MR-guided Laser Ablation in Oncology

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Introduction

- MR-guided laser ablation is seeing increased use in brain, spine, prostate, liver and other organs.

- MR-guidance plays a critical role in assuring a safe and effective treatment, particularly in its role in providing temperature imaging feedback.

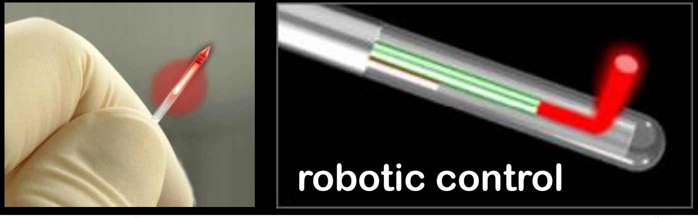
- Here we overview the MR-guided laser ablation process to identify potential pitfalls physicists should be aware of which could negatively impact the safety and efficacy of treatment delivery.

Thermal Ablation Modalities: Laser

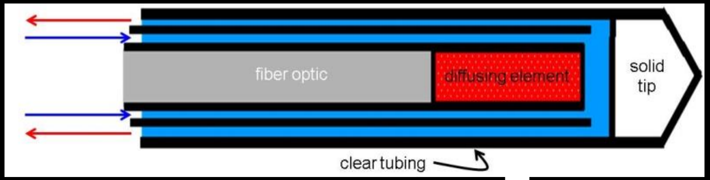
- Cryoablation
- Radiofrequency
- Microwave
- Ultrasound
- **Laser**

Compact CW or pulsed diode lasers

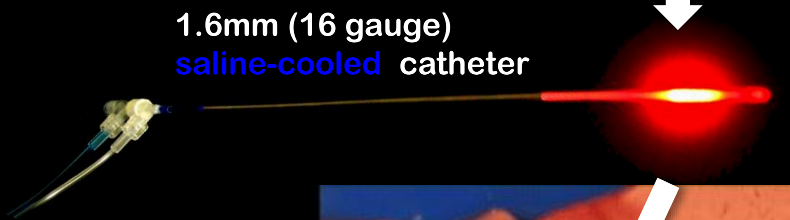
Diffusing or side fire fiber optics

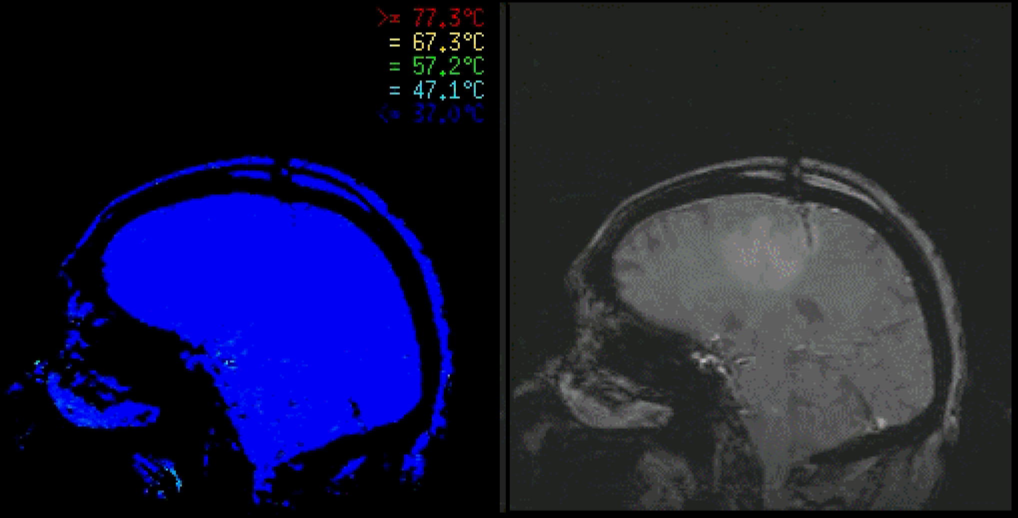


Actively cooled catheters



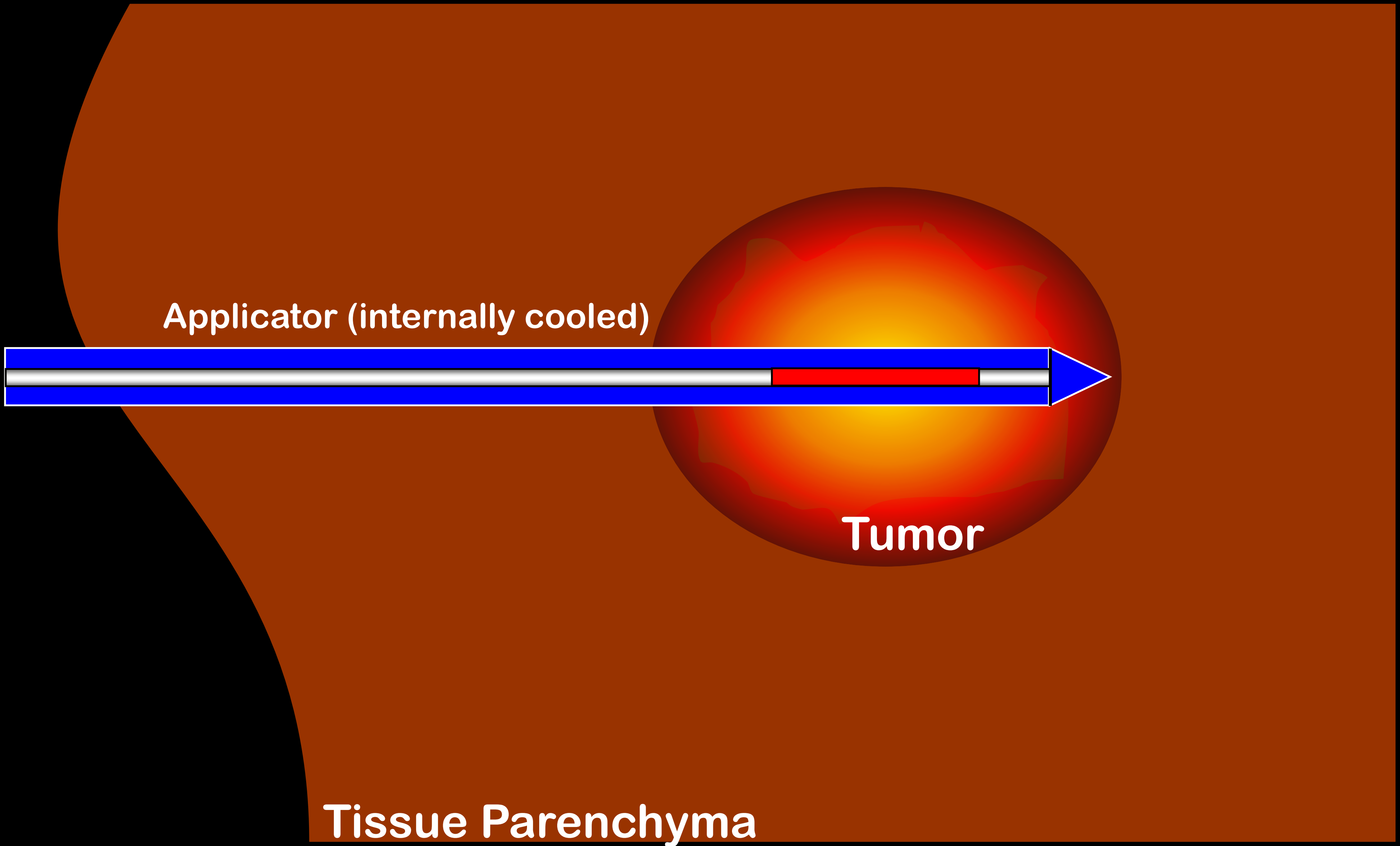
1.6mm (16 gauge) saline-cooled catheter





Stafford RJ, et al, Crit Rev in Biomed Eng, 2010.

Overview of laser ablation



Overview of laser ablation

$$\underbrace{\rho c \frac{\partial T(q_i, t)}{\partial t} = \nabla \cdot [(k \nabla T(q_i, t))]}_{\text{heat diffusion}} + \underbrace{\rho_b C_b V \left(\kappa - 1\right)\left(T - T_a\right)}_{\text{heat convection}} + \underbrace{P(q_i, t)}_{\text{heat source}}$$

HEAT SOURCES (laser, ultrasound, RF, microwave, etc) :
P = absorbed power density (W m^{-3}) = SAR*ρ

SAR = Specific Absorption Rate (W/kg) →

g = anisotropy factor
μ_a = optical scattering
μ_a = optical absorption

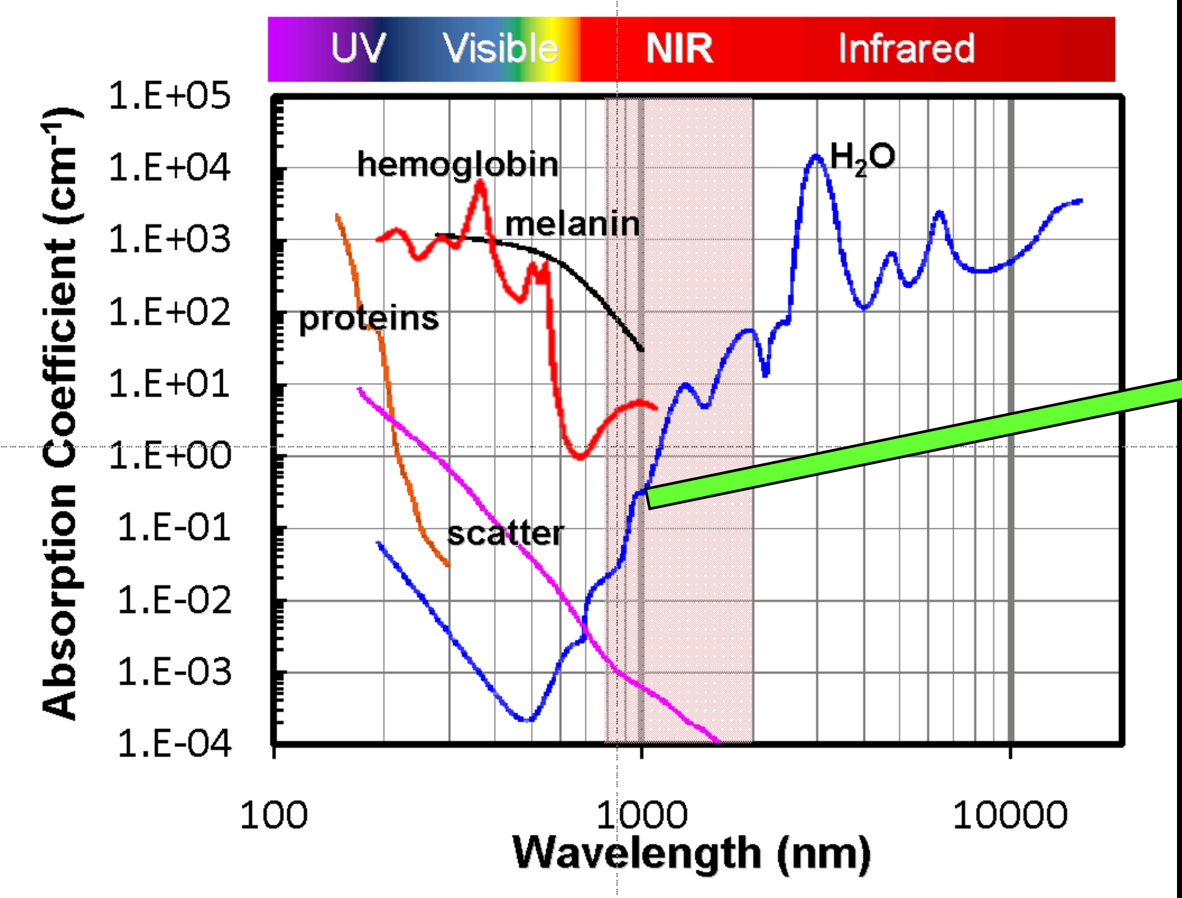
HEAT CONDUCTION (diffusion):
T = temperature (Kelvin)
c = specific heat of material (J kg^{-1} °C^{-1})
ρ = density (kg/m^3)
k = thermal conductivity of tissue (W m^{-1} °C^{-1})

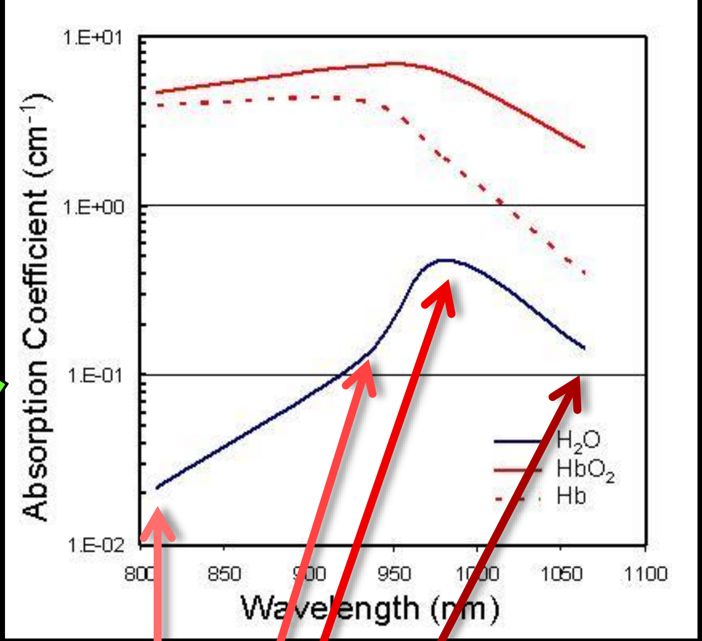
HEAT CONVECTION (effects of perfusion):
ρ_b = blood density (kg m^{-3})
V = volume flow rate per unit volume (s^{-1})
C_b = specific heat of blood (J kg^{-1} °C^{-1})
κ = dimensionless convection scale factor

Tissue thermal conductivity largely governs conductive heat transfer
Tissue perfusion largely governs convective heat transfer in tissue

Pennes HH, J Appl Physiol. 1: 93–122 (1948)

Overview of laser ablation

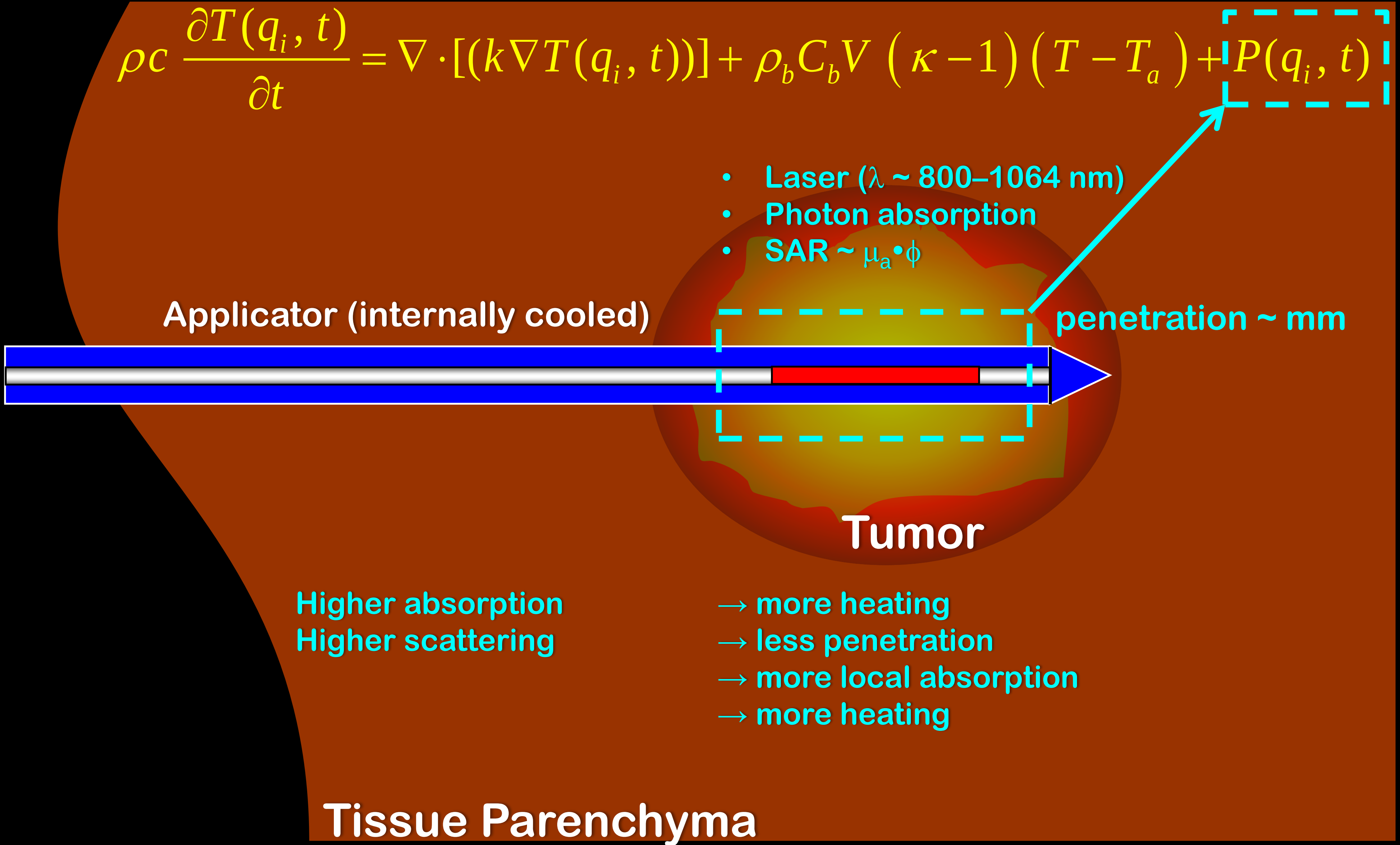




805nm	Diode	Absorption:	Blood +++	Water +
940nm	Diode	Absorption:	Blood +++	Water ++
980nm	Diode	Absorption:	Blood ++	Water +++
1064nm	Nd:YAG	Absorption:	Blood +	Water ++

Stafford RJ, et al, Crit Rev in Biomed Eng, 2010.

Overview of laser ablation



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- Laser (λ ~ 800–1064 nm)
- Photon absorption
- SAR ~ $\mu_a \bullet \phi$

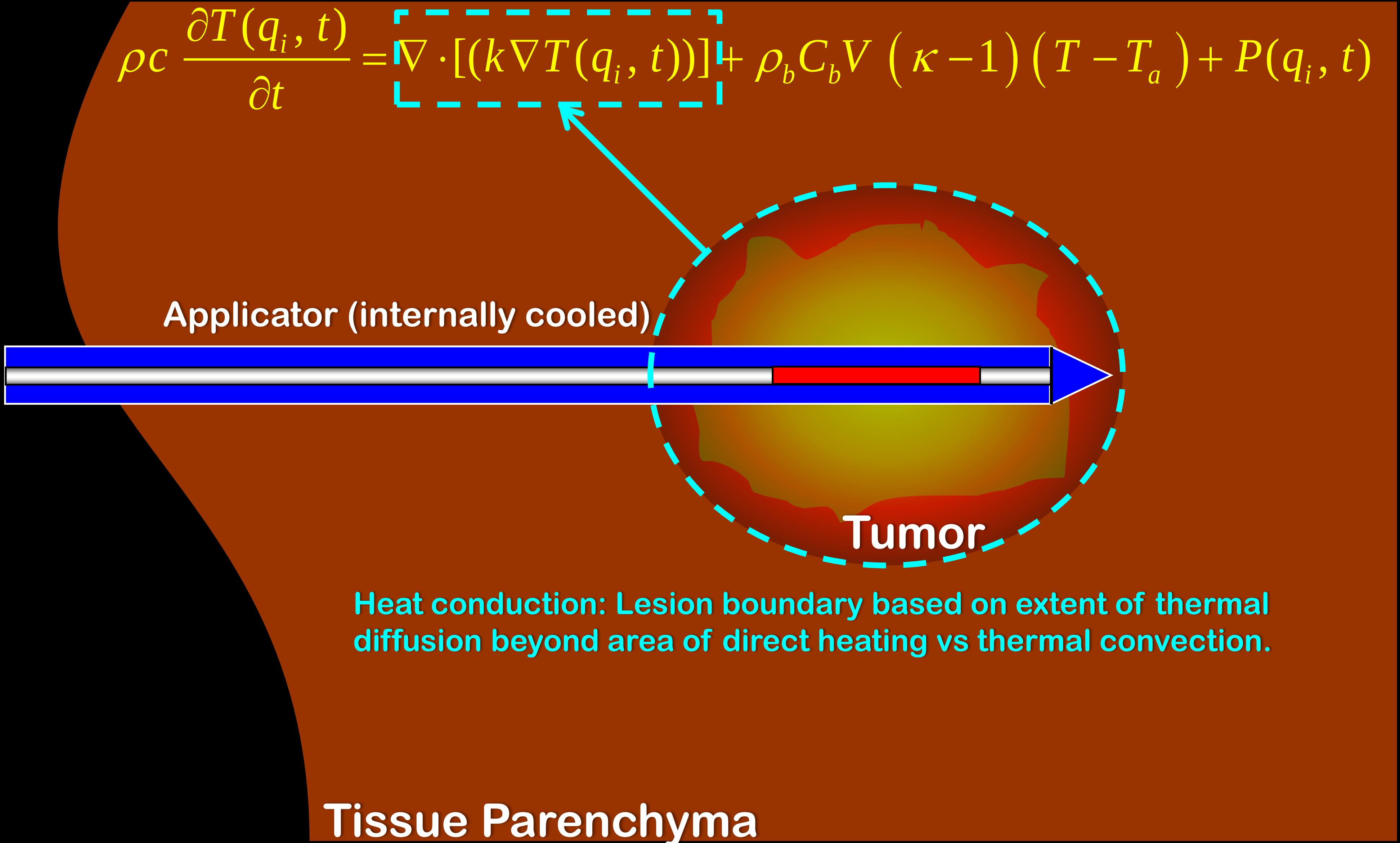
Higher absorption → more heating

Higher scattering → less penetration

→ more local absorption

→ more heating

Overview of laser ablation



$$\rho c \frac{\partial T(q_i, t)}{\partial t} = \boxed{\nabla \cdot [(k \nabla T(q_i, t))]} + \rho_b C_b V \left(\kappa - 1 \right) \left(T - T_a \right) + P(q_i, t)$$

Heat conduction: Lesion boundary based on extent of thermal diffusion beyond area of direct heating vs thermal convection.

Overview of laser ablation

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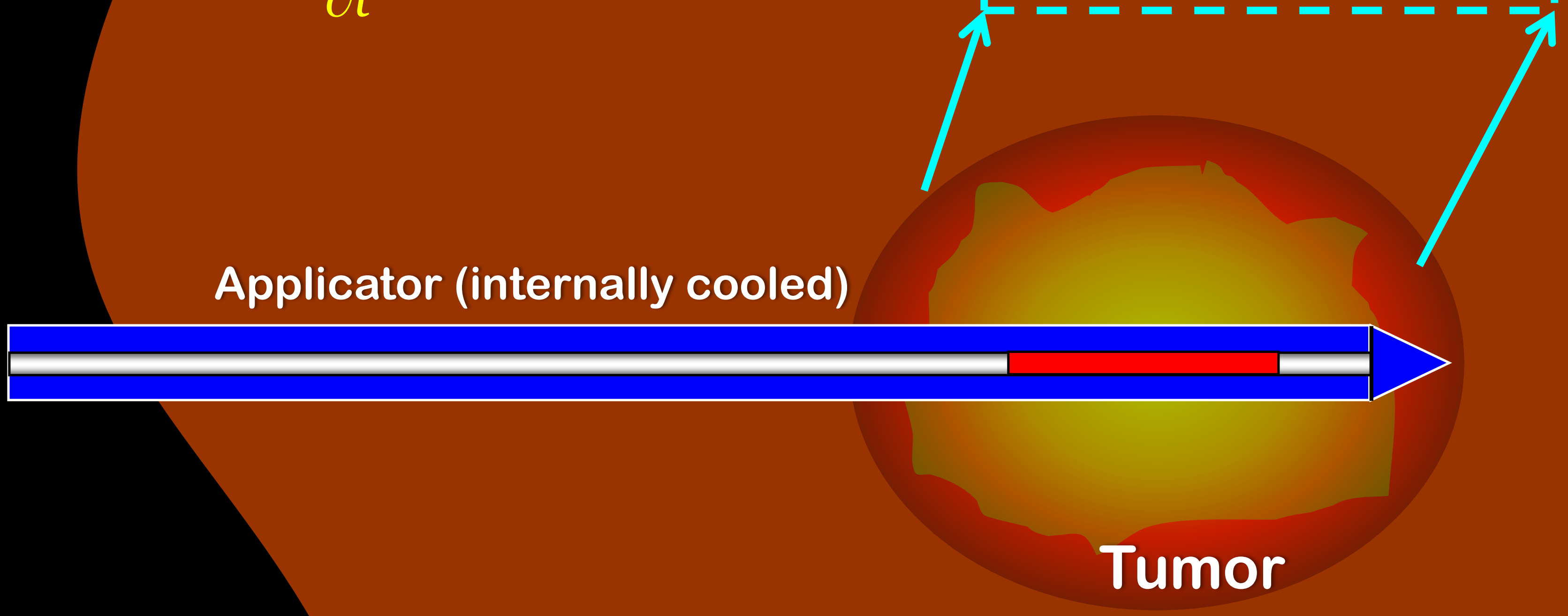

Heat convection: Heated blood in perfused tissue is replaced by arterial blood at body temperature.

Perfusion in lesion destroyed by ablation.

Large lesions: heat deposited over larger OAR region

Kok HP, et al, Int J Hyperthermia. 2013 Jun; 29(4): 336–345.

Overview of laser ablation

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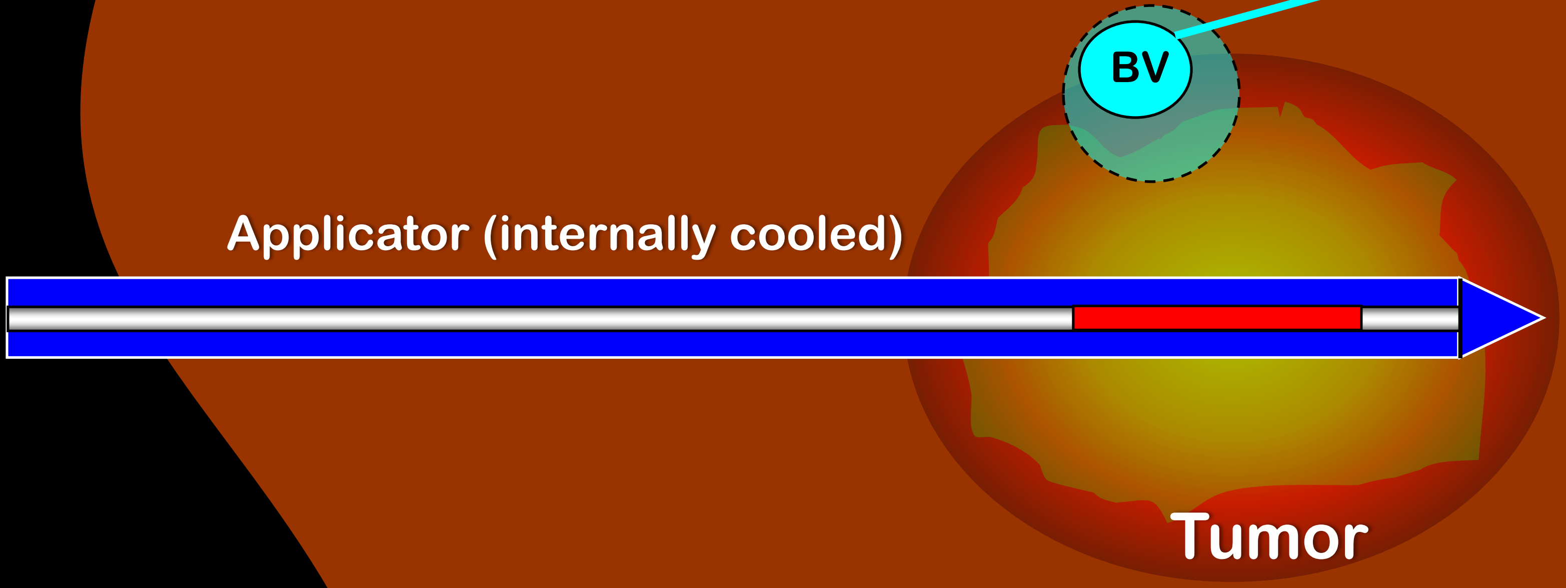

Heat convection: Large vessels or areas of ventilation can rapidly disperse heat resulting in a ‘heat sink’ effect.

This can result in cold spots.

Kok HP, et al, Int J Hyperthermia. 2013 Jun; 29(4): 336–345.

Overview of laser ablation

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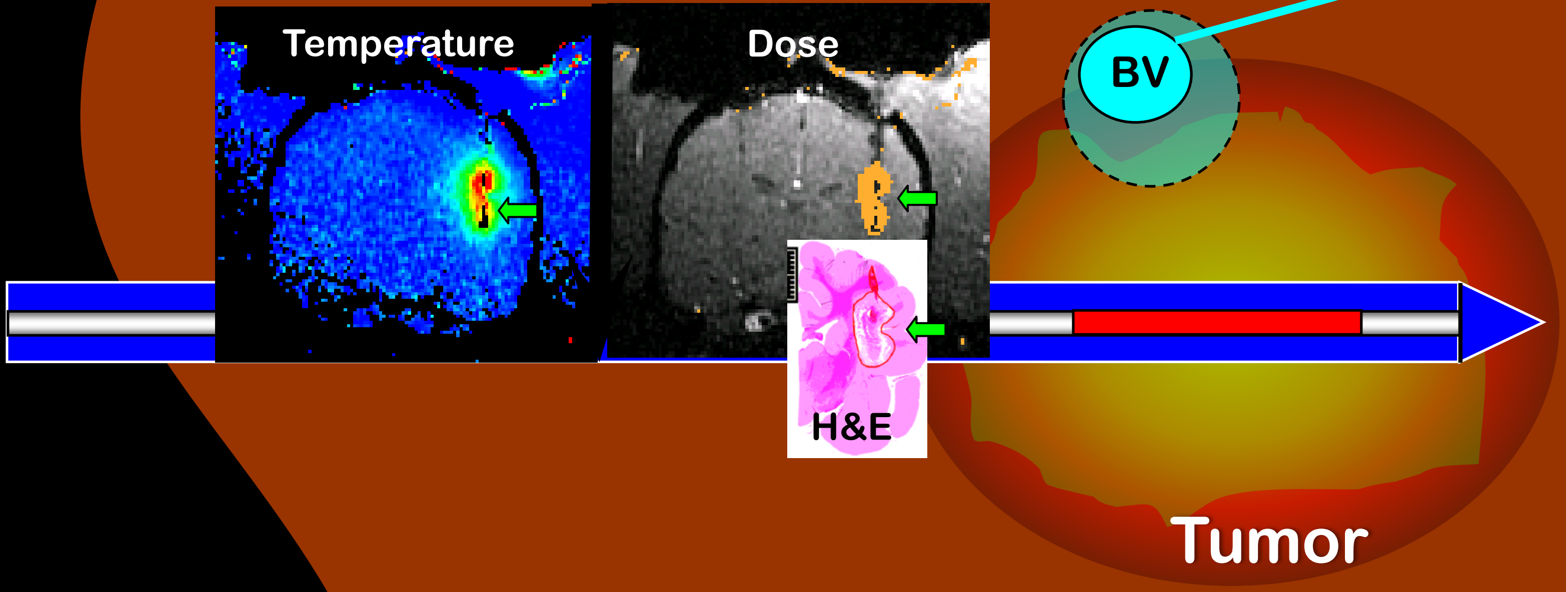

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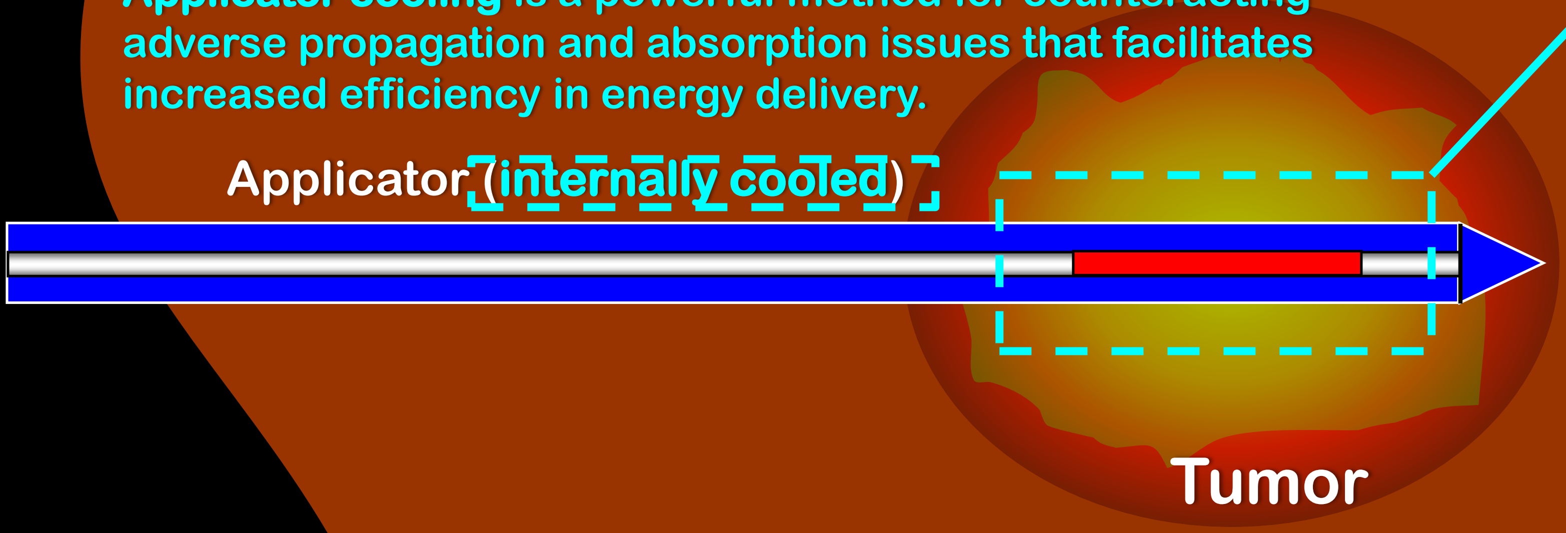
Modality interactions with tissue (redux):
Applicator cooling is a powerful method for counteracting adverse propagation and absorption issues that facilitates increased efficiency in energy delivery.

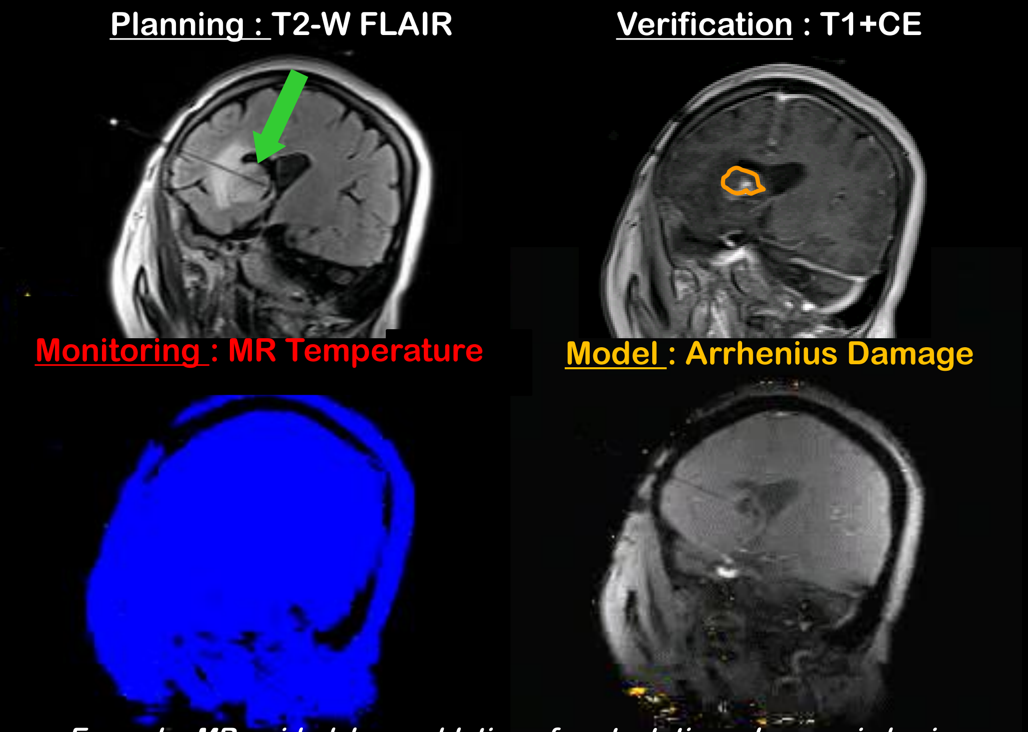


Cooling functions a a much stronger BV 'heat sink'.
Begin just prior starting ablation
Set MRTI reference prior to turning on
Should be kept on post ablation to dissipate heat
(minimize risk to surrounding OAR)
Careful not to cool tissue below baseline if setting a new reference

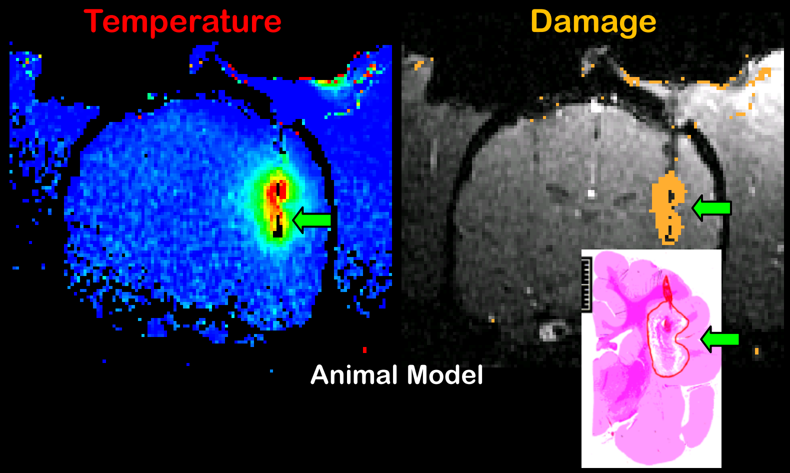
Tissue Parenchyma

MR-guidance in thermal ablation

- MRI-guidance useful for
  - planning
  - navigation & targeting
  - monitoring & control
  - verification
- Synergy with biological and physical modeling & simulation
- Endgame
  - ‘close the loop’
  - increase safety + efficacy
  - facilitate minimally invasive approaches previously not considered safe or effective

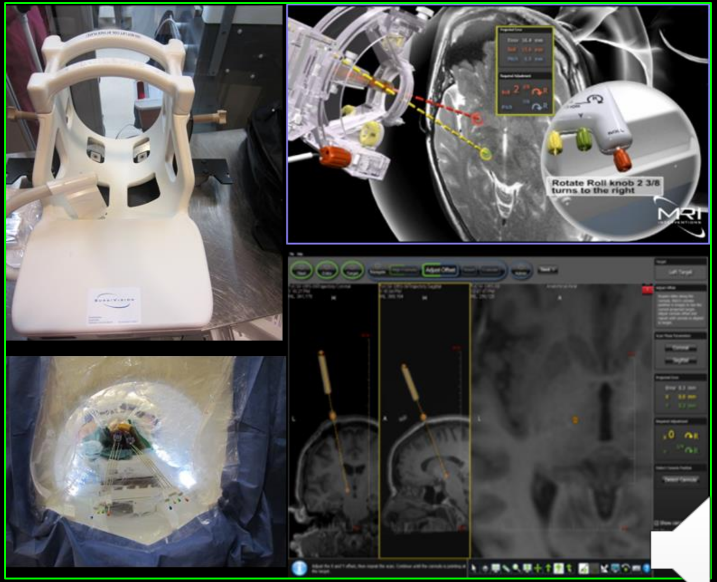


Example: MR-guided laser ablation of metastatic melanoma in brain



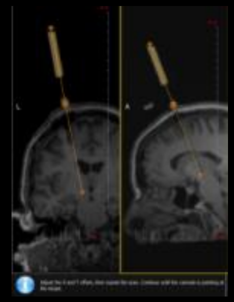
MR-guidance in thermal ablation

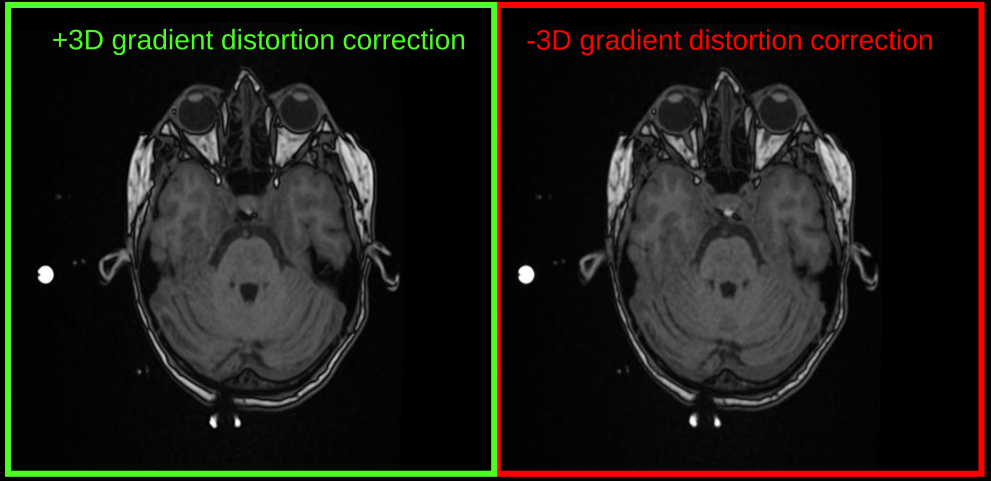
- Potential to use MRI for
  - planning
  - navigation & targeting
  - monitoring & control
  - verification
- Lesion & OAR visualization and delineation critical
- Targeting accuracy
  - Geometric distortion
  - MR-guided navigation systems
- MR protocols: CNR & resolution
- Must verify device placement vs plan

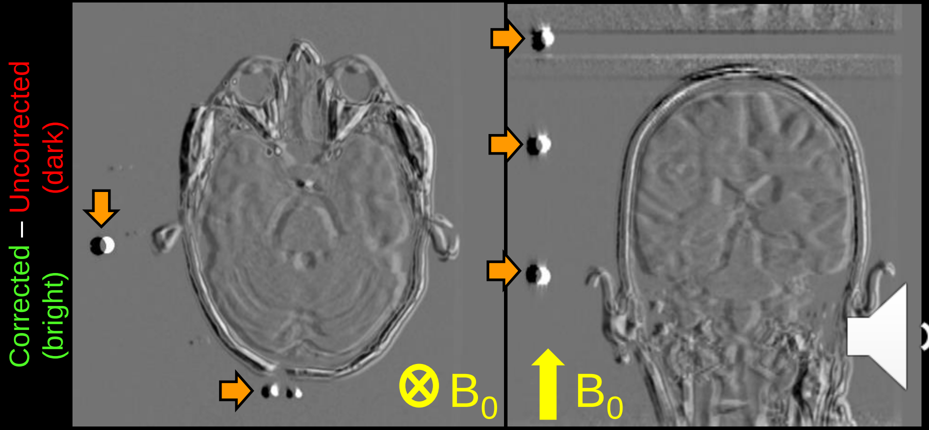


Geometric distortion in MRI

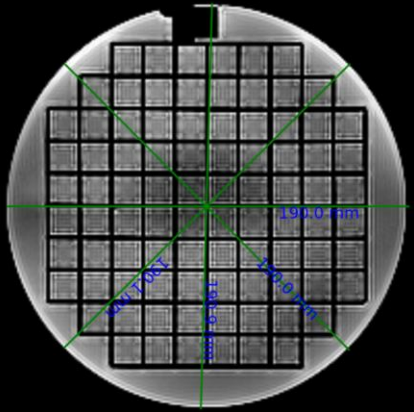
- Field inhomogeneity (δB_0)
  - 2D vs 3D
  - higher rBW
  - higher resolution
  - shimming
- Non-linear gradients
  - software correction
  - 2D vs 3D
- Both effects worsen away from magnet isocenter
  - often this is where navigation fiducials are

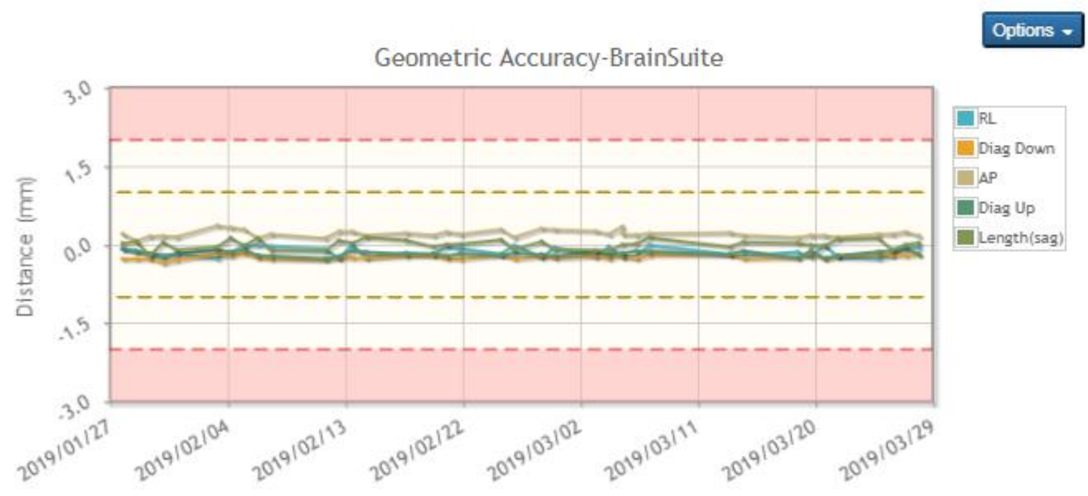


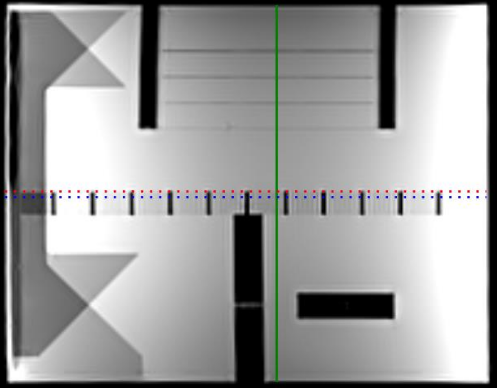


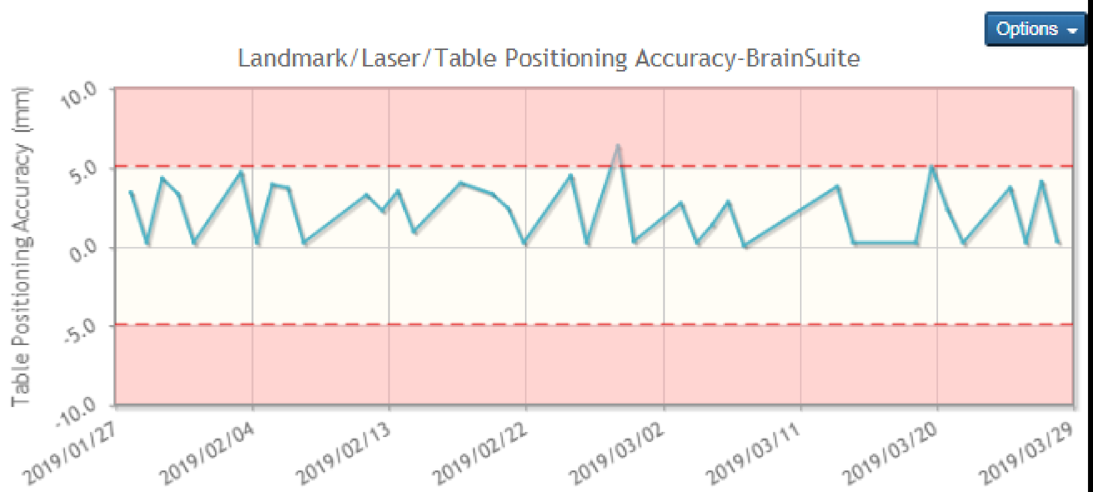


Daily & Periodic MRI Quality Assurance







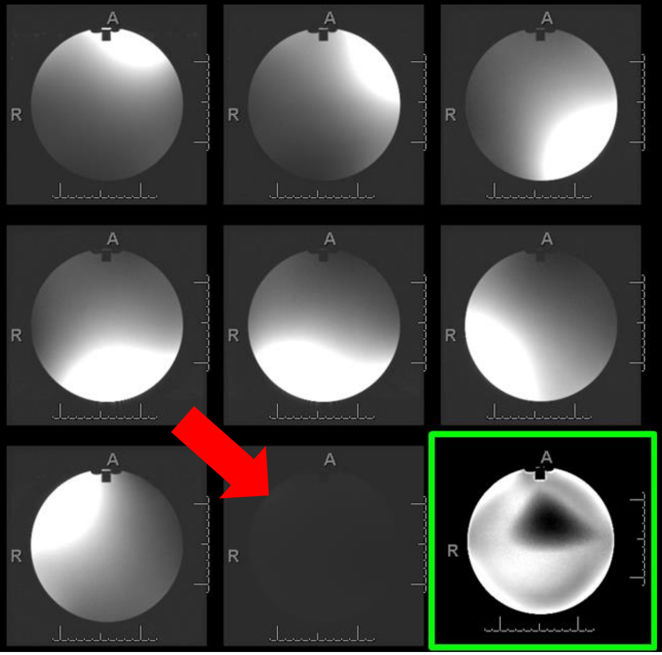


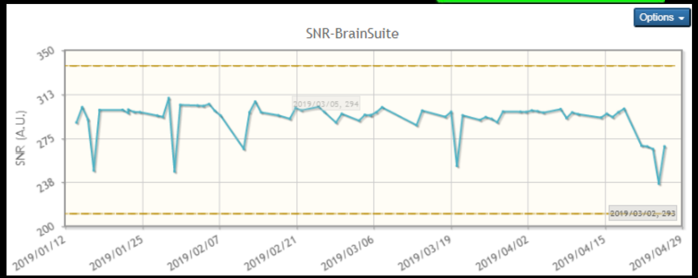
Daily & Periodic MRI Quality Assurance

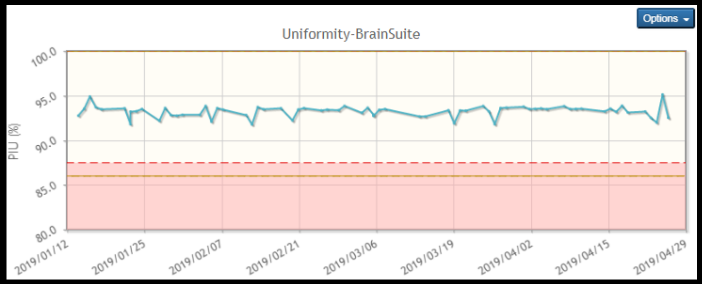
- Periodic equipment performance evaluations mimic recommendations of ACR program
  - daily instead of weekly QA
  - tighter geometric distortion constraint
  - test coil used for procedures
  - ARTIFACT ASSESSMENT

- Tight control over software/hardware upgrades that may impact therapeutic equipment performance

- Approve/review vendor PM







MR-guidance in thermal ablation

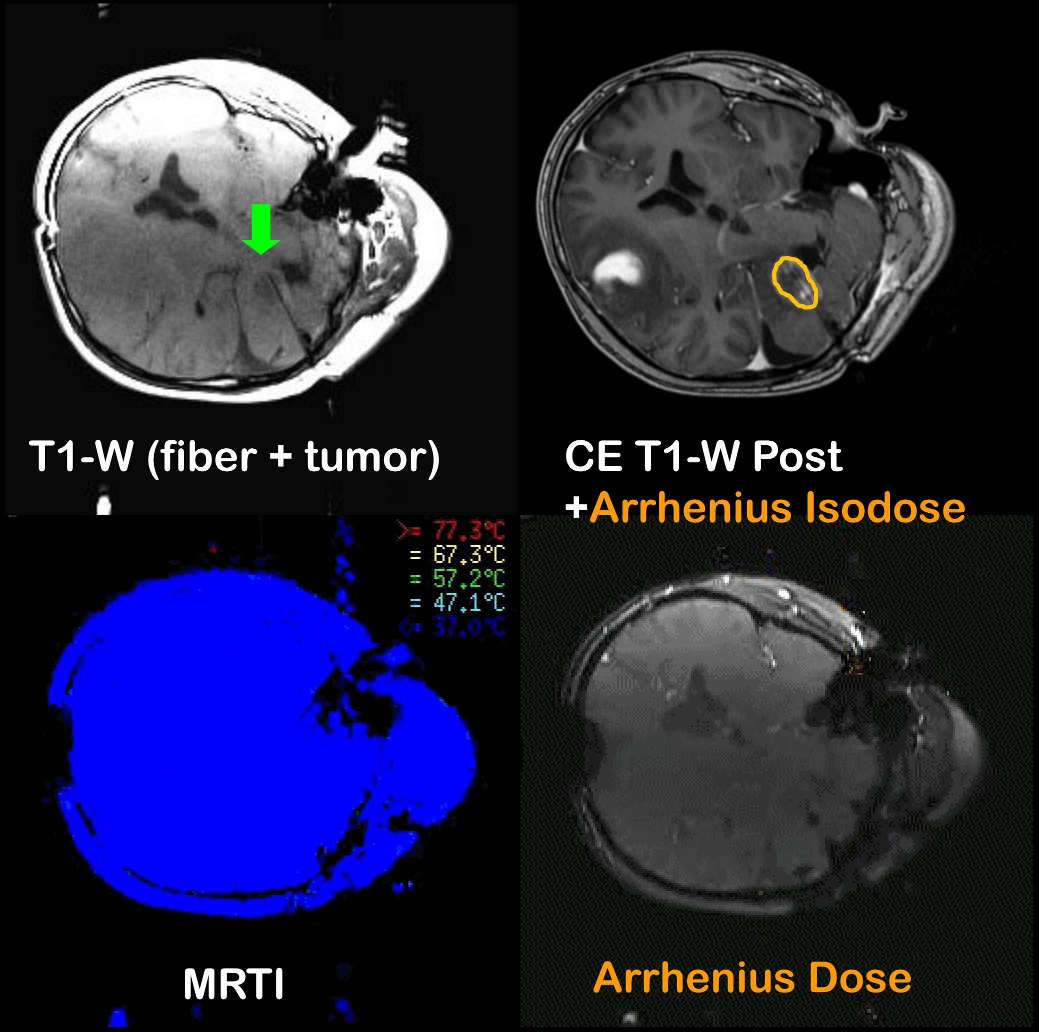
- Potential to use MRI for
  - planning
  - navigation & targeting
  - monitoring & control
  - verification

- Monitor treatment progress

- High temp: device
- Low temp/dose: OAR

- Dose: prediction & control

HIGH-GRADE ASTROCYTOMA



T1-W (fiber + tumor)

CE T1-W Post +Arrhenius Isodose

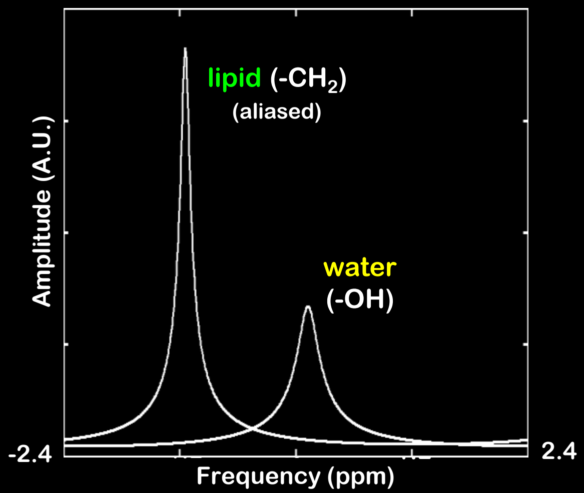
MRTI

Arrhenius Dose

MR Temperature Imaging for monitoring

- Diffusion
- T1-relaxation
- **PRF Shift**

(water proton resonance frequency)

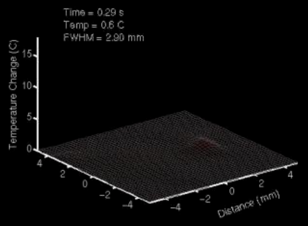


Fast chemical shift imaging
(1x1x3mm voxel)

- Linear shift in frequency (γB_0) of α (-0.01 ppm/°C) measured using fast gradient-echo phase-change ($\Delta\phi$)

$$\Delta\phi = (2\pi \cdot \gamma B_0 \cdot TE) \cdot \alpha \cdot \Delta T$$

- $$SNR_{\Delta\phi} = \frac{\Delta\phi}{\sigma_{\Delta\phi}} \propto TE \cdot SNR_{magnitude}$$
  - $TE_{opt} \sim T2*$
  - optimize magnitude SNR for $\sigma_{\Delta\phi}$



GRE phase

- Challenges
  - *relative* temperature changes
  - lipid does not shift with temperature
  - field drift, susceptibility, motion/flow

Reviews: Kuroda, K., Int J Hyperthermia, 21:547-60 (2006); Rieke, V. & Butts Pauly, K, JMRI, 27:376-90 (2008)

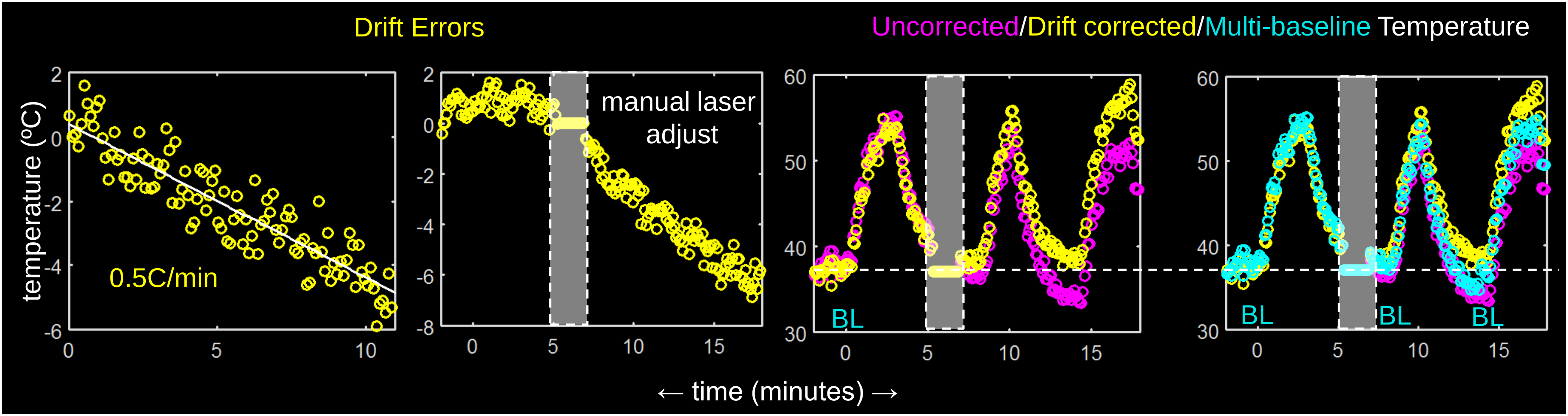
MR thermometry: managing key assumptions

- Phase-changes from temperature only
  - drift
  - magnetic susceptibility
  - phase-wrap
  - motion and/or flow

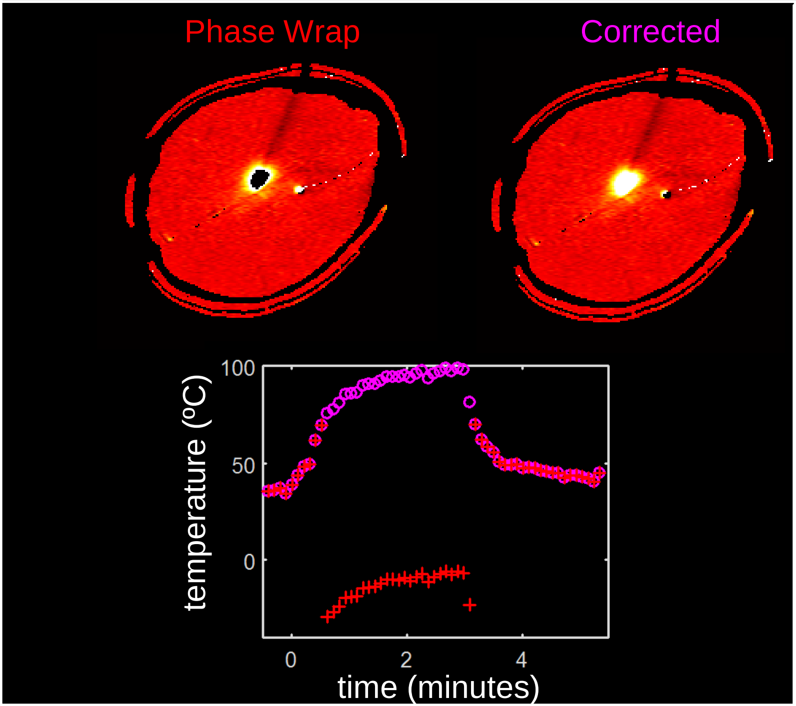
- Baseline temperature is known
  - remember only temperature change measured
  - *must* acquire reference prior to heating/cooling
  - drift correction: points *cannot* be in area of active heating or cooling
  - multi-reference: temperature *must* be back to baseline
    - leave cooling on after ablation to carry away heat
    - *do not* cool below baseline and then set reference

- Temperature sensitivity coefficient is known
  - lipid, magnetic susceptibility, blood, contrast agents

MR thermometry: managing key assumptions


Drift Errors

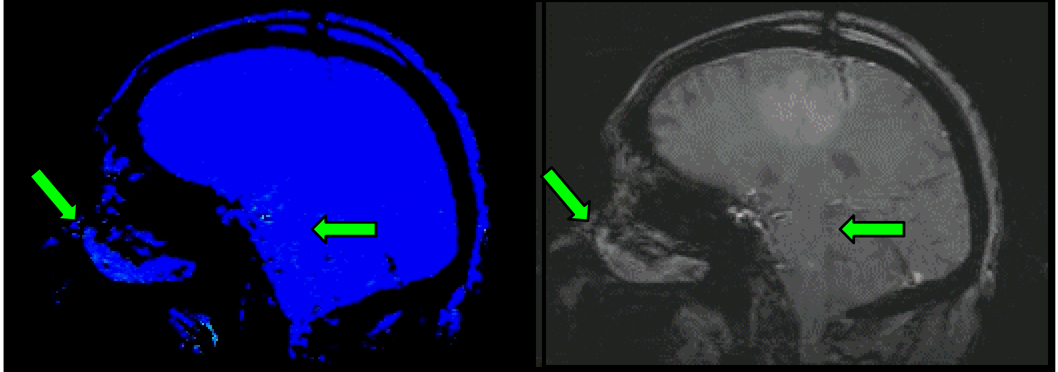
Uncorrected/Drift corrected/Multi-baseline Temperature



Motion & Flow

Temperature
(errors may be transient)

Integral Dose
(errors accumulate)



Thermal dose considerations

- Thermal damage is cumulative effect
  - isotherm characterization of bioeffects limited
  - high/low isotherms good for device/OAR protection
- Arrhenius models (Ω): damage as function of thermal exposure

$$\Omega = A\int_0^t e^{\frac{-E_a}{RT(\tau)}}d\tau$$

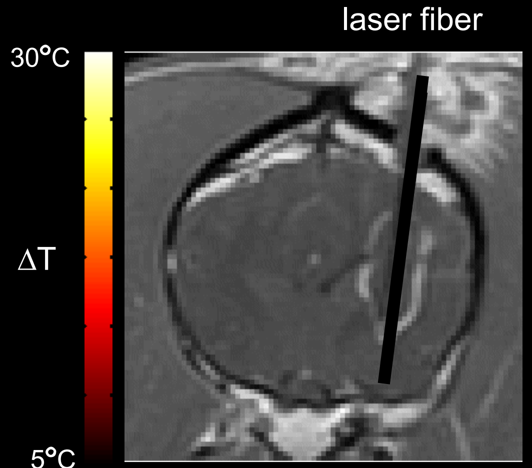
R = Universal Gas Constant
A = Frequency Factor (3.1 x 10^{98} s^{-1})
E_a = Activation Energy (6.3 x 10^5 J)

Henriques FC, Arch Pathol, (1947)

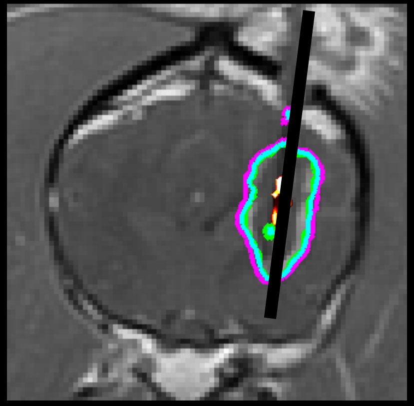
- Cumulative Equivalent minutes @ 43°C (CEM_{43})
  - compare with hyperthermia exposure isoeffects

$$\mathrm{CEM}_{43}(t_n) = \sum_{t=0}^{n\cdot\Delta t} \mathrm{R}^{(43-T_n)}\cdot\Delta t,\ \text{with R=}\begin{cases}0.25 & T_n < 43°C \\ 0.50 & T_n \geq 43°C\end{cases}$$

Sapareto SA, Dewey WC Int. J. Rad. Onc. Bio. Phys., 1984.; Damianou C, Hynynen K, JASA, 1994.



Normal Canine Brain

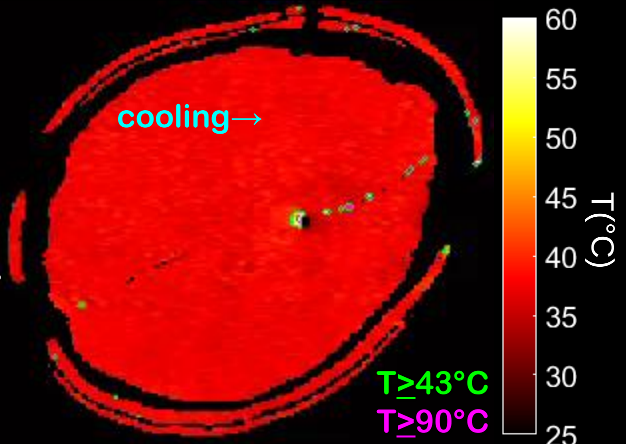


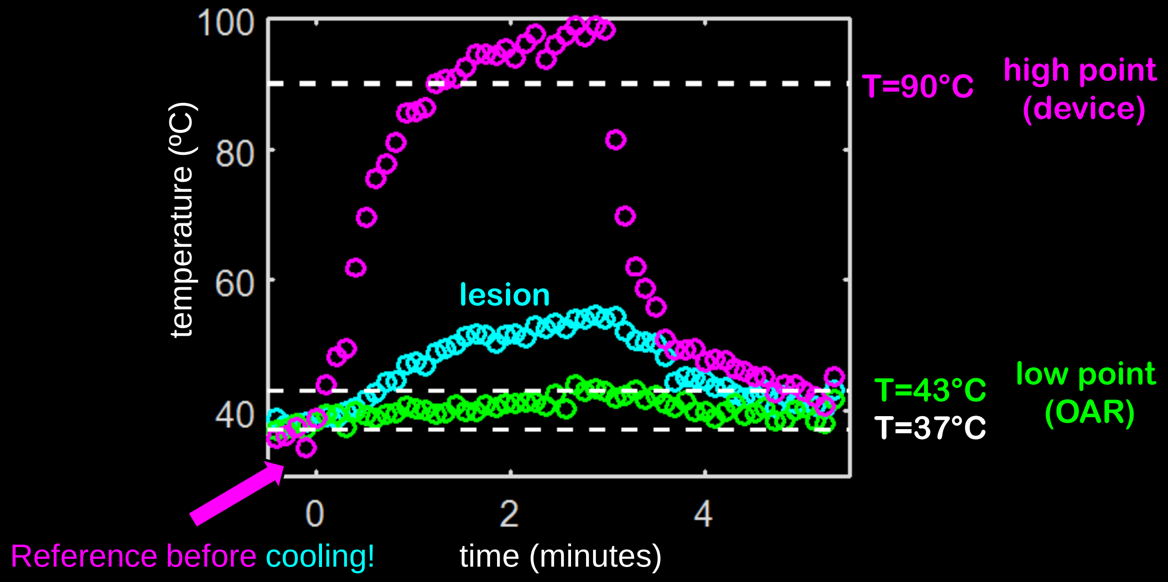
$\Omega \geq 1$
$T \geq 57°C$
$CEM_{43} \geq 240$ min

Thermal dosimetry model reviews: Pearce J, J Biomech Eng (2015) & Int J Hyperthermia (2011)

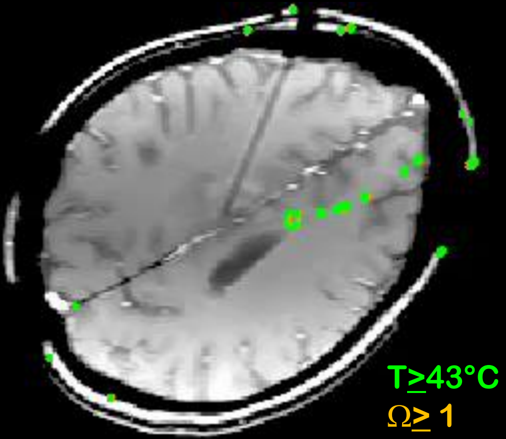
Putting it together: monitoring laser ablations

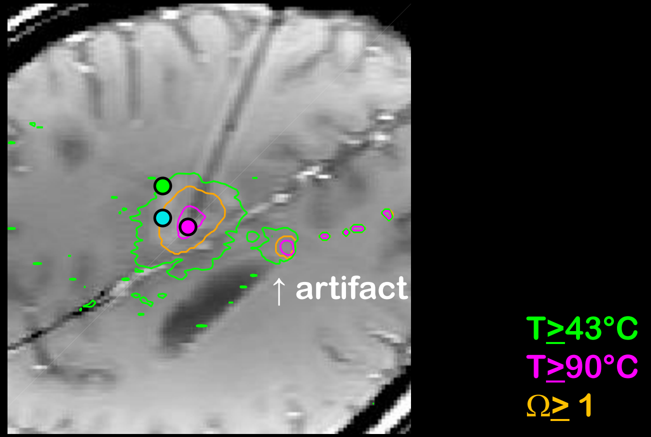
Temperature



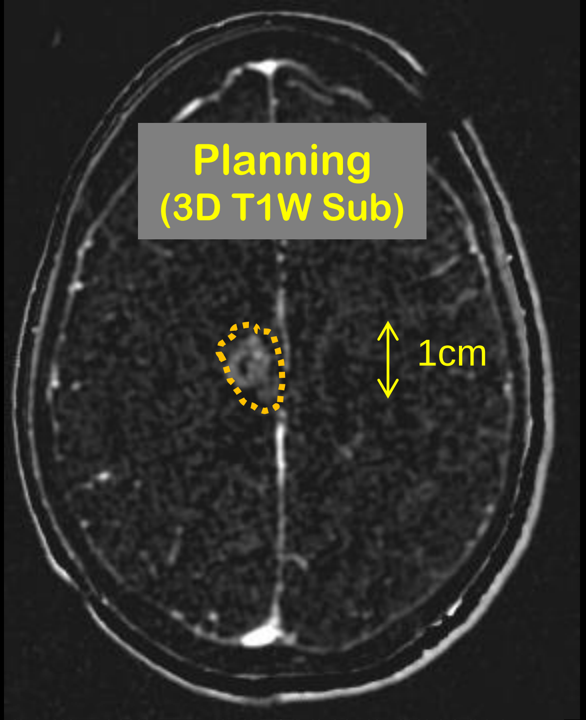


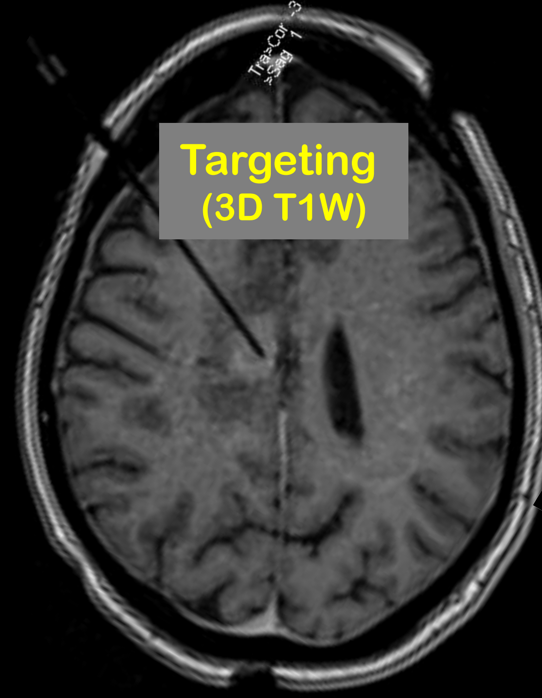
Thermal Dose

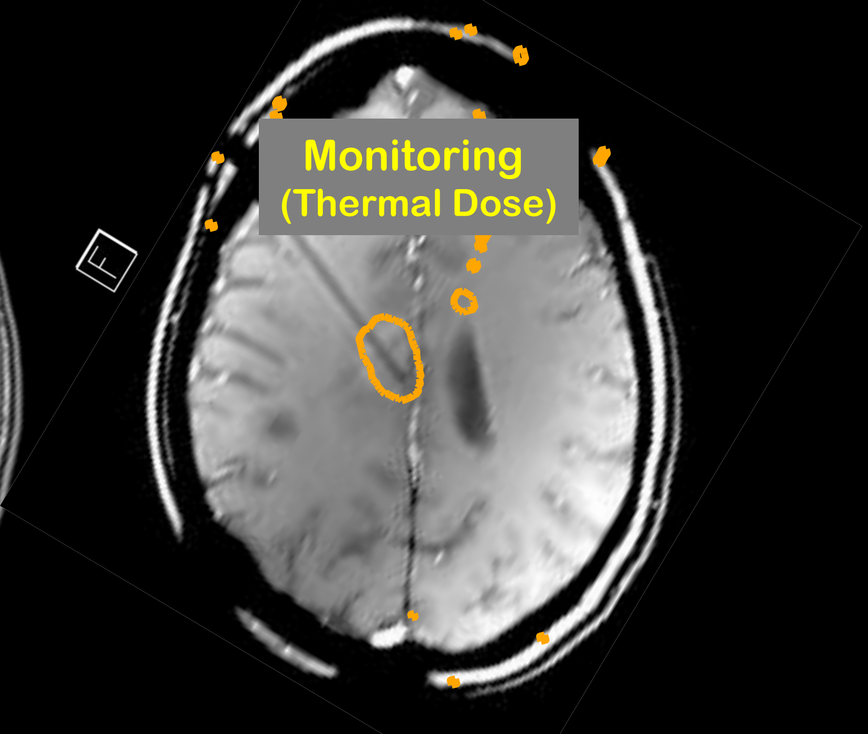


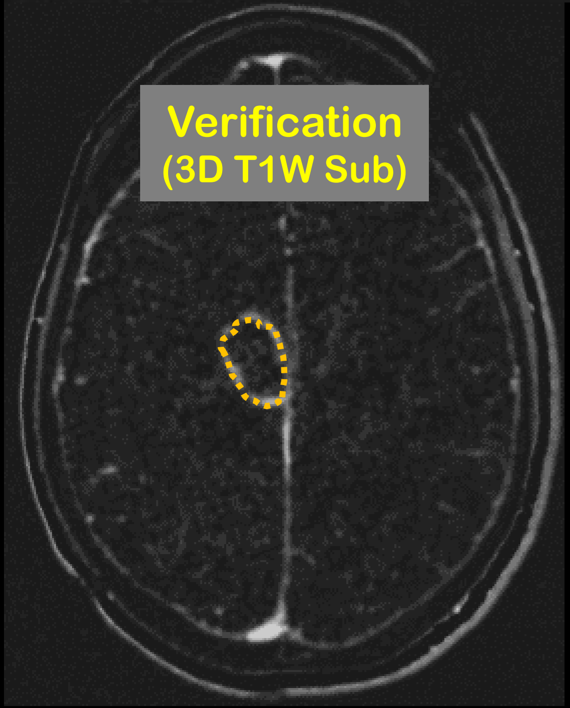


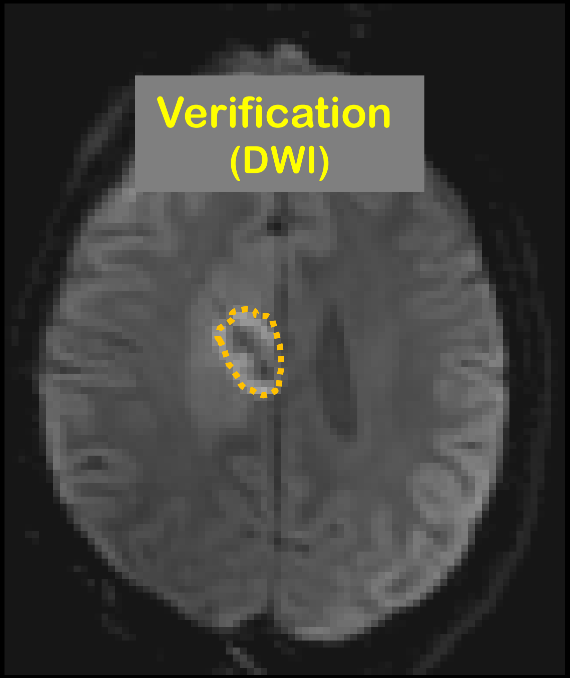
OAR: if you can't see it, you're not protecting it!

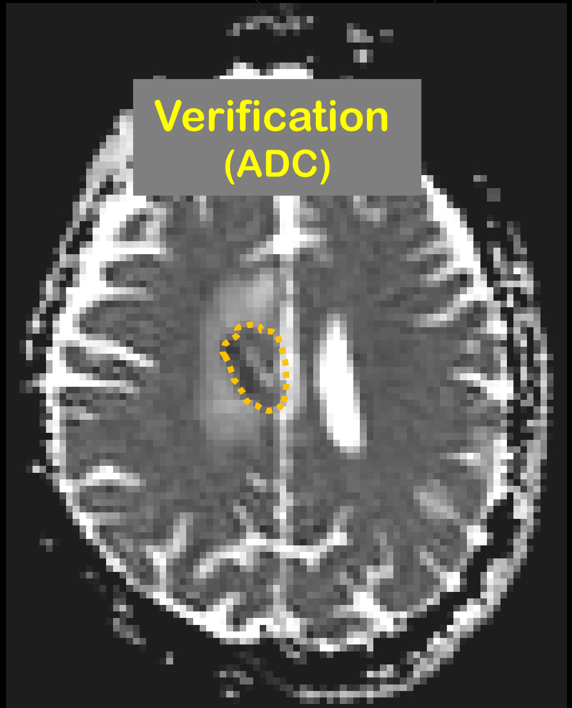

Planning
(3D T1W Sub)
1cm


Targeting
(3D T1W)


Monitoring
(Thermal Dose)
F


Verification
(3D T1W Sub)


Verification
(DWI)


Verification
(ADC)

Conclusions

- Holistic understanding of technical laser ablation and MR monitoring process helps avoid pitfalls
  - basic physics, order of operations & procedures
- Some key considerations include:
  - patient & equipment selection
  - planning: size, needed exposure(s) and OAR
    - anatomy to be monitored and ability to perform MRTI over region
  - targeting: distortions and image-verification
  - monitoring: temperature/dose regulation points
    - when to turn cooling on/off
    - when to set/reset MR temperature references
    - MRI protocols vs laser vendor limitations
      - *temperature/anatomy overlay limitations*
      - *do not heat faster than can monitor*
    - interpreting and avoiding temperature & dose artifacts

Thank you for your time!

Email: jstafford@mdanderson.org