Pitfalls in SBRT Treatment Planning for a Moving Target

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I have no conflicts of interests to disclose

In memory of Lynn

- Lynn Verhey, mentor and boss
- 7th medical physics resident at UCSF
- Stayed on as Cyberknife physicist – SBRT treatment planning

Outline

- Brief summary of SBRT Treatment Planning
  - Dose Constraints
  - What other matrices to check, 10/20 Gy isodose line? D_{2cm}?
  - Calculation Algorithms
- Pitfalls in Lung/Liver SBRT Treatment Planning:
  - Motion Management Methodologies
    - Which method to use?
    - What planning CT to use?
    - What PTV margins?

Basics of SBRT Treatment Planning

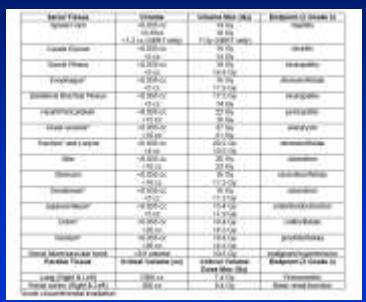
- Goal of SBRT: ablate tissues within PTV
- Minimize normal tissues receiving high dose - sharp dose fall off outside PTV
- Dose conformity more important than dose homogeneity (potentially more advantageous).

$$CIPaddick = \frac{TV^2_{PIV}}{(TVx\ VRI)} \text{ or } CI_{Lomax} = \frac{TV_{PIV}}{TV}$$

$$HI = \frac{I_{max}}{RI}$$

Dose Constraints: TG101 Table III

- RTOG protocols - Spine 0631



Basics of SBRT Treatment Planning

- Dose Constraints based on RTOG protocols
  - Lung : 0813 and 0915

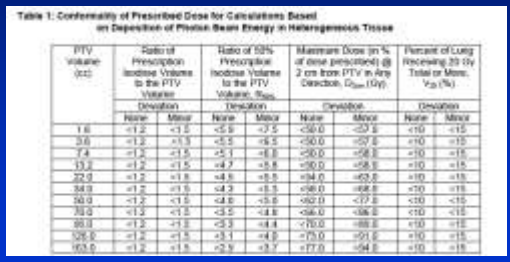


Table 1: Conformality of Prescribed Dose for Calculations Based on Deposition of Photon Beam Energy in Heterogeneous Tissue

PTV volume (cc)	Ratio of Prescription Isodose Volume to the PTV Volume		Ratio of 50% Prescription Isodose Volume to the PTV Volume: $R_{50\%}$		Maximum Dose (in % of dose prescribed) @ 2 cm from PTV in Any Direction, D_{2cm} (Gy)		Percent of Lung Receiving 20 Gy Total or More, V_{20} (%)	
	Deviation		Deviation		Deviation		Deviation	
	None	Minor	None	Minor	None	Minor	None	Minor
1.6	<1.2	<1.5	<5.9	<7.5	<50.0	<57.9	<10	<15
3.6	<1.2	<1.5	<5.5	<6.5	<50.0	<57.0	<10	<15
7.4	<1.2	<1.5	<5.1	<6.0	<50.0	<58.0	<10	<15
13.2	<1.2	<1.5	<4.7	<5.8	<50.0	<58.0	<10	<15
22.0	<1.2	<1.5	<4.5	<5.5	<54.0	<63.0	<10	<15
34.0	<1.2	<1.5	<4.3	<5.5	<56.0	<66.0	<10	<15
50.0	<1.2	<1.5	<4.0	<5.0	<62.0	<77.0	<10	<15
70.0	<1.2	<1.5	<3.5	<4.8	<66.0	<86.0	<10	<15
95.0	<1.2	<1.5	<3.3	<4.4	<70.0	<88.0	<10	<15
126.0	<1.2	<1.5	<3.1	<4.0	<73.0	<91.0	<10	<15
163.0	<1.2	<1.5	<2.9	<3.7	<77.0	<94.0	<10	<15

Basics of SBRT Treatment Planning

- Dose Constraints based on RTOG protocols

Table 2

Serial Tissue	Volume	Volume Max (Gy)	Max Point Dose (Gy)	Avoidance Endpoint
Spinal cord	<0.35 cc <0.5 cc	22.5 Gy (3.5 Gy/fx) 13.5 Gy (2.1 Gy/fx)	30 Gy (5 Gy/fx)	myelitis
Ipsilateral brachial Plexus	<3 cc	30 Gy (4 Gy/fx)	33 Gy (5.4 Gy/fx)	neuropathy
Skin	<10 cc	30 Gy (5 Gy/fx)	32 Gy (5.4 Gy/fx)	ulceration
Parallel Tissue	**Critical Volume**	**Critical Volume Dose Max (Gy)**		**Avoidance Endpoint**
Lung (Right & Left)	1000 cc	12.5 Gy (2.0 Gy/fx)		Basic Lung Function
Lung (Right & Left)	1000 cc	13.3 Gy (2.1 Gy/fx)		Pneumonitis

Table 3

Serial Tissue*	Volume	Volume Max (Gy)	Max Point Dose (Gy)	Avoidance Endpoint
Esophagus, non-adjacent wall	<5 cc	37.5 Gy (5.3 Gy/fx)	100% of PTV prescription	stenosis/fistula
Heart/Pericardium	<15 cc	32 Gy (5.4 Gy/fx)	100% of PTV prescription	pericarditis
Great vessels, non-adjacent wall	<15 cc	47 Gy (5.4 Gy/fx)	100% of PTV prescription	aneurysm
Trachea and proximal bronchial, non-adjacent wall	<4 cc	50 Gy (3.5 Gy/fx)	100% of PTV prescription	stenosis/fistula

Basics of SBRT Treatment Planning

- Dose Constraints based on RTOG protocols
  - Liver : 0438 and 1112

Prescription dose	Liver (minus GTV) mean dose:		
	per protocol	variation acceptable	deviation unacceptable
50 Gy	≤13 Gy	13-13.2 Gy	> 13.2 Gy
45 Gy	≤15 Gy	15-15.2 Gy	> 15.2 Gy
40 Gy	≤15 Gy	15-15.2 Gy	> 15.2 Gy
35 Gy	≤15.5 Gy	15.5-15.7 Gy	> 15.7 Gy
30 Gy	≤16 Gy	16-16.2 Gy	> 16.2 Gy
27.5 Gy	≤17 Gy	17-17.2 Gy	> 17.2 Gy

Non-liver OARs	per protocol	variation acceptable	deviation unacceptable
Esophagus max (to 0.5 cc):	32 Gy	> 32 but ≤34 Gy	> 34 Gy
Stomach max (to 0.5 cc):	30 Gy	>30 but ≤32 Gy	> 32 Gy
Duodenum max (to 0.5 cc):	30 Gy	>30 but ≤32 Gy	> 32 Gy
Small bowel max (to 0.5 cc):	30 Gy	>30 but ≤32 Gy	> 32 Gy
Large bowel max (to 0.5 cc):	32 Gy	>32 but ≤34 Gy	> 34 Gy
Cord + 5 mm max (0.5cc):	25 Gy	>25 but ≤28 Gy	> 28 Gy
Kidneys, Bilateral mean dose	≤10 Gy	>10 but ≤12 Gy	> 12 Gy

Dose values in these tables should be read as physical dose for photons, or RBE-weighted dose for protons (assuming RBE = 1.1).

Basics of SBRT Treatment Planning

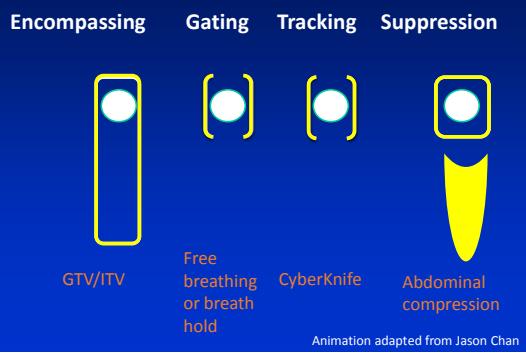
- CT slice thickness 1-3 mm per TG101
- Typical scan length extends at least 5–10 cm superior and inferior beyond the treatment field borders
- Non-coplanar 15 cm
- Calculation Grid Size: 2 mm or less
- Calculation algorithms
  - CSA/AAA perform better than PBAs
  - EPL overestimated dose compared with MC for SBRT of lung tumors

S. E. Davidson, Med. Phys. 35 (12) 2008
M Liu e al, PRO 3(4), 2013

Pitfalls of SBRT treatment planning for a moving target

- What CT scans to use?
- What margins to use with specific CT?

Motion management methodologies

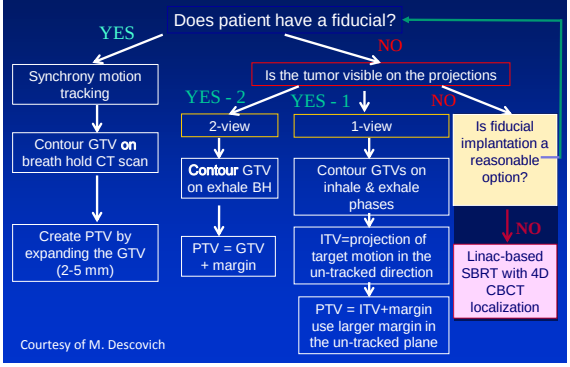


Animation adapted from Jason Chan

Different Platforms for Lung/Liver SBRT

- Cyberknife
  - Synchrony
  - Lung Optimized Treatment (LOT)
- Linac – Based SBRT
  - Free Breathing
  - Gating
  - Breath Hold
  - Abdominal Compression

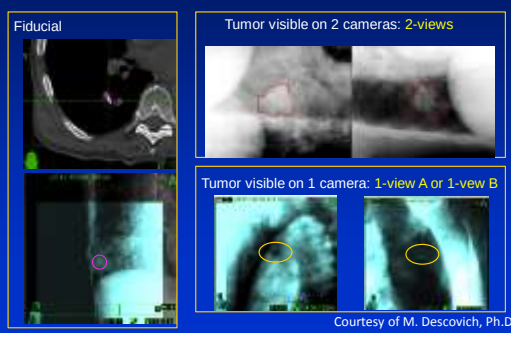
CT & Target Contouring for Lung on CK



Courtesy of M. Descovich

Internal target position

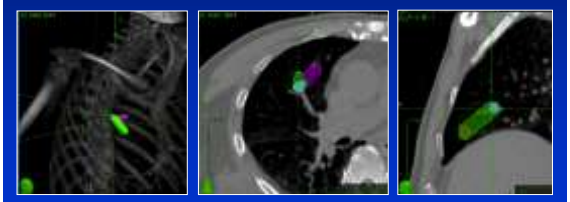
- The internal target position can be extracted based on gold markers or large/dense tumors visible on 2 cameras or just 1 camera



Courtesy of M. Descovich, Ph.D.

1-view tracking

- Tumors visible in only 1 projection image
- The component of motion in the image plane is tracked
- Partial ITV expansion in the the un-tracked direction
  - Sup-Inf motion is tracked (principal component of motion)

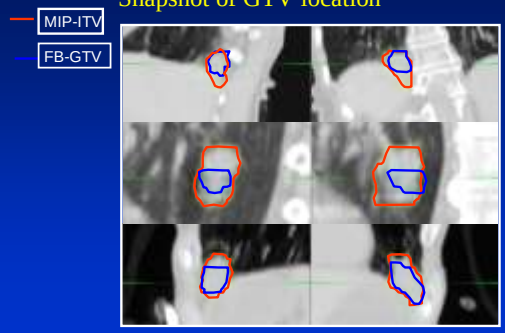


Courtesy of M. Descovich, Ph.D.

Planning CT for Linac-Based Lung SBRT

- Free breathing CT does not record the average target position
- Severe geometric distortion could result, lengthen or shorten the target in random fashion
- Center of the imaged target could be displaced as much as the amplitude of the motion
- Breath hold CT or average phase CT (from 4D CT) should be used as the baseline CT

Free Breathing CT Only Represents a Snapshot of GTV location



Courtesy of Ping Xia, Ph.D.

Difference in FBCT and 4DCT volume

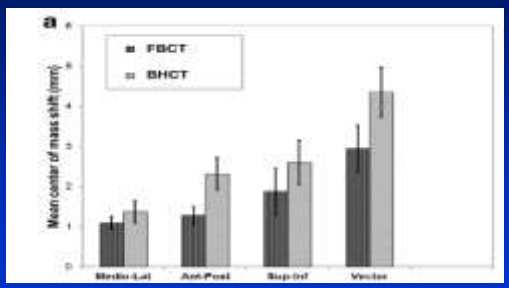
Table 1. Volume of liver and lung tumor obtained by manual contouring on helical CT scan and 4D-CT volumes

Scan/phase	Liver tumor volume (cm^3)	Lung tumor volume (cm^3)
Helical CT, light breathing	296.68	24.35
4D-CT 0%	246.38	19.10
4D-CT 20%	275.46	21.20
4D-CT 40%	248.53	19.65
4D-CT 60%	257.22	23.94
4D-CT 80%	253.68	24.91

Abbreviation: 4D-CT = four-dimensional computed tomography.

Rietzel E, et. al. Red J. Vol. 61, 1535-1550 (2005)

COM Shifts Between FBCT and BHCT



Courtesy of Ping Xia, Ph.D.

Potential Misalignment Between CBCT and FBCT

- If align to tumor between the CBCT and FBCT, the isocenter could be potentially misaligned, depending on which breathing phase of the tumor was captured in FBCT.

NM Woody et al, J Radiat Oncol, 2015

Free Breathing CT Only Represents a Snapshot of GTV location

CBCT align to tumor of AIP

CBCT align to bone of FB

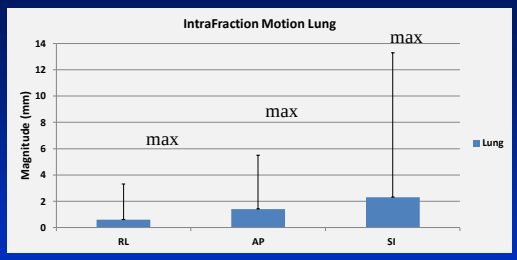
Courtesy of Ping Xia, Ph.D.

Planning CT for Lung SBRT

- How to align patient using kV-CBCT?
- If align to Free breathing CT, the iso-center could be misaligned
  - Depending on which phase the FBCT was acquired
- AIP should be used for planning CT
- What is AIP?
  - A synthetic CT derived from 4DCT using average intensity projections

How Big Are Intra-fractional Margins?

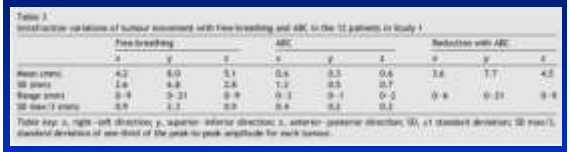
- Inconsistent data in the literature
- Tumor size and tumor location dependent
  - Small tumor moves more
  - Tumor in the lower lobe or near diaphragm moves more
- Intra-fraction margins are patient dependent and method/device dependent.



11 SBRT lung patients obtained 3CTs with three separate breath holds during simulation.

Courtesy of Ping Xia, Ph.D.

Breath Hold Reduces Intra-Fraction Tumor Motion



Mean (mm)	**3.6**	**7.7**	**4.5**
SD (mm)			

N. Panakis et al. Radiotherapy and Oncology 87 (2008) 65–73

PTV Margin?

- Free Breathing, obtain 4DCT to obtain ITV
- Tumor motion < 1 cm: PTV = 5 mm
- Tumor motion > 1 cm: PTV = 8 mm
- Irregular breathing trace: PTV = 8 mm
- Each direction is determined individually

Dosimetric Implication?

- AIP-based VMAT-SBRT planning approach is practical for lung tumor near diaphragm
- Discrepancy between AIP and 4D plans were less than 3% different
- However, AIP underestimates doses for OARs with large respiratory motion, such as liver and stomach

S Ohira et al, J Radiat Res 57(1), 2016.

Planning CT for Liver SBRT

- Multi-Phase IV contrast scans obtained using breath hold should be used for target delineation
- Exhale breath hold CT or average phase CT (from 4D CT) may be used as the baseline CT
- Exhale breath hold more reproducible and is closer to the average position than inhale
- Free Breathing CT are strongly discouraged
  - may be used if breath hold is not possible or if motion is < 5 mm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Potential systematic uncertainties in IGRT when FBCT reference images are used for pancreatic tumors

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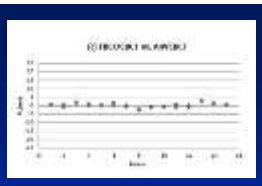
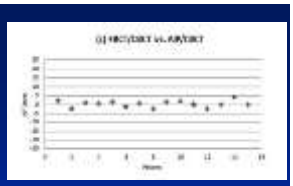
- For a total of 15 patients treated with conventional fractionation, with stent or implant markers.
- Both FBCT and 4DCT were acquired.
- The absolute mean discrepancies in iso-center shifts by aligning the markers between FBCT/CBCT and AIP/CBCT were studied.

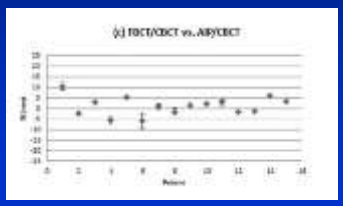
Courtesy of Ping Xia, Ph.D.



R/L: 1.1 mm ± 0.8 mm



A/P: 1.3 mm ± 0.9 mm



S/I: 3.3 mm ± 2.6 mm

Magnitude of Liver Motion

Reference	Technique	Magnitude of motion		
		CC (mm)	AP (mm)	RL (mm)
(17)	High-speed MRI	21.0	8.0	9.0
(18)	4DCT (w fiducials)	17.8±5.1	5.1±3.1	3.0±2.0
	CBCT (w fiducials)	16.5±5.7	5.3±3.1	2.8±1.8
(20)	4DCT	9.7±0.0	NA	NA
(19)	RTRT (w fiducials)	15.88±8.82	7.20±2.96	4.19±2.48

CC, cranial-caudal; AP, anterior-posterior; RL, right-left; MRI, magnetic resonance imaging; NA, not available.

Abbas 2014 J Gastrointest Oncol

Liver/Pancreas SBRT PTV Margins

- Dawson et al, IJROBP 2001
  - ABC Breathhold
  - Intrafraction: LR 1 mm, AP 1 mm, SI 2 mm
  - Interfraction: LR 4 mm, AP 4 mm, SI 7 mm
- Case et al, IJROBP 2010
  - Free Breathing with/WO abdominal compression
  - RL 2 mm, AP 4 mm, SI 8 mm
  - Liver amplitude consistent during TX
  - Beware of baseline shifts in soft tissue

Liver/Pancreas SBRT PTV Margins

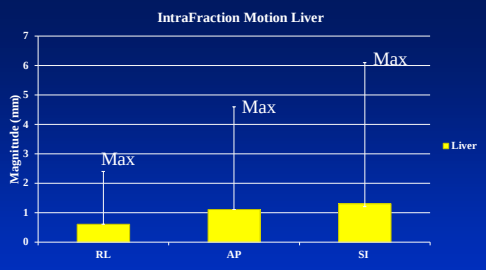
- Jayachandra et al, IJROBP 2010
  - Free breathing, respiratory gating
  - Align to bony anatomy
  - Shift based on Fiducials
    - AP: 95th percentile, 7 mm
    - LR: 95th percentile, 7 mm
    - SI: 95th percentile, 12 mm
  - Only 20% does not require shifts
- At UCSF, we expand breath hold GTV by 5 mm Axially and 8 mm Superior/Inferior

Pancreatic data

- Fusion between breath hold planning CT and CBCT based on vertebral bodies
- Location of dome and fiducials were measured
- Difference between dome position in relationship to bony anatomy and fiducial position in relationship to bony anatomy is within 1-2 mm S/I direction
- Dome of Diaphragm reasonable surrogate for Fiducial/Tumor position
- One patient has baseline shift, all CBCT are close in position, but differ from planning CT (7.5 – 10.5 mm with only 0.02 L difference in breath hold volume)

Liver data

- Fusion between breath hold planning CT and CBCT based on vertebral bodies
- Location of dome was measured
- SDX breath hold volumes were examined
- In general, patients breath hold volume deviate from 0.2 L by minute amount, ranging from 0.01 to 0.03 L in most patients.
- 2 patients have larger breath hold volume deviation, ranging from 0.04 – 0.07 L, generally worse during TX
- However, this does not translate to larger dome position deviations
- S/I positions differ from CT ranging from 1.5 – 2.4 mm, A/P < 1 mm and L/R 1 – 2 mm



14 SBRT liver patients obtained 3CTs with three separate breath holds during simulation.

Courtesy of Ping Xia, Ph.D.

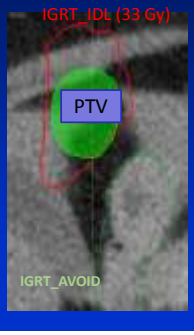
What's Next?

- Current margins are good for accurate and safe treatments
- Individualized margin might be good for patient whose SDX breath hold volume deviation from 0.2 L by less than 0.02 L
- Baseline shift could be an issue for some patients since S/I margin might need to be increased to 1 cm to account for the inter-fraction difference in dome/fiducial location

Planning CT and Margins for Liver SBRT

- Inter-fractional variation and soft tissue baseline shifts – 5 mm axially and 8 mm Superior/Inferior

IGRT: Avoidance isodose surfaces



- At time of treatment, assess overlap between IGRT_IDL and avoidance OAR
- IGRT_AVOID provides guidance for identifying OAR(s) of interest
- Treatment should be cancelled if significant overlap cannot be avoided
- Consider dietary counselling

Summary

- 4D-CT is useful to understand the profile of the intra-fraction tumor motion.
- Using abdominal compression, or breath-hold treatment to minimize intra-fraction motion.
- Due to interfractional soft tissue baseline shift, margin consideration is important, and could be individual
- Under CBCT guidance, using free breathing CT may introduce a misalignment if directly aligning to the tumor or implant markers.
- AIP CT is a better choice as planning CT under CBCT IGRT.