Stereotactic Body Radiation Therapy (SBRT) II: Physics and Dosimetry Considerations

Kamil M. Yenice, Ph.D.

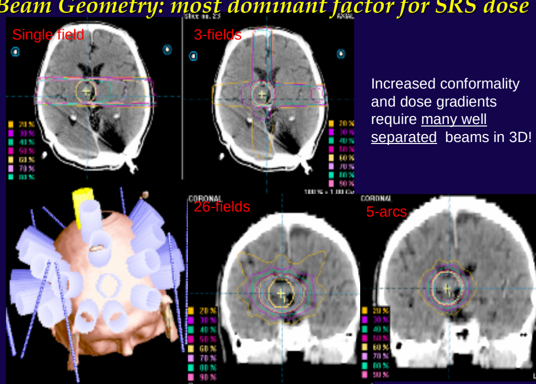
University of Chicago

Houston: July 28, 2008

Overview

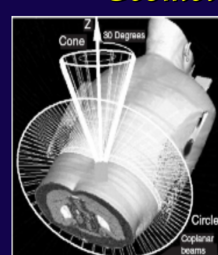
- SBRT planning and delivery considerations
  - Beam margins – lung
  - Beam geometry
  - Image-guidance and system accuracy, QA
- Institutional experience
  - U of Chicago Multiple Mets Trial
  - Treatment process
    - Planning
    - Delivery
    - Verification and QA
  - Summary

Beam Geometry: most dominant factor for SRS dose



Increased conformality and dose gradients require many well separated beams in 3D!

Limited non-coplanar Beam Geometry for SBRT



Restricted deliverable beam space for SBRT(Liu et al PMB, 2004)

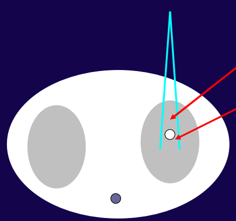
Lung: geometrically optimized beams

	Prescription isodose (%)	PITV	Effective gradient (mm)
Non-coplanar plan 11 beams	85	1.22	10.9
Coplanar plan 11 beams	83	1.22	11.8

Liver: geometrically optimized beams

	Prescription isodose (%)	PITV	Effective gradient (mm)
Non-coplanar plan 11 beams	84	1.13	14.7
Coplanar plan 11 beams	83	1.10	14.5

Beam "penumbra" margin



For the same prescription dose at the tumor:
- smaller beam margin ⇒ higher MU and higher dose to lung in the beam path
- larger beam margin ⇒ less MU and more normal lung outside tumor

What is the optimal beam/block margin that minimizes normal tissue toxicity?

<u>Study 1.</u> Cardinale et al (IJROBP, 1999) – DVH parameters (PITV, V100%,V50%, etc) and NTCP for lung and liver for 6MV photon beam margins of -2.5 to 10 mm.

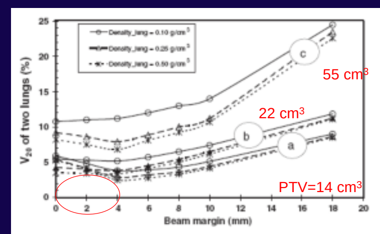
Margin (mm)	MDPD	PITV	100%	90%	80%	50%	25%
10	1.3	2.2	27	58	86	205	525
5	1.4	1.6	14	32	49	140	424
2.5	1.5	1.6	13	25	40	123	400
0.0	1.6	1.4	9	18	29	105	387
−2.5	1.9	1.4	10	18	31	113	444

Margin (mm)	Lung case NTCP (%)	Liver case NTCP (%)
10	46	62
5	13	15
2.5	9	5
0.0	5	5
−2.5	6	10

Investigation of optimal beam margins for stereotactic radiotherapy of lung-cancer using Monte Carlo dose calculations

L Jin, L Wang, J Li, W Luo, S J Feigenberg and C-M Ma

(PMB 2007)



Beam margins of <u>0-4mm</u> yields optimal normal lung sparing based on V20 Gy
Zero beam margins result in best V10Gy lung sparing

Test of Overall Accuracy

SYSTEM
- CT scan phantom with "hidden" targets
- Localize target on segmented images (coordinates, etc)
- Position target/phantom in treatment beam isocenter
- Image phantom and determine deviation of target position
  - <u>Image registration accuracy</u>
  - Evaluate <u>concordance of treatment and imaging isocenters</u>

PATIENT TREATMENT
- Immobilize patient
- CT scan patient
- Delineate targets
- Determine isocenter – tattoo patient or define SBF coordinates
- Setup patient with room lasers
- Image patient (3D or 2D)
- Determine corrections
- Apply shifts
- Verify position (re-image) frequently

QA procedure must test all steps including verification of image guidance with treatment beam

University of Chicago Oligomets Trial

Five or less metastatic lesions
- Lung
- Liver
- Abdomen
- Extremity
- Life expectancy > 3 months
- No prior RT to currently involved sites
- Each site ≤ 10 cm or 500cc (caution!)
- Normal organ and marrow function

Dose Limiting Toxicities (DLT)
- Grade 3-5 non-hematological toxicities
- Grade 4-5 hematological toxicities
- Grade 3 mucositis or esophagitis lasting ≤ 7 days will not be considered a DLT.

Dose escalation tiers:
- 8 Gy/ fx x 3 = 24 Gy
- 10 Gy/fx x 3 = 30 Gy
- 12 Gy/fx x 3 = 36 Gy
- 14 Gy/fx x 3 = 42 Gy
- 16 Gy/fx x 3 = 48 Gy
- 18 Gy/fx x 3 = 52 Gy
- 20 Gy/fx x 3 = 60 Gy

Current: Lung and abdomen

UC SBRT Simulation Procedure

- Near full-body immobilization: upper and lower alpha cradles, knee cushion, indexing to CT and treatment tables
- Gated CT and 4DCT for all abdominal and lung sites, free-breathing for others
- Treatment planning CT scans
  - Gated non-contrast ⇒ dose calculations
  - Gated contrast ⇒ tumor volume delineation (augmented by PET-CT/MR)
  - Retrospective (4DCT) ⇒ customized ITV's

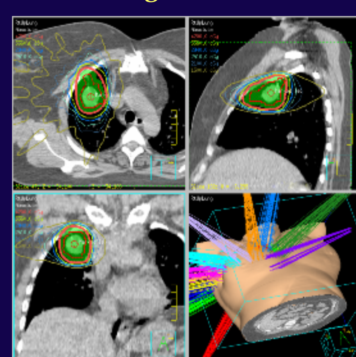
Treatment Planning

- Nine to thirteen coplanar and non-coplanar non-opposing static conformal beams
- Beams eye-view blocking with MLC at the isocenter with a margin of 0-2 mm
- PTV (Rx Dose) ≥ 95%
- Normal tissue dose limits: hard constraints

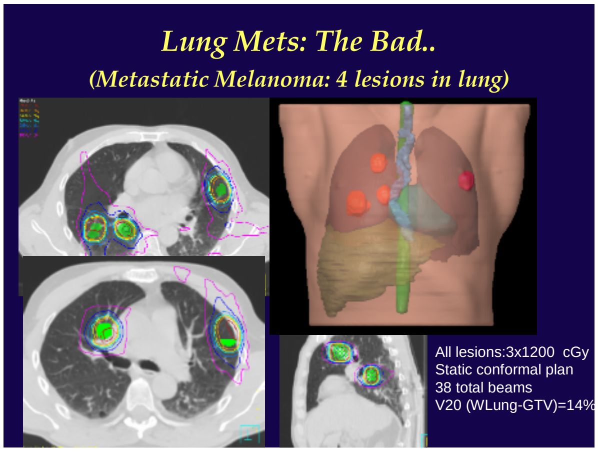
Normal Tissue Tolerances

Organ	RTOG*	Karolinska
Spinal Cord	6 Gy/fx	No published recommendation
Heart	10 Gy/fx	8 Gy per fraction
Brachial Plexus	8 Gy	
Trachea/Ipsilateral Bronchus	10 Gy	6 Gy for 3-5 fractions
Esophagus	9 Gy	5 Gy x 5 to 100% circum 7 Gy x 4 to 25% circum
Lung	•V13<10% •Mean< 7-8 Gy	
Liver	> 700 cc normal liver < 5 Gy	Hilus < 7 Gy per for 4-5 fractions
Stomach Small Bowel	10 Gy	7 Gy 4-5 fractions
Kidney	<5 Gy 35% kidney	•Primary < 10 cm 8 Gy x 5 fractions •Metastases in remaining kidney: 10 Gy x 3

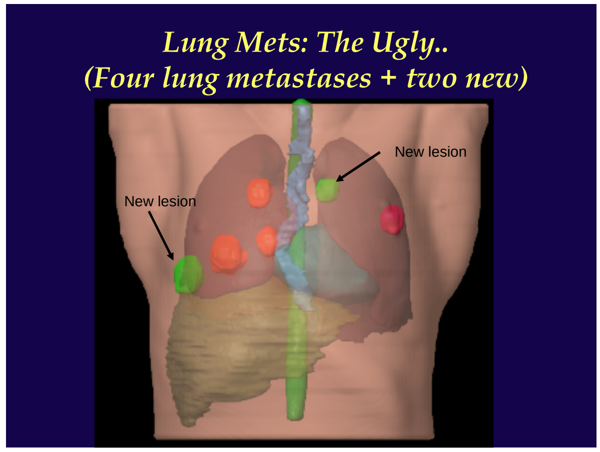
Lung Mets: The "Good"..



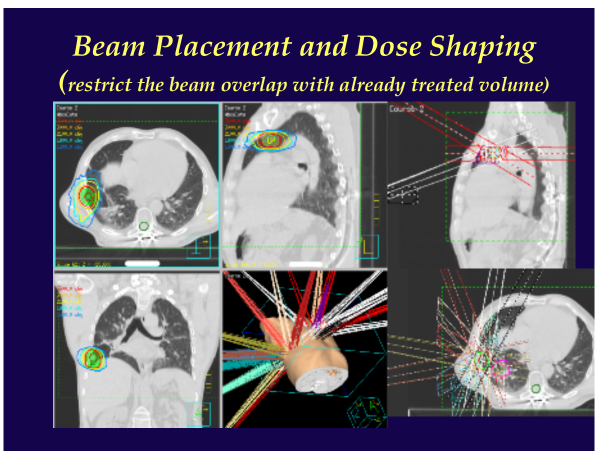
ITV derived from 4DCT, free-breathing tx delivery
11 non-coplanar beams
Rx= 3 x 1400 cGy
PTV: V4200cy = 96%
Lung-ITV(2000cGy) < 8%



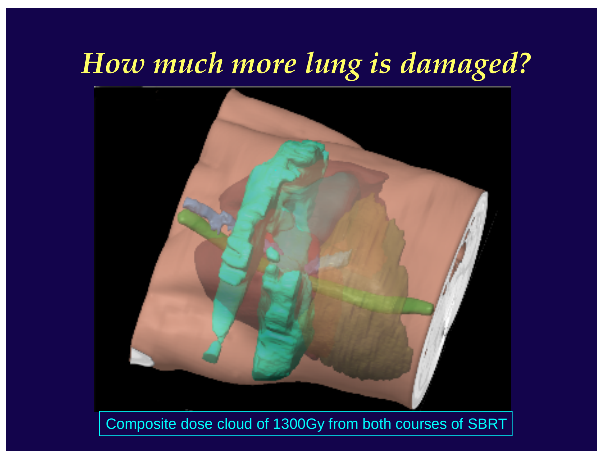
Lung Mets: The Bad..
(Metastatic Melanoma: 4 lesions in lung)
All lesions:3x1200 cGy
Static conformal plan
38 total beams
V20 (WLung-GTV)=14%



Lung Mets: The Ugly..
(Four lung metastases + two new)
New lesion
New lesion



Beam Placement and Dose Shaping
(restrict the beam overlap with already treated volume)



How much more lung is damaged?
Composite dose cloud of 1300Gy from both courses of SBRT

How much more lung is damaged?

Dose cloud of 1300Gy from course 1 and course 2

Lung DVH Characteristics versus RTOG0236

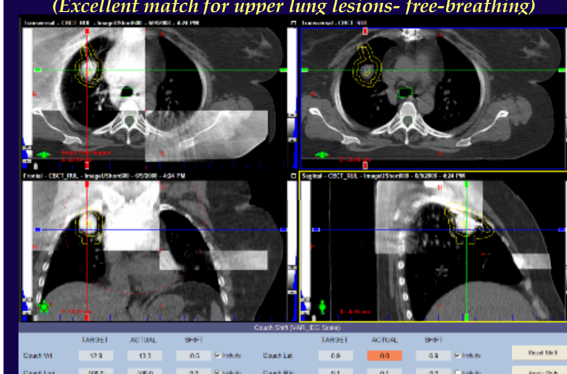
Patient	Toxicity	Location	PTV max dimension (cm)	PTV (cc)	Prescription	Max dose at 2cm from PTV (Gy)		
						IC on	IC off	RTOG 0236
1	3	RLL	3.9	21	14Gyx3	27.28	28.88	21.88-22.68
		Pericardial	6.7	126.6	8Gyx3	33.39	35.18	16.8-17.6
2	2	RLL	3.1	19.5	14Gyx3	24.27	21.5	21.28-22.68
3	2	LUL	9.1	148.4	12Gyx3	34.26	32.71	25.89-27.09
4	2	RLL	4.1	30.5	12Gyx3	41.48	40.97	19.62-20.82
		RUL	4.1	14.5	12Gyx3			
		R HILUM	4.1	8.23	10Gyx3			
		LUL	4.1	13.15	12Gyx3	28.18	28.38	16.86-18.06
5	0	LLung	8.5	133.9	14Gyx3	32.74	32.12	42.5-44.0
6	0	LLL	3.9	19.78	12Gyx3	24.82	25.01	30.4-32.4
7	0	Med LN, Hilar LN	13.6	265.6	8Gyx3	24.36	22.65	48.56-50.28
8	0	med LN	5.06	60.86	10Gyx3	20.8	20.88	18.05-19.78
9	0	RUL	5.5	40.3	14Gyx3	34.25	34.12	24.29-25.27
		LUL	9.72	114.42	5Gyx10	50.09	45.23	29.25-30.91
10	0	RUL	6.16	72.26	14Gyx3	27.83	26.86	26.18-29.19
11	0	RUL	5.2	76.65	20Gyx3	57.41	58.1	37.4-41.7

Image-Guidance: Treatment Verification

- *Pre-treatment verification: 3D*
  - *Non-contrast gated CT (big-bore, 16-slice scanner)*
  - *CBCT*
- *On-board kV/MV imaging: 2D*
  - *Image registration to reference DRR's*
  - *Orthogonal and portal verification gated images*
- *Mid and post procedure imaging*
  - *Evaluation of intrafraction patient/target motion*

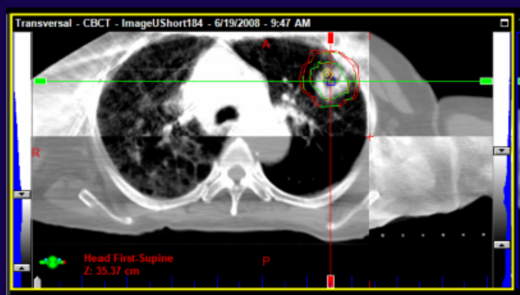
Patient 1: CBCT Verification

(Excellent match for upper lung lesions- free-breathing)



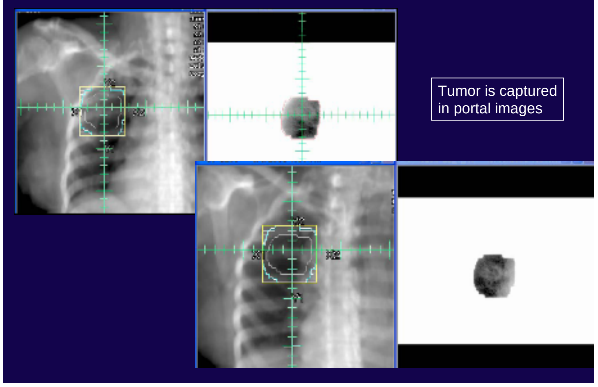
Patient 2: CBCT Verification

(Good match in bone and lung)



Registered CBCT overlaid on planning CT: Patient setup adjusted 5 mm post

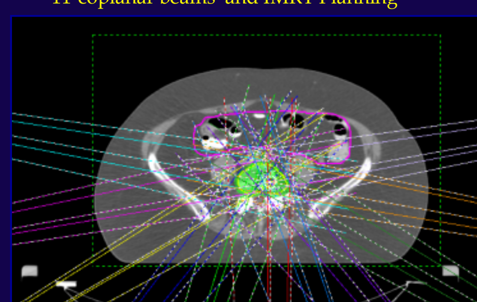
Patient 2: MV Portal Verification



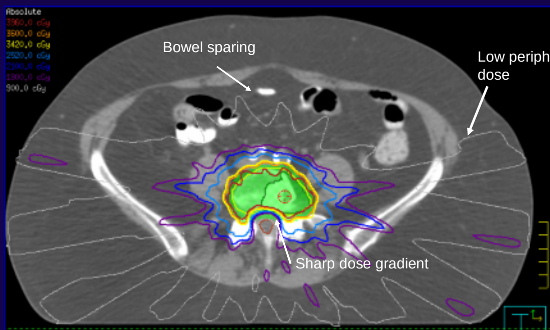
Patient Immobilization Issues with Spine

L4 Spinal Met: 3 x 1200 cGy

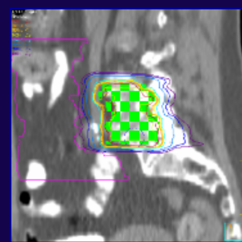
11-coplanar beams and IMRT Planning

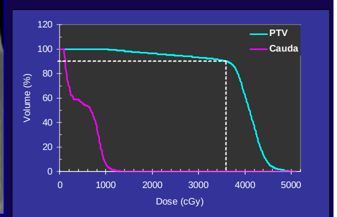


L4 Spinal Met: 3 x 1200 cGy



L4 Spinal Met: 3 x 1200 cGy

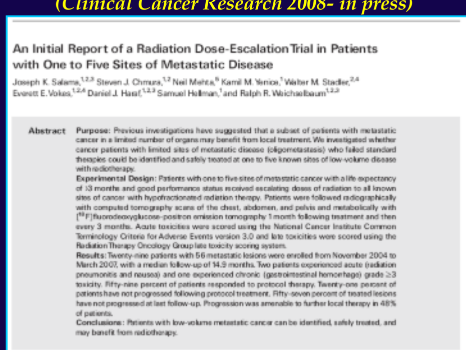




100% of Prescription (3600 cGy) =90% of PTV
Cauda: D_{max} = 1400 cGy

UC Trial Clinical Outcome Analysis

(Clinical Cancer Research 2008- in press)



An Initial Report of a Radiation Dose-Escalation Trial in Patients with One to Five Sites of Metastatic Disease

Joseph K. Salama,[1,2,3] Steven J. Chmura,[1,2] Neil Mehta,[5] Kamil M. Yenice,[1] Walter M. Stadler,[2,4] Everett E. Vokes,[1,2,4] Daniel J. Haraf,[1,2,3] Samuel Hellman,[1] and Ralph R. Weichselbaum[1,2,3]

Abstract **Purpose:** Previous investigations have suggested that a subset of patients with metastatic cancer in a limited number of organs may benefit from local treatment. We investigated whether cancer patients with limited sites of metastatic disease (oligometastasis) who failed standard therapies could be identified and safely treated at one to five known sites of low-volume disease with radiotherapy.
Experimental Design: Patients with one to five sites of metastatic cancer with a life expectancy of ≥3 months and good performance status received escalating doses of radiation to all known sites of cancer with hypofractionated radiation therapy. Patients were followed radiographically with computed tomography scans of the chest, abdomen, and pelvis and metabolically with $[^{18}F]$fluorodeoxyglucose-positron emission tomography 1 month following treatment and then every 3 months. Acute toxicities were scored using the National Cancer Institute Common Terminology Criteria for Adverse Events version 3.0 and late toxicities were scored using the Radiation Therapy Oncology Group late toxicity scoring system.
Results: Twenty-nine patients with 56 metastatic lesions were enrolled from November 2004 to March 2007, with a median follow-up of 14.9 months. Two patients experienced acute (radiation pneumonitis and nausea) and one experienced chronic (gastrointestinal hemorrhage) grade ≥3 toxicity. Fifty-nine percent of patients responded to protocol therapy. Twenty-one percent of patients have not progressed following protocol treatment. Fifty-seven percent of treated lesions have not progressed at last follow-up. Progression was amenable to further local therapy in 48% of patients.
Conclusions: Patients with low-volume metastatic cancer can be identified, safely treated, and may benefit from radiotherapy.

Metastatic Lung/Mediastinal Lesions

	n	24 Gy	30 Gy	36 Gy	42 Gy
		Initial Response/LRC	Initial Response/LRC	Initial Response/LRC	Initial Response/LRC
# Lesions	46				
Primary Histology					
NSCLC	10	CR (1/1) PR (0/1)	CR (1/4)	---	PR (1/1)(NE)
HNC	9	CR (1/1), PR (2/3)	CR (1/1)	CR (1/1) PR (3/3)	
Colon	3			CR (2/2), SD (1/1)	
RCC	4	SD (0/2)	SD(0/1)		(NE)
SCLC	4	PR (0/1)	CR (1/1)	PR (1/1)	PR (1/1)
Sarcoma	4	CR (0/1) PR (0/3)	---	---	---
Melanoma	4	---	---	SD (4/4)	---
Breast	1	PR (0/1)	---	---	---
Ovarian	1	---	---	CR (1/1)	---
Basal Cell	3	---	---	---	PR (3/3)
Thyroid	2	---	---	---	PR (2/2)*
PNET	1	---	---	---	CR (1/1)
Metastatic Local Control		4/14 (29%)	3/7 (43%)	13/13 (100%)	12/12 (100%)

Metastatic Abdominal Lesions

	n	24 Gy	30 Gy	36 Gy	42 Gy
		Initial Response/LRC	Initial Response/LRC	Initial Response/LRC	Initial Response/LRC
# Patients	18				
# Lesions	24				
Primary Histology					
NSCLC	6	SD (0/1) CR(0/2)	CR (3/3)	---	---
Chromophobe	4	SD (2/2)	SD (2/2)	---	---
Sarcoma	4	---	SD (4/4)	---	---
SCLC	3	PR (0/1)	---	PR (1/1) CR (1/1)	---
Breast	3	---	CR (1/1)	CR (2/2)	---
RCC	3		SD (1/1)	PR (1/2)	
Duodenal	1	---	---	---	CR (1/1)
Metastatic Local Control		2/6 (33%)	11/11 (100%)	5/6 (83%)	1/1 (100%)

Q1. The optimal beam margin for SBRT planning with 6 MV photon beams in the lung that minimizes the normal tissue complication probability is typically

0% 1. - 2 mm
0% 2. 0 to 4 mm
0% 3. 5 to 9 mm
0% 4. 10 mm
0% 5. 18 mm

10

Q1. The optimal beam margin for SBRT planning with 6 MV photon beams in the lung that minimizes the normal tissue complication probability is typically

1. - 2 mm
2. 0 to 4 mm
3. 5 to 9 mm
4. 10 mm
5. 18 mm

Q2. Unlike conventional radiotherapy, SBRT uses a greater number of beams to achieve

0% 1. larger dose heterogeneities
0% 2. smaller hot spots
0% 3. better target dose conformity and rapid dose fall-off away from the target
0% 4. a shallower dose gradient
0%

10

Q2. Unlike conventional radiotherapy, SBRT uses a greater number of beams to achieve

1. larger dose heterogeneities
2. smaller hot spots
3. better target dose conformity and rapid dose fall-off away from the target
4. a shallower dose gradient

Q3. The most important aspect of a rigorous QA program for an image guided SBRT approach is

0% 1. Room lasers are accurately calibrated
0% 2. Stereotactic Frame is indexed to the treatment table
0% 3. Patient skin marks are consistently documented
0% 4. An end to end test confirms the link between imaging and dose delivery steps in the overall treatment process
0%

10

Q3. The most important aspect of a rigorous QA program for an image guided SBRT approach is

1. Room lasers are accurately calibrated
2. Stereotactic Frame is indexed to the treatment table
3. Patient skin marks are consistently documented
4. An end to end test confirms the link between imaging and dose delivery steps in the overall treatment process

Summary

- SBRT requires multi-disciplinary team approach
- Clinical experience with conventional radiotherapy does not extrapolate to SBRT
- Verification of each step in the SBRT treatment process is a must

"We are like blind men peeping through a fence"

Japanese Proverb

Acknowledgements

Karl Farrey, MS
Joseph Salama, MD
Steve Chmura, MD, PhD
Ralph Weichselbaum, MD

THE UNIVERSITY OF CHICAGO

*Mary Martel, PhD**
**MD Anderson*

Michael Lovelock, PhD
Josh Yamada, MD
Mark Bilsky, MD

References

1. R. M. Cardinale, Q. Wu, S. H. Benedict, B. D. Kavanagh, E. Bump, R. Mohan "Determining the optimal block margin on the planning target volume for extracranial stereotactic radiotherapy," Int J Radiat Oncol Biol Phys **45**, 515-520 (1999).
2. L. Lin, L. Wang, J. Li, W. Luo, S. J. Feigenberg, C-M. Ma, „Investigation of optimal beam margins for stereotactic radiotherapy of lung-cancer using Monte Carlo dose calculations" Phys Med Biol 52, 3549-3561 (2007)
3. R Liu, TH Wagner, JM Buatti, J Modrick, J Dill, SL Meeks, "Geometrically based optimization for extracranial radiosurgery", Phys Med Biol **49**, 987-996 (2004)
4. JM Galvin, G Bednarz, "Quality assurance procedures for stereotactic body radiation therapy" Int J Radiat Oncol Biol Phys, 71, S122-125 (2008)