Sources of Motion: Imaging and Monitoring

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Outline

- Within the context of photon Stereotactic Body Radiation Therapy (SBRT)
  - Definition SBRT and margin consideration
  - Sources of motion and management
  - Special consideration in SBRT for various sites

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Why SBRT needs special attention on motion management?

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Definition of SBRT

- Important characteristics:
  - High fractional dose
  - Precise target definition
  - Margin in millimeter range
  - Direct imaging monitoring and accurate dose delivery
- SBRT is used in various sites: lung, liver, pancreas, prostate, spine, head-and-neck, and others

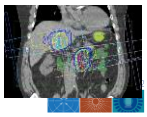
NRG-BR001/002: SBRT for Multiple Metastases

Metastatic Locations	Initial Starting Dose
Lung–Peripheral	45 Gy (3 fractions)
Lung – Central	50 Gy (5 fractions)
Mediastinal/Cervical Lymph Node	50 Gy (5 fractions)
Liver	45 Gy (3 fractions)
Spinal/Paraspinal	30 Gy (3 fractions)
Osseous	30 Gy (3 fractions)
Abdominal pelvic metastases (lymph node/adrenal gland)	45 Gy (3 fractions)

Fraction dose 10-15Gy in 3-5 fractions

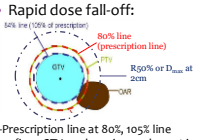
Benedict et al. AAPM TG101

Characteristic	3D/IMRT	SBRT
Dose/fraction	1.8–3 Gy	6–30 Gy
No. of fractions	10–30	1–5
Target definition	CTV/PTV (gross disease + clinical extension): Tumor may not have a sharp boundary.	GTV/CTV/ITV/PTV (well-defined tumors: GTV=CTV)
Margin	Centimeters	Millimeters
Physics/dosimetry monitoring	Indirect	Direct



PTV Margin Consideration

- Tight margin:
  PTV=GTV/ITV + 3-7mm margin
- Rapid dose fall-off:



--Prescription line at 80%, 105% line confines GTV, and maximum dose at iso

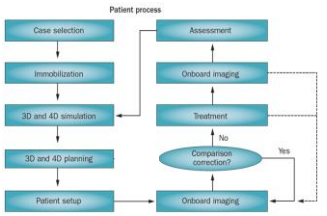
--R50% and Dmax at 2cm also tightly restricted

NRG-BR001/002: SBRT for Multiple Metastases

Planning Parameter	Metastatic Location: Lung Central	Lung Peripheral	Liver	Abdominal pelvic	Mediastinal Cervical Lymph Nodes	Osseous	Spinal
CT window/level	Pulmonary/ mediastinal	Pulmonary/ mediastinal	Hepatic	Soft tissue	Pulmonary/ mediastinal	Bone/soft tissue	Bone/soft tissue
Additional Studies	PET/CT	PET/CT	PET/CT MRI	PET/CT MRI	PET/CT	PET/CT MRI	PET/CT MRI
Multiphase CT	N/A	N/A	N/A	Yes	N/A	N/A	N/A
Anatomy of focus for multi modality fusion	Bony Anatomy	Bony Anatomy	Liver	Bony anatomy	Bony anatomy	Bony anatomy	Bony anatomy
GTV definition	metastasis	metastasis	metastasis	metastasis	metastasis	metastasis	metastasis
CTV definition	= GTV/ITV*	= GTV/ITV*	= GTV/ITV*	=GTV/ITV*	= GTV/ITV*	= GTV	= GTV
PTV axial expansion	= CTV + 5mm**	= CTV + 5mm**	= CTV + 5mm**	= CTV + 5mm**	= CTV + 5mm**	= CTV + 5mm**	= PTV in RTOG 0631** (see Figure 8-2)
PTV craniocaudal expansion	= CTV + 7mm**	= CTV + 7mm**	= CTV + 7mm**	= CTV + 7mm**	= CTV + 7mm**	= CTV + 7mm**	= PTV in RTOG 0631** (see Figure 8-2)

Achieve Precision in SBRT Workflow

- PRECISION is the key for the success of SBRT treatment
- Consider motion management in every step



Sources of motion and their management

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Sources of Motion in RT

- Level One: patient position/external motion:
  - Patient position at treatment differs from the planning scan
  - i.e. moving a limb, head tilt, body rotation, etc.
- Level two: Inter-fractional organ/target motion:
  - GTV/CTV position changes on a day-to-day level;
  - OARs position/volume changes, i.e. bladder, rectum, bowel, etc.
- Level three: Intra-fraction organ/target motion
  - HN region: upper airway motion and swallowing
  - Lung/upper abdominal region: respiratory motion, cardiovascular system motion, etc.
  - Lower abdominal region: prostate, cervix, etc.

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Level One Management: Patient Immobilization

- Importance:
  - Provide an initial approximate patient setup and target localization
  - Provide body fixation, high reproducibility and accuracy
  - Solely relying on image guidance is not allowed
- Typical devices:
  - Thermoplastic mask,
  - Platform/couch-top, vacuum cushion, bridge with respiratory plate or belt
  - Knee fix, feet fix, etc.

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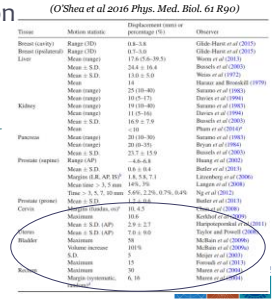
Inter-fraction Organ Motion

- Daily organ displacement can be significant
  - Prostate: bladder, rectum, prostate, etc.
  - Liver, pancreas, kidney all have day-to-day displacement
- Level two motion management strategies
  - Organ immobilization
  - IGRT localization

(O'Shea et al 2016 Phys. Med. Biol. 61 R90)



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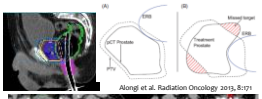
Organ Immobilization

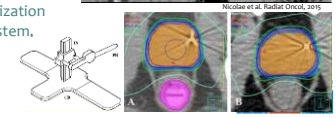
- Bladder
  - Full bladder protocol (volume change still significant >20%)
- Rectum
  - Endorectal balloon (ERB): high dose of the anterior rectal surface, deformation
  - Rectal spacers: biocompatible liquid gel to create physical separation, no evidence of prostate immobilization
  - Endorectal immobilization system, intra-fraction motion<3mm

B L Jones et al, Phys. Med. Biol. 58 (2013)



Alongi et al. Radiation Oncology 2013, 8:171

Nicolae et al. Radiat Oncol. 2015



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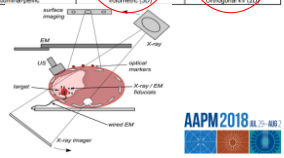
IGRT for Target Localization

- Daily In-room Image Guidance
  - Target visualization and localization
  - Online correction (minimal 3 orthogonal directions)
- Available imaging modalities:
  - Volumetric 3D: kV-CBCT, MV-FBCT, MV-CBCT, CT-on-rail, MRgRT,
  - 2D orthogonal with metal/EM fiducials: kV OBI, ExacTrac, Cyberknife, etc.
  - Others: 4D CBCT, 3D Ultrasound, 6D couch, etc.

NRG-BR001/002: SBRT for Multiple Metastases

Metastatic Location	Minimum IGRT Requirement	
	No Fiducials	With Fiducials*
Lung--Peripheral*	Volumetric (3D)	Orthogonal kV (2D)
Lung--Central*	Volumetric (3D)	Orthogonal kV (2D)
Mediastinal/Cervical LN	Volumetric (3D)	N/A
Liver*	Volumetric (3D)	Orthogonal kV (2D)
Spinal	Orthogonal kV (2D)	Orthogonal kV (2D)
Osseous*	Orthogonal kV (2D)	N/A
Abdominal-pelvic*	Volumetric (3D)	Orthogonal kV (2D)



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Intra-fraction Target/Organ Motion

- Level three motion management: further minimize and/or monitor target motion to meet the tight margin requirement (3-7mm)
- Thoracic and abdominal sites:
  - Respiratory motion
  - Cardiovascular system motion, etc.
- Prostate motion
- HN: upper airway motion, swallowing

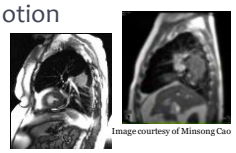

Image courtesy of Minsong Cao

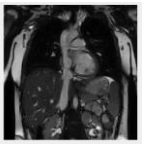

Image courtesy of Hua Li

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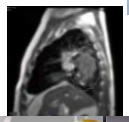
Intra-fractional Monitoring

- 2D Modalities:
  - Onboard kV-Fluoroscopy
  - Onboard MV-Cine
  - Floor/ceiling mount kV-kV: ExacTrac and CyberKnife
  - MR-Cine
- Application
  - Motion assessment at simulation
  - Motion monitoring during treatment
- Others: Surface imaging, Ultrasound, EM system, etc.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Special Consideration for Lung/Abdominal SBRT

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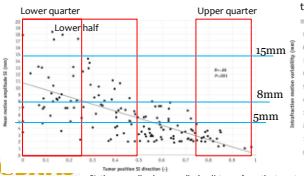
Lung Tumor Motion Pattern

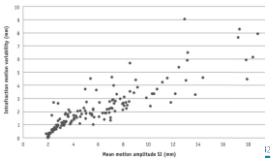
Knybel et al. IJROBP 2016

- 145 lung SBRT patient treated with CyberKnife
- Motion range in SI direction during treatment



SI: the normalized perpendicular distance from the target center to the apex of the diaphragm, exhale CT

The larger the tumor motion amplitude, the higher the intra-fraction amplitude variability observed



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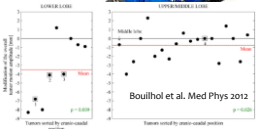
Abdominal Compression

- Lung SBRT with compression:
  - Mean motion reduction: 3.5mm for lower lobe and 0.8mm for upper/middle lobe
  - Mean ITV reduction: 3.6cc for lower lobe and 0.2cc for upper/middle lobe
- Liver SBRT with compression:
  - Mean liver motion measured with 4D CBCT prior to treatment: 1.2 mm (LR), 2.3mm (AP) and 4.7 mm (SI)



Bouilhol et al. Med Phys 2012

Shimohigashi et al Radiot Oncol 2017

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ITV volume reduction with the abdominal compression

Uncertainties should be taken into account for ITV → PTV margin

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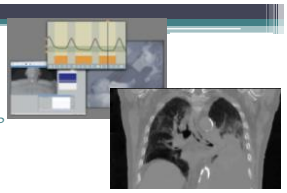
Simulation with Motion

- Common Practice:
  - 4D CT Imaging using surface motion trajectory →10phases CT, MIP, AIP, MinIP
  - Additional scans: FB-CT, Inhale/Exhale BH-CT
- 4D CT Image Quality Challenges:
  - Poor soft-tissue contrast
  - Breathing Irregularity, rely on only one breathing cycle
  - Poor correlation between internal target and external surrogates



Verification of 4D CT

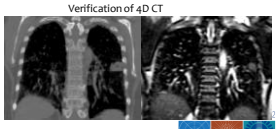


Image courtesy of Jing Cai

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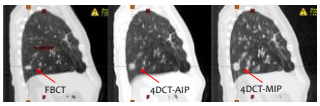
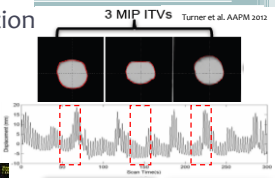
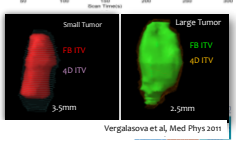
Uncertainties in ITV Definition

- ITV uncertainties caused by
  - Different breathing pattern
  - Phase binning vs. amplitude binning
  - Different imaging mode
  - Tumor size







Vergalasova et al, Med Phys 2011

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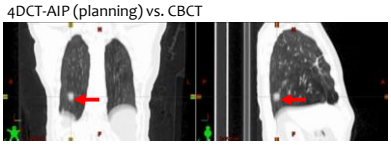
Uncertainties in 3D Target Matching

- 4DCT-AIP (planning) vs. CBCT



Cai et al, AAPM 2015

FB CT

- Inter-observer variations:
- kV CBCT vs. MVCT:

Cui et al, JIROBP, 2011

Table 3 Registration differences between institutions and reviewers (for different imaging modalities)

Imaging modality	No. of datasets	Absolute value of difference of shifts (mm), mean ± SD (range)		
		Left-right	Superior-inferior	Anterior-posterior
kV CBCT	96	1.7 ± 1.1 (0.0-6.7)	1.6 ± 0.9 (0.0-6.9)	1.7 ± 1.1 (0.0-5.0)
MVCT	37	1.5 ± 1.0 (0.1-5.1)	1.7 ± 1.7 (0.1-8.2)	1.9 ± 0.9 (0.0-7.3)
Overall	133	1.7 ± 1.0 (0.0-6.7)	2.2 ± 1.5 (0.0-8.2)	1.8 ± 1.0 (0.0-7.3)

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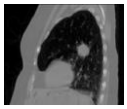
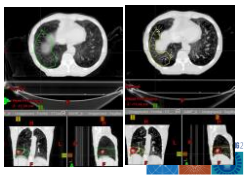
Uncertainties in Treatment Planning

- 4DCT AIP vs. MIP
  - MIP has slightly better target coverage
  - MIP is susceptible to motion artifacts
  - MIP is prone to under- or over-estimate both OAR and target volumes
- 4DCT AIP is recommended for planning





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Tian et al, Med Phys 2012

Tumor Motion and Overall Uncertainties

- Inter- and Intra-fractional Tumor Motion
- Uncertainties during simulation, treatment planning, treatment delivery
- Can we safely conform target dose within the required margin?
- Other strategies…

PTV=ITV+5-7 mm MARGIN

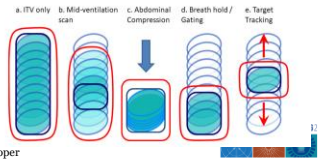

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Image courtesy of Ben Cooper

Special Consideration for other SBRT Sites: Prostate, HN, Heart, etc.

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Prostate Motion

- Prostate SBRT requires high fraction dose and tight margin (3-5mm)
- Intra-fractional prostate motion is observed
  - Prostate motion and volume deformation
  - Involuntary prostate motion due to bowel gas movement (>1cm)

NRG GU005 Prostate SBRT protocol

Arm 2: SBRT

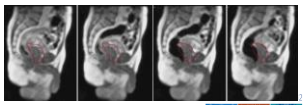
36.25 Gy in 5 fractions of 7.25 Gy to the prostate +/- proximal 1 cm of seminal vesicles

Minimal Margins:
5 mm superior inferior & laterally,
3 mm anterior & posterior

RTOG 0938
PTV = CTV + **3 mm** posterior margin and **5 mm** in all other dimensions. (If necessary, the ant margin can be reduced to 3 mm.)

Nicolae et al. Radiat Oncol, 2015

Study	Sample size (n)	Technique	Immobilization	Motion Evaluation	3D intrafraction motion	Treatment time (min)
Current study	20	VMAT	EIS	Pre-post CBCT	0 % > 3 mm	>6
Chiang et al. 2014 [10]	30	VMAT	ERB	Pre-post CBCT	3.4 % > 3.1 mm	>6
Smeenk et al. 2012 [11]	30	IMRT	ERB	Real-time EM tracking	7.0 % > 3 mm	>8
Wang et al. 2012 [10]	30	IMRT or VMAT	ERB	Real-time EM tracking	5.0 % > 3 mm	>8
Both et al. 2011 [12]	24	IMRT or VMAT	ERB	Real-time EM tracking	3.2 % > 3 mm	>8

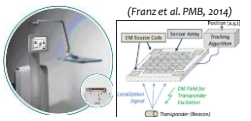


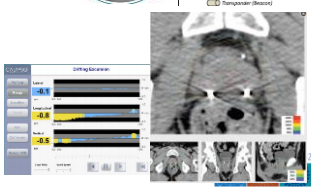
Prostate motion due to rectal distention
Hegde et al, Cureus, 2018

Electromagnetic System

- Calypso system: EM source coils, EM transponders (Beacon™), and sensor array
- Advantages: patient positioning and intra-fraction monitoring;
- Accuracy 1-2 mm
- Limitations:
  - Invasive, need to implementing 3 markers
  - Special Calypso kVue™ couch
  - Patient size, metal implants, pacemaker

(Franz et al. PMB, 2014)





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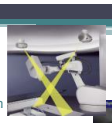
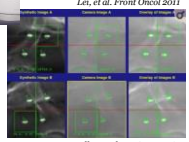
CyberKnife

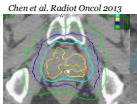
- CyberKnife system
  - Robotic gantry, 6D couch, tracking system
  - Transrectal Implant 3 gold markers
  - kV-kV images acquired during treatment, at intervals 5-90s
- Achieve sub-millimeter accuracy
  - 36.25Gy/4 fractions to PTV (margin: 5mm, 3mm posterior)
  - 38Gy/4 fractions to PTV (virtual HDR dose, with 2-5mm margin, 0mm posterior)



Lei, et al. Front Oncol 2011



Chen et al. Radiot Oncol 2013



Fuller, et al. IJROBP 2008

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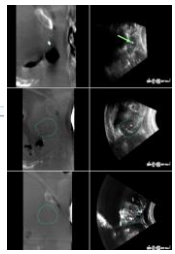
3D Ultrasound System

- Clarity Autoscan System
  - TPUS probe, a baseplate, knee rest, IR camera tracking the probe
  - Acquired baseline image at SIM
  - Intra-fractional monitoring and correction, compared with the baseline image
- Autoscan vs. marker-measured motion: median error<3mm



Limit of agreement	u-Axis, mm	v-Axis, mm	2D magnitude, mm
25%	−0.2 to 0.3	−0.2 to 0.4	0.6
50%	−0.5 to 0.6	−0.5 to 0.7	1.0
75%	−0.9 to 1.0	−1.1 to 1.1	1.5
95%	−2.0 to 2.1	−2.5 to 1.9	2.6
|Δ|	0.6	0.6	1.0

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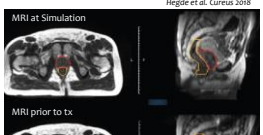
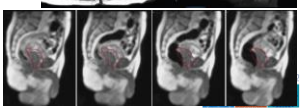
MRgRT

Hegde et al. Cureus 2018

- MRgRT for Localization
  - No need for gold marker/EM beacon implantation
  - Improved image quality and visualization
- MR-Cine for Target Monitoring
  - Intra-fractional prostate motion (thin red line) due to rectal distension from bowel gas movement
  - Treat with 3mm PTV margin, Gated delivery with dose shut-off at >3mm (*Hegde et al. Cureus 2018*)





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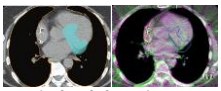
Hegde et al. Cureus 2018

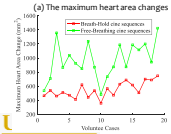
Heart SBRT

Cuculich et al, NEJM 2017

- Heart motion monitoring and management is needed for Ventricular Tachycardia Ablation (25Gy in one fraction)
- Heart volume change and centroid shift (2-8mm)
- MR Cine application: in-treatment motion analysis and heart margin assessment



Targeting the arrhythmogenic scar regions, matching with CBCT



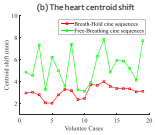


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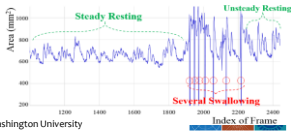
Image Courtesy of Hua Li, Washington University

Head and Neck SBRT

- Upper airway motion during resting
  - **Non-symmetric** displacements of anterior (mean 2.6mm), posterior (2.9mm), inferior (3.5mm), and superior (0.7mm) boundaries
  - For patients **with tracheostomy tube**, displacement > 4 mm
- Displacement can be higher during swallowing



Slide Courtesy of Hua Li, Washington University

Summary

- SBRT indicates high fraction dose, tight PTV margin, and rapid dose falloff
- Sources of motion and different levels of management strategies
- Special motion management consideration for all SBRT sites
  - Lung/abdomen SBRT
  - Prostate SBRT
  - Heart and HN SBRT

Thank You