Optimization of Gamma Knife Radiosurgery

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Supported by Microsoft, NSF and AFOSR

Overview

- Details of machine and problem
- Formulation
  - modeling dose
  - shot/target optimization
- Results
  - Two-dimensional data
  - Real patient (three-dimensional) data

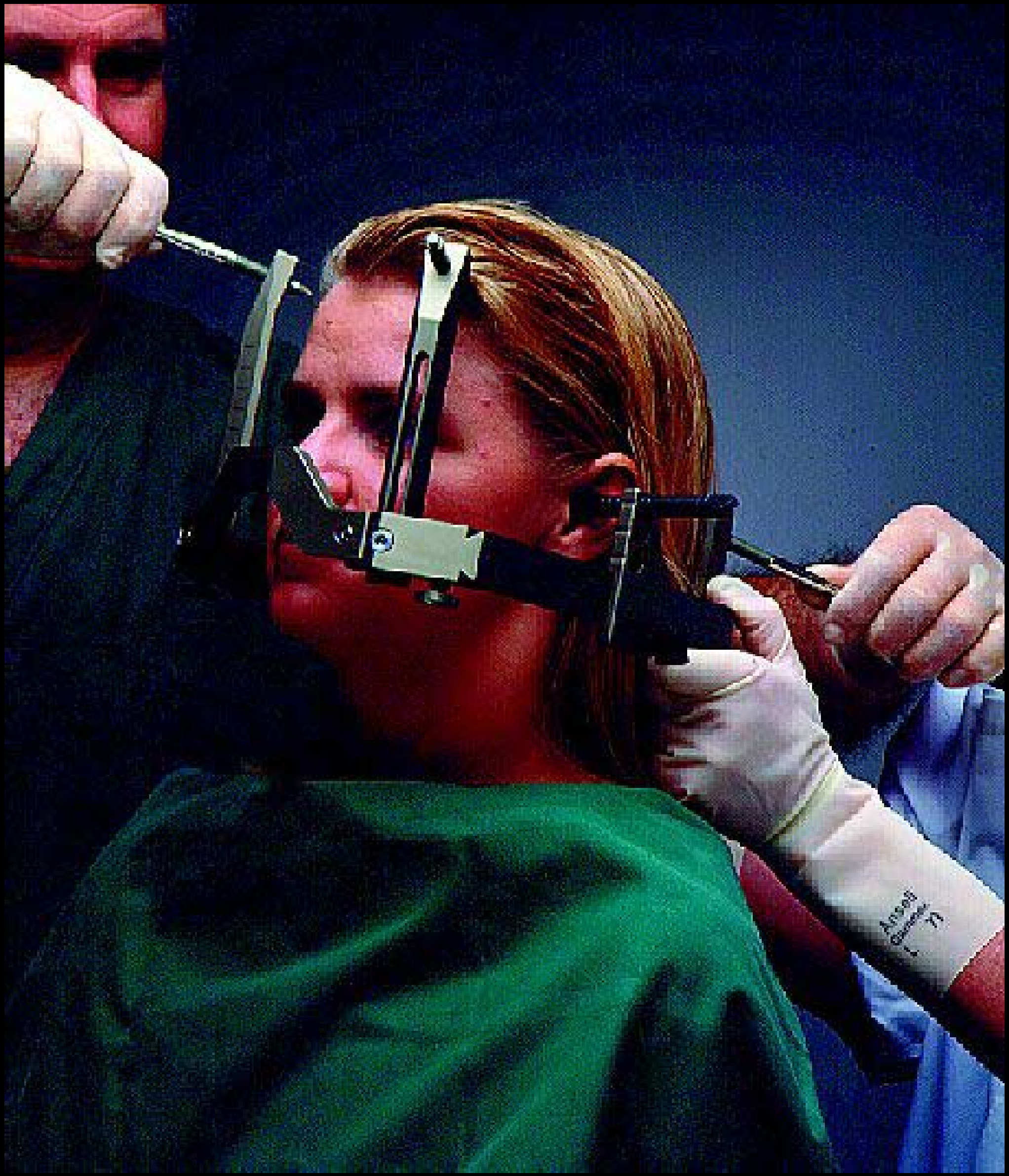
The Gamma Knife

What disorders can the Gamma Knife treat?

- Malignant tumors from elsewhere in the body
- Malignant brain tumors
- Benign tumors within the head
- Vascular malformations
- Functional disorders of the brain
  - Parkinson's disease

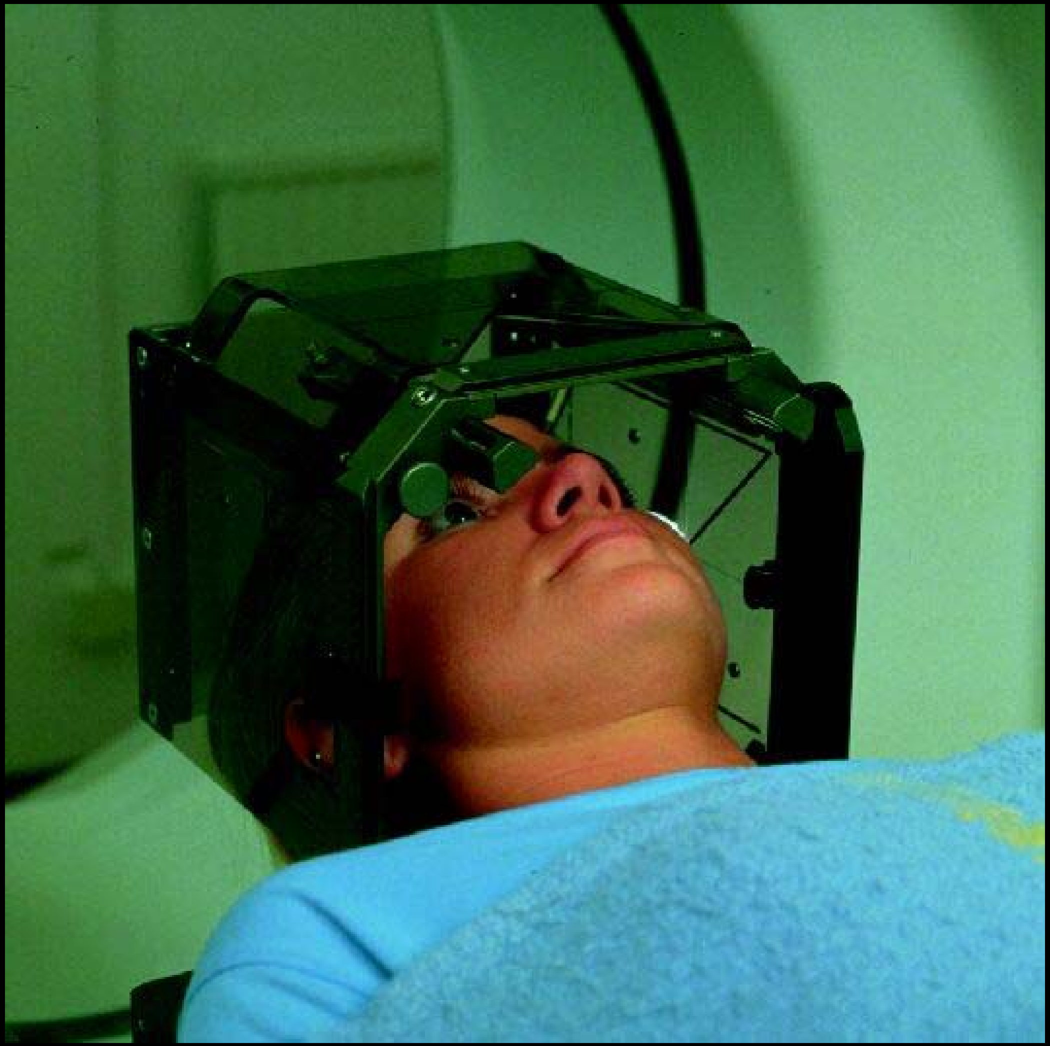
201 cobalt gamma ray beam sources are arrayed in a hemisphere and aimed through a collimator to a common focal point.

The patient's head is positioned within the Gamma Knife so that the tumor is in the focal point of the gamma rays.

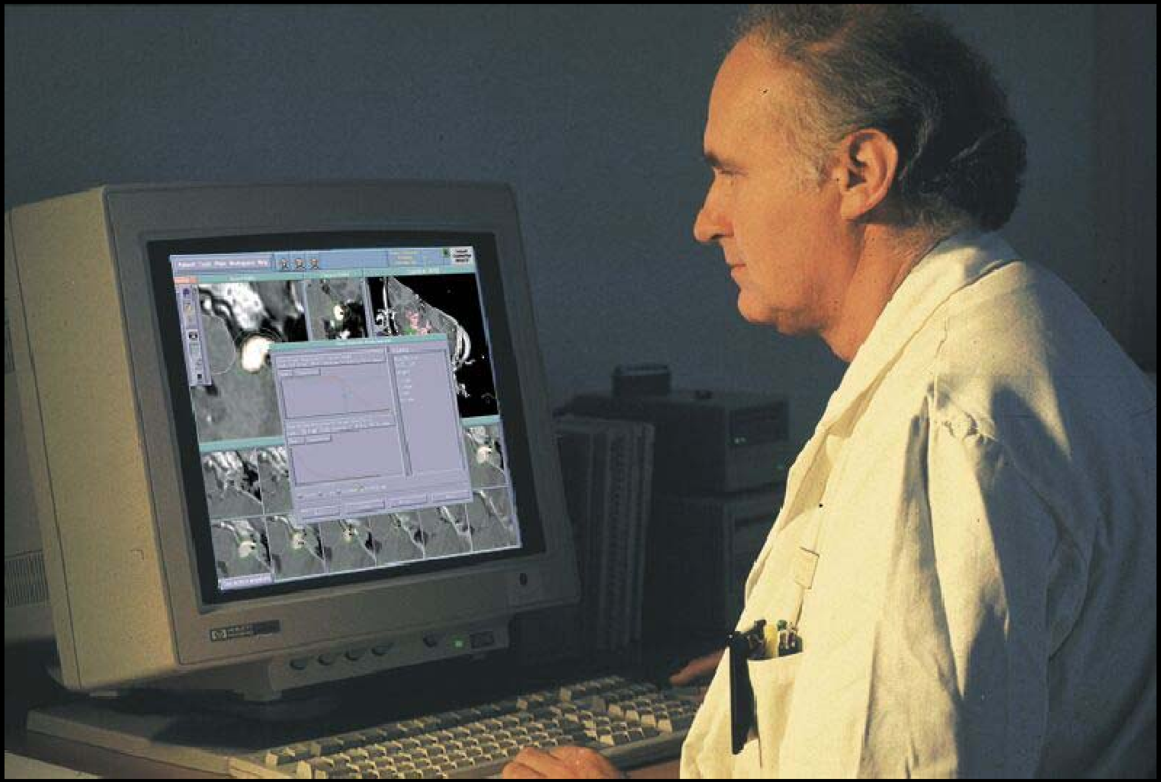


How is Gamma Knife Surgery performed?

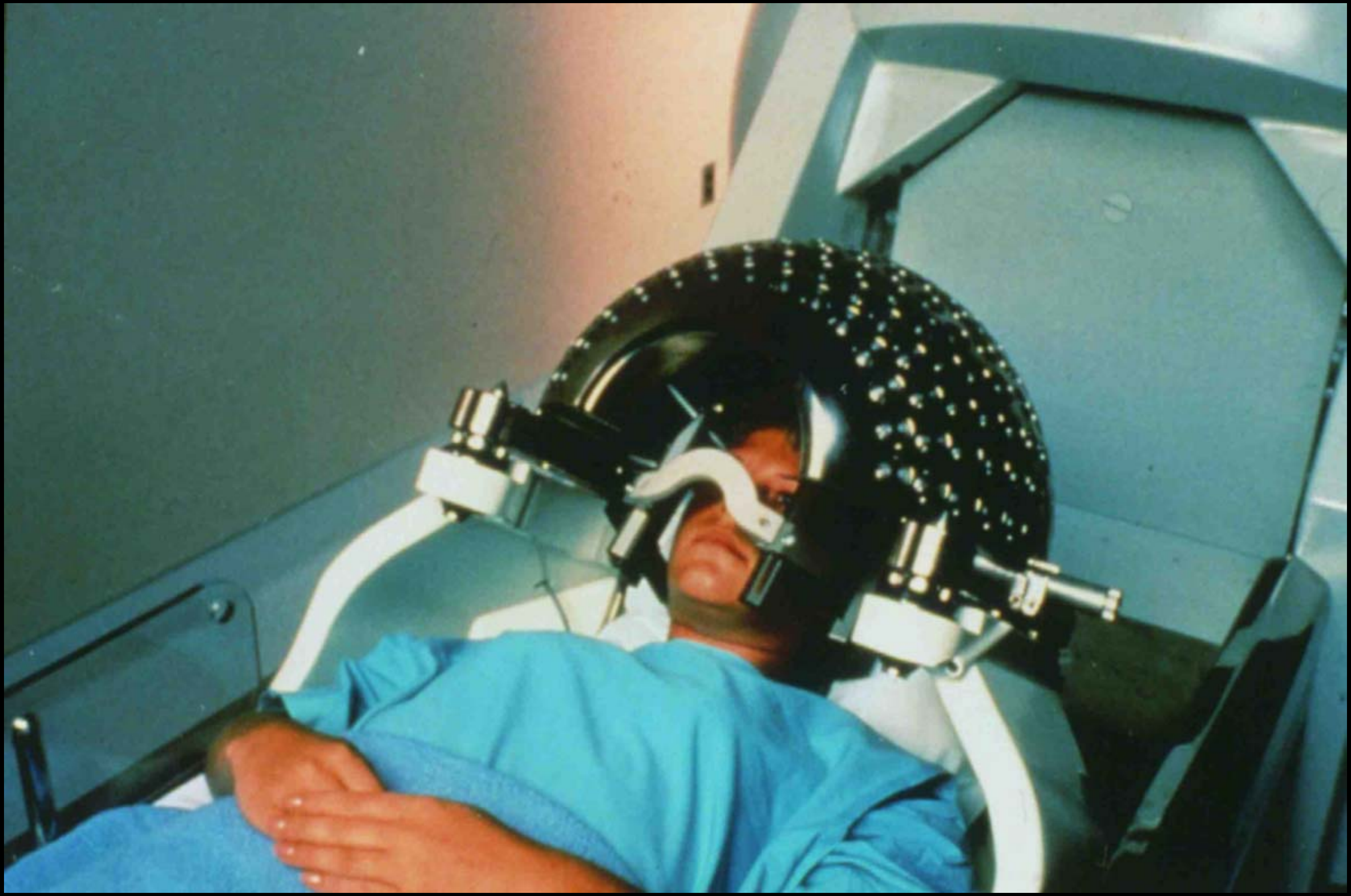
Step 1: A stereotactic head frame is attached to the head with local anesthesia.



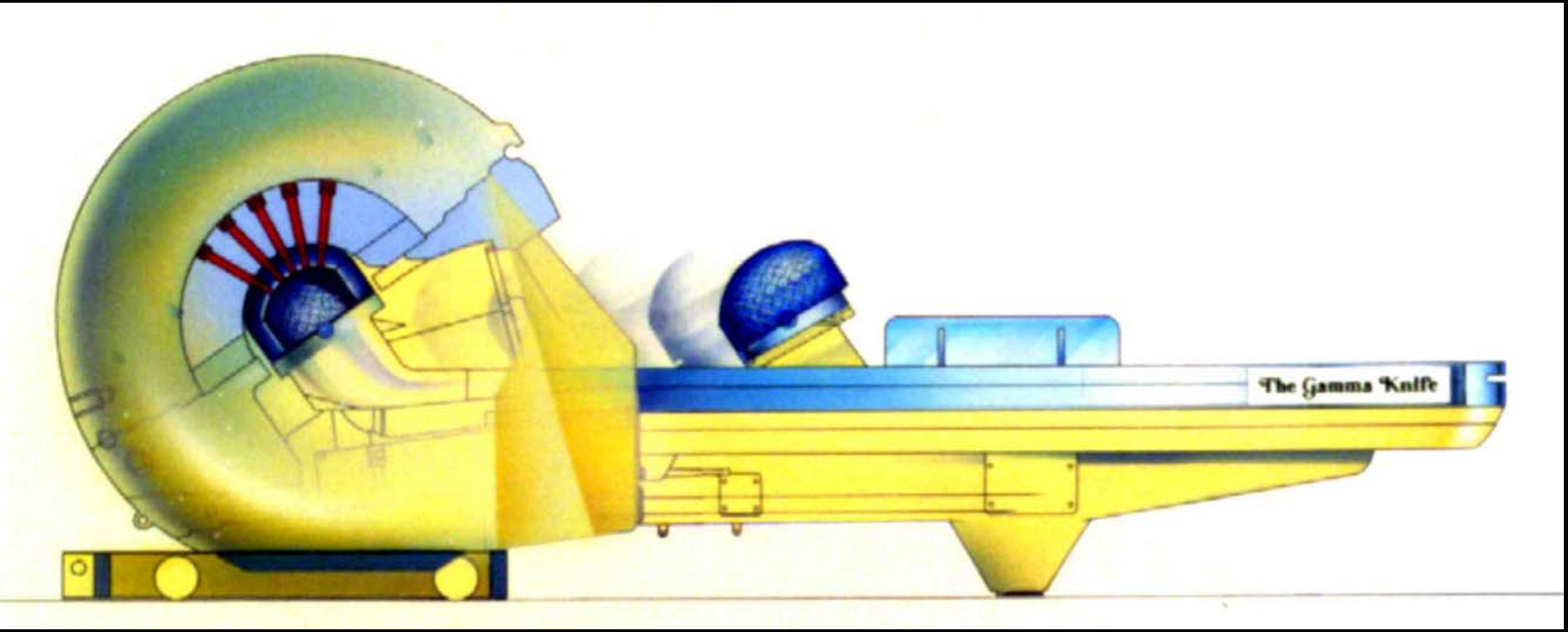
Step 2: The head is imaged using a MRI or CT scanner while the patient wears the stereotactic frame.



Step 3: A treatment plan is developed using the images. Key point: very accurate delivery possible.



Step 4: The patient lies on the treatment table of the Gamma Knife while the frame is affixed to the appropriate collimator.



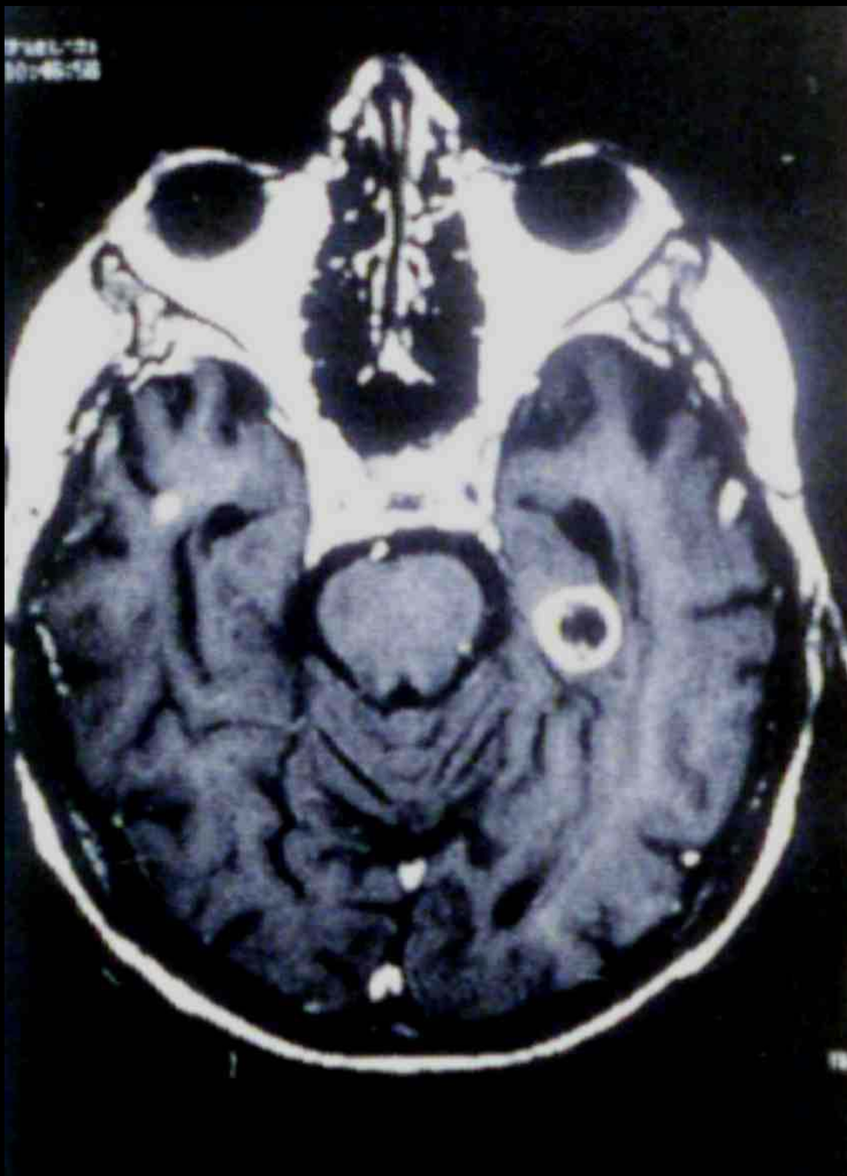
Step 5: The door to the treatment unit opens. The patient is advanced into the shielded treatment vault. The area where all of the beams intersect is treated with a high dose of radiation.

Gamma Knife Statistics

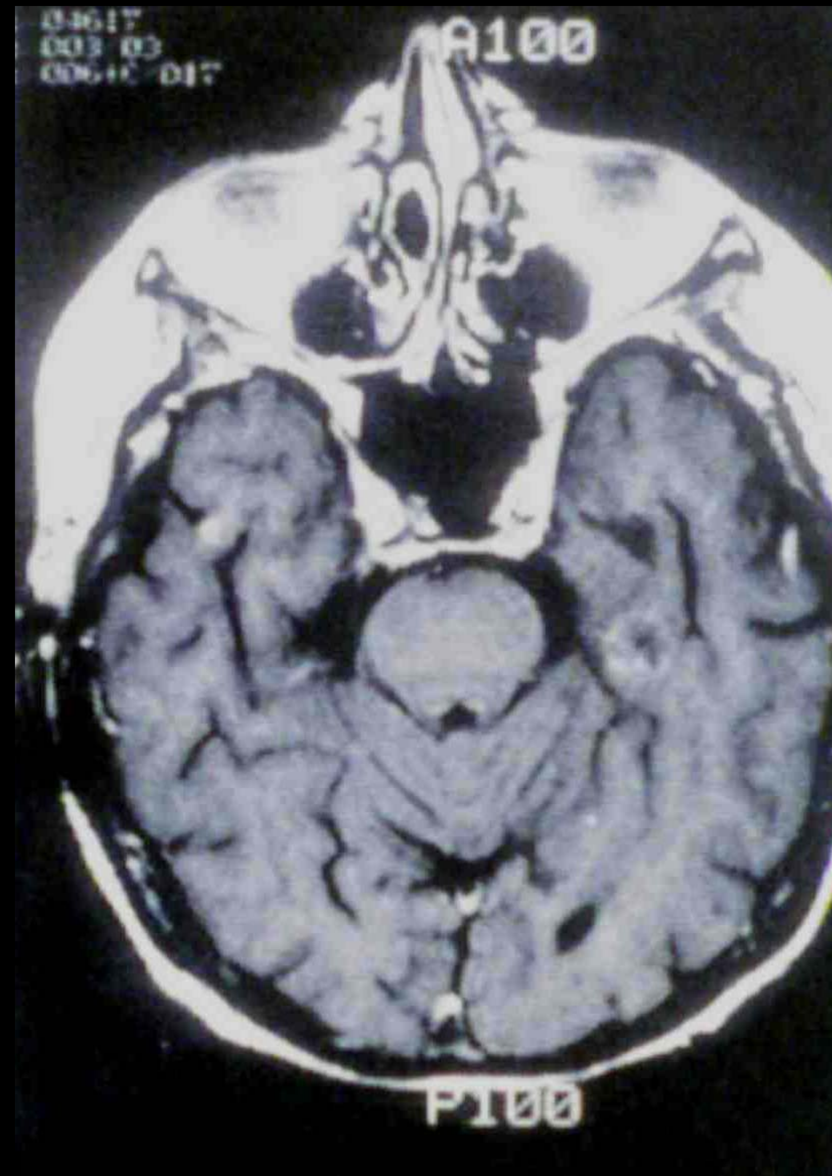
- 120 Gamma Knife units worldwide
- Over 20,000 patients treated annually
- Accuracy of surgery without the cuts
- Same-day treatment

- Expensive instrument

Before

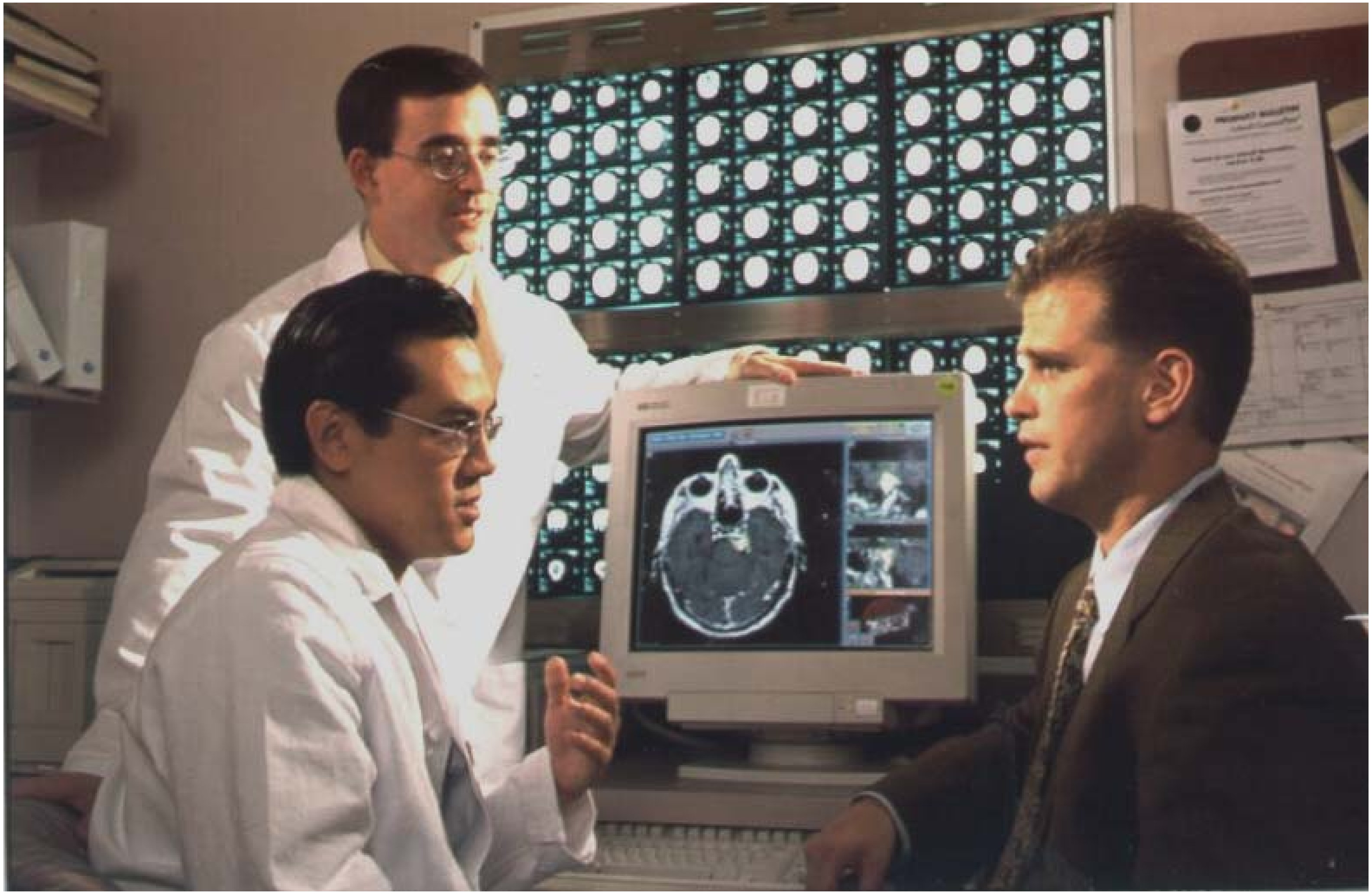


After




4
4
8
8
14

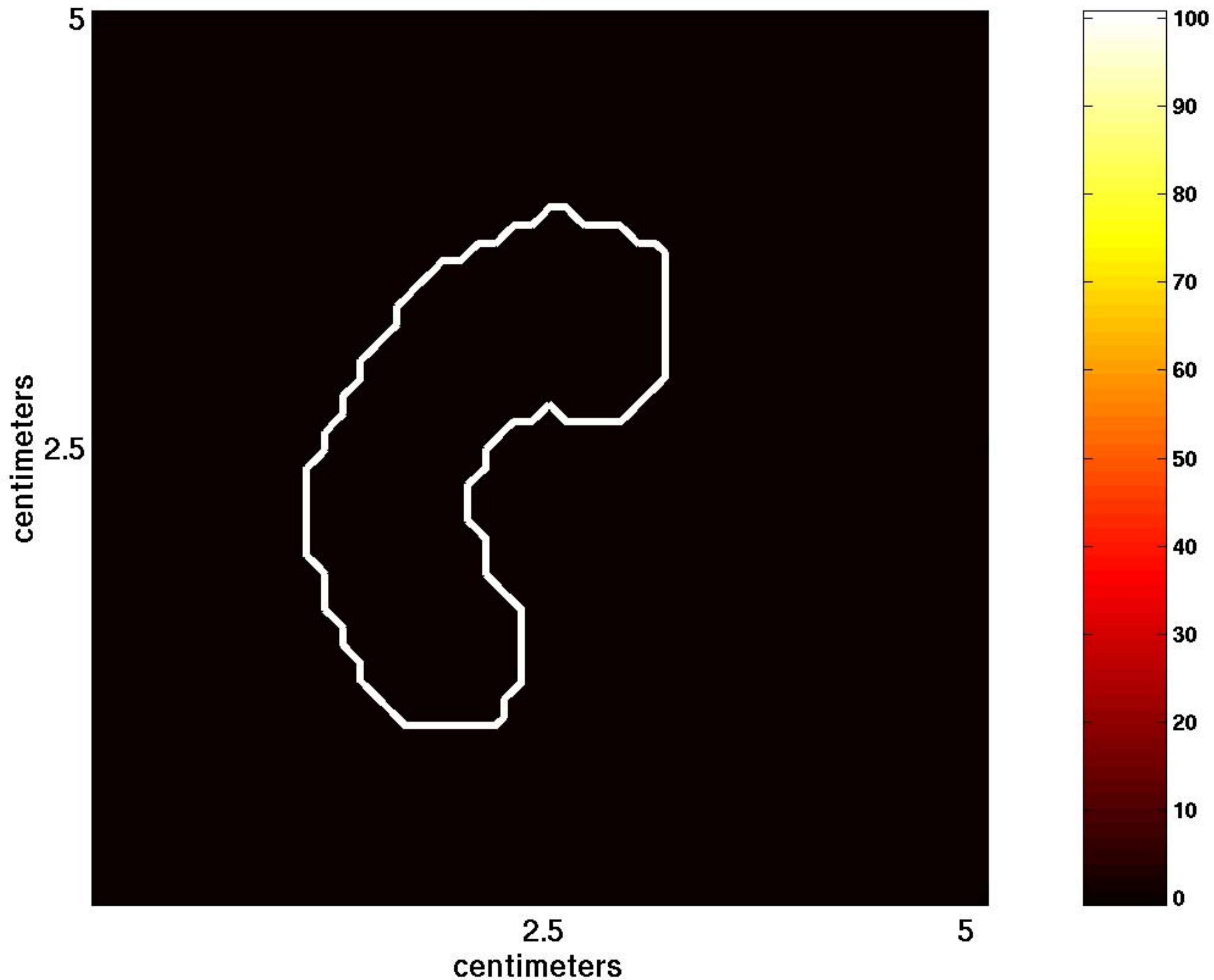
Treatment Planning



Treatment Planning

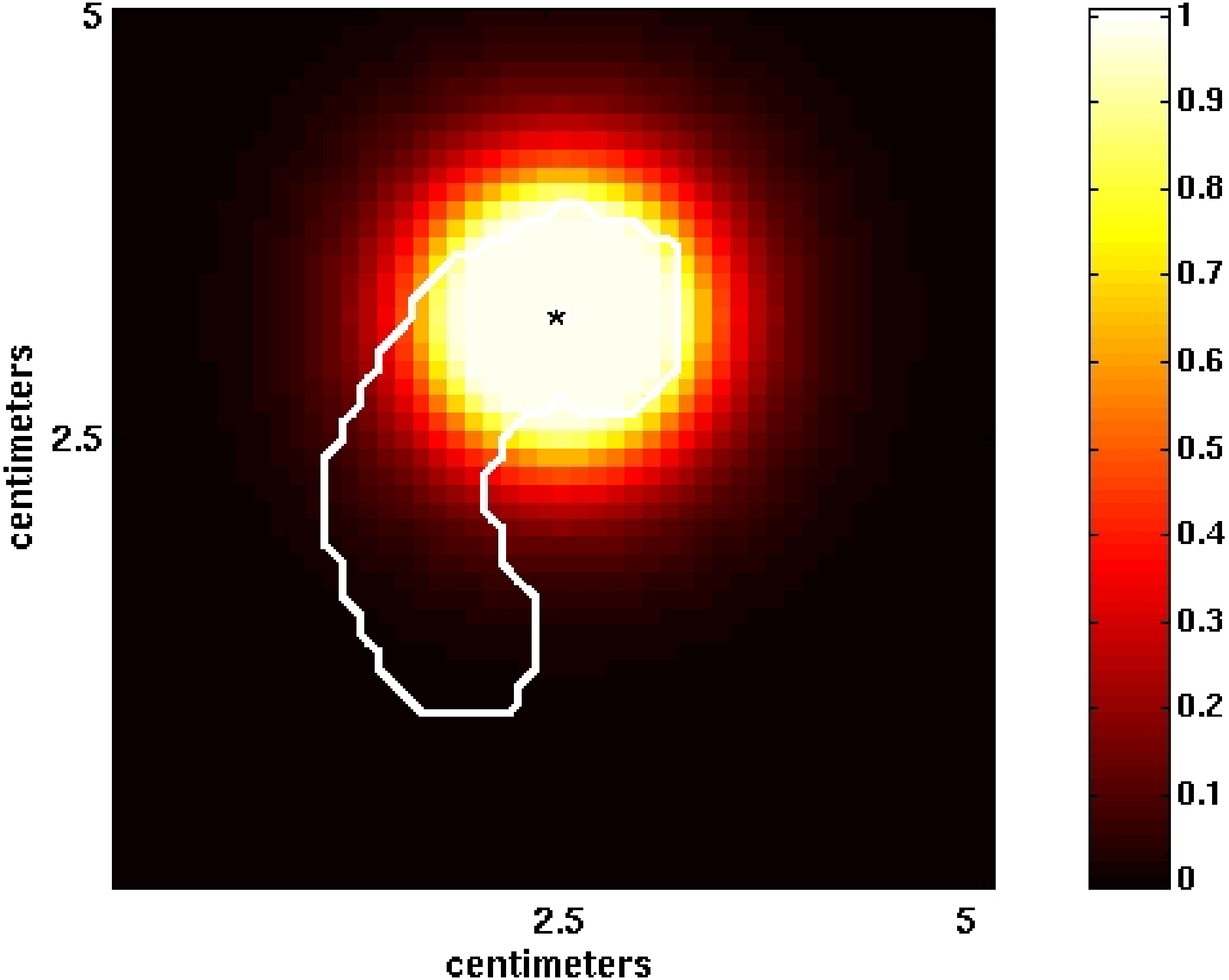
- Through an iterative approach we determine:
  - the number of shots
  - the shot sizes
  - the shot locations
  - the shot weights
- The quality of the plan is dependent upon the patience and experience of the user

Target

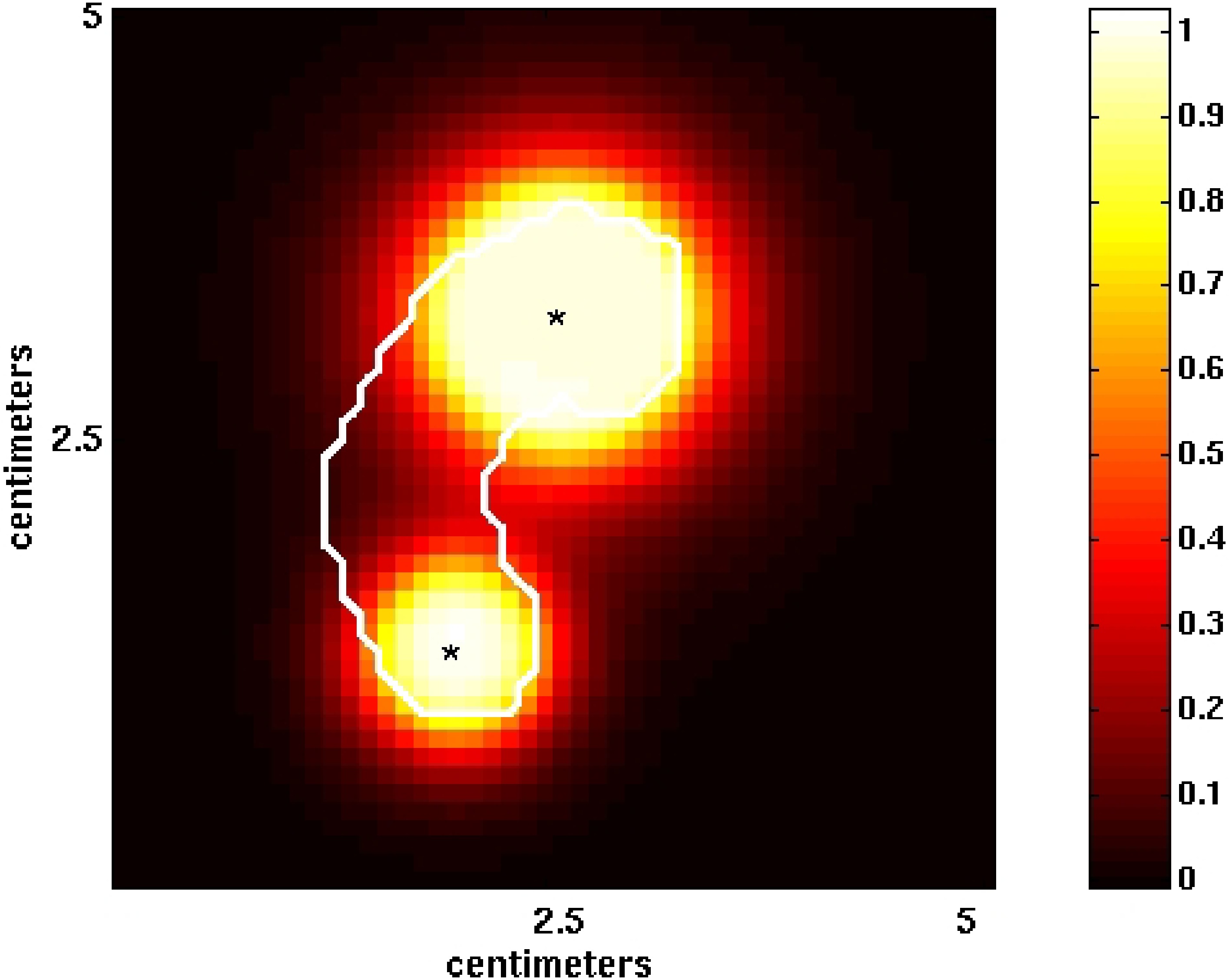


5
2.5
centimeters
2.5
5
centimeters
100
90
80
70
60
50
40
30
20
10
0

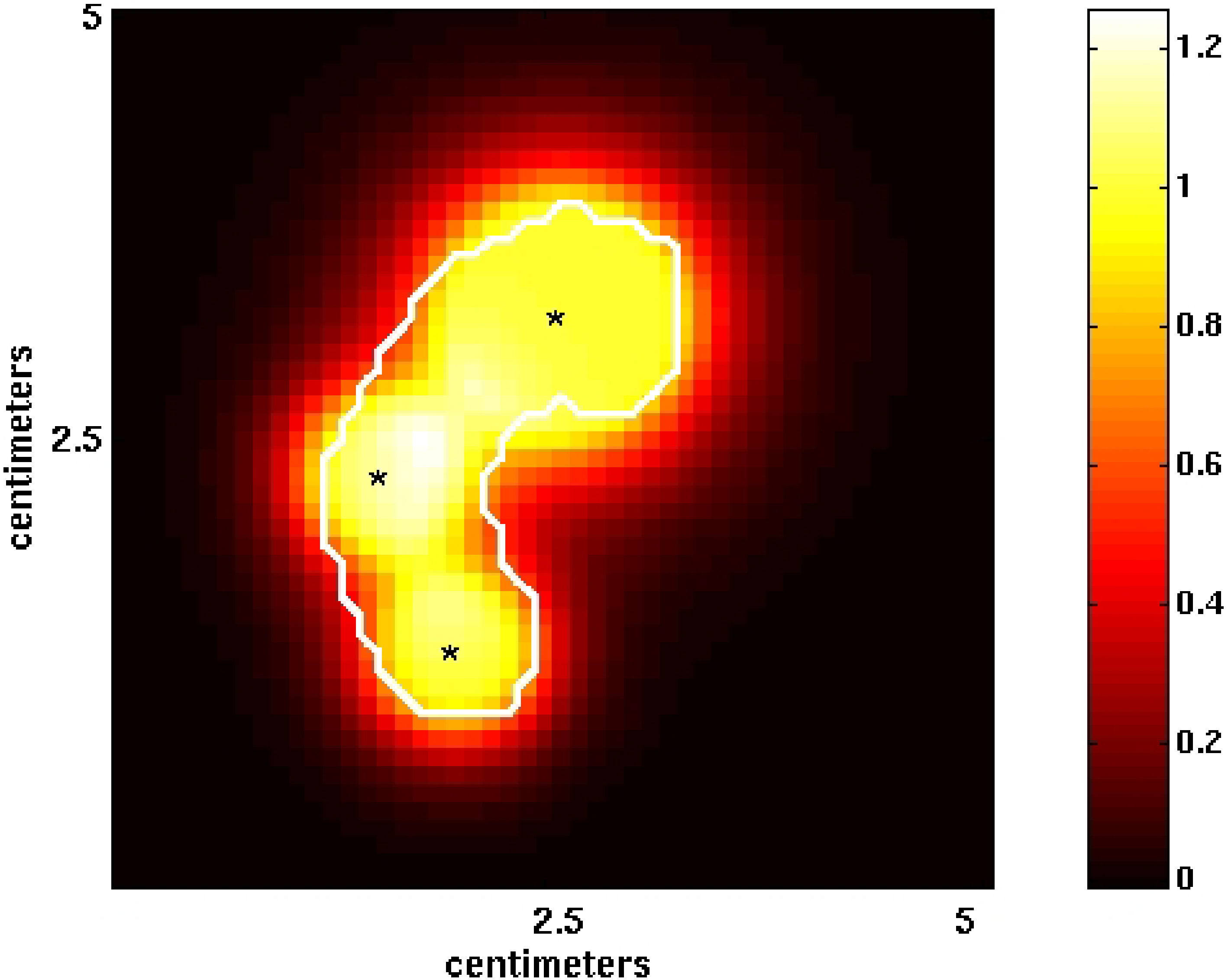
1 Shot



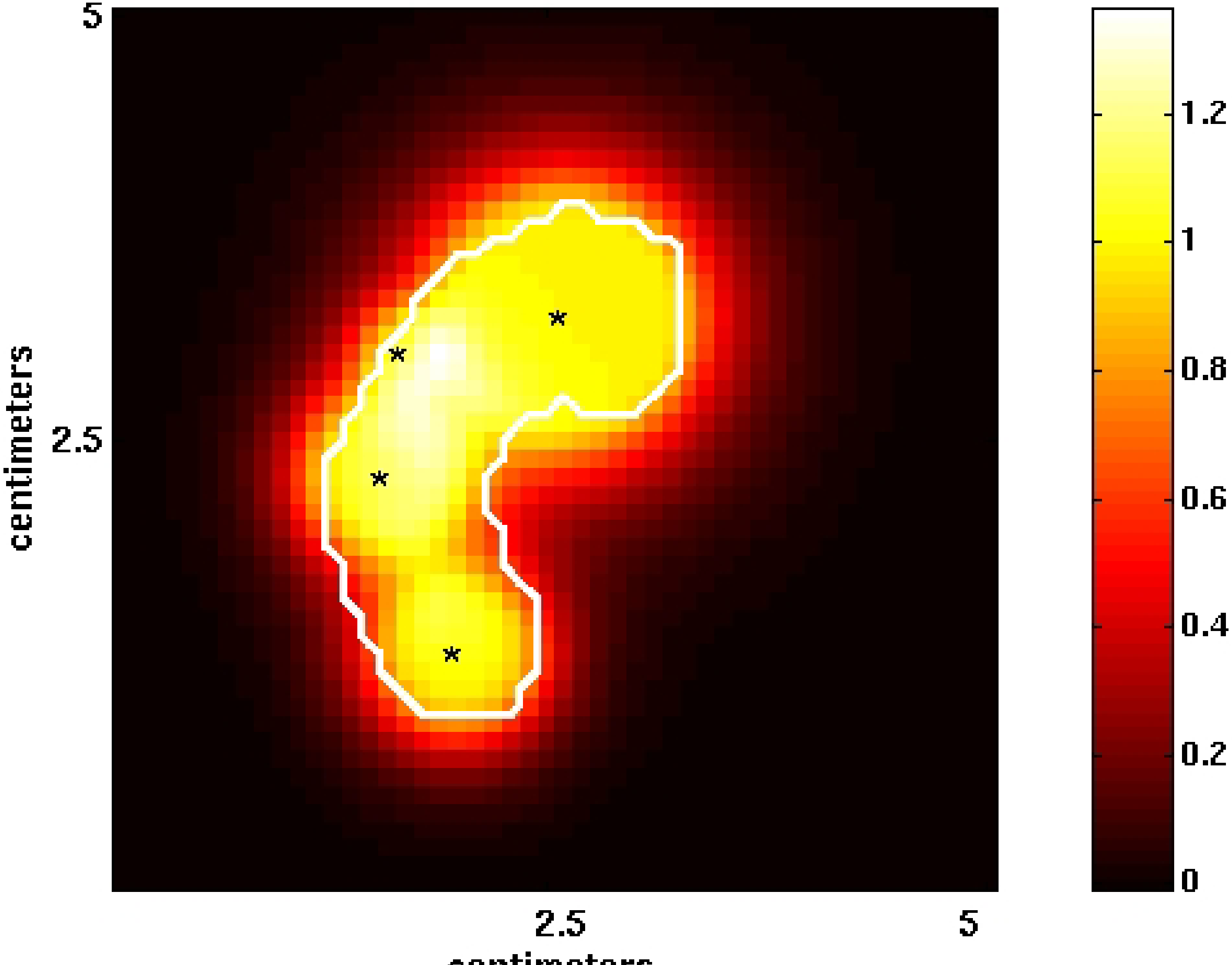
2 Shots



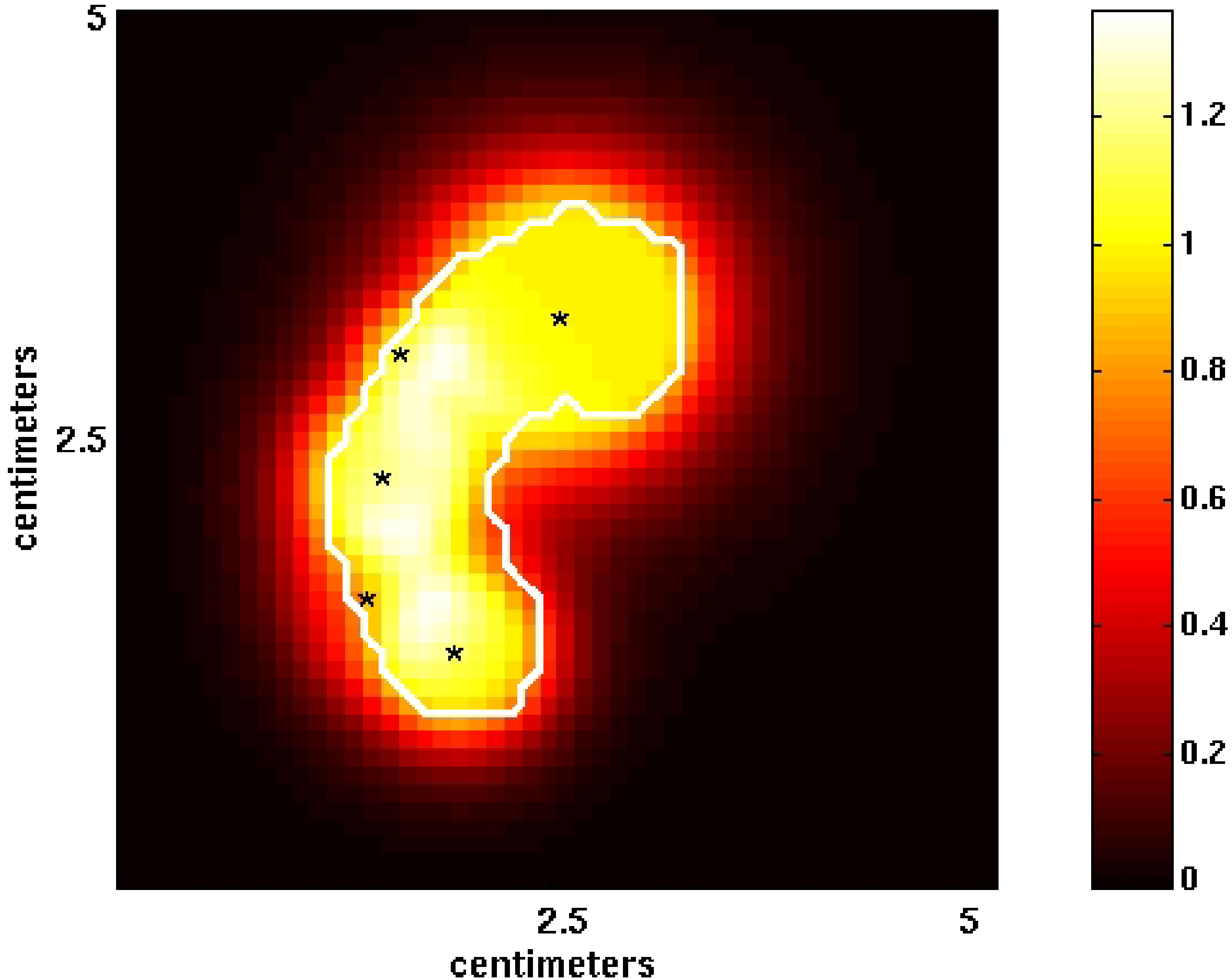
3 Shots



4 Shots



5 Shots



Automated Planning

- Develop a fully automated approach to Gamma Knife treatment planning

- Better tumor dose coverage
- Reduced dose to normal tissue
- More efficient treatments
- Reduced time commitment for neurosurgeon

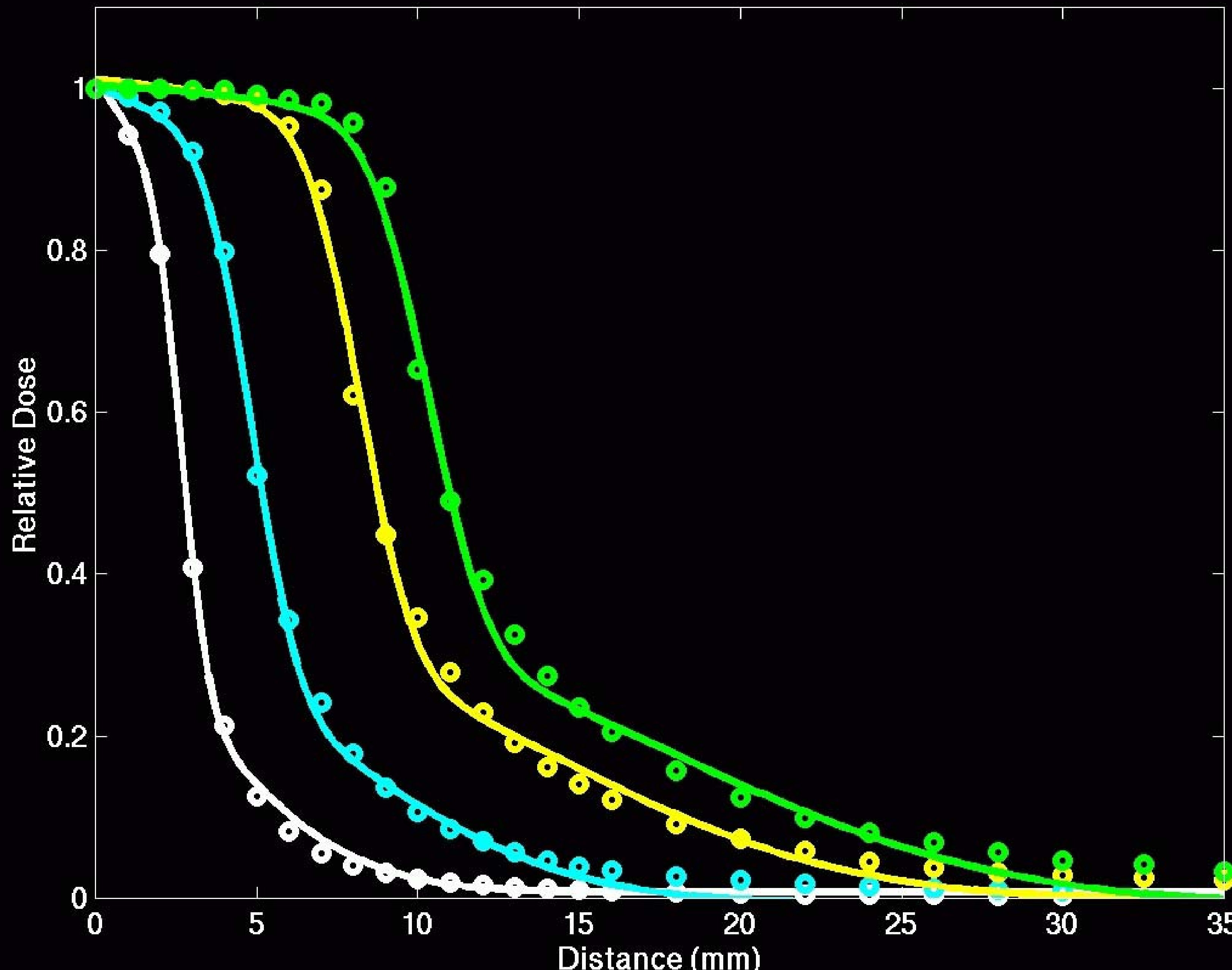
Computational Model

- Target volume (from MRI or CT)
- Maximum number of shots to use
  - Which size shots to use
  - Where to place shots
  - How long to deliver the shot

  - Conform to Target (50% isodose curve)
  - Real-time optimization

Ideal Optimization

$$\begin{aligned}
\min_{t_{s,w},x_s,y_s} \quad & Dose(NonTarget) \\
subject\ to \quad & Dose(i,j) = \sum_{s\in S, w\in W} t_{s,w} D_w(x_s, y_s, i, j) \\
& 0.5 \le Dose(Target) \le 1 \\
& t_{s,w} \ge 0 \\
& |S| \le N
\end{aligned}$$


Relative Dose
Distance (mm)
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20
25
30
35

Dose calculation

- Measure dose at distance from shot center in 3 different axes
- Fit a nonlinear curve to these measurements (nonlinear least squares)
- Functional form from literature, 10 parameters to fit via least-squares

$$m_1\, erf(\frac{d_1(x) \quad r_1}{\sigma_1}) + m_2\, erf(\frac{d_2(x) \quad r_2}{\sigma_2})$$

Environment

- All data fitting and optimization models formulated in GAMS
  - Ease of formulation / update
  - Different types of model
- Nonlinear programs solved with CONOPT (generalized reduced gradient)
- LP's and MIP's solved with CPLEX

Nonlinear Approach

$$Let\ x_s, y_s\ be\ variable\ locations$$

$$s = 1, 2, \ldots, N$$

$$D_w(x_s, y_s, i, j)\ is\ nasty\ nonlinear\ function$$

$$What\ width\ shot\ to\ use\ at\ x_s, y_s?$$

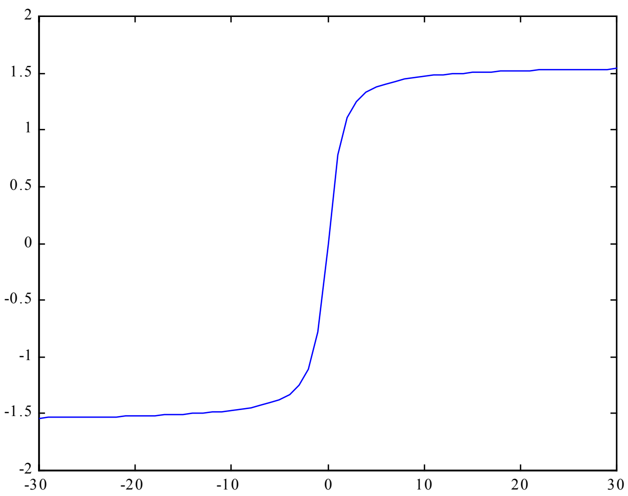
$$\psi_{s,w} = \begin{cases} 1 & \text{if shot s is width w} \\ 0 & \text{else} \end{cases}$$

$$\underline{T}\psi_{s,w} \leq t_{s,w} \leq \overline{T}\psi_{s,w}$$

$$\sum_w \psi_{s,w} \leq 1$$

Iterative Approach

- Approximate via "arctan"



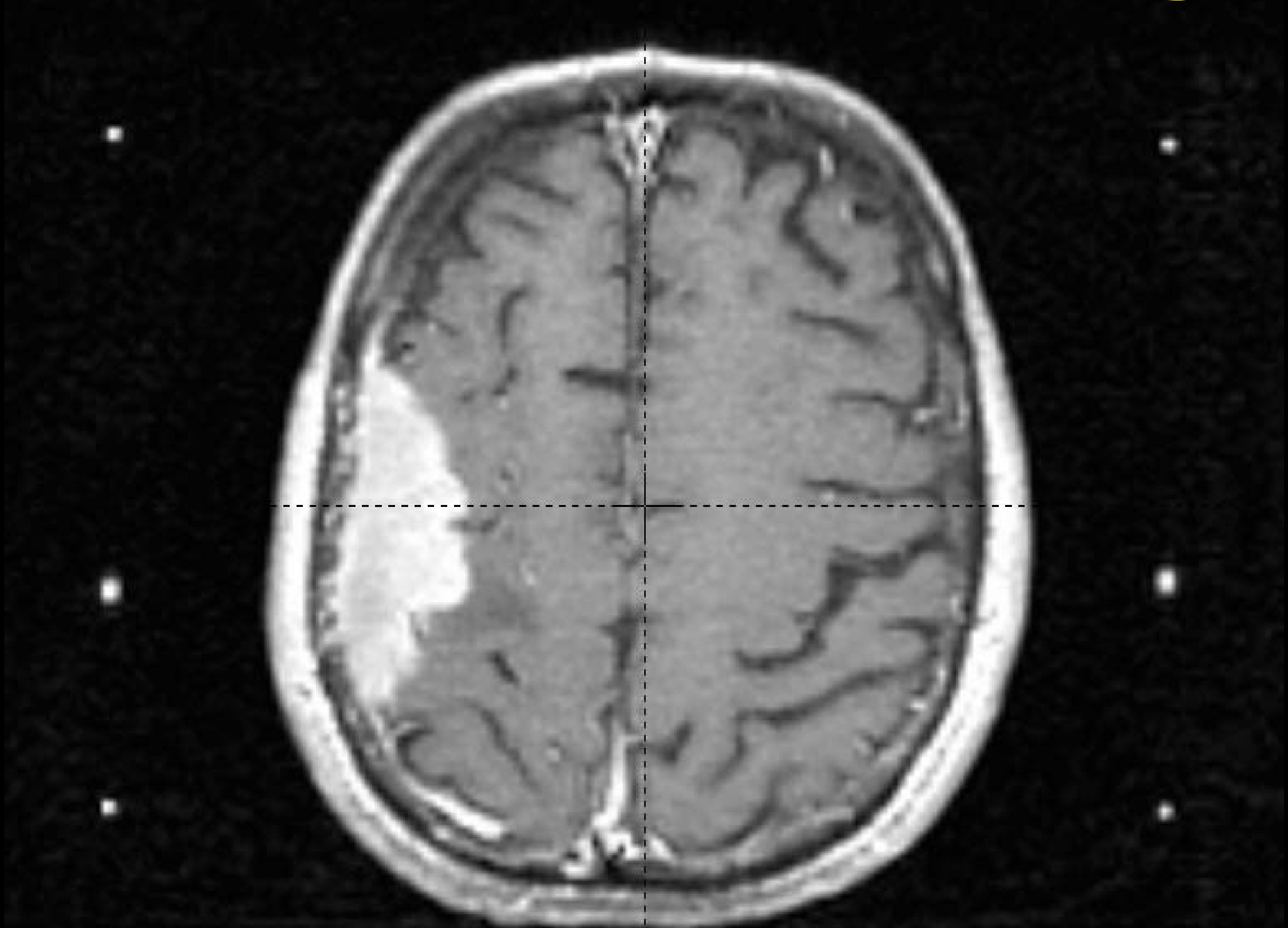
$$\forall s \in S$$
$$\sum_w arctan(t_{s,w}) \leq \frac{\pi}{2}$$

- First, solve with coarse approximation, then refine and reoptimize

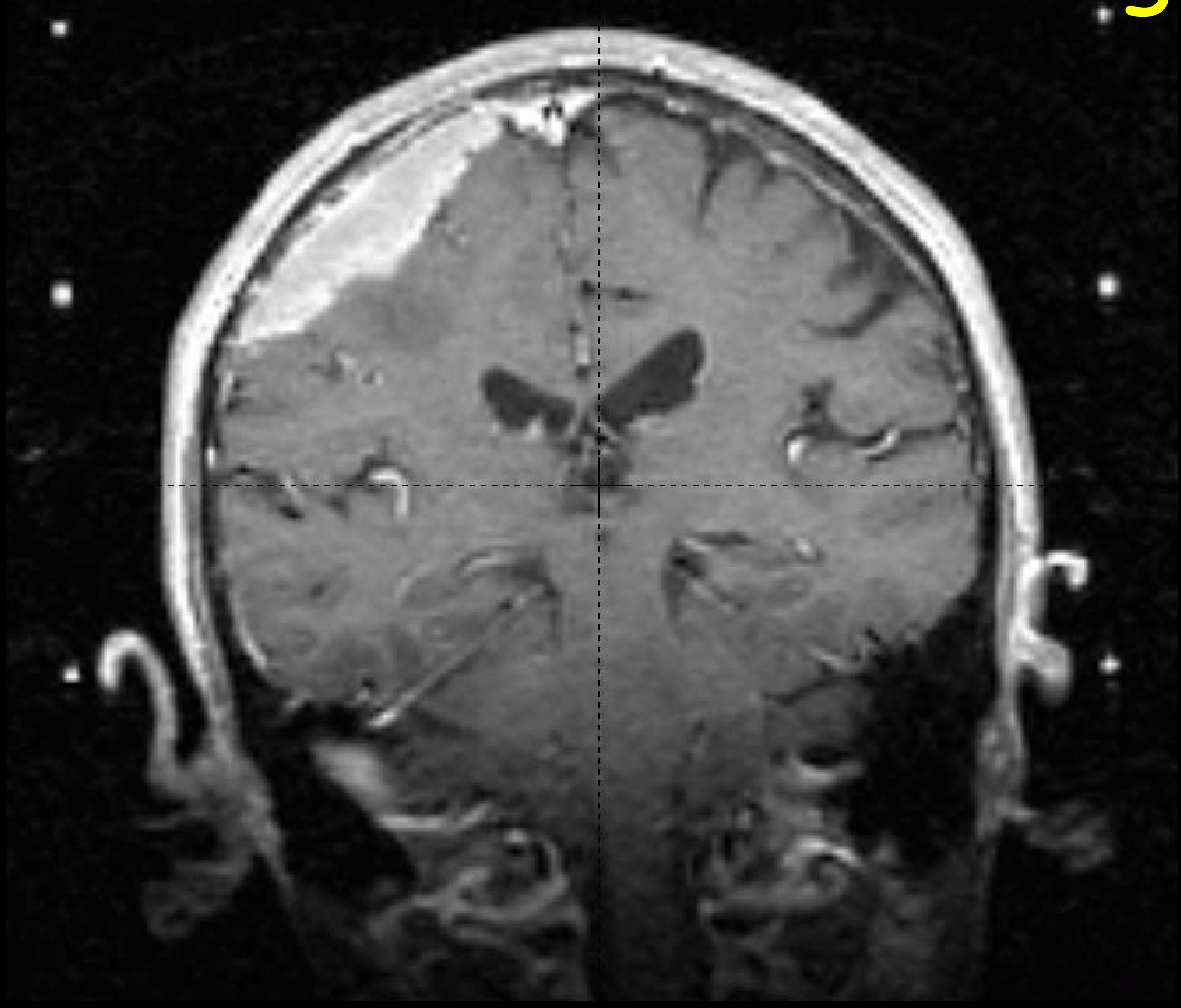
Continuation Approach

- Rotate data (prone/supine)
- Conformity subproblem (P)
- Coarse grid shot optimization
- Refine grid (add violated locations)
- Refine smoothing parameter
- Round and solve MIP for exposure times

Patient 1 - Axial Image

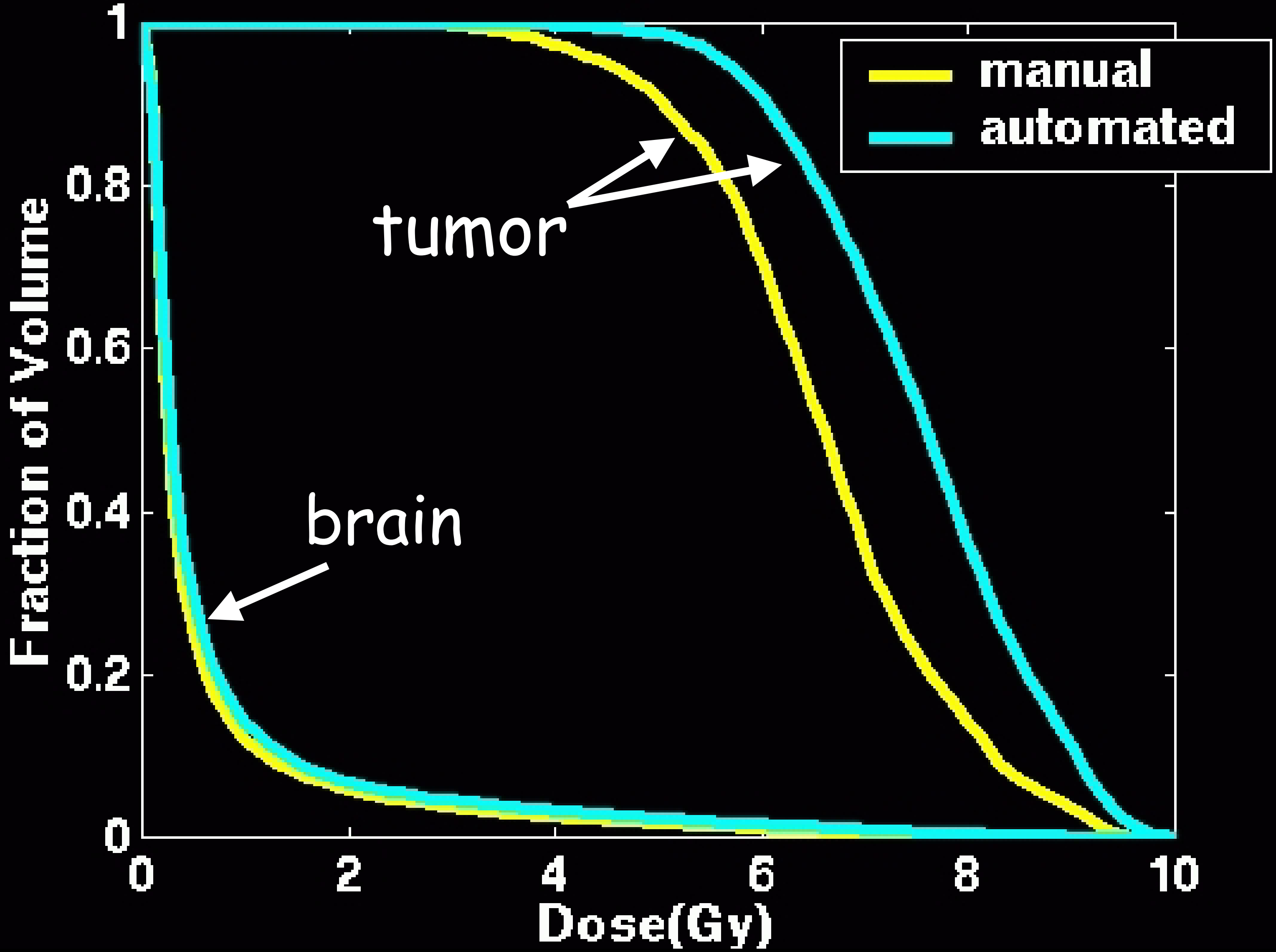


Patient 1 - Coronal Image



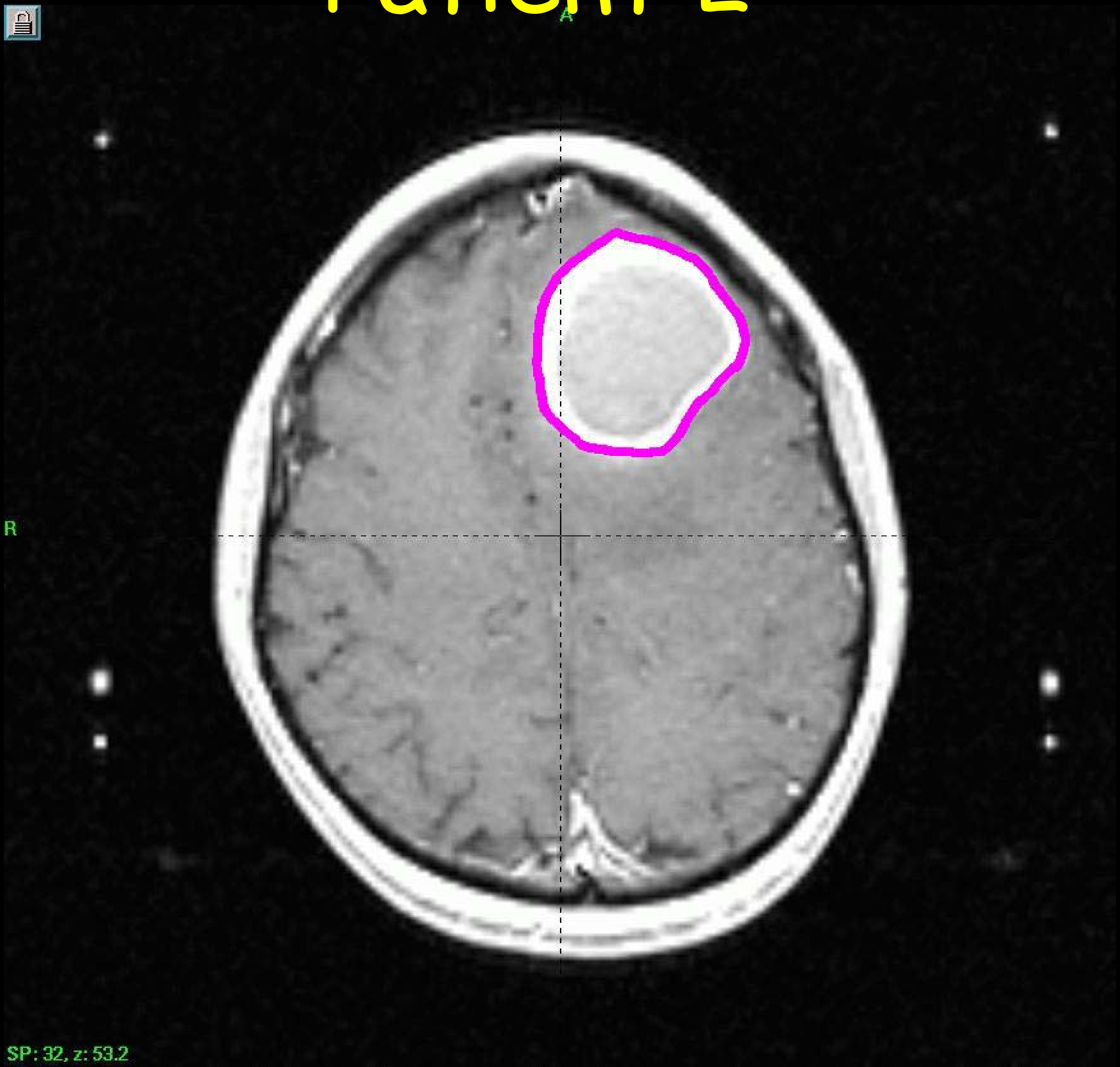
manual

optimized



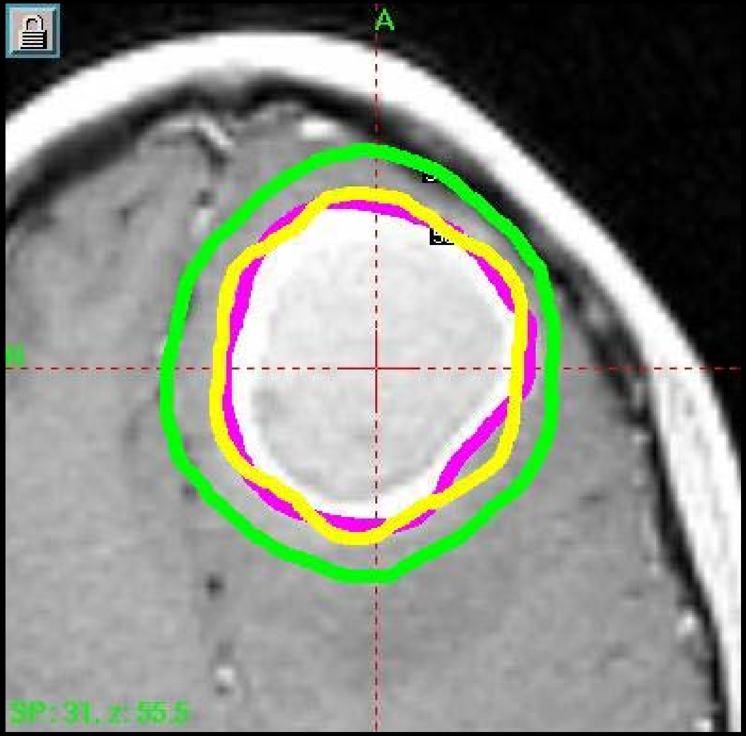
manual
automated
tumor
brain
Fraction of Volume
Dose(Gy)
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10

Patient 2

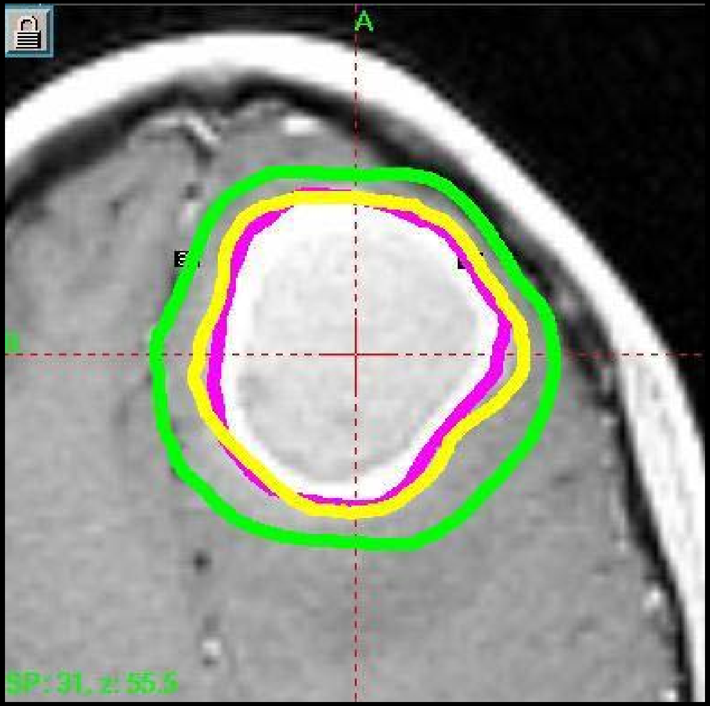


Patient 2 - Axial slice

15 shot manual



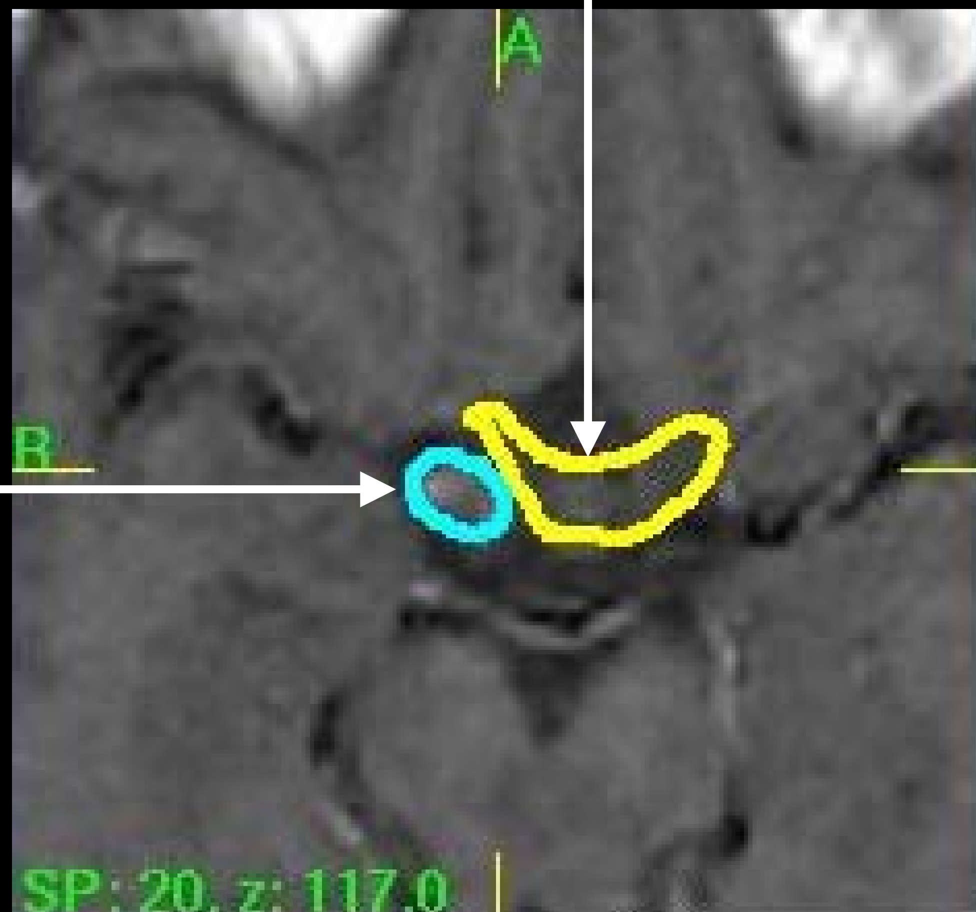
12 shot optimized

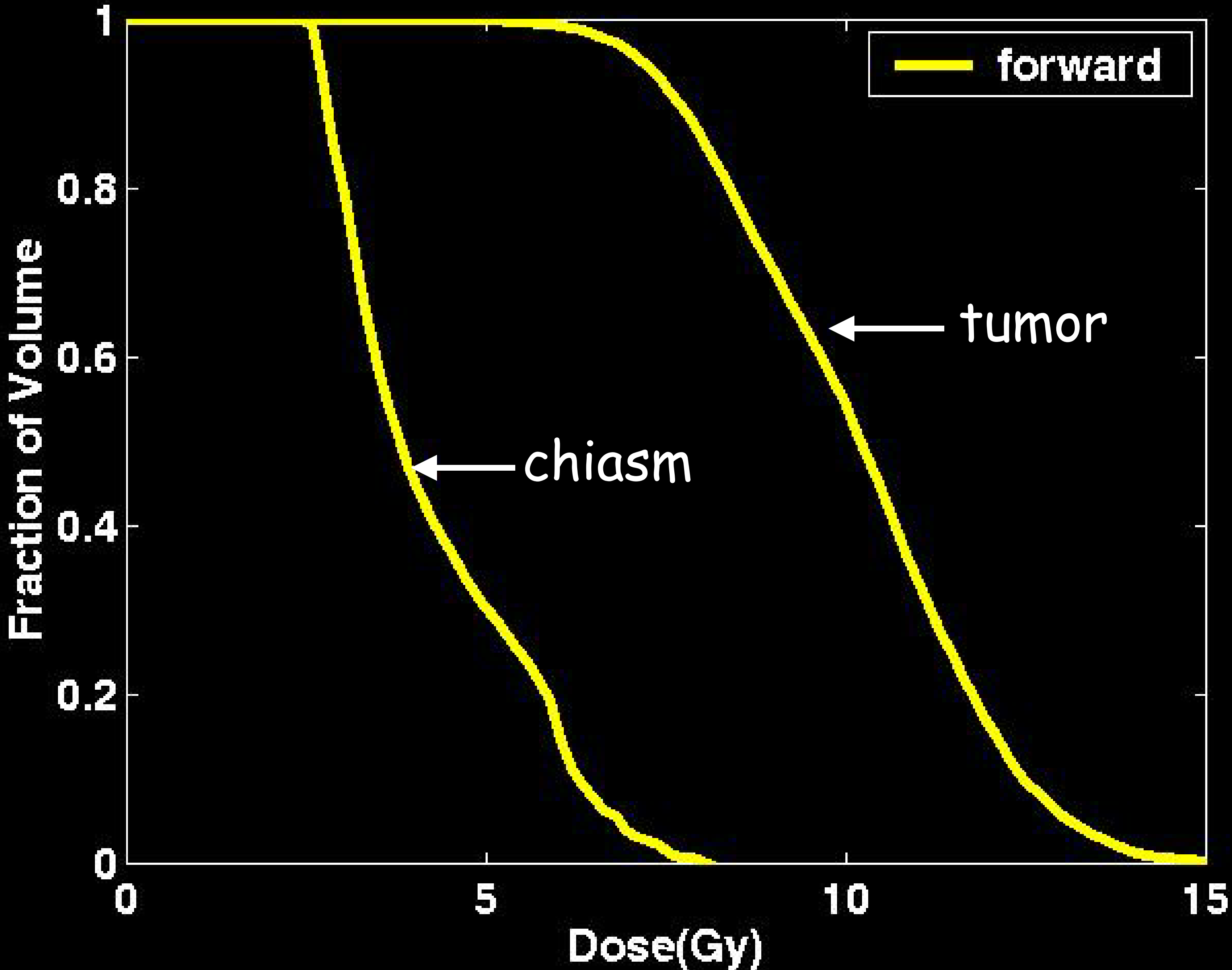


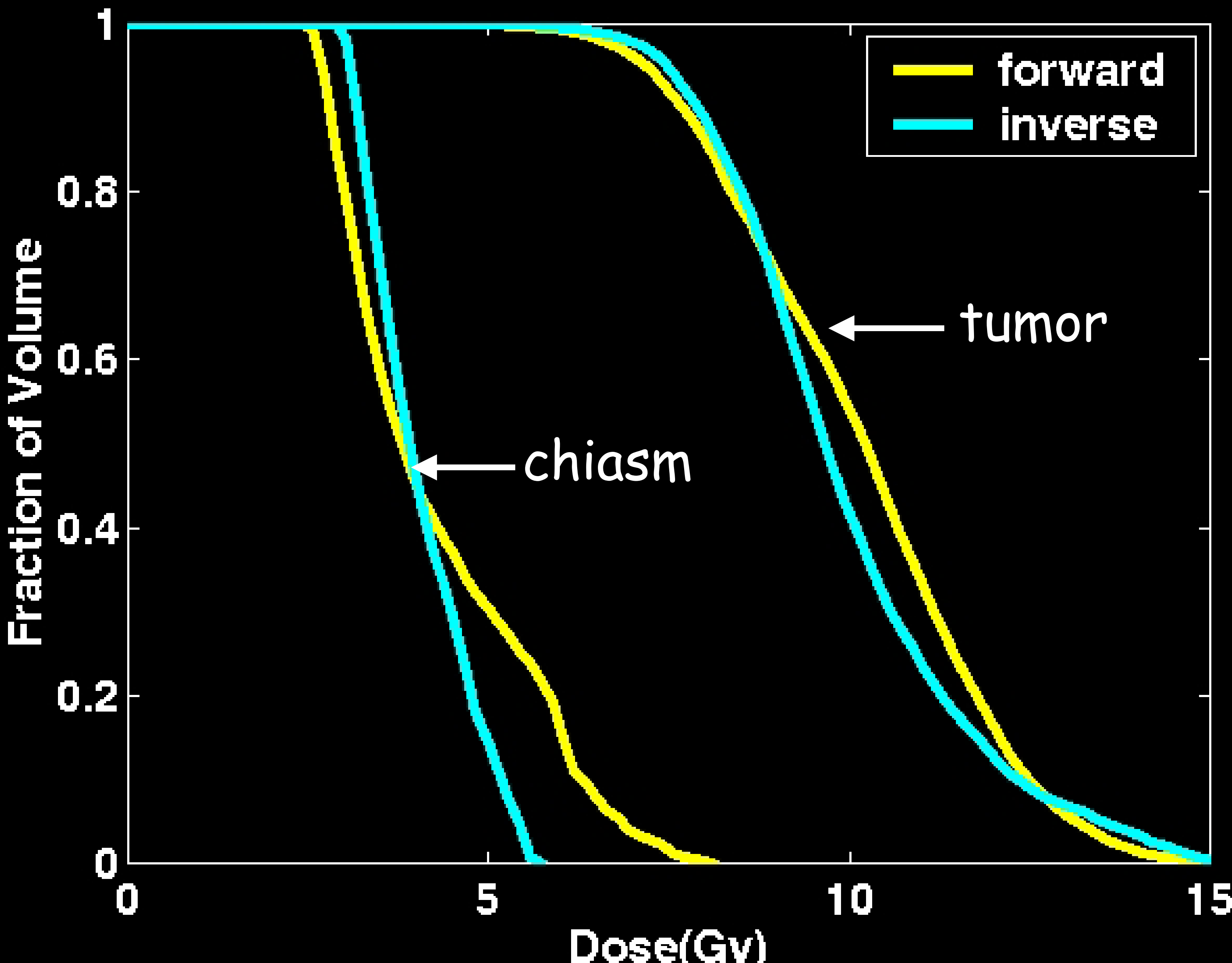
Patient 3

optic chiasm

pituitary adenoma

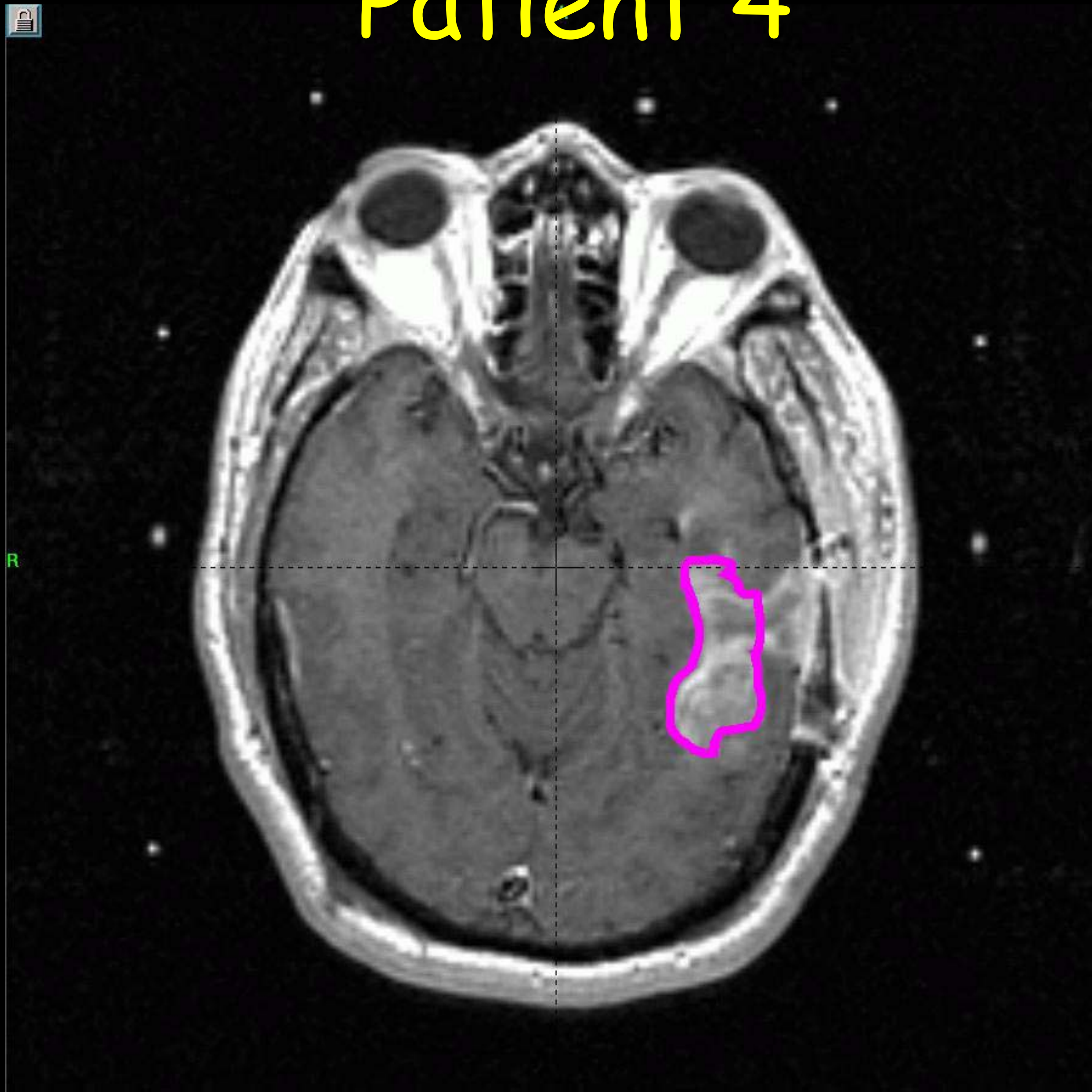



forward
tumor
chiasm
Fraction of Volume
Dose(Gy)
0
0.2
0.4
0.6
0.8
1
0
5
10
15



forward
inverse
tumor
chiasm
Fraction of Volume
0
0.2
0.4
0.6
0.8
1
0
5
10
15
Dose(Gy)

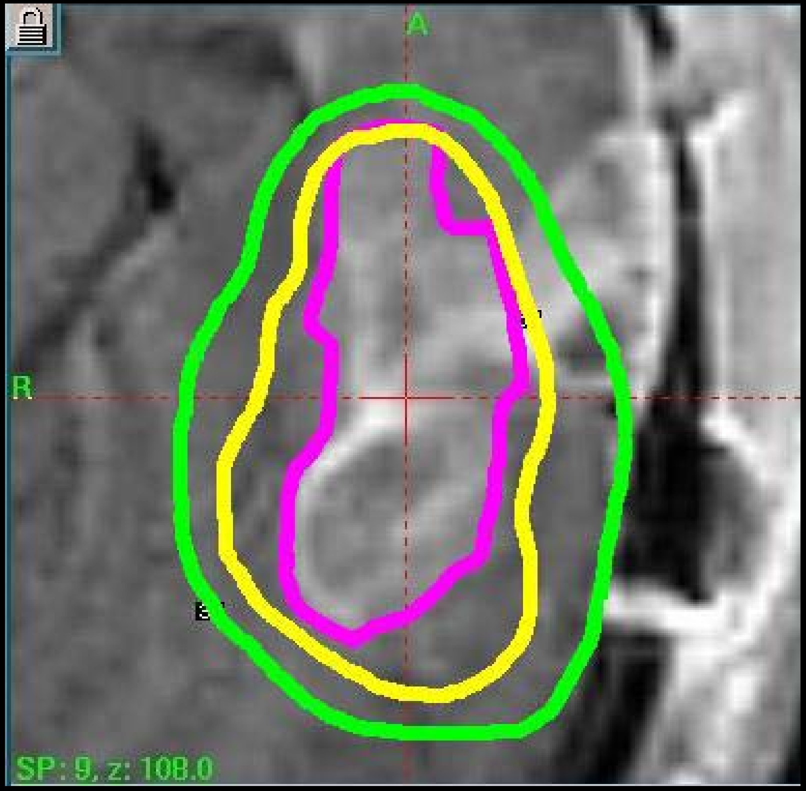
Patient 4



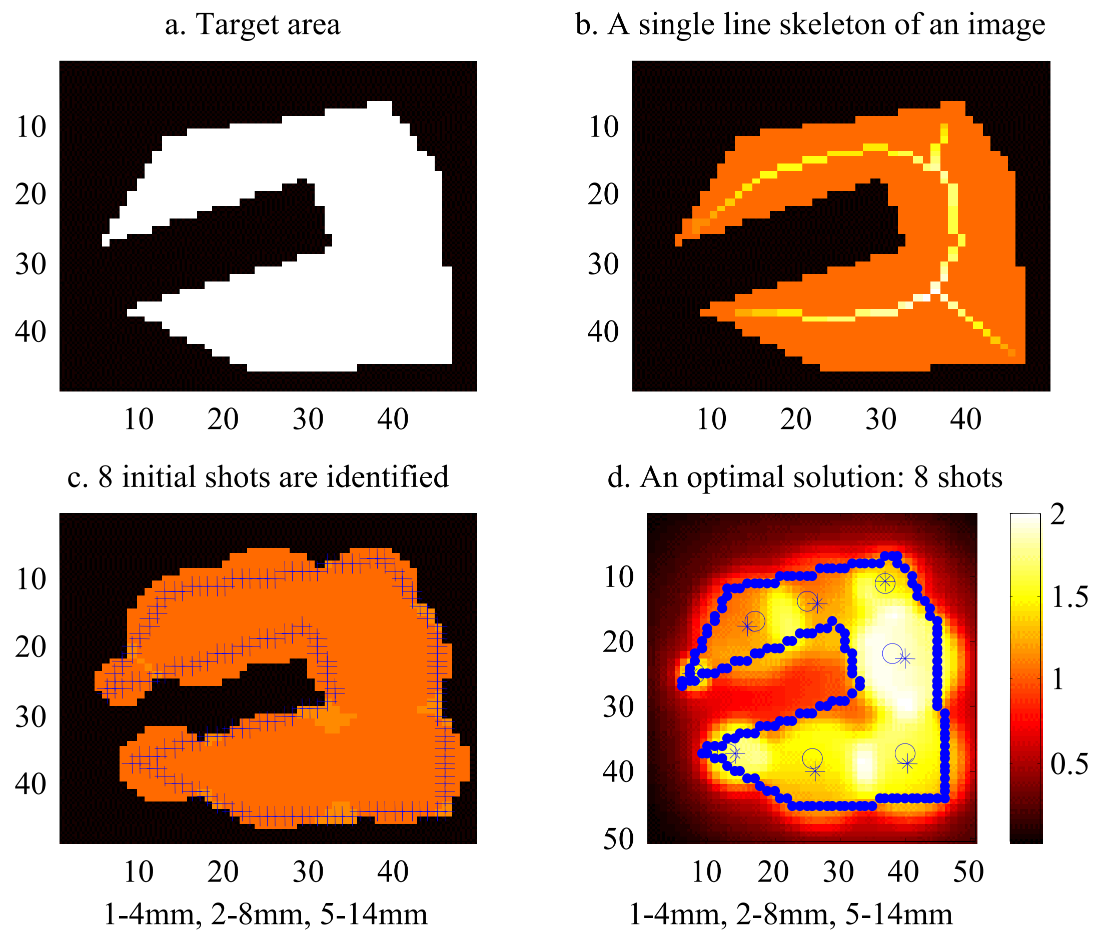
Patient 4 - Axial slice

7 shot manual

7 shot optimized



Skeletons (J.-H. Lim)



Starting Point Comparison

Average Run Time	Size of Tumor		
	Small	Medium	Large
Random (Std. Dev)	2 min 33 sec (40 sec)	17 min 20 sec (3 min 48 sec)	373 min 2 sec (90 min 8 sec)
SLSD (Std. Dev)	1 min 2 sec (17 sec)	15 min 57 sec (3 min 12 sec)	23 min 54 sec (4 min 54 sec)

Status

- Automated plans have been generated retrospectively for over 30 patients
- The automated planning system is now in use at U. Maryland Hospital
- Head to head against the neurosurgeon

Robustness

- High-quality conformal dose distributions are obtained independent of starting point
- Optimization performs well for targets over a wide range of sizes and shapes

Conclusions

- An automated treatment planning system for Gamma Knife radiosurgery has been developed using optimization techniques (GAMS, CONOPT and CPLEX)
- The system simultaneously optimizes the shot sizes, locations, and weights
- Automated treatment planning should improve the quality and efficiency of radiosurgery treatments