Organbewegung und Planungsaspekte bei der SBRT der Niere

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https://www.erc-munich.com

International Reference Site for Cyberknife® & Zap-X®

Disclosure

ERCM

C. Fürweger has previously received speaker fees from Accuray Inc. (Sunnyvale, CA, USA) and ZAP Surgical (San Carlos, CA, USA).

The ERCM is a reference site for Cyberknife® and ZAP-X®.
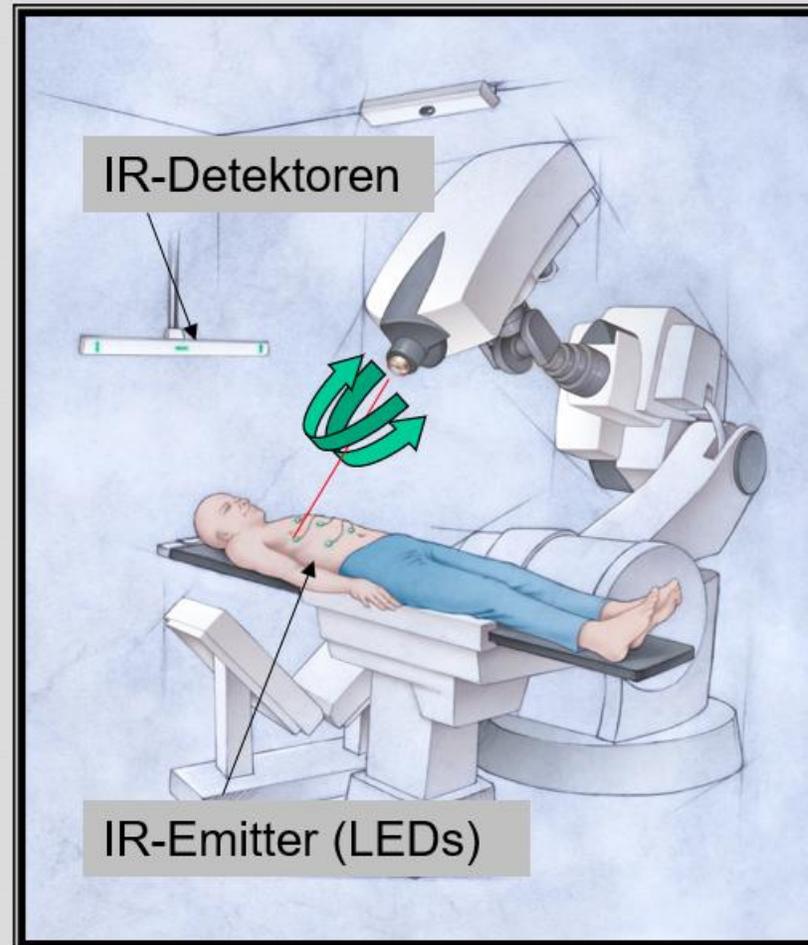
Cyberknife S7

ZAP-X

Cyberknife M6

SBRT in der Niere:
Robotergestütze Kompensation der Atembewegung…

Ein "neues" Konzept?

Erste Nieren-SBRT im ERCM: 12/2007

A. Muacevic, CyberKnife Radiosurgery for Lung/Liver Tumors, **07/2007**

CYBERKNIFE München

Bewegte Organe: Bewegungsmodell
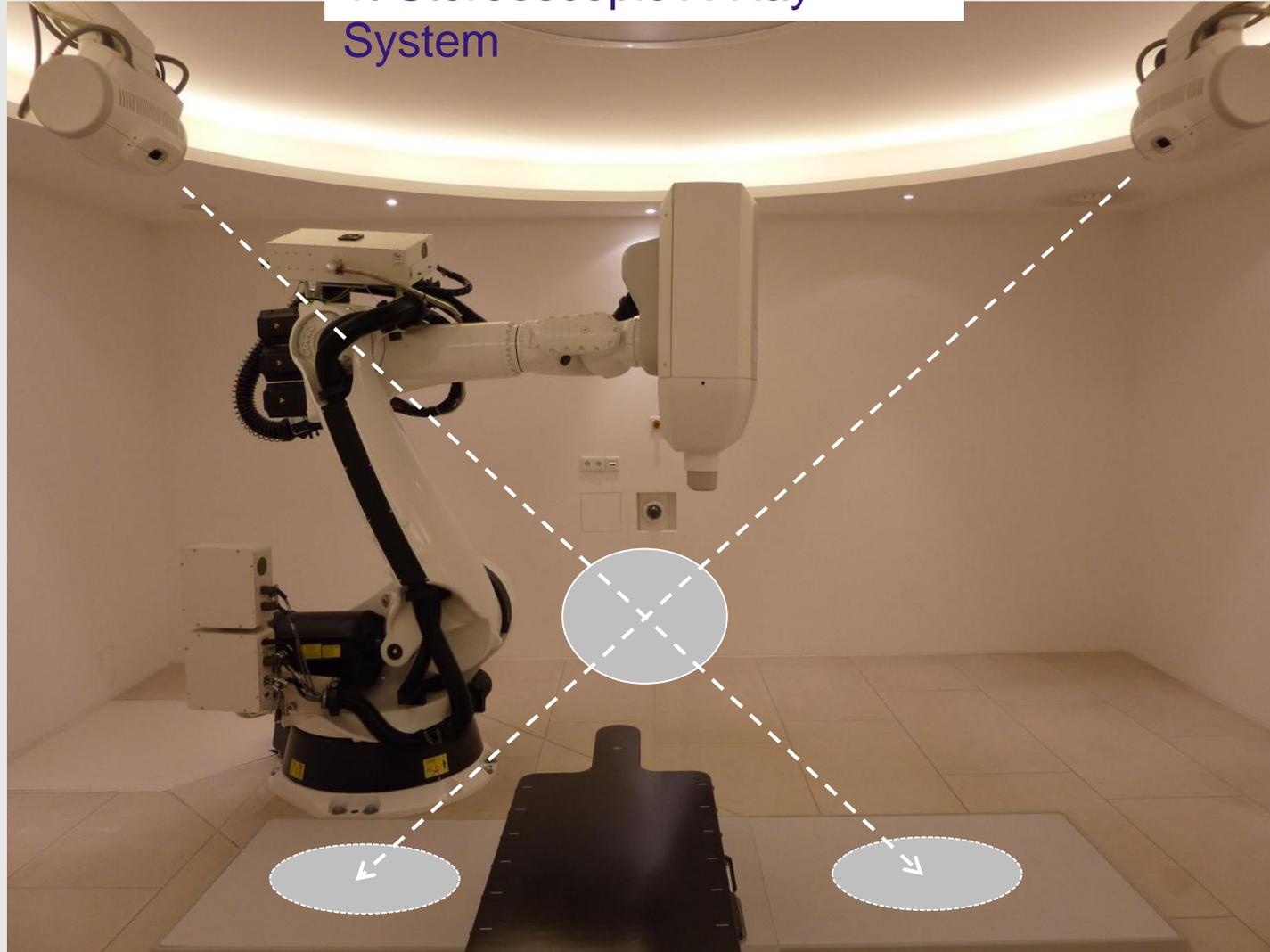
IR-Detektoren

IR-Emitter (LEDs)

- Definition der Organbewegung (Marker)
- Messung der Atembewegung (IR-LED-system)
- Kalkulation eines Korrelationsmodells (interne/externe Bewegung)
- Interative Korrektur der Korrelation durch systemisch wiederholte Bildgebungskontrolle

3

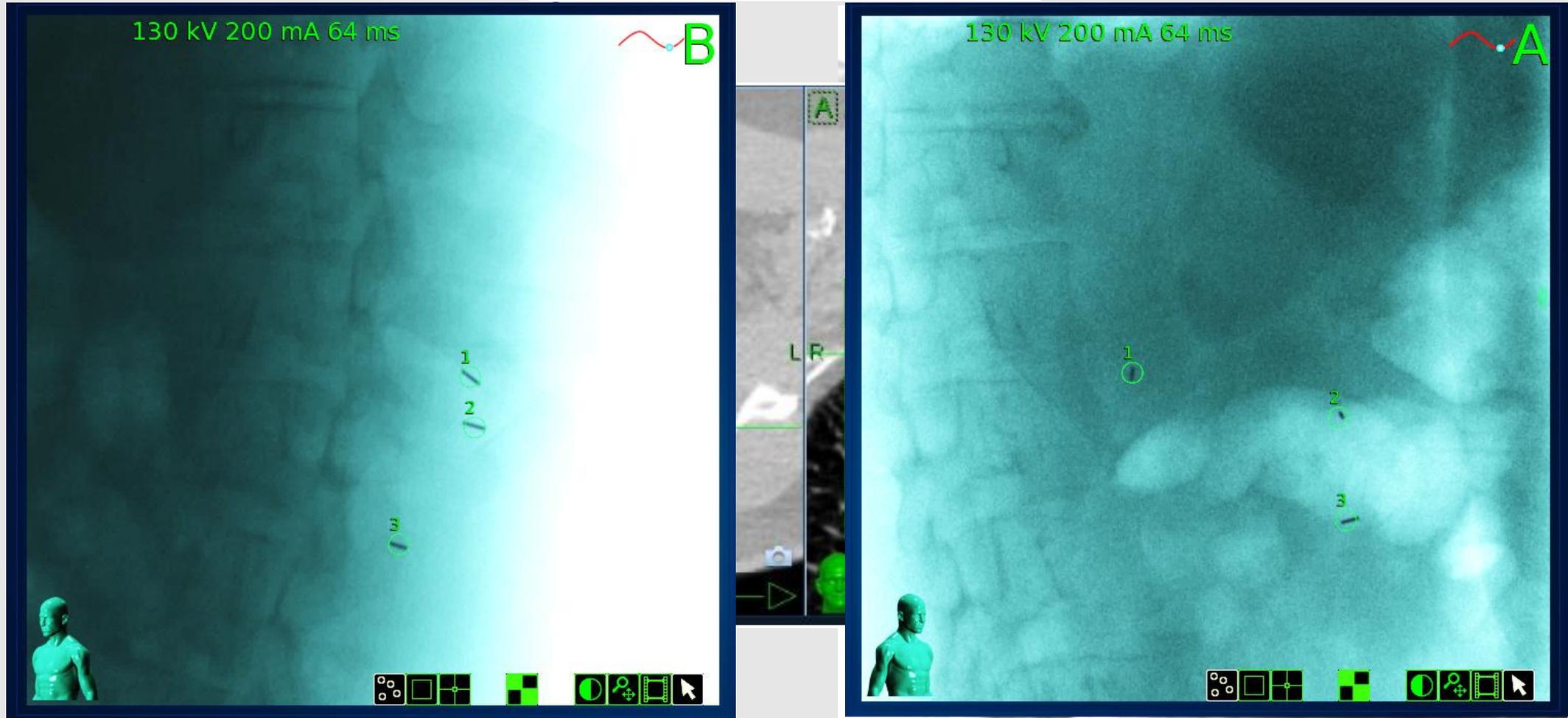# CyberKnife®: Respiratory Motion Compensation

1. Stereoscopic X-Ray System

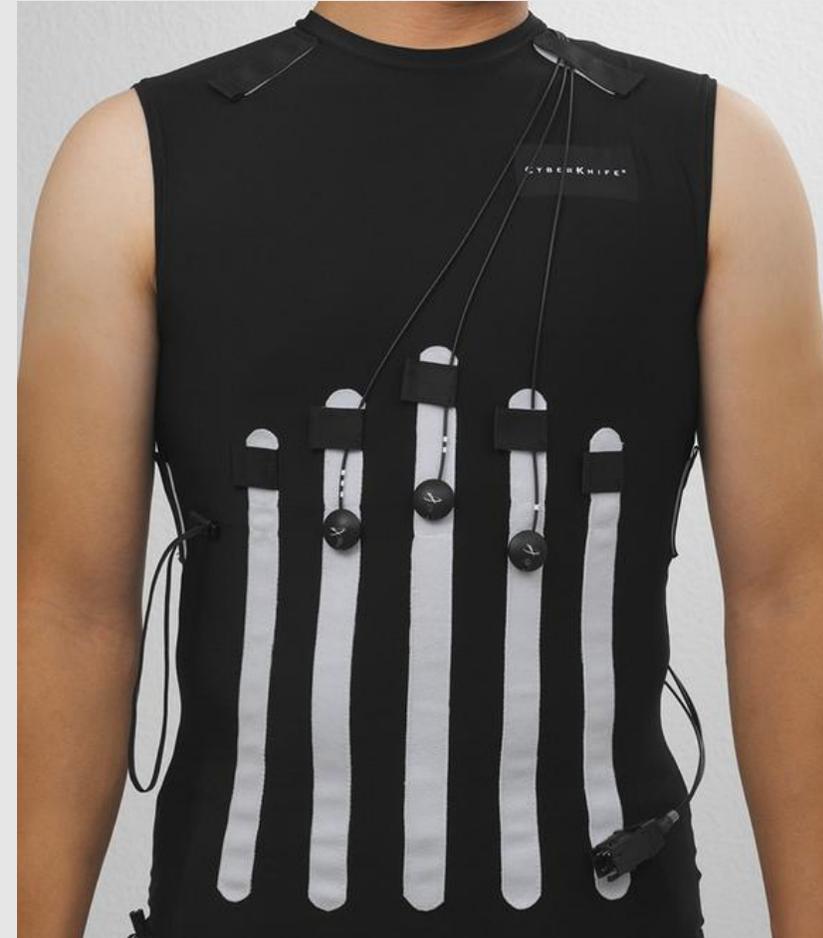# CyberKnife®: Respiratory Motion Compensation

1. Stereoscopic X-Ray

Periodic determination of the target position

CyberKnife®: Respiratory Motion Compensation

2. 3D camera array to record the external breathing motion

Continuous breathing signal during treatment

Respiratory Motion Compensation
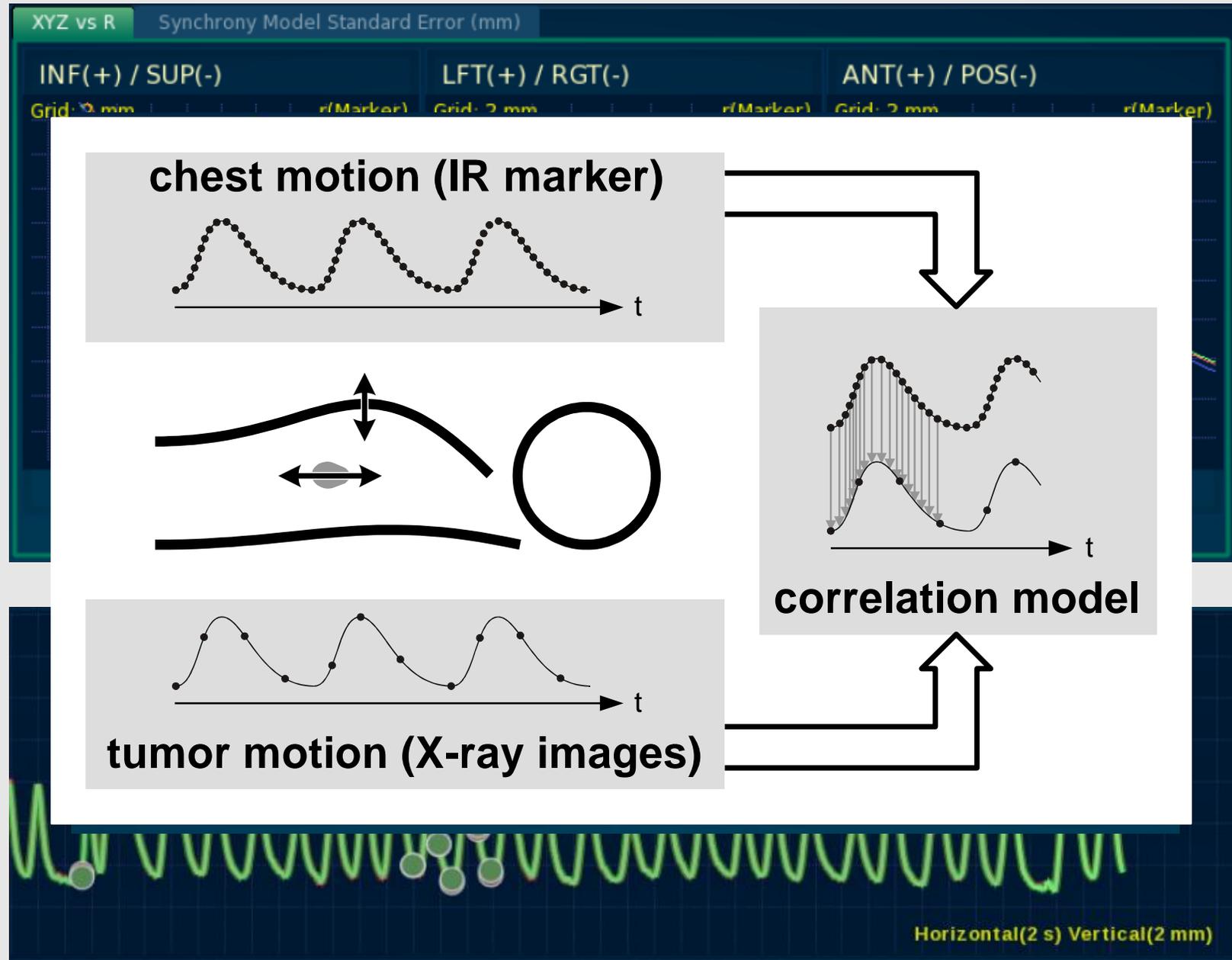
➢ Continuous breathing signal

➕

➢ Periodic determination of target position

⬇

➢ **Correlation Model**:
Continuous information about the tumor location to guide the beam
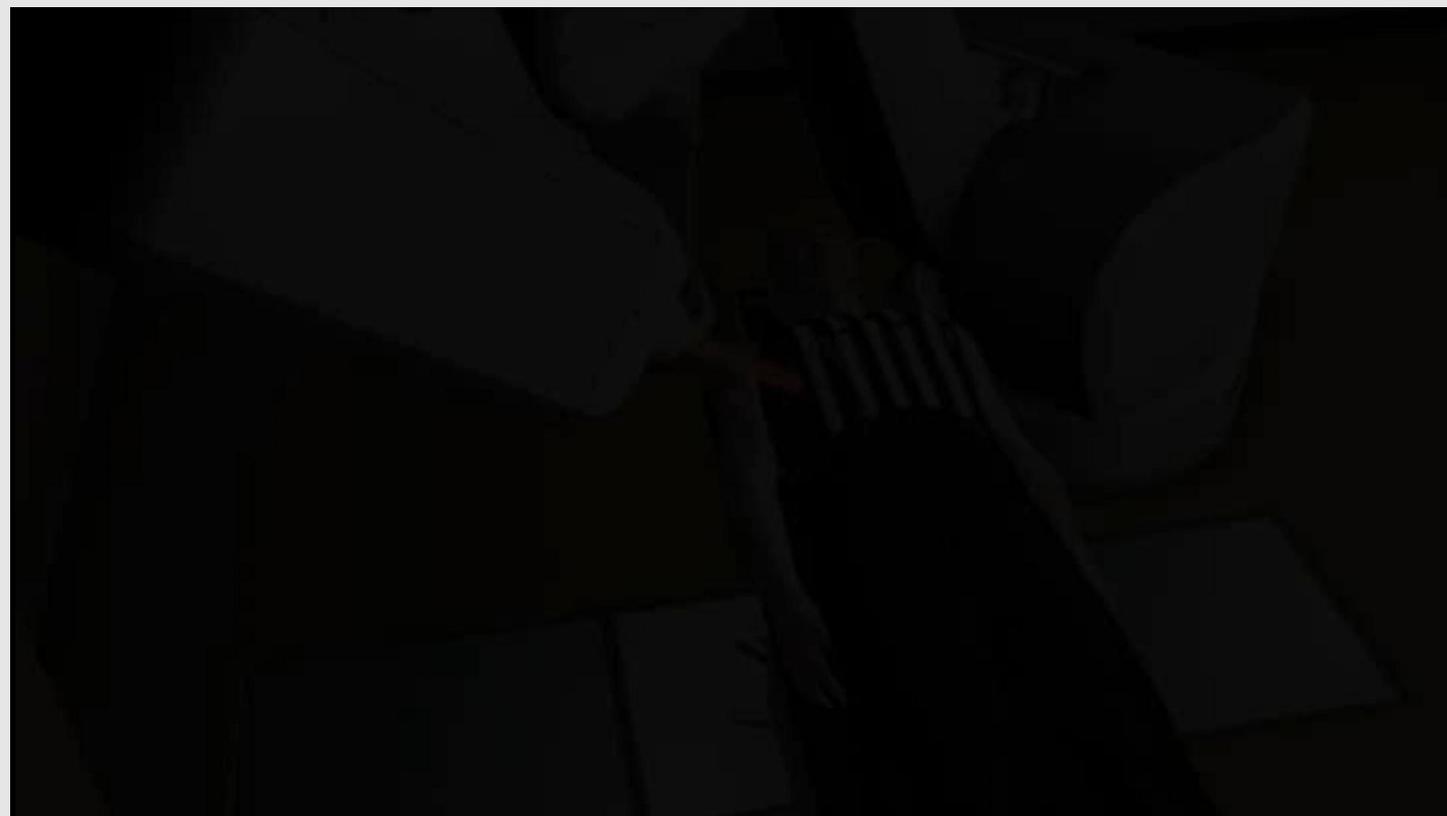
Respiratory Motion Compensation

➢ Continuous breathing signal

➕

➢ Periodic determination of target position

⬇
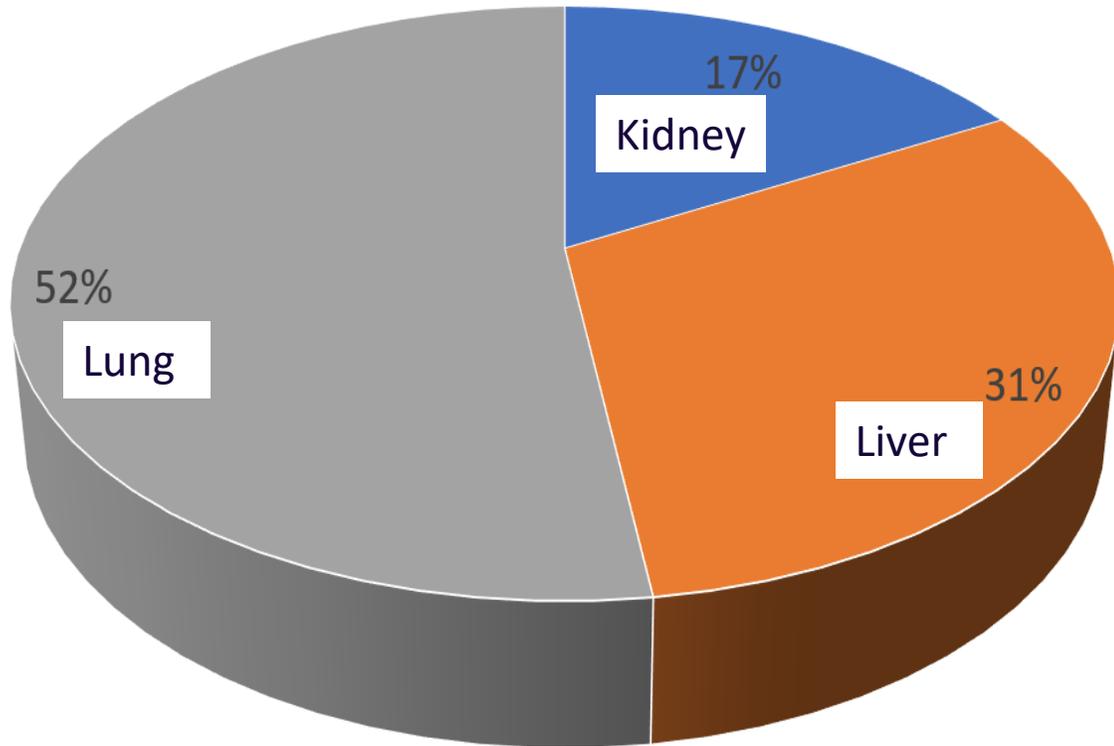
➢ Correlation Model:
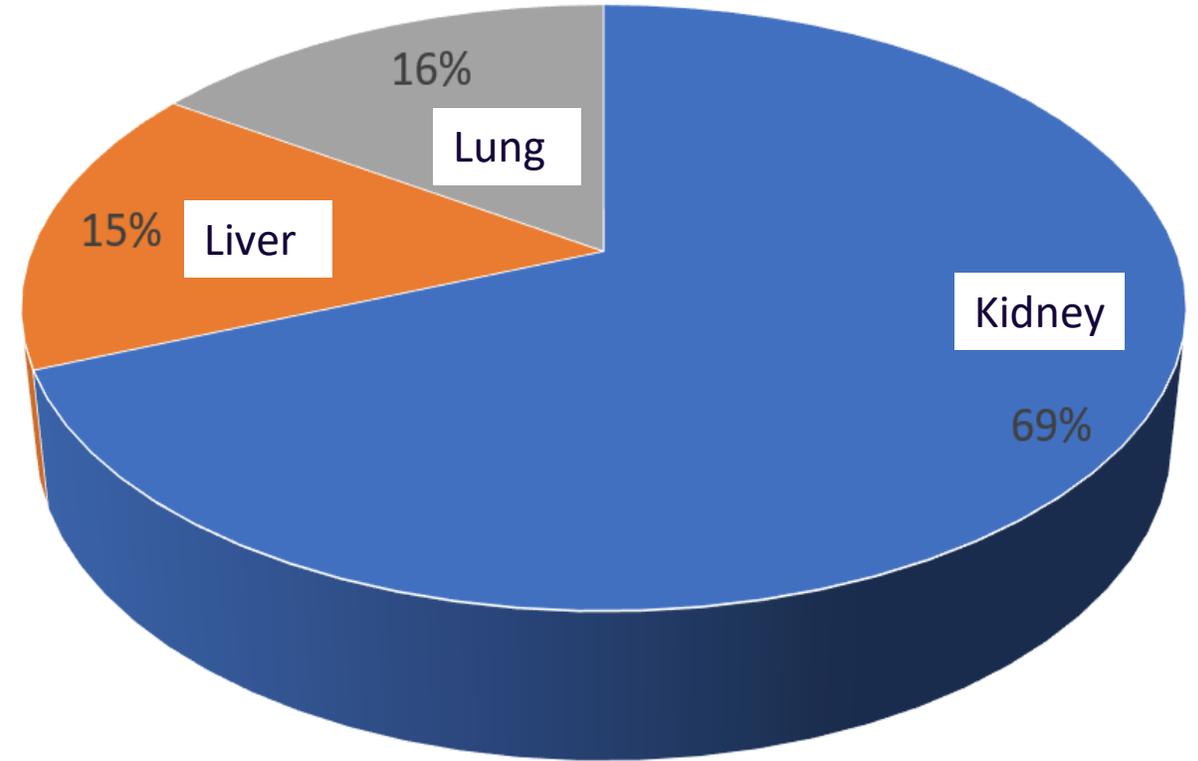*Continuous information about the tumor location to guide the beam*

Moving Targets: Treatment Indications

2013
- Kidney 17%
- Liver 31%
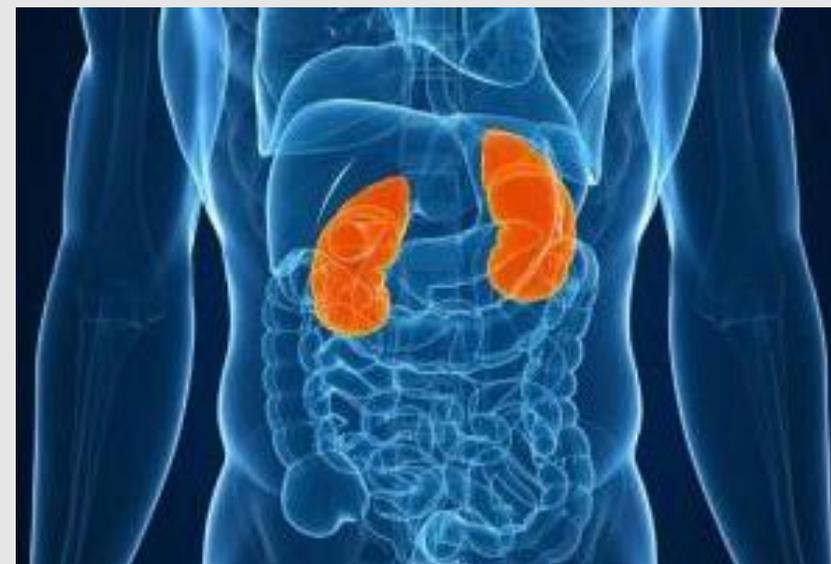- Lung 52%

2025
- Kidney 69%
- Liver 15%
- Lung 16%

~ 550 renal treatments with robotic SBRT as of Jan 2026

Clinical Accuracy of Robotic Radiosurgery for Renal Lesions

- SBRT: emerging therapy for renal lesions (IROCK)

- However: Inconsistent margins in clinical use[1]

http://www.ngopulse.org/article/2016/12/08/about-our-kidneys

1) Consensus statement from the International Radiosurgery Oncology Consortium for Kidney for primary renal cell carcinoma, S Siva, R J Ellis, L Ponsky, B S Teh, A Mahadevan, **A Muacevic,** M Staehler, H Onishi, P Wersall, T Nomiya, and S S Lo, Future Oncology 2016 12:5, 637-645

Uncertainty / Margins for Robotic SBRT with Respiratory Motion Compensation

- Lung: Hoogeman 2009[1], Lu 2008[2], Pepin 2011[3], Yang 2017[4] etc.

- Liver: Winter 2015[5], Chan 2017[6], Nakayama 2019[7] etc.

- *Kidney: ??*

1) Hoogeman M, Prévost JB, Nuyttens J, Pöll J, Levendag P, Heijmen B. Clinical accuracy of the respiratory tumor tracking system of the cyberknife: assessment by analysis of log files. Int J Radiat Oncol Biol Phys. 2009 May 1;74(1):297-303.

2) Lu XQ, Shanmugham LN, Mahadevan A, Nedea E, Stevenson MA, Kaplan I, Wong ET, La Rosa S, Wang F, Berman SM. Organ deformation and dose coverage in robotic respiratory-tracking radiotherapy. Int J Radiat Oncol Biol Phys. 2008 May 1;71(1):281-9.

3) Pepin EW, Wu H, Zhang Y, Lord B. Correlation and prediction uncertainties in the cyberknife synchrony respiratory tracking system. Med Phys. 2011 Jul;38(7):4036-44.

4) Yang ZY, Chang Y, Liu HY, Liu G, Li Q. Target margin design for real-time lung tumor tracking stereotactic body radiation therapy using CyberKnife Xsight Lung Tracking System. Sci Rep. 2017 Sep 7;7(1):10826.

5) Winter JD, Wong R, Swaminath A, Chow T. Accuracy of Robotic Radiosurgical Liver Treatment Throughout the Respiratory Cycle. Int J Radiat Oncol Biol Phys. 2015 Nov 15;93(4):916-24.

6) Chan M, Grehn M, Cremers F, Siebert FA, Wurster S, Huttenlocher S, Dunst J, Hildebrandt G, Schweikard A, Rades D, Ernst F, Blanck O. Dosimetric Implications of Residual Tracking Errors During Robotic SBRT of Liver Metastases. Int J Radiat Oncol Biol Phys. 2017 Mar 15;97(4):839-848.

7) Nakayama M, Uehara K, Nishimura H, Tamura S, Munetomo Y, Tsudou S, Mayahara H, Mukumoto N, Geso M, Sasaki R. Retrospective assessment of a single fiducial marker tracking regimen with robotic stereotactic body radiation therapy for liver tumours. Rep Pract Oncol Radiother. 2019 Jul-Aug;24(4):383-391.

Robotic Radiosurgery for Renal Lesions

Accuracy?

- **Analysis of system log files**

- **Simulation of target rotation**

Analysis: Patient Cohort

Renal cell carcinoma

165 consecutive treatments

02/2013 – 09/2019

Sex	
Male	110 (66.7 %)
Female	55 (33.3 %)
Side	
Right	90 (54.5 %)
Left	75 (45.5 %)
Pretreatment	
Surgery	62 (37.6 %)
No surgery	103 (62.4 %)

|	Mean / median	Range (min to max)
Patient age [years]	– / 76	40 to 93
Treatment volume	45.5 cm^3 / 31.1 cm^3	4.9 cm^3 to 318.4 cm^3
Prescribed Dose		
1 fraction (n = 141)	24.5 Gy / 25 Gy	18 Gy to 25 Gy
3 fraction (n = 22)	13 Gy / 13 Gy	13 Gy to 14 Gy
5 fraction (n = 2)	9 Gy	9 Gy
Prescription isodose line	68.6 % / 70 %	50 % to 75 %
Number of implanted fiducials	3.2 / 3.0	1 to 6

Results: Tumor Motion

Tumor motion:

➢ **mostly sup/inf**

➢ **~ 2 cm excursion**
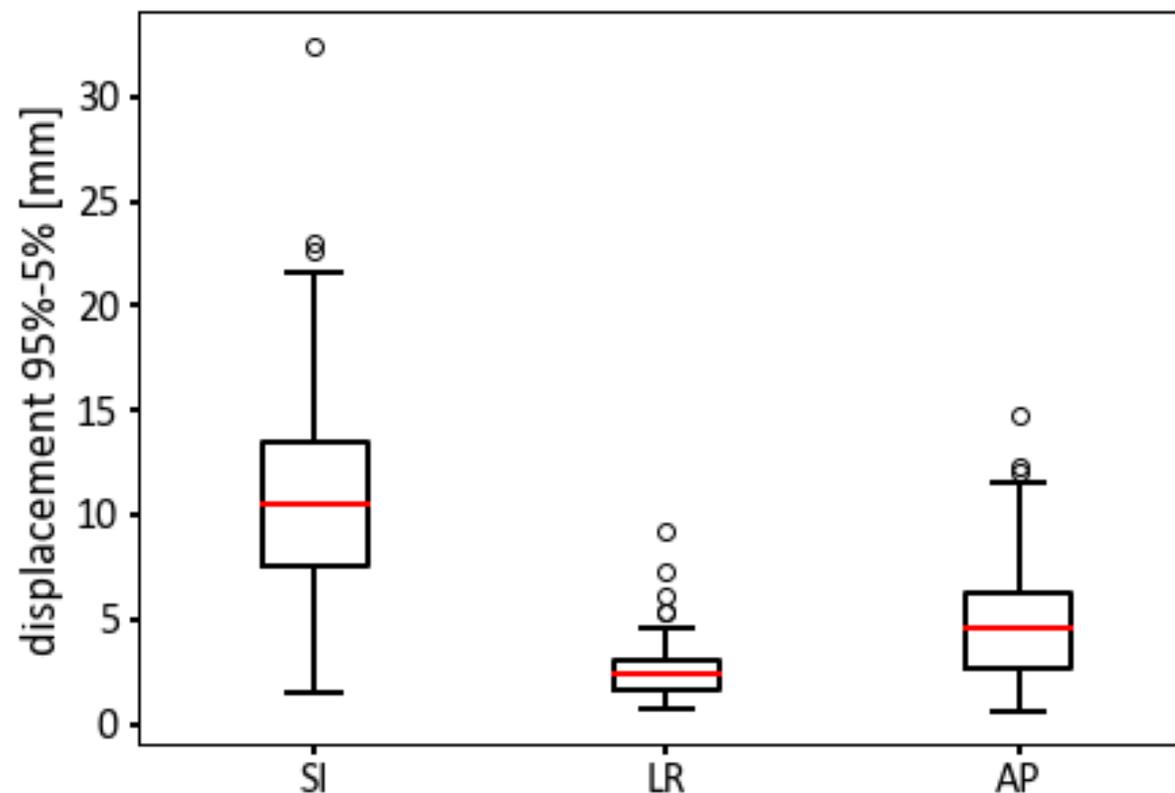
Treating Renal Targets: Sources of Uncertainty

1. **Correlation model error**

Displacement optical markers
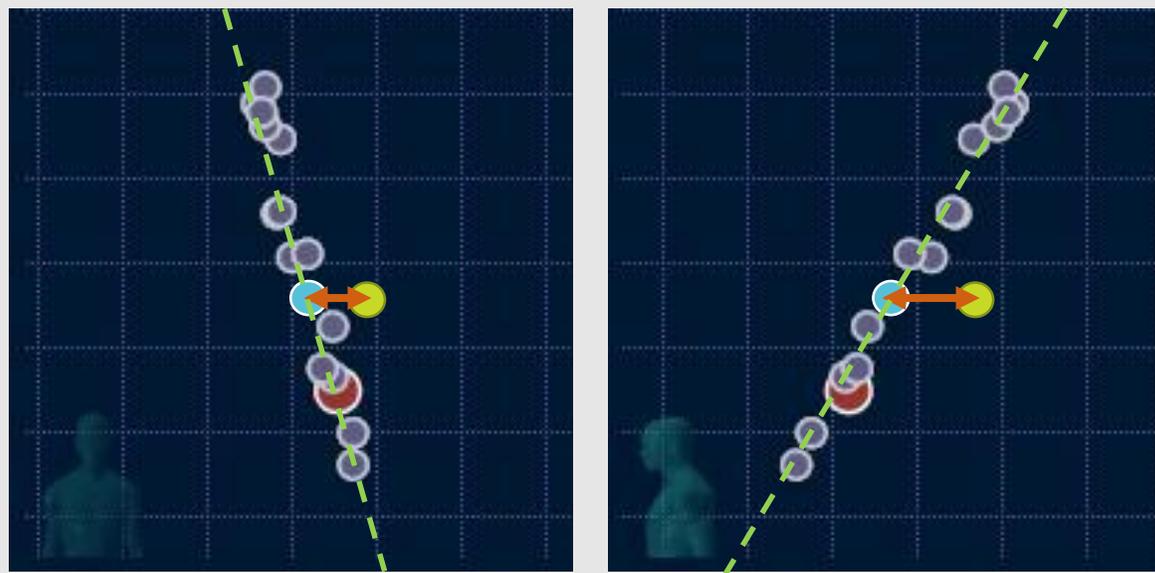
Time

Correlate to breathing signal
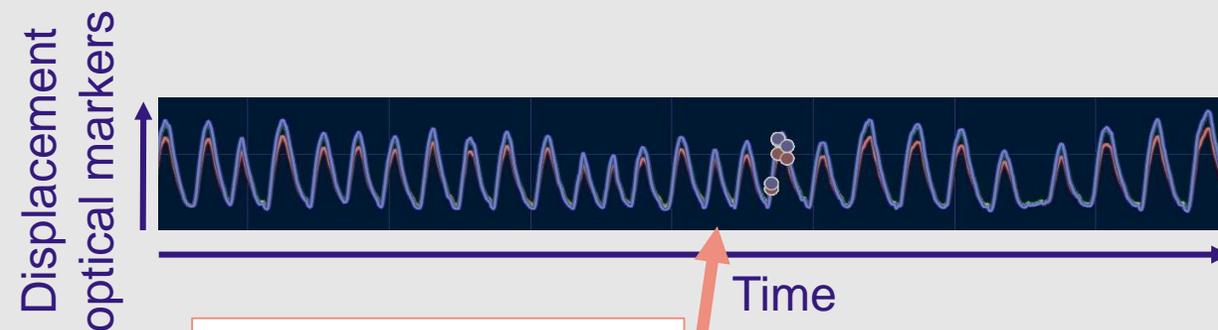
3D fiducial positions from kV images

Treating Renal Targets: Sources of Uncertainty

1. Correlation model error

Correlation error = Absolute distance between **expected** position and **measured** position
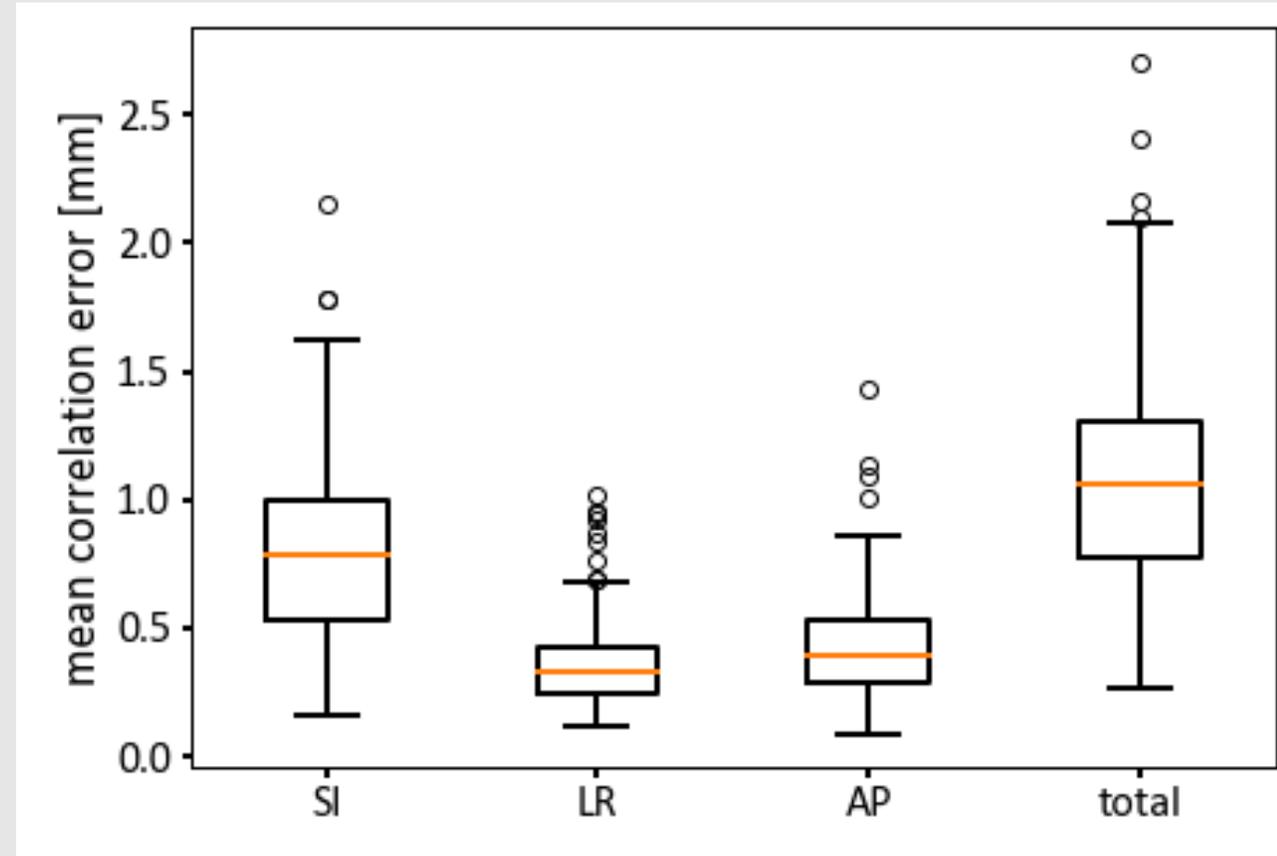
Results: Correlation Model Error

95th percentile

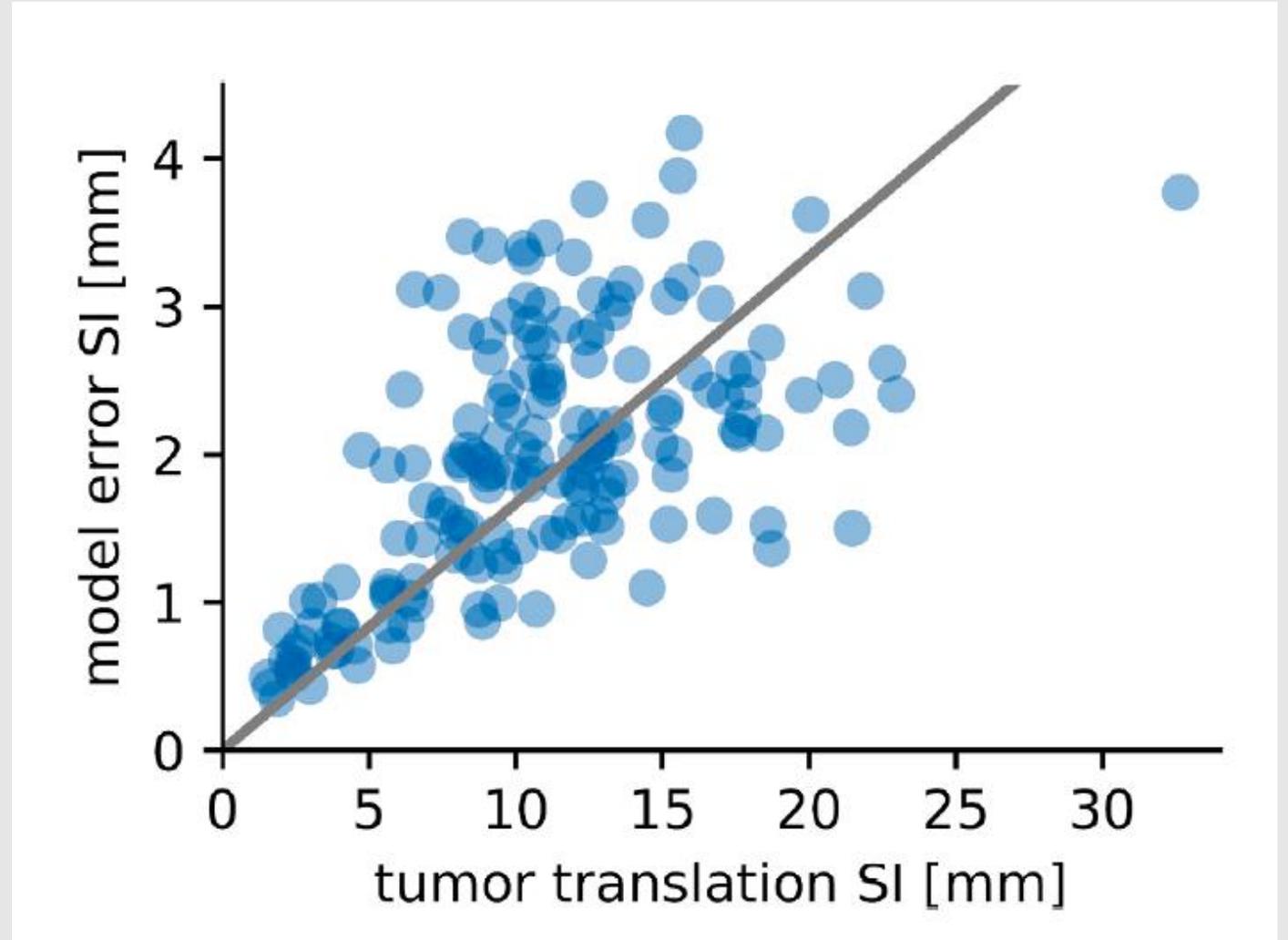|	95th percentile
SI:	2.0 mm
LR:	0.8 mm
AP:	0.9 mm
Total:	2.9 mm

Results: Correlation Error vs Motion

95th percentile

	95th percentile
SI:	2.0 mm
LR:	0.8 mm
AP:	0.9 mm
Total:	2.9 mm

Treating Renal Targets: Sources of Uncertainty

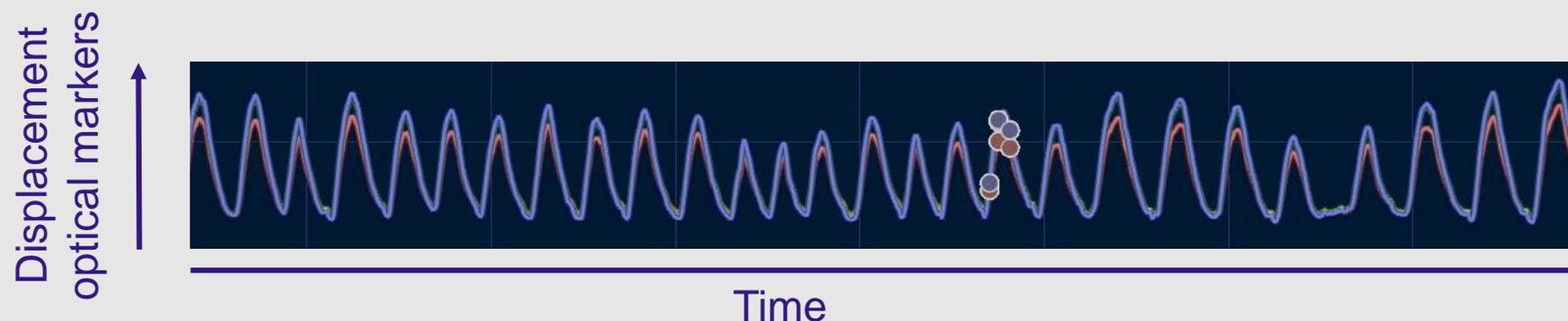1. Correlation error

2. Prediction error

Sayeh et al. (2007) Respiratory Motion Tracking for Robotic Radiosurgery. In: Urschel H.C., Kresl J.J., Luketich J.D., Papiez L., Timmerman R.D., Schulz R.A. (eds) Treating Tumors that Move with Respiration. Springer, Berlin, Heidelberg

Treating Renal Targets: Sources of Uncertainty

2. Prediction error

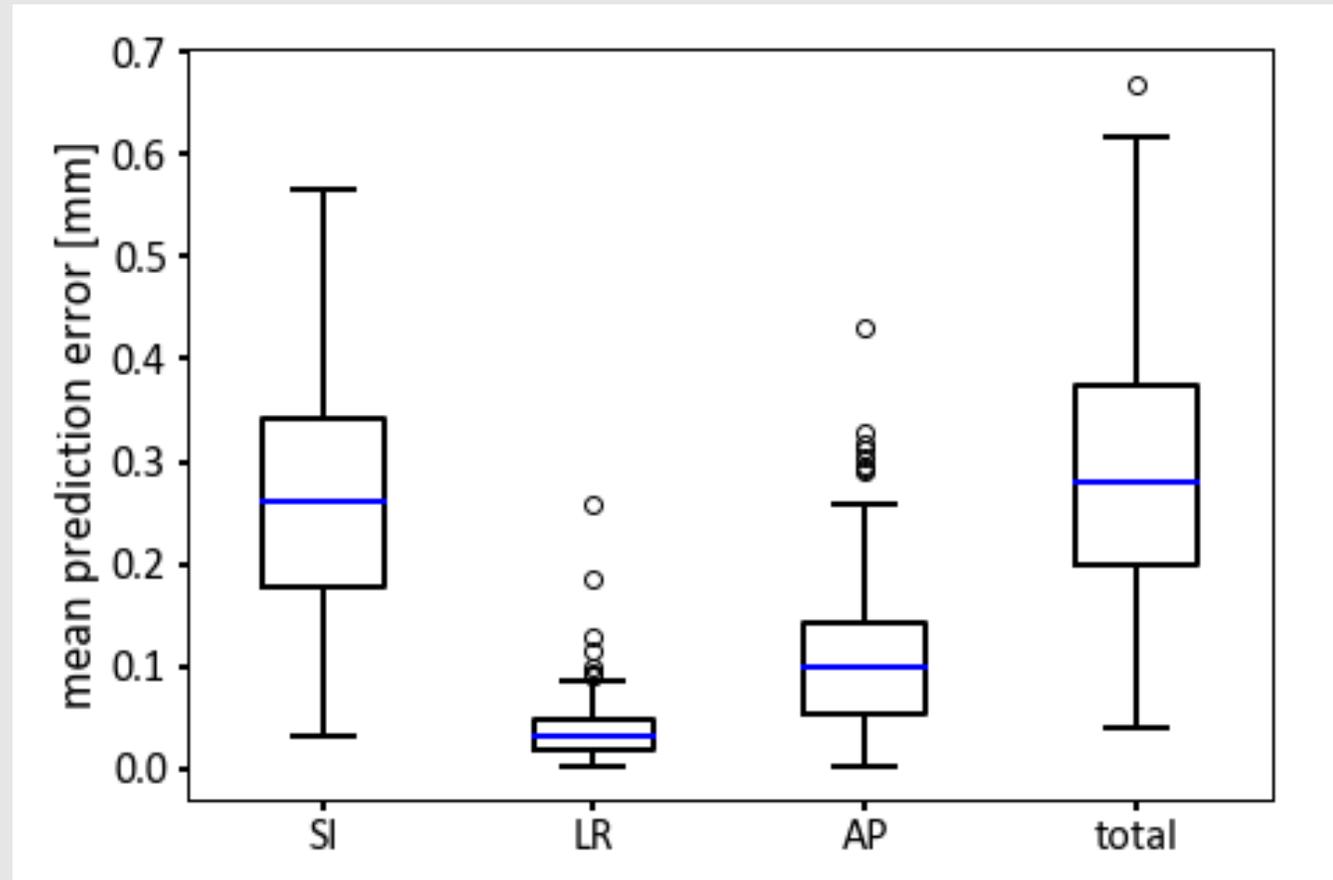- System latency of 115 ms

- Compensation: Prediction algorithm

Prediction error = Absolute difference between current target position and the position predicted 115 ms ago

Results: Prediction error

	95th percentile
SI:	0.6 mm
LR:	0.1 mm
AP:	0.3 mm
Total:	0.6 mm

Treating Renal Targets: Sources of Uncertainty

1. Correlation error

2. Prediction error

3. E2E accuracy

Sayeh et al. (2007) Respiratory Motion Tracking for Robotic Radiosurgery. In: Urschel H.C., Kresl J.J., Luketich J.D., Papiez L., Timmerman R.D., Schulz R.A. (eds) Treating Tumors that Move with Respiration. Springer, Berlin, Heidelberg
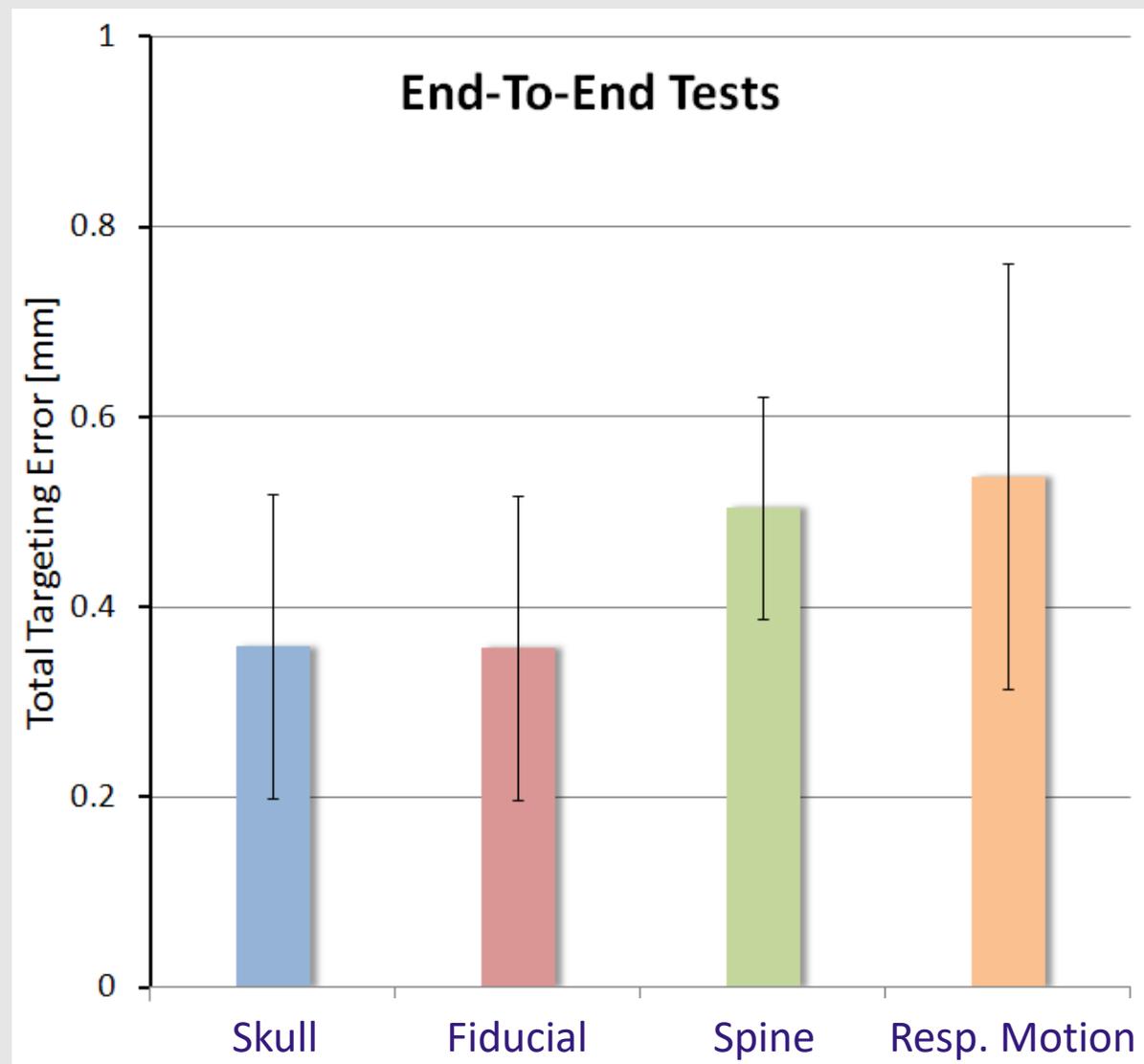
Results: E2E Accuracy

Realistic delivery, film exposure

Total targeting error (radial, respiratory motion phantom):

0.52 ± 0.24 mm

Manufacturer specification:

< 0.95 mm

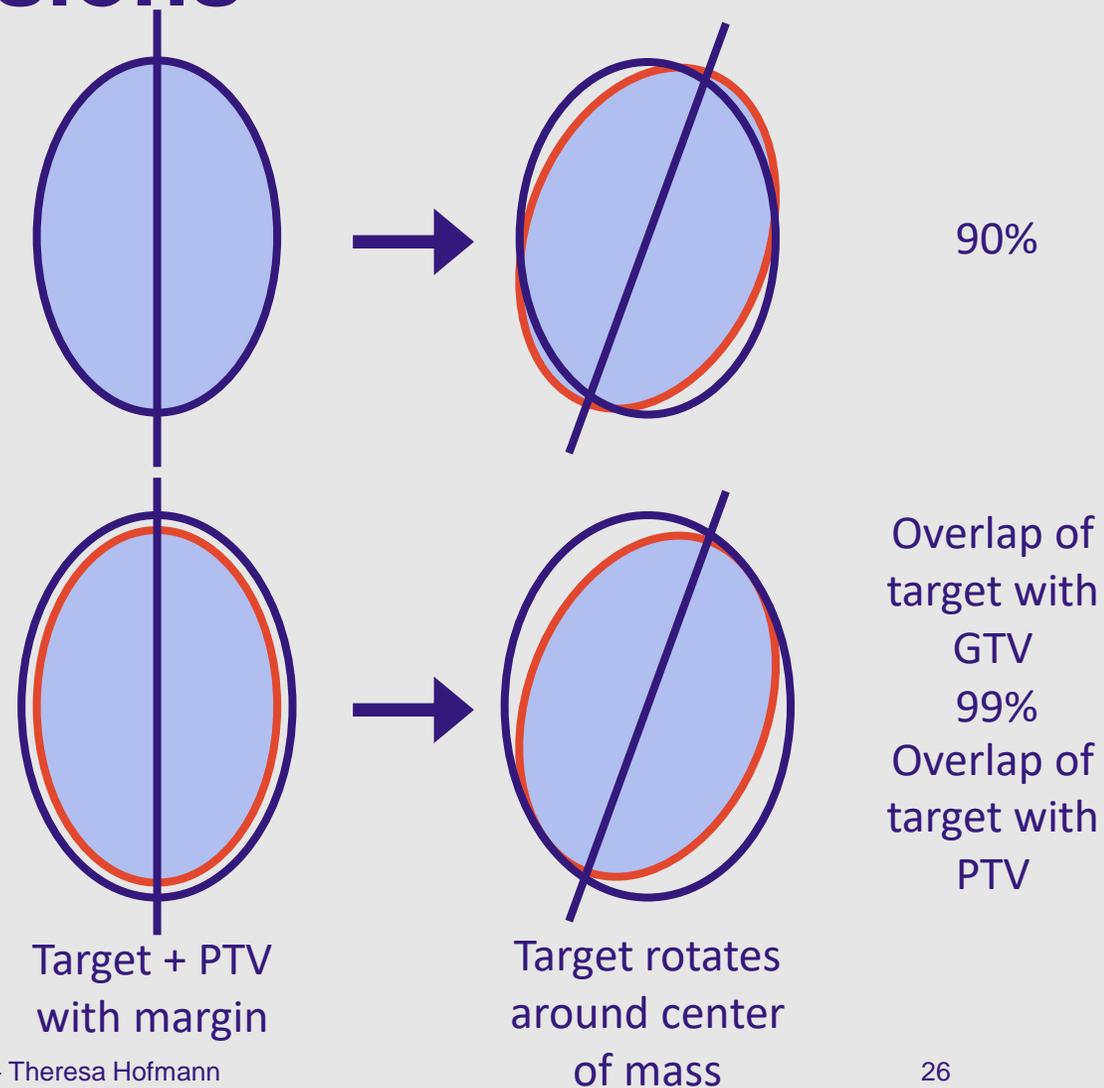# Clinical Accuracy of Robotic Radiosurgery for Renal Lesions

1. Correlation error

2. Prediction error

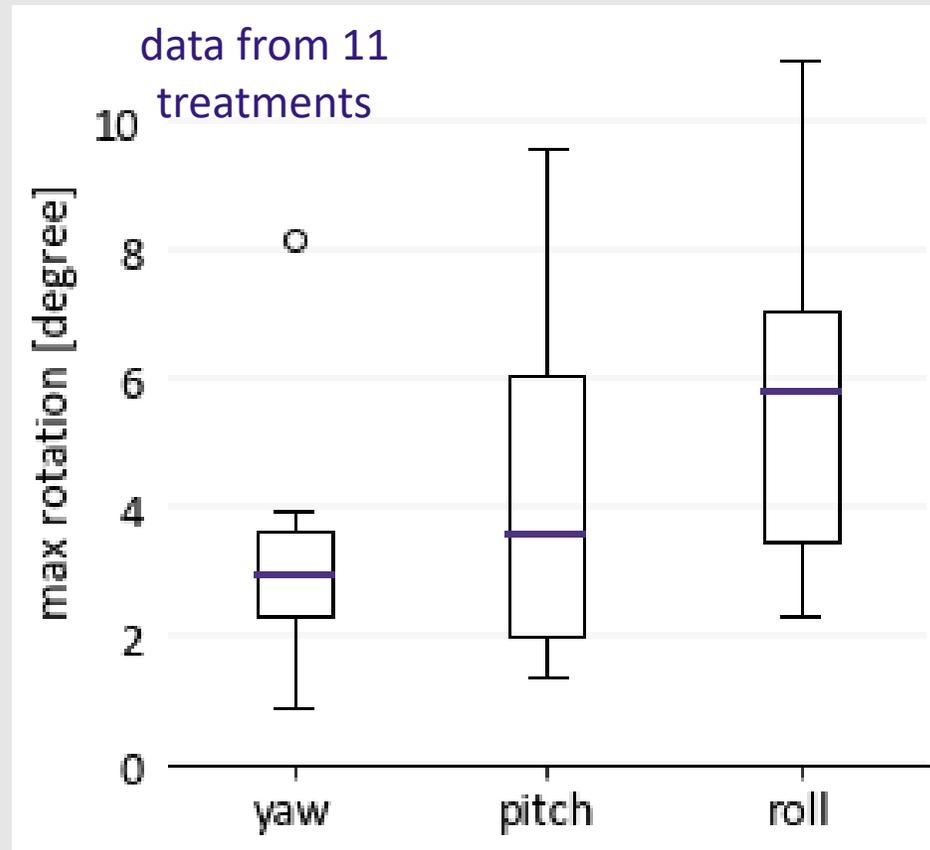3. E2E accuracy

4. Target rotation error

Sayeh et al. (2007) Respiratory Motion Tracking for Robotic Radiosurgery. In: Urschel H.C., Kresl J.J., Luketich J.D., Papiez L., Timmerman R.D., Schulz R.A. (eds) Treating Tumors that Move with Respiration. Springer, Berlin, Heidelberg

Clinical Accuracy of Robotic Radiosurgery for Renal Lesions

1. **Correlation error**

2. **Prediction error**

3. **E2E accuracy**

4. **Target rotation error**

90%

Target + PTV with margin

Target rotates around center of mass

Overlap of target with GTV 99% Overlap of target with PTV

Results: Organ Rotation

data from 11 treatments

Results: Target rotation

#Pat	2D slice	Volume [cm³]	Margin for rotation up to 15°
1		6	1 mm
2		82	1 mm
3		30	1 mm
4		14	1 mm
5		116	1 mm
6		13	1 mm
7		5	1 mm
8		6	2 mm
9		9	2 mm
10		2	2 mm
11		42	3 mm

Results: Target rotation
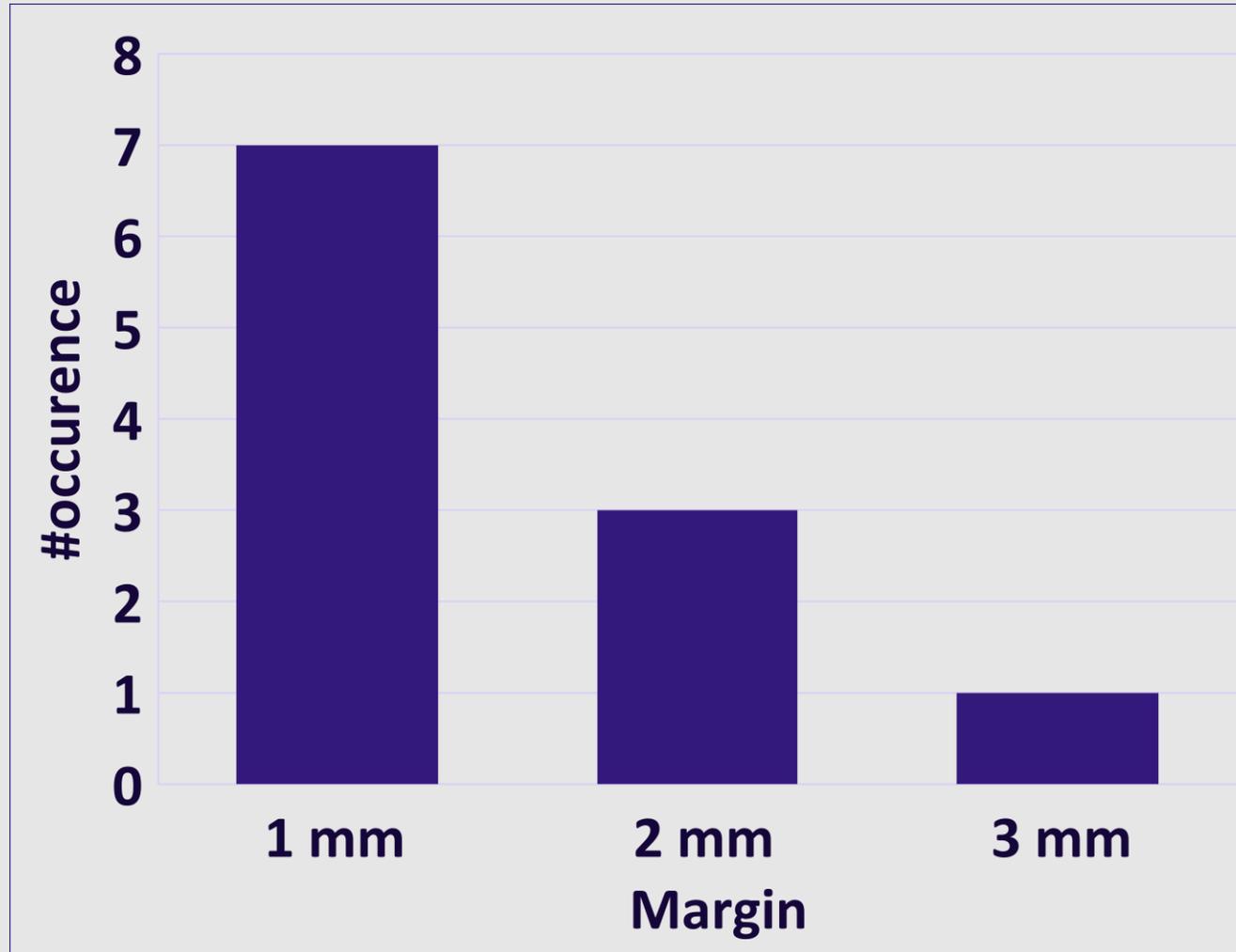
Margin to account for target rotation: 2 mm

# Renal Targets: Margins

Original paper

Accuracy of robotic radiosurgery in renal cell carcinoma

Theresa Hofmann [a,*], Nadja Kohlhase [a], Dochka Eftimova [a], Michael Martin Eder [a], Michael Staehler [b], Maximilian I. Ruge [c], Alexander Muacevic [a], Christoph Fürweger [a,c]

Total margin estimation
(Hofmann et al., P

1. Correlation mo
2. Prediction err
3. E2E accuracy
4. Target rotation

... or anisotropic:
4.3 mm Sup/Inf
2.6 mm L/R
3.0 mm Ant/Pos
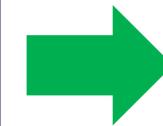
➡ *ERCM:*
4 mm Sup/Inf
3 mm L/R
3 mm Ant/Pos

Minimum PTV margin estimation   3.7 mm (isotropic)

Clinical Consequences: Does Margin Size Matter?

To be determined, but… Tan et al. 2024 (IROCK)[1]:

"A multivariable analysis demonstrated that <u>increasing tumor size</u> (odds ratio [OR] per 1 cm: 1.57; 95% confidence interval [CI]: 1.14-2.16, $p = 0.0055$) [..] was <u>associated with an eGFR decline</u> of ≥15 ml/min at 1 yr."

1) Tan VS, Correa RJM, Warner A, Ali M, Muacevic A, Ponsky L, Ellis RJ, Lo SS, Onishi H, Swaminath A, Suk Kwon Y, Morgan SC, Cury FL, Teh BS, Mahadevan A, Kaplan ID, Chu W, Hannan R, Staehler M, Zaorsky NG, Louie AV, Siva S. Long-term Renal Function Outcomes After Stereotactic Ablative Body Radiotherapy for Primary Renal Cell Carcinoma Including Patients with a Solitary Kidney: A Report from the International Radiosurgery Oncology Consortium of the Kidney. Eur Urol Oncol. 2024 Jul 9:S2588-9311(24)00159-7.

Does Margin Size Matter?

5 mm margin → +1 cm diameter

5 mm

3 mm

35% volume reduction
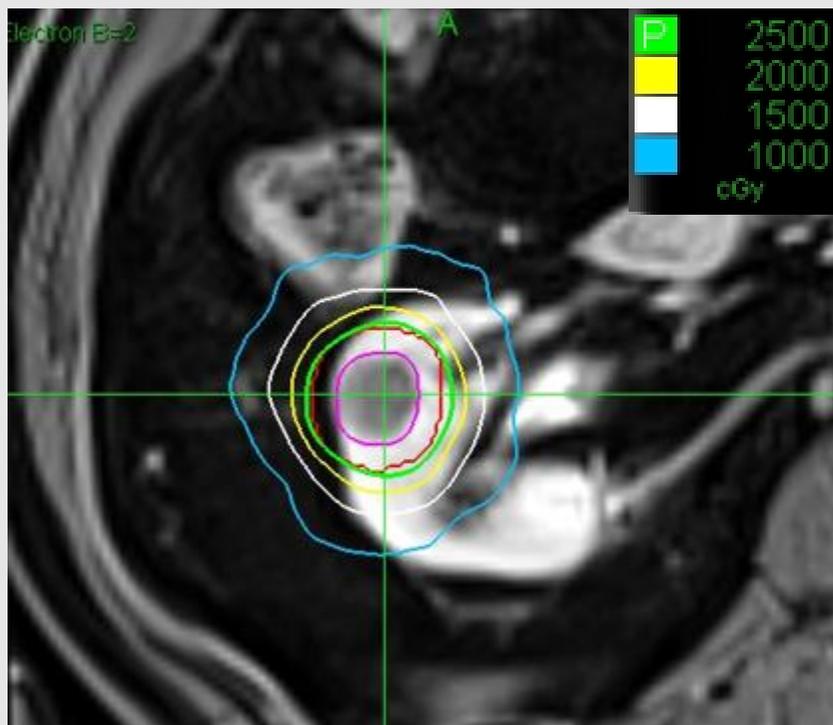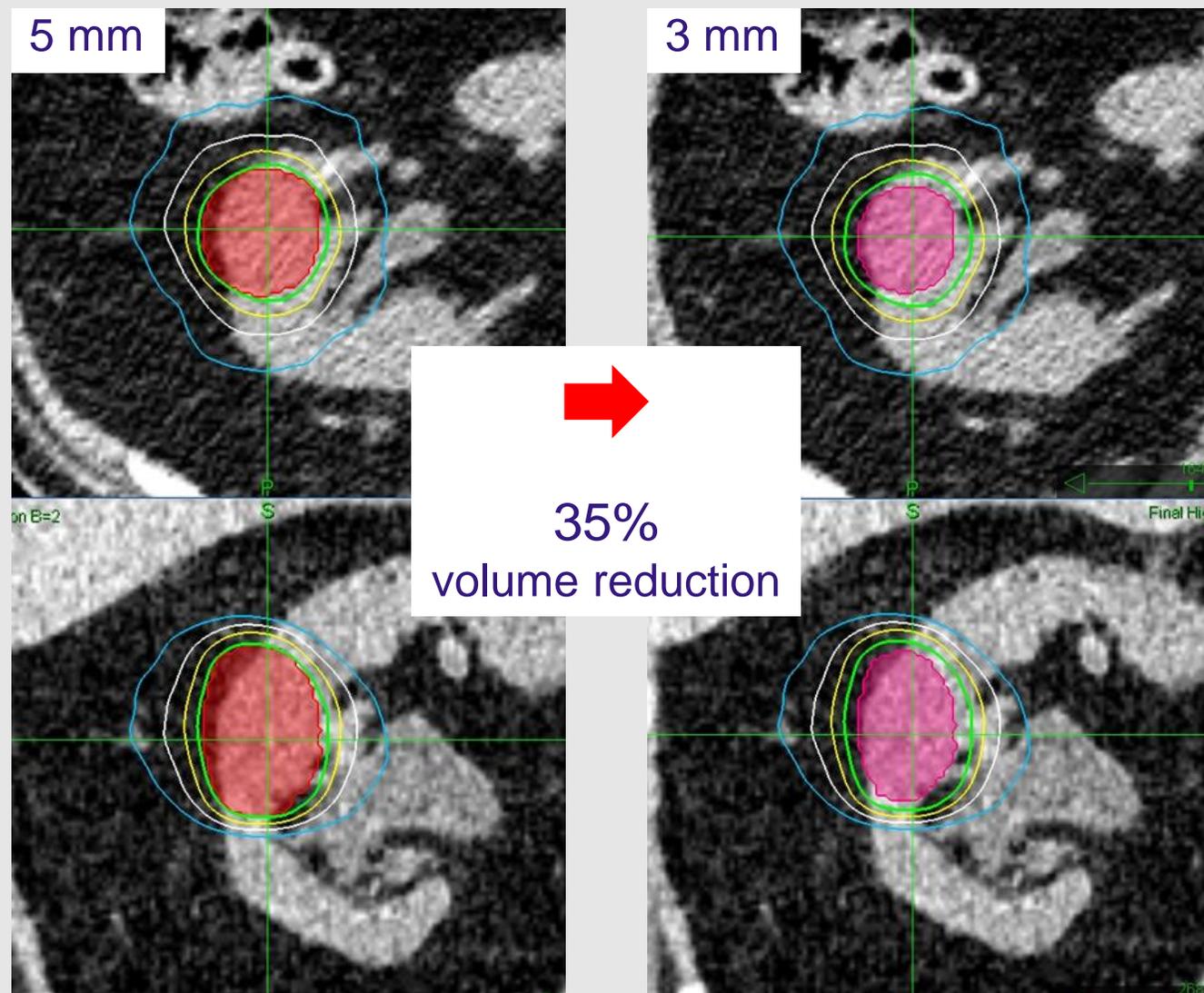
Patient-Specific Margins

Hofmann et al., Phys Med 2024:

"…<u>tumor movement in patients without prior surgical treatment was larger</u> [..]. This difference in tumor motion between previously operated and non-operated patients is significant with Mann-Whitney U test p-values of p < 0.0005 in the SI, LR and AP directions."

…smaller margins for specific patients or groups

Beispiel #1

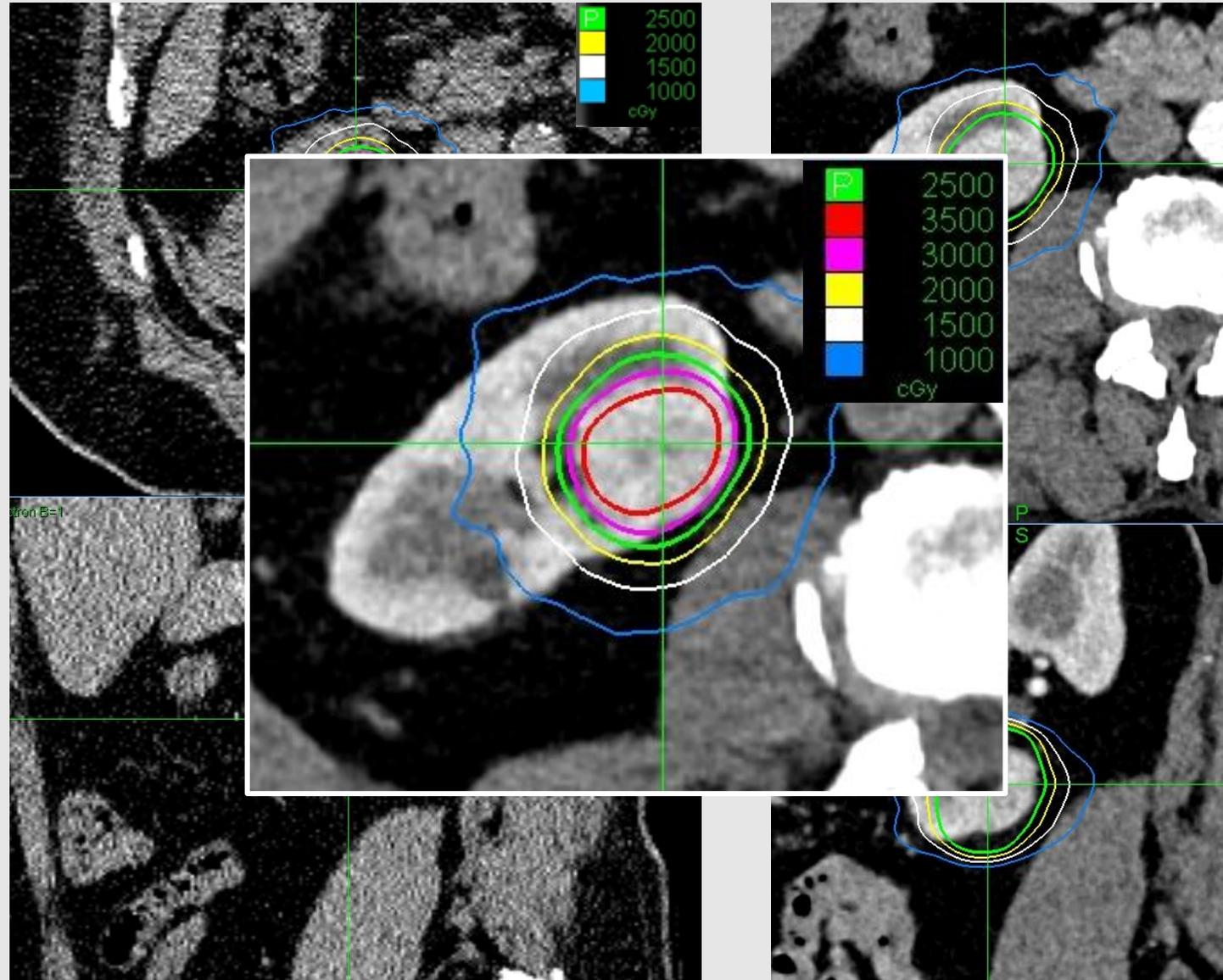Kleines RCC re:

PTV 23.0 cm³

1 Fraktion

25 Gy @ 65% IDL

nCI 1.10

GI 3.27

30 min Behandlungszeit

Beispiel #2

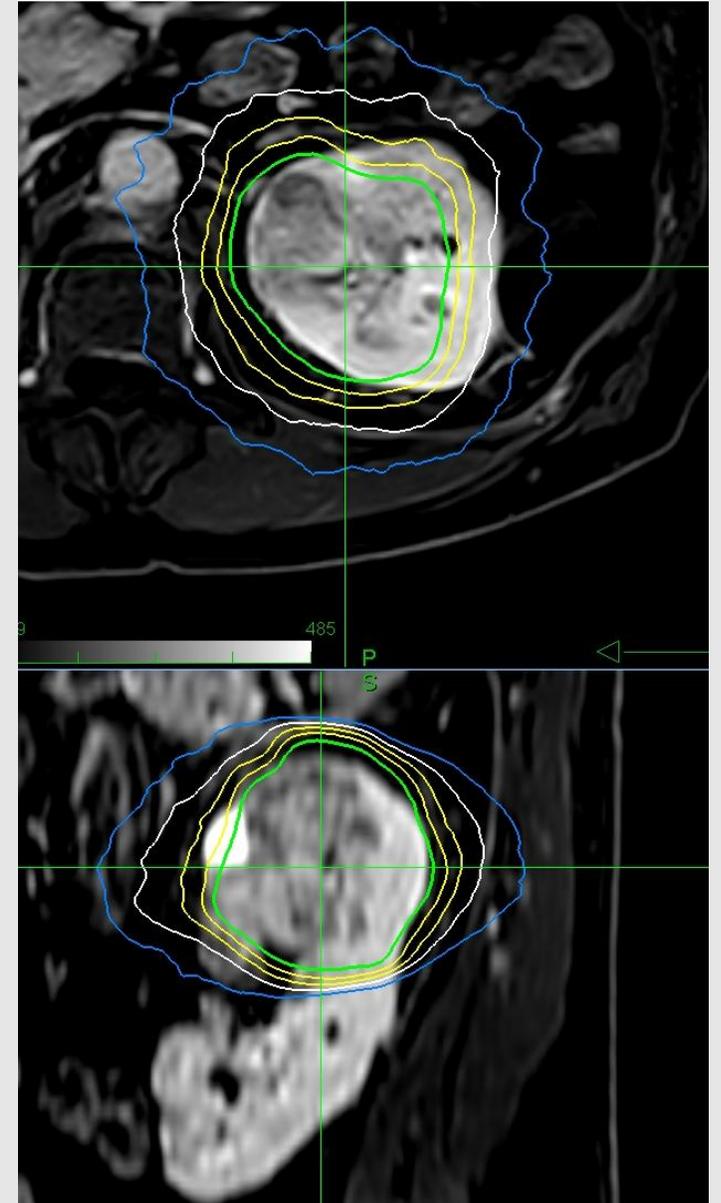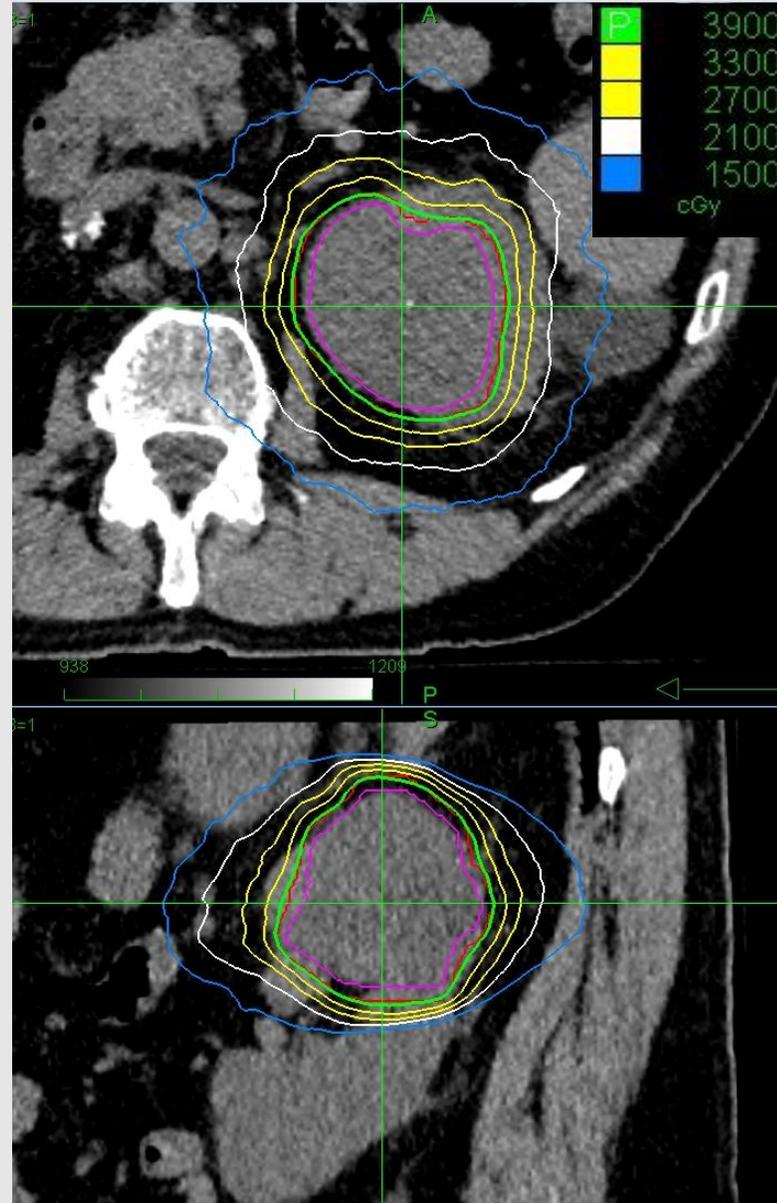Großes RCC li:

PTV 117 cm³

3 Fraktionen

3 x 11 Gy @ 65% IDL

nCI 1.06

GI 3.01

30 min / Fraktion
Behandlungszeit

Bestrahlungsplanung in der Niere

ERCM Richtwerte zur Dosierung in der Niere:

- PTV < 80 cm³: 25 Gy @ 65-70% IDL

- PTV > 80 cm³: 3 x 13 Gy @ 65-70% IDL

Randbedingungen:

- Anliegende Risikoorgane gem. Timmermann IJROBP 2021

- Nierenbelastung so gering wie erreichbar

Timmerman R. A Story of Hypofractionation and the Table on the Wall. Int J Radiat Oncol Biol Phys. 2022 Jan 1;112(1):4-21.

Zusammenfassung

➢ **Robotergestützte Nieren-SBRT wird seit fast 20 Jahre durchgeführt**

➢ **Neue, evidenzbasierte PTV-Margins: 4 mm SI, 3 mm LR, 3 mm AP**

➢ **Unsicherheiten hängen von Bewegung, Tumorform und von vorheriger Operation ab -> *patientenspezifische Margins*?**

➢ **ERCM Behandlungskonzept: 1 x 25 Gy bzw. 3 x 13 Gy @ 65-70%**