Motion management and adaptive control for treating abdominal tumors

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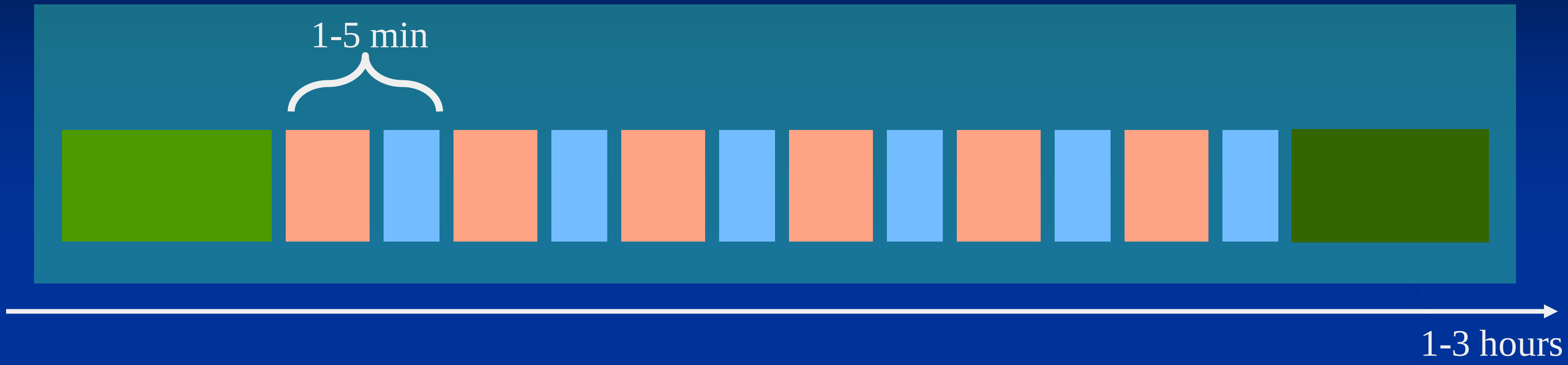
Workflow of a MR-HIFU intervention



- Positioning
- T_1/T_2-weighted planning images
- Tumor specific MRI (DWI, CE-T1w)

Preparation (anatomical imaging)

- Real-time motion compensation (gating or tracking)
- Real-time thermometry and thermal dose estimation

Therapy guidance during energy delivery

- Measurement of slow motion for dose realignment
- Observation of near field cool-down

Therapy guidance between energy delivery

- Perfusion imaging for NPV validation
- T_2-weighted imaging for edema detection

Validation of the therapeutic endpoint

MR-guided HIFU in abdominal organs

Overview of physiological motions

Challenges for efficient energy delivery

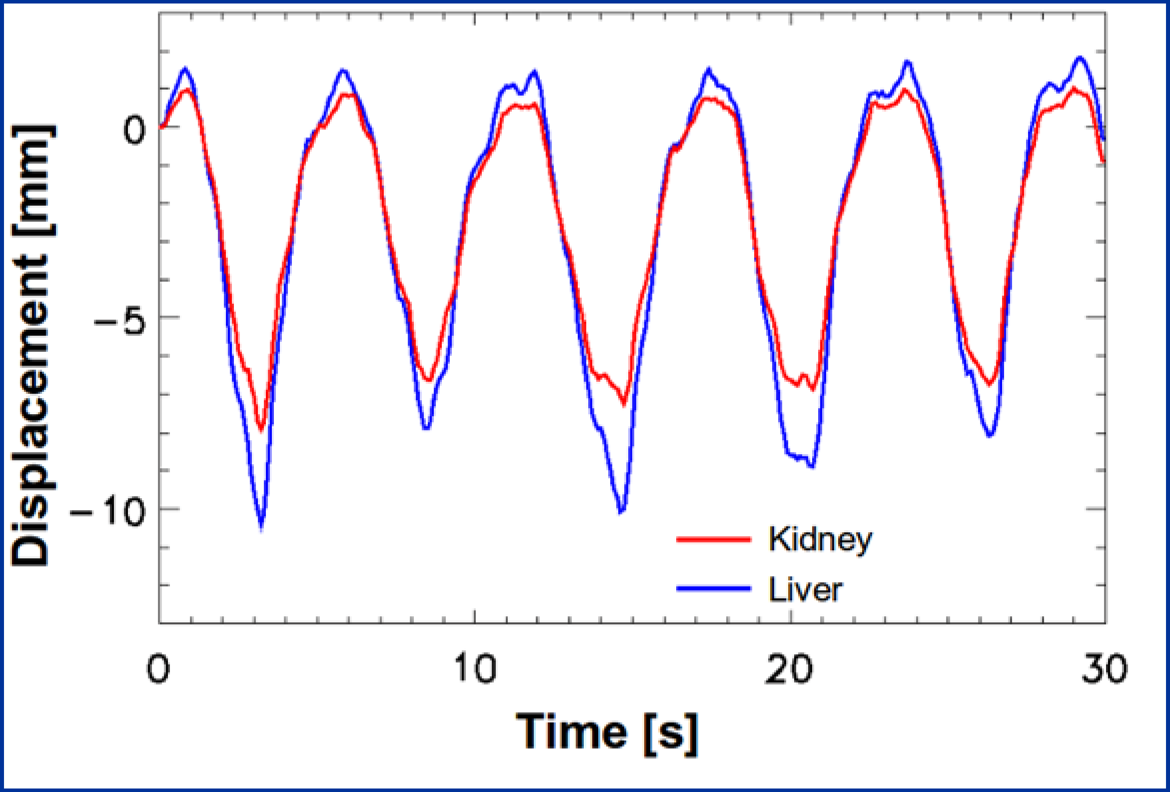
Image-based motion estimation

Control for intra-fraction

Control for inter-fraction

Physiological motion

Respiratory motion



MR-guided HIFU in abdominal organs

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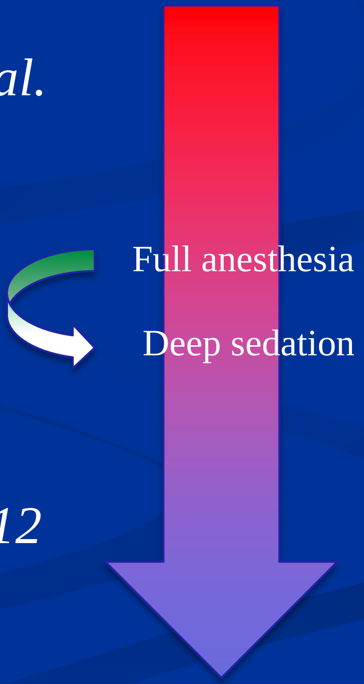
Control for inter-fraction

Challenges for efficient energy delivery in the liver

Technical solutions

Complete Respiratory Depression



- Induced apneas *[Gedroyc et al. 2006, Kopelman et al. 2006, […]]*
- Gating strategies *[Vigen 2003, Wu et al. 2005, Cornelis et al. 2011, […]]*
- Real-time beam steering strategies *[de Zwart et al. 2001, de Senneville et al. 2007, Auboiroux et al. 2012 […]]*

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Image-based motion estimation

- **General** formulation

Optimisation *Transformation*

$$\hat{T} = \underset{T}{\operatorname{argmin}}\, S\left(I_{ref}, T(I_{cur})\right)$$

Metric

> - **Elastic** organ deformation (voxelwise estimation)
> - Low **computation time**
> - Low number of **control parameters**

- **Inverse problem** solved throw a **variational** approach

Data fidelity *Regularization*

$$E(\vec{V}) = \int_{\Omega} D(\vec{V}) + \alpha R(\vec{V}) \mathrm{d}\vec{r}$$

weigth

- *Optical Flow algorithms*
- *[Horn&Schunck, 1981]*

Image-based motion estimation

Optical flow algorithm

$$E(\vec{V}) = \int_{\Omega} \left| \vec{\nabla} I \cdot \vec{V} + I_t I \right| + \alpha \left\| J(\vec{V}) - 1 \right\|_2^2 \mathrm{d}\vec{r}$$

- **Data fidelity term :**

$$I_t + \vec{V} \cdot \vec{\nabla} I = 0$$

$$D(\vec{V}) = \left| I_t + \vec{V} \cdot \vec{\nabla} I \right|$$

- *Transport equation*
- *[Horn&Schunck, 1981]*
- *[Zachiu et al. PMB 2016]*

- **Regularization term :**

$$\vec{\nabla} \cdot \vec{V} = 0$$

$$R(\vec{V}) = \left\| J(\vec{V}) - 1 \right\|_2^2$$

- *Incompressibility of the tissue*
- *Continuum mechanics :*
  Incompressible material subjected to an external force
- *[Zachiu et al. PMB 2018]*

Image-based motion estimation

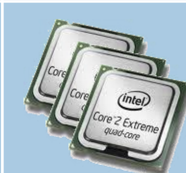
Variational approaches

Data fidelity *Regularization*

$$E(\vec{V}) = \int_{\Omega} D(\vec{V}) + \alpha R(\vec{V}) \mathrm{d}\vec{r}$$

weigth

- ***Multi-resolution*** approach
- ***Iterative refinement*** approach
- ***Deep-learning*** approach
- ***Mono-/Multi- modal*** registrations

	 **Matlab CPU**	 **C++ CPU**	 **C++ 8 CPUs**	 **CUDA GPU**
Mono-modal 128×84	**> 10 s**	**300 ms**	**50 ms**	**< 10 ms**
Multi-modal 256×256×64	**> 1h**	**600 s**	**100 s**	**~ 20 s**

MR-guided HIFU in abdominal organs

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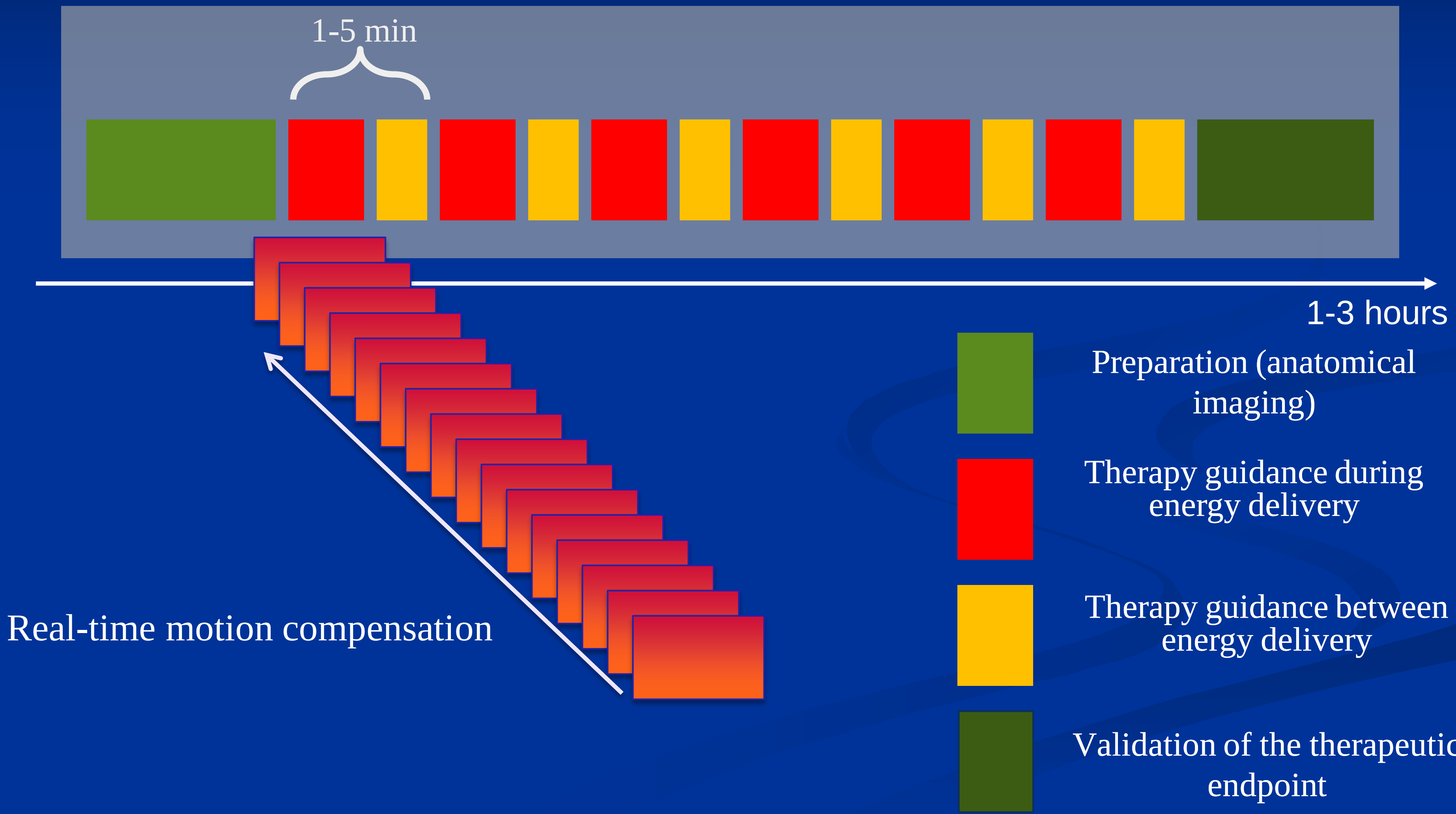
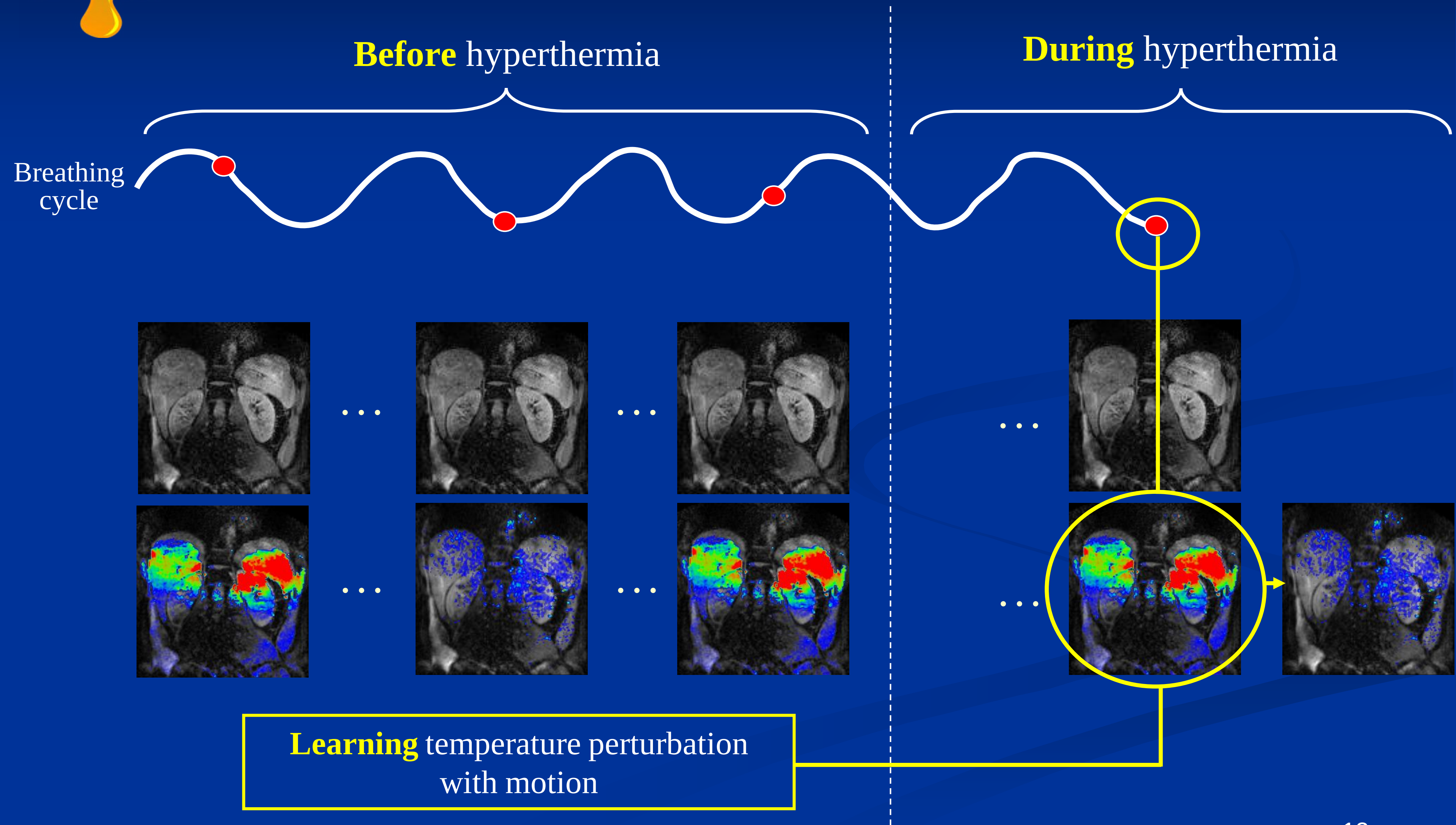
Control for inter-fraction

Fast 2D motion correction



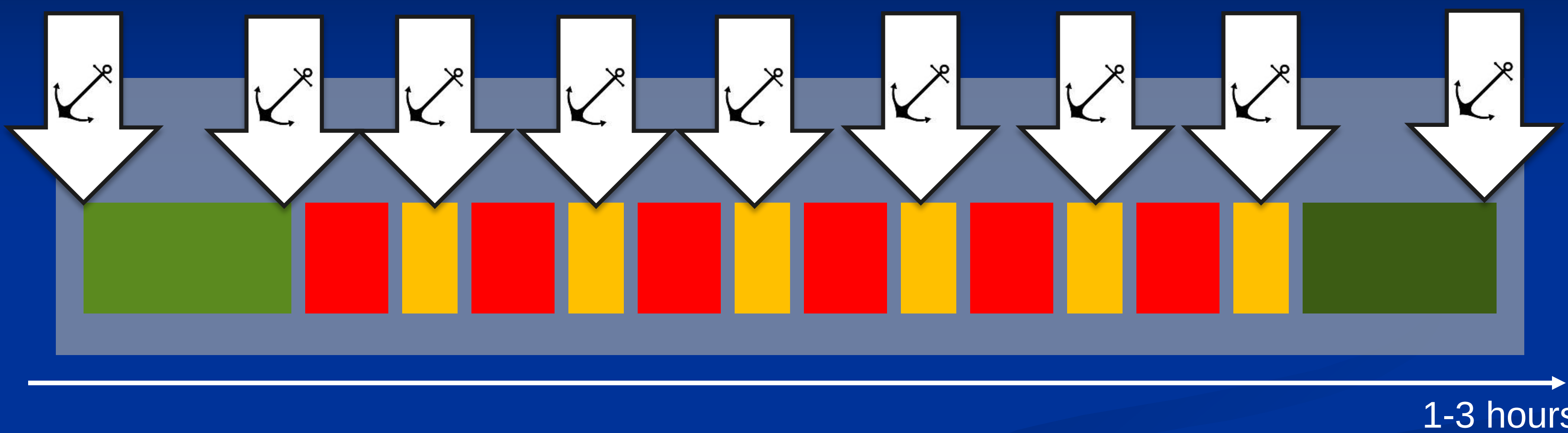
Thermometry in the presence of physiological motion



MR-guided HIFU in abdominal organs

- Overview of physiological motions
- Challenges for efficient energy delivery
- Image-based motion estimation
- Control for intra-fraction
- **Control for inter-fraction**

« Slow » 3D Motion correction for abdominal HIFU



3D anchor images are periodically obtained and compared to a reference.

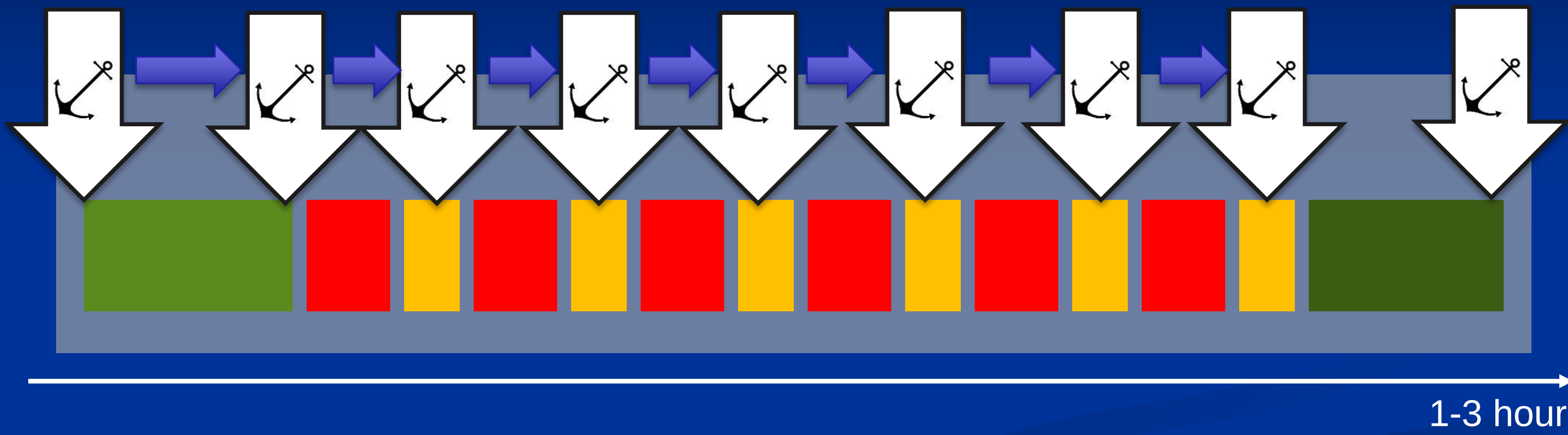
Preparation (anatomical imaging)

Therapy guidance during energy delivery

Therapy guidance between energy delivery

Validation of the therapeutic endpoint

« Slow » 3D Motion correction for abdominal HIFU



Propagate the initial treatment plan down the flow of the motion
(for the RT-community: "virtual couch shift")

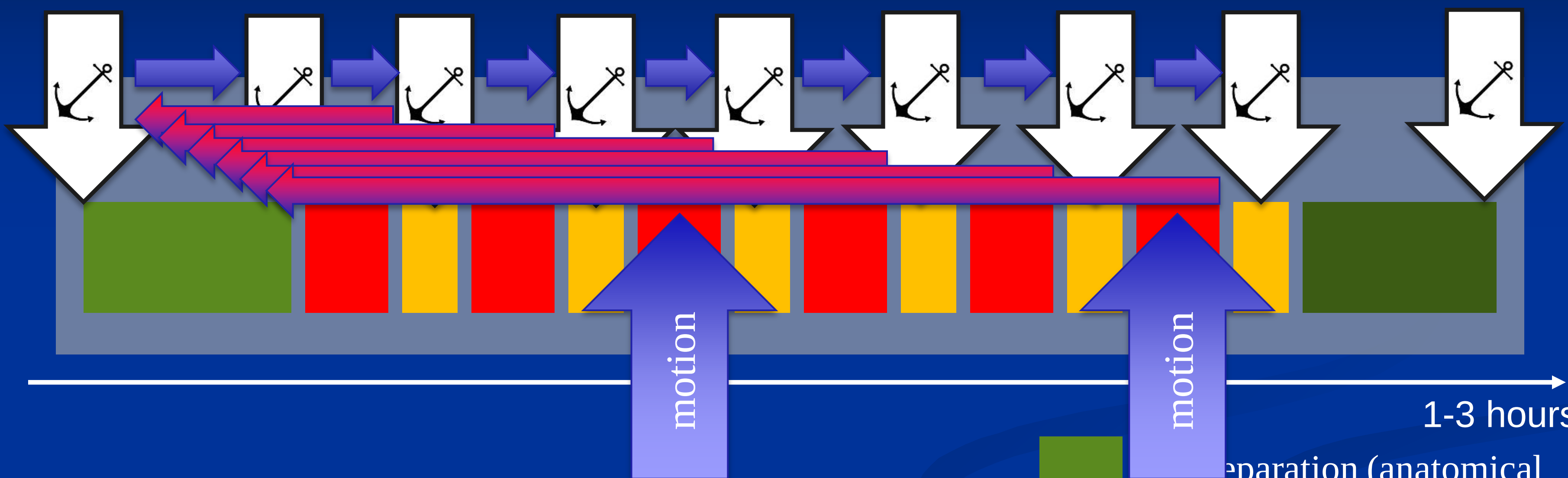
Preparation (anatomical imaging)

Therapy guidance during energy delivery

Therapy guidance between energy delivery

Validation of the therapeutic endpoint

Experimental validation: In-Vivo Ablation of a Porcine Liver



Propagate the initial treatment plan down the flow of the motion
(for the RT-community: “virtual couch shift”)

Project and accumulate the currently delivered thermal dose on the initial treatment plan “upstream” the flow of the motion
(for the RT-community: “Continuous dose accumulation”)

- Preparation (anatomical imaging)
- Therapy guidance during energy delivery
- Therapy guidance between energy delivery
- Validation of the therapeutic endpoint

Concluding remarks

- **Gating** strategies can be easily implemented in MR-guided HIFU
- MRI allows detailed intra- and inter- procedure **motion tracking** of the order of 1 mm
- A framework has been developed for **3D** correction of (slow) **peristaltic** motion and **2D** correction for **respiratory** motion
- MR motion tracking can be combined with **MR thermometry**
- MR **PRFS thermometry** can be adapted for moving organs
- Further technical progress is needed to reach ablation rates that allow **widespread clinical applications**