Ultra High-Field MRI as a Therapeutic Modality for the Treatment of Brain Metastases with Comparison to MR Guided Focused Ultrasound

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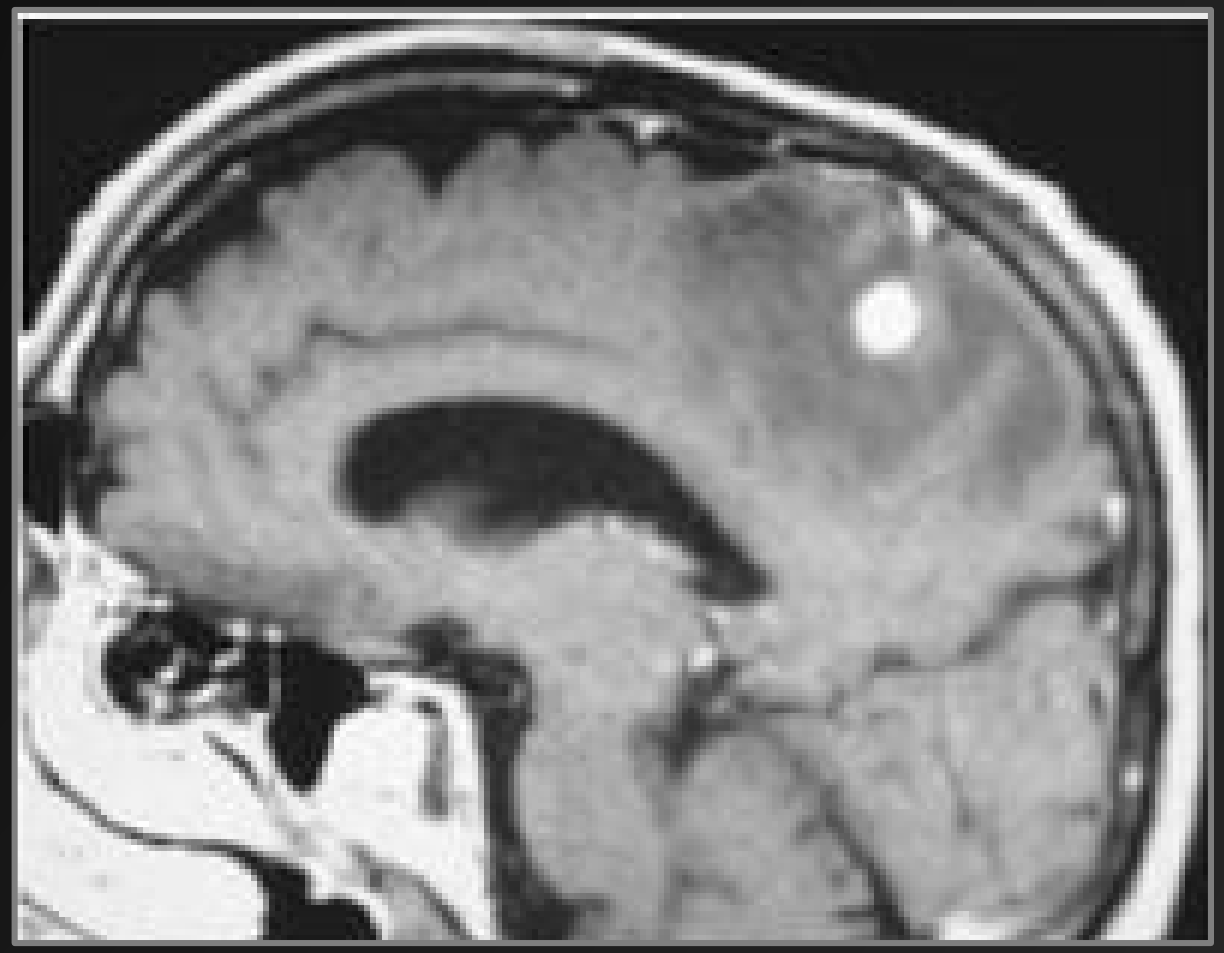
SCIT STANFORD CANCER IMAGING TRAINEESHIP

Overview

- Brain Mets: Motivation and Challenges
- MR guided Focused Ultrasound (MRgFUS)
- Ultra High-Field (UHF) MR Hyperthermia
  - “Focused RF”

Brain Mets: Motivation and Challenges

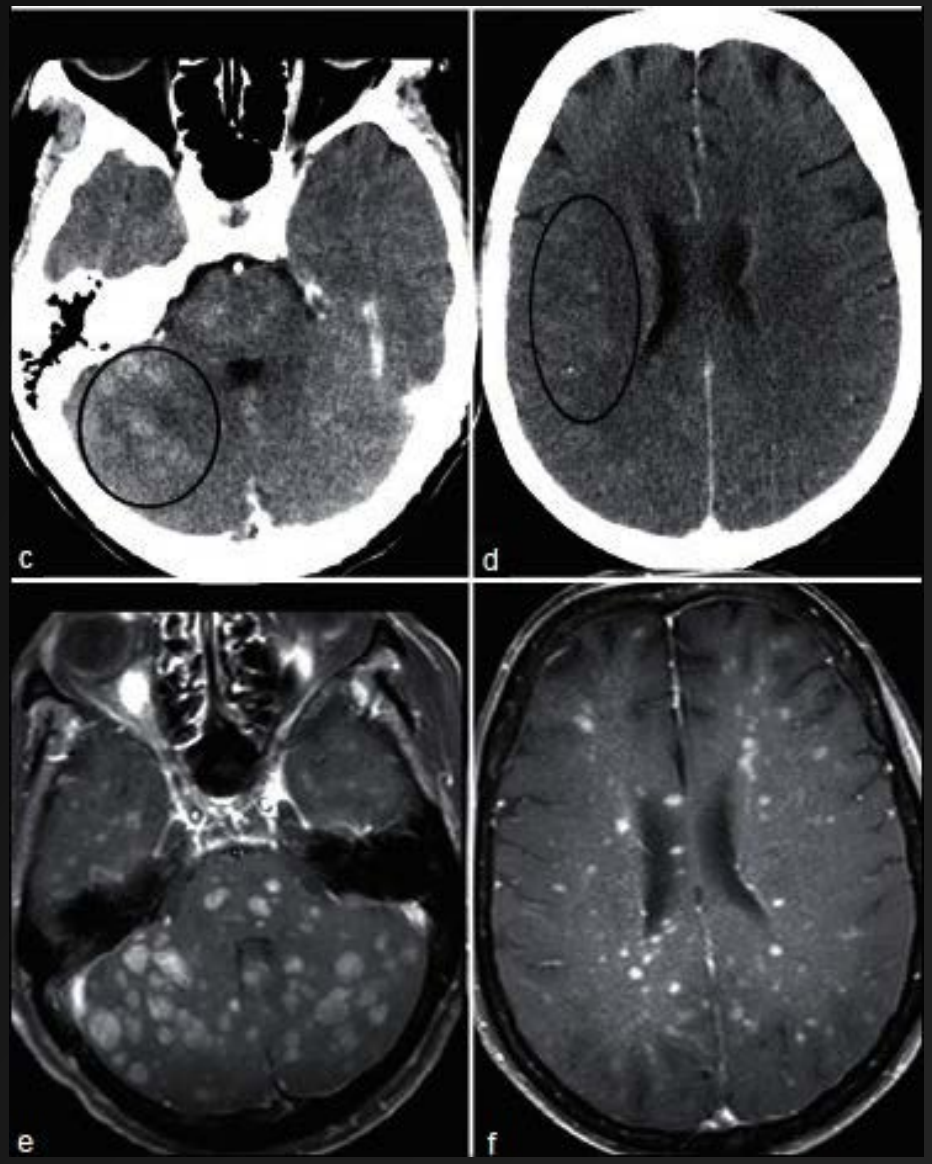
- Most common type of brain tumors
  - ~200,000 cases per year (USA)
  - > all intracranial tumors
- Treatment options
  - Surgical resection
  - Whole-brain radiation therapy (WBRT)
  - Corticosteroids
  - Stereotactic Radiosurgery (SRS)
- Median overall survival:
  - Untreated: 1 month
  - With treatment: 3-11 months



T1w - Gd

Ultra High-Field MRI

- MRI w Gd leads in BM detection
- 66-75% of patients who present with a single lesion on CT actually have multiple lesions
- Higher Field = More Signal
- Increase: Resolution, speed, etc



CECT

MRI w Gd

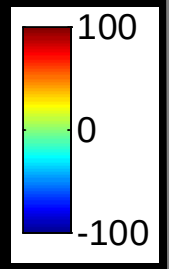
Fink *et al*, *SNI*, 2013

Ultra High-Field MRI: Challenges

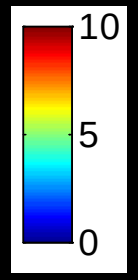
BIRDCAGE MODE

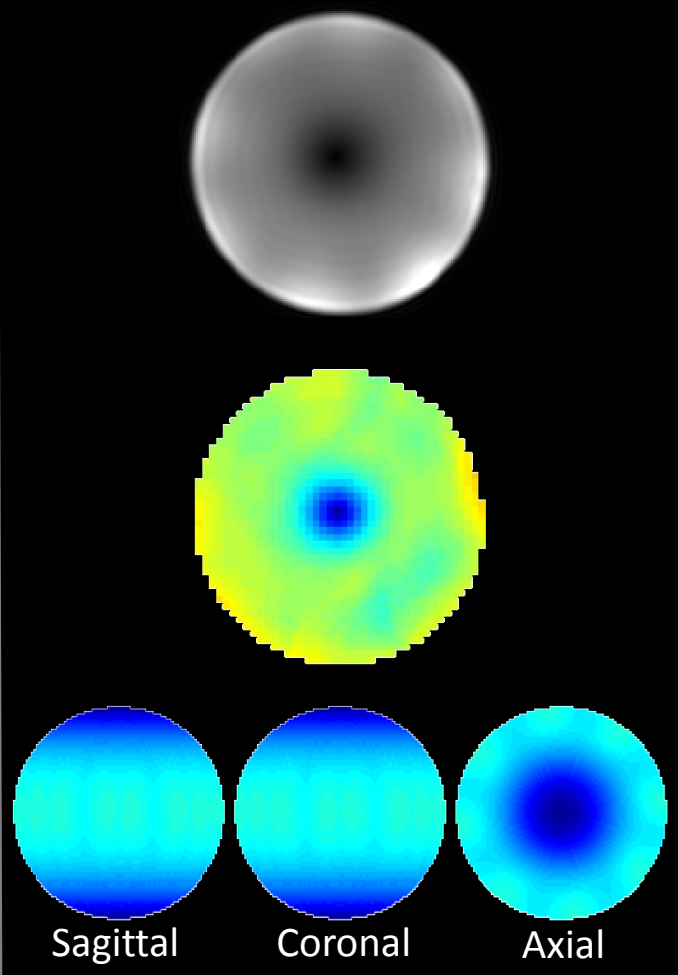
SPGR
TR=4000ms
FA = 30°

FA error (%)



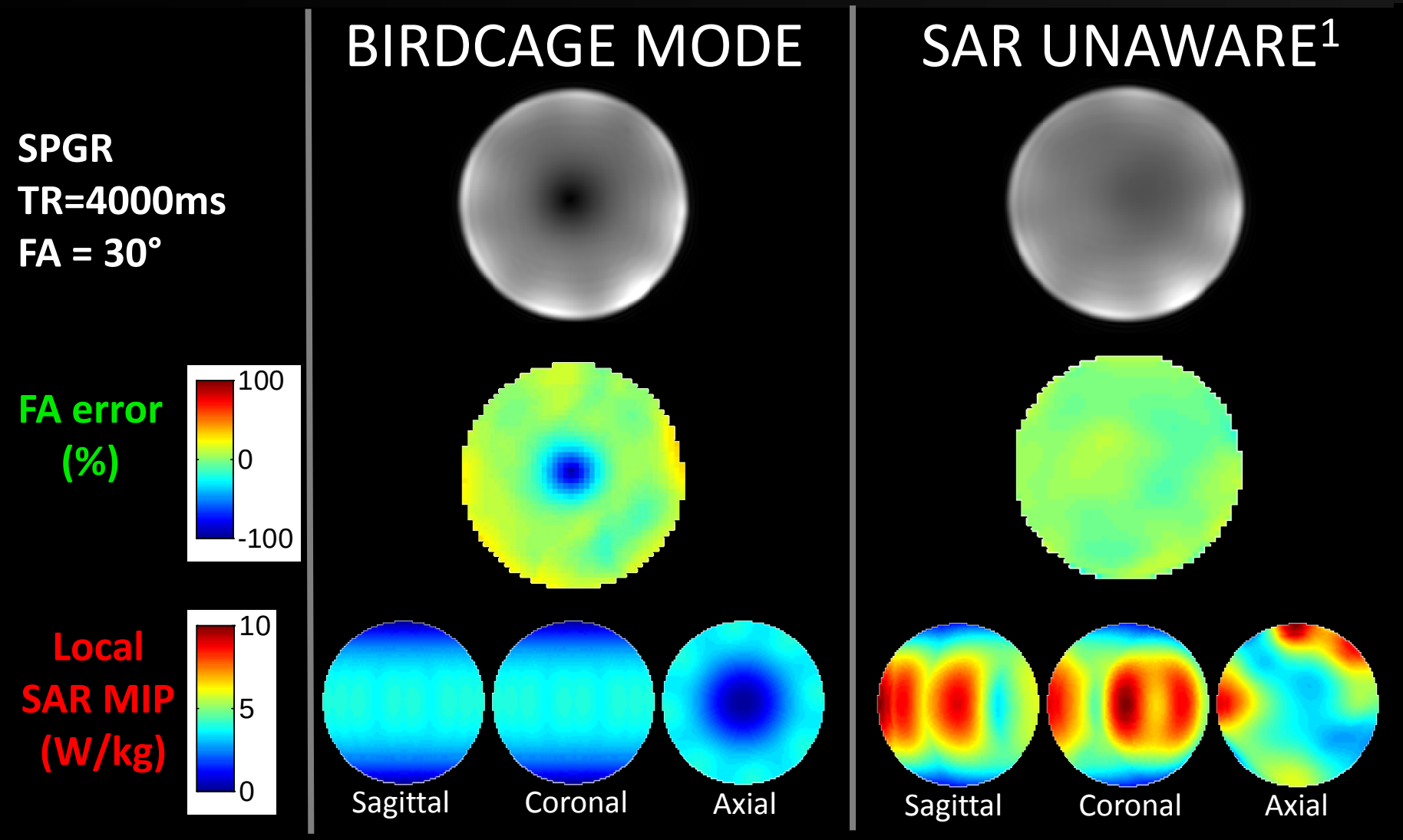
Local SAR MIP (W/kg)





Courtesy of: Mehir Pendse, ISMRM 2015 #573

Ultra High-Field MRI: Challenges



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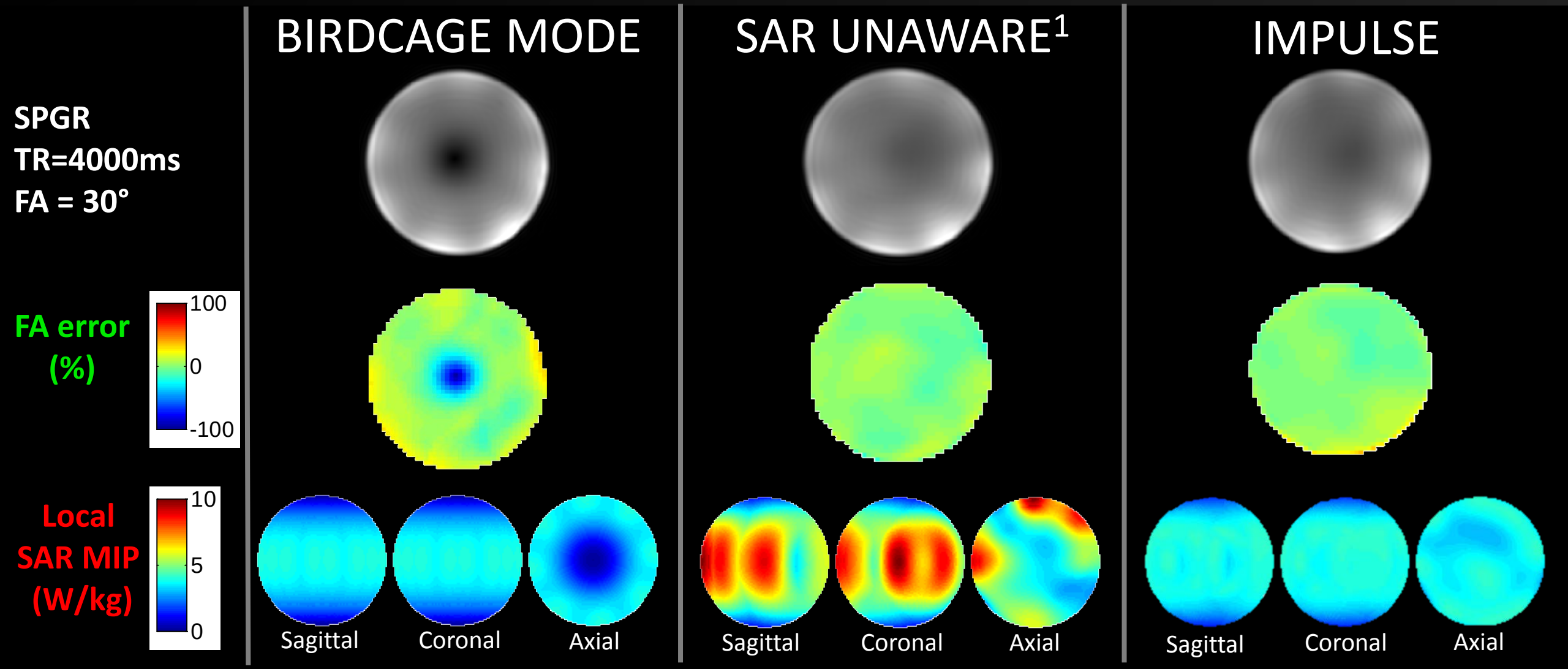
[1]Grissom, MRM 2012;68:1553–1562

Ultra High-Field MRI: Challenges



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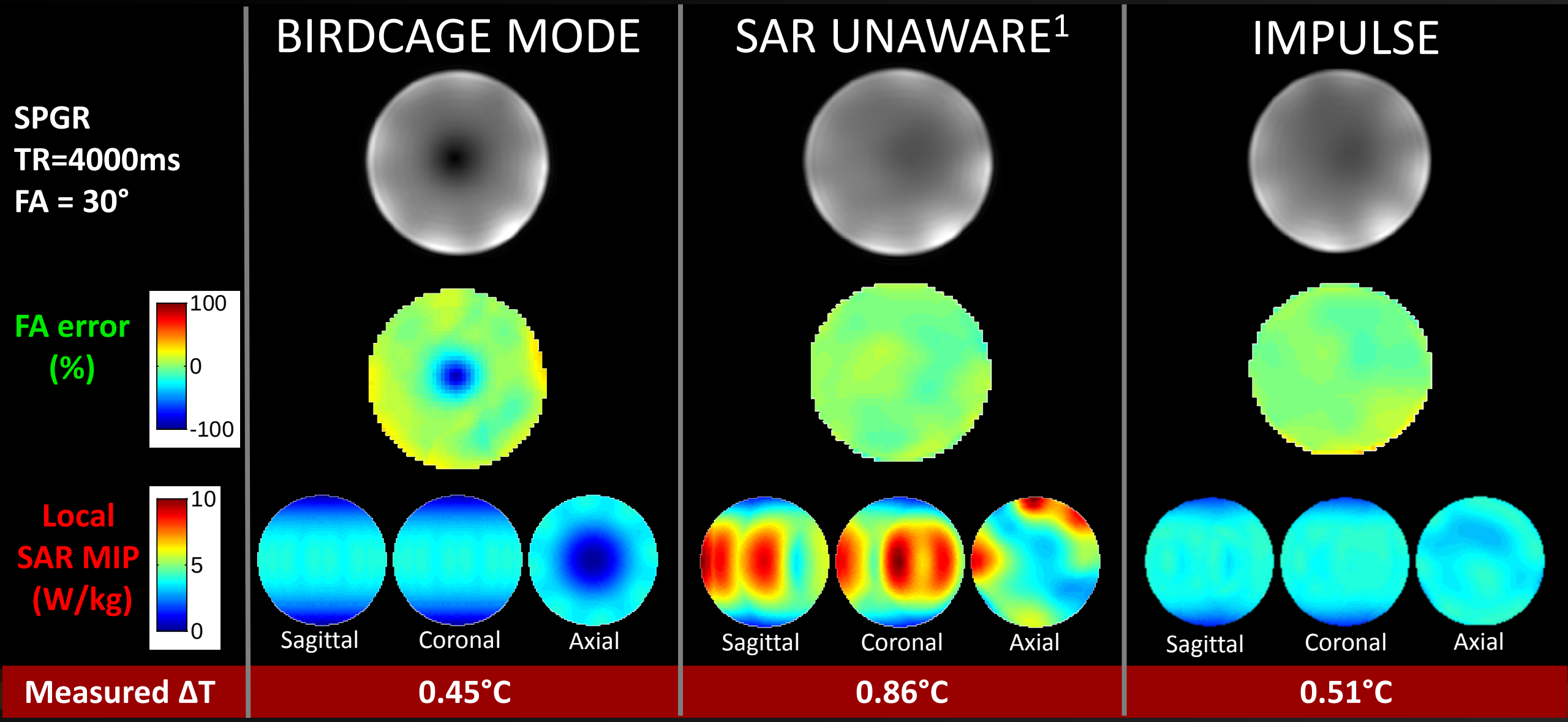
Ultra High-Field MRI: Challenges



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[1]Grissom, MRM 2012;68:1553–1562

Q: Can this undesired heating been turned into something positive?

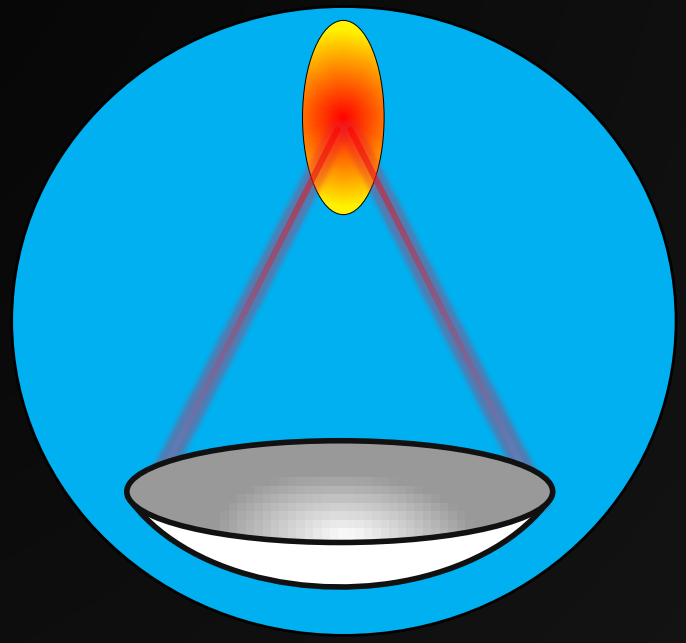
Overview

- Brain Mets: Motivation and Challenges
- **MR guided Focused Ultrasound (MRgFUS)**
- Ultra High-Field (UHF) MR Hyperthermia
  - “Focused RF”

- PhD – Robotics
  - NSF IGERT Award

- Dennis Parker
- Robert Roemer
- Doug Christensen
- John Hollerbach

MR Guided Focused Ultrasound



+

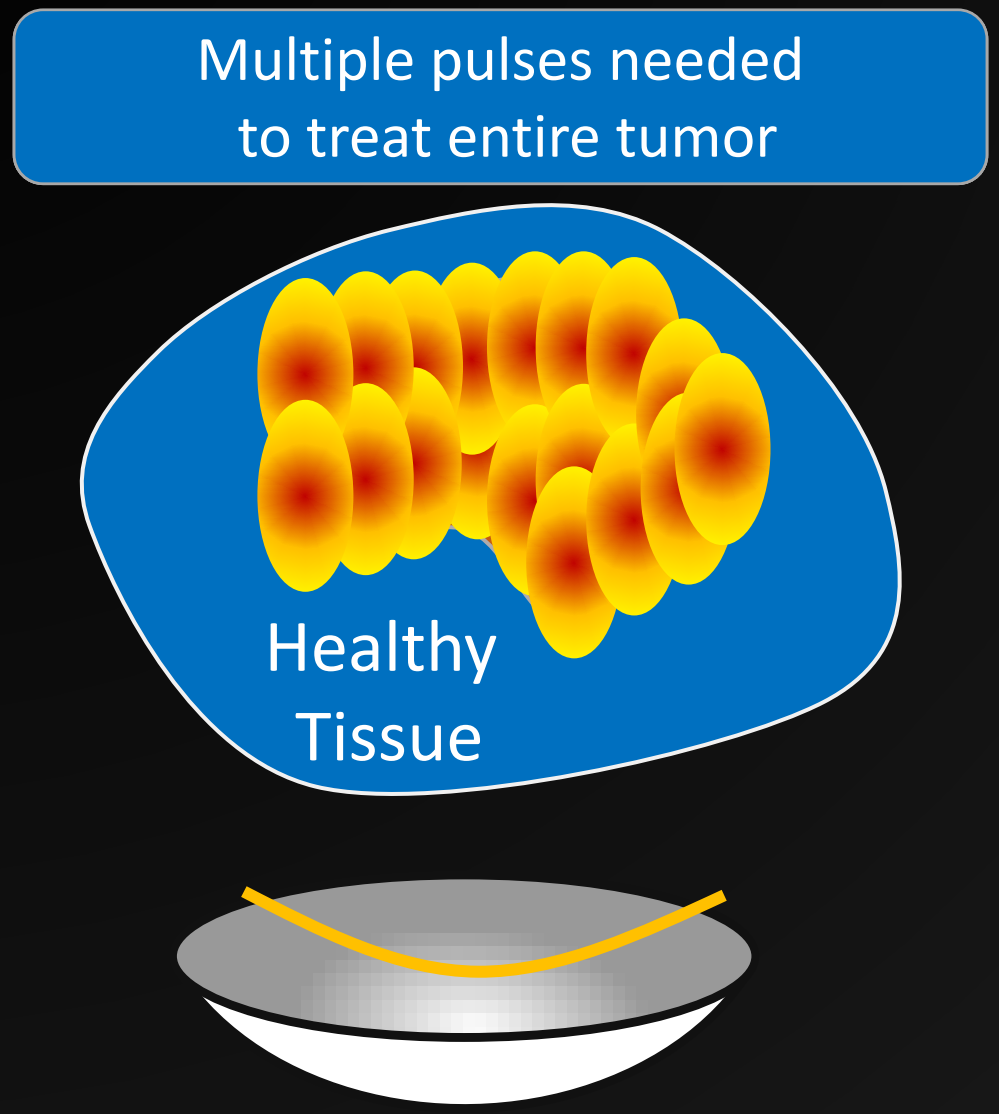
FUS creates *localized* intense heating

MRI provides anatomical imaging and monitoring

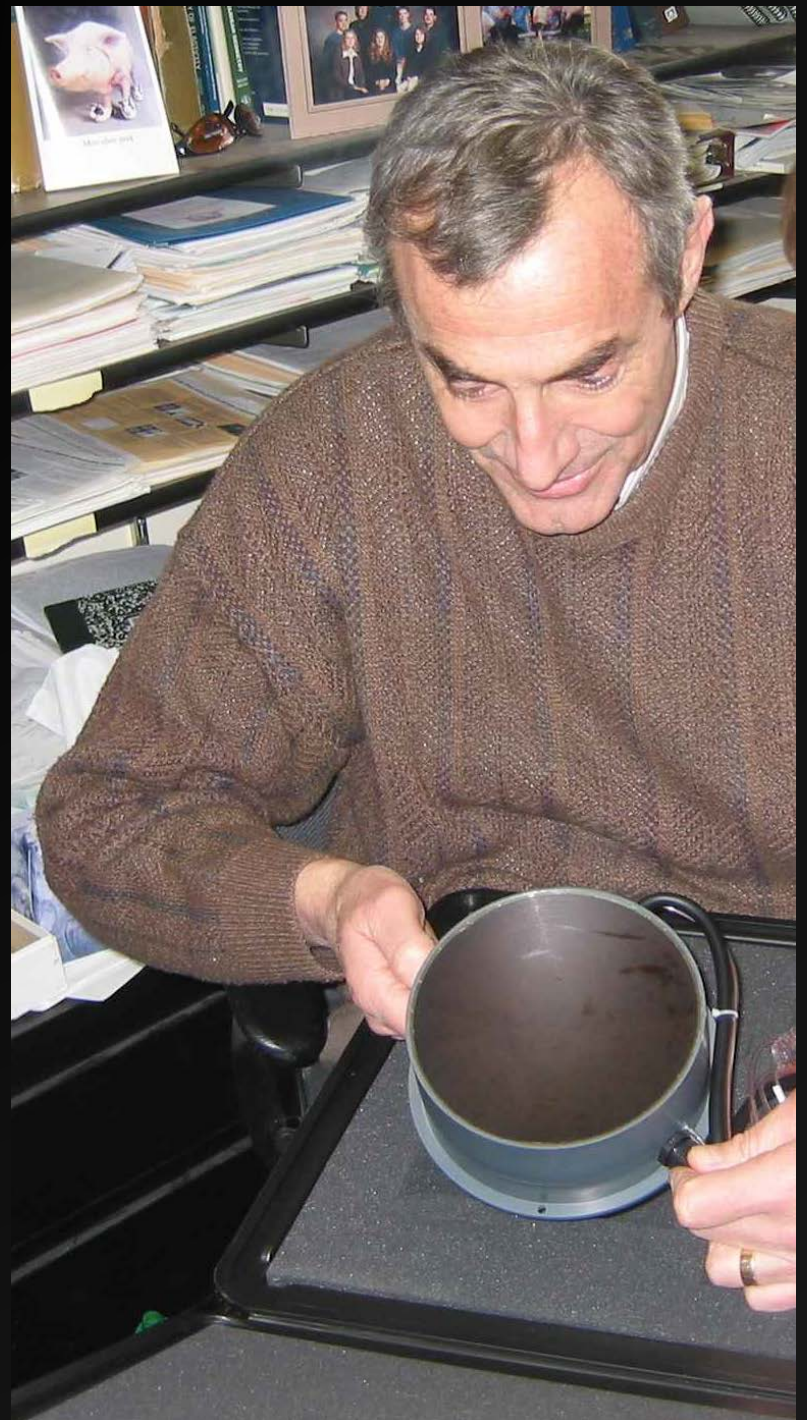
Cancer Therapy Wish List: MRgFUS

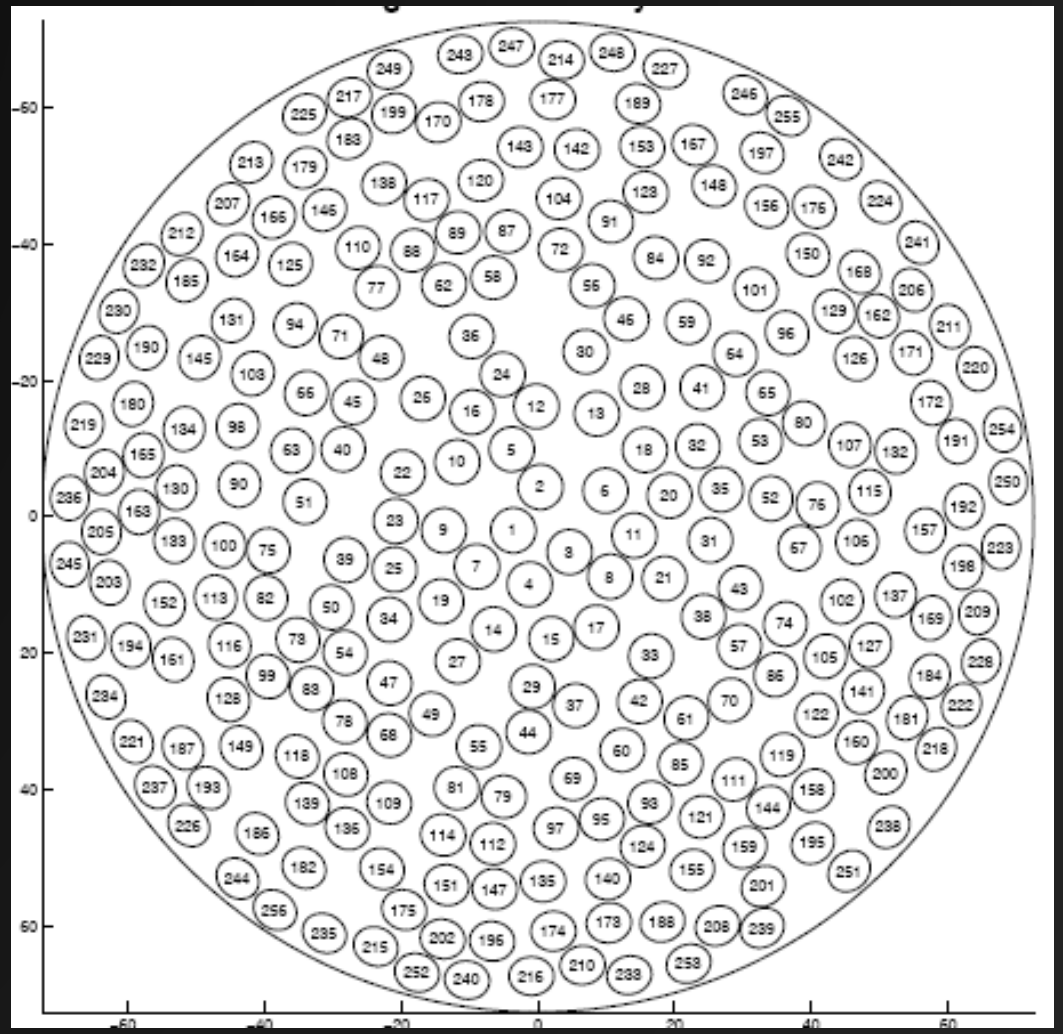
- ✓ Non-Invasive
- ✓ Free of Ionizing Radiation
- ✓ Free of Toxic Chemicals
- ✓ Monitoring: MR thermometry

MRgFUS Cancer Therapy



- Treatment goals:
  - Kill all cancerous tissue
  - Protect healthy tissue
  - Minimize treatment time




-60
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-40
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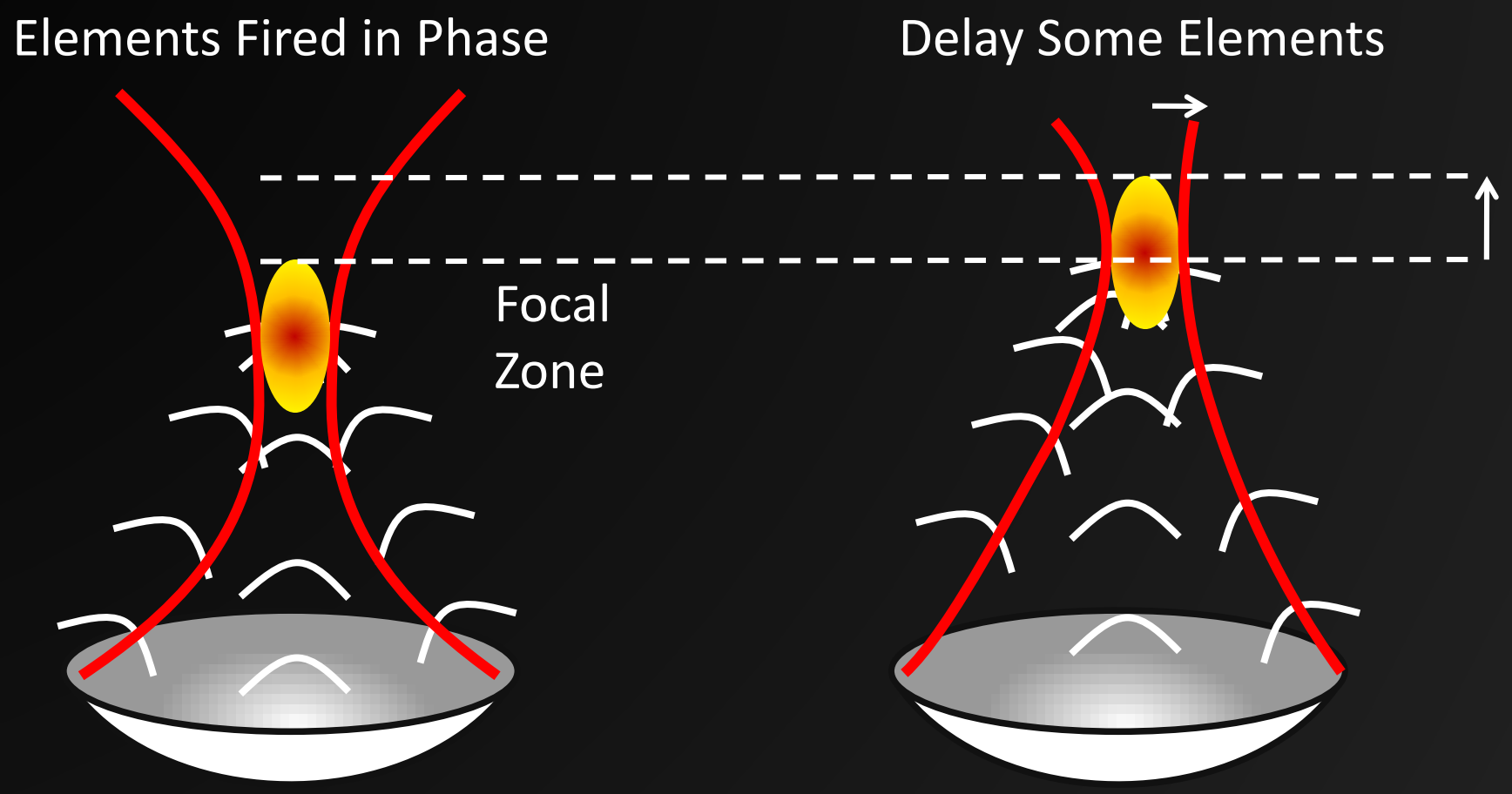
20
40
60

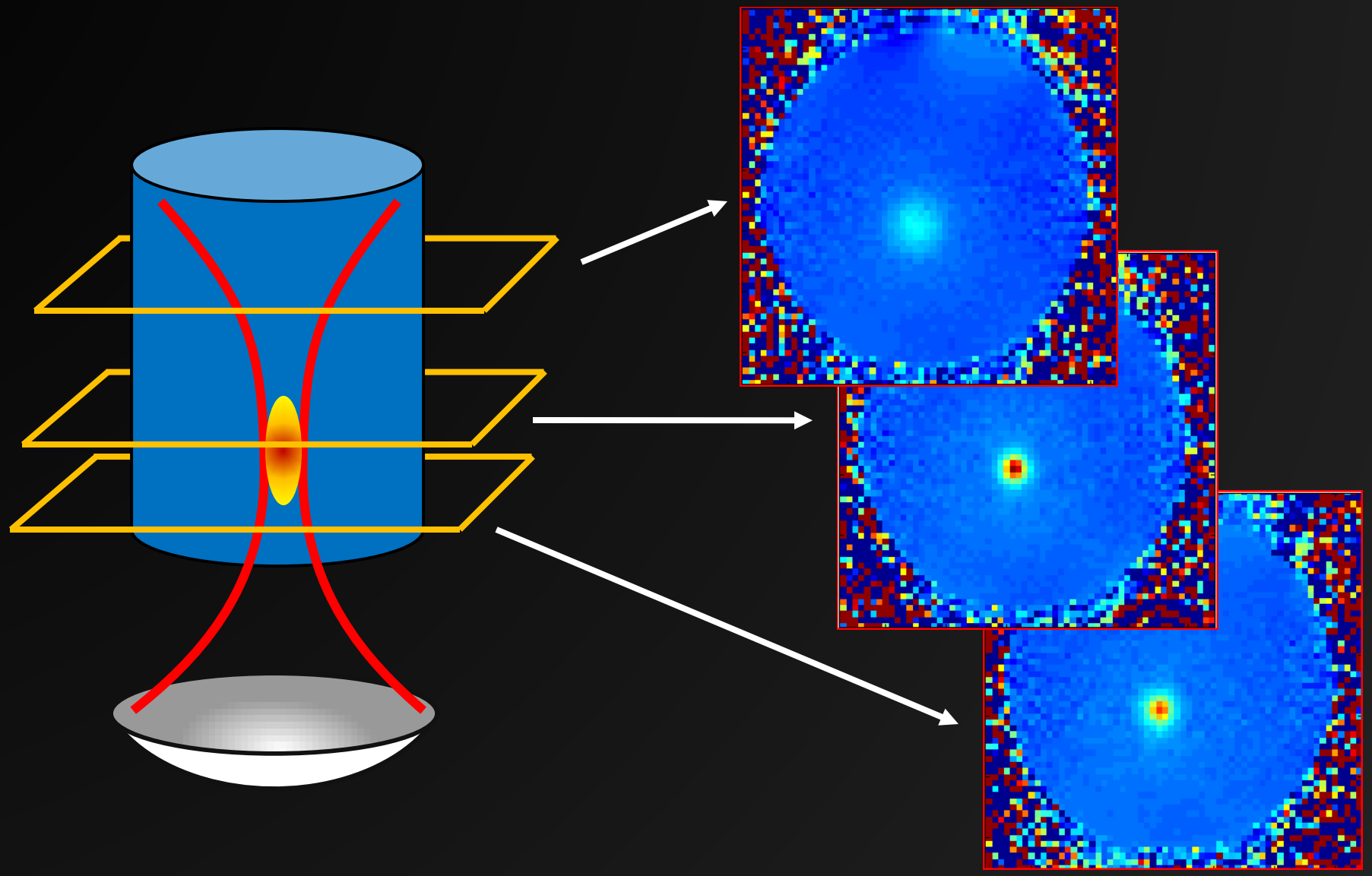
Beam Focusing & Steering



Phased-Array allows 3D focal spot steering
without physical movement of transducer


SIEMENS
University Health Care
MAGNETOM Trio
A Tim System

MR Thermometry



Robotics

Robotics

Cognition

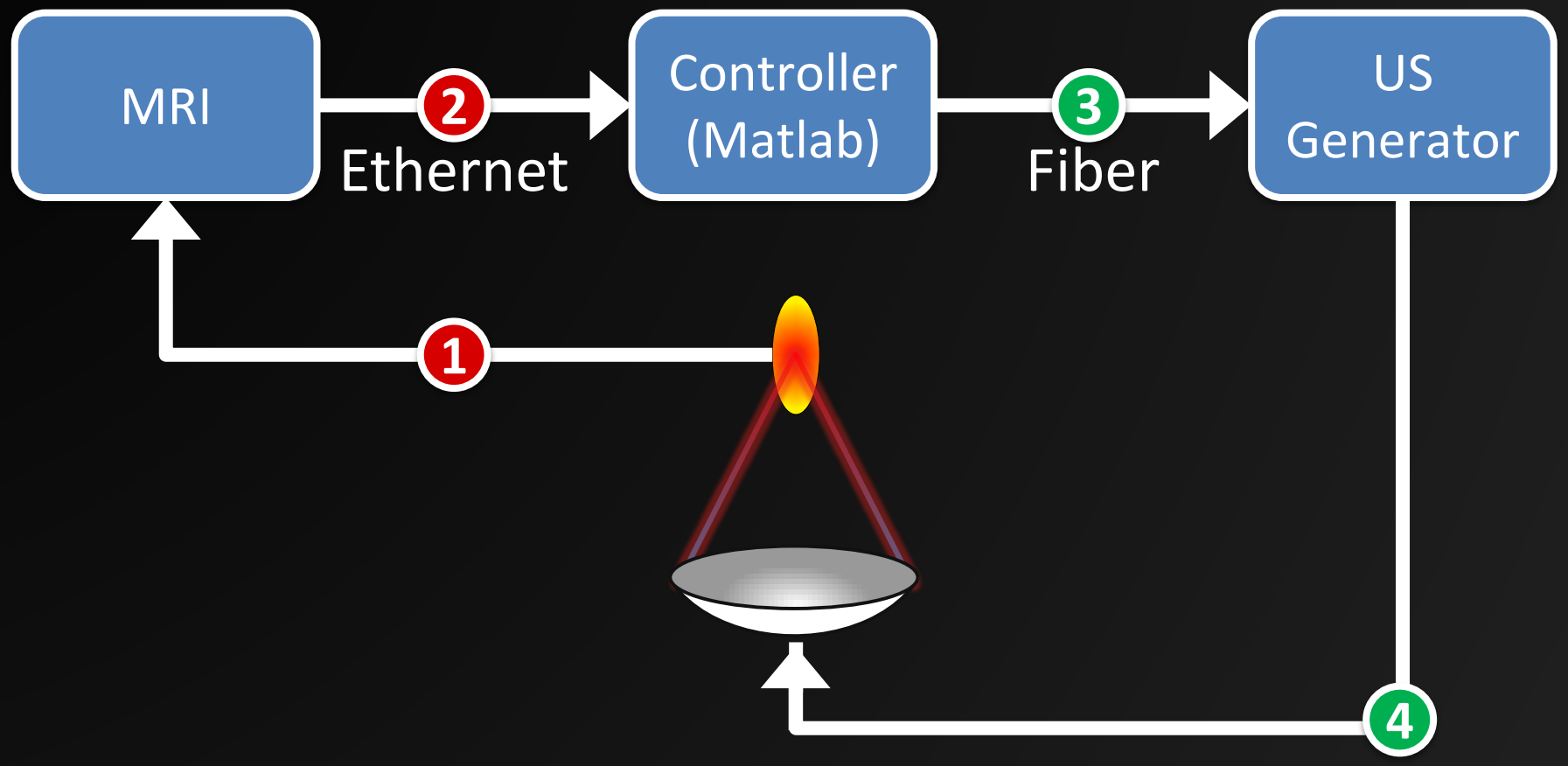
Action

Robotics

Robotics

Adaptive Model-Predictive Controller (AMPC)

Control Loop



Temperature Measurement

US command

Control Challenges

- Protect healthy tissue
- Conform treatment to tumor shape, may be surrounded by complex anatomy
- MRgFUS treatments take a long time
- Faster heating makes control more difficult

Thermal Dose and Tissue Damage

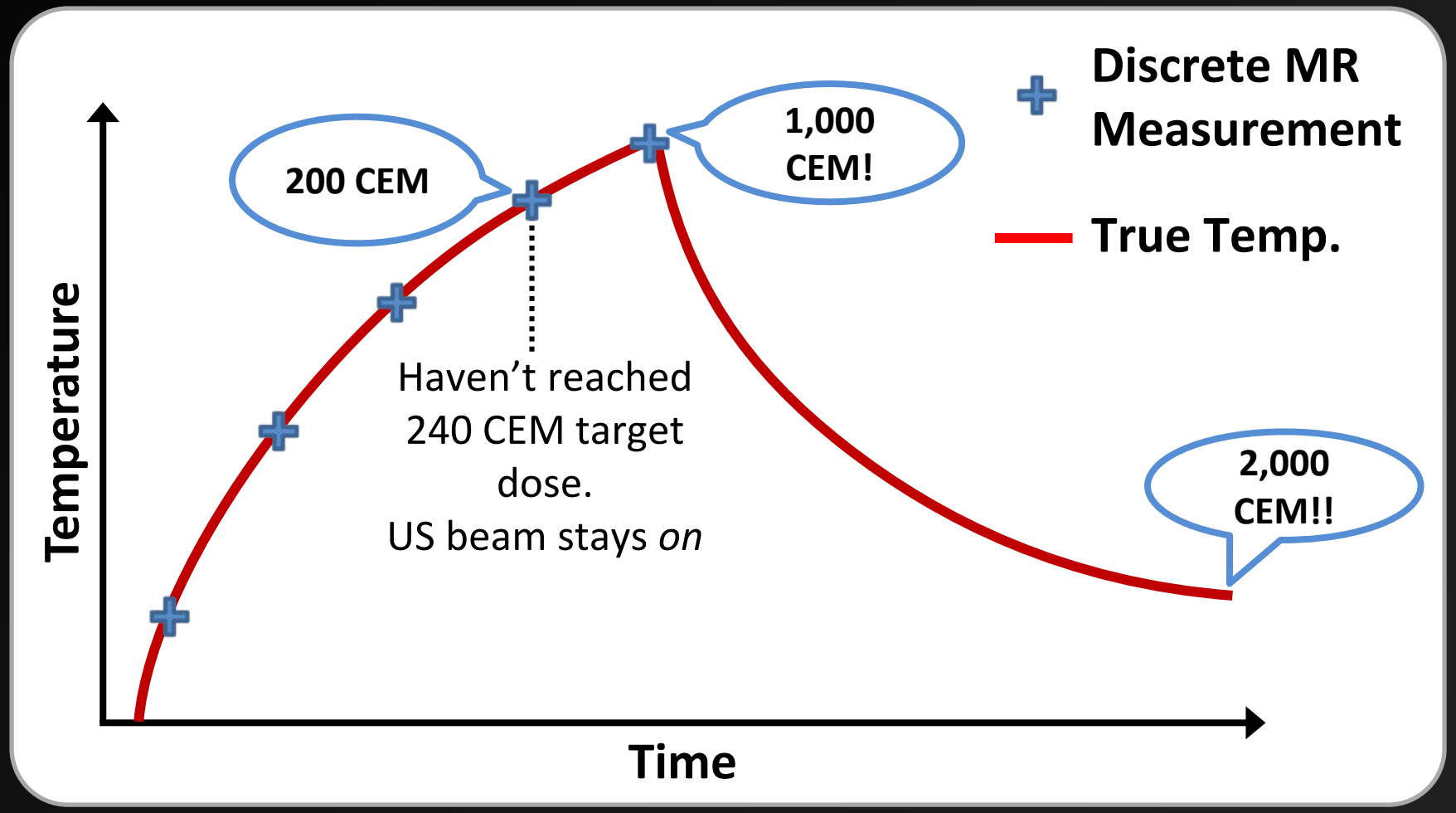
$$CEM_{43} = \int R^{(T(t)-43)} dt \quad \begin{cases} T \geq 43°C : R = 2 \\ T \leq 43°C : R = 4 \end{cases}$$

CEM: Cumulative Equivalent Minutes @ 43°C

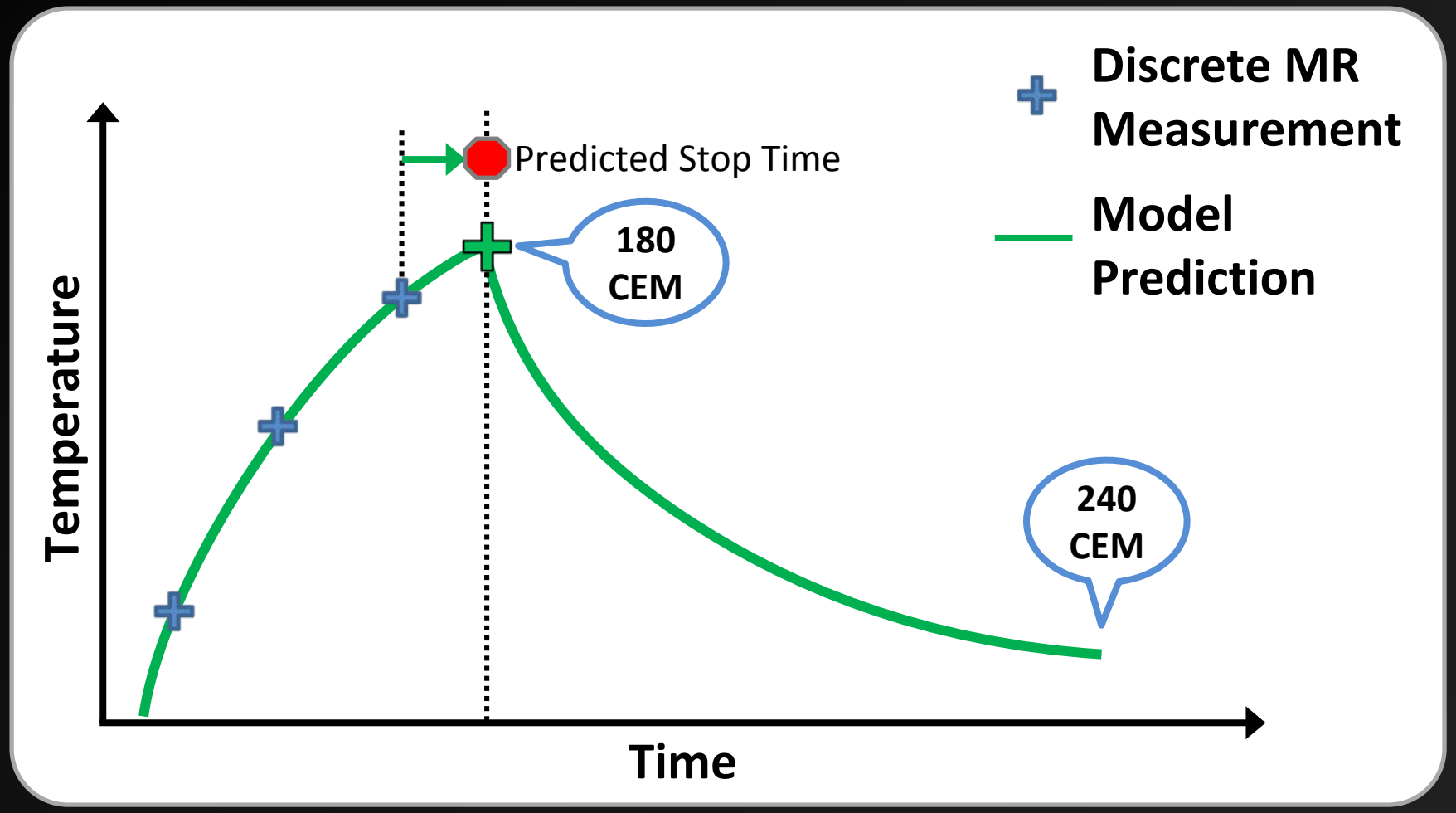
- 240 CEM = Tissue Necrosis
- Dose rate ***doubles*** every 1°C rise

Temperature	Time to Deliver 240 CEM
43 °C	240 min
44 °C	120 min
50 °C	~2 min
55 °C	~3.5 sec

Treatment Without Prediction



Adaptive Model-Predictive Control



Adaptive Model-Predictive Controller

- Patient specific model derived and adapted in real-time
  - Reduced setup time, adapts to changing tissue environment
- Protect normal tissue w. configurable temperature constraints
- Conform treatment using any path or treatment scheme

Prediction Model

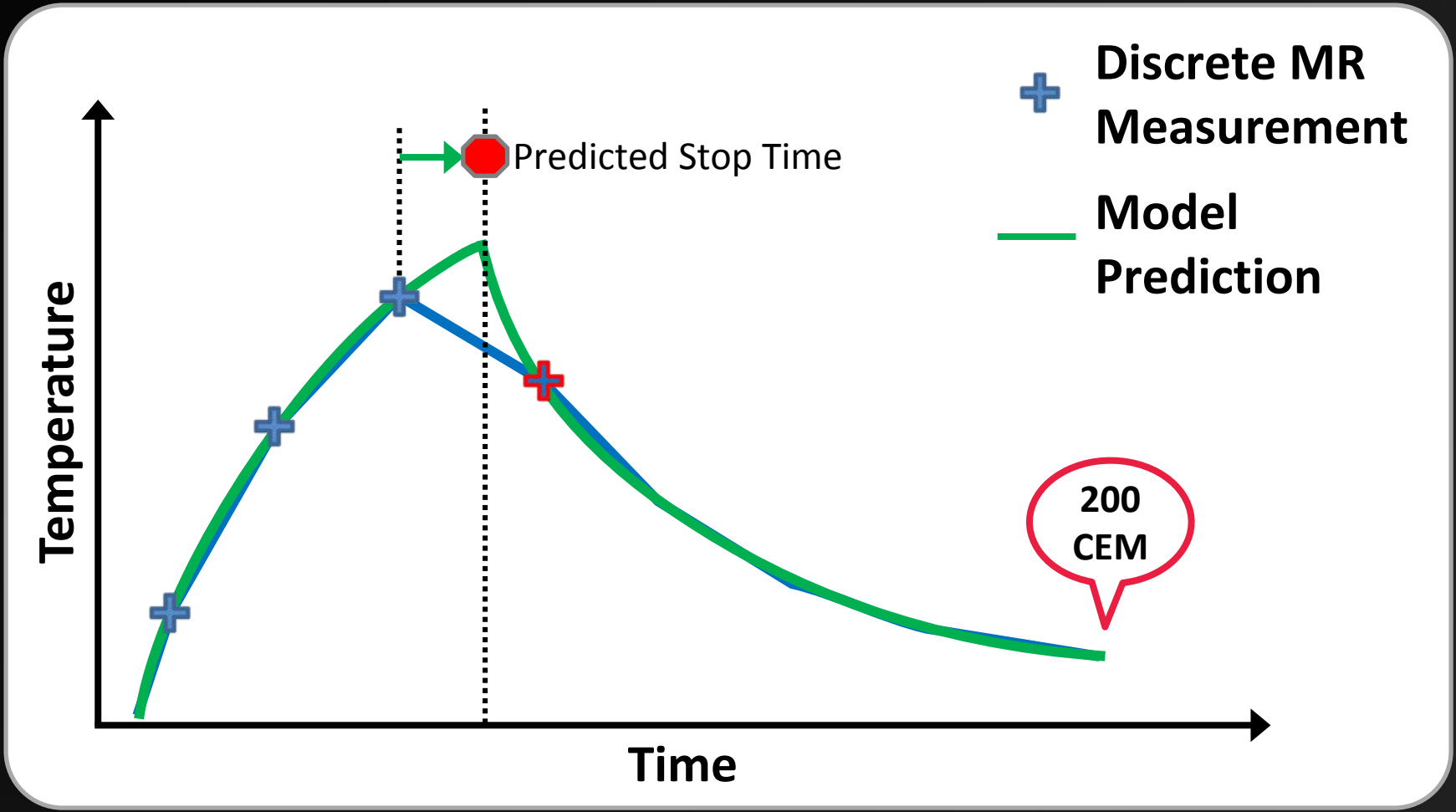
- Every treatment voxel modeled by:
  - Exponential Heating

$$T_{heat_i}(t) = A\left(1 - e^{-t/\tau_{Heat_i}}\right) + C$$

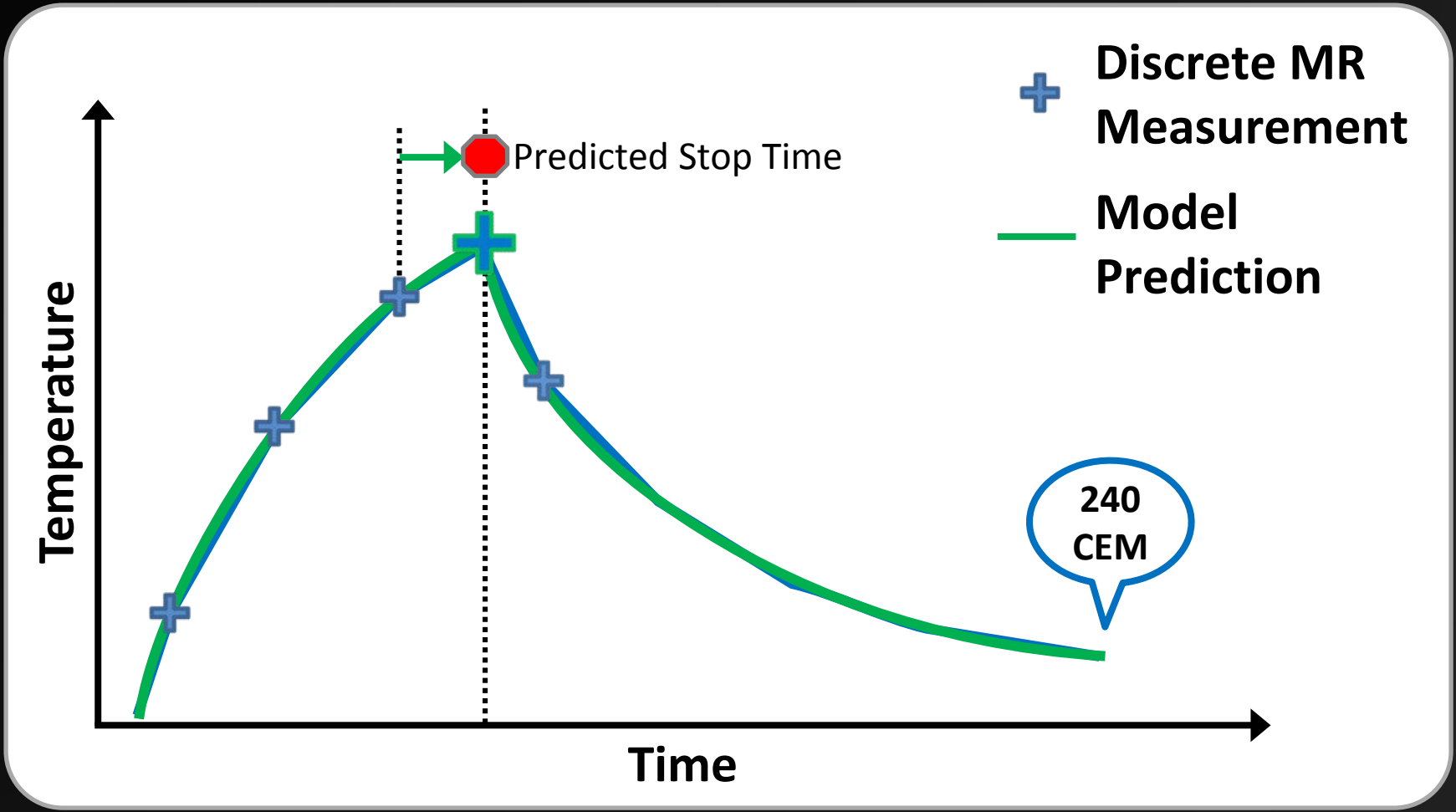
  - Exponential Cooling

$$T_{cool_i}(t) = -Ae^{-t/\tau_{cool_i}} + C$$

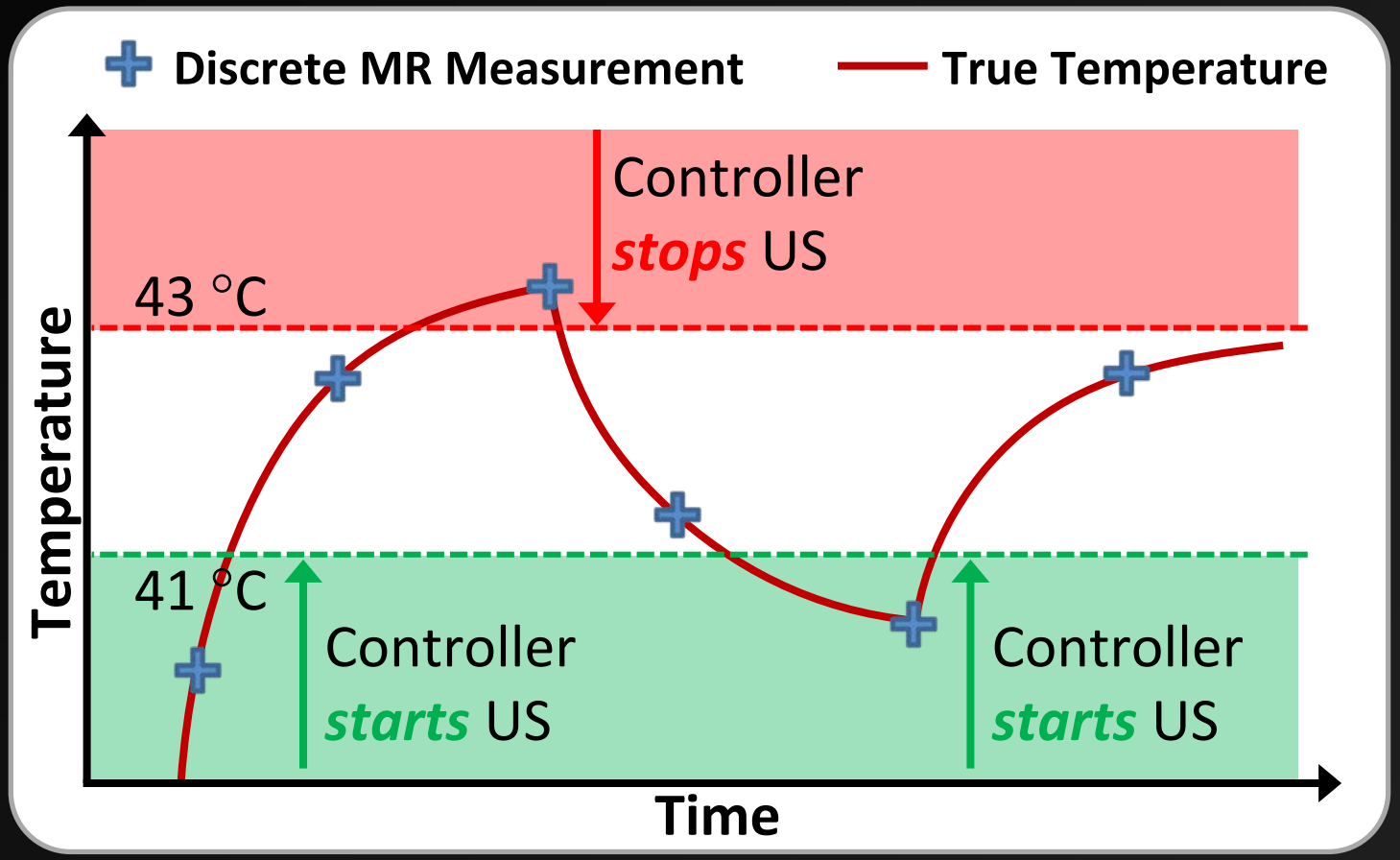
Adaptive Model-Predictive Control



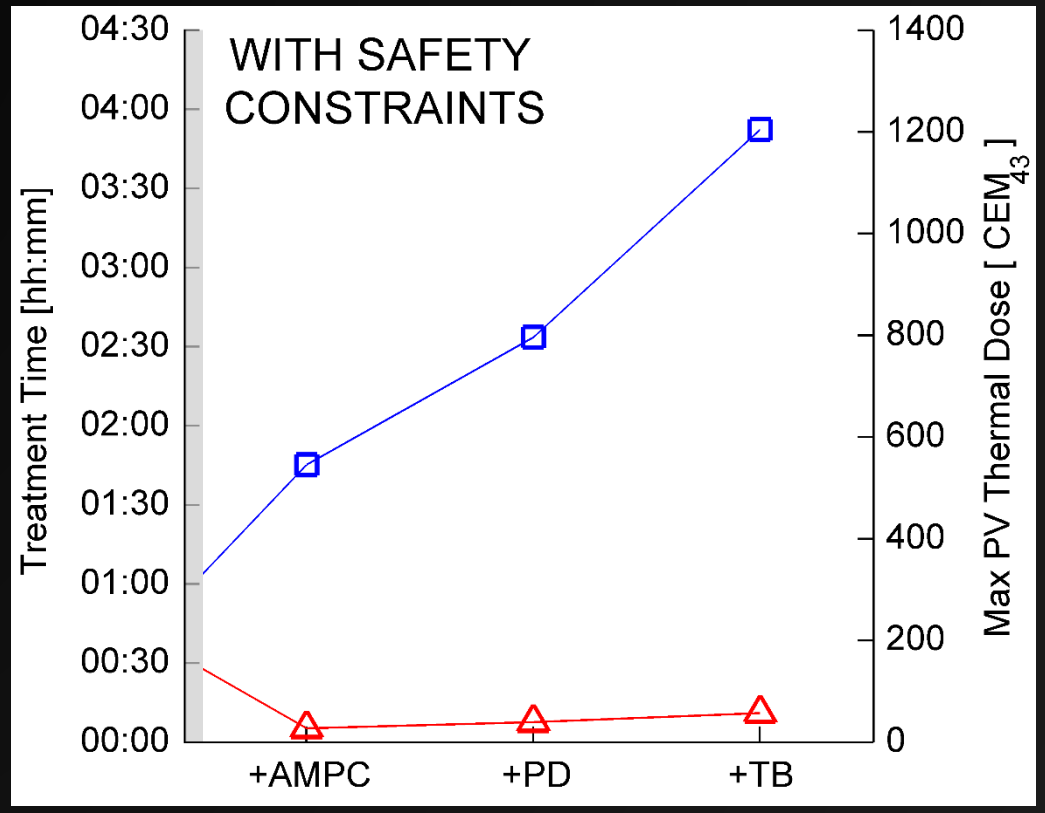
Adaptive Model-Predictive Control



Normal Tissue Safety



Results: Simulation

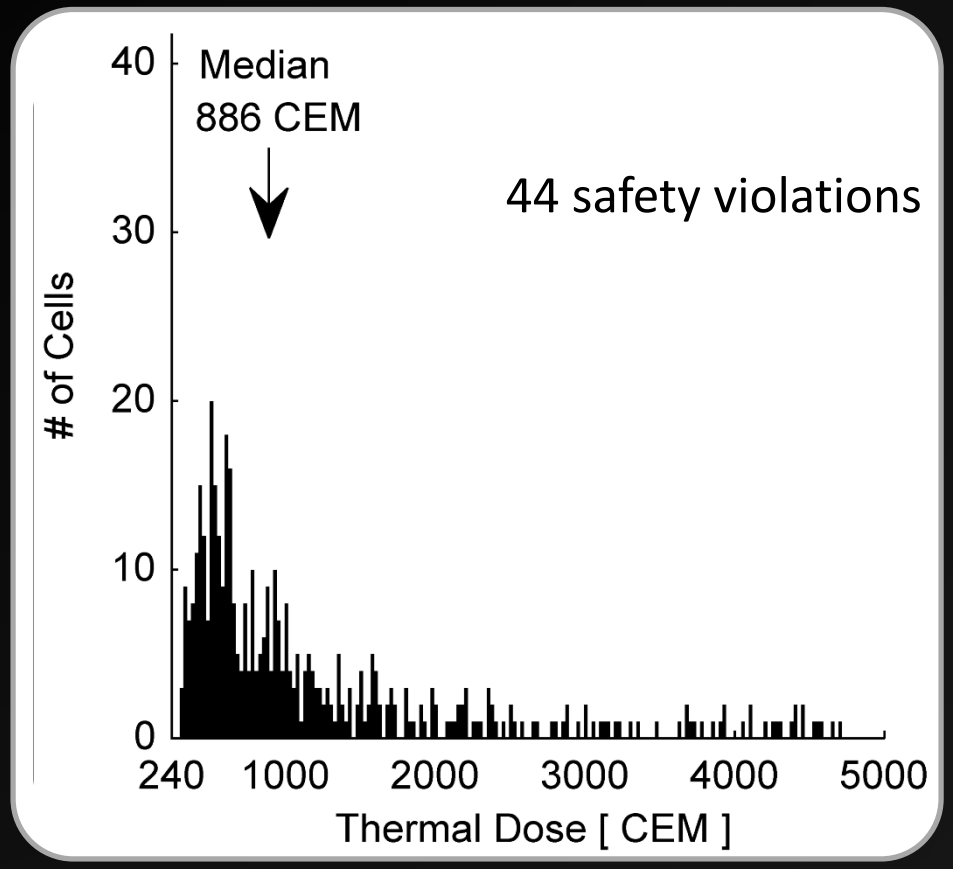


Prediction saves time!

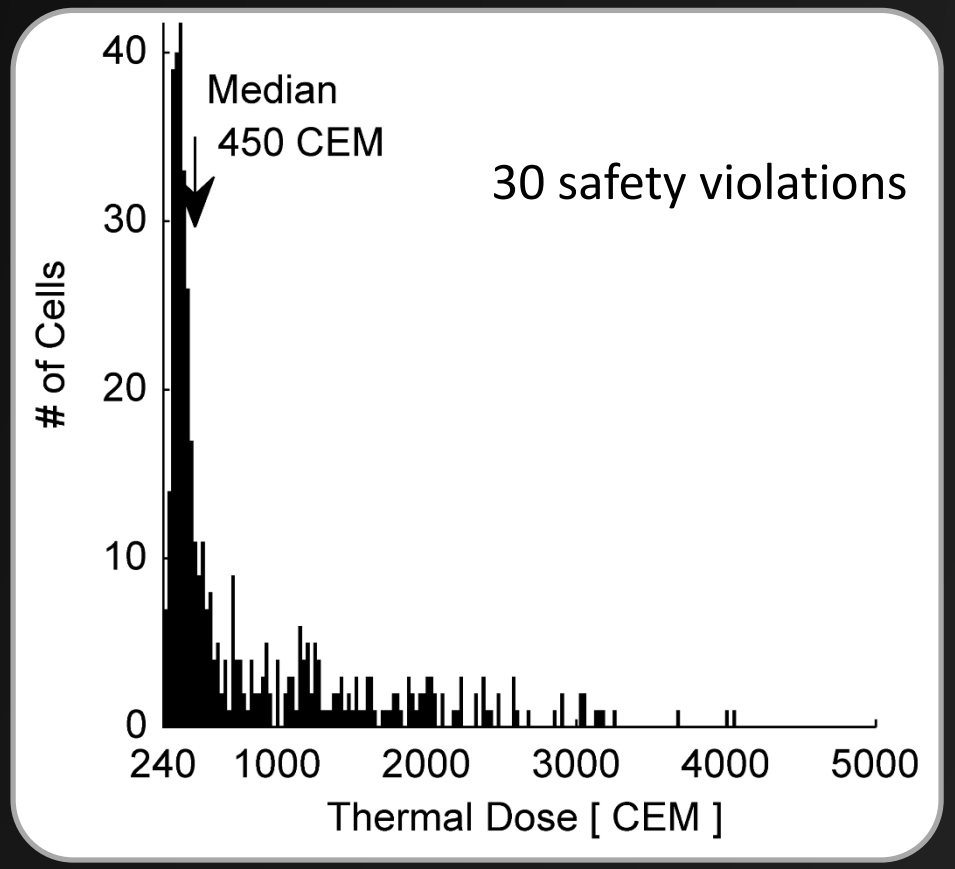
AMPC can protect healthy tissue

Results: Simulation

Prediction ***Disabled***



Prediction **Enabled**

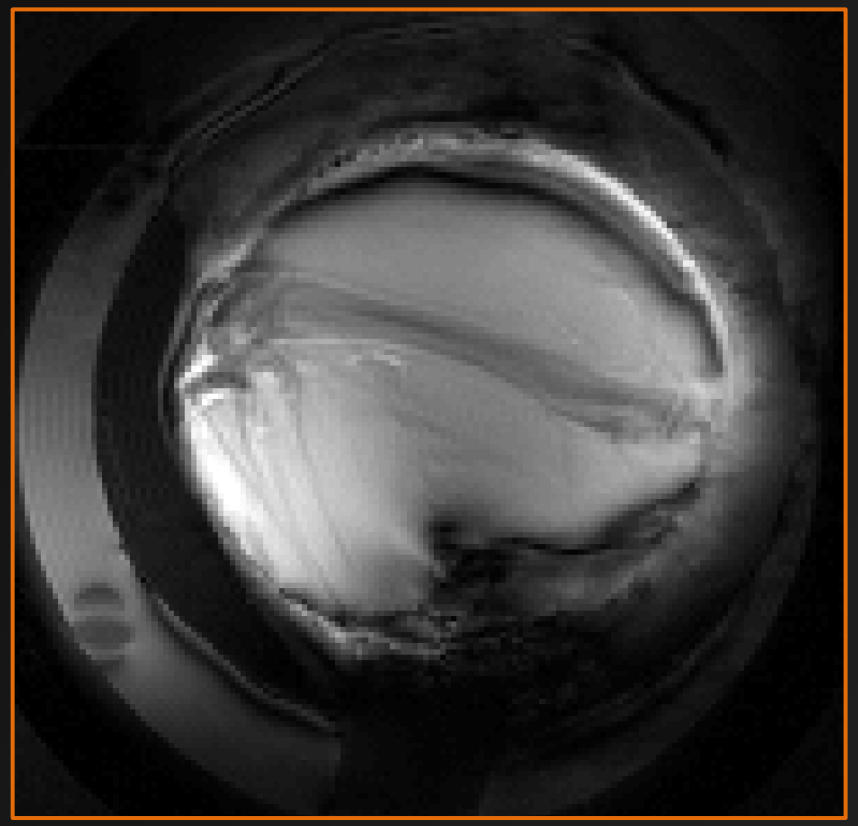


Prediction delivers target dose more accurately.
Improved safety, time saved.

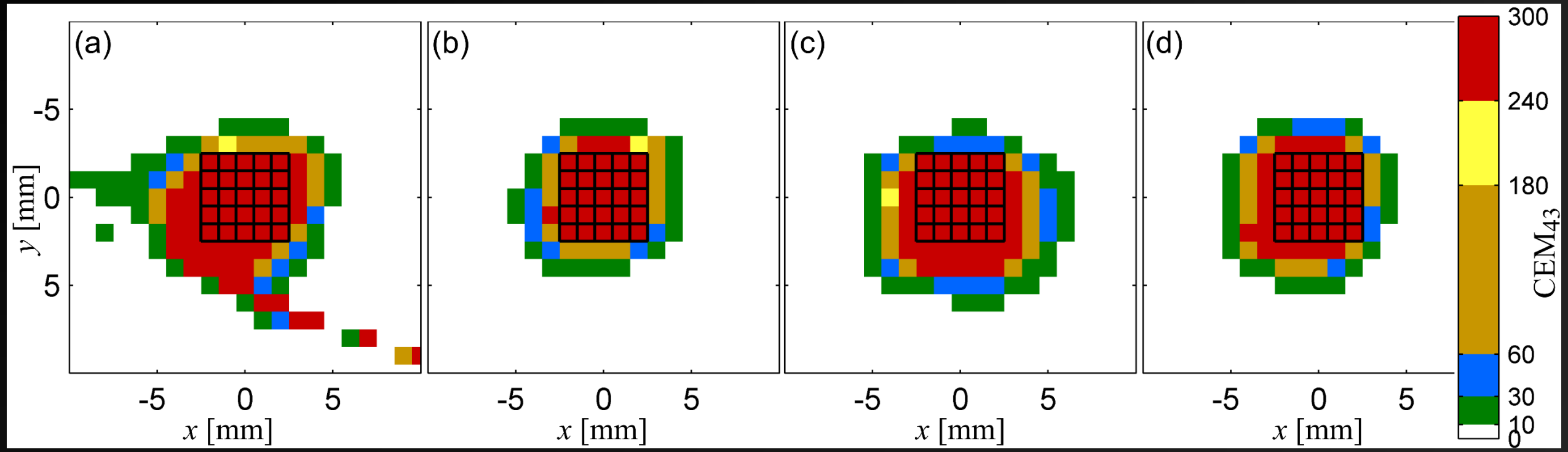
In Vivo: Experiment Setup

Sagittal Slice

Coronal Slice

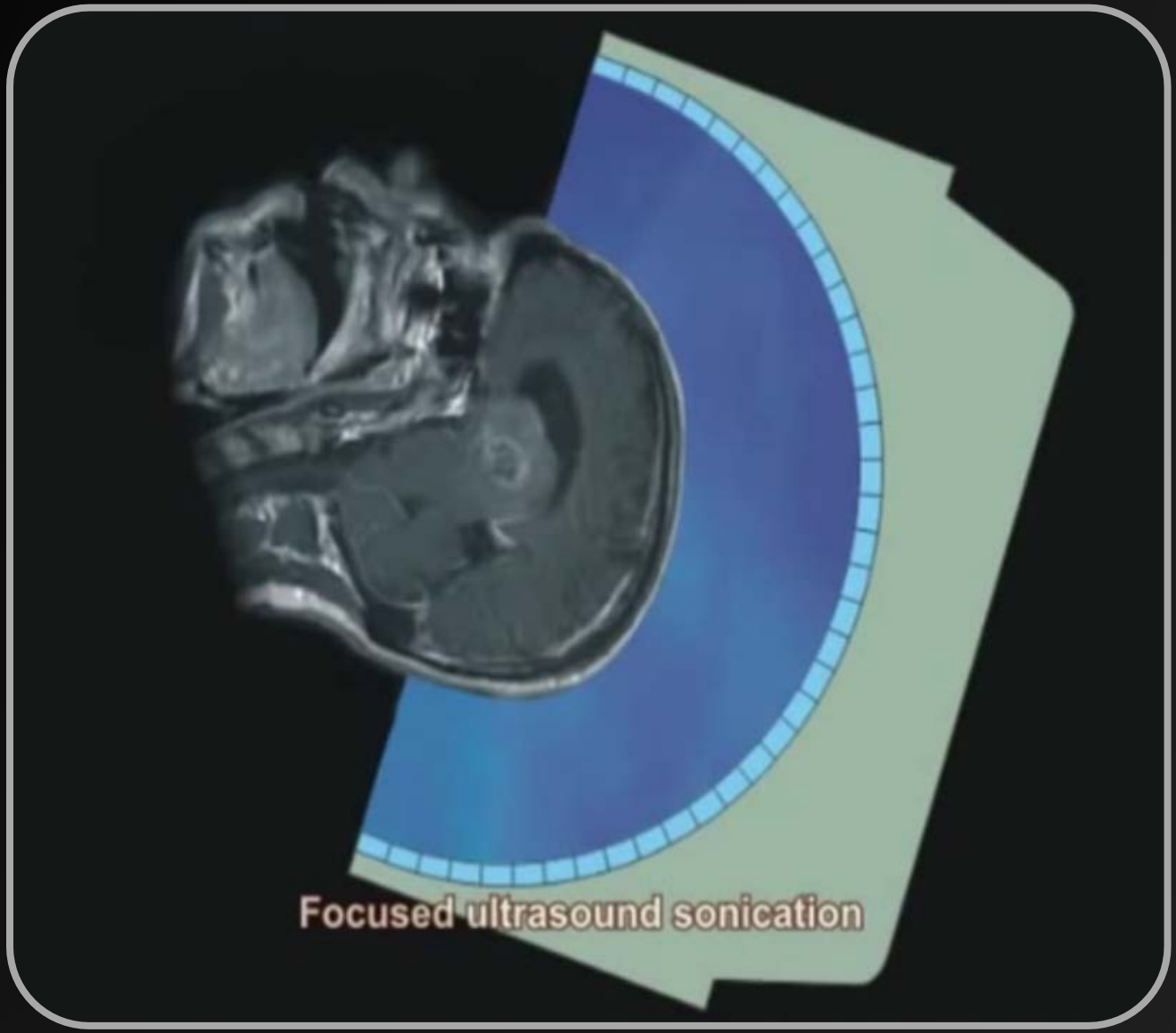


Results: In Vivo - Efficacy



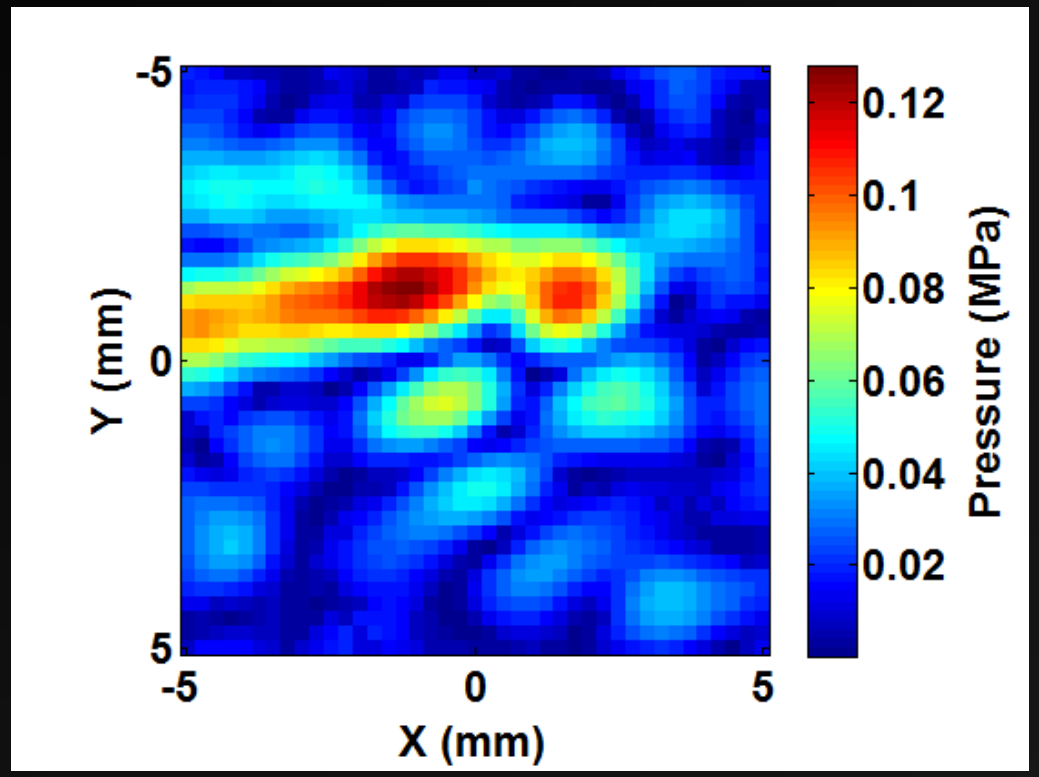
Transcranial FUS

Transcranial FUS

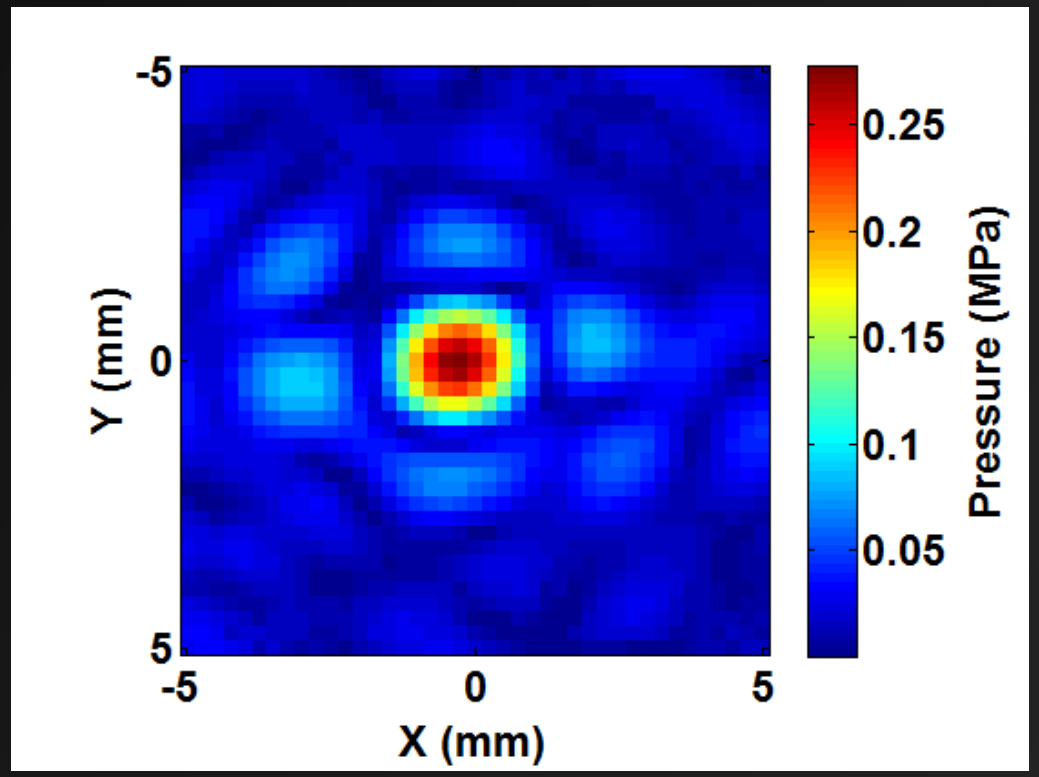


FUS Through Skull Flap

No Correction

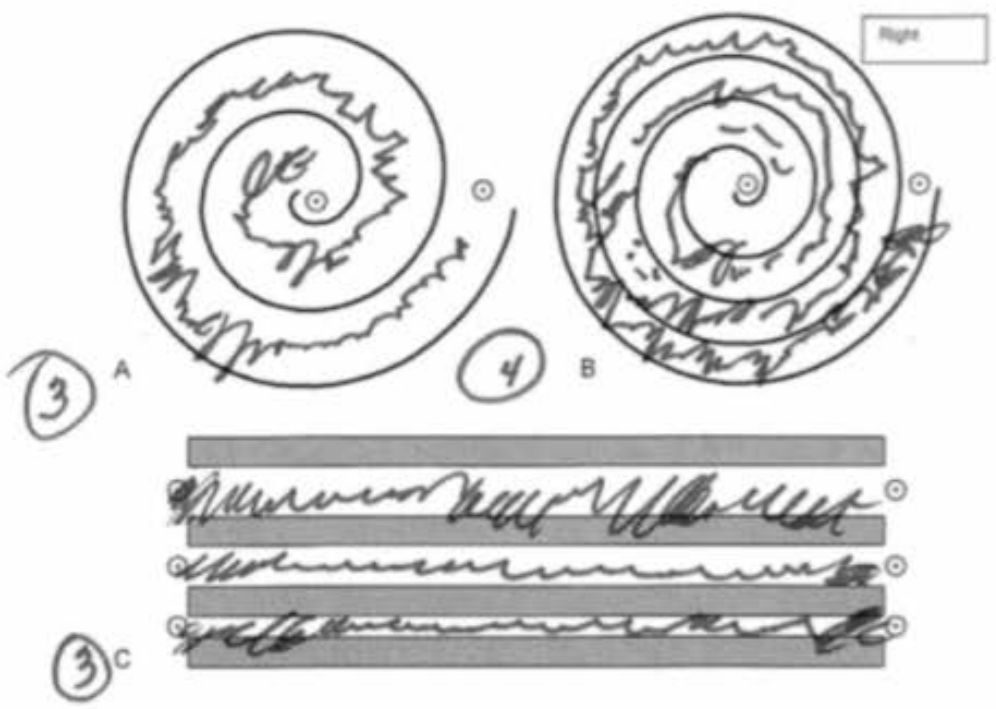


After Phase Correction

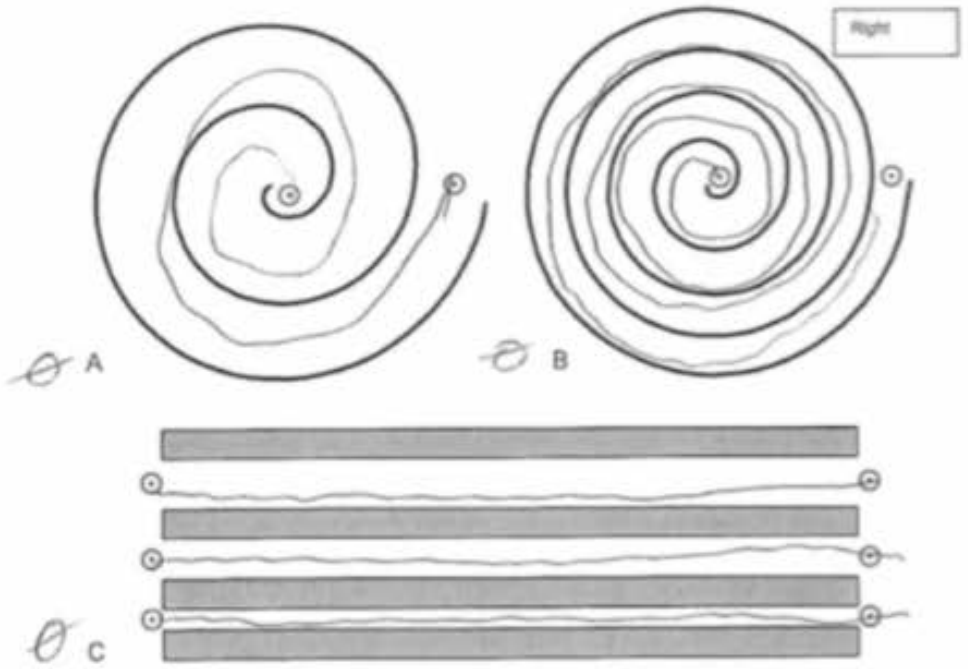


Courtesy of Scott Almquist – Univ. Of Utah

Essential Tremor



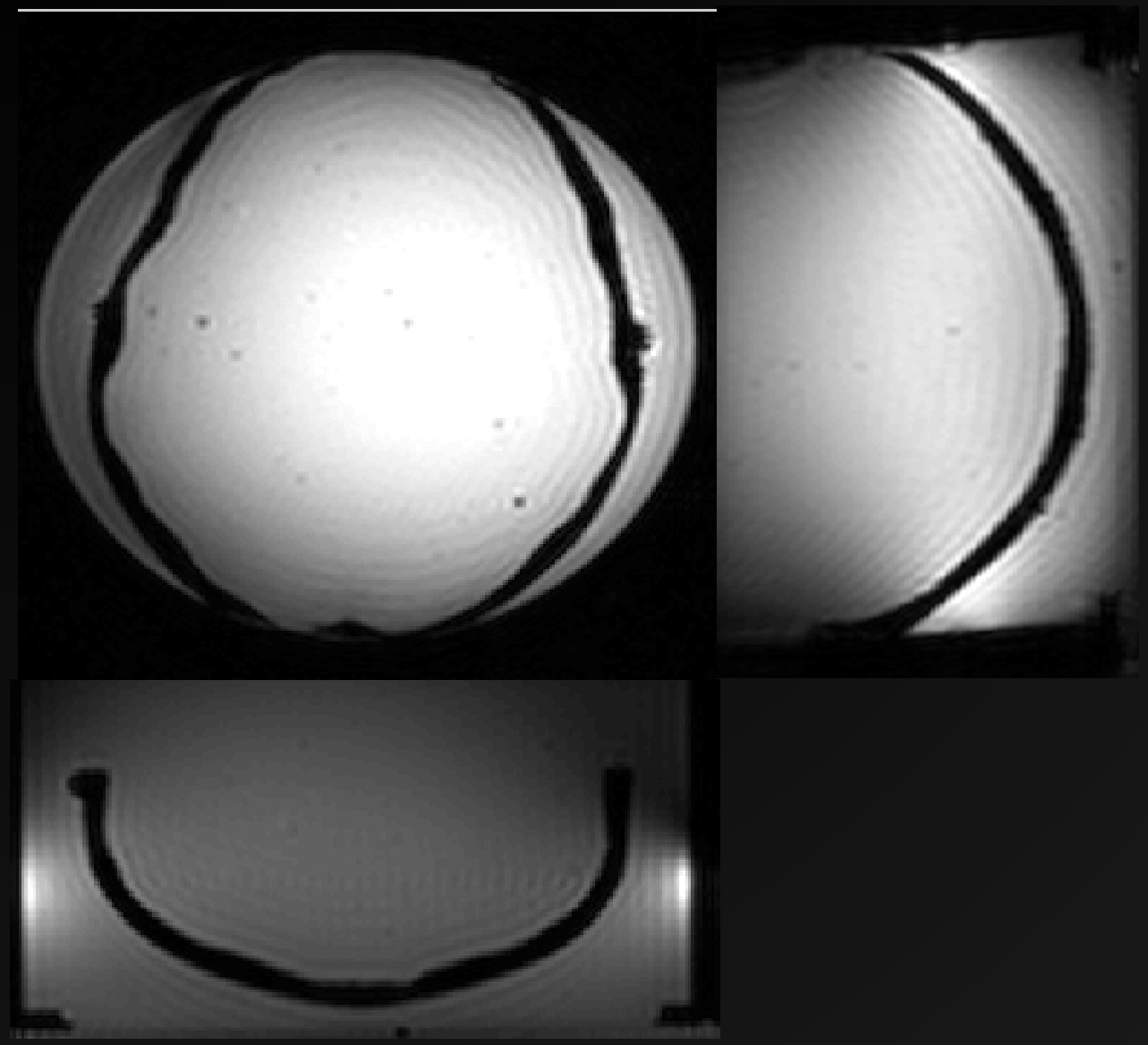
PRE-TREATMENT

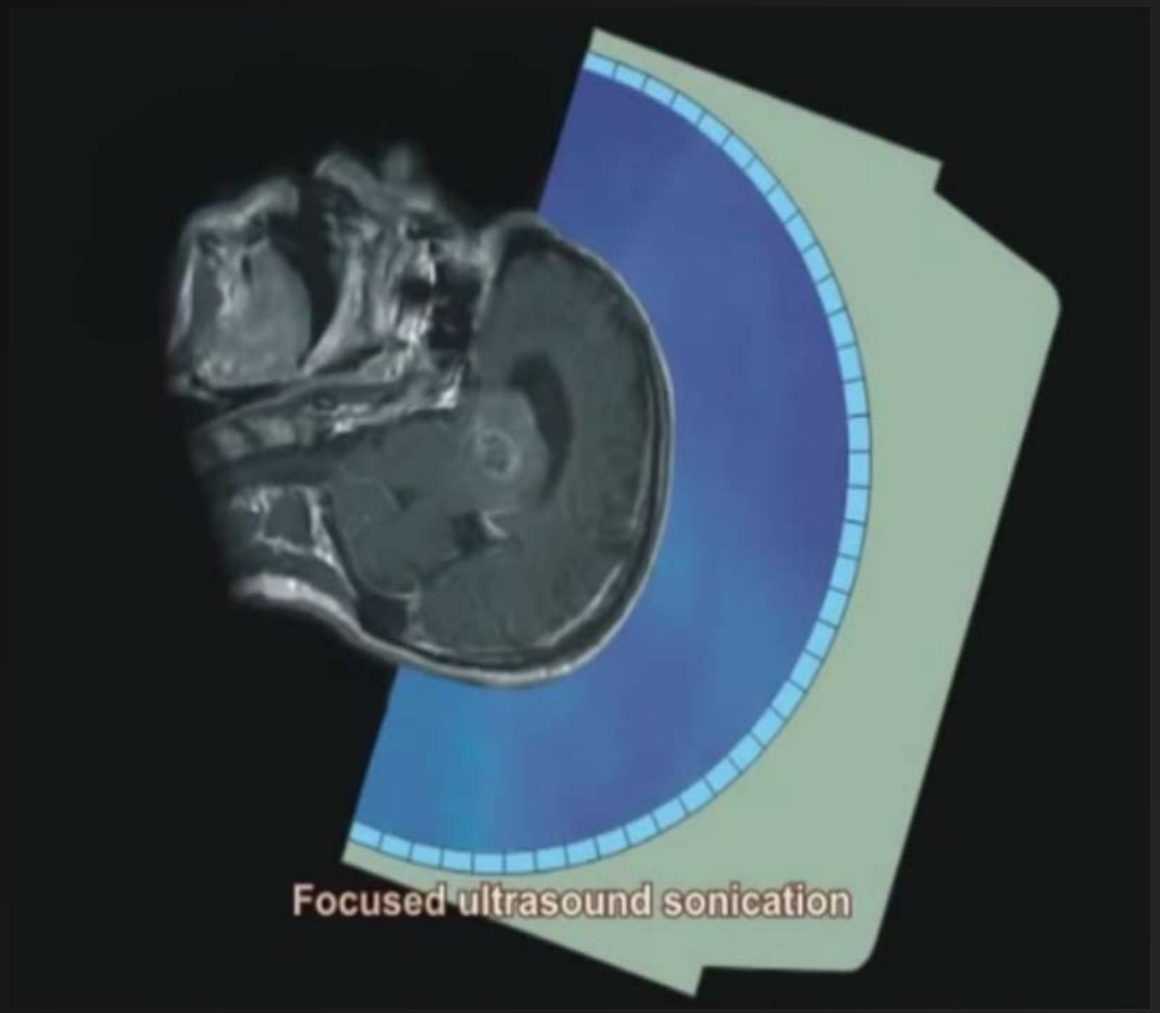


POST-TREATMENT

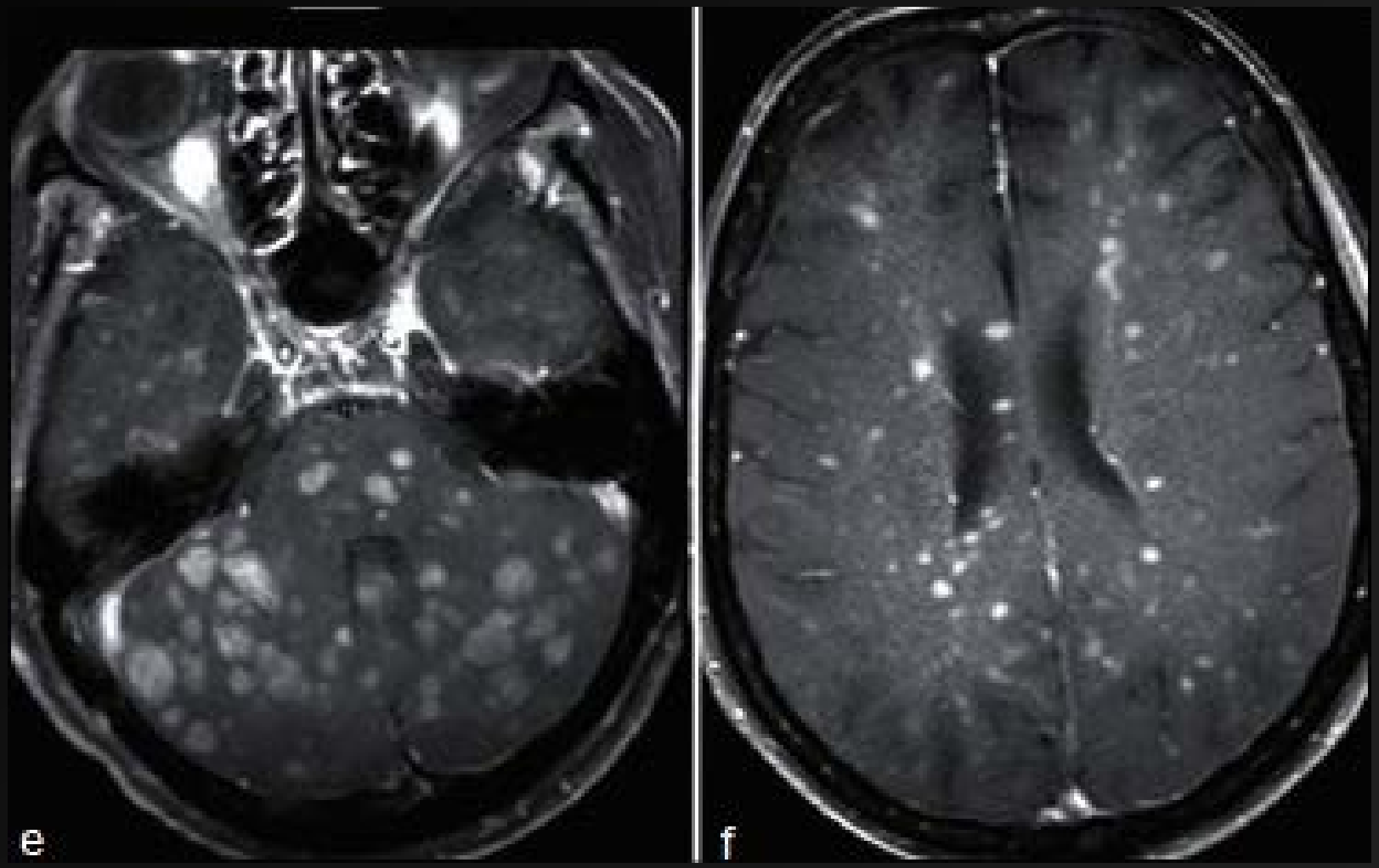
Treating Brain Metastases Transcranial FUS

Transcranial FUS: Challenges





Multiple Brain Metastases



Fink, *SNI,* 2013

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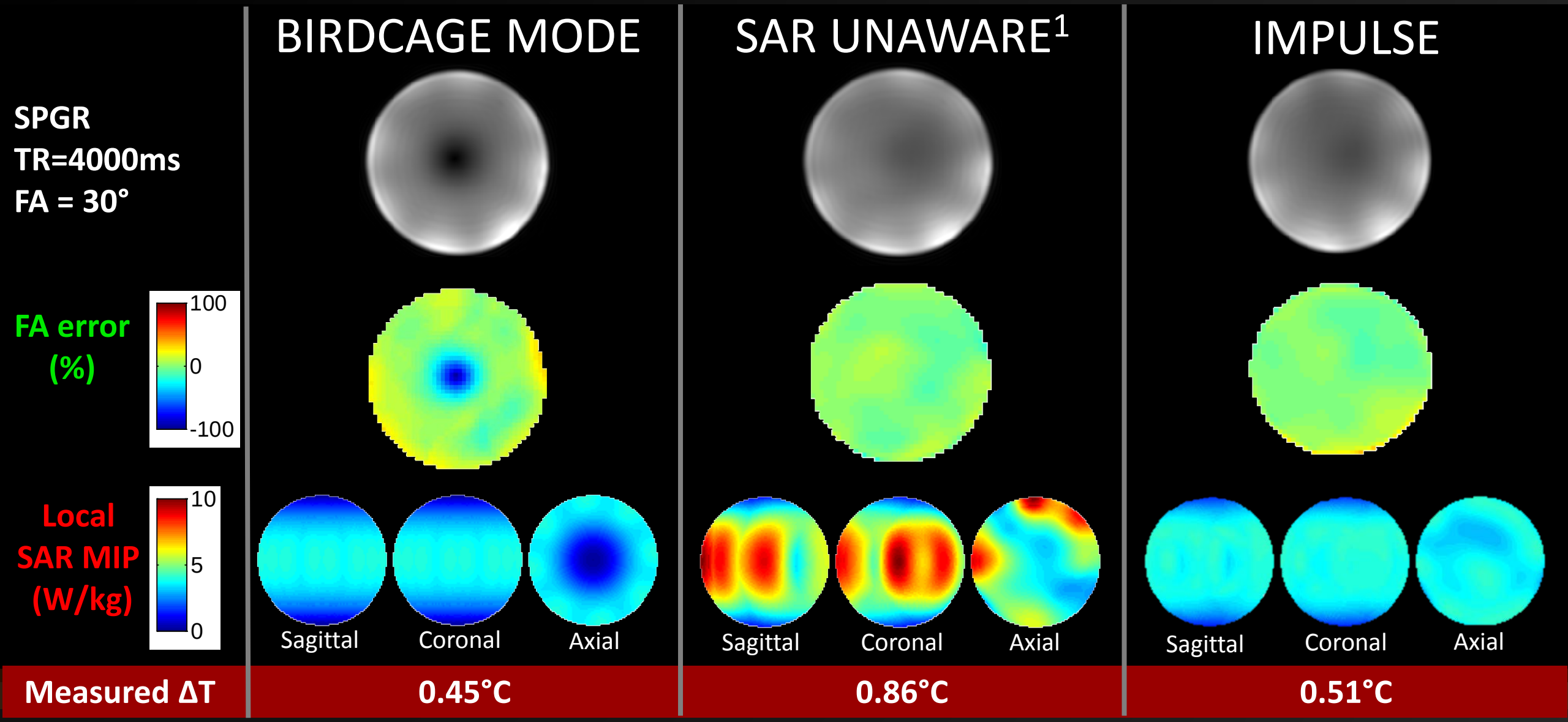
Ultra High-Field MRI: Challenges



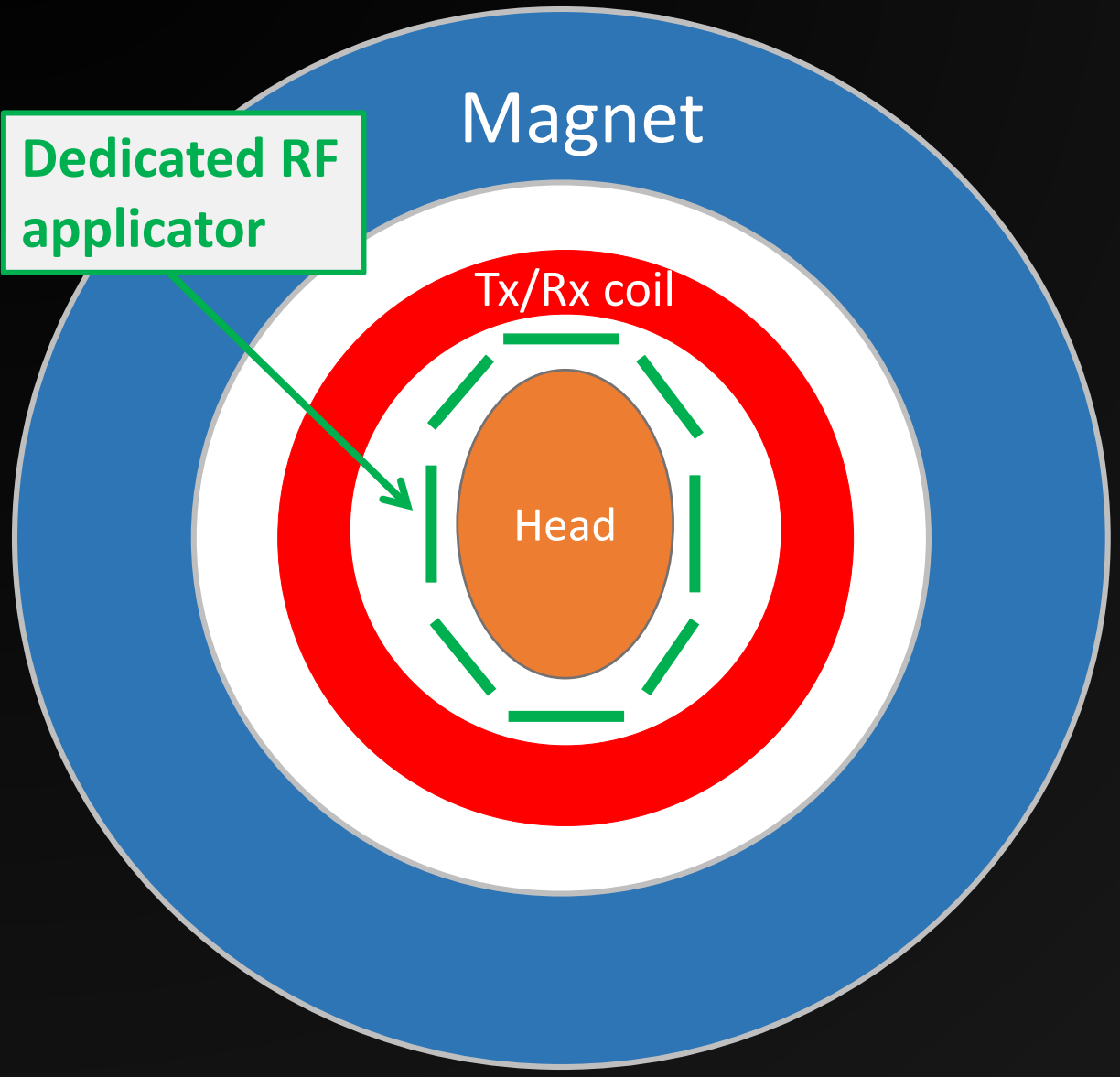
Courtesy of: Mehir Pendse, ISMRM 2015 #573

[1]Grissom, MRM 2012;68:1553–1562

Q: Can this undesired heating been turned into something positive?

A: We're going to find out….

Configuration 1: Dedicated Applicator



Advantages:

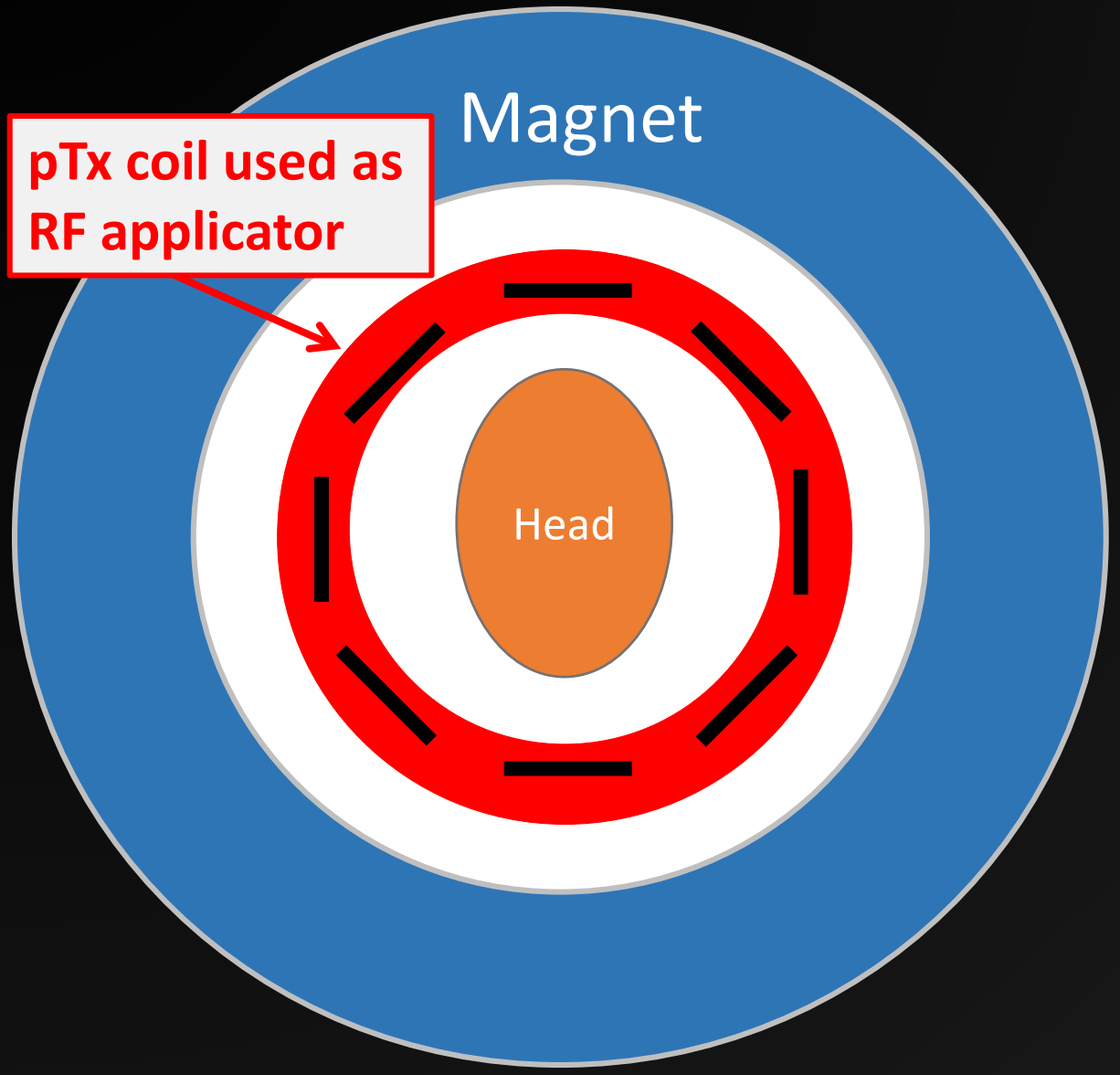
- Applicator is close to anatomy; better spatial control
- Thermometry and hyperthermia can occur simultaneously
- Frequency of applicator can be different from imaging frequency

Disadvantages

- More hardware, cables
- Coupling between two transmitters is possible

Courtesy of: Mihir Pendse, ISMRM 2015 #3224

Configuration 2: All-In-One



Courtesy of: Mihir Pendse, ISMRM 2015 #3224

Advantages

- Single piece of hardware: fewer cables and coupling issues

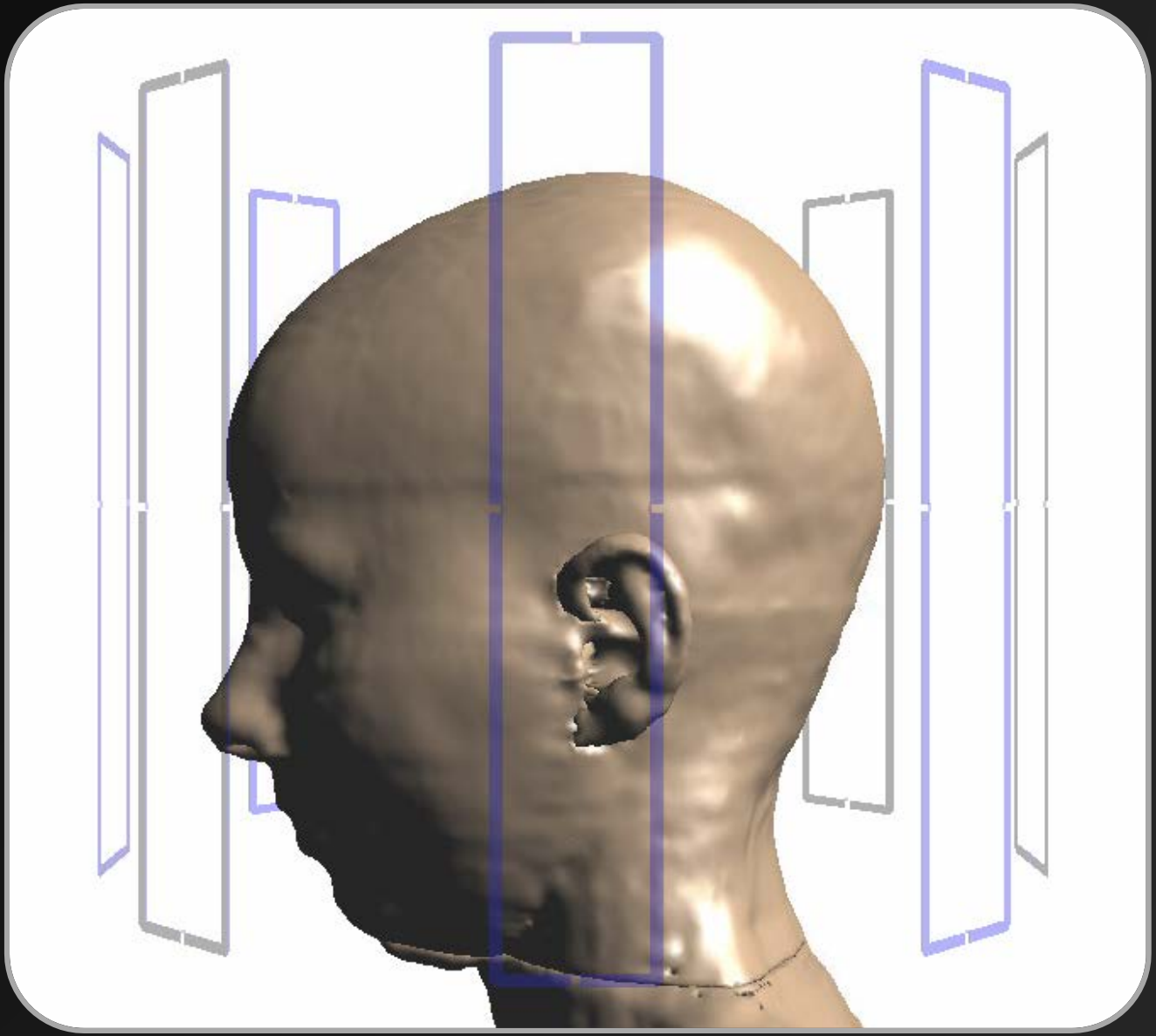
Disadvantages

- Only possible at ultra-high-fields
  - Need high Larmour frequency to achieve focal heating
- Must interleave hyperthermia & imaging
- Spatial control is limited by size and frequency of pTx coil

Optimize for MAX-SAR instead of MIN-SAR

Max SAR Algorithm: Focused RF

- 8ch pTx coil for 7T (298 MHz)
  - Loop height = 16 cm
  - Loop width = 5 cm
  - Coil diameter = 28.5 cm



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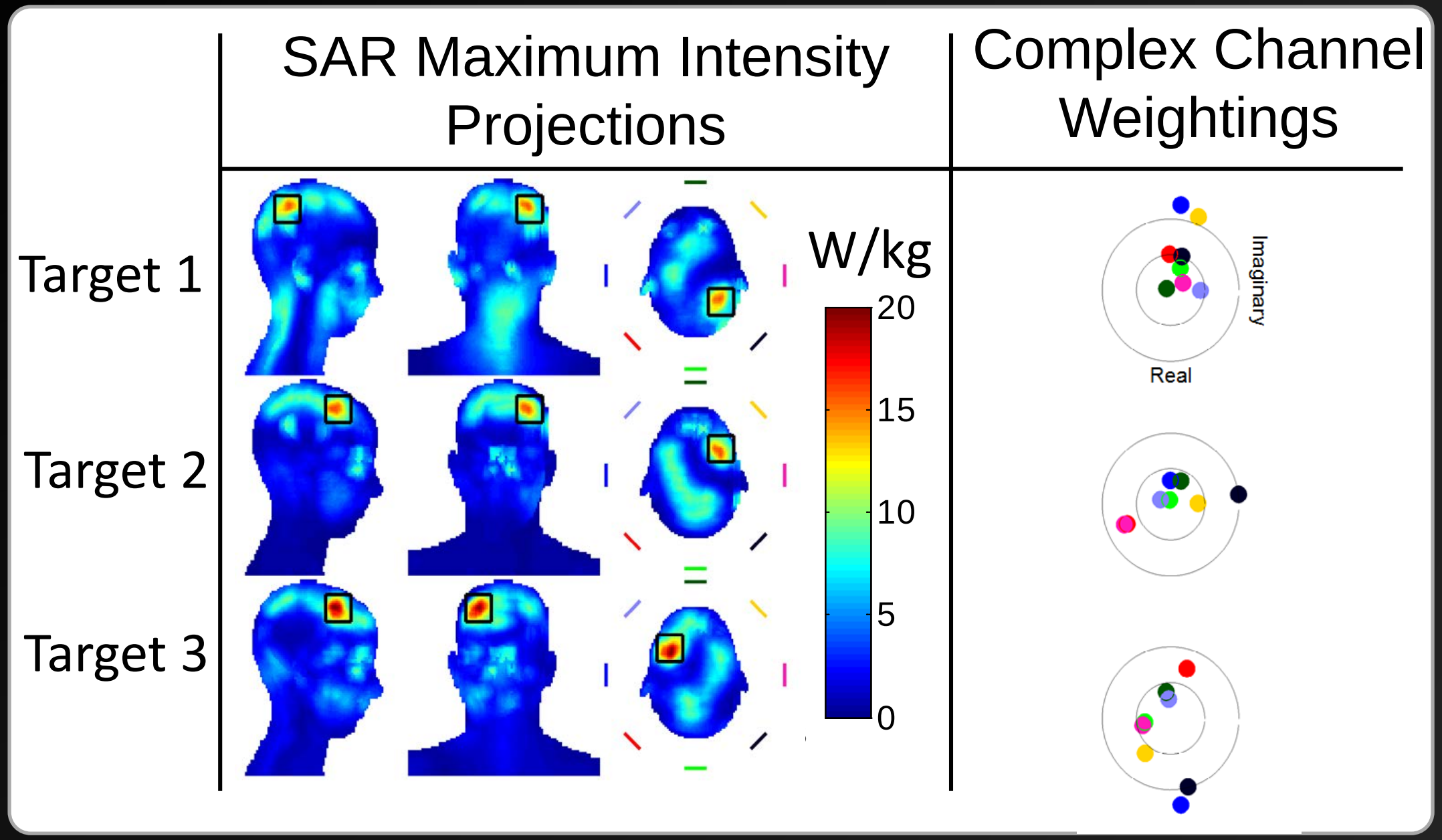
SAR Maximum Intensity Projections
Complex Channel Weightings
Target 1
Target 2
Target 3
W/kg
20
15
10
5
0
Imaginary
Real

Potential

- FRF has all the positives of MRgFUS
  - Non-invasive, monitoring, free of ionizing radiation, etc.
- Hyperthermia
  - Can improve outcomes of radiation and chemotherapy
  - Treat multiple metastases
- Ablation - Direct cell death
  - May not be possible
  - Increase local SAR via Tumor-Targeted Nanoparticles?
- BBB Opening

Road Map

- Investigate optimal coil designs
  - Sim4Life – Realistic body models
- Simulate treatments
  - Integrate adaptive model-predictive controller
- Experimentally verify simulations with 8-Ch pTx coil on 7 T MRI

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- Stanford SCIT (NCI)
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Prof. Allison Payne

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THANK YOU!