3D surface imaging for image guidance in Stereotactic body RT and deep inspiration breath hold RT for left-sided breast cancer

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NKI-AVL

Disclosure

Research collaboration with:

- Elekta Oncology Systems
- VisionRT
- RaySearch Laboratories

Our department licenses software to:

- Elekta Oncology Systems
- Precision X-Ray Inc.
- Xstrahl Ltd.

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“LASER”

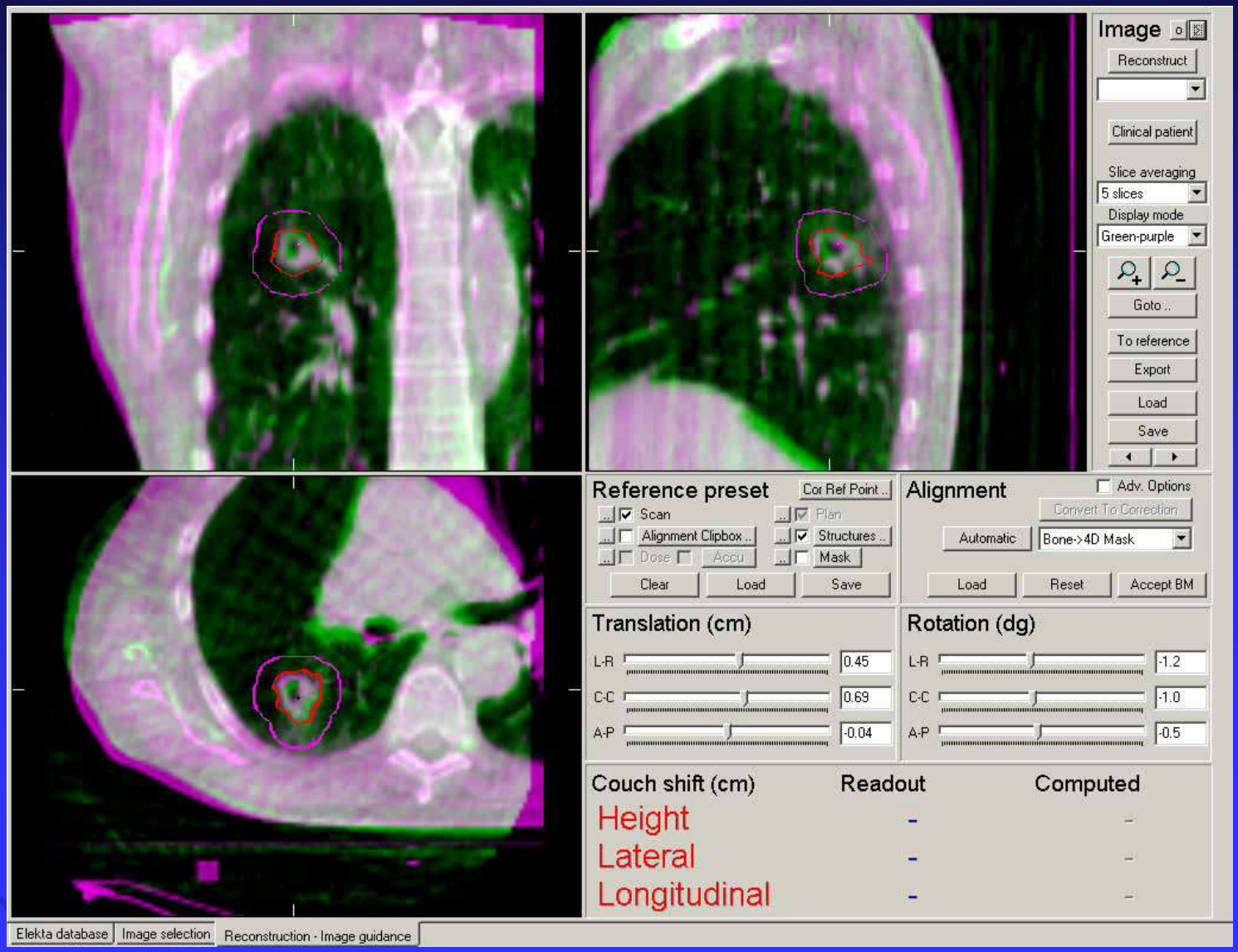
Lung SBRT Surveillance

Introduction

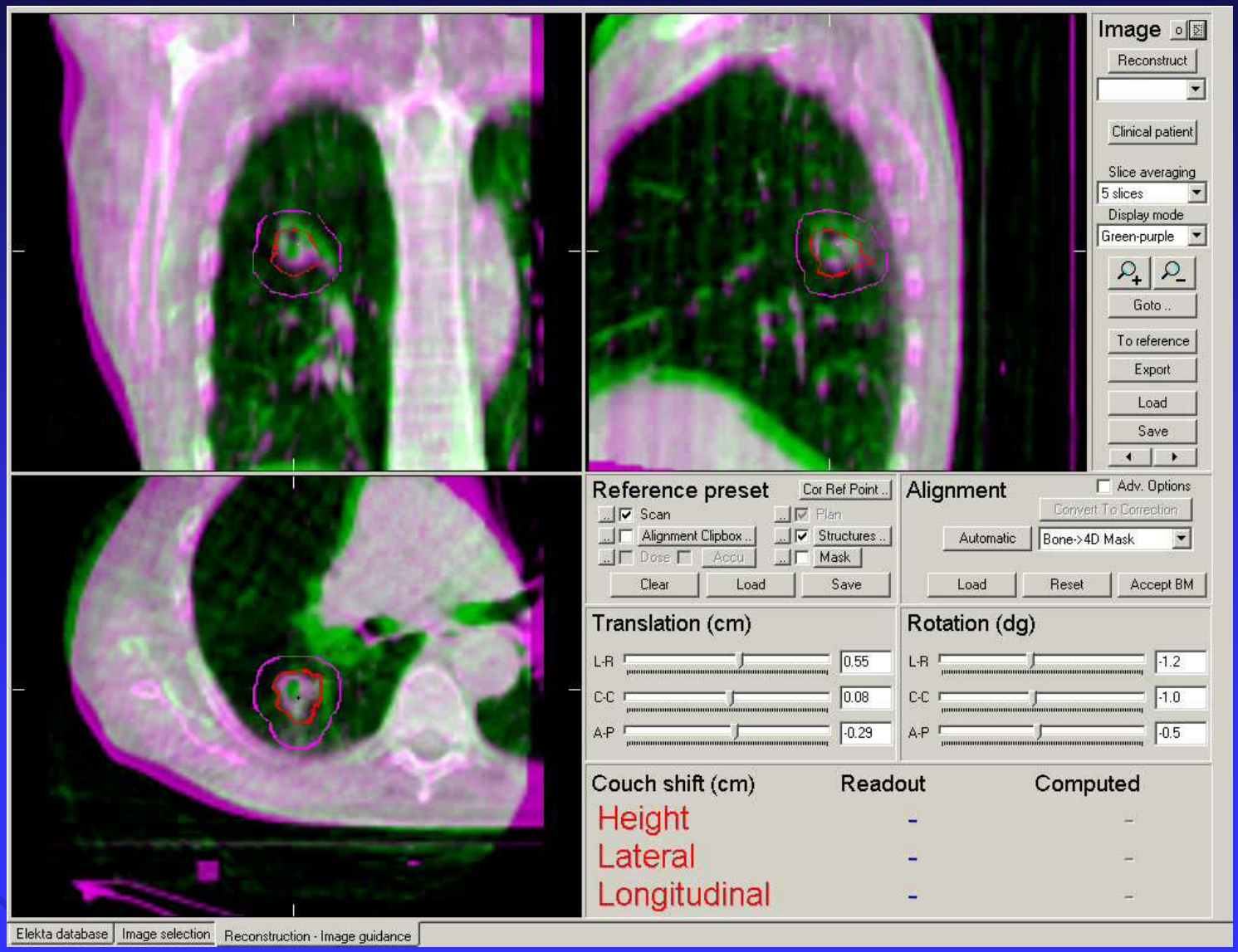
SBRT @ NKI-AVL

- 3 fractions of 18 Gy
- Immobilization:
  - Arm supports
  - Knee supports
- 4D-CBCT-guided correction protocol
- Initially non-coplanar IMRT, now VMAT

SBRT Lung: Pre-Alignment



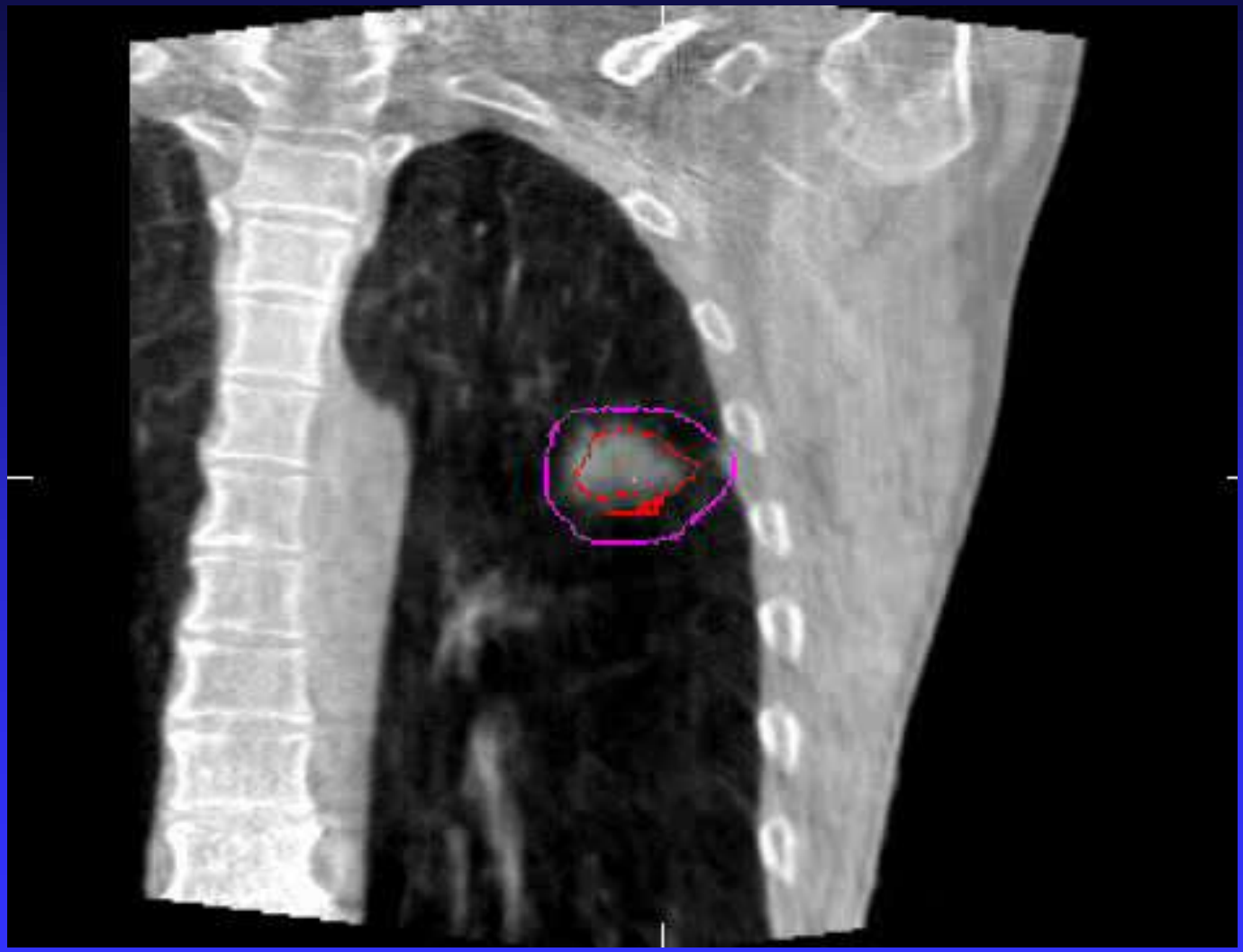
SBRT Lung: Tumor Aligned



Residual Error after Correction

3 consecutive fractions

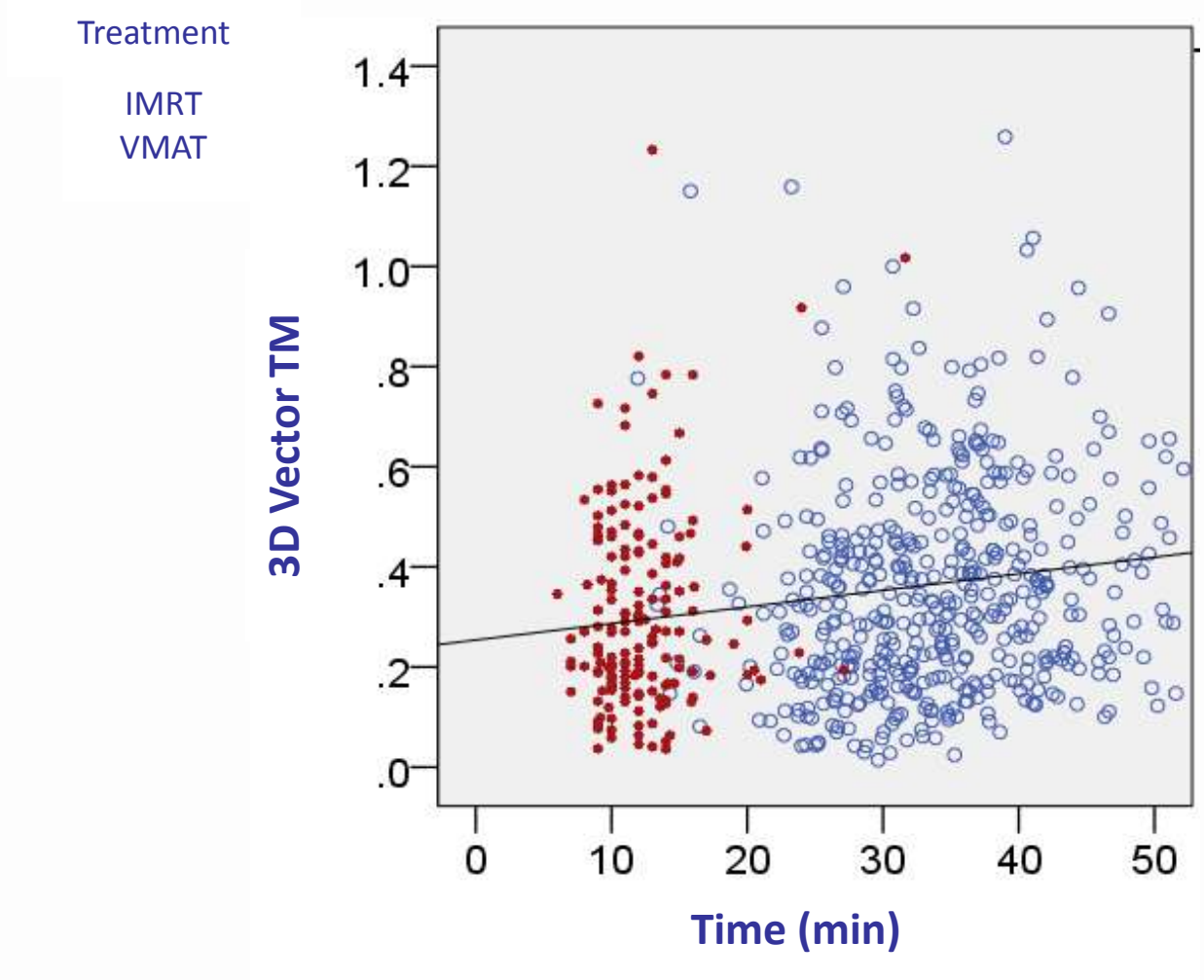
Intra-fraction Variability



3 consecutive fractions

Time and Intra-fraction Motion

Median 3DV (cm)
0.29 IMRT, 0.21 VMAT



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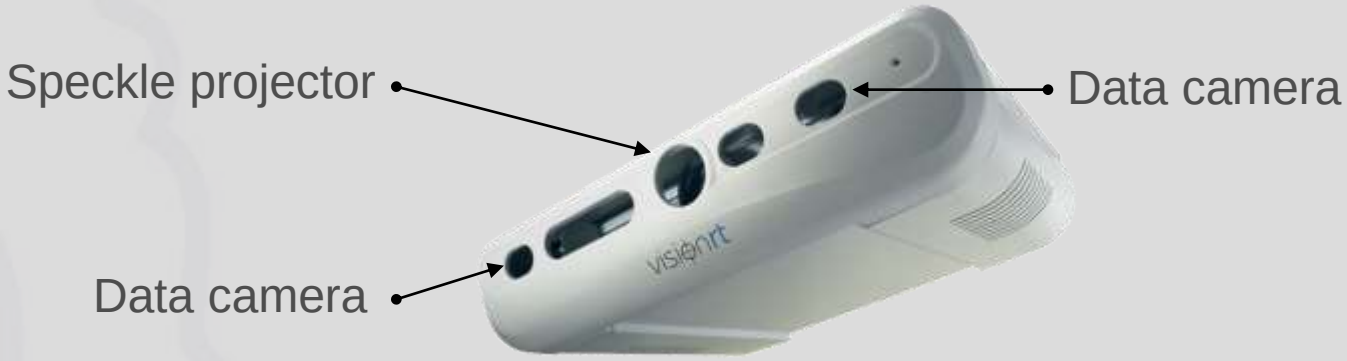
Time is a significant predictor for both 3D vectors in a linear regression model ($p<0.001$)

Aim

Validate the use of a 3D surface imaging system for monitoring intrafraction motion in frameless SBRT of lung cancer by comparison with CBCT

Material and Methods



AlignRT (Vision RT Ltd, London, UK)

3D surface imaging system

Beam on/off detection*

** Black Cat Systems, Westminster, USA*

Materials and Methods

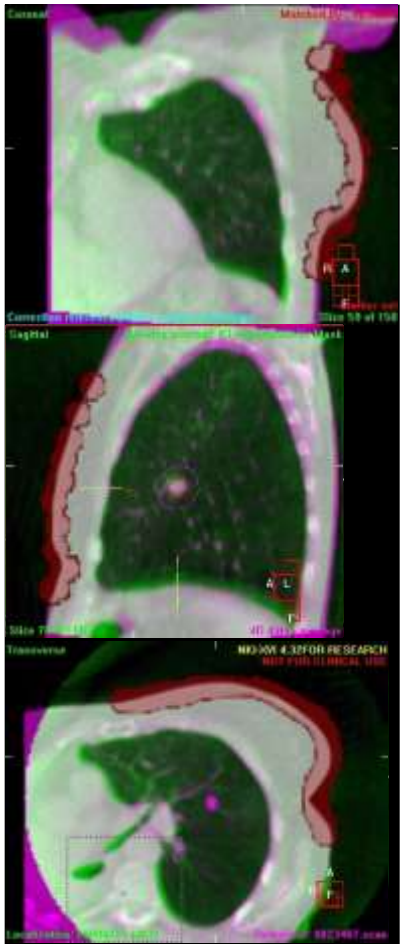
- Correction protocol
  - Alignment to room lasers
1. – (4D-)CBCT — CBCT1 — Surface1
  - Registration CBCT – Planning CT
    - Local rigid tumor alignment
  - Couch shift
2. – (4D-)CBCT for verification — CBCT2 — Surface2
  - Treatment delivery
3. – (4D-)CBCT to assess intrafraction variability — CBCT3 — Surface3

→ 3D surfaces were captured during CBCT acquisition

Materials and Methods

Registrations

- Local rigid registration
  - Correlation ratio as cost function[2]
- ROI
  - Clipbox: bony anatomy
  - Tumor mask (GTV + 5 mm)
  - Surface mask (side treated lung)



[2] *Roche, A., et al.: The correlation ratio as a new similarity measure for multimodal image registration. In: Wells III, W.M., Colchester, A.C.F., Delp, S.L. (eds.) MICCAI 1998. LNCS, vol. 1496, pp. 1115-1124, Springer, Heidelberg (1998)*

Materials and Methods

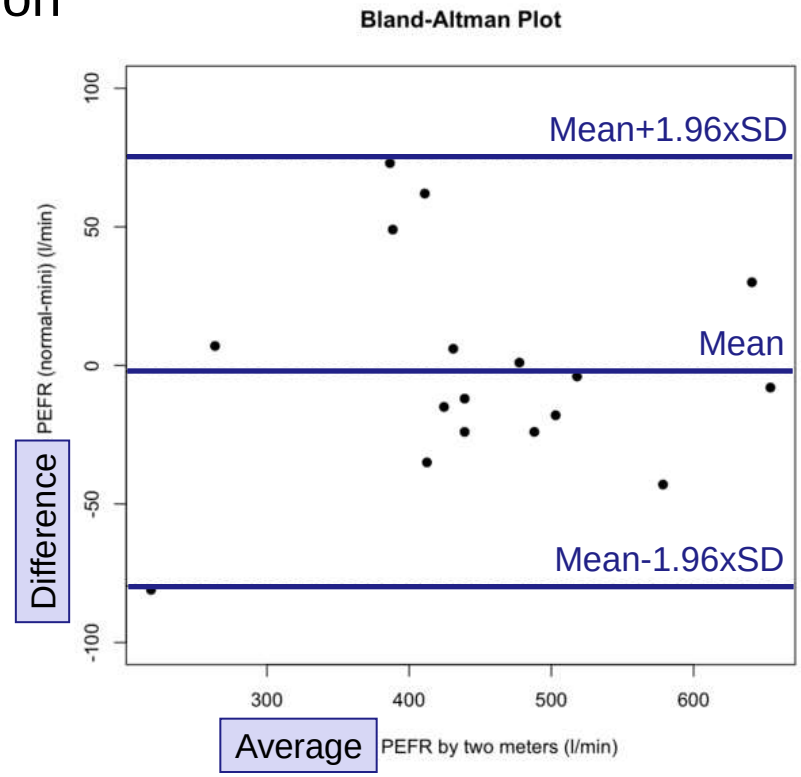
- Data

	Surface vs. CBCT clipbox	Surface vs. CBCT tumor	Surface vs. CBCT surface
Females	41	41	32
Males	34	34	20

CBCT: surface was not always in field of view

Materials and Methods

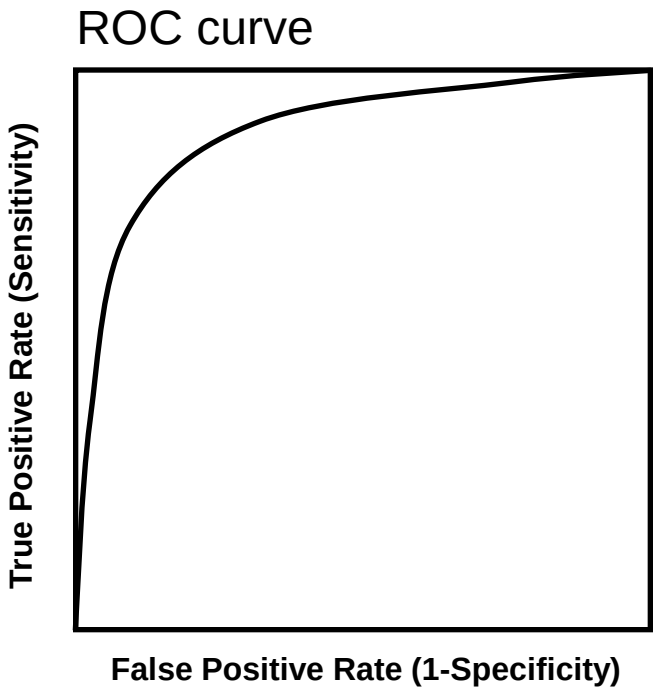
- Bland and Altman analysis – Measuring agreement
  - Differences in Intrafraction Motion
    - Estimated bias:
      Mean
    - Random fluctuations:
      Standard deviation (SD)
  - 95% limits of agreement
    - Mean±1.96xSD



Also known as a Tukey mean-difference plot

Materials and Methods

- ROC analysis
  - Binary classifier system (predict: tumor movement ≥ threshold)
  - Point: sensitivity / specificity pair corresponding to threshold



Results

M, Σ, σ

Δ intrafraction motion (mm)		Surface vs. CBCT clipbox	Surface vs. CBCT tumor	Surface vs. CBCT surface
		3D	3D	3D
Females	M	1.7	0.8	0.2
	Σ	1.6	1.8	1.3
	σ	2.4	2.1	1.9
Males	M	1.9	1.3	0.5
	Σ	3.1	3.2	3.0
	σ	3.1	3.4	4.0

Results

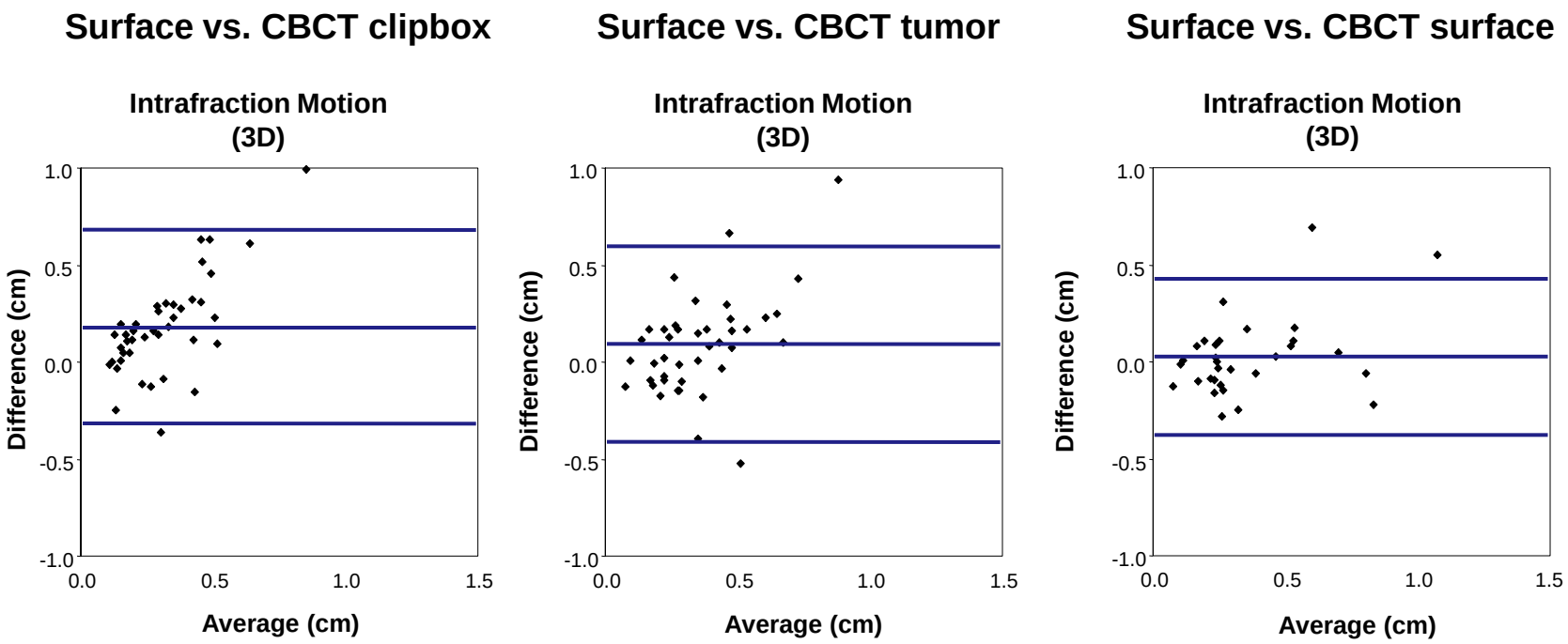
- Bland and Altman analysis

Δ intrafraction motion (mm)		Surface vs. CBCT clipbox	Surface vs. CBCT tumor	Surface vs. CBCT surface
		3D	3D	3D
Females	Mean	1.8	0.9	0.3
	SD	2.6	2.6	2.0
	Mean-1.96xSD	-3.2	-4.2	-3.7
	Mean+1.96xSD	6.8	5.9	4.3
Males	Mean	2.4	1.8	0.4
	SD	3.8	4.1	4.1
	Mean-1.96xSD	-5.1	-6.3	-7.5
	Mean+1.96xSD	9.8	9.8	8.4

Results females more promising than results males

Results

- Bland and Altman plots (Females)



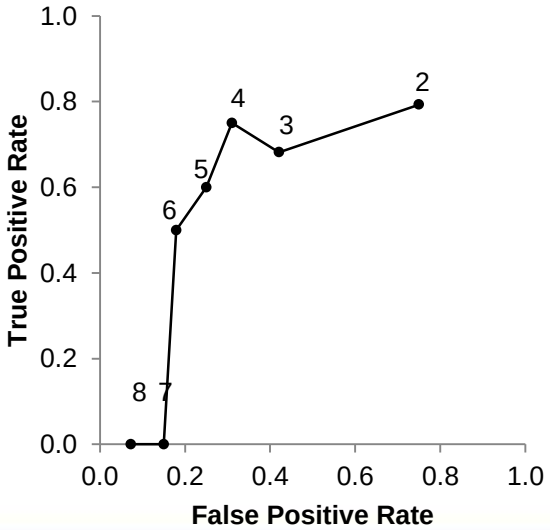
CBCT clipbox, CBCT tumor:
discrepancy tends to increase with increasing intrafraction motion

Results

- ROC analysis (Females)

Surface vs. CBCT tumor

Threshold (mm)	2	3	4	5	6	7	8
FN	6	7	3	2	1	1	0
FP	9	8	9	9	7	6	3
TP	23	15	9	3	1	0	0
TN	3	11	20	27	32	34	38
FPR	0.75	0.42	0.31	0.25	0.18	0.15	0.07
TPR	0.79	0.68	0.75	0.60	0.50	0.00	0.00



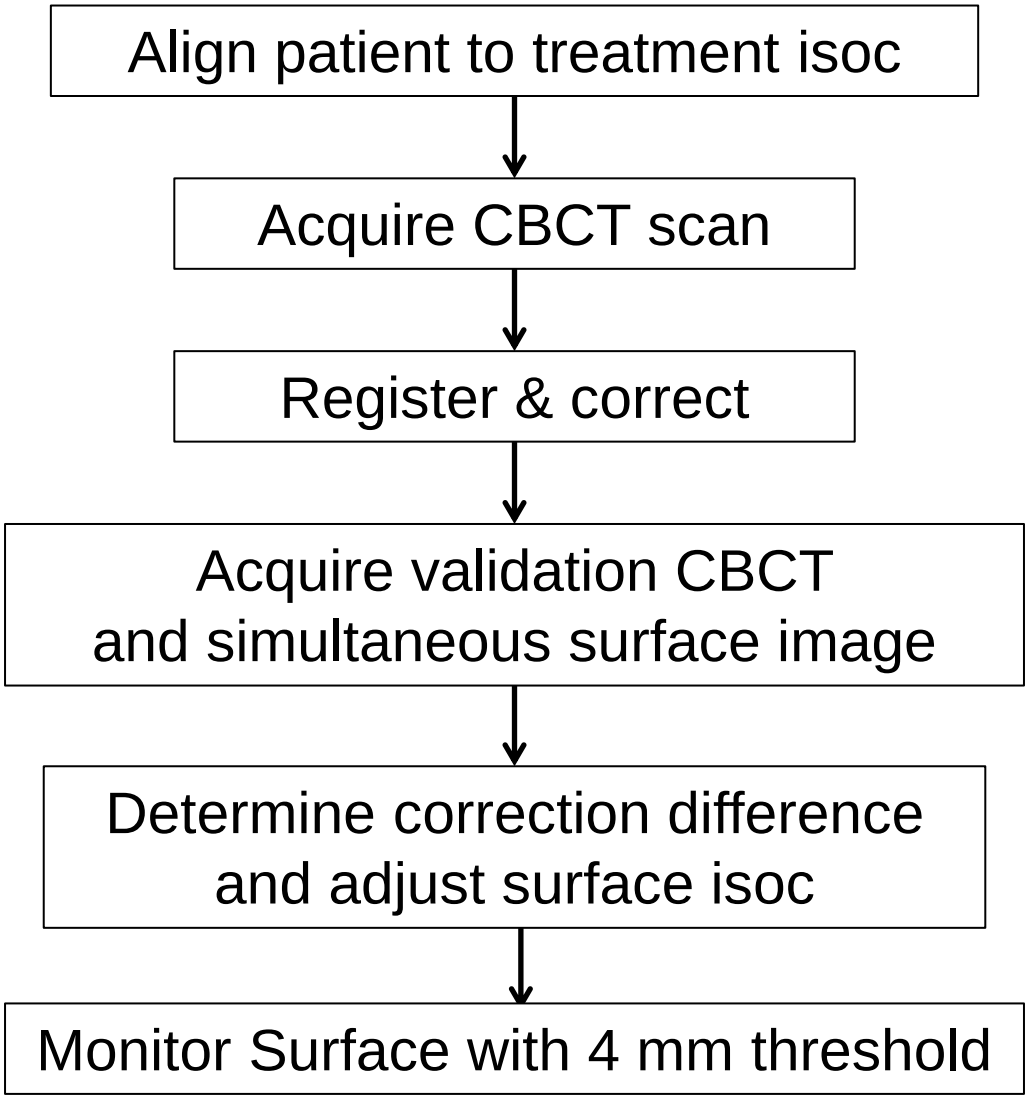
Threshold 4 mm promising prediction model?

Intrafraction motion - CBCT tumor

(mm)	LR	CC	AP	3D
average	0.4	1.3	-0.8	3.1
min	-4.5	-1.1	-5.7	0.4
max	4.7	6.0	4.8	7.7

Alderliesten et al. R&O, 2012

Workflow SBRT Surveillance

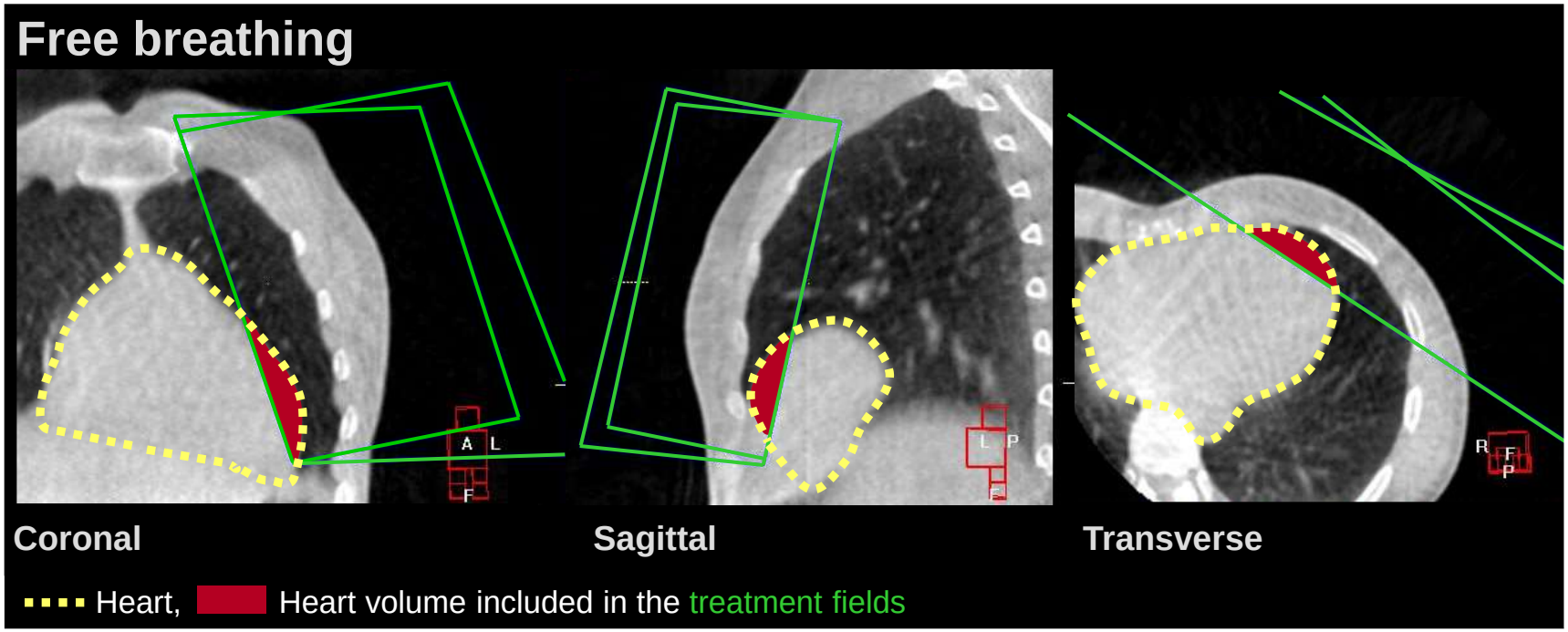


Breath-hold Monitoring

Introduction

Left-sided breast cancer radiation

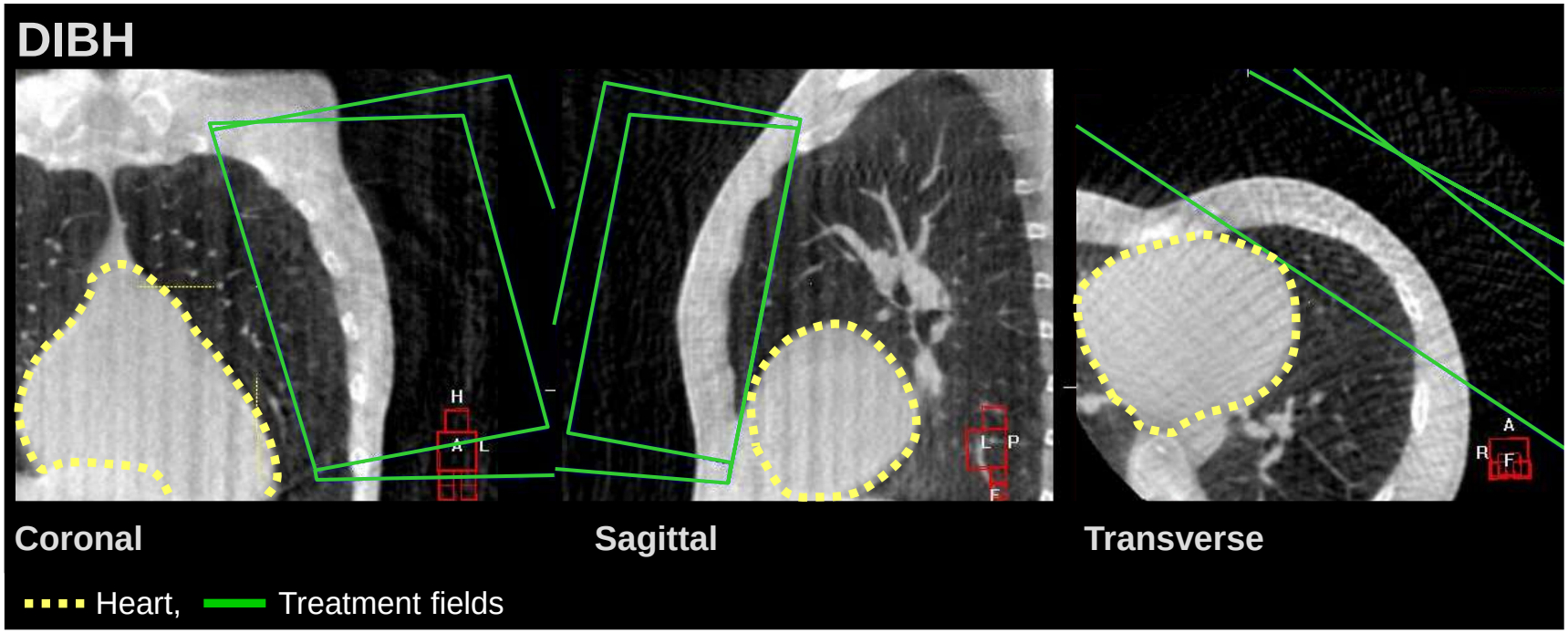
- Increased risk for long term heart disease



Introduction

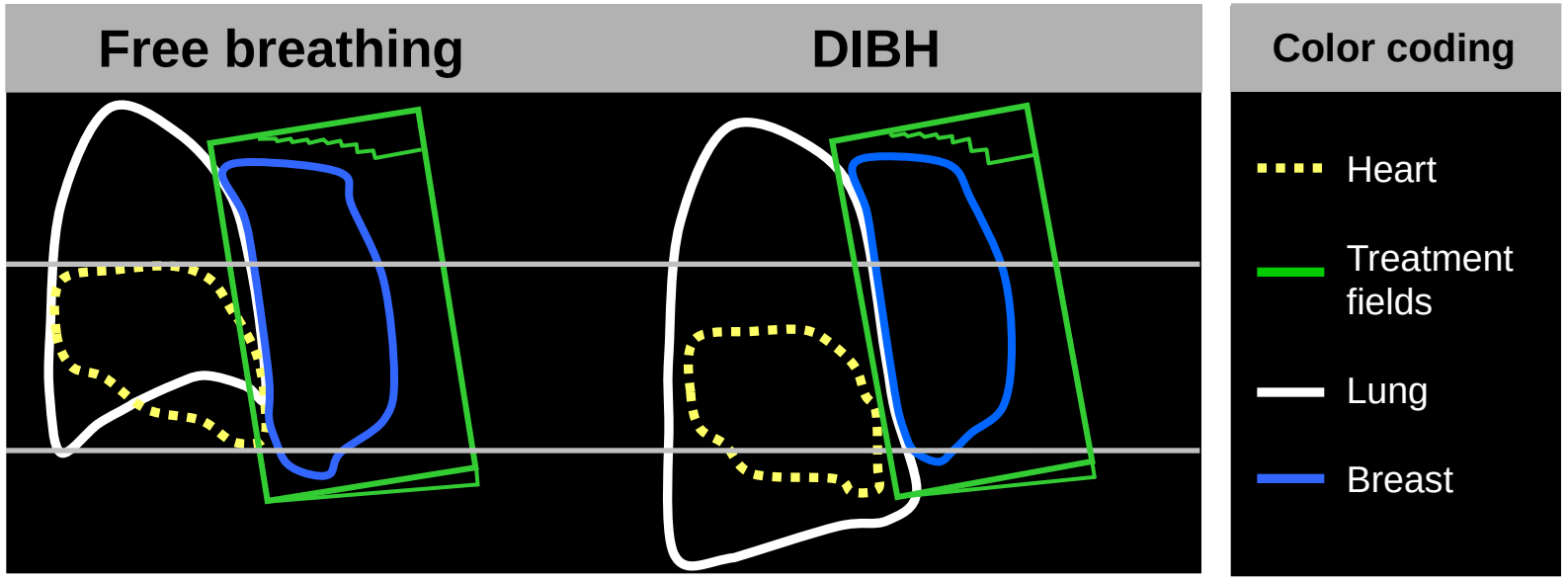
To decrease the irradiated heart volume

- Voluntary deep inspiration breath hold (DIBH)



Introduction

Beam's eye view of medial tangential field



During inspiration*:

- Lung volume is increased
- Breast is moved cranioventrally
- Heart is moved caudally

** Vikstrom et al. Acta Oncologica; 50, 2011*

Guidance Protocol @ NKI

Setup verification (DIBH)

- CBCT (half scan protocol: 30 sec, arc of 200°)
- Rigid registration CBCT – planning CT

Dose delivery

- Lateral fields (DIBH)
- Medial fields (DIBH)

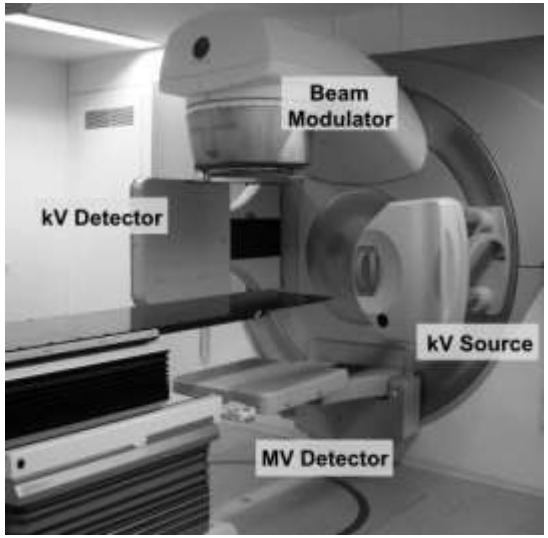
Monitoring depth breath hold

- kV fluoroscopy (IMRT segments)
- MV fluoroscopy EPID (open fields)

Introduction

Disadvantages

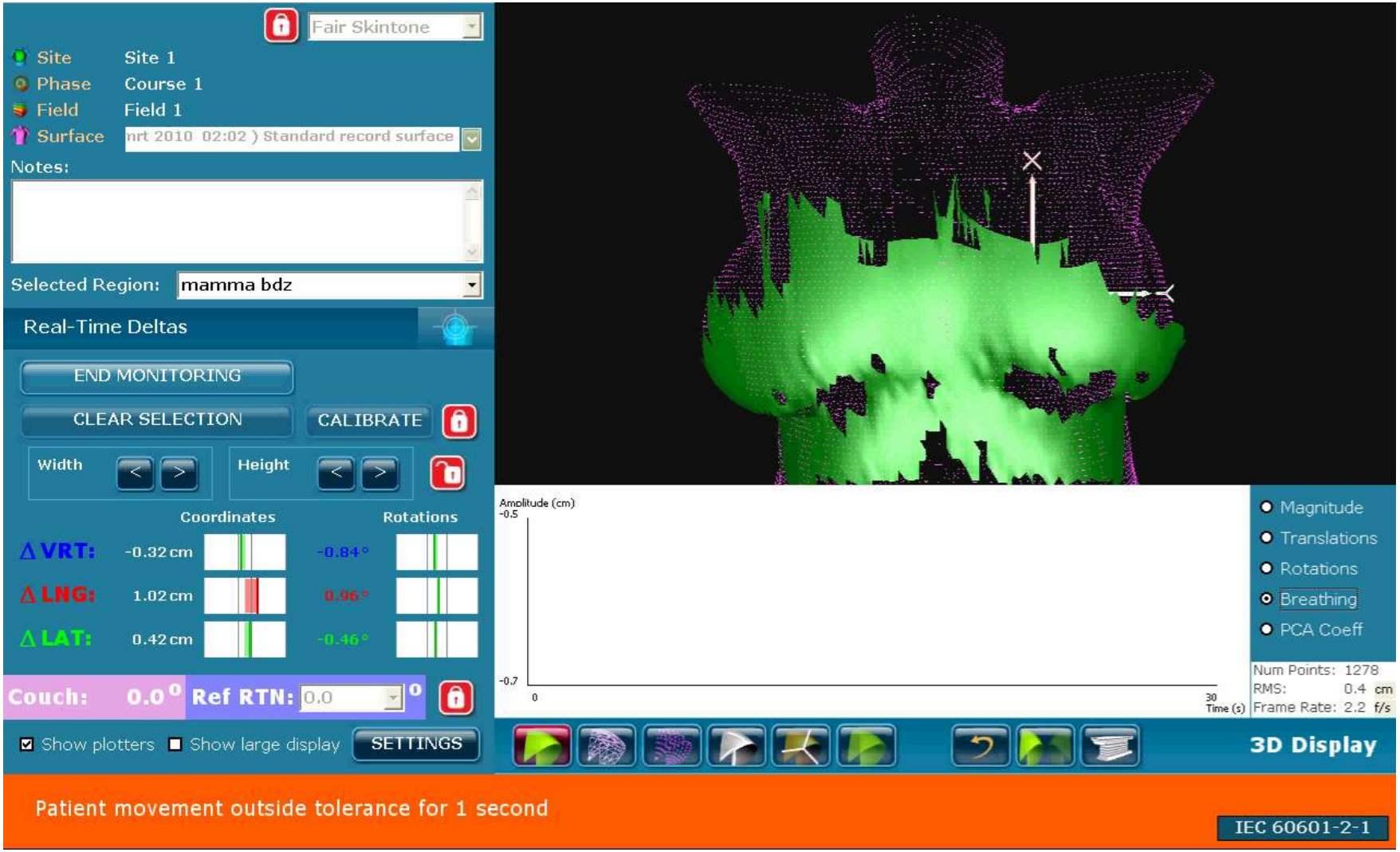
- 2D
- Additional imaging dose
- kV source and kV imaging panel at 90 degrees to treatment line
- Monitoring with EPID not possible during IMRT segments



Purpose

Investigate the applicability of a 3D surface imaging system for image guidance in DIBH RT for left-sided breast cancer by comparison with CBCT

Purpose


Fair Skintone
Site
Site 1
Phase
Course 1
Field
Field 1
Surface
nrt 2010 02:02) Standard record surface
Notes:
Selected Region:
mamma bdz
Real-Time Deltas
END MONITORING
CLEAR SELECTION
CALIBRATE
Width
Height
Coordinates
Rotations
ΔVRT:
-0.32 cm
-0.84°
ΔLNG:
1.02 cm
0.96°
ΔLAT:
0.42 cm
-0.46°
Couch:
0.0°
Ref RTN:
0.0°
Show plotters
Show large display
SETTINGS
Amplitude (cm)
-0.5
-0.7
0
30
Time (s)
Magnitude
Translations
Rotations
Breathing
PCA Coeff
Num Points: 1278
RMS: 0.4 cm
Frame Rate: 2.2 f/s
3D Display
Patient movement outside tolerance for 1 second
IEC 60601-2-1

Materials and Methods

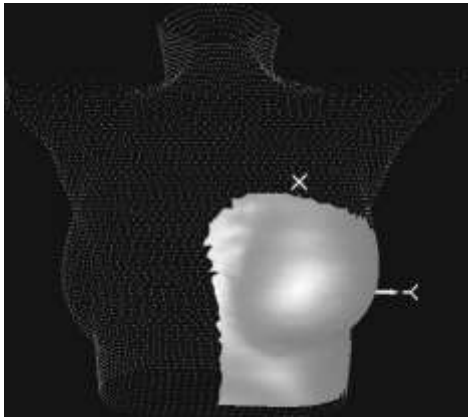
Patients (n=20)

- Left-sided breast cancer
- Breast conserving therapy
  - BCS
  - DIBH RT in treatment
    - WBI, n=1
    - SEQ, n=2
    - SIB, n=17

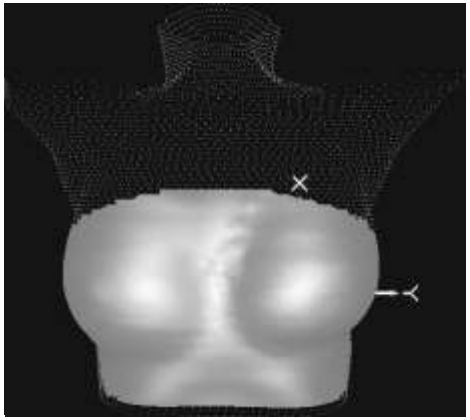
Materials and Methods

Registration

- Planning CT surface – captured 3D surface
  - Iterative closest point algorithm*
  - ROI defined on reference surface



Left side



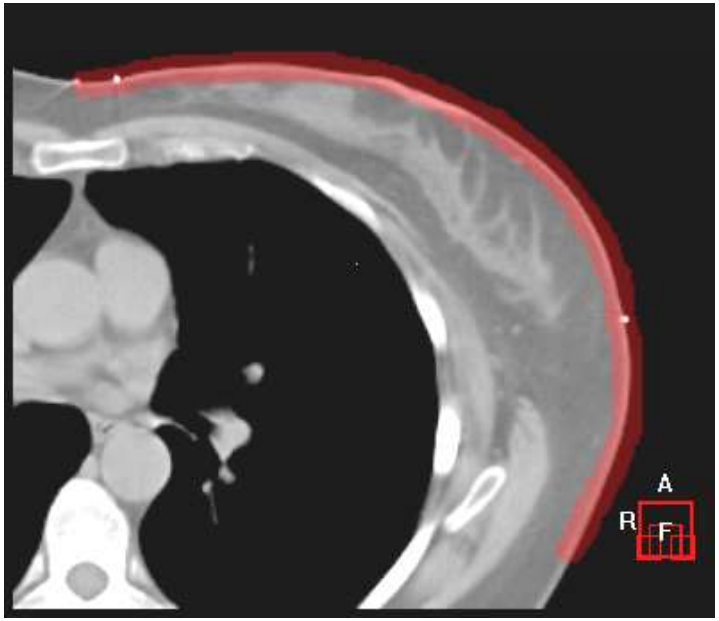
Both sides

** Besl, P.J. and McKay, N.D., IEEE Trans. Pattern. Anal. Mach. Intell. 14(2), 1992*

Materials and Methods

Registration

- Planning CT– CBCT
  - Local rigid registration
    - Cost function: correlation ratio*
  - ROI defined on planning CT scan
    - Surface left side



** Roche, A., et al.: MICCAI, LNCS, vol. 1496, Springer, Heidelberg, 1998*

Materials and Methods

Mean residual registration error (RRE)

- RMS distance between
  - planning CT surface (reference)
  - registered CBCT / AlignRT (target) surface

$$\text{RRE} = \sqrt{\frac{1}{k}\sum_{i=0}^{k-1}\left\| p_i^r - T(p_i^t)\right\|^2}$$

Where

p_i^r denotes a point in the reference surface

$T(p_i^t)$ denotes a point in the transformed target surface

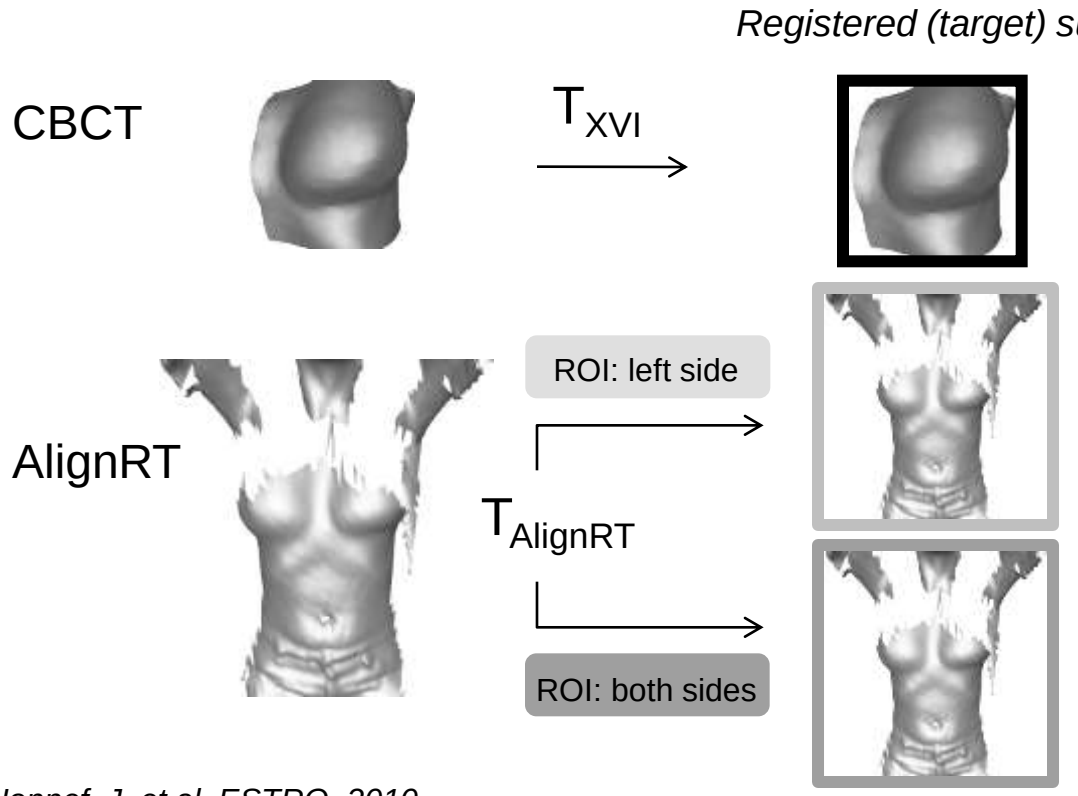
k the number of points

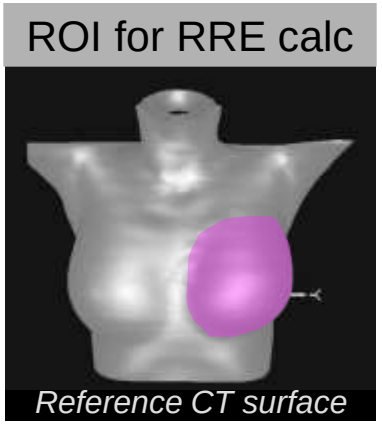
- Mean residual setup error after setup correction and shape changes

Materials and Methods

Mean residual registration error (RRE)

- CBCT surface segmentation (thresholding and smoothing)*





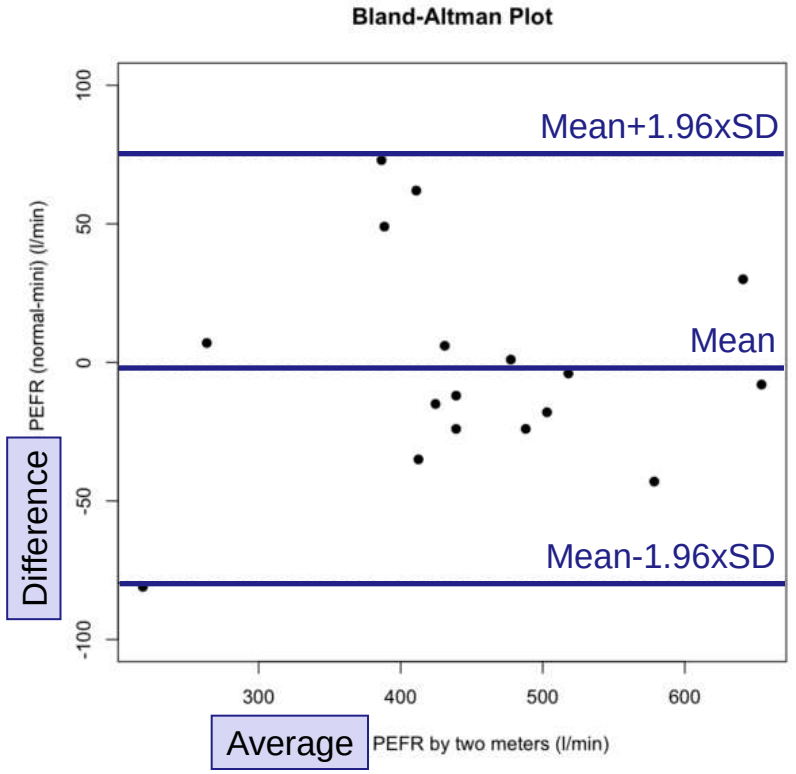
- ROI projected to target surface
- *Ignored*: points without corresponding point

** Honnef, J. et al. ESTRO, 2010*

Materials and Methods

Bland and Altman analysis – Measuring agreement

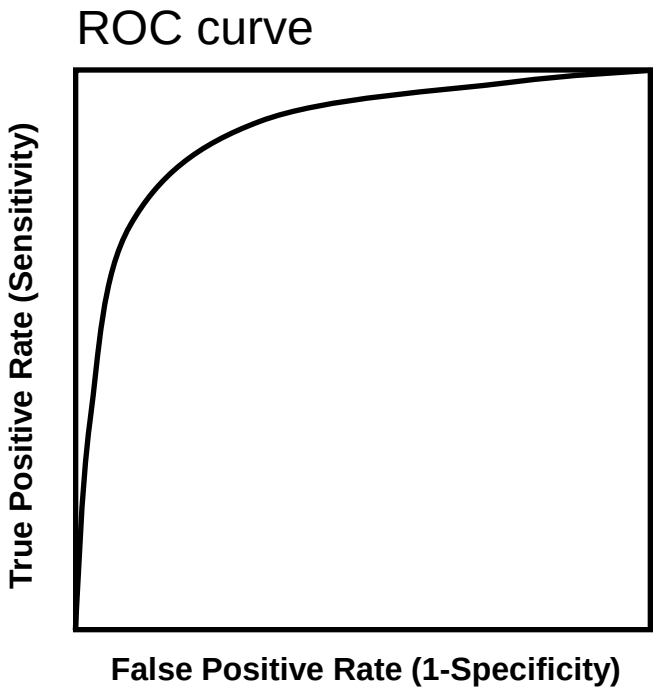
- Difference between setup errors
  - Estimated bias:
    Mean
  - Random fluctuations:
    Standard deviation (SD)
- 95% limits of agreement
  - Mean±1.96xSD



Materials and Methods

ROC analysis

- Binary classifier system (predict: movement ≥ threshold)
- Point: sensitivity / specificity pair corresponding to threshold



Results

RRE

	AlignRT – Planning CT				CBCT – Planning CT	
	ROI: both sides		ROI: left side		ROI: left side	
	RRE (cm)	nr of points	RRE (cm)	nr of points	RRE (cm)	nr of points
min	0.05	92	0.03	99	0.08	165
max	0.82	526	0.44	525	0.48	767
mean	0.23	230	0.19	229	0.21	398
stdev	0.13	92	0.09	88	0.09	112

Results

RRE

	AlignRT – Planning CT ROI: both sides		AlignRT – Planning CT ROI: left side		CBCT – Planning CT ROI: left side	
	RRE (cm)	nr of points	RRE (cm)	nr of points	RRE (cm)	nr of points
min	0.05	92	0.03	99	0.08	165
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mean	0.23	230	0.19	229	0.21	398
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- Wilcoxon signed ranks test
  - AlignRT [ROI: left side] < CBCT < AlignRT [ROI: both sides] *p<0.001*

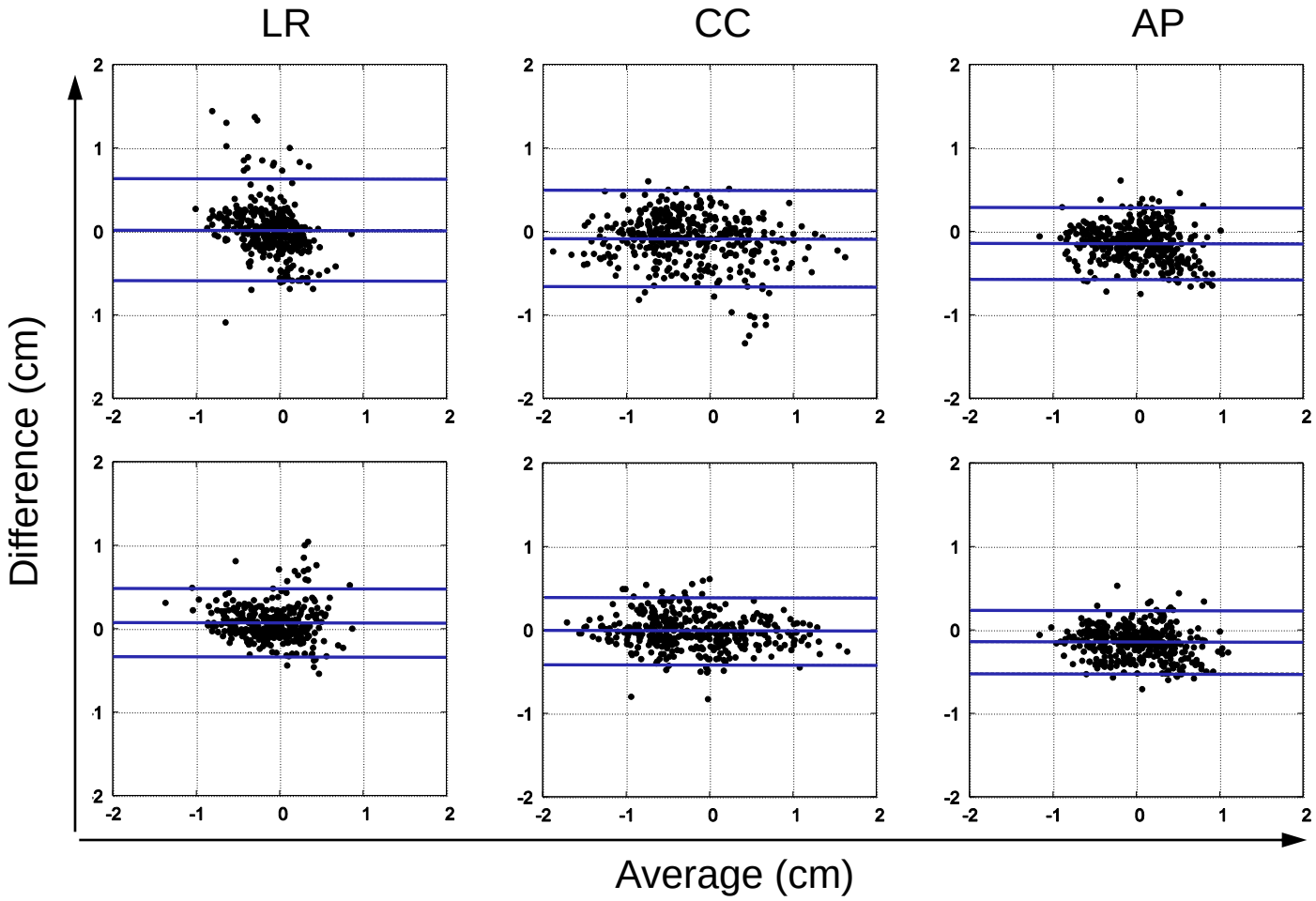
- No time trends were observed for the RRE values

Results

Bland and Altman analysis

ROI:
both sides

ROI:
left side



Results

Bland and Altman analysis

ROI	cm	LR	CC	AP
Both sides	m	0.02	-0.08	-0.14
	sd	0.31	0.30	0.22
	m-1.96xsd	-0.59	-0.66	-0.57
	m+1.96xsd	0.63	0.50	0.29
Left side	m	0.07	-0.01	-0.15
	sd	0.21	0.21	0.19
	m-1.96xsd	-0.34	-0.42	-0.52
	m+1.96xsd	0.48	0.39	0.23

ROI left side tighter limits of agreement than ROI both sides

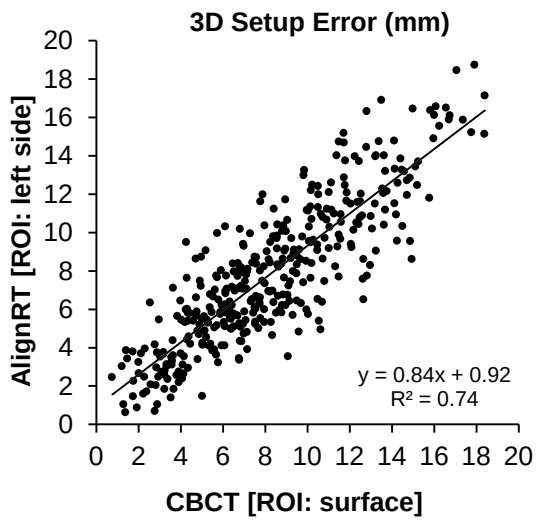
Results

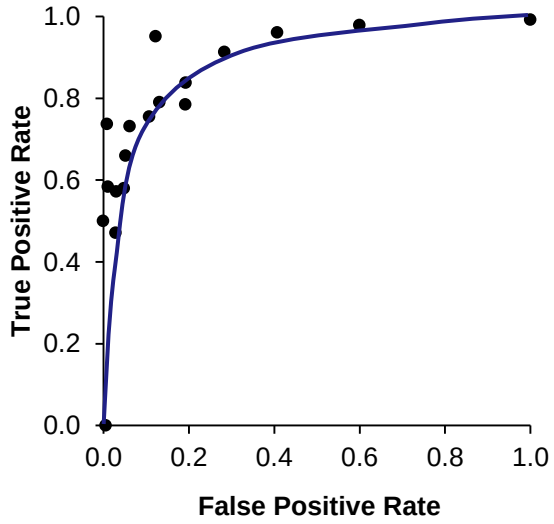
ROC analysis (3D movement >= Threshold)

AlignRT surface (ROI: left side) vs CBCT surface

Threshold (mm)	1	2	3	4	5	6	7	8
FN	3	8	14	16	26	43	47	38
FP	1	6	11	6	23	22	31	26
TP	375	261	338	314	272	222	171	143
TN	0	4	16	43	58	92	130	172
FPR	1.00	0.60	0.41	0.12	0.28	0.19	0.19	0.13
TPR	0.99	0.98	0.96	0.95	0.91	0.84	0.78	0.79

...





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ROC analysis (3D movement >= Threshold)

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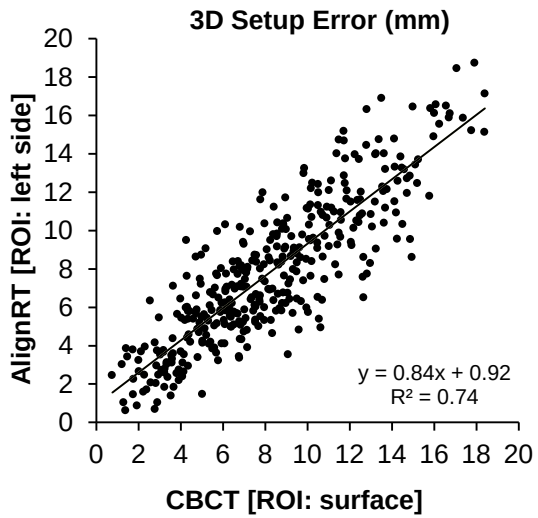
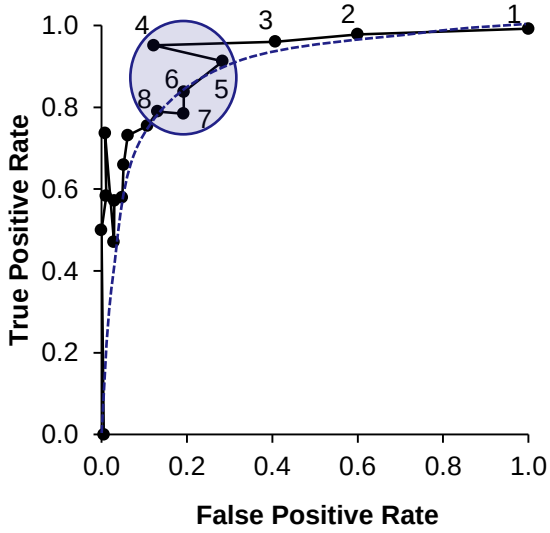
TPR	0.99	0.98	0.96	0.95	0.91	0.84	0.78	0.79

...





Threshold
4-8 mm
promising
prediction model?

Alderliesten et al. IJROBP, 2013

Statistics on Discrepancies

M, Σ, σ in cm and R^2

ROI		LR	CC	AP
Both sides	M	0.04	-0.07	-0.13
	Σ	0.29	0.23	0.18
	σ	0.14	0.19	0.13
	R^2	0.33	0.79	0.75
Left side	M	0.08	-0.01	-0.14
	Σ	0.17	0.15	0.15
	σ	0.13	0.15	0.12
	R^2	0.70	0.90	0.83

Is the Surface an adequate surrogate for the Tumor Bed?

- 20 breast cancer patients
- Three registration methods:
  - Bony anatomy
  - Breast surface
  - Tumor bed
- Compare residual geometric uncertainties

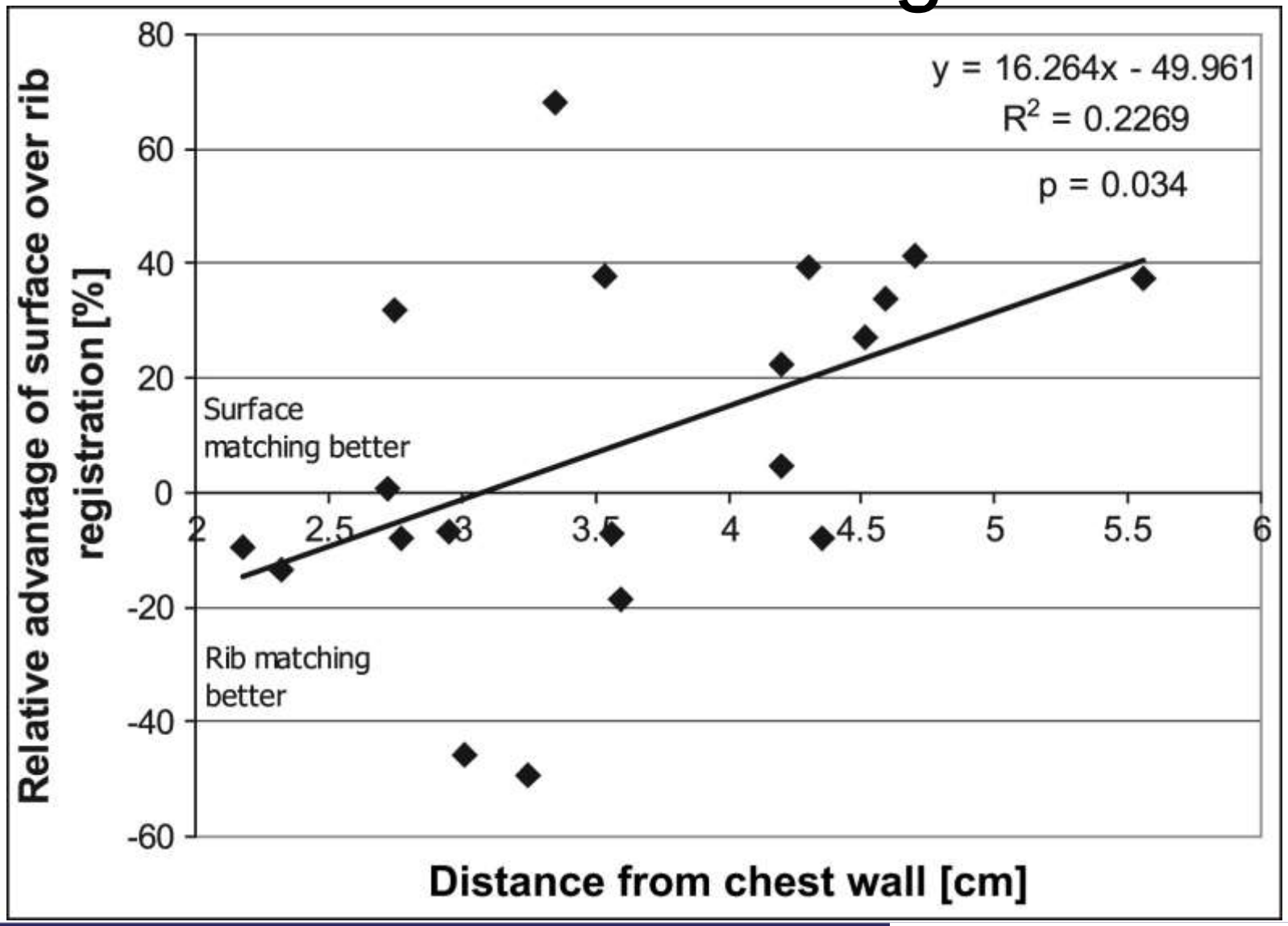
Boost position variability – Surrogate accuracy

	No-correction			Bone			Surface		
	CC	LR	AP	CC	LR	AP	CC	LR	AP
M (mm)	1.4	0.2	−3.1	0.5	−0.9	0.9	−0.4	1.0	−0.3
Σ (mm)	3.0	3.8	2.7	2.0	2.3	1.5	1.8	1.7	1.1
σ (mm)	2.6	3.2	2.9	1.8	2.3	1.9	1.7	1.6	1.6
Margin	8.3	10.6	7.7	5.6	6.5	4.5	5.1	4.8	3.3

Margin=2.5Σ + 0.3σ

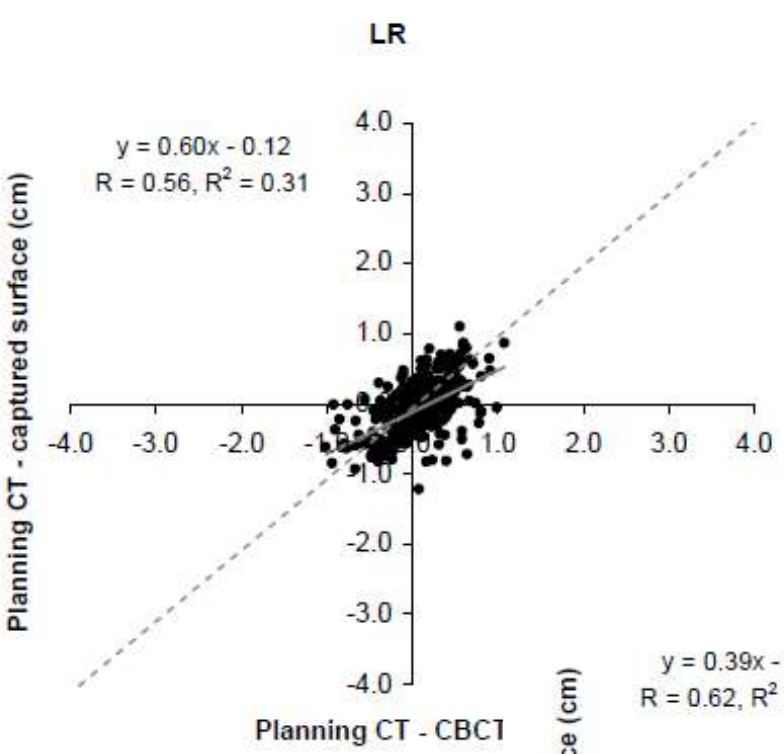
Topolnjak et al. IJROBP 2008

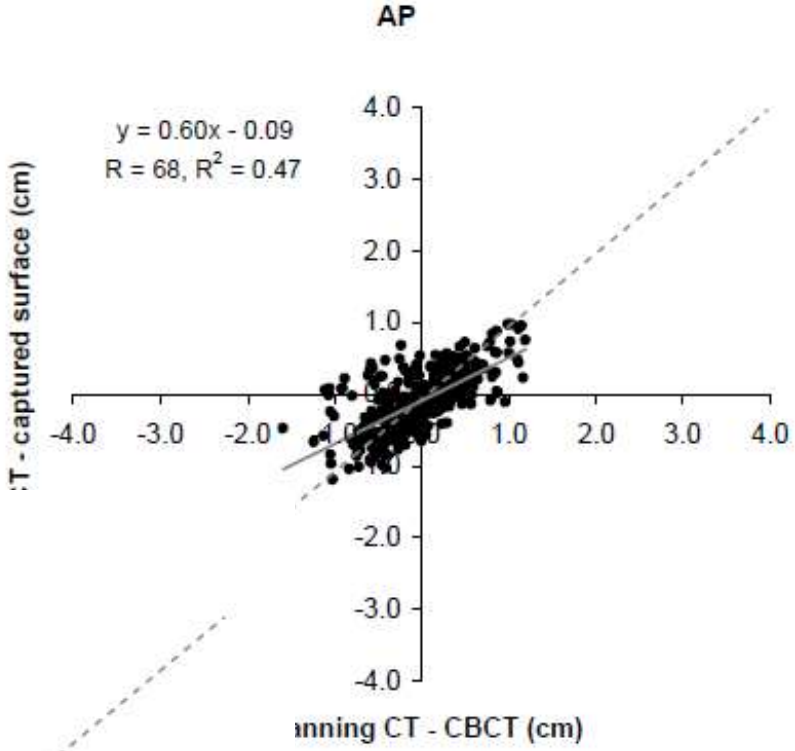
Relative Surface surrogate benefit

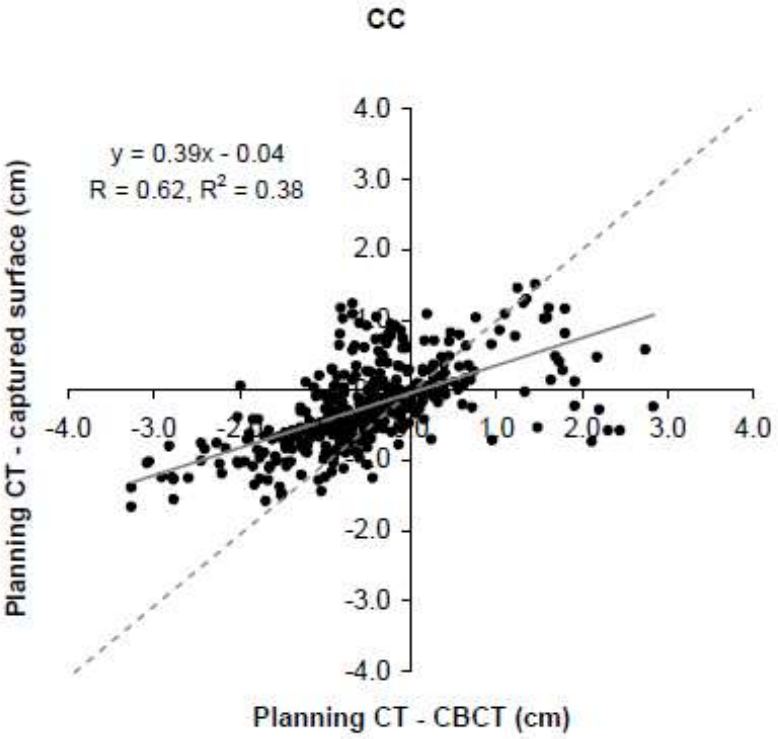


Topolnjak et al. IJROBP 2008

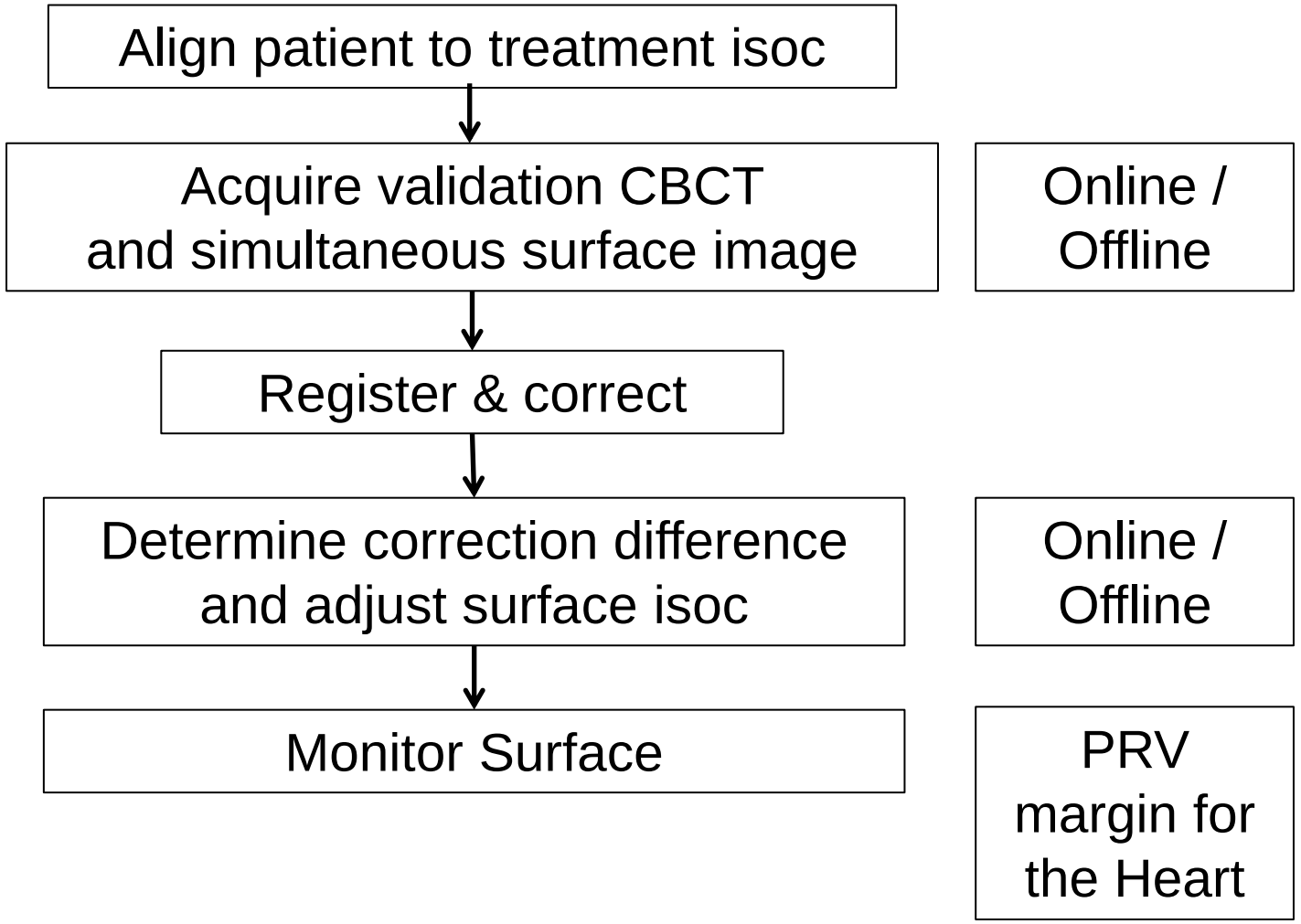
Is the Surface Correlated with the Heart Correlation







Workflow Breath-hold Monitor



Conclusions

- Surface imaging promising for SBRT surveillance and breath-hold monitoring
- Male thorax is challenging
- Better integration with other imaging technology for internal anatomy required