Methods and Experience in Image-guided SRS/SBRT

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ELEKTA SYNERGY™ RESEARCH GROUP

Some of the work performed in conjunction with
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Conflict of Interest

Presenter has financial interest in some of the imaging technology described here.

Presenter has research agreements with the following industrial partners:

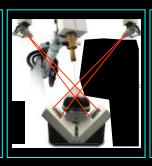
Elekta, Philips, Raysearch, IMRIS

SRS/SBRT: Technology, Geometry, and the Therapeutic Ratio

- Imaging Advances for Target Delineation
  - MR, CT, FDG-PET
- Software and Hardware Developments for Dose Conformality
  - MLC, IMRT, Tomotherapy, IMAT, Robotics
- Precision and Accuracy in Dose Placement
  - IGRT, Immobilization, Higher Dose Rates

Volumetric IG Technologies

Ultrasound



kV Radiographic

Portal Imaging

Markers (Active and Passive)

Volumetric IG Technologies

Siemens PRIMATOM™

kV CT Approach

TomoTherapy Hi-Art™

MV CT Approach

Elekta Synergy™

Siemens MVision™

Varian OBI™

Siemens Artiste™

kV and MV Cone-beam CT Approach

CT – Linac system with RTRT

Yamaguchi University Hospital, Japan

Table 1 Commercially available systems for in-room kV imaging

System Configuration		Rail-Track Mounted Systems		Ceiling Floor Mounted Systems		Gantry Mounted Systems			Hybrid System
Manufacturers		Varian/ General Electric ExaCT	Siemens PRIMATOM	BrainLAB Novalis Body	Accuray CyberKnife	Elekta Synergy	Varian On-Board Imager	Siemens ARTISTE (Pending FDA)	Varian/ BrainLab NovalisTx
Imaging Capabilities	Radiography	No	No	Stereoscopic	Stereoscopic	Yes	Yes	Yes	Yes
	Fluoroscopy	No	No	No	Stereoscopic	Yes	Yes	Yes	Yes
	Tomography	Yes	Yes	No	No	Yes	Yes	Yes	Yes
Reference Images		Planning CT	Planning CT	Digitally reconstructed radiograph	Digitally reconstructed radiograph	Digitally reconstructed radiograph / Planning CT	Digitally reconstructed radiograph /Planning CT	Digitally reconstructed radiograph / Planning CT	Digitally reconstructed radiograph /Planning CT
Correction Methods	Translation	Couch motion	Couch motion	Couch motion	Source moves on robotic arm/ couch motion	Couch motion	Couch motion	Couch motion	Couch motion
	Rotation	No	No	Couch motion	Source moves on robotic arm/ couch motion	No	No	No	Couch motion
Projection Imaging	Flat Panel X-ray Detectors	0	0	2	2	1	1	1	3
Tomographic Imaging	Image Quality	Diagnostic	Diagnostic	N/A	N/A	Sufficient for localization	Sufficient for localization	Sufficient for localization	Sufficient for localization
	Field of View (HxWxL cm)	50 cm	50 cm	N/A	N/A	50 x 50 x 25.6	45 x 45 x 17	48 x 48 x 27?	45 x 45 x 17
Verification Imaging		No	No	Stereoscopic	Fluoroscopic monitoring of treatment	Possible	Possible	Possible	Possible
Target Surrogates		Bone/Fiducial markers / Soft tissue	Bone/Fiducial markers / Soft tissue	Bone/Fiducial markers	Bone/Fiducial markers	Bone/Fiducial markers / Soft tissue	Bone/Fiducial markers / Soft tissue	Bone/Fiducial markers / Soft tissue	Bone/Fiducial markers / Soft tissue
Potential Uncertainty Reduction		Interfraction positioning/ adaptive planning	Interfraction Positioning/ adaptive planning	Interfraction /intrafraction positioning	Interfraction /intrafraction positioning	Interfraction positioning/ adaptive planning	Interfraction positioning/ adaptive planning	Interfraction positioning/ adaptive planning	Interfraction /intrafraction positioning/ adaptive planning
Installation in Conventional Treatment Room		Possibly	Possibly	Yes	No	Yes	Yes	Yes	Yes
Works in Progress		Siemens CBCT with C-arm				IRIS, Digital Tomosynthesis, Combined kV/MV CBCT			

Can you use general IGRT technologies for SBRT?

Yes…

- Establish QA program to assure performance.
  - Few fraction treatments relatively intolerant to random error.
    - Approaches the effect of a systematic error as the number of fractions goes to one.
  - Must consider <u>all the components</u> of the system
- Must consider <u>how they will be used</u>

TG-104

The role of kV imaging in patient setup.

Description.

IGRT Workflow.

Specific Processes.

Manpower.

AAPM REPORT NO. 104

The Role of In-Room kV X-Ray Imaging for Patient Setup and Target Localization

Report of Task Group 104 of the Therapy Imaging Committee
American Association of Physicists in Medicine

Yin et al. 2009

Task Group 142 report: Quality assurance of medical accelerators[a)]

4203 Klein *et al.*: Task Group 142 Report: QA of Medical Accelerators

TABLE VI. Imaging.

Procedure	Application-non-SRS/SBRT	SRS/SBRT
Daily[a]		
Planar kV and MV (EPID) imaging		Functional
Collision interlocks	Functional	≤1 mm
Positioning/repositioning	≤2 mm	≤1 mm
Imaging and treatment coordinate coincidence (single gantry angle)	≤2 mm	
Cone-beam CT (kV and MV)		
Collision interlocks	Functional	
Imaging and treatment coordinate coincidence	≤2 mm	
Positioning/repositioning	≤1 mm	Functional
		≤1 mm
		≤1 mm

Daily test of accuracy and reproducibility

* Recommendations for Imaging System QA - Daily

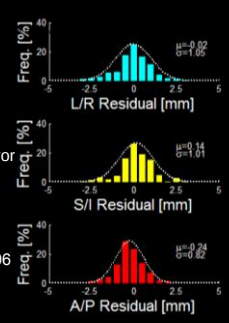
Remote Couch Performance for IGRT

Background

- The XVI system is linked to the Remote Automatic Table Movement (RATM).
- The patient is shifted per the image-guidance system via the remote couch interface.
- The stability of the system and residual error is measured through verification scans acquired following a table shift.

Methodology

- Collection Period Oct 19th '06 – Nov 17th '06
- Patients with repeat (verification) scans were measured and matched using an Automatic Algorithm



- 34 patients with 135 scans

W Li et al. J Appl Clin Med Phys. 2009 Oct 7;10(4):305

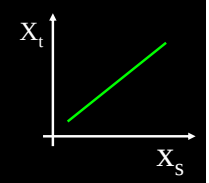
Do you need to see 'the tumor' to target with SBRT?

No…

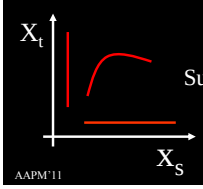
- Employ surrogates to localize the dose.
  - Markers
  - Surfaces (3D or projected; bone/high contrast)
  - 3D Volumes (soft tissue; bone/high contrast)
- Confirm registration methods and operator interpretation (systematic error risk; physician present for at least Fx #1)
- Normal tissues and the PRV

What is a good surrogate?

- We very rarely image the tumor.
- Usually image something that is a *surrogate*, X_s, of the target position, X_t.
- Strength of surrogate needs to be accommodated in margin design.



High Quality Surrogate



Poor Surrogate

Surrogates for target are often not robust for OARs

Examples of Common Surrogates

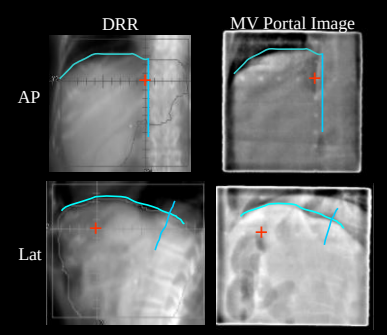
- Points
  - E.g. Gold seeds for alignment
- Surfaces
  - 2D and 3D surface alignment (e.g. liver)
  - 3D soft tumor alignment (e.g. in lung)
- Intensity
  - 3D registration using CC and MI
  - Limiting the field of view

Minimize the difference!

Common Surrogates

- Points
- Surface
- Intensity

Chamfer Matching
$\Sigma(\text{min distance})^2$

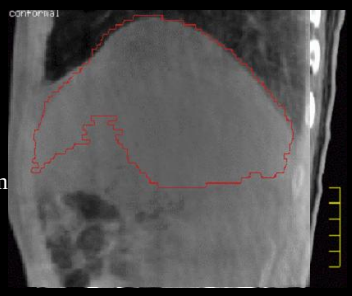


Courtesy of Laura Dawson, PMH

Common Surrogates

- Points
- Surface
- Intensity

Matching Organ Volum

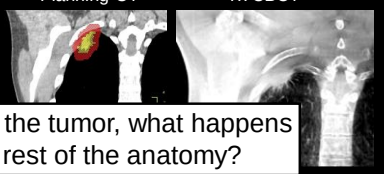


Courtesy of Laura Dawson, PMH

Common Surrogates

Planning CT

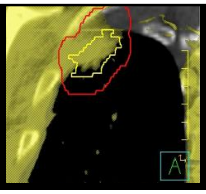
Tx CBCT



- Points
- Surface
- Inter

If we align the tumor, what happens to the rest of the anatomy?

Matching Tumour Volume



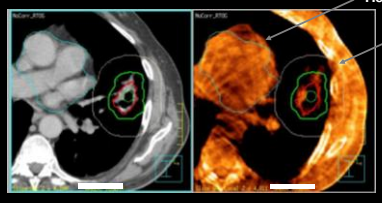
Courtesy of Tom Purdie, PMH

Image-guidance: Don't Get Carried Away

- Targets can move within the patient
- Normal tissues can move within the patient
- These don't necessarily move <u>together</u>

- 'Chasing' a target with IGRT can lead to overdosing adjacent normal tissues.
- Value in visualizing normal tissues at the time of treatment (vs marker-based targeting)

Hitting the Target <u>and</u> Avoiding Organs at Risk

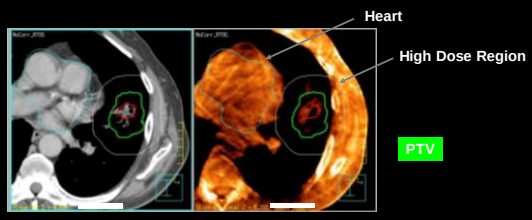


Planning CT

CBCT
- Target Localized
- Heart <u>Outside</u> High Dose Region

RTOG 0236 Protocol

Hitting the Target and Avoiding Organs at Risk



Planning CT

CBCT
- **Target Localized**
- **Heart Outside High Dose Region**

RTOG 0236 Protocol

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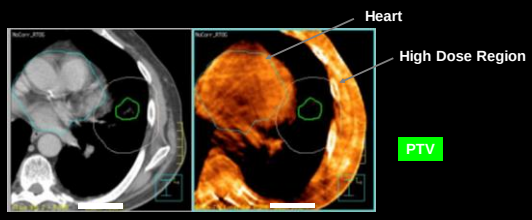
Hitting the Target and Avoiding Organs at Risk



Planning CT

CBCT
- **Target Localized**
- **Heart Inside High Dose Region**

RTOG 0236 Protocol

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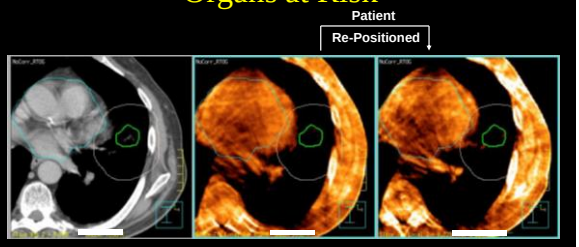
Hitting the Target and Avoiding Organs at Risk



Planning CT

CBCT
- **Target Localized**
- **Heart Inside High Dose Region**

CBCT
- **Target Re-Localized**
- **Heart Outside High Dose Region**

RTOG 0236 Protocol

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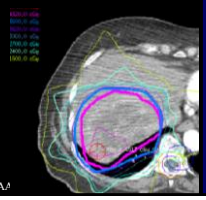
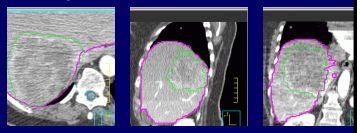
Hitting the Target and Avoiding Organs at Risk

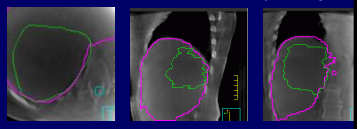
- Liver-liver match led to higher spinal cord dose, requiring re-planning



Planning CT, with liver, cord and GTV contours



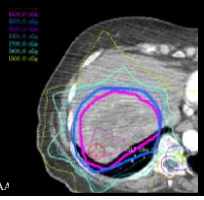
Cone beam CT, with contours from planning CT



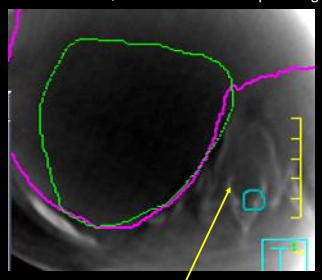
AA

Hitting the Target and Avoiding Organs at Risk

- Liver-liver match led to higher spinal cord dose, requiring re-planning.



Cone beam CT, with contours from planning CT



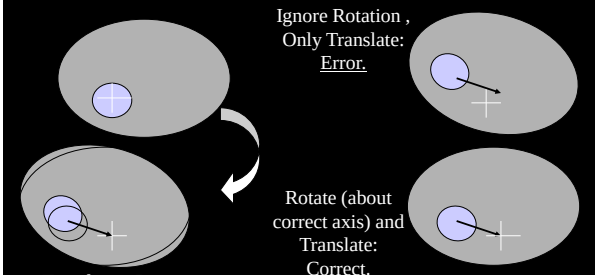
Cord at treatment is closer to tumor, receiving higher dose

Knowing the transformation is not the end.

- How will the resulting registration be used?
  - Fusion for visualization (inspection)
  - Transfer of Regions-of-interest (inspection of high dose regions vs OARs)
  - Adjustment of the patient's position (e.g. robotic couch)
- Need to test if the registration produces the desired effect.
  - E.g. registration in 6D and correction in 3D.
- Verification imaging on all SBRT techiques.

Example: Care with Rotational Transforms

A rotational component needs to be specified with respect to an axis (or point in the reference image).



Note: Minimize rotational effects by defining rotations wrt a point in the target (preferably the isocentre)

PMH Experience in Application of CBCT to SRS/SBRT

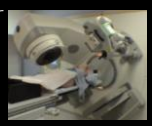
- Clinical Applications
  - Cranial SRT - since 2005: ~ 400 cases
  - Lung SBRT - since 2004: ~200 cases
  - Liver SBRT - since 2003: > 150 cases
  - Spine SBRT since 2008: > 100 cases
- New Technology Developments

CBCT Guidance for Replacement of Frame-based Positioning in SRT of the Head and Cranium

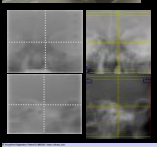
Methods

- Standard Frame Setup
  - GTC Frame (depth helmet check, lasers, alignment box, etc.)
  - Micro-positioner on Radionics Couch Extension
    - Output: Adjusted Patient Position (0,0,0)
- IG Measurements
  - Elekta Synergy XVI v3.5 on "Synergy S"
  - Registration with the Planning CT (Automatic Mode: Bone and Grayscale, no Rotations)
    - Output: Estimated Patient Position Error (X,Y,Z)
- CBCT Evaluation, 10 Patients, up to 35 Fx/Patient, 2 Scans per Session
- Analysis
  - Reported discrepancy is X,Y,Z (pre, post RT)
  - Systematic and Random Components

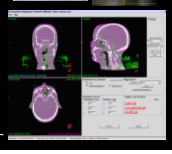
Setup and Measurements



Stereotactic Setup (Xr,Yr,Zr) 1/session

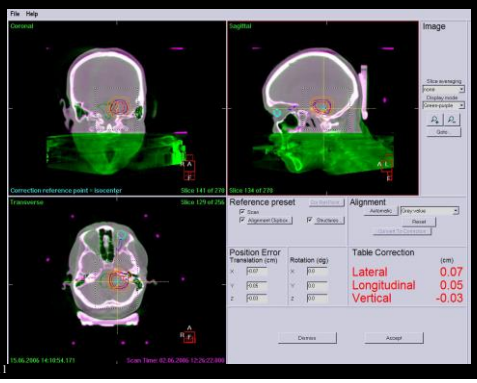


MV Portal Images (Xp,Yp,Zp) 1/week

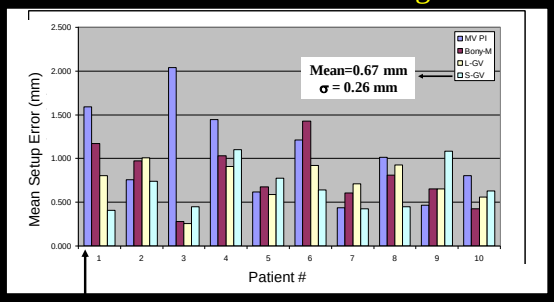


Cone-beam CT (Xc,Yc,Zc) 2/session

3D Alignment: Automatic



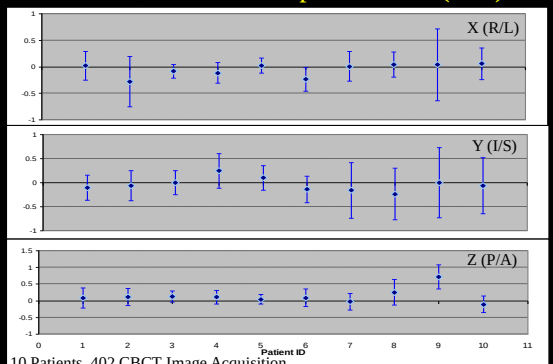
Setup Error: Mean 3D Deviation using Frame-based Positioning



Purple: MV Portal Imaging

10 Patients, 402 CBCT Image Acquisition

Intra-fraction Motion: Standard Deviation of Pre-, Post-Tx Displacements (mm)



10 Patients, 402 CBCT Image Acquisition

Comments on CBCT-guided SRT/SRS

- CBCT methods are highly consistent with frame-based positioning
- Frame (GTC) demonstrates excellent immobilization
- Discrepancies with portal imaging may be due to lack of 3D alignment tools for portal imaging (i.e. could be improved with software tools)
- CBCT has become internal standard for positioning of SRT/SRS cases.

CBCT Guidance of SBRT Lung

SBRT IGRT Workflow

Patient immobilized
Setup using skin marks

↓

Acquire **Localization CBCT**

↓

Image Registration
Target to ITV

↓

Acquire **Verification CBCT**

↓

Treat all co-planar beams

↓

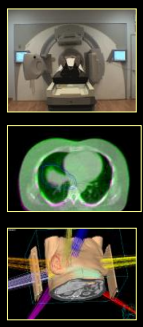
Acquire **Mid-treatment CBCT**
Assess Target to PTV

↓

Treat all non co-planar beams

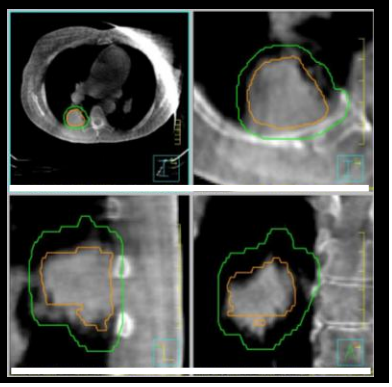
↓

Acquire **Post-treatment CBCT**



Soft-tissue Targeting of Lung Lesions

CBCT – Case 1

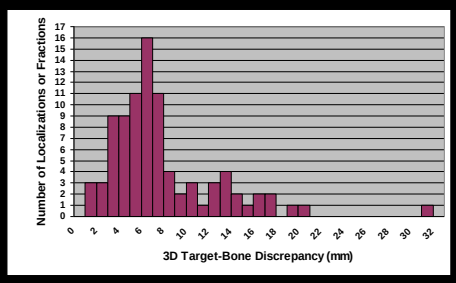


RTOG 0236 Protocol

Inter-fraction target position compared to bone-based positioning

28 Patients

89 Fractions



Purdie et al., IJORBP, 2006

Intra-fraction targeting assessed using repeat CBCT imaging

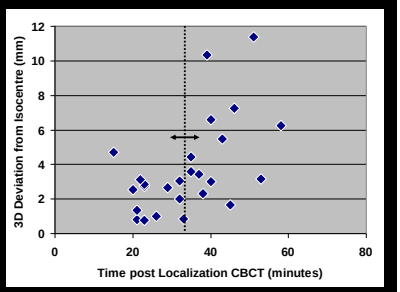
RTOG 0236 Protocol

8 patients, 26 repeat scans

Median time between imaging: 34 minutes

Residual for lower half: 2.2 mm

Residual for upper half: 5.3 mm



Purdie et al., IJORBP, 2006

Lung SBRT – Analysis of Positioning Results

- 108 patients from a prospective SBRT study
- Immobilized in evacuated cushion (n=67), evacuated cushion + abdominal compression (n=27), or chestboard (n=14)
- Stratification based on performance status: ECOG 0 (n=26), ECOG 1 (n=61), ECOG 2 (n=21)
- Treatments were delivered mostly in 3-4 fractions, while 8-10 fractions were used for central tumors
- CBCT guidance performed at each treatment fraction

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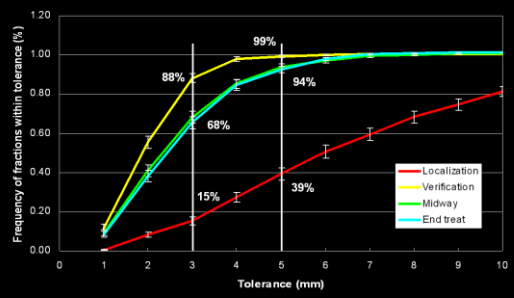
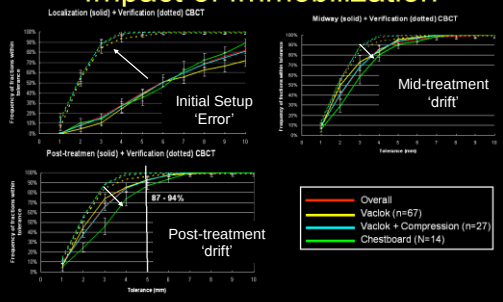
Geometric Accuracy of Lung SBRT(1660 CBCTs)

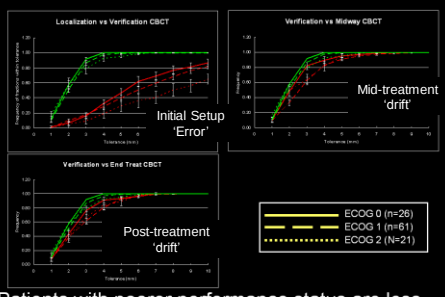


Impact of Immobilization



- With the use of CBCT for treatment localization, all immobilization groups have similar set-up performance.
- Positional accuracy maintained within 5 mm (PTV margin) for most patients at mid and post treatment CBCT

Performance Status



- Patients with poorer performance status are less reproducible in their initial setup
- Positional accuracy maintained with 5 mm for most patients at mid and post treatment CBCT

Comments on Lung SBRT

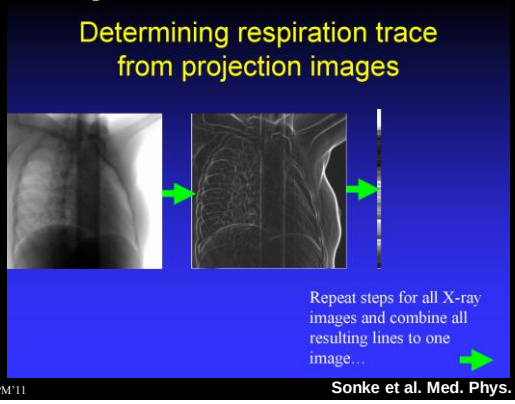
- Highly stable process
- 4DCT for volume definition (ITV)
- No gating
  - Abdominal compression for 'movers'
- CBCT soft-tissue targeting
- Physician present for first fraction
  - Radiation Therapists perform IGRT
- WRT Intra-fraction motion concerns, the method of immobilization not critical

4D Cone-beam CT in Lung and Liver

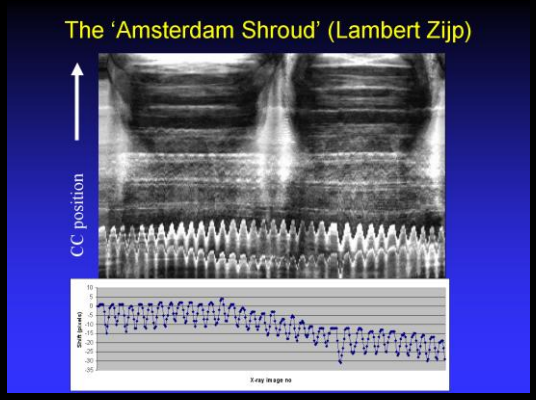
Breathing Motion During Acquisition

- CT Reconstructions operate on the assumption that there is an object to reconstruct
- Motion results in inconsistent information in the project data
- Resulting reconstruction is inaccurate
- Image-based sorting

Respiration Correlated Cone-beam CT



Sonke et al. Med. Phys. 2005

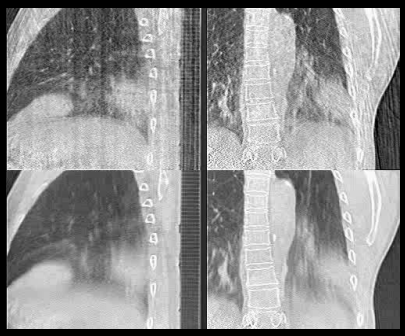


Sonke et al. Med. Phys. 2005

4D Cone-beam CT

Sorted

Unsorted



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Courtesy of JJ. Sonke and M. van Herk, NKI

4D CBCT + GTV Contour

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Courtesy of JJ. Sonke and M. van Herk

Apply Correction

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Courtesy of JJ. Sonke and M. van Herk

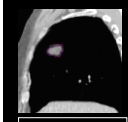
4D CBCT Verification of Target Motion

Sample Case

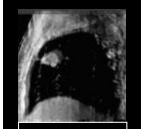
	Tumour Excursion (mm)		
	Lateral	Anterior/ Posterior	Superior/ Inferior
4DCT Planning Scan	0.7	1.0	3.1
Respiration Correlated CBCT			
Fraction 1	0.5	0.8	5.7
Fraction 2	0.3	0.8	2.9
Fraction 3	0.0	0.9	3.4

Verification of Position and Amplitude of Respiration for Margin QA

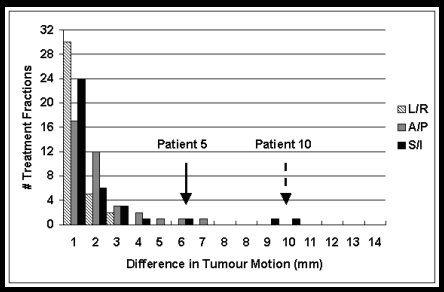
Verification of Range of Respiratory Motion at the Treatment Unit



Planning 4DCT



4D CBCT



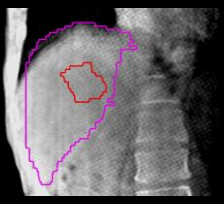
The difference in tumour motion between planning and treatment for 12 patients treated using SBRT.

Purdie et al., Acta Oncologica (2006)

Liver SBRT - IGRT Process

- Liver-to-liver (or liver region) alignment

Planning CT

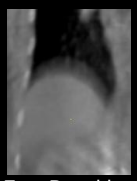


kV cone beam CT

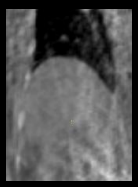
Liver SBRT: Respiration Correlated Cone Beam CT

Respiratory sorting of free breathing CBCT

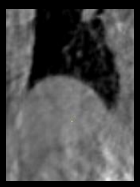
Offline analysis (exhale – exhale liver registration)



Free Breathing CBCT



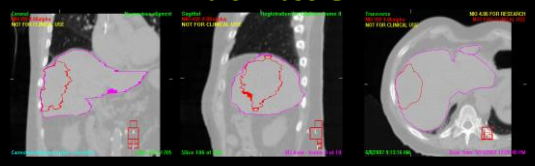
Exhale



Inhale

Respiratory Sorted Cone Beam CT Improves Image Interpretation

Exhale Phase CT



Exhale Phase CBCT

Exhale Liver GTV Inhale Liver

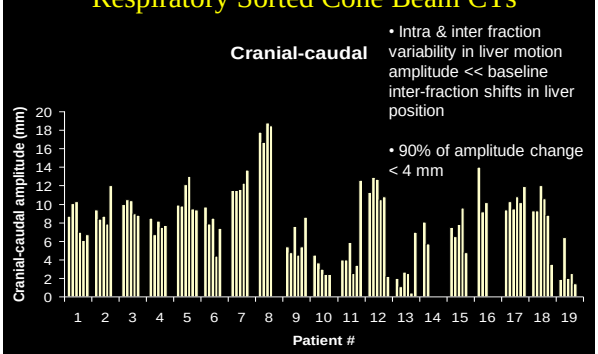
Liver SBRT: Respiration Correlated Cone Beam CT

- 194 CBCT scans analysed in 18 patients
  - 8 free breathing (41 fractions)
  - 10 abdominal compression (56 fractions)
- Mean Intra-Fraction Time (Range)
  - 13:02 (8:04 – 25:37) [min:sec]

Liver Motion Amplitude (mm)			
	ML	CC	AP
MEAN $_{\text{Pre-Treatment}}$	1.9	8.2	4.5

*Retrospective analysis.

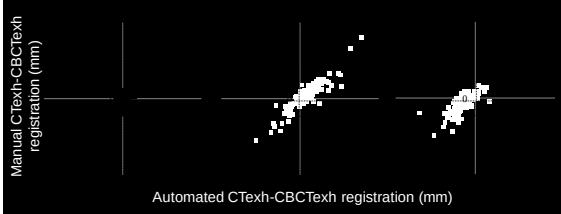
Reproducibility of Liver Motion Amplitude - Respiratory Sorted Cone Beam CTs



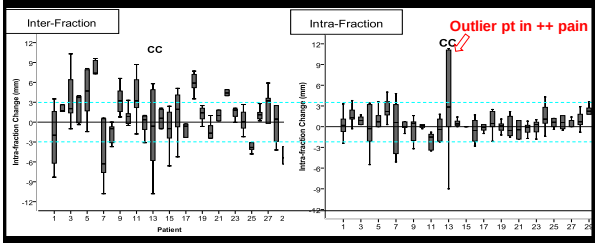
- Intra & inter fraction variability in liver motion amplitude << baseline inter-fraction shifts in liver position
- 90% of amplitude change < 4 mm

Liver SBRT: Manual vs Automated Exhale Liver Alignment

- Correlation Plots for automated and manual CT_{exh}-$CBCT_{exh}$ registrations

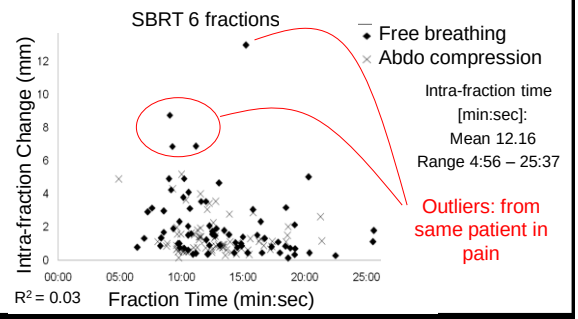


Intra-fraction Changes: Reproducibility in Amplitude (inter-Fx and intra-Fx)



- 314 respiratory sorted CBCT from 29 patients
- Liver cancer, 6 fraction SBRT, non-breath hold
- Intra-fraction time [min:sec]: Mean 12.16 Range 4:56 – 25:37

Intra-fraction Changes: Free breathing and Compression



*Relative to Vertebral Bodies

Comments on role of 4D CBCT in Lung/Liver SBRT

- On-line 4D CBCT is a valuable clinical tool
- Allows 'ITV' margin QA - confirmation of 4D CT derived value
- Need to be clear/internally-consistent regarding margins for accommodation of motion and reference CT
- Even with noise issues, 4D CBCT can improve interpretation of images (with respect to IG)
- Beginning the process of deploying 4D CBCT in routine clinical use.

Summary

- Image-guidance is central to SBRT and general systems can be employed with additional monitoring/QA program
- Benefits for both targeting and normal tissue avoidance.
  - Enabling more aggressive treatments (e.g. single Fx SBRT)
- Defined process and training/supervision are key.
- New deployment of SBRT adopting end-to-end testing methods to assure combined geometric and dosimetric performance (VMAT)


AAPM'11