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Registration Tools for Image Guided External Beam Radiotherapy

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Summary for today

I. External beam radiotherapy (EBRT)

1. Purpose
2. Typical workflow
3. Benefits of image guidance

II. Image registration methods in image-guided EBRT (IGRT)

1. Therapy guidance
2. Planning
3. Follow-up

III. Validation and quality assurance of registration in IGRT

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Standard of care for cancer patients

Surgery

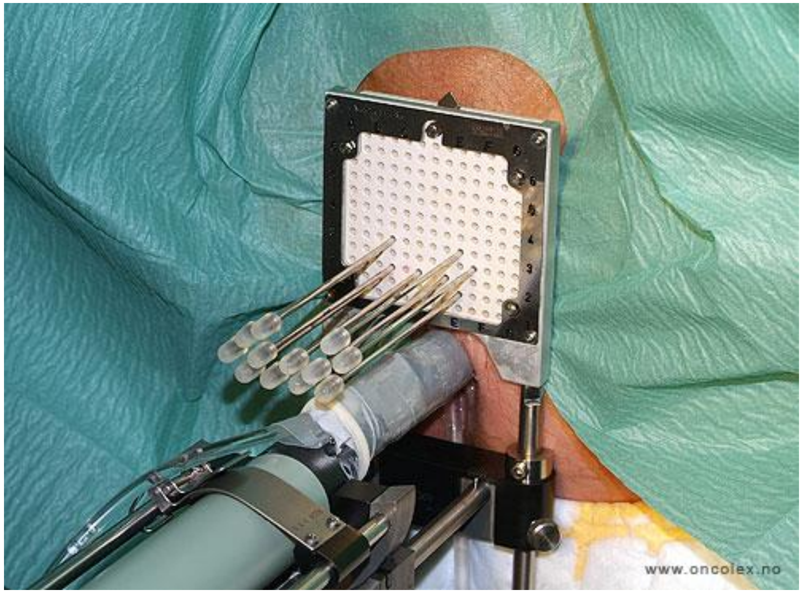
Cancer Care

Chemotherapy

Radiotherapy

Radiotherapy

Brachytherapy (Iodine – 125, Cesium- 131)



http://oncolex.org/Prostate-cancer

Radiotherapy

External beam radiotherapy (LinAc)

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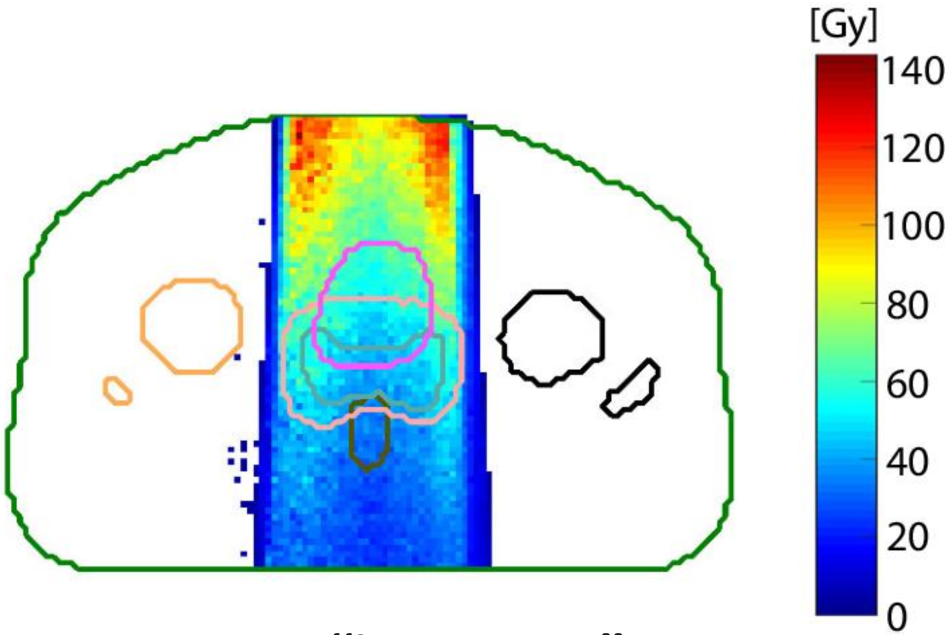
http://med.stanford.edu/news/all-news/2007/04/medical-linear-accelerator-celebrates-50-years-of-treating-cancer1.html

External beam radiotherapy (EBRT)

- “Setting the stage”:

Patient is referred for EBRT → **Amount of radiation is prescribed ([Joules/kg] = [Gy])** → **Therapy delivery**



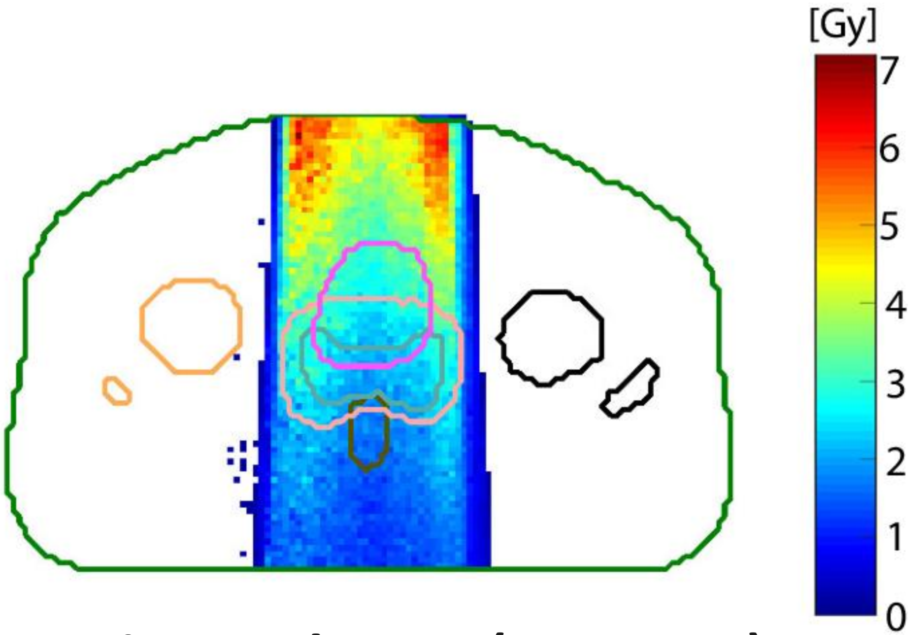
EBRT “in one go”

Critical damage to the tissues in the beam path !!!

External beam radiotherapy (EBRT)

➢ "Setting the stage":

Patient is referred for EBRT → **Amount of radiation is prescribed ([Joules/kg] = [Gy])** → **Therapy delivery**



Fractionated EBRT (20 x 3 Gy)

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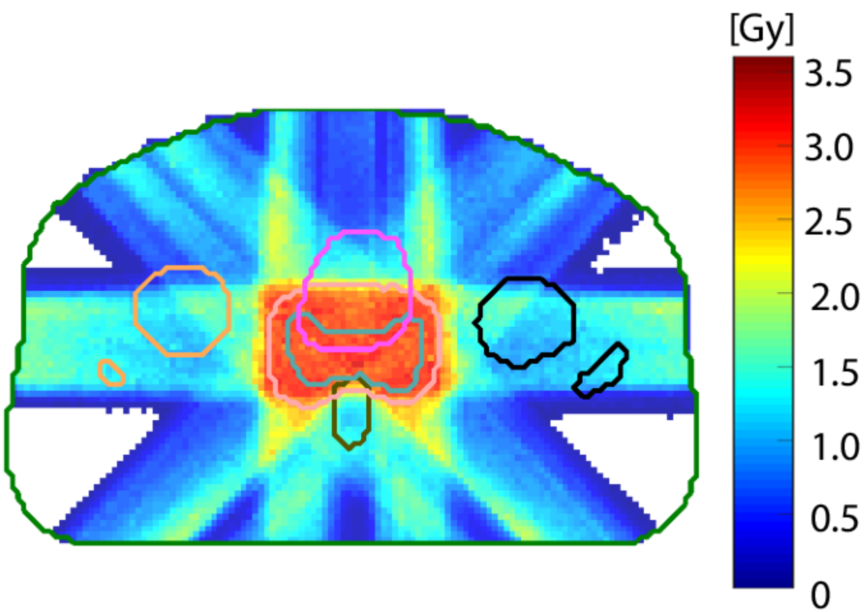
External beam radiotherapy (EBRT)

- "Setting the stage":

Patient is referred for EBRT → Amount of radiation is prescribed ([Joules/kg] = [Gy]) → Therapy delivery



Fractionated/Multi-beam EBRT (20 x 3 Gy)

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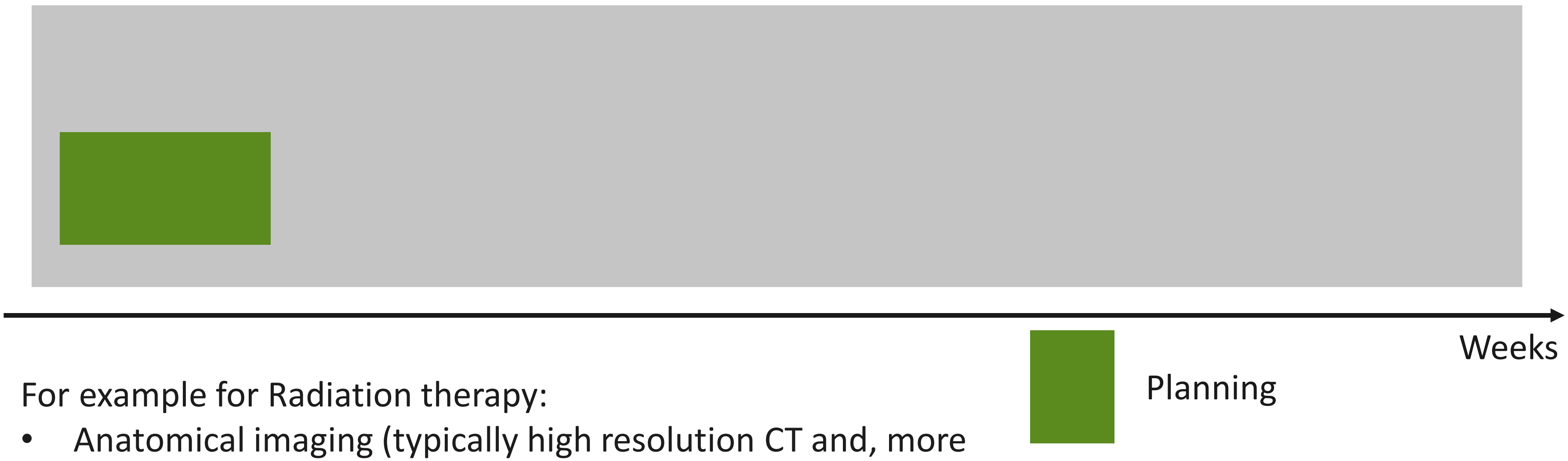
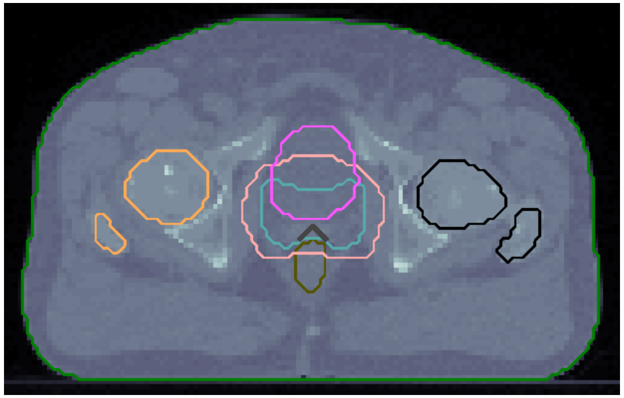
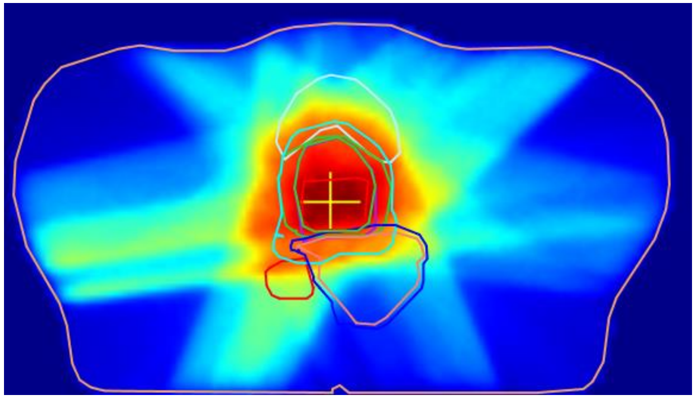
Radiotherapy: Overall workflow



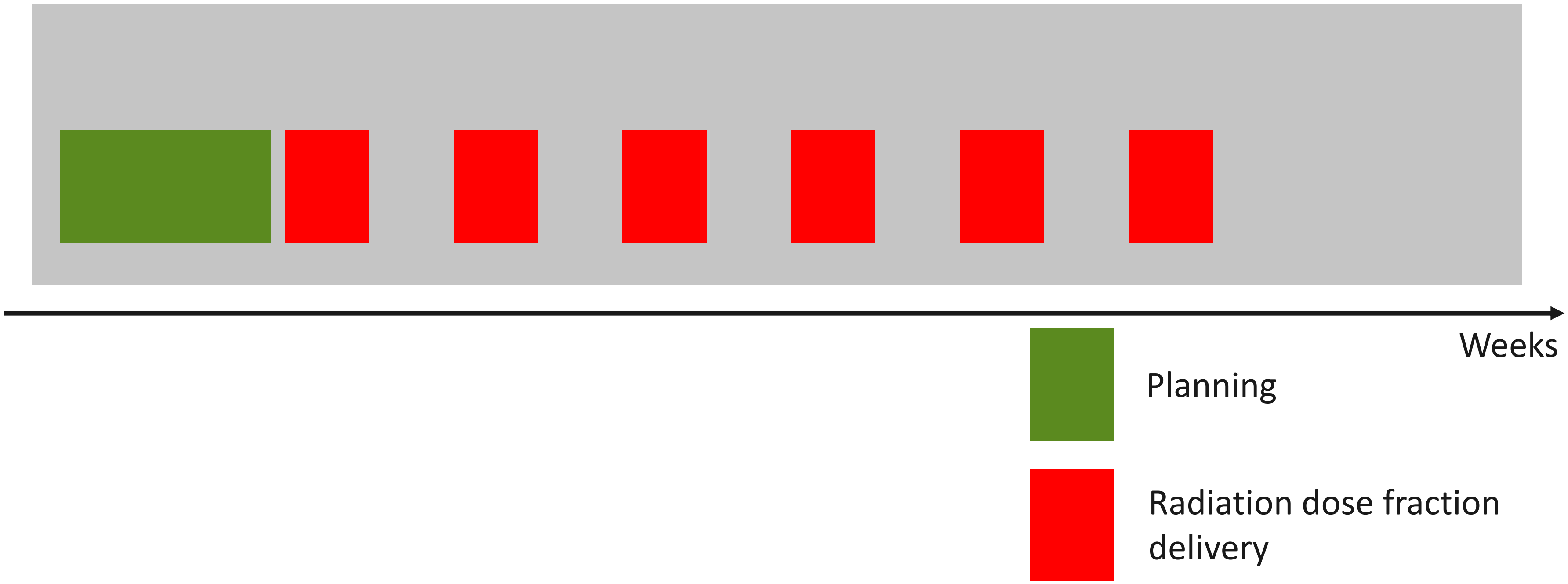
For example for Radiation therapy:

- Anatomical imaging (typically high resolution CT and, more recently, MRI)
- Delineation of the pathology and organs at risk
- Establish target radiation dose for the pathology and organs at risk, followed by treatment plan optimization





Radiotherapy: Overall workflow



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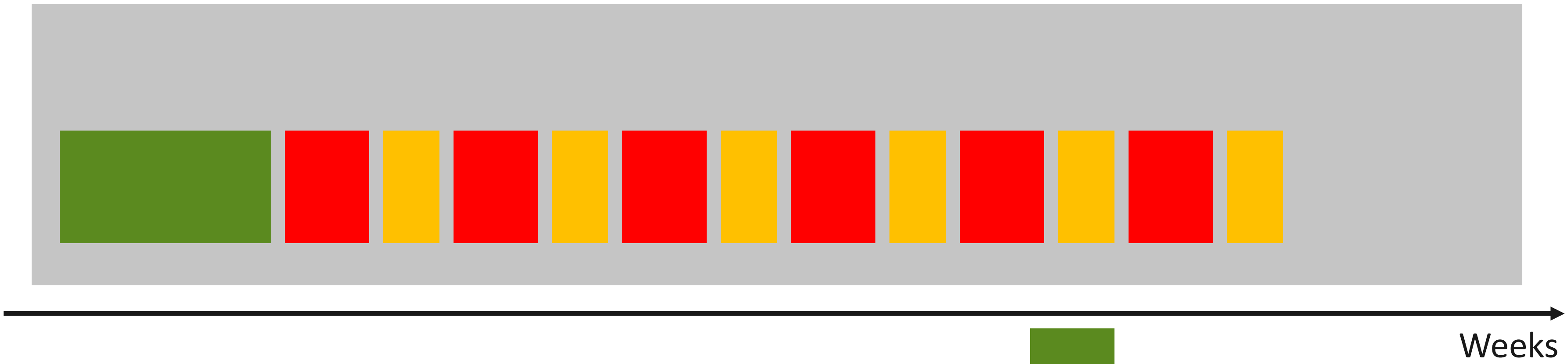
Radiotherapy: Overall workflow



For example for Radiation therapy:

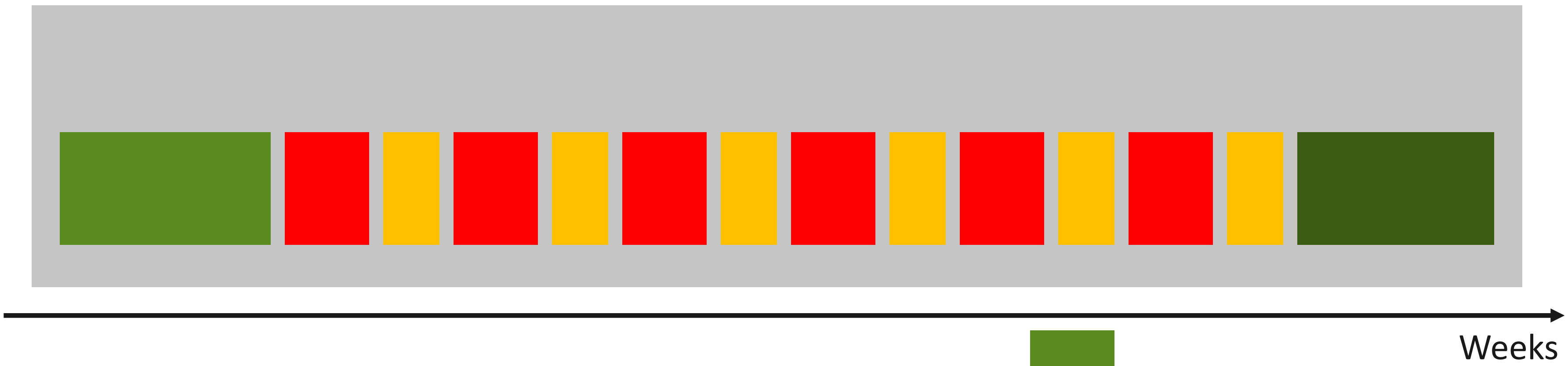
- Allow healthy tissues to recover from the effects of radiation
- Treatment response monitoring
- Plan re-optimization

Planning

Radiation dose fraction delivery

Inter-fraction time interval

Radiotherapy: Overall workflow



For example for Radiation therapy:

- Periodic inspection for timely recurrence detection
- Patient quality-of-life monitoring

Planning

Radiation dose fraction delivery

Inter-fraction time interval

Validation of the therapeutic endpoint

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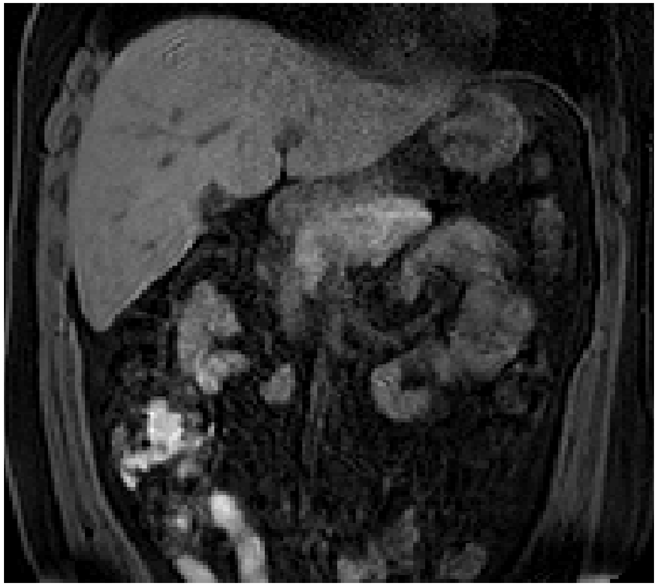
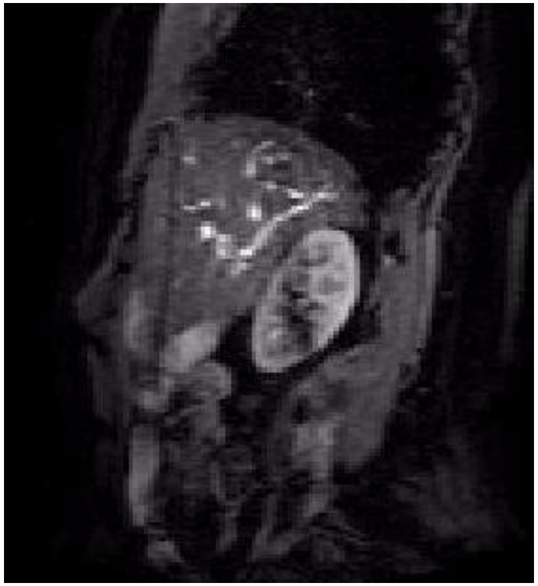
Radiotherapy: Anatomical motion

Respiratory	Peristaltic	Spontaneous
		

M. Ries et al, Magn Reson Med., 64(6), 2010
C. Zachiu et al, Med Phys., 42(7), 2015
C. Zachiu et al, Phys Med Biol., 60(23) 2015

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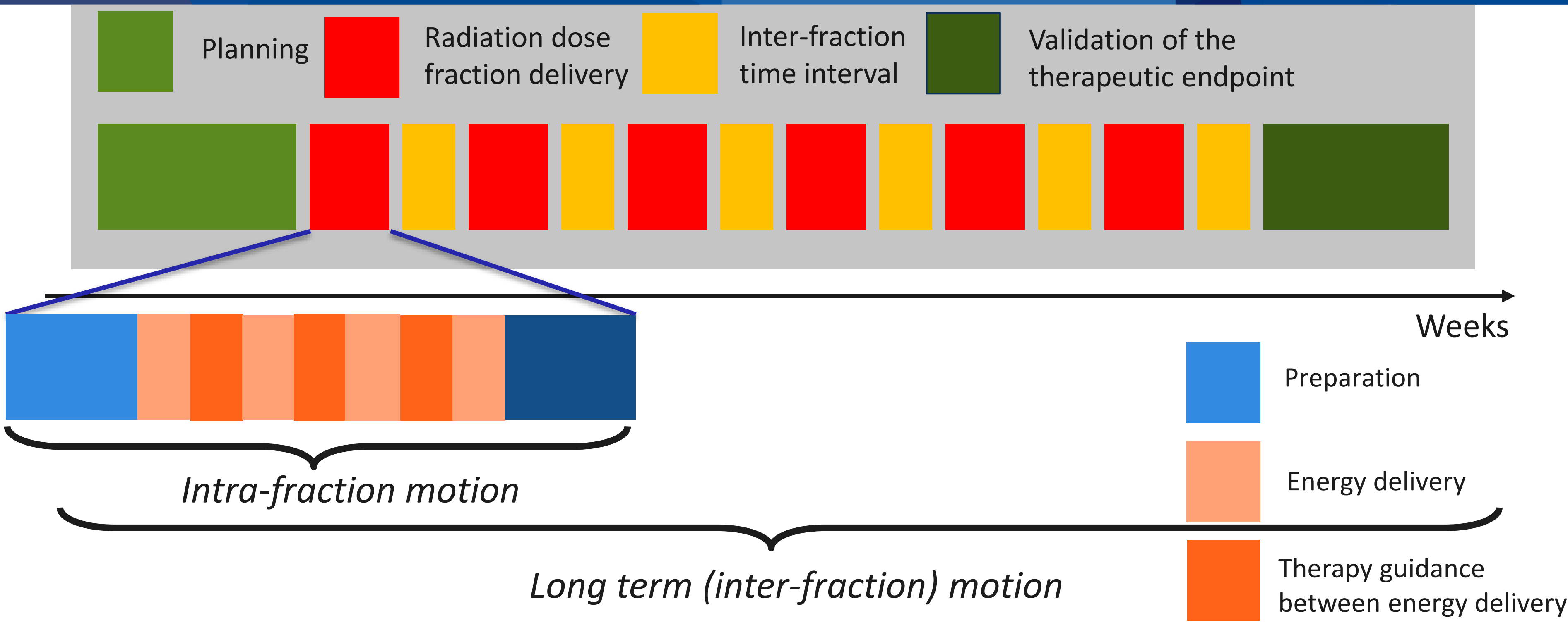
Radiotherapy: Anatomical motion



- Long term motion can include: positioning errors, tumor deformations as a response to treatment, different degrees of bowel/bladder filling, patient weight loss, changes in respiration baseline;
- Intra-fraction motion can include: respiration, drift of the respiration baseline, peristaltic motion;

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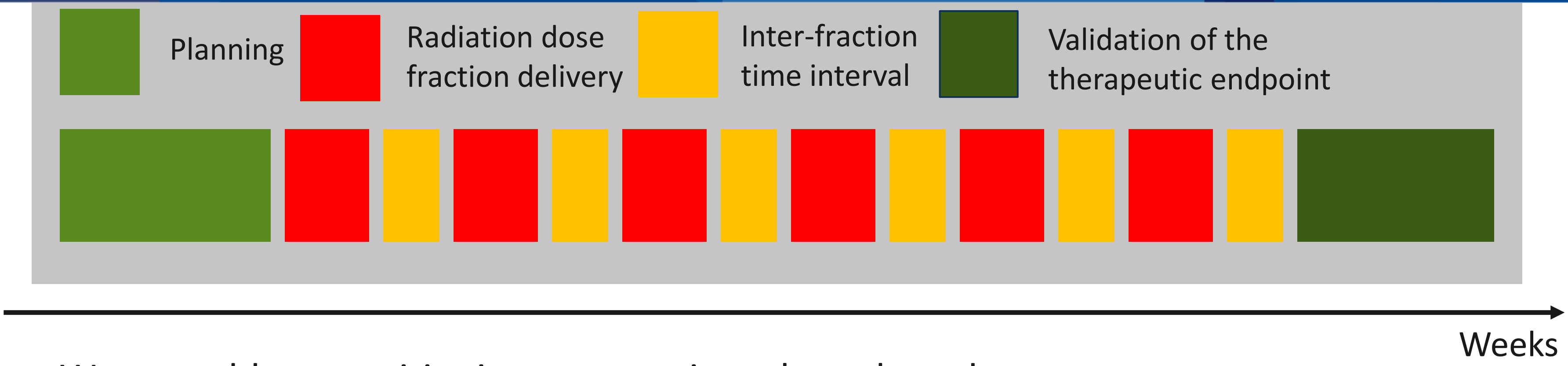
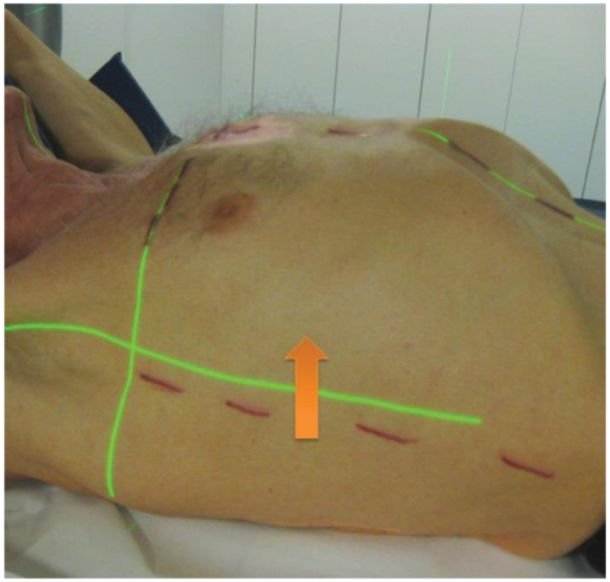
Radiotherapy: Day-to-day or inter-fraction motion



- We can address positioning errors using a laser-based system



Does not account for internal organ motion !!!

P.M. Putora et al, Breathe, 8, 2011

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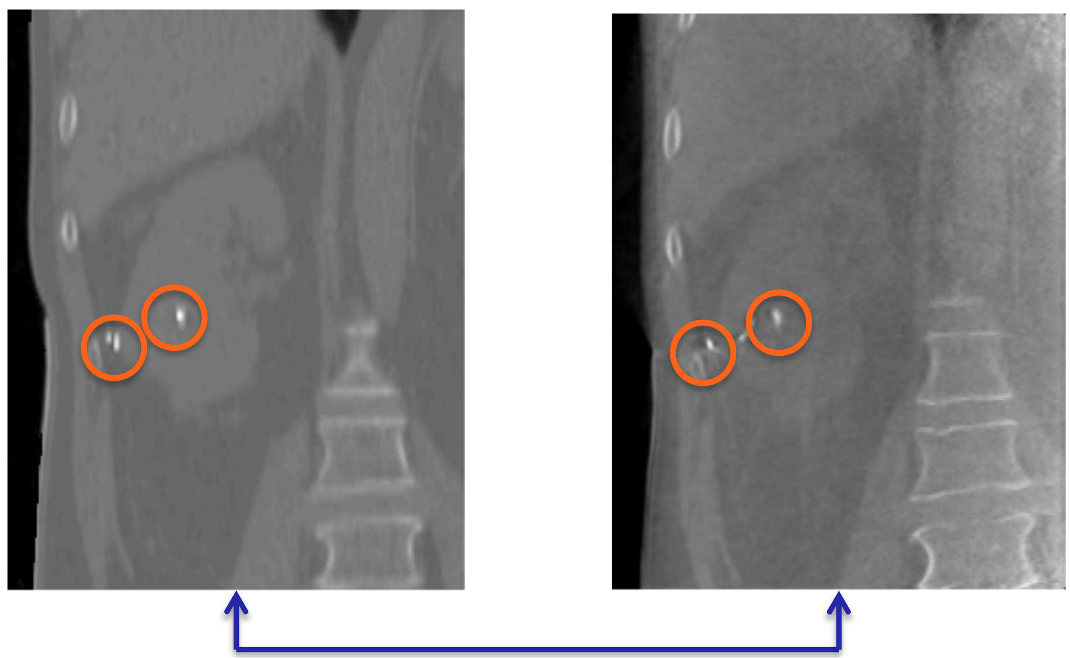
Radiotherapy: Day-to-day or inter-fraction motion

- We can address positioning and internal motion using implanted markers

Planning CT **Daily CT**



Match

- *Does not account for surrounding tissue deformations*
- *Implanting the markers is uncomfortable for the patient*

C. Zachiu et al, Phys Med Biol., 63(1), 2017

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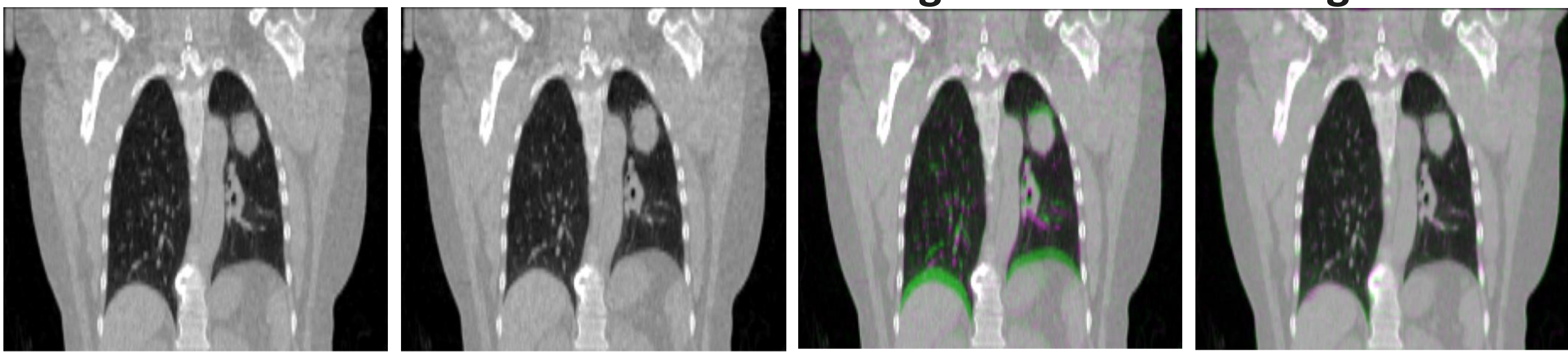
Radiotherapy: Day-to-day or inter-fraction motion

- …or we could just use *deformable image registration*

Planning CT | **Daily CT** | **Overlap Before Registration** | **Overlap After Registration**



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C. Zachiu et al, Phys Med Biol. 2020 (Epub ahead of print)

The Horn – Schunck registration algorithm

- Hypothesis: Pixels conserve their intensity along the followed trajectory (reference and moving image have the same (displaced) content).

$$I(x + dx, y + dy, t + dt) = I(x, y, t)$$

- Taylor expansion of the lefthand term:

$$I(x + dx, y + dy, t + dt) = I(x, y, t) + I_x dx + I_y dy + I_t dt + \ldots$$

with $(I_x, I_y, I_t) = (\frac{\partial I}{\partial x}, \frac{\partial I}{\partial y}, \frac{\partial I}{\partial t})$

- Using the pixel intensity conservation hypothesis and ignoring high order terms of the Taylor expansion:

$$I_x dx + I_y dy + I_t dt = 0$$

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The Horn – Schunck registration algorithm

- Using the pixel intensity conservation hypothesis and ignoring high order terms of the Taylor expansion:

$$I_x dx + I_y dy + I_t dt = 0 \quad \Big| : dt$$

$$I_x u + I_y v + I_t = 0$$

with $\quad (u, v) = (dx/dt, dy/dt)$

- The motion estimation problem is reduced to the minimization with respect to *u* and *v* of the functional:

$$E = \iint_{xy} [I_x u + I_y v + I_t]^2 \, dx dy$$

- Problems:
  - The existence of a solution cannot be ensured;
  - Even if a solution exists, its uniqueness is not guaranteed;

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The Horn – Schunck registration algorithm

- The motion estimation problem is reduced to the minimization of the functional:

$$E = \iint_{xy} \left[I_x u + I_y v + I_t\right]^2 dxdy$$

- The ill-posedness of the problem has been addressed by assuming that the motion fields are smooth (we do not have discontinuities):

$$E = \iint_{xy} \left(\left[I_x u + I_y v + I_t\right]^2 + \alpha^2 \left[\|\nabla u\|_2^2 + \|\nabla v\|_2^2\right] \right) dxdy$$

where $\|\nabla u\|_2^2 = u_x^2 + u_y^2, \ \|\nabla v\|_2^2 = v_x^2 + v_y^2,$

$$(u_x = \partial u/\partial x, \ u_y = \partial u/\partial y, \ v_x = \partial v/\partial x, \ v_y = \partial v/\partial y)$$

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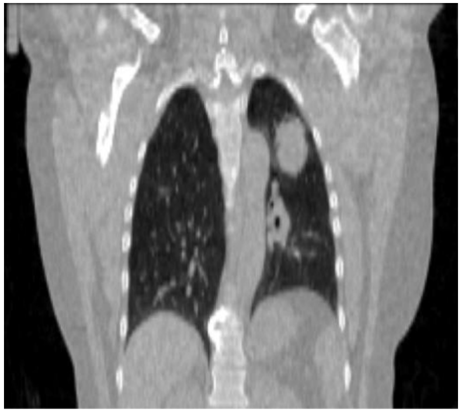
The Horn – Schunck registration algorithm

$$E = \iint_{xy} \Big(\underbrace{[I_x u + I_y v + I_t]^2}_{\text{Pixel intensity is conserved}} + \alpha^2 \underbrace{\left[\|\nabla u\|_2^2 + \|\nabla v\|_2^2 \right]}_{\text{Assumes deformations are smooth}} \Big)\, dx\, dy$$

Accuracy and Precision [mm]		
Patient no.	Before reg.	HS OF
#1	3.89 ± 2.78	1.04 ± 0.49
#2	4.33 ± 3.90	1.10 ± 0.60
#3	6.94 ± 4.05	1.38 ± 0.87
#4	9.83 ± 4.86	1.78 ± 1.63
#5	7.47 ± 5.51	2.09 ± 2.09
Average	**6.49 ± 4.22**	**1.48 ± 1.13**

Planning CT

Daily CT



- *As a rule of thumb, accuracy and precision should be under the maximum voxel size (0.97 x 0.97 x 2.5 mm^3 in this case)*

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The Horn – Schunck registration algorithm

$$E = \iint_{xy} \Big(\underbrace{[I_x u + I_y v + I_t]^2}_{\text{Pixel intensity is conserved}} + \alpha^2 \underbrace{\left[\|\nabla u\|_2^2 + \|\nabla v\|_2^2 \right]}_{\text{Assumes deformations are smooth}} \Big)\, dx dy$$

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Average	**6.49 ± 4.22**	**1.48 ± 1.13**

- Features:
  - Convex cost function;
  - Fast convergence;
  - It has a low number of control parameters;

- *As a rule of thumb, accuracy and precision should be under the maximum voxel size (0.97 x 0.97 x 2.5 mm^3 in this case)*

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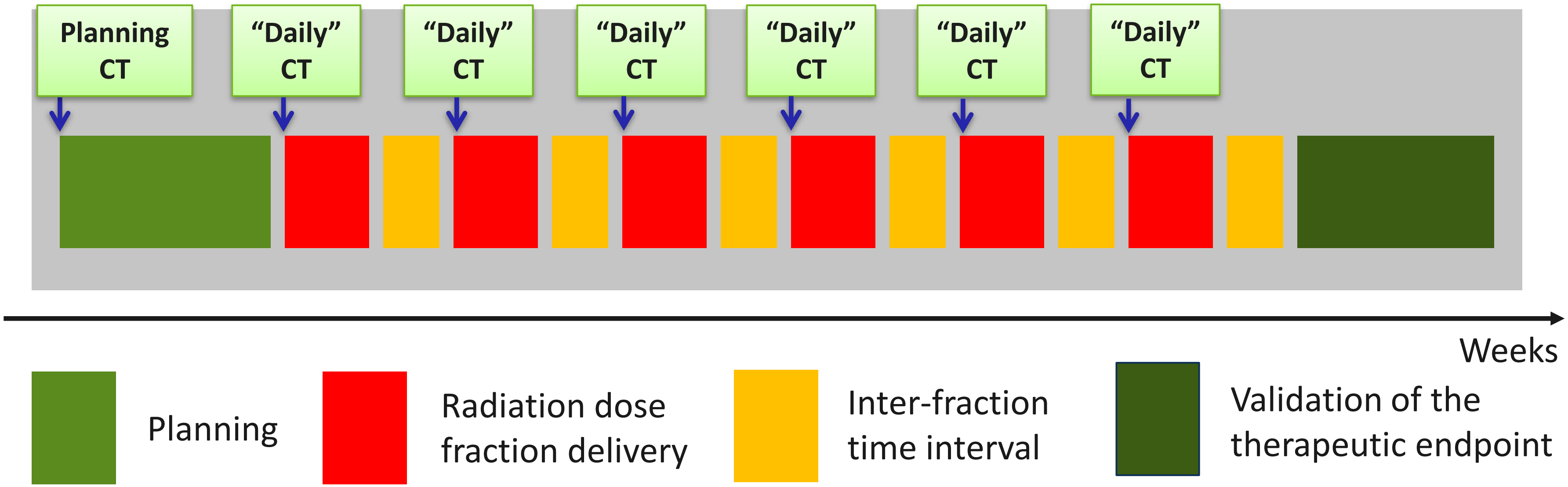
Radiotherapy: CT-based DIR guidance



- CT-to-CT deformable image registration (DIR) could be used to account for positioning errors and “day-to-day” anatomical changes;
- *Problem: CT imaging itself delivers a small amount of radiation, which accumulates over time;*
- *Potential solution: perform daily cone-beam CT (CBCT) imaging*

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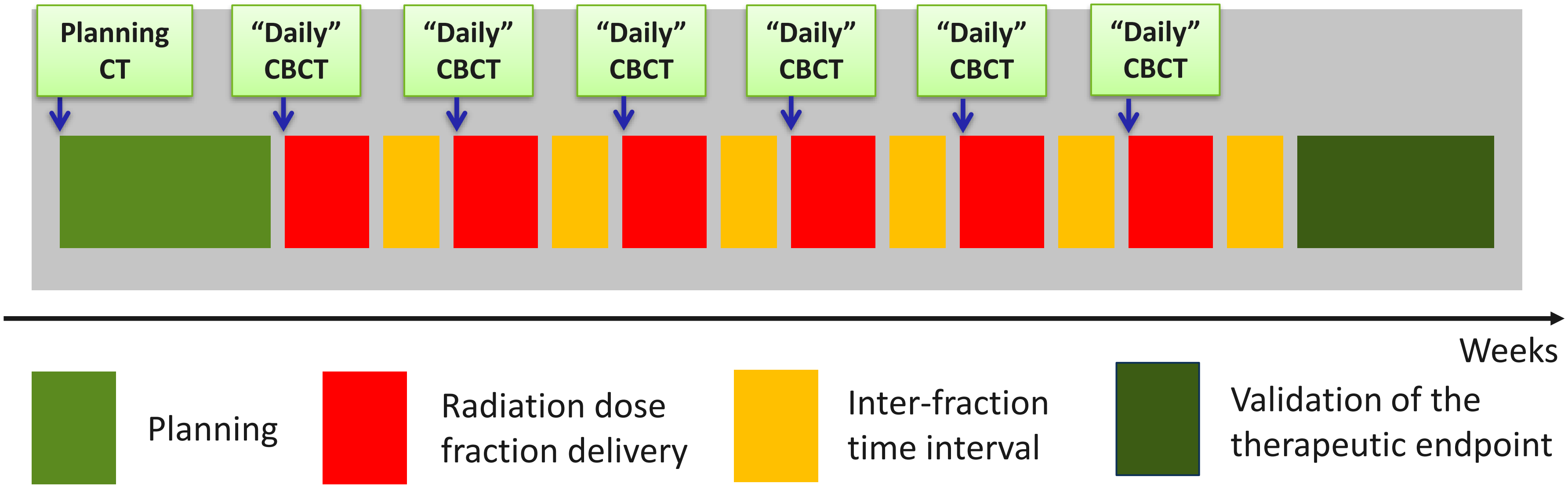
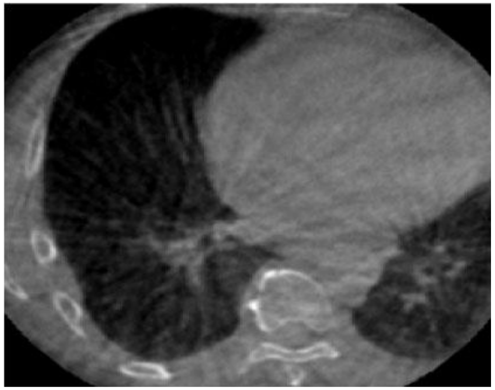
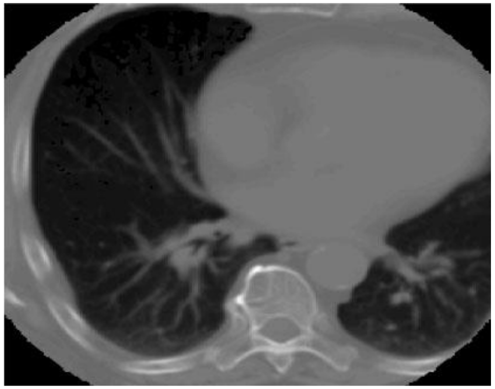
Radiotherapy: CBCT-based DIR guidance



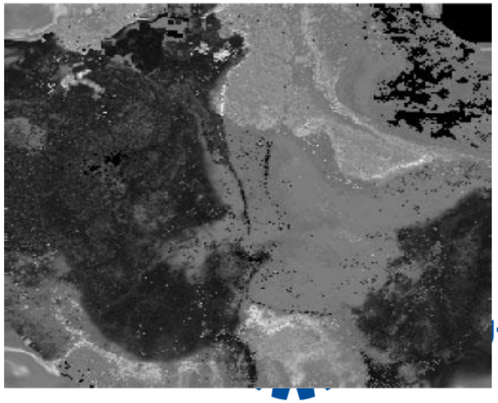
"Daily" CBCT image



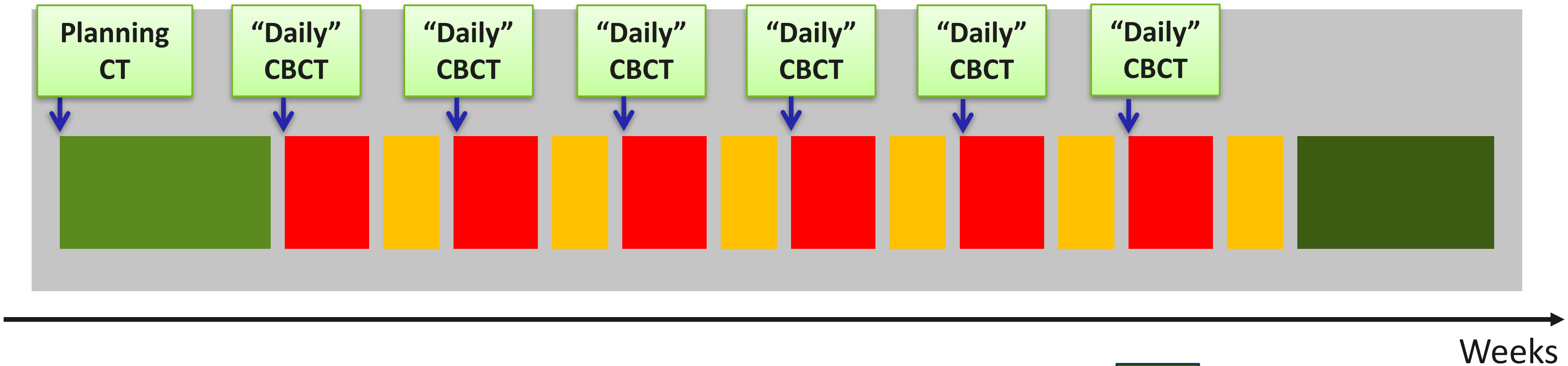
Planning CT image



Registered CT image



Radiotherapy: CBCT-based DIR guidance



Planning

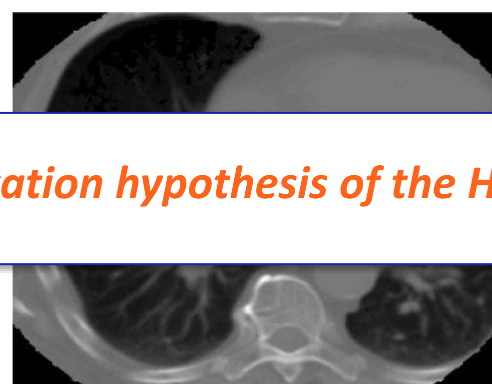
Radiation dose fraction delivery

Inter-fraction time interval

Validation of the therapeutic endpoint

"Daily" CBCT image

Planning CT image



Registered CT image

The voxel intensity conservation hypothesis of the HS algorithm is not valid !!!

Radiotherapy: CBCT-based DIR guidance

EVOLUTION: an edge-based variational method for non-rigid multi-modal image registration

B Denis de Senneville[1,2], C Zachiu[1], M Ries[1] and C Moonen[1]

[1] Imaging Division, UMC Utrecht, Heidelberglaan 100, 3584 CX, Utrecht, Netherlands

[2] "Institut de Mathématiques de Bordeaux", Université Bordeaux, 351 Cours de la Libération, 33405 Talence Cedex, France

$$E_{EVO}(\boldsymbol{u}) = \sum_{\vec{r}\in\Omega} D(\boldsymbol{u}(\vec{r})) + \frac{\boldsymbol{\alpha}}{\boldsymbol{2}}\left\|\vec{\boldsymbol{\nabla}}\boldsymbol{u}\right\|_2^2 \quad D(\boldsymbol{u}) = \exp\left(-\frac{\sum_{\vec{s}\in\Gamma}\left|\vec{\nabla}_I(\boldsymbol{u}(\vec{s}))\cdot\vec{\nabla}_J(\vec{s})\right|}{\sum_{\vec{s}\in\Gamma}\left\|\vec{\nabla}_I(\boldsymbol{u}(\vec{s}))\right\|_2\left\|\vec{\nabla}_j(\vec{s})\right\|_2}\right)$$

- Capable of both rigid and elastic registration;
- Can be used both intra and cross-modality;
- High degree of accuracy and precision;
- Fast convergence;

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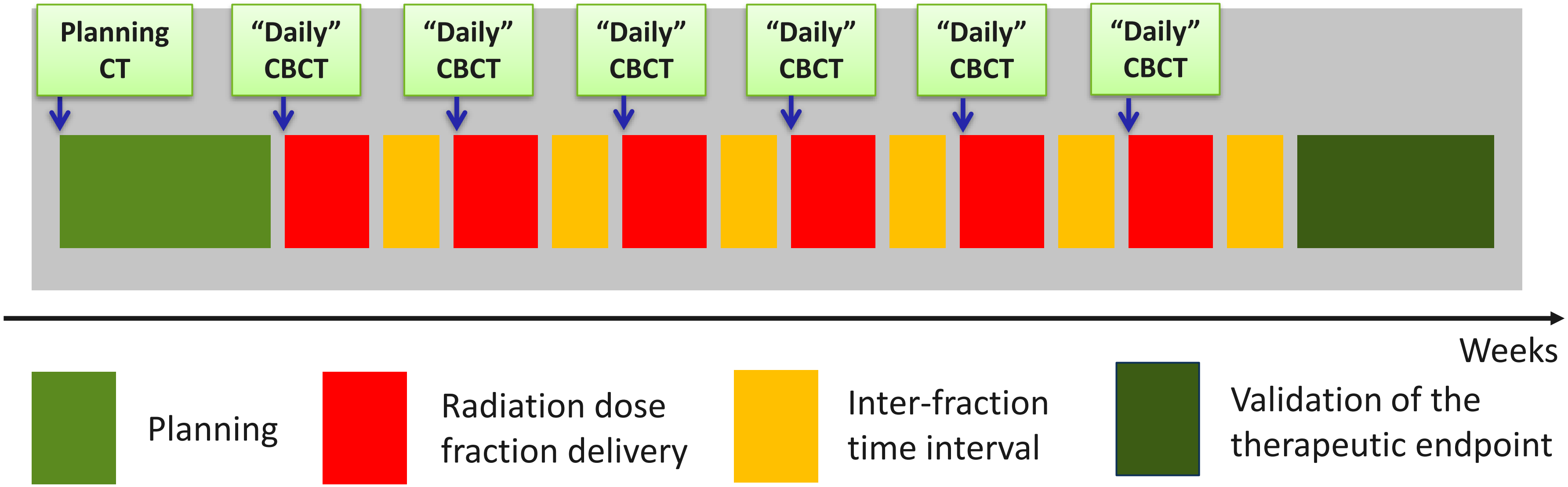
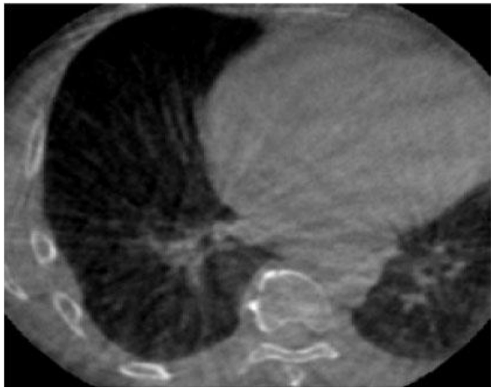
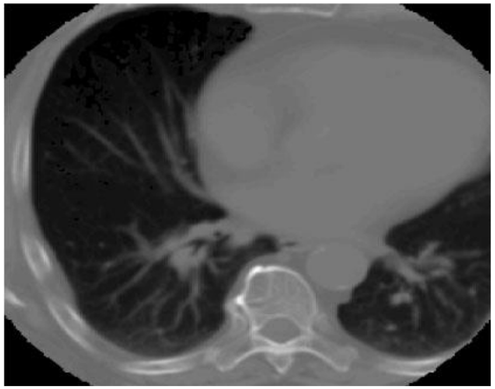
Radiotherapy: CBCT-based DIR guidance



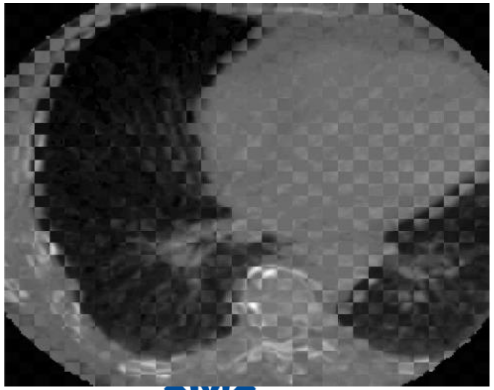
"Daily" CBCT image



Planning CT image



Before registration



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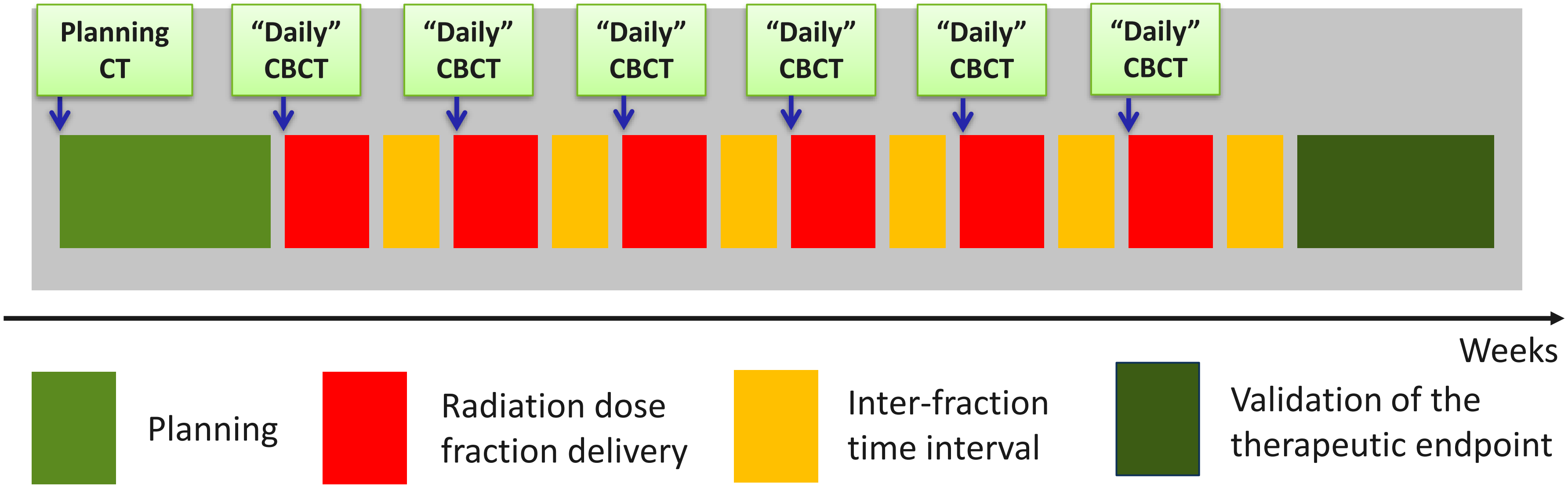
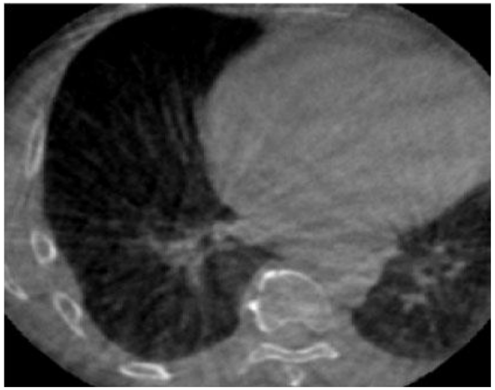
C. Zachiu et al "Non-rigid CT/CBCT to CBCT registration for online external beam radiotherapy guidance", PMB, 2017.

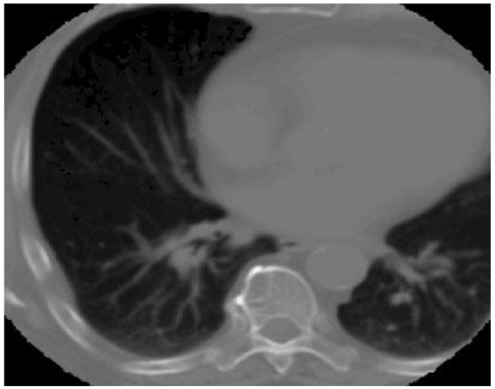
Radiotherapy: CBCT-based DIR guidance



"Daily" CBCT image



Planning CT image



After registration

Tracking error (10 landmarks): 0.9 mm ± 0.3 mm

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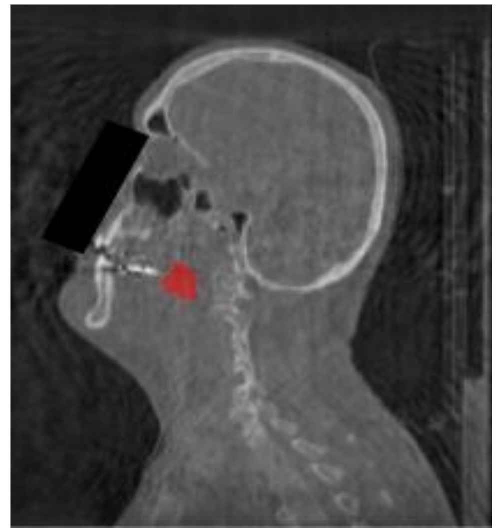
Head and Neck radiotherapy: CBCT-based DIR guidance

Planning CT

Daily CBCT



VOI	FEP before[mm] (mean±stdev)	FEP after[mm] (mean±stdev)
CTV	16.58 ± 2.2	0.31 ± 0.18
Lymph node 1	15.85 ± 1.27	0.7 ± 0.37
Lymph node 2	14.38 ± 1.68	0.65 ± 0.33
Body	16.1 ± 3.45	0.66 ± 0.6
Spinal cord	16.21 ± 1.74	0.15 ± 0.09
Left parotid	16.38 ± 1.63	0.73 ± 0.42
Right parotid	12.7 ± 1.12	0.65 ± 0.35

C. Zachiu et al "Non-rigid CT/CBCT to CBCT registration for online external beam radiotherapy guidance", PMB, 2017.

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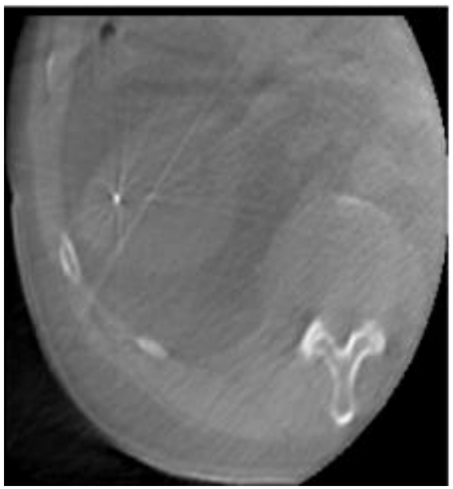
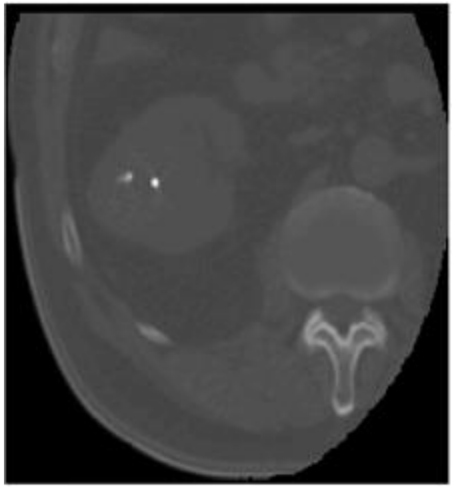
Kidney radiotherapy: CBCT-based DIR guidance

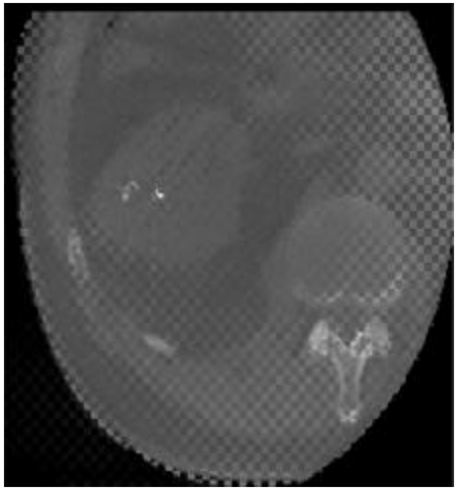
Reference CBCT image



Moving CT image



Before registration



Tracking error: 1.1 mm ± 0.3 mm

C. Zachiu et al "Non-rigid CT/CBCT to CBCT registration for online external beam radiotherapy guidance", PMB, 2017.

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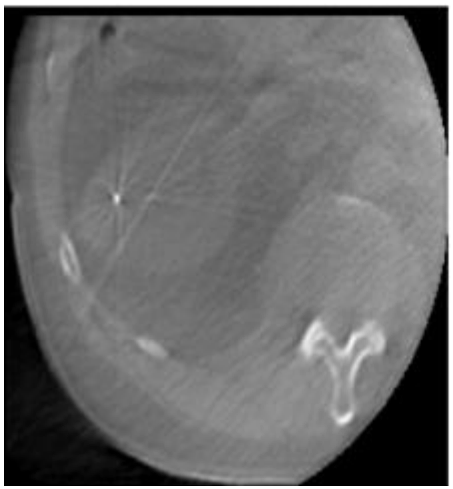
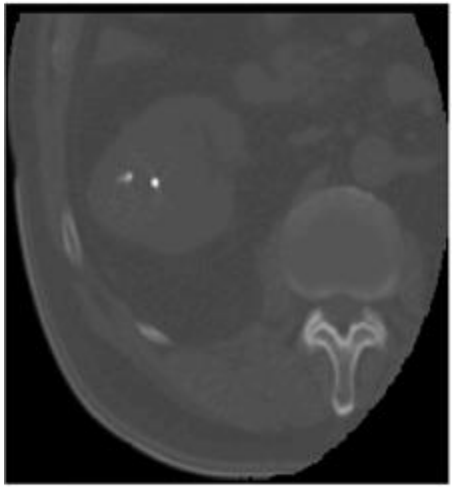
Kidney radiotherapy: CBCT-based DIR guidance

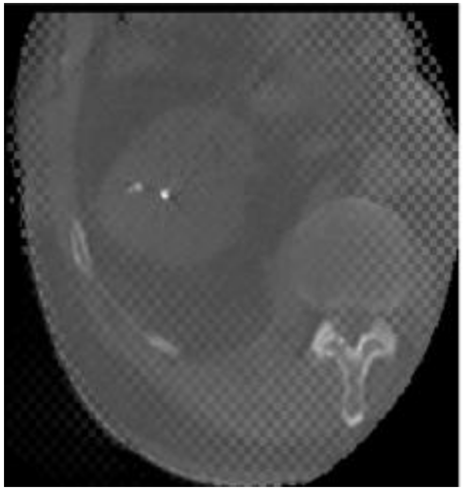
Reference CBCT image



Moving CT image



After registration



Tracking error: 1.1 mm ± 0.3 mm

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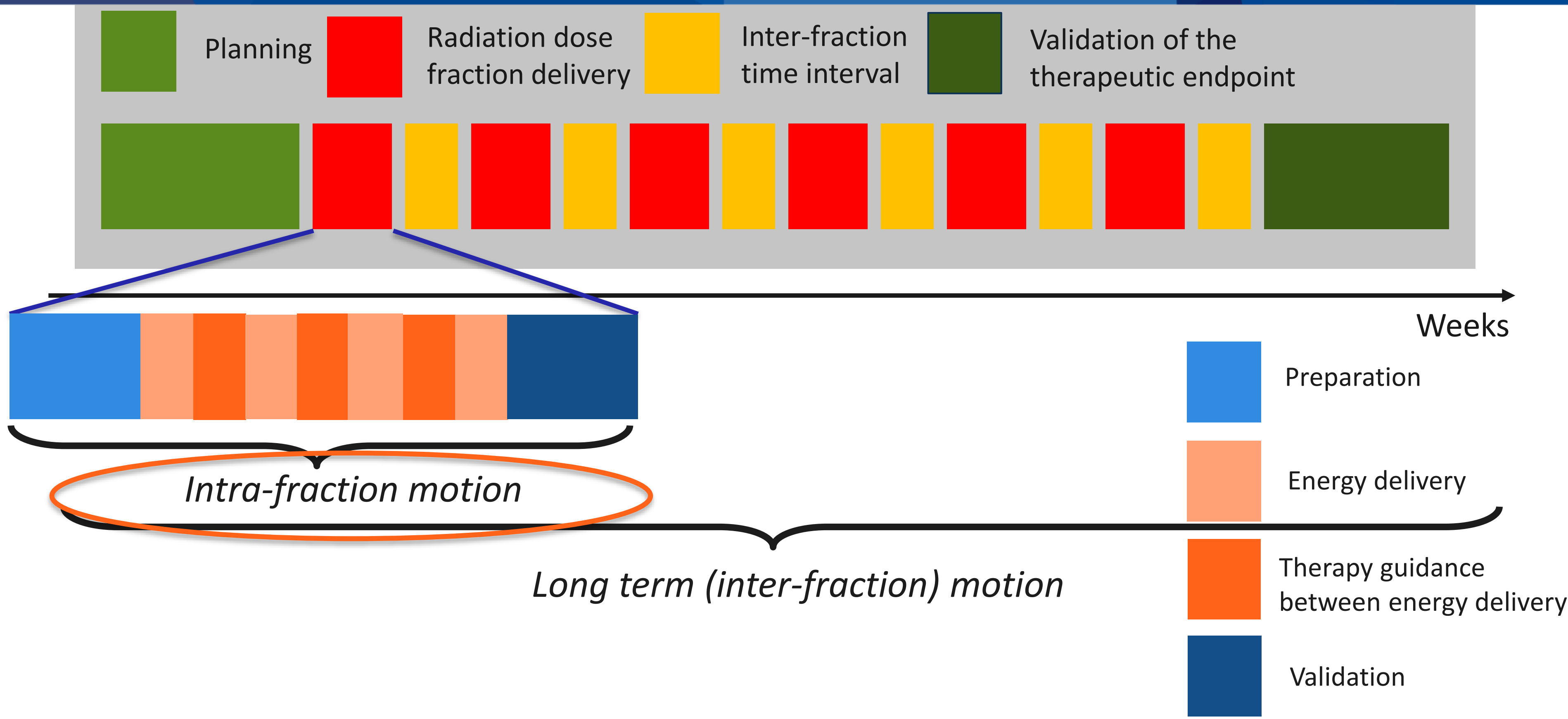
C. Zachiu et al "Non-rigid CT/CBCT to CBCT registration for online external beam radiotherapy guidance", PMB, 2017.

Radiotherapy: Intra-fraction motion



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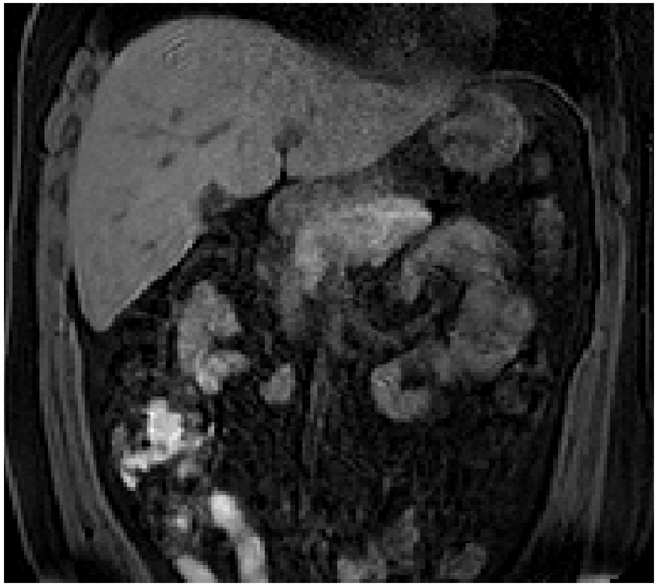
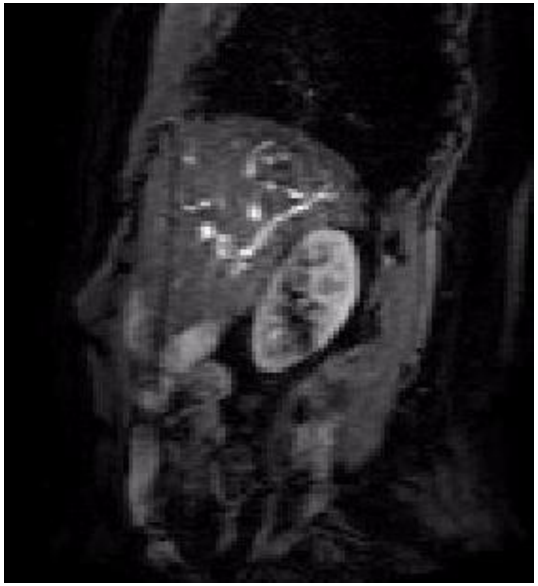
Radiotherapy: Intra-fraction motion

Respiratory

Peristaltic



Spontaneous



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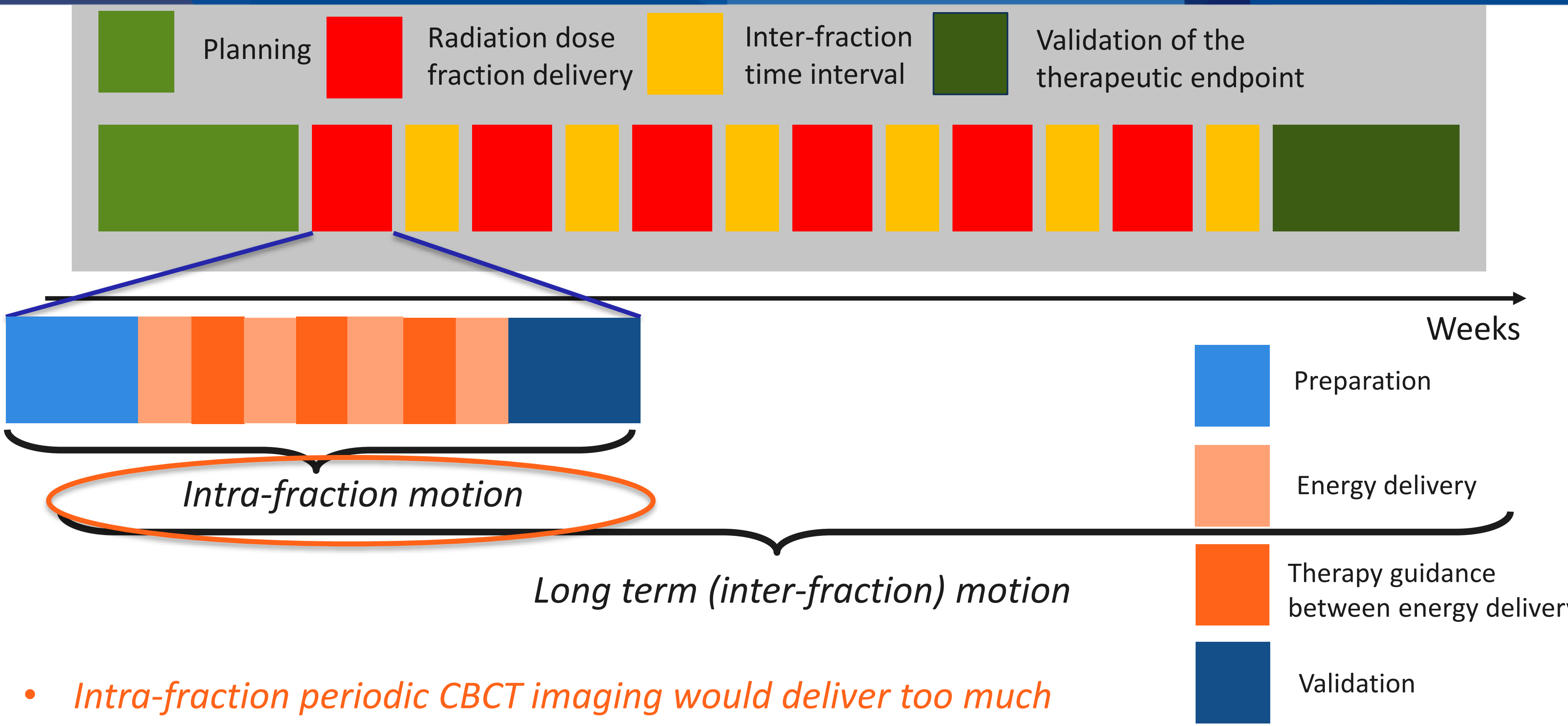
Radiotherapy: Intra-fraction motion



- *Intra-fraction periodic CBCT imaging would deliver too much radiation + it may not be fast enough to sample the continuously changing anatomy (acquisition is on the order of minutes)*

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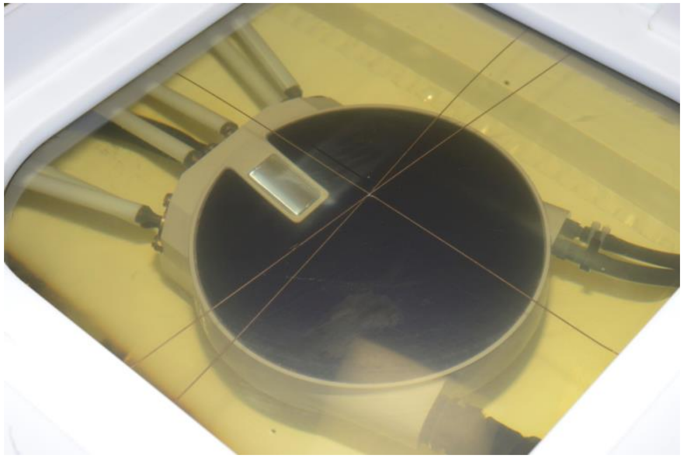
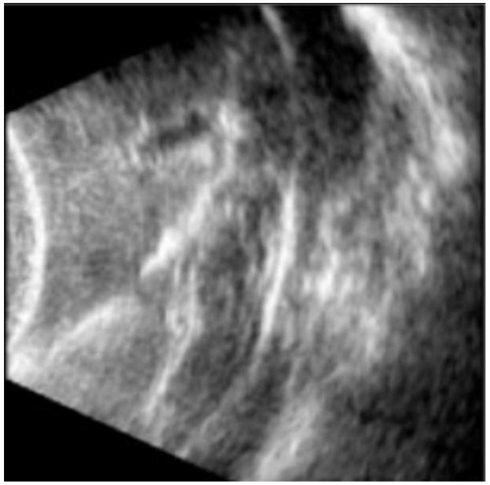
Radiotherapy: Intra-fraction ultrasound guidance?

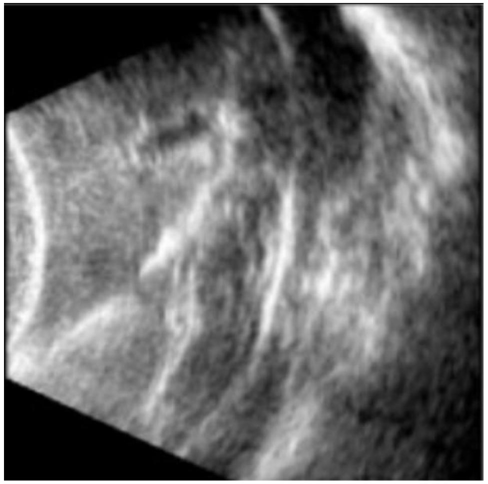


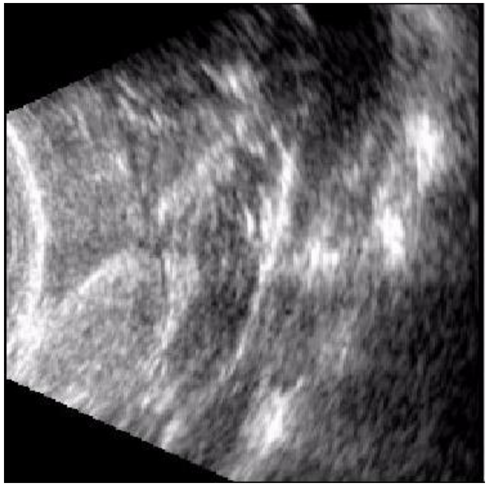


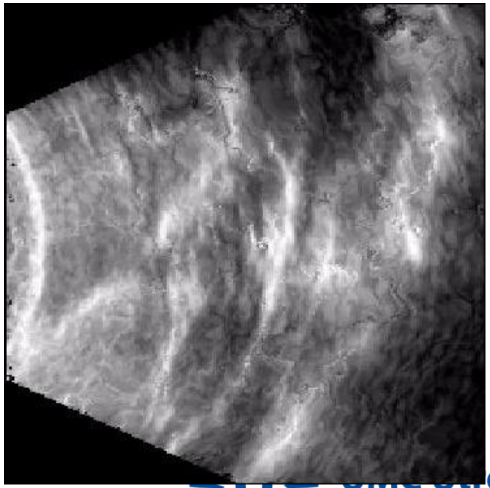
Reference image

Moving Images

Registered Images (H&S)



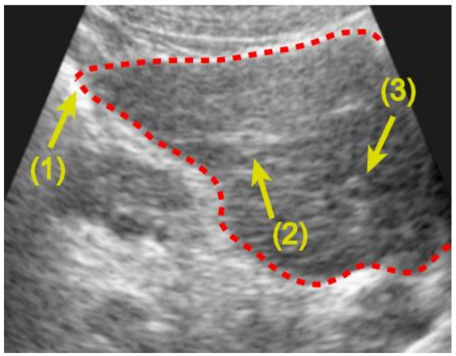


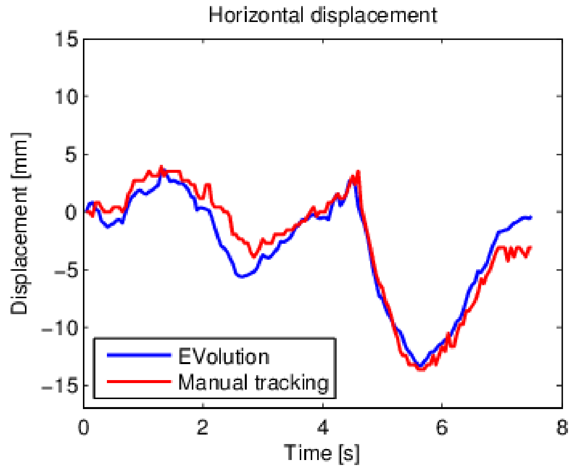


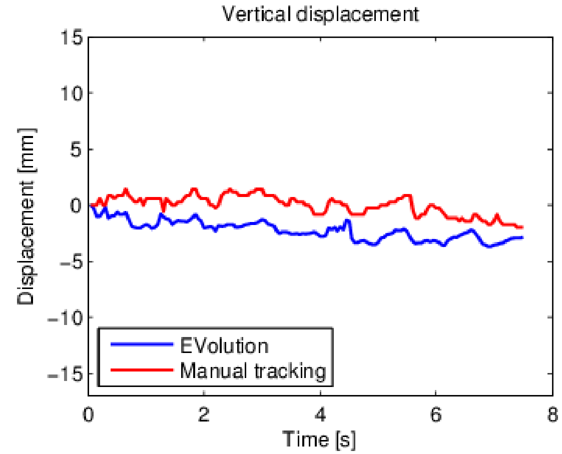
C. Zachiu et al, Phys Med Biol., 62(20), 2017

Radiotherapy: Intra-fraction ultrasound guidance?

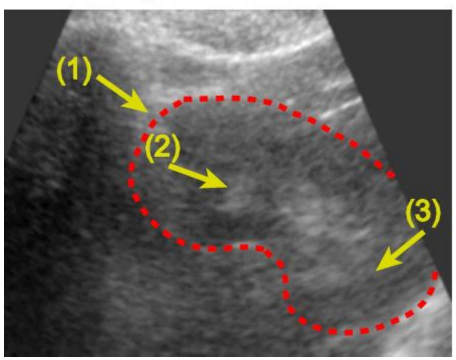
Liver contact ultrasound

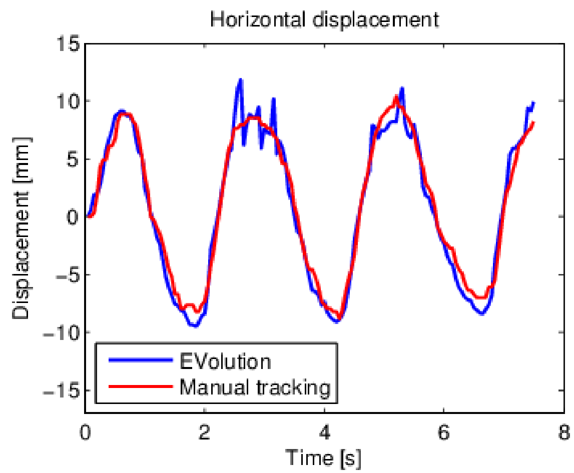


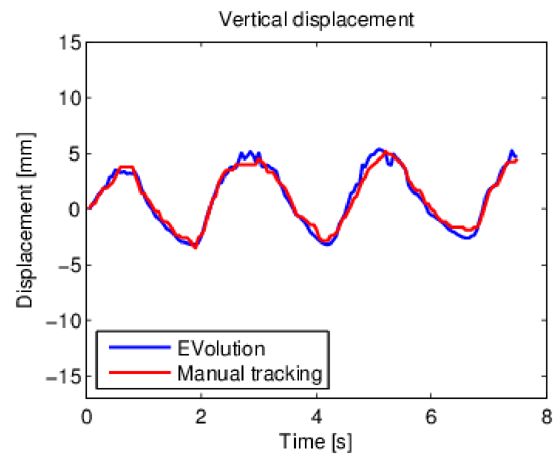




Kidney contact ultrasound







Tracking error: 1.5 mm ± 1.1 mm

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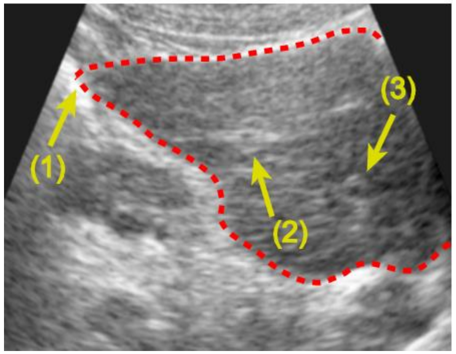
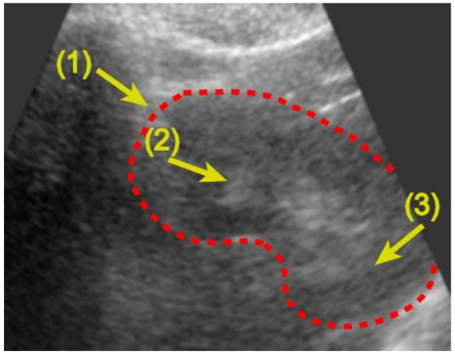
C. Zachiu et al, Phys Med Biol., 62(20), 2017

Radiotherapy: Intra-fraction ultrasound guidance?

Liver contact ultrasound



Kidney contact ultrasound

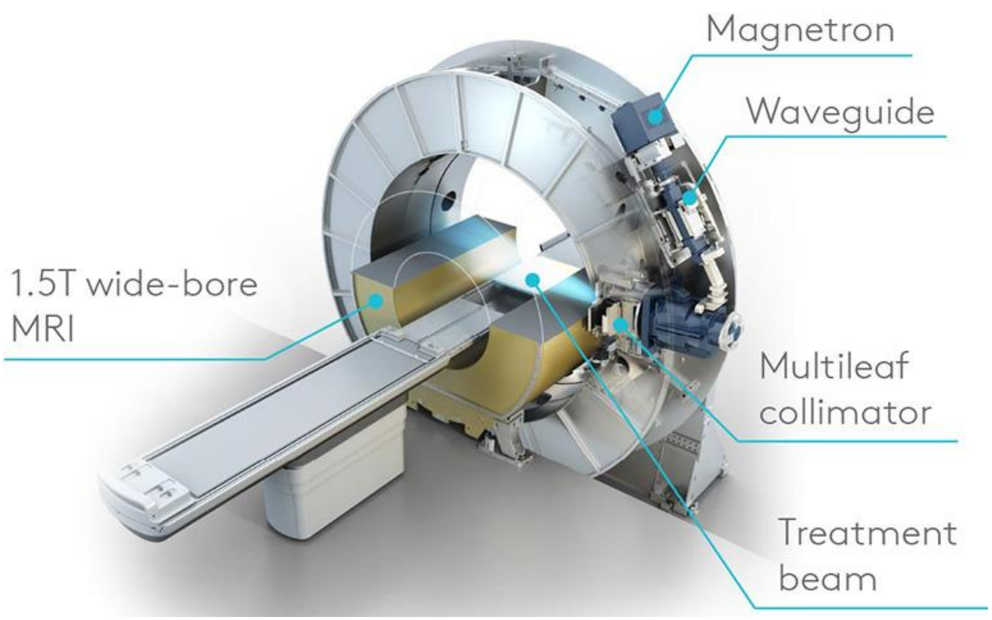


- *Poor overall image quality;*
- *Limited field of view;*
- *Poor soft-tissue contrast;*
- *Difficult to "link" with the daily CBCT;*

C. Zachiu et al, Phys Med Biol., 62(20), 2017

Radiotherapy: Intra-fraction Magnetic Resonance Guidance

The Elekta Unity MR-Linac



D. Winkel et al, Clin Transl Radiat Oncol., 18, 2019

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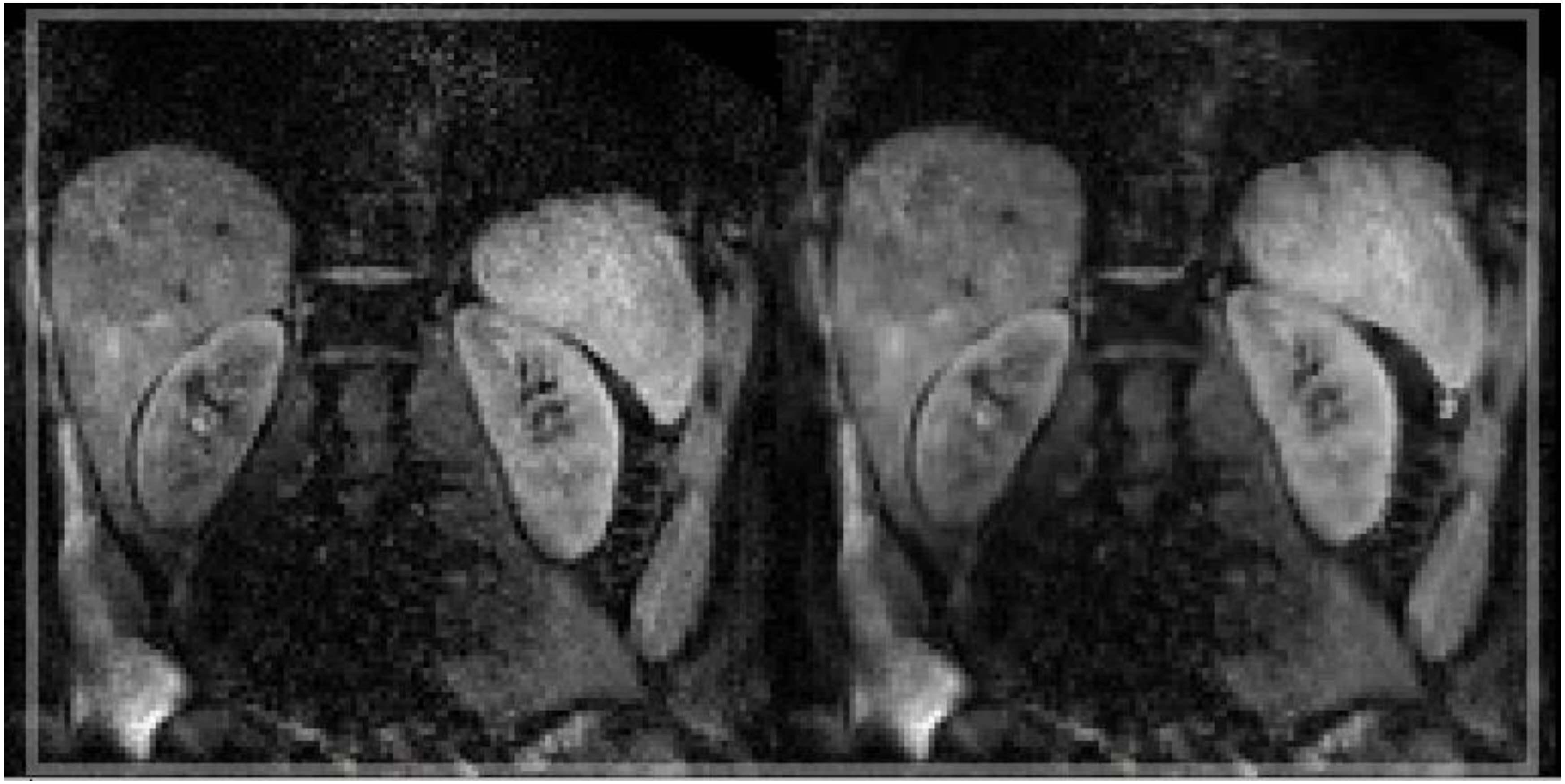
Radiotherapy: Intra-fraction Magnetic Resonance Guidance



Moving Images

Registered images (Horn – Schunck)

Tracking error: 0.65 mm ± 0.6 mm

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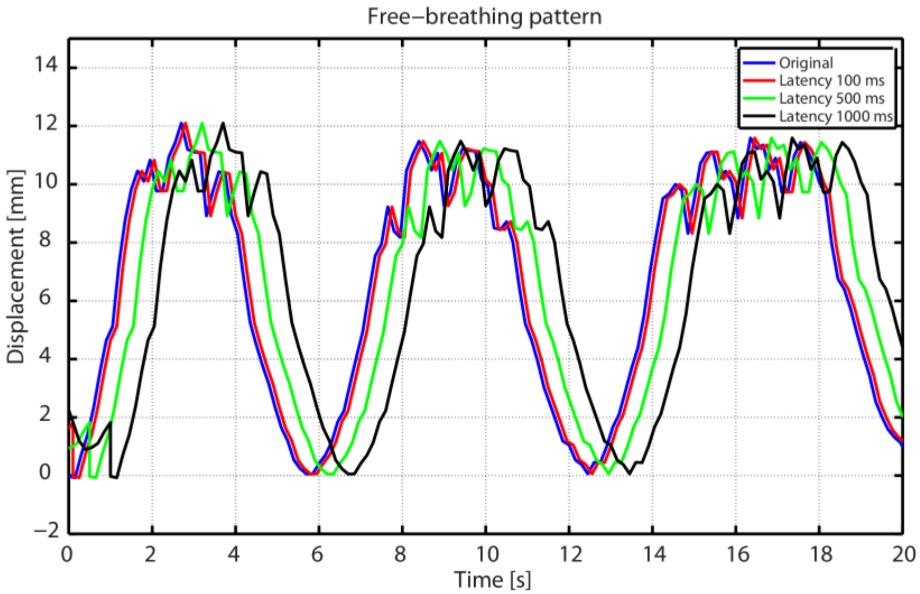
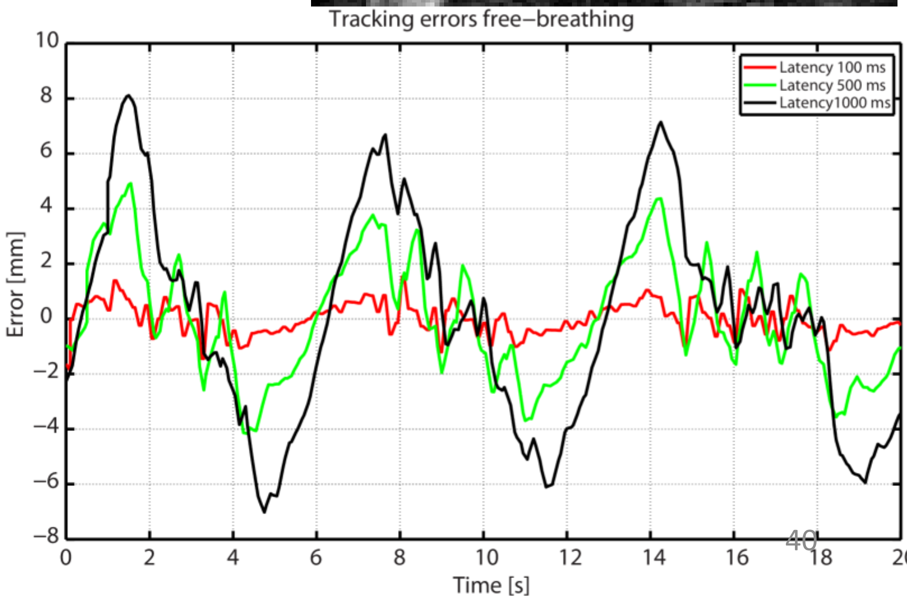
Radiotherapy: Intra-fraction Magnetic Resonance Guidance

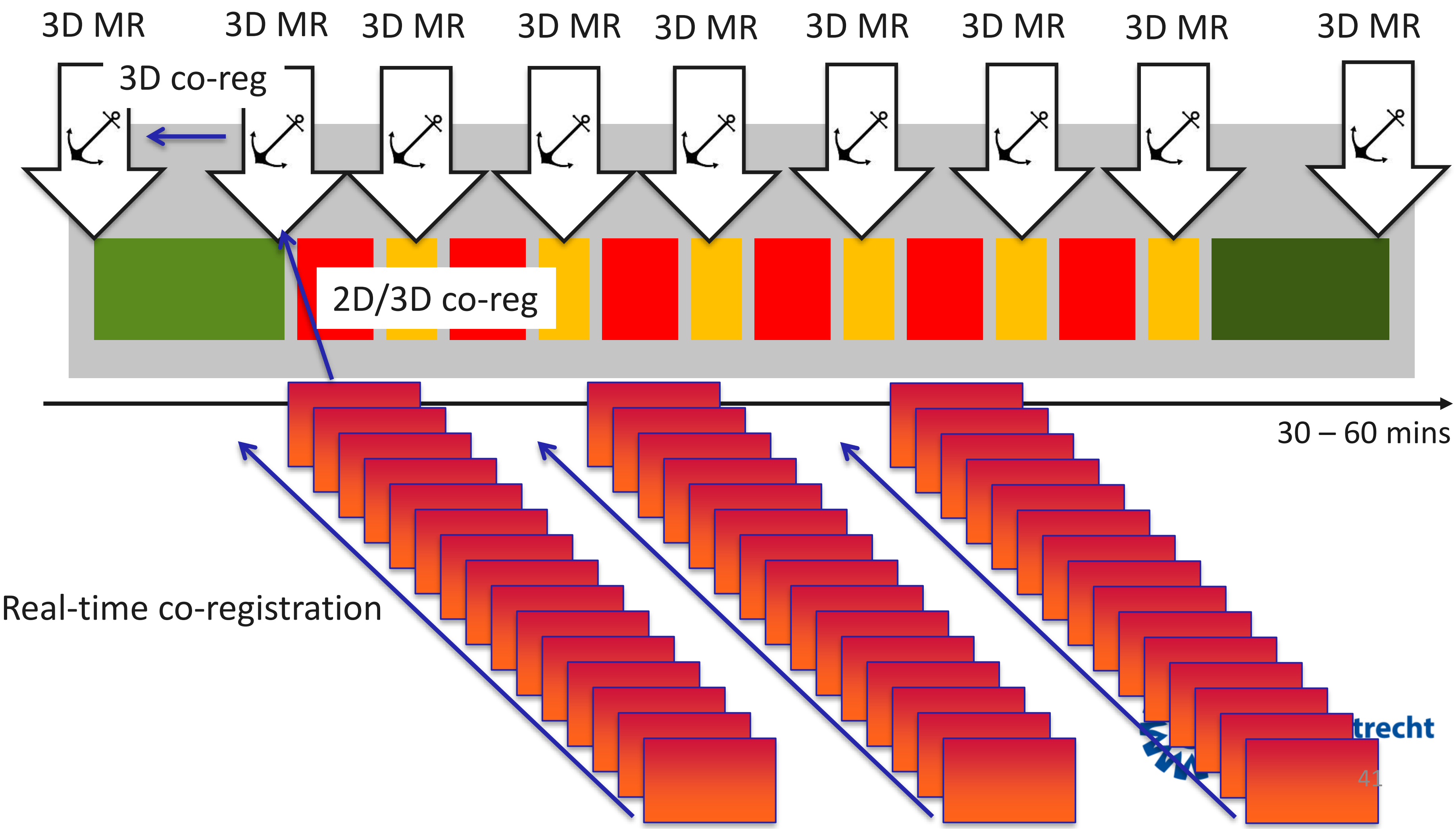
- Extra specifications for registering respiratory motion:
  - Acquisition and convergence speed is important;
  - Motion prediction algorithms may be necessary due to processing latencies



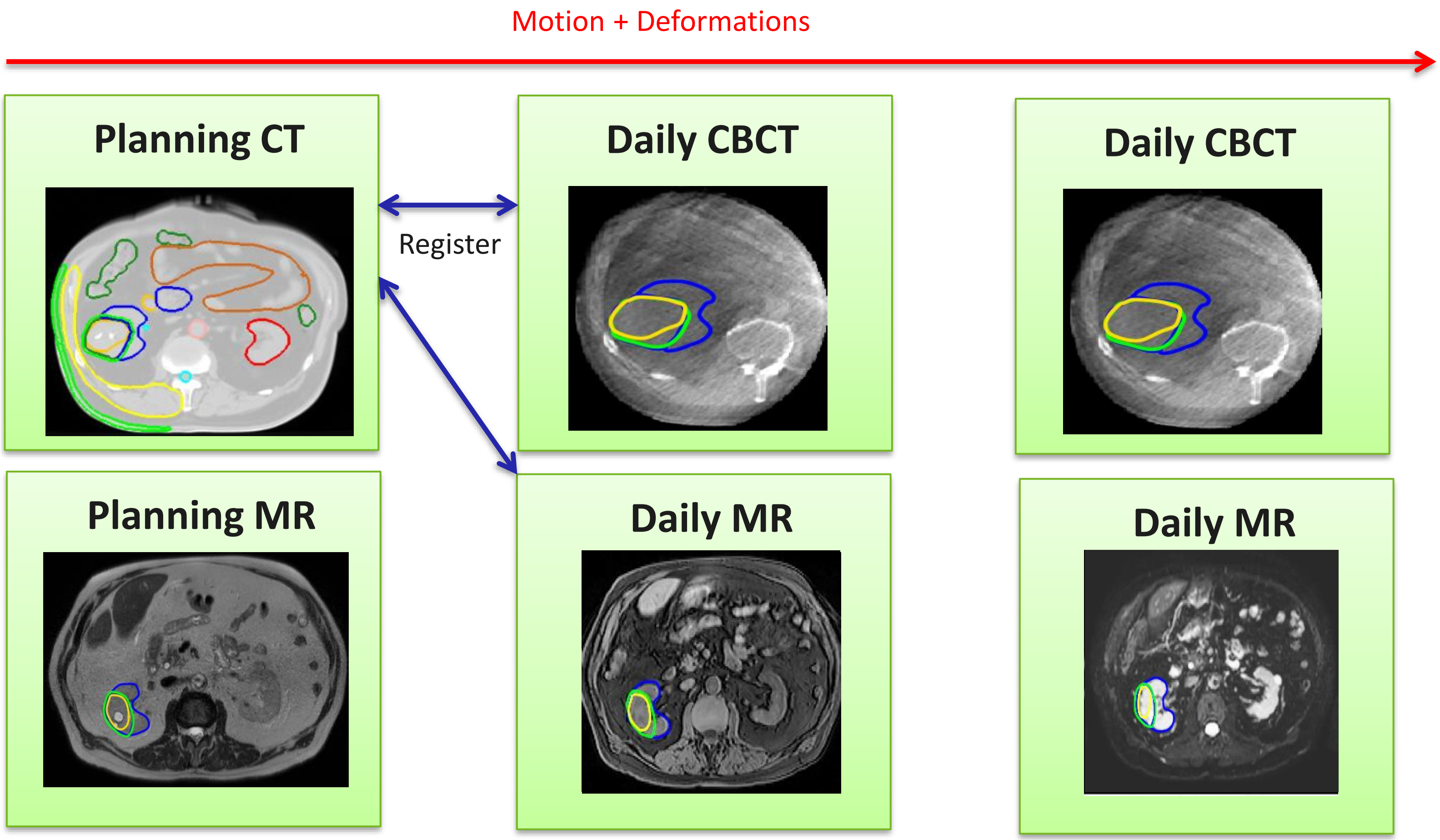


Radiotherapy: Intra-fraction Magnetic Resonance Guidance

Potential framework for respiratory and peristaltic motion compensation via deformable image registration on the MR-Linac



Deformable image registration in image-guided radiotherapy



- Adjust patient position + account for daily anatomical changes
- Track the tumor and organs-at-risk from CT to CBCT to MR to MR

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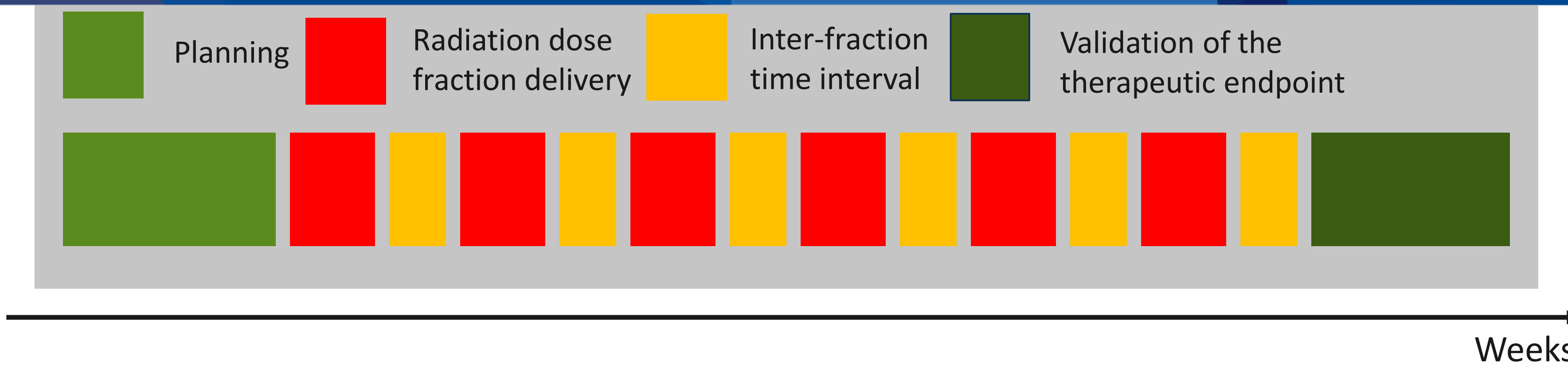
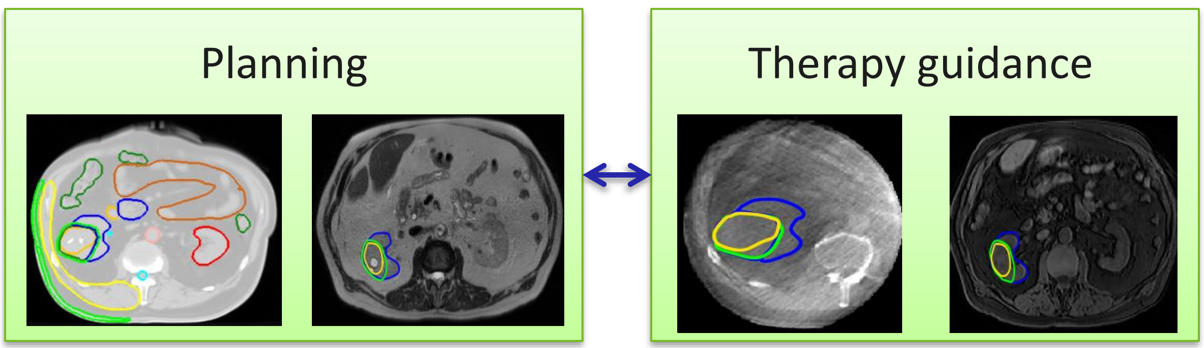
Deformable image registration in image-guided radiotherapy





This implies, however:

- *Estimating the displacement and/or deformation of the pathology and organs-at-risk with respect to the planning image over images acquired using different modalities, MR-contrasts, acquisition schemes and upon which the pathologies may or may not be visible.*

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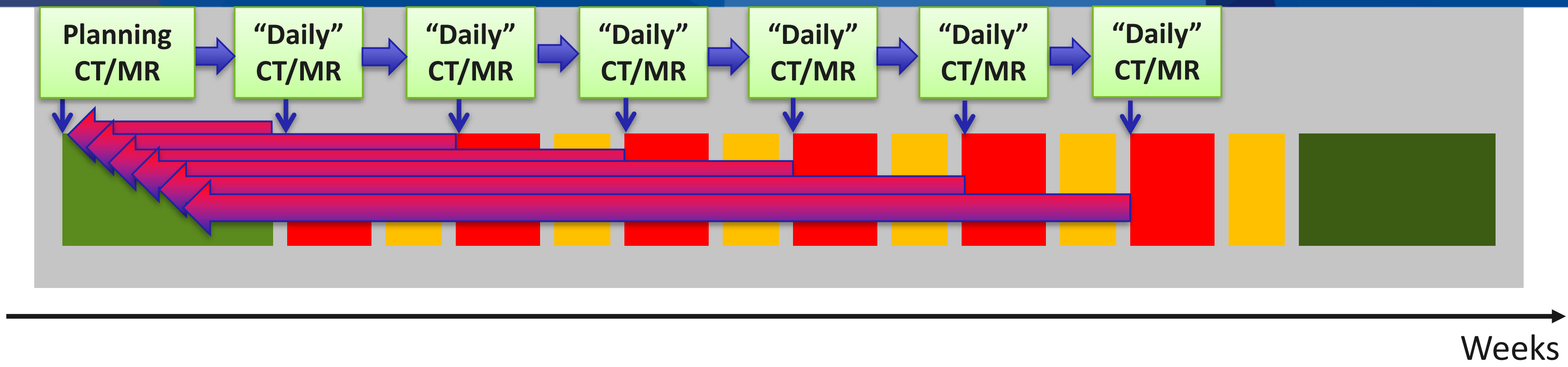
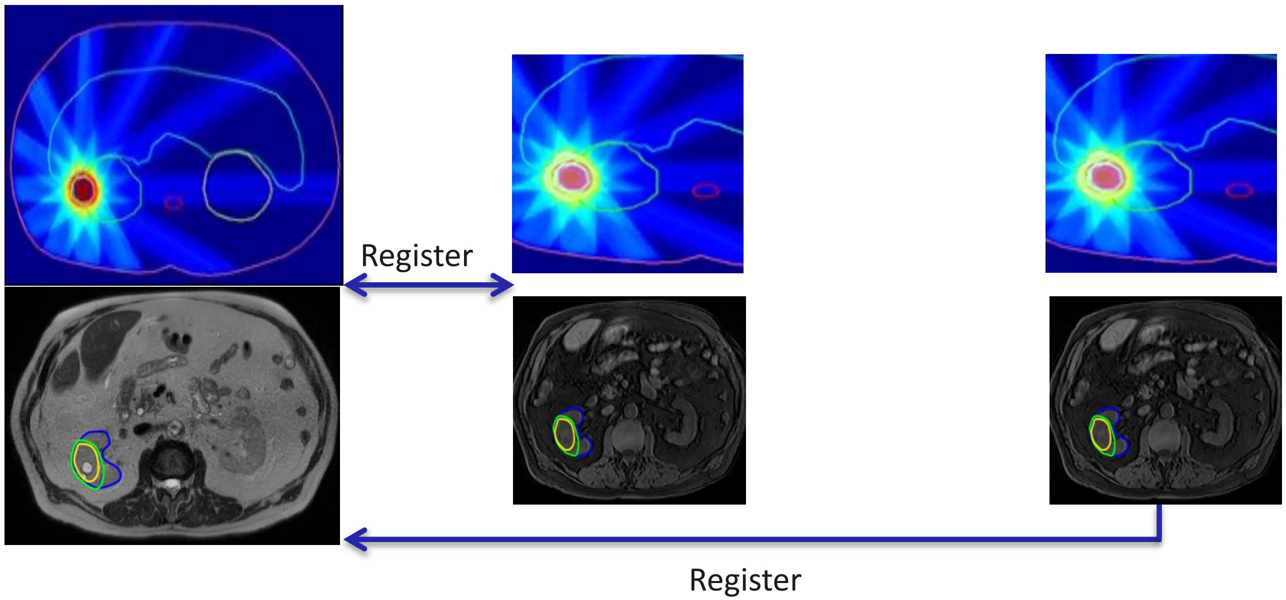
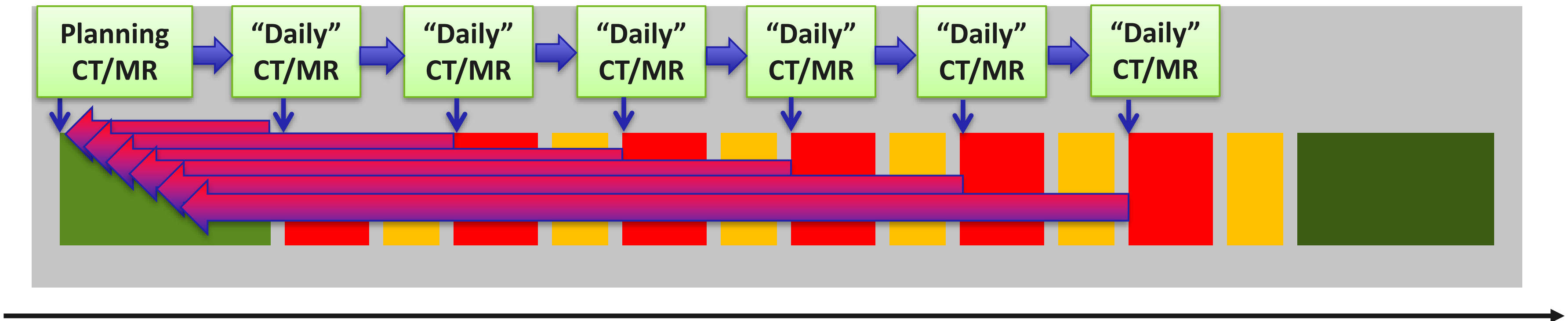
Deformable image registration in image-guided radiotherapy





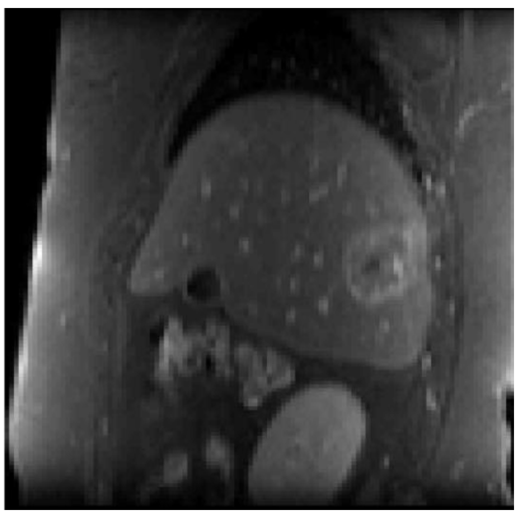
- Track the tumor and organs-at-risk over the course of the treatment
- *Project and accumulate the radiation dose delivered by each fraction, “upstream” the motion flow*

Image-guided radiotherapy: Dose Accumulation

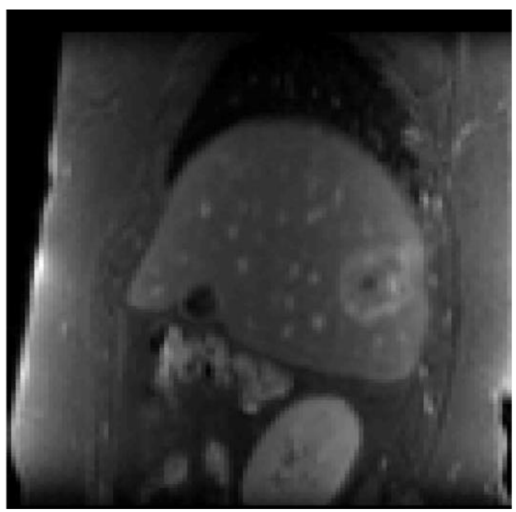


Weeks

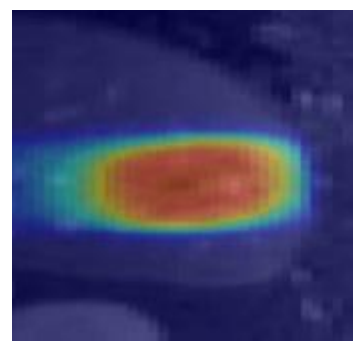
Planning MR Image



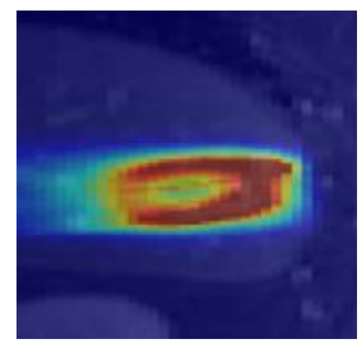
Daily MR Image #1



Planned dose



Accumulated Dose



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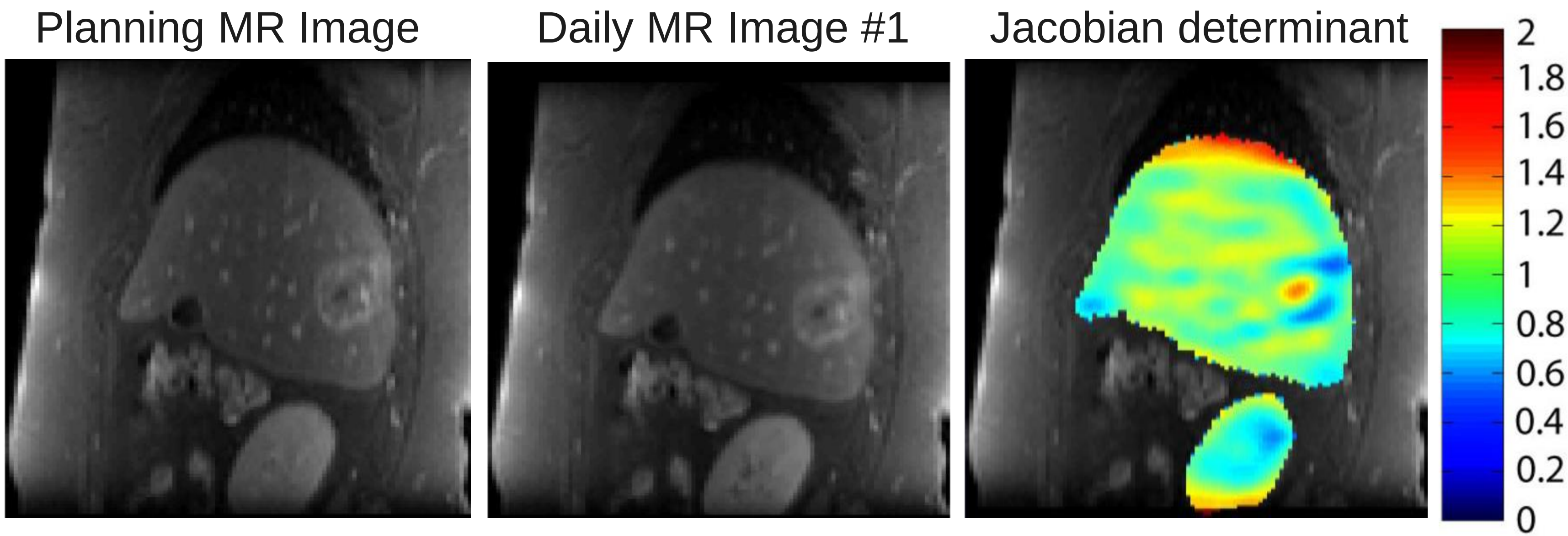
C. Zachiu et al., Phys Med Biol., 65(1) , 2020

Image-guided radiotherapy: Dose Accumulation

$$E(\boldsymbol{u}) = \sum_{\vec{r}\in\Omega} D(\boldsymbol{u}(\vec{r})) + \frac{\boldsymbol{\alpha}}{\mathbf{2}}\boxed{\left\|\vec{\boldsymbol{\nabla}}\boldsymbol{u}\right\|_2^2} \qquad D(\boldsymbol{u}) = \exp\left(-\frac{\sum_{\vec{s}\in\Gamma}\left|\vec{\nabla}_I(\boldsymbol{u}(\vec{s}))\cdot\vec{\nabla}_{\boldsymbol{J}}(\vec{s})\right|}{\sum_{\vec{s}\in\Gamma}\left\|\vec{\nabla}_{\boldsymbol{I}}(\boldsymbol{u}(\vec{s}))\right\|_{\mathbf{2}}\left\|\vec{\nabla}_{\boldsymbol{j}}(\vec{s})\right\|_{\mathbf{2}}}\right)$$



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C. Zachiu et al., Phys Med Biol., 65(1) , 2020

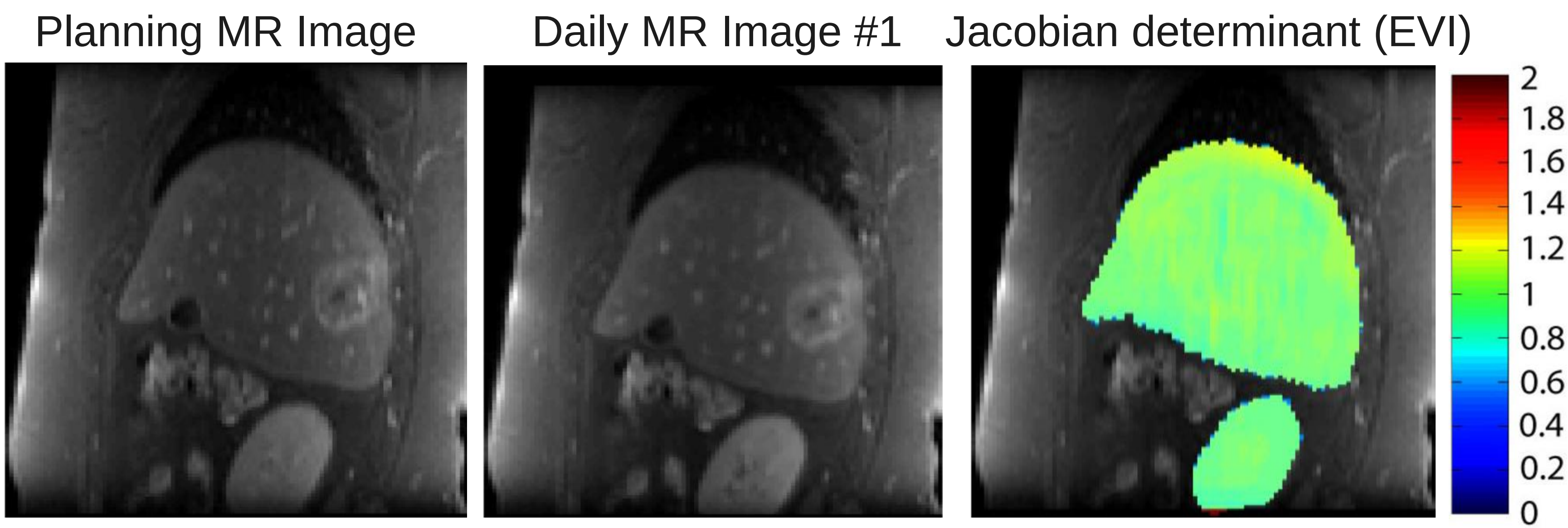
Image-guided radiotherapy: Dose Accumulation

- The "Incompressible" EVolution algorithm (EVI):

$$E_{EVI}(\boldsymbol{u}) = \sum_{\vec{r}\in\Omega} D(\boldsymbol{u}(\vec{r})) + \frac{\boldsymbol{\alpha}}{\mathbf{2}}\|\boldsymbol{J} - \mathbf{1}\|_2^2 \qquad J = \begin{vmatrix} 1+u_x & u_y & u_z \\ v_x & 1+v_y & v_z \\ w_x & w_y & 1+w_z \end{vmatrix}$$

$\boldsymbol{u} = (u, v, w)$

$u_x, \dots, w_z$ - 3D spatial derivatives



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C. Zachiu et al., Phys Med Biol., 65(1) , 2020

Image-guided radiotherapy: Dose Accumulation

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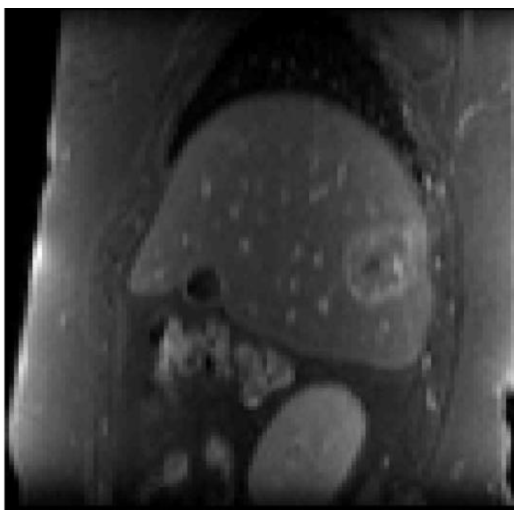
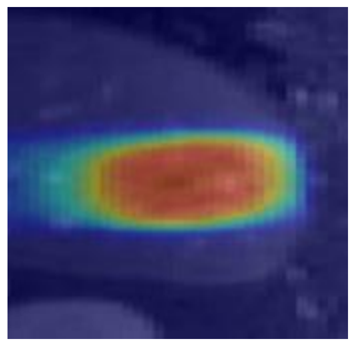
$\boldsymbol{u} = (u, v, w)$

$u_x, \ldots, w_z$ - 3D spatial derivatives

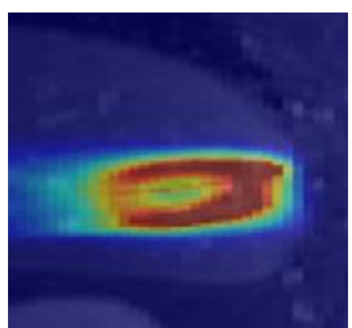
Planning MR Image



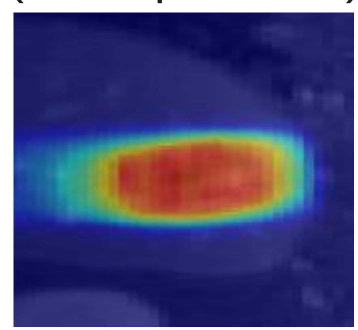
Planned dose



Accumulated Dose (Smooth)



Accumulated Dose (Incompressible)



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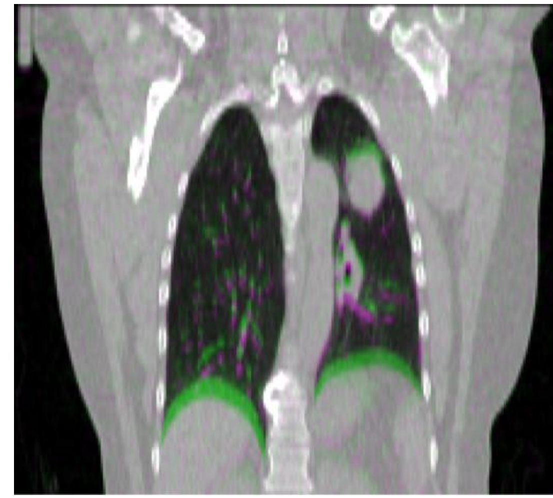
C. Zachiu et al., Phys Med Biol., 65(1) , 2020

Image-guided radiotherapy: Dose Accumulation

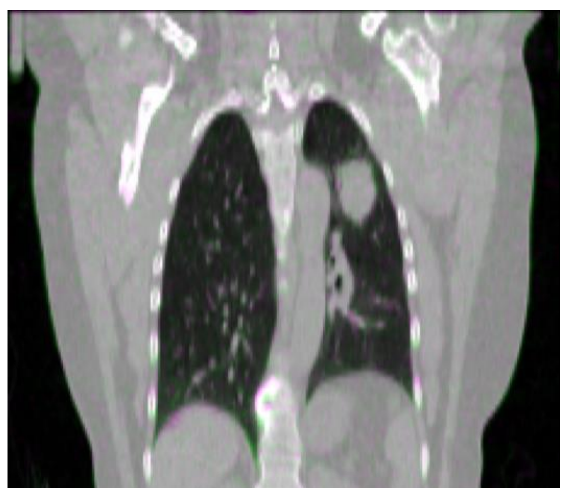
Reference CT

Moving CT

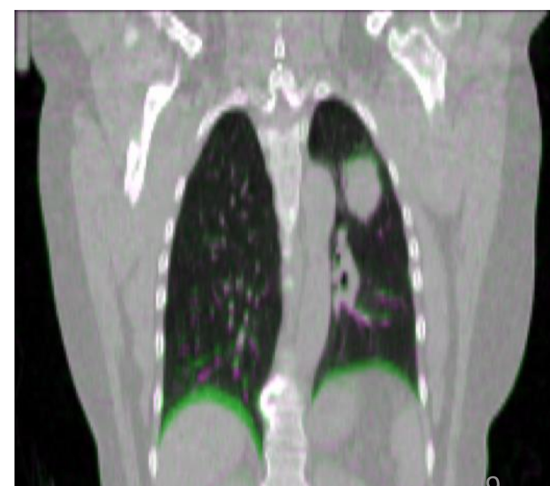
Overlap before



Overlap EVO



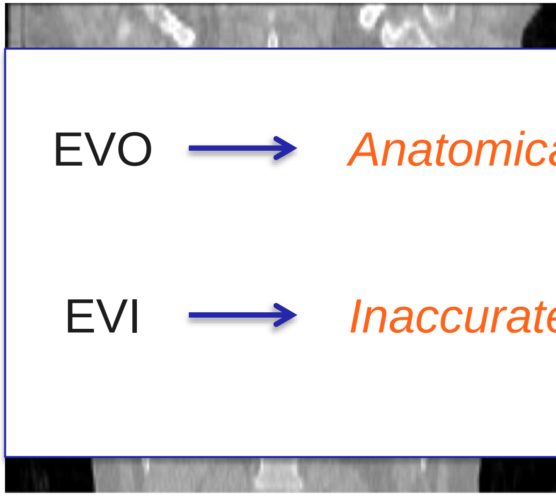
Overlap EVI



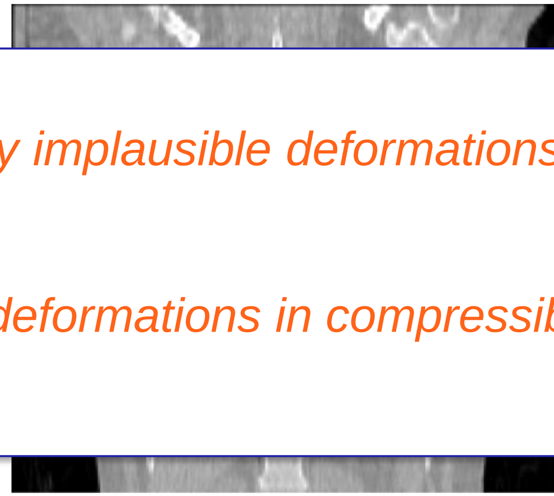
C. Zachiu et al, Phys Med Biol. 2020 (Epub ahead of print)

Image-guided radiotherapy: Dose Accumulation

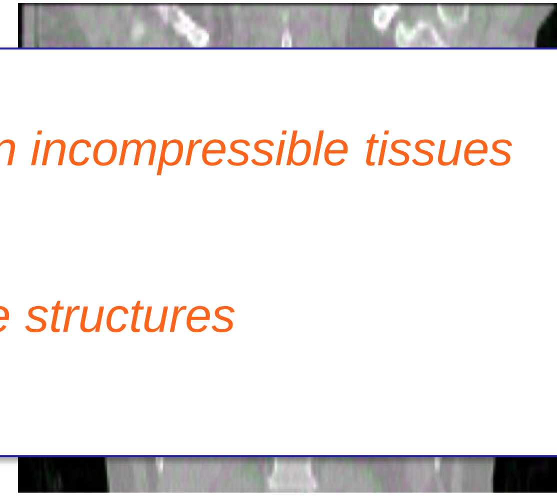
Reference CT



Moving CT



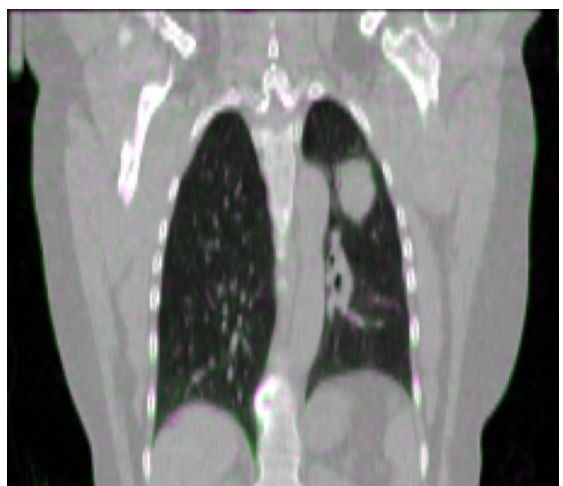
Overlap before



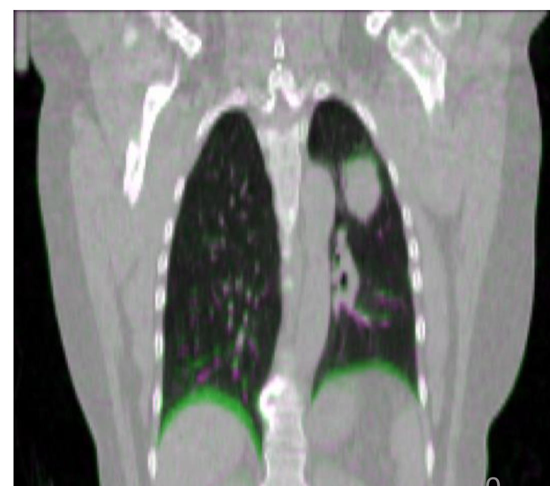
EVO → *Anatomically implausible deformations in incompressible tissues*

EVI → *Inaccurate deformations in compressible structures*

Overlap EVO



Overlap EVI

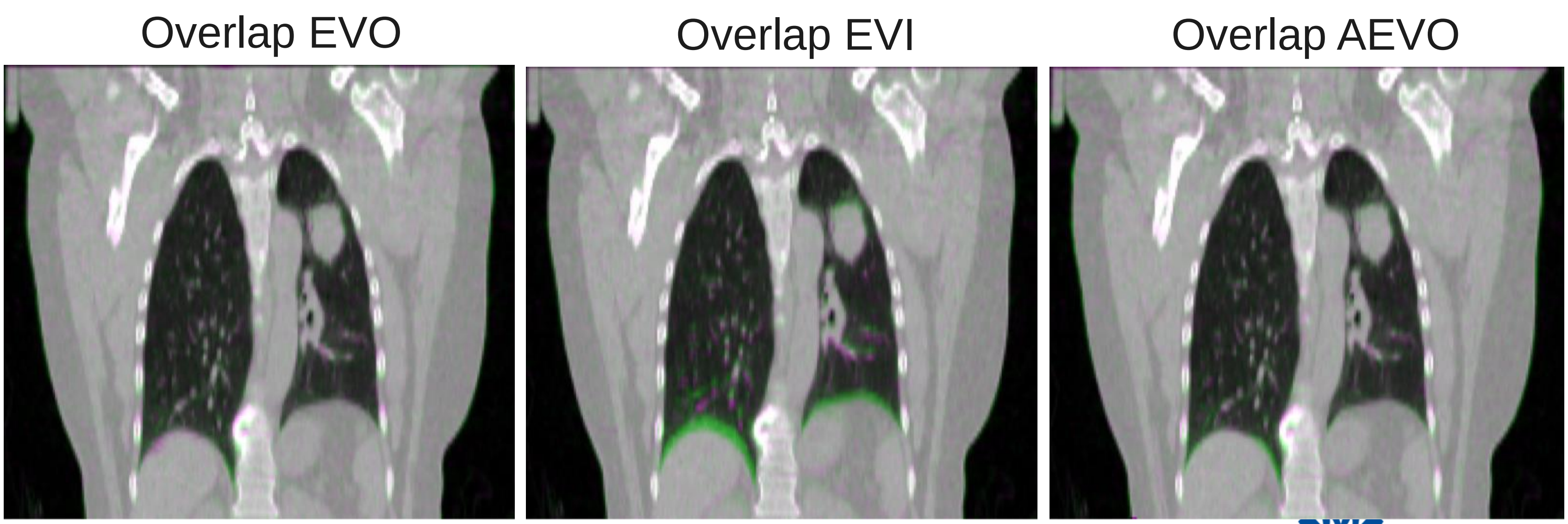


C. Zachiu et al, Phys Med Biol. 2020 (Epub ahead of print)

Image-guided radiotherapy: Dose Accumulation

$$E_{AEVO}(\boldsymbol{u}) = \sum_{\vec{r}\in\Omega} D(\boldsymbol{u}(\vec{r})) + \boldsymbol{M_S}(\vec{r})\frac{\boldsymbol{\alpha}}{\mathbf{2}}\left\|\vec{\boldsymbol{\nabla}}\boldsymbol{u}\right\|_2^2 + \boldsymbol{M_I}(\vec{r})\frac{\boldsymbol{\beta}}{\mathbf{2}}\|\boldsymbol{J} - \mathbf{1}\|_2^2$$

→ $\boldsymbol{M_S}$ and $\boldsymbol{M_I}$ are binary masks defining the compressible and incompressible areas



C. Zachiu et al, Phys Med Biol. 2020 (Epub ahead of print)

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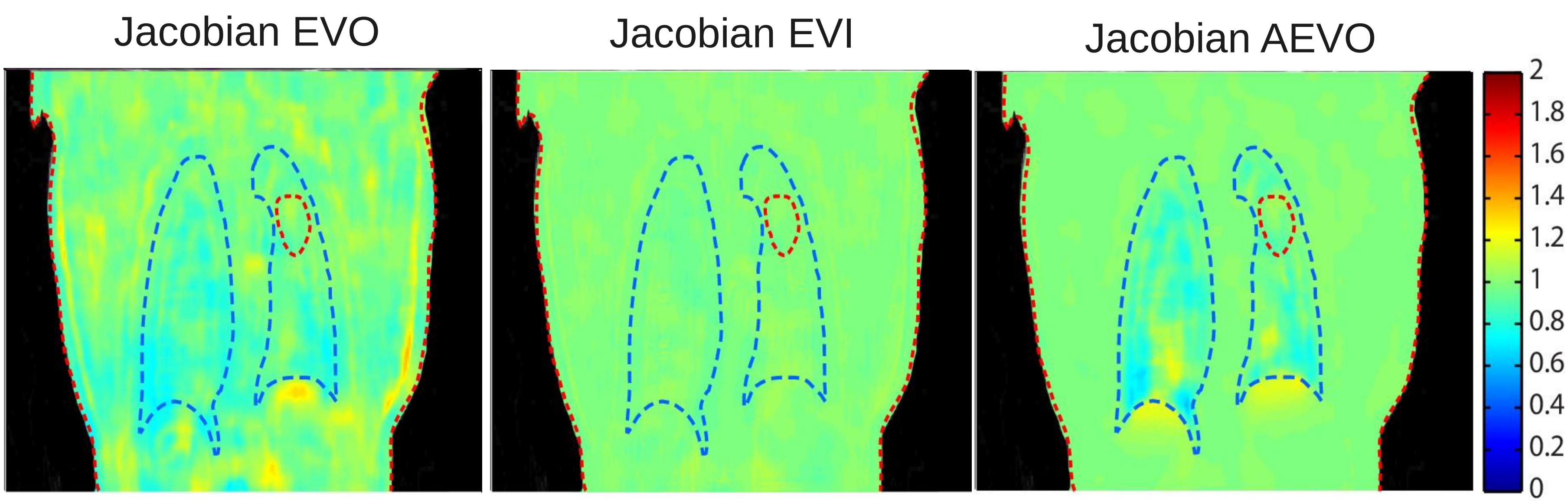
Image-guided radiotherapy: Dose Accumulation

$$E_{AEVO}(\boldsymbol{u}) = \sum_{\vec{r} \in \Omega} D(\boldsymbol{u}(\vec{r})) + \boldsymbol{M_S}(\vec{r}) \frac{\boldsymbol{\alpha}}{\mathbf{2}} \left\| \vec{\boldsymbol{\nabla}} \boldsymbol{u} \right\|_2^2 + \boldsymbol{M_I}(\vec{r}) \frac{\boldsymbol{\beta}}{\mathbf{2}} \| \boldsymbol{J} - \mathbf{1} \|_2^2$$

→ $\boldsymbol{M_S}$ and $\boldsymbol{M_I}$ are binary masks defining the compressible and incompressible areas



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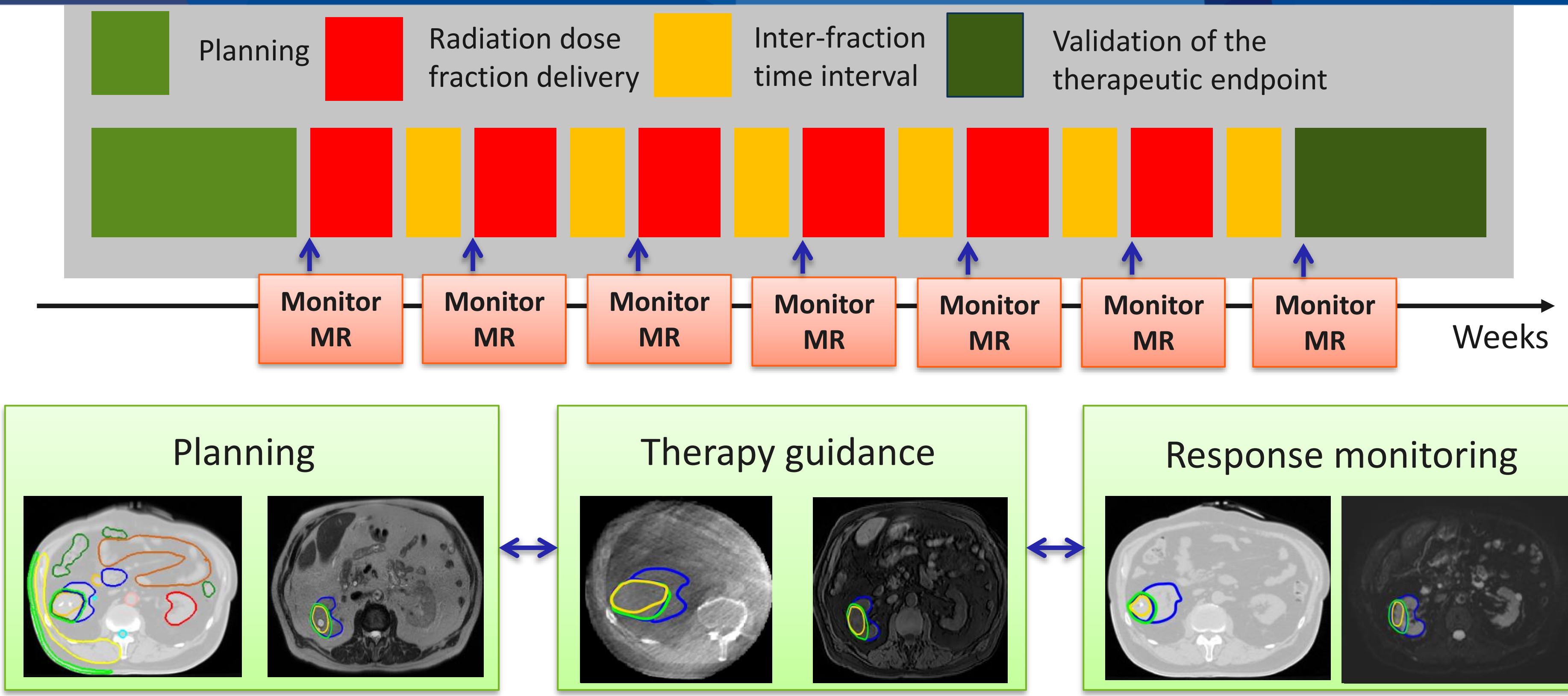
C. Zachiu et al, Phys Med Biol. 2020 (Epub ahead of print)

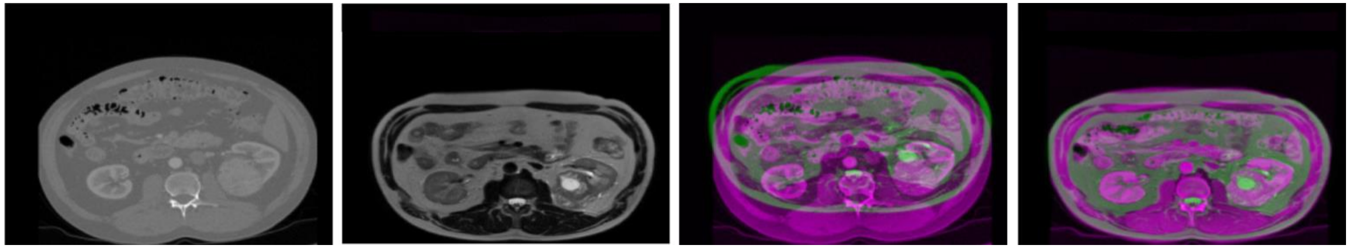
Image-guided radiotherapy: Therapy Response Assessment



DIR methods in IGRT: Validation

Before clinical commissioning, DIR algorithms have to pass several complementary validation benchmarks !

- Visual inspection of organ boundary alignment



L. Laffite et al, Phys Med Biol., 63(23), 2018

- Possible objective criterion:

Dice Similarity Coefficient (DSC)

$$DSC(A,B) = \frac{2|A \cap B|}{|A| + |B|}$$

Jaccard index (JI)

$$JI(A,B) = \frac{|A \cap B|}{|A| + |B| - |A \cap B|}$$

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DIR methods in IGRT: Validation

Dice Similarity Coefficient (DSC) benchmarking for prostate IGRT

ROI	Algorithm	MR-MR Mono	MR-MR Multi	MR - CT
Bladder	None	0.79	0.79	0.73
	EVO	0.93	0.91	0.86
	EVI	0.86	0.85	0.81
	AEVO	0.93	0.90	0.85
Prostate (CTV)	None	0.83	0.78	0.78
	EVO	0.92	0.83	0.82
	EVI	0.92	0.84	0.83
	AEVO	0.93	0.84	0.82
Rectum	None	0.75	0.79	0.73
	EVO	0.88	0.85	0.80
	EVI	0.82	0.82	0.80
	AEVO	0.88	0.85	0.80

- *And average DSC and Jaccard above 0.8 – 0.9 is recommended for clinical deployment*

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C. Zachiu et al, Phys Med Biol. 2020 (Epub ahead of print)

DIR methods in IGRT: Validation

- **Target Registration Error (TRE)**

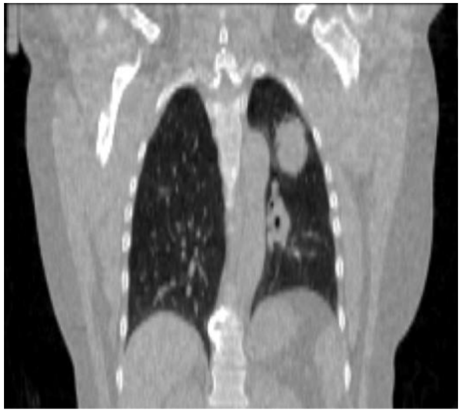
$$TRE(u_{est}(\vec{r})) = \left\| x_{ref}(\vec{r}) - x_{mov}(\vec{r}) + u_{est}(\vec{r}) \right\|_2$$

- **with respect to:**
  - **manually annotated landmarks;**
  - **known displacements/deformations;**

Accuracy and Precision [mm]		
Patient no.	Before reg.	HS OF
#1	3.89 ± 2.78	1.04 ± 0.49
#2	4.33 ± 3.90	1.10 ± 0.60
#3	6.94 ± 4.05	1.38 ± 0.87
#4	9.83 ± 4.86	1.78 ± 1.63
#5	7.47 ± 5.51	2.09 ± 2.09
Average	**6.49 ± 4.22**	**1.48 ± 1.13**

Planning CT

Daily CT



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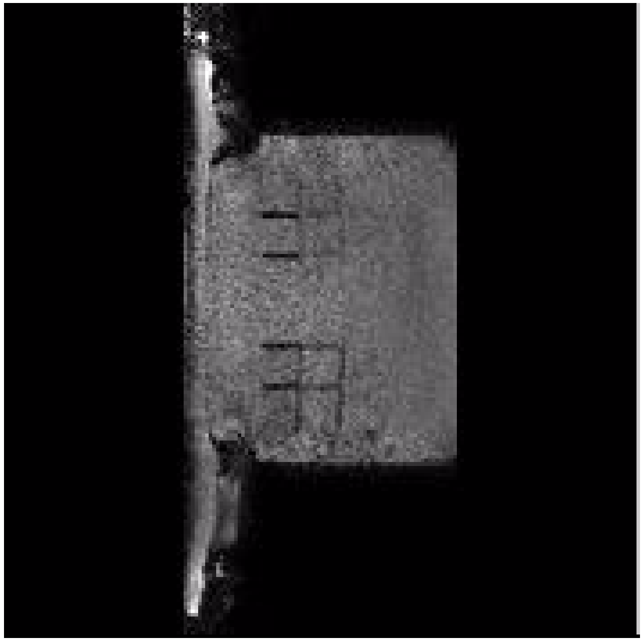
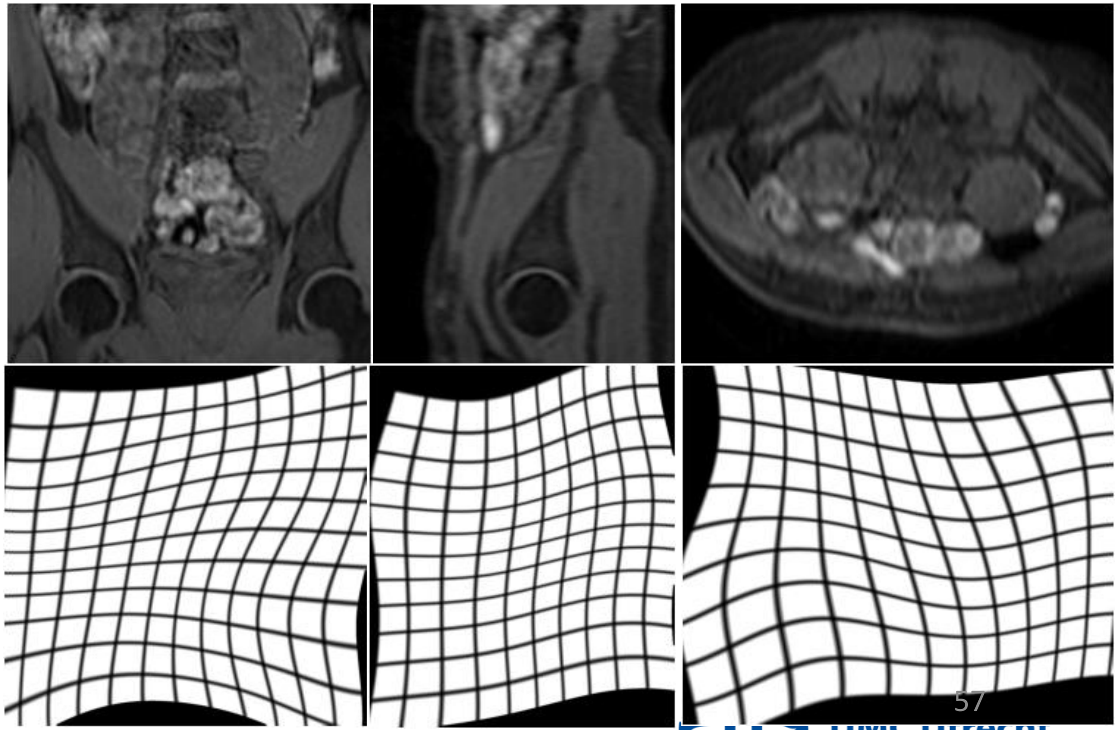
DIR methods in IGRT: Validation

- **Target Registration Error (TRE)**

$$TRE(u_{est}(\vec{r})) = \left\| x_{ref}(\vec{r}) - x_{mov}(\vec{r}) + u_{est}(\vec{r}) \right\|_2$$ **< 2 – 3 mm (on average)**

- **with respect to:**
  - **manually annotated landmarks;**
  - **known displacements/deformations (on hardware or software phantoms);**





L. Laffite et al, Phys Med Biol., 63(23), 2018
C. Zachiu et al, Phys Med Biol., 62(20), 2017

DIR methods in IGRT: Online quality assurance

- Benchmarks such as DSC, Jaccard and TRE can provide information on expected algorithm performance;
- They cannot guarantee that algorithm performance is maintained during clinical deployment (and also require expert input);
- Online quality assurance mechanisms must be put in place to ensure patient safety;

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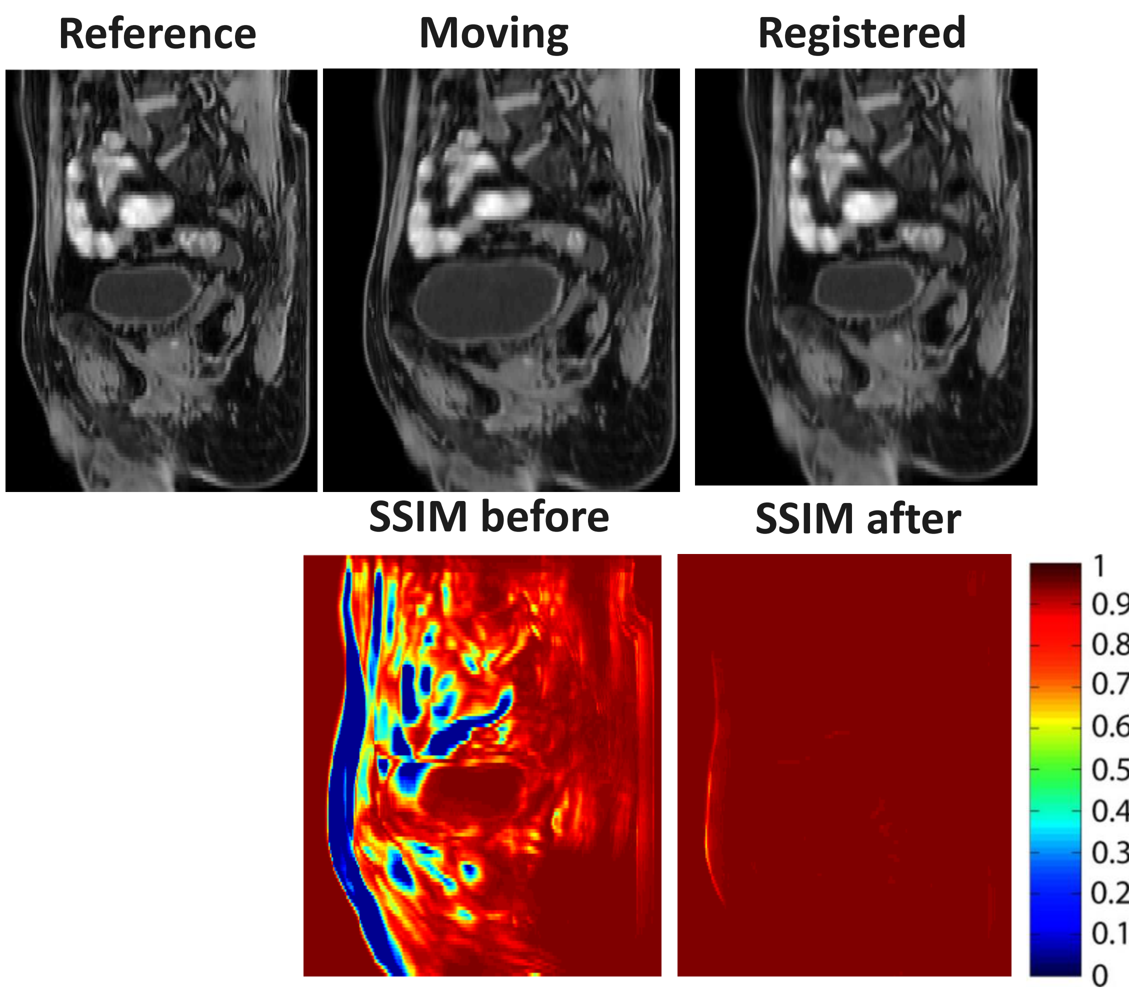
DIR methods in IGRT: Online quality assurance

- Objective criterion for boundary alignment:
  - **Structural similarity index (SSIM)** **> 0.8 – 0.9**



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C. Zachiu et al, Phys Med Biol. 2020 (Epub ahead of print)

DIR methods in IGRT: Online quality assurance

- **Criteria for inside organ boundaries: Rely on biomechanical properties**
- Evaluation of the spatial distribution of the **Jacobian determinant** (J);

$$J = \begin{vmatrix} 1 + u_x & u_y & u_z \\ v_x & 1 + v_y & v_z \\ w_x & w_y & 1 + w_z \end{vmatrix}$$

$\boldsymbol{u} = (u, v, w)$

$u_x, \dots, w_z$ - 3D spatial derivatives

- *For incompressible tissues J = 1;*

- Measure for local vorticity: the magnitude of the **curl** of the motion vector field

$$\mathrm{curl}(\vec{\mathbf{u}}) = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ u_1 & u_2 & u_3 \end{vmatrix}$$

- *Deep within soft tissue boundaries curl magnitude ≈ 0;*

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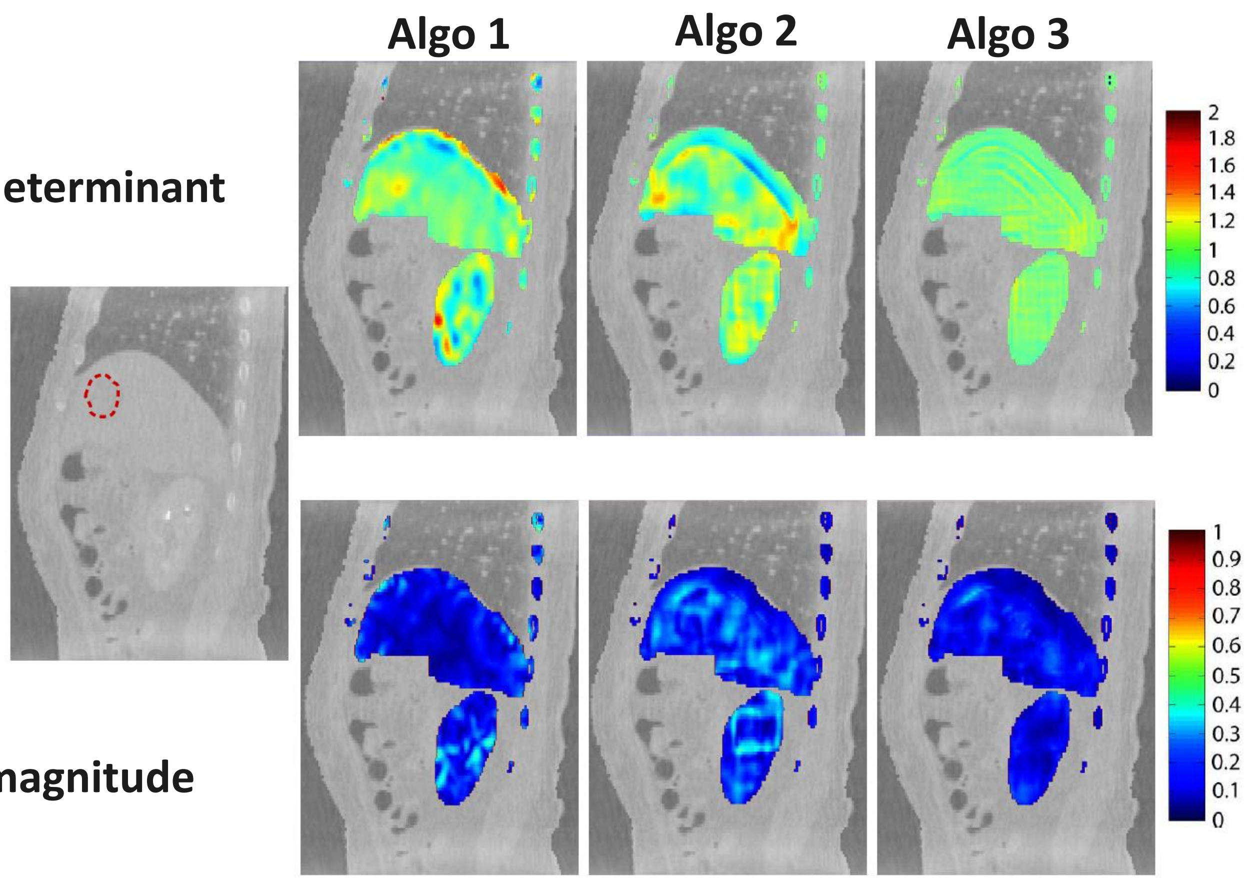
Jacobian determinant

Curl magnitude



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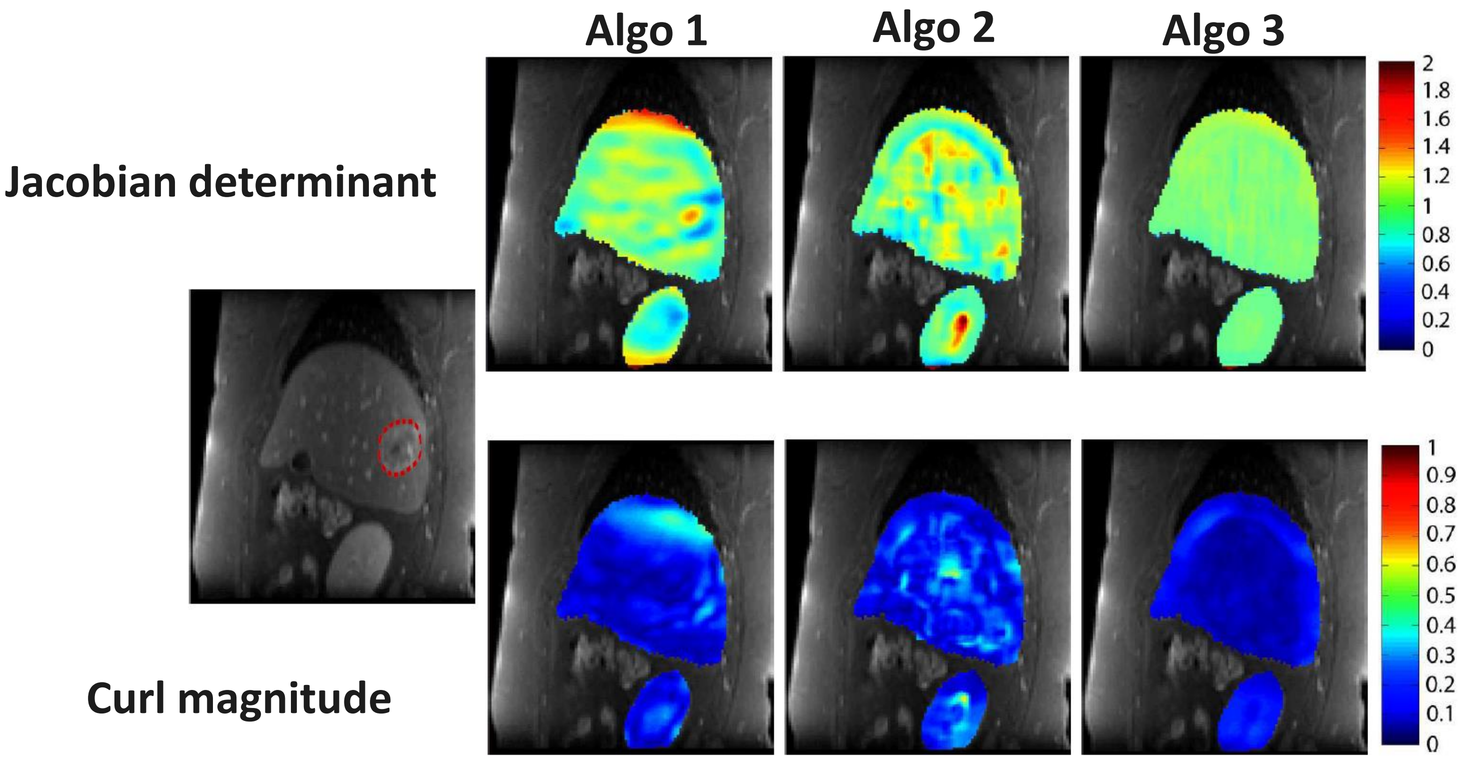

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- Compressive/expansive mechanical stress:

Elastic modulus of the tissue

Jacobian determinant

$$\sigma(\vec{r}) = \frac{\boxed{E}(\vec{r})}{3(1-2\boxed{\nu}(\vec{r}))}(\boxed{J}(\vec{r})-1)$$

Poisson ratio of the tissue

- Shear mechanical stress:

Shear modulus of the tissue

$$\gamma_{xy}(\vec{r}) = \frac{\boxed{G}(\vec{r})}{2}\left[\frac{\partial u_1(\vec{r})}{\partial y} + \frac{\partial u_2(\vec{r})}{\partial x}\right]$$

$$\gamma_{xz}(\vec{r}) = \frac{G(\vec{r})}{2}\left[\frac{\partial u_2(\vec{r})}{\partial z} + \frac{\partial u_3(\vec{r})}{\partial y}\right]$$

$$\gamma_{yz}(\vec{r}) = \frac{G(\vec{r})}{2}\left[\frac{\partial u_1(\vec{r})}{\partial z} + \frac{\partial u_3(\vec{r})}{\partial x}\right]$$

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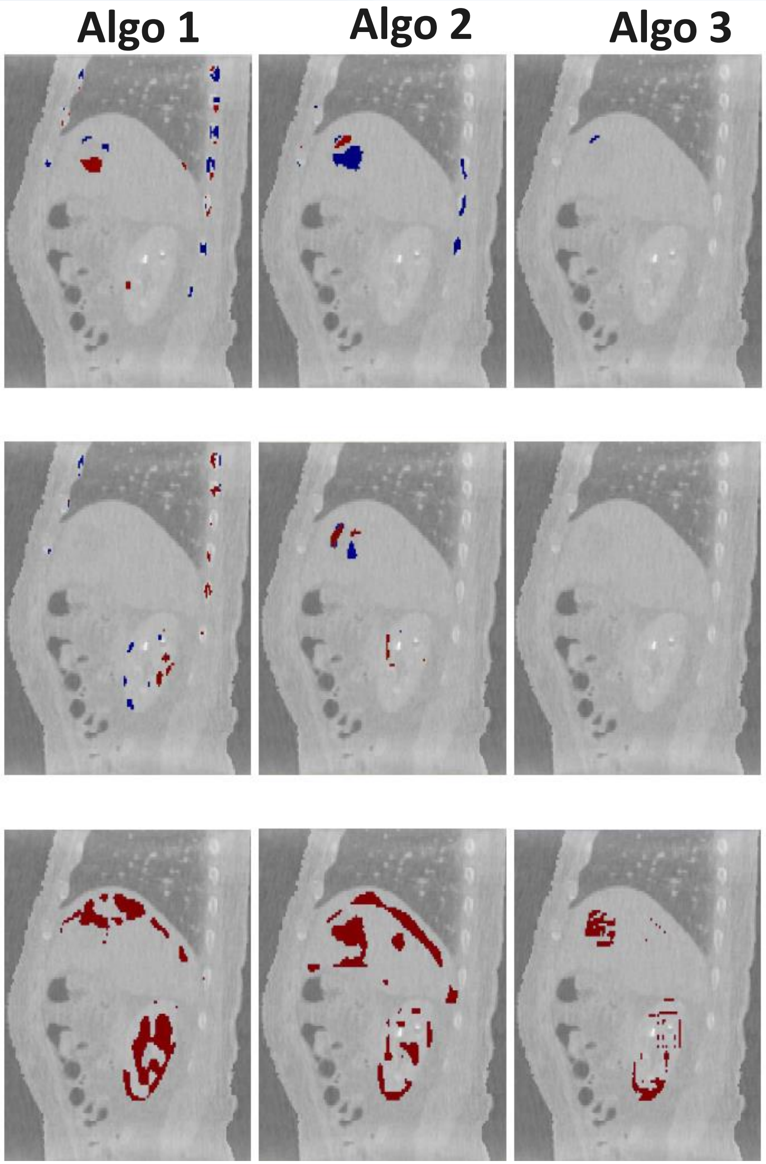

Rupture compressive/ expansive stress

Rupture shear stress

Blood pressure excess

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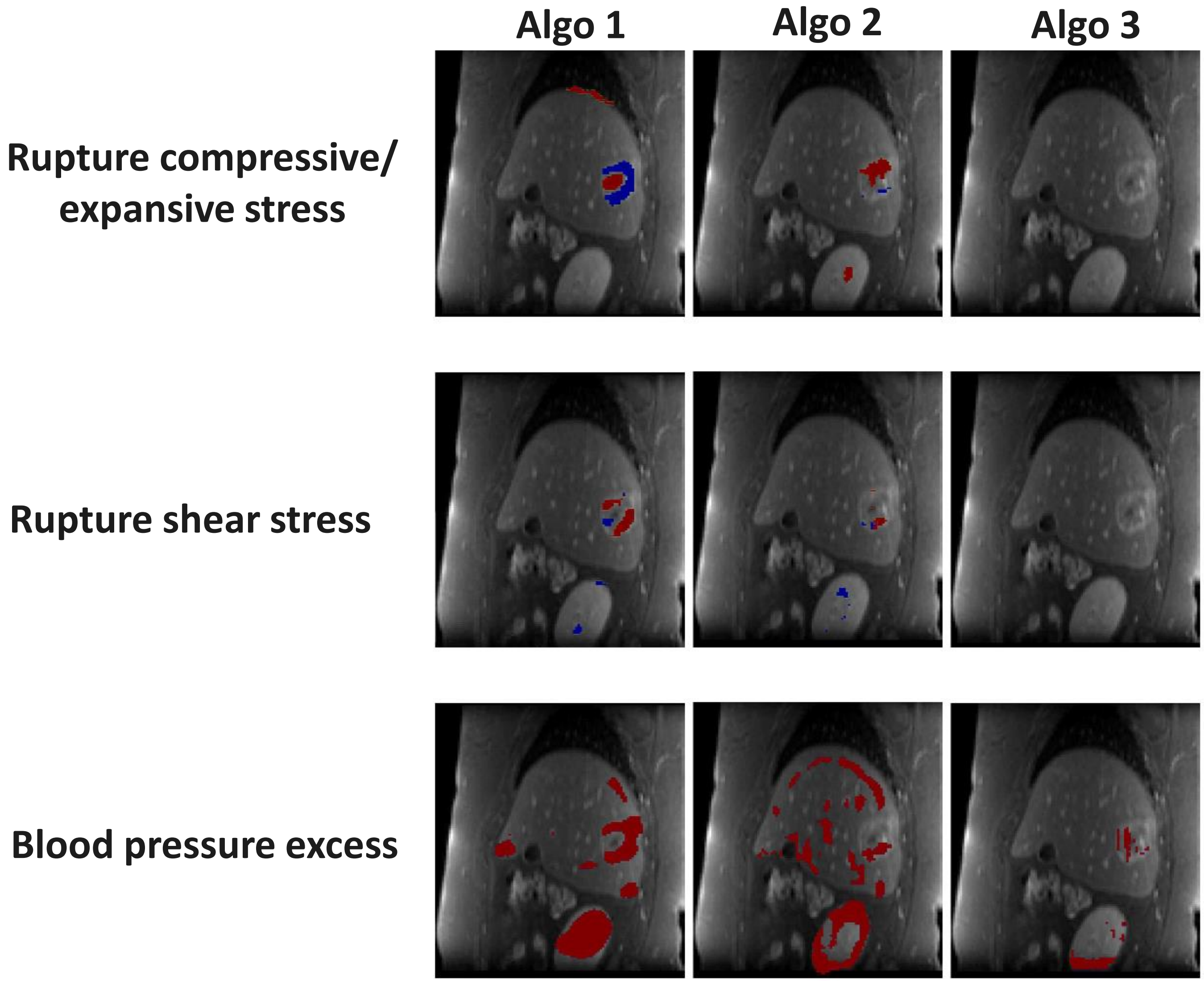

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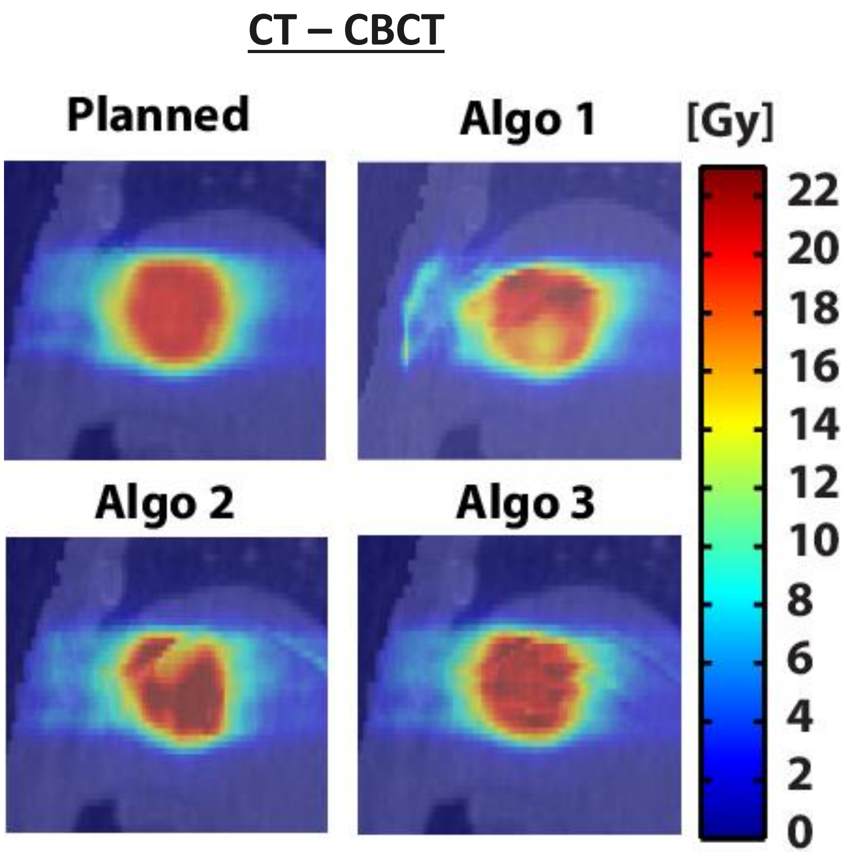

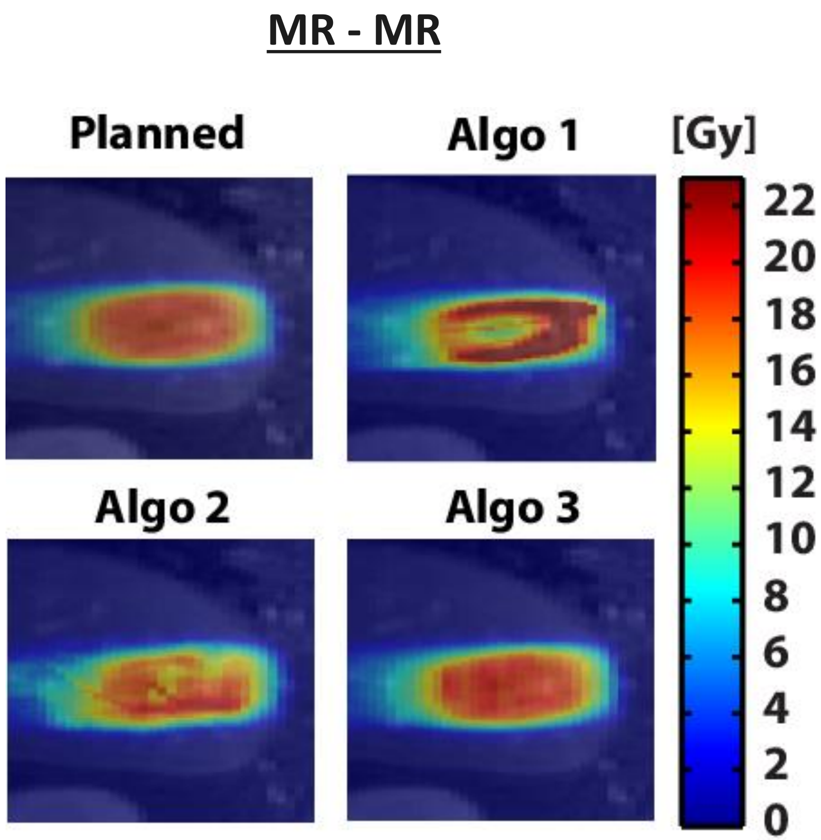

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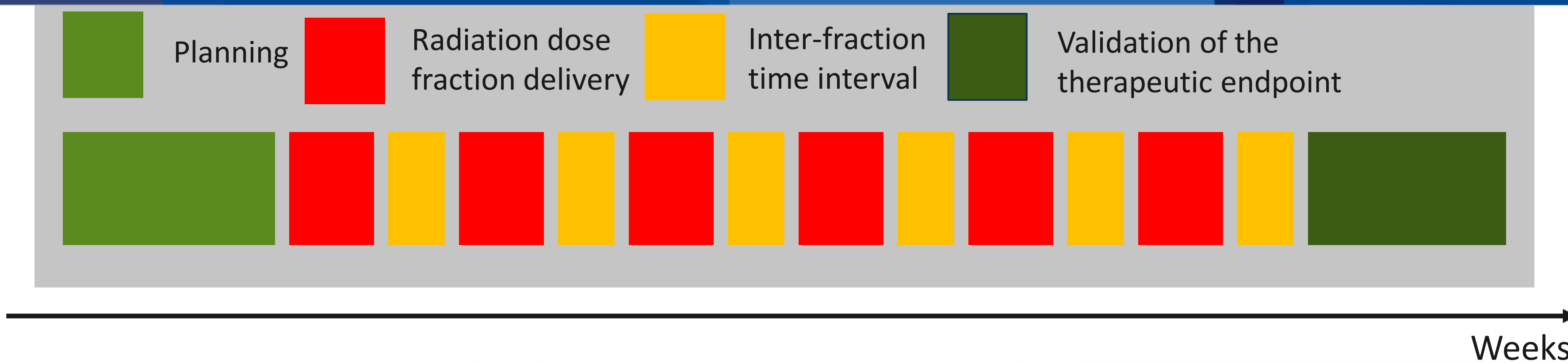
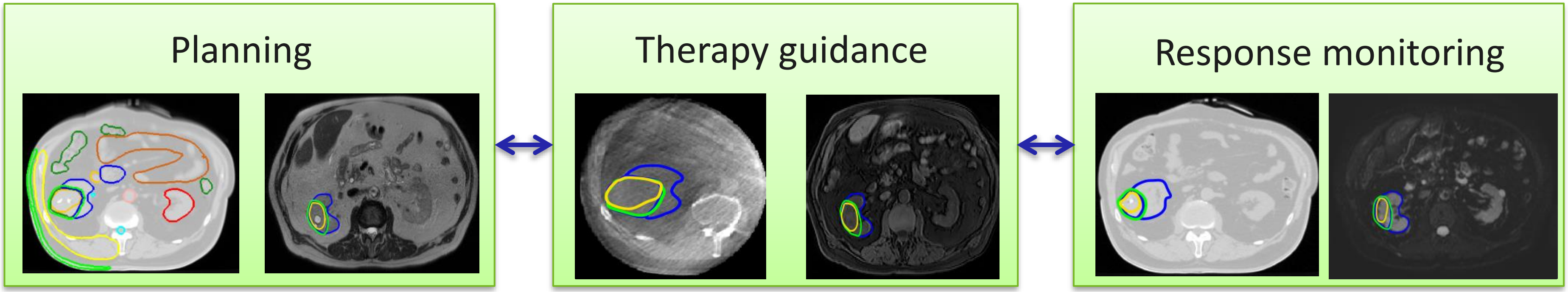
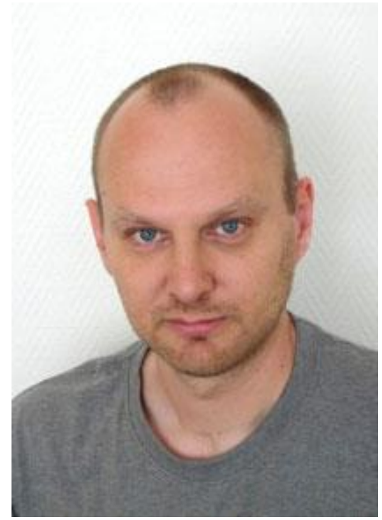




DIR in IGRT:

- *Automatic non-invasive estimation of displacement, deformation and shape of the pathology and organs-at-risk with respect to the planning image over images acquired using different modalities, MR-contrasts, acquisition schemes and upon which the pathologies may or may not be visible.*
- *Automatic monitoring of the delivered radiation dose in a spatially accurate and anatomically meaningful manner, giving way to potential treatment re-adjustment.*
- *Interpret changes in tumor size and morphology in relation to the accumulated dose for the purpose of automatic treatment response assessment.*

Who are we?



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  - ***Gijsbert Bol***
  - ***Charis Kontaxis***
  - ***Pim Borman***
  - ***Lando Bosma***

Further reading

Image-guided radiotherapy:

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Registration Tools for Image Guided External Beam Radiotherapy

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