Site Specific IGRT Considerations for Clinical Imaging Protocols

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Outline

- Image registration accuracies for different modalities
  - What imaging modality best suited for each site, and Tx type?
- For each site, will discuss
  - Site-specific goals and uncertainties
  - Dosimetric consequences of exceeding tolerances
  - Desirable IGRT characteristics and feasible systems to achieve goals
  - IGRT process designs to minimize site-specific uncertainties
  - Sites used as examples of critical thinking process in this presentation: lung, liver, prostate, spine SBRT, H&N
- Offline and on-line correction strategies
  - Differences
  - Importance of time and efficiency of verification.
  - How to use them and when to use them

- Image registration accuracies for different modalities
  - What imaging modality best suited for each site?
  - What imaging modality best suited for each Tx type ?

Executive summary of AAPM/ASTRO on image guided technologies

Critical Review

Image Guided Radiation Therapy (IGRT) Technologies for Radiation Therapy Localization and Delivery

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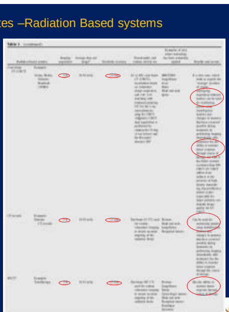
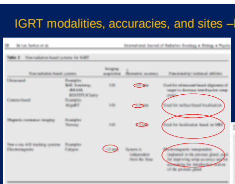
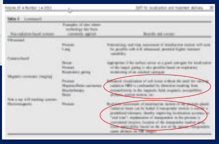
IGRT modalities, accuracies, and sites –Radiation Based systems



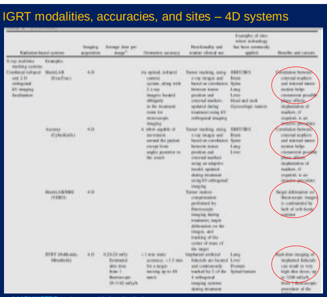
IGRT modalities, accuracies, and sites –Non Radiation based systems





Executive summary of AAPM/ASTRO on image guided technologies
J. De Los Santos et al. “ Iimage guided radiation therapy (IGRT) technologies for radiation therapy localization and delivery”
IJROBP 87(1) 33-45; 2013

IGRT modalities, accuracies, and sites – 4D systems



Executive summary of AAPM/ASTRO on image guided technologies

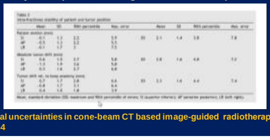
J. De Los Santos et al. " Iimage guided radiation therapy (IGRT) technologies for radiation therapy localization and delivery" IJROBP 87(1) 33-45; 2013

Site specific Inter and intra fraction mobility

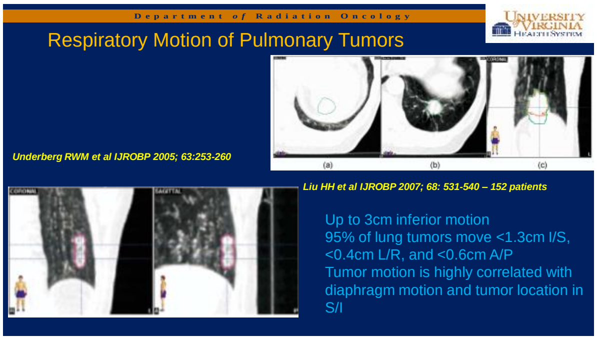
- Site-specific goals and uncertainties
- Dosimetric consequences of exceeding tolerances
- Desirable IGRT characteristics and feasible systems to achieve goals
- IGRT process designs to minimize site-specific uncertainties

Intra-fractional uncertainty of Pulmonary tumors with SBRT Tx

- Stereotactic body frame
- Motion of bony anatomy used as a surrogate for patient motion
- 1 -3 fractions lung SBRT, 27 lung lesions
- CBCT pre and post Tx – change in motion envelope
- Bony anatomy is a poor surrogate for tumor position



M. Guckenberger et al. " Intra-fractional uncertainties in cone-beam CT based image-guided radiotherapy (IGRT) of Pulmonary tumors" Radiotherapy Oncology 83 (2007) 57-64



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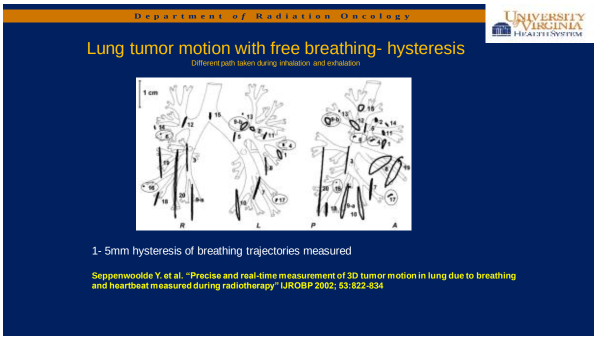
Respiratory Motion of Pulmonary Tumors

Underberg RWM et al IJROBP 2005; 63:253-260

Liu HH et al IJROBP 2007; 68: 531-540 – 152 patients

Up to 3cm inferior motion
95% of lung tumors move <1.3cm I/S, <0.4cm L/R, and <0.6cm A/P
Tumor motion is highly correlated with diaphragm motion and tumor location in S/I



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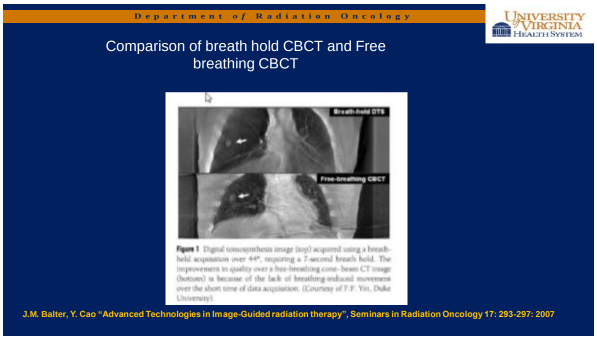
Lung tumor motion with free breathing- hysteresis

Different path taken during inhalation and exhalation

1- 5mm hysteresis of breathing trajectories measured

Seppenwoolde Y. et al. "Precise and real-time measurement of 3D tumor motion in lung due to breathing and heartbeat measured during radiotherapy" IJROBP 2002; 53:822-834



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Comparison of breath hold CBCT and Free breathing CBCT

Figure 1 Digital tomosynthesis image (top) acquired using a breath-held acquisition over 44°, requiring a 7-second breath hold. The improvement in quality over a free-breathing cone- beam CT image (bottom) is because of the lack of breathing-induced movement over the short time of data acquisition. (Courtesy of F.F. Yin, Duke University).

J.M. Balter, Y. Cao "Advanced Technologies in Image-Guided radiation therapy", Seminars in Radiation Oncology 17: 293-297: 2007

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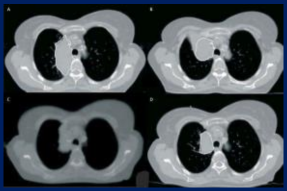
Change in volume and position of adenocarcinoma of right lung during radiotherapy



GTV changes from original CT scan (A), to repeat CT scan on day 24 (B), MVCT scan from Tomotherapy on day 60 ©, kVCT scan on day 67 (D)

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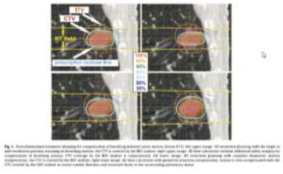
Gating and real-time tracking to improve pulmonary accuracy of SBRT



M. Guckenberger, T. Krieger, et al. "Potential of image-guidance, gating and real-time tracking to improve accuracy in pulmonary stereotactic body radiotherapy", Radiotherapy Oncology 19: 288-295: 2009

Lung

- Site-specific goals and uncertainties (e.g. periodic breathing motion, need soft tissue visualization)
- Desirable IGRT characteristics (e.g. soft tissue visualization, ability to assess if breathing motion similar to time of sim → CBCT)
- IGRT Process Decisions (e.g. Transfer ITV for matching to ensure motion-averaged CBCT target aligns within ITV)

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Liver motion with free breathing

- Intra-fraction liver motion – 3-18 mm in CC dimension

Case. R. et al "Interfraction and intrafraction changes in amplitude of breathing motion in stereotactic liver radiotherapy ", IJROBP 77 (3): 918- 925: 2010

- Inserted fiducial marker motion has shown Intra fraction liver tumor motion
  - ML direction ~ 1 -12 mm
  - CC direction ~ 2 -19 mm
  - Ap direction ~ 2 – 12 mm

Kitamura, K. , Shirato, H., Seppenwoolde Y. et al "Tumor location, cirrhosis, and surgical history contribute to tumor movement in the liver, as measured during stereotactic irradiation using a real-time tumor-tracking radiotherapy system", IJROBP 56: 221 -228: 2003

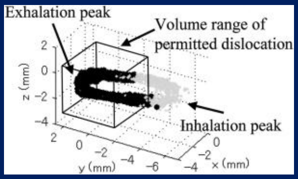
Liver motion with free breathing

- The tumor motion of the left lobe was significantly less than that of the right lobe in the LR (2± 1 vs 5 ± 4 mm, *p* = 0.01) and AP (3 ± 2 vs. 6 ± 3 mm, *p* = 0.01) directions.
- The tumor motion of the patients with liver cirrhosis was significantly greater than that of the patients without liver cirrhosis in the LR (7 ± 4 vs. 2 ± 1 mm, *p* = 0.0008) and AP (7 ± 3 vs. 3 ± 2 mm, *p* = 0.004) directions.
- The tumor motion of the patients who had received partial hepatectomy was significantly less than that of those who had no history of any operation on the liver in the LR (5 ± 4 vs. 2 ± 1 mm, *p* = 0.04) and AP (6 ± 3 vs. 3 ± 2 mm, *p* = 0.03) directions.

Kitamura, K. , Shirato, H., Seppenwoolde Y. et al "Tumor location, cirrhosis, and surgical history contribute to tumor movement in the liver, as measured during stereotactic irradiation using a real-time tumor-tracking radiotherapy system", IJROBP 56: 221 -228: 2003

Liver motion with free breathing- hysteresis

Different path taken during inhalation and exhalation



3D path of tumor during beam delivery for a single day. Black dots represent irradiated tumor position; gray dots represent nonirradiated tumor position every 0.09 s. Permitted dislocation shown as a 2-mm box around the exhalation peak. x, LR; y, CC; and z, AP.

Kitamura, K. , Shirato, H., Seppenwoolde Y. et al "Tumor location, cirrhosis, and surgical history contribute to tumor movement in the liver, as measured during stereotactic irradiation using a real-time tumor-tracking radiotherapy system", IJROBP 56: 221 -228: 2003

Measurements of Abdominal Tumor Motion

Bradner GS et al IJROBP 2006; 65: 554-560 – 13 patients

- Up to 2.5cm inferiorly for all tumors, motion up to 1.2 cm A/P observed for liver and kidneys
- Mean S/I displacements: Liver 1.3cm; Spleen 1.3 cm; Kidneys 1.2cm

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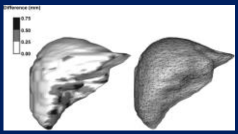
Liver motion with breath hold (ABC) and intra-arterial microcoils

- Intra-fraction liver motion in CC dimension
  - 2.5 mm (range 1.8 –3.7 mm) -diaphragm
  - 2.3 mm (range 1.2–3.7 mm) – hepatic microcoils
- Inter-fraction liver motion in CC dimension
  - 4.4 mm (range 3.0–6.1 mm) -diaphragm
  - 4.3 mm (range 3.1–5.7 mm)- hepatic microcoils

Need daily on-line imaging and repositioning if treatment margins smaller than those required for free breathing are a goal.

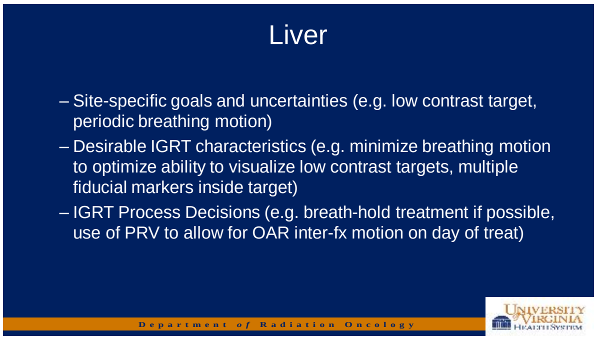
Dawson, LA, Brock,KK et. al. "The reproducibility of organ position using active breathing control (ABC) during liver radiotherapy", IJROBP 51; 1410-21 (2001)

Intra-fraction reproducibility of liver with ABC breath hold



breath-hold computed tomography (CT) scans at the time of simulation. On the left, the liver from the second CT is registered to the liver from the first CT scan using a finite element mesh-based deformable registration tool. The gray scale shows the absolute difference in the position of the liver surfaces. White represents differences within 2.5 mm, whereas black representing differences of 5–7.5 mm. On the right, the first CT is shown in solid and the second is shown in wire frame.

Eccles C., Brock K.K. et. al. "Reproducibility of liver position using active breathing coordinator for liver cancer radiotherapy", IJROBP 64 (3); 751-759 (2006)



Liver

- Site-specific goals and uncertainties (e.g. low contrast target, periodic breathing motion)
- Desirable IGRT characteristics (e.g. minimize breathing motion to optimize ability to visualize low contrast targets, multiple fiducial markers inside target)
- IGRT Process Decisions (e.g. breath-hold treatment if possible, use of PRV to allow for OAR inter-fx motion on day of treat)

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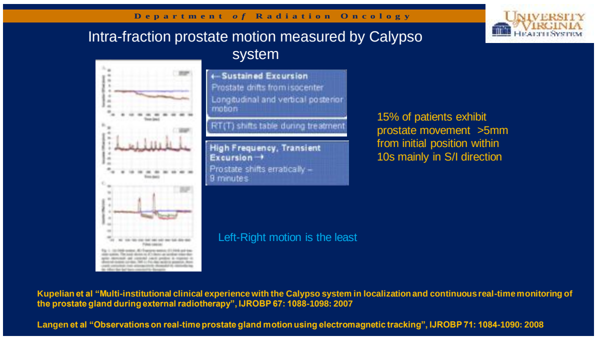

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Intra-fraction prostate motion measured by Calypso system

←Sustained Excursion
Prostate drifts from isocenter
Longitudinal and vertical posterior motion
RT(T) shifts table during treatment

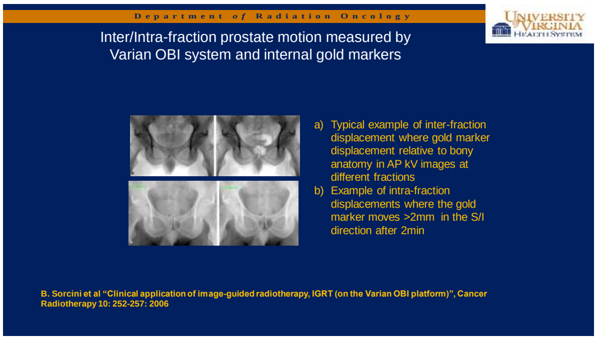
High Frequency, Transient Excursion→
Prostate shifts erratically – 9 minutes

15% of patients exhibit prostate movement >5mm from initial position within 10s mainly in S/I direction

Left-Right motion is the least

Kupelian et al "Multi-institutional clinical experience with the Calypso system in localization and continuous real-time monitoring of the prostate gland during external radiotherapy", IJROBP 67: 1088-1098: 2007

Langen et al "Observations on real-time prostate gland motion using electromagnetic tracking", IJROBP 71: 1084-1090: 2008



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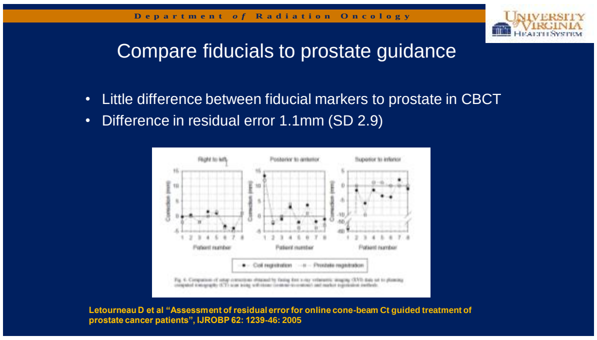
Inter/Intra-fraction prostate motion measured by Varian OBI system and internal gold markers

a) Typical example of inter-fraction displacement where gold marker displacement relative to bony anatomy in AP kV images at different fractions
b) Example of intra-fraction displacements where the gold marker moves >2mm in the S/I direction after 2min

B. Sorcini et al "Clinical application of image-guided radiotherapy, IGRT (on the Varian OBI platform)", Cancer Radiotherapy 10: 252-257: 2006



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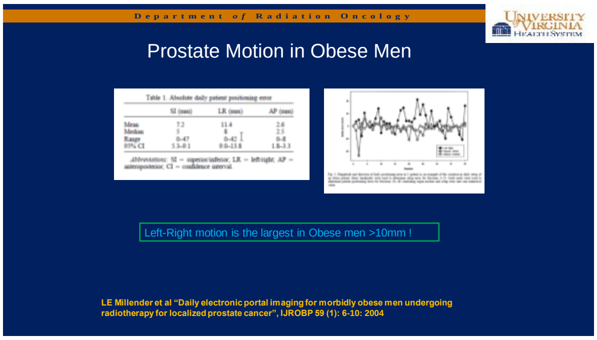
Compare fiducials to prostate guidance

- Little difference between fiducial markers to prostate in CBCT
- Difference in residual error 1.1mm (SD 2.9)

Letourneau D et al "Assessment of residual error for online cone-beam Ct guided treatment of prostate cancer patients", IJROBP 62: 1239-46: 2005



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Prostate Motion in Obese Men

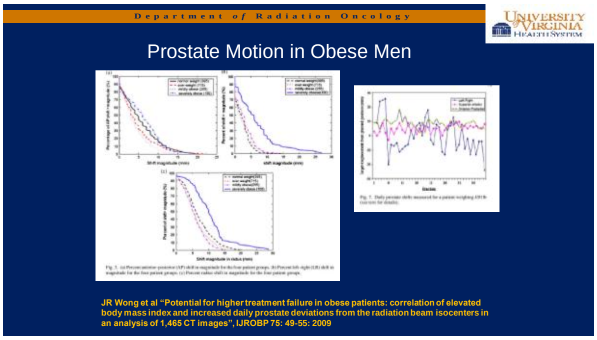
Table 1. Absolute daily patient positioning error

	SI (mm)	LR (mm)	AP (mm)
Mean	7.2	11.4	2.6
Median	5	8	2.5
Range	0–47	0–42	0–8
95% CI	5.3–9.1	9.0–13.8	1.8–3.3

Abbreviations: SI = superior/inferior; LR = left/right; AP = anteroposterior; CI = confidence interval.

Left-Right motion is the largest in Obese men >10mm !

LE Millender et al "Daily electronic portal imaging for morbidly obese men undergoing radiotherapy for localized prostate cancer", IJROBP 59 (1): 6-10: 2004



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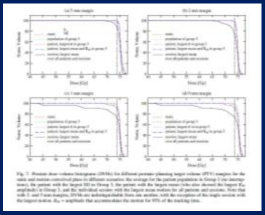
Prostate Motion in Obese Men

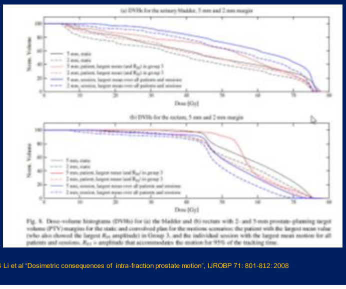
JR Wong et al "Potential for higher treatment failure in obese patients: correlation of elevated body mass index and increased daily prostate deviations from the radiation beam isocenters in an analysis of 1,465 CT images", IJROBP 75: 49-55: 2009

Dosimetric consequences of prostate motion



- HS Li et al "Dosimetric consequences of intra-fraction prostate motion", IJROBP 71: 801-812: 2008

Dosimetric consequences of prostate motion



- HS Li et al "Dosimetric consequences of intra-fraction prostate motion", IJROBP 71: 801-812: 2008

Clinical impact of prostate motion in Obese Men

Probability of 10-year biochemical failure-free survival after EBRT for obese patients is:
20-25% lower than that for the normal weight
62-65% lower than for mildly obese patient group

- Strom et al "Influence of obesity on biochemical and clinical failure after external-beam radiotherapy for localized prostate cancer", Cancer 107: 631-639: 2006

Prostate

- Site-specific goals and uncertainties (e.g. discrete and unpredictable target motion)
- Desirable IGRT characteristics (e.g. soft tissue visualization, periodic intra-fx verification)
- IGRT Process Decisions (e.g. tradeoffs and clinical use of CBCT and OBI-fiducial-based imaging)

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Intra-Fraction Motion of Spine During SBRT

3.3 mm –Using a stereotactic body frame

Shiu AS, Chang AL, et al. "Near simultaneous computed tomography image guided stereotactic spine radiotherapy: an emerging paradigm for achieving true stereotaxy" IJROBP 57: 605-613 (2013)

5.2 mm – using whole body vaccum cushion

Yanice kM,Lovelock DM, et al. "CT image guided intensity odulated radiation therapy for paraspinal tumors using stereotactic immobilization", IJROBP 55: 583-593 (2003)

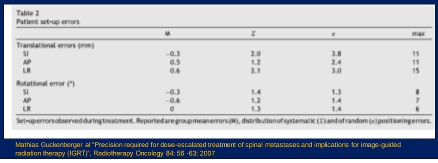

Table 2
Patient set-up errors

	M	Σ	σ	max
Translational errors (mm)				
SI	−0.3	2.0	3.8	11
AP	0.5	1.2	2.4	11
LR	0.6	2.1	3.0	15
Rotational error (°)				
SI	−0.3	1.4	1.3	8
AP	−0.6	1.2	1.4	7
LR	0	1.3	1.4	6

Set-up errors observed during treatment. Reported are group mean errors (M), distribution of systematic (Σ) and of random (σ) positioning errors.

Mathias Guckenberger al "Precision required for dose-escalated treatment of spinal metastases and implications for image-guided radiation therapy (IGRT)", Radiotherapy Oncology 84: 56 -63: 2007

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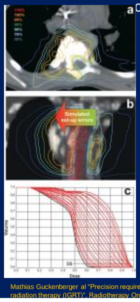
Precision Requirements for Spine SBRT –Dosimetric consequences

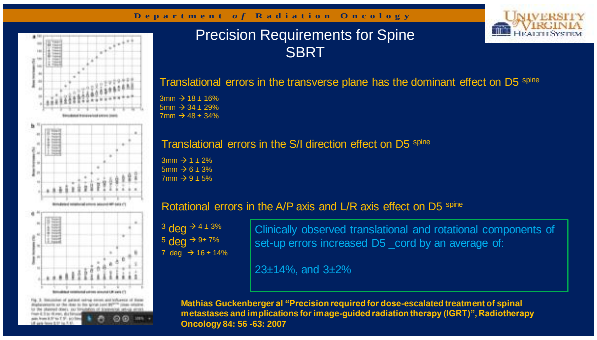


a) Dose distribution in the axial plane
b) Simulated transversal patient set-up errors (0.5-1.00mm) with resulting displacements of the spinal cord
c) Dose to the spinal cord:
    - Black – prescribed dose from Tx plan
    - Red – dose distributions resulting from simulated set up errors

To keep dose to spinal cord within ± 5% (± 10%) of the Rx dose maximum errors should be within

1mm (2mm)- transverse
4mm (7mm) – S/I
3.5 deg (5 deg) - rotations

Mathias Guckenberger al "Precision required for dose-escalated treatment of spinal metastases and implications for image-guided radiation therapy (IGRT)", Radiotherapy Oncology 84: 56 -63: 2007



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Precision Requirements for Spine SBRT

Translational errors in the transverse plane has the dominant effect on D5 ^{spine}

3mm → 18 ± 16%
5mm → 34 ± 29%
7mm → 48 ± 34%

Translational errors in the S/I direction effect on D5 ^{spine}

3mm → 1 ± 2%
5mm → 6 ± 3%
7mm → 9 ± 5%

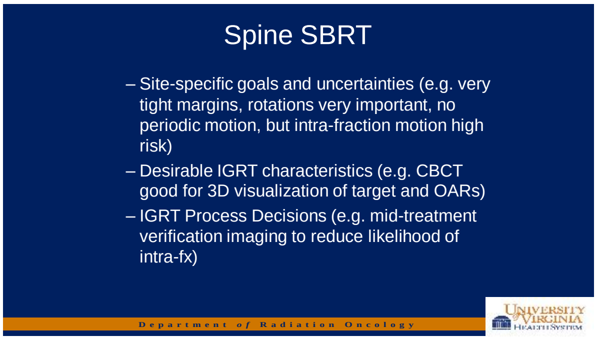
Rotational errors in the A/P axis and L/R axis effect on D5 ^{spine}

^{3} deg → 4 ± 3%
^{5} deg → 9± 7%
7 deg → 16 ± 14%

Clinically observed translational and rotational components of set-up errors increased D5 _cord by an average of:

23±14%, and 3±2%

Mathias Guckenberger al "Precision required for dose-escalated treatment of spinal metastases and implications for image-guided radiation therapy (IGRT)", Radiotherapy Oncology 84: 56 -63: 2007



Spine SBRT

- Site-specific goals and uncertainties (e.g. very tight margins, rotations very important, no periodic motion, but intra-fraction motion high risk)
- Desirable IGRT characteristics (e.g. CBCT good for 3D visualization of target and OARs)
- IGRT Process Decisions (e.g. mid-treatment verification imaging to reduce likelihood of intra-fx)

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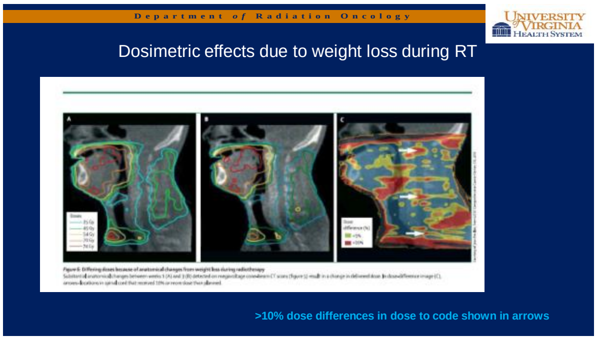

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Dosimetric effects due to weight loss during RT

Figure 6: Differing doses because of anatomical changes from weight loss during radiotherapy

>10% dose differences in dose to code shown in arrows

H&N IMRT

- Site-specific goals and uncertainties (e.g. complex dose distributions adjacent to many critical structures, and sensitive to rotations due to long target)
- Desirable IGRT characteristics (e.g.soft tissue visualization and ability to detect rotations)
- IGRT Process Decisions (e.g. may use OBI for daily setup and CBCT weekly to assess if replan needed)

Correction stratergies for setup errors
Adaptive RT

- Online procedures – tumor is in close proximity to critical structures or high dose RT
  - Acquires images daily
  - Assesses info from daily imaging prior to Tx
  - Simple corrections implemented to compensate noted deviations in position
  - Larger reduction in geometric errors than offline approaches
- Offline procedures -
  - frequent acquisition of images without immediate intervention
  - Calculate systematic and random uncertainties of set up error
  - Correction for systematic error made for the remaining fractions

Adaptive Rt –

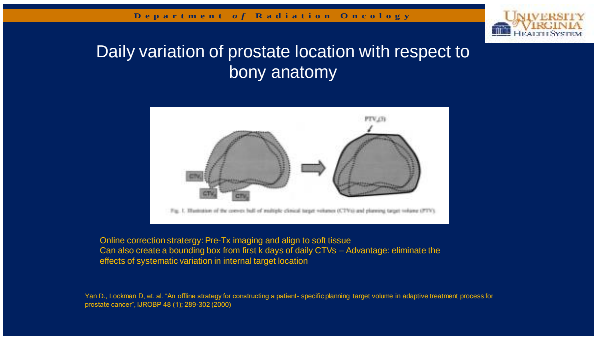
Replanning before every tx based on 3D image acquired

Replan only when substantial changes to anatomy is observed

Time lag between image acquisition and decision to enable/disable beam

- 0.03 seconds is fast enough to maintain target position within 1mm of predicted for motions with speeds up to 3.3 cm/s
- The issues of lag and dose suggest we would benefit from combining internal and external guidance – Cyberknife uses implanted markers and periodic radiography, but uses an external coordinate to estimate the internal position

J.M. Balter, Y. Cao "Advanced Technologies in Image-Guided radiation therapy", Seminars in Radiation Oncology 17: 293-297: 2007



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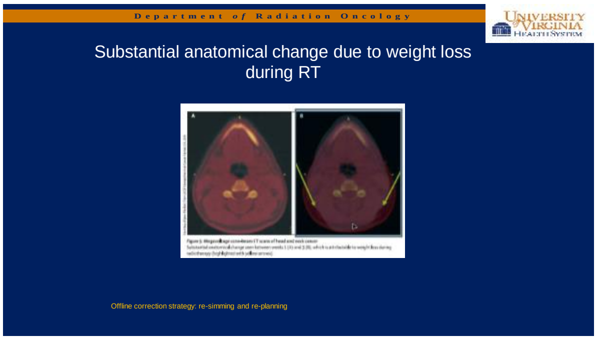
Daily variation of prostate location with respect to bony anatomy

Online correction stratergy: Pre-Tx imaging and align to soft tissue
Can also create a bounding box from first k days of daily CTVs – Advantage: eliminate the effects of systematic variation in internal target location

Yan D., Lockman D, et. al. "An offline strategy for constructing a patient- specific planning target volume in adaptive treatment process for prostate cancer", IJROBP 48 (1); 289-302 (2000)



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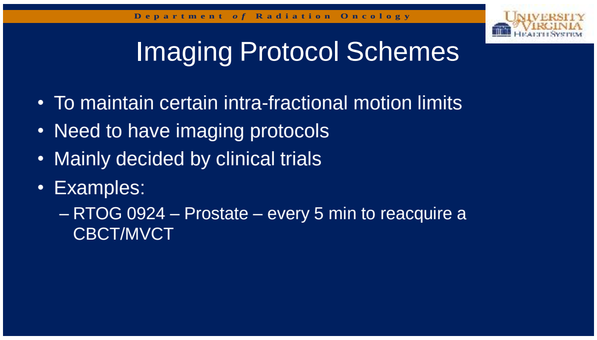
Substantial anatomical change due to weight loss during RT

Offline correction strategy: re-simming and re-planning



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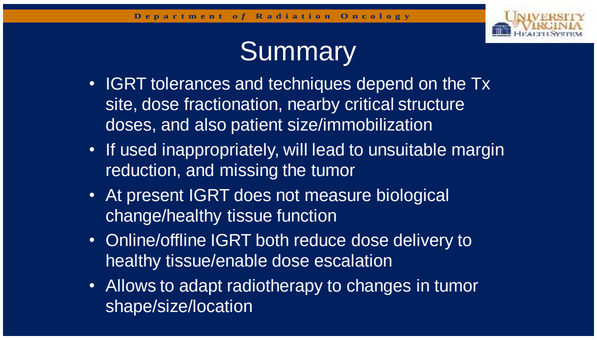
Imaging Protocol Schemes

- To maintain certain intra-fractional motion limits
- Need to have imaging protocols
- Mainly decided by clinical trials
- Examples:
  - RTOG 0924 – Prostate – every 5 min to reacquire a CBCT/MVCT



Department of Radiation Oncology

Summary

- IGRT tolerances and techniques depend on the Tx site, dose fractionation, nearby critical structure doses, and also patient size/immobilization
- If used inappropriately, will lead to unsuitable margin reduction, and missing the tumor
- At present IGRT does not measure biological change/healthy tissue function
- Online/offline IGRT both reduce dose delivery to healthy tissue/enable dose escalation
- Allows to adapt radiotherapy to changes in tumor shape/size/location