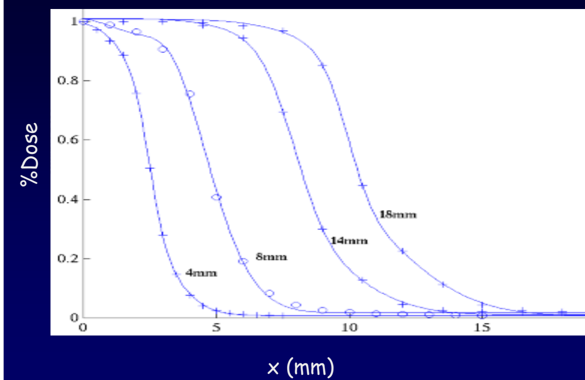
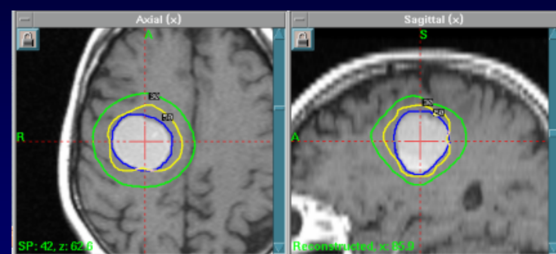

Gamma Knife eXtend™
1. High accuracy fixation
Vacuum pillow fixation
Vacuum

Collimator Dose Profiles



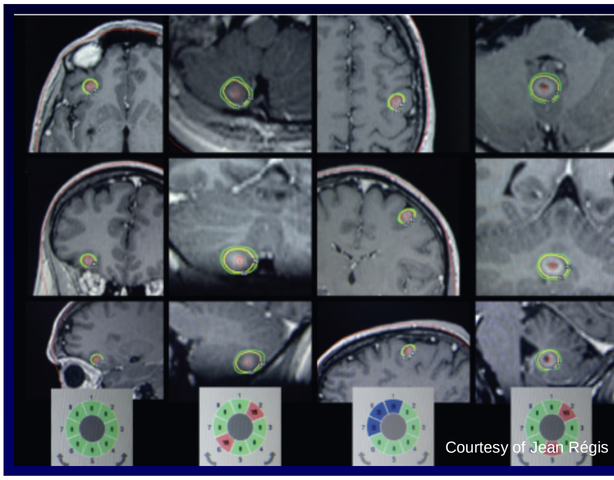
Met – 11 shots (18mm)

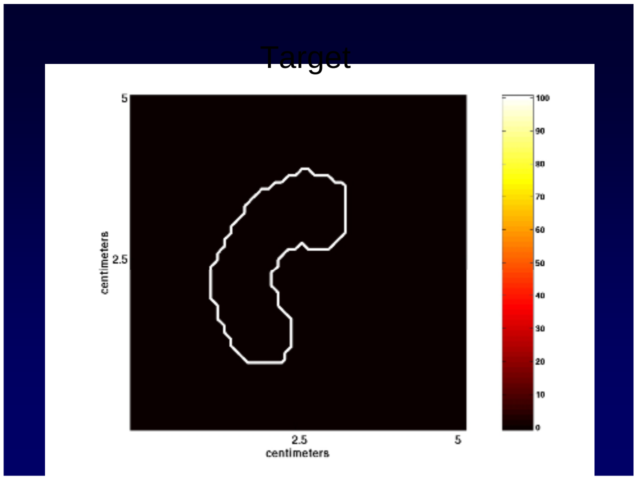


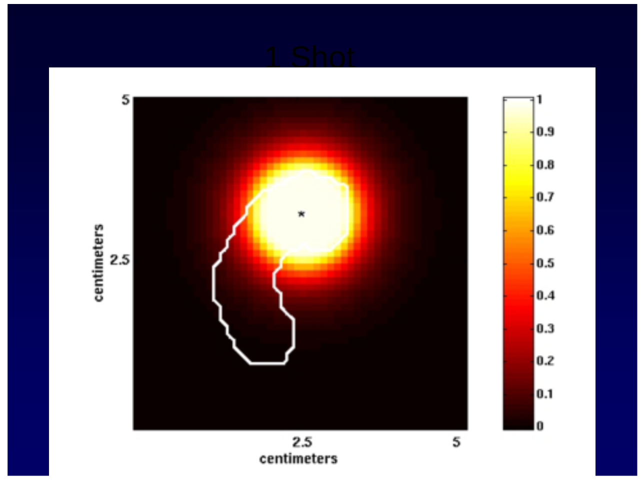
Perfexion vs. 4C – Prospective Study

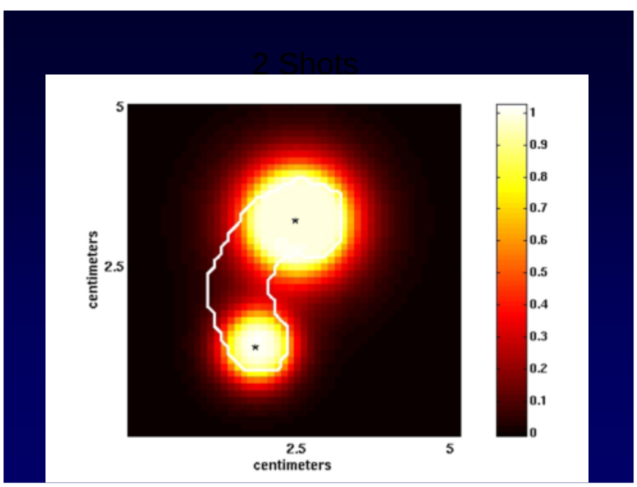
- At Timone University Hospital 59 patients were enrolled in a prospective study comparing the Perfexion and the Gamma Knife 4C.
- With Perfexion the median total treatment time was reduced from 65 minutes to 44.5 minutes.
- With Perfexion there were no collision issues while with the 4C 20.7% patients treated in trunion mode.
- The Perfexion unit on average reduced dose to the gonads by a factor of 15.

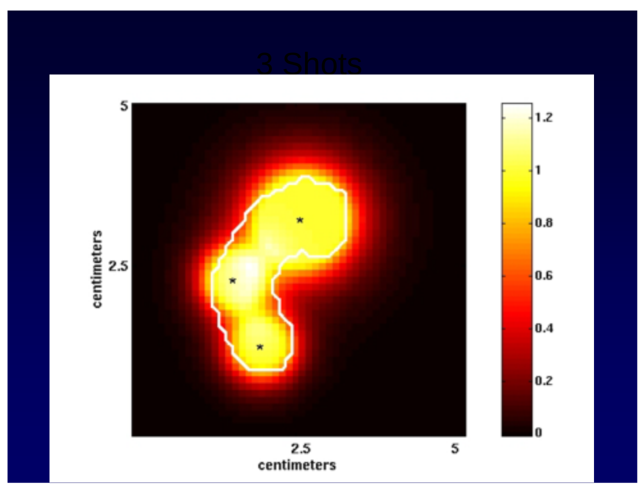
Courtesy of Jean Régis



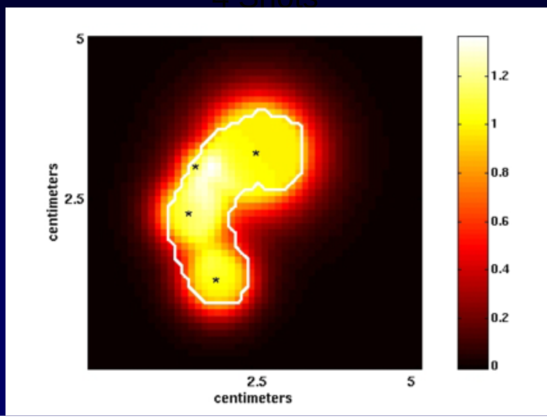

Target
centimeters
2.5
5
centimeters


1 Shot
centimeters
2.5
5
centimeters

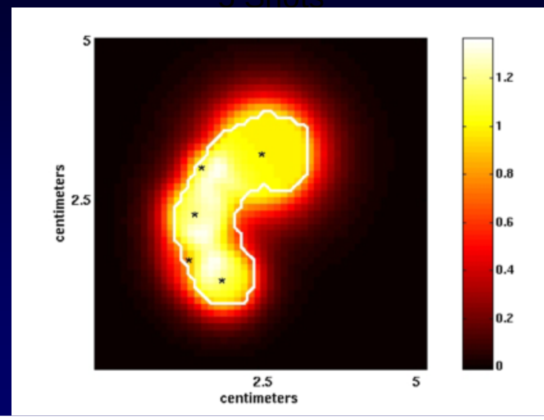

2 Shots
centimeters
2.5
5
centimeters


3 Shots
centimeters
2.5
5
centimeters

4 Shots



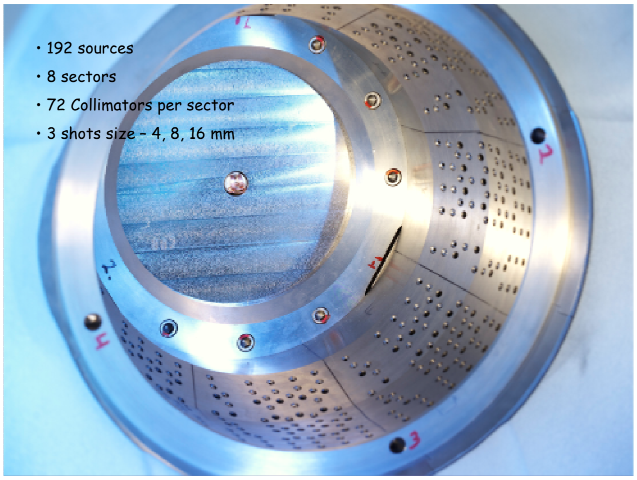
5 Shots

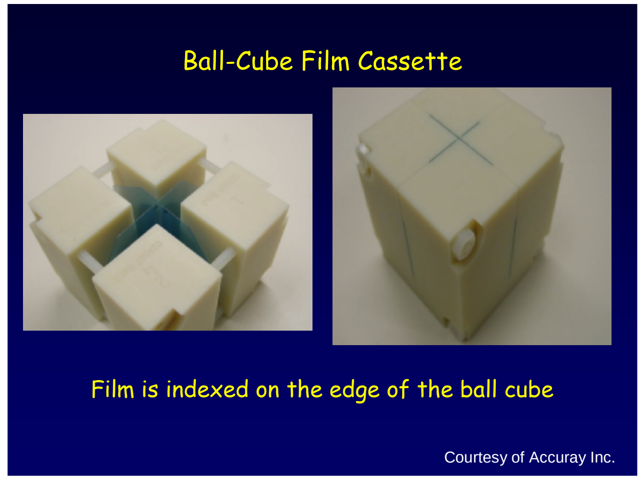


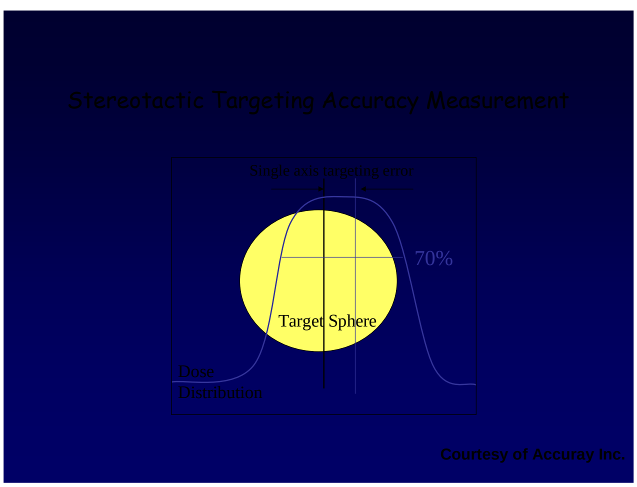
Defining the Prescription

- When multiple shots of radiation are used, the target dose will be highly non-uniform due to the overlap between the spherical dose distributions.
- Target is covered by typically 50% of the maximum dose.

- Advantages of the CyberKnife
  - Frameless
    - Fractionated delivery
  - Can be used for both intracranial and extracranial stereotactic delivery.
- Disadvantages of the CyberKnife
  - The use of a pencil beam based delivery is inefficient and can lead to treatment times that can be up to several hours.


• 192 sources
• 8 sectors
• 72 Collimators per sector
• 3 shots size – 4, 8, 16 mm


Ball-Cube Film Cassette
Film is indexed on the edge of the ball cube
Courtesy of Accuray Inc.


Stereotactic Targeting Accuracy Measurement
Single axis targeting error
70%
Target Sphere
Dose
Distribution
Courtesy of Accuray Inc.


U.S. CyberKnife® Customers: 2007
Installed Units
2 Installed Units