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


Ex vivo porcine liver
15W for 120s @980nm
Overview of laser ablation

Applicator (internally cooled)

Tumor

Tissue Parenchyma
Overview of laser ablation

**HEAT SOURCES** (laser, ultrasound, RF, microwave, etc):

\[ P = \text{absorbed power density (W m}^{-3}\text{)} = \text{SAR} \times \rho \]

**HEAT CONDUCTION** (diffusion):

\[ T = \text{temperature (Kelvin)} \]
\[ \rho = \text{density (kg/m}^3\text{)} \]
\[ c = \text{specific heat of material (J kg}^{-1} \text{ºC}^{-1}\text{)} \]
\[ k = \text{thermal conductivity of tissue (W m}^{-1} \text{ºC}^{-1}\text{)} \]

**HEAT CONVECTION** (effects of perfusion):

\[ \rho_b = \text{blood density (kg m}^{-3}\text{)} \]
\[ V = \text{volume flow rate per unit volume (s}^{-1}\text{)} \]
\[ C_b = \text{specific heat of blood (J kg}^{-1} \text{ºC}^{-1}\text{)} \]
\[ \kappa = \text{dimensionless convection scale factor} \]

\[ g = \text{anisotropy factor} \]
\[ \mu_a = \text{optical scattering} \]
\[ \mu_i = \text{optical absorption} \]

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

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Laser Type</th>
<th>Absorption: Blood</th>
<th>Absorption: Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>805</td>
<td>Diode</td>
<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>940</td>
<td>Diode</td>
<td>+++</td>
<td>++</td>
</tr>
<tr>
<td>980</td>
<td>Diode</td>
<td>++</td>
<td>+++</td>
</tr>
<tr>
<td>1064</td>
<td>Nd:YAG</td>
<td>+</td>
<td>++</td>
</tr>
</tbody>
</table>

Overview of laser ablation

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

- Laser (\( \lambda \approx 800-1064 \) nm)
- Photon absorption
- SAR \( \approx \mu_a \varphi \)

Tumor

Applicator (internally cooled)

Tissue Parenchyma

Higher absorption \( \rightarrow \) more heating
Higher scattering \( \rightarrow \) less penetration
\( \rightarrow \) more local absorption
\( \rightarrow \) more heating

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Overview of laser ablation

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

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.

Overview of laser ablation

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

This can result in cold spots.

Overview of laser ablation

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

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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.

Applicator (internally cooled)

Cooling functions 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
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
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 ($\delta B_0$)
  - 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

Geometric Accuracy - BrainSuite

Landmark/Laser/Table Positioning Accuracy - BrainSuite
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
MR Temperature Imaging for monitoring

- Diffusion
- T1-relaxation
- PRF Shift

Linear shift in frequency ($\gamma B_0$) of $\alpha$ (-0.01 ppm/°C) measured using fast gradient-echo phase-change ($\Delta \phi$)

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

- $TE_{opt} \sim T2^*$
- optimize magnitude $SNR$ for $\sigma_{\Delta \phi}$

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

MR thermometry: managing key assumptions

- Phase-changes from temperature only
  - drift - phase-wrap
  - magnetic susceptibility - 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**
  - Temperature (ºC)
  - Time (minutes)
  - Drift corrected
  - Manual laser adjust

- **Uncorrected/Drift corrected/Multi-baseline Temperature**

- **Phase Wrap**
  - Corrected

- **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 ($\Omega$): damage as function of thermal exposure

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

- $R_e = $ Universal Gas Constant
- $A = $ Frequency Factor (3.1 x $10^9$ 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

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


Putting it together: monitoring laser ablations

Temperature

- $T > 43\, ^\circ\text{C}$
- $T > 90\, ^\circ\text{C}$

Thermal Dose

- $T > 43\, ^\circ\text{C}$
- $\Omega \geq 1$

Reference before cooling!

$T=90\, ^\circ\text{C}$

$T=43\, ^\circ\text{C}$

$T=37\, ^\circ\text{C}$

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

Lesion

low point (OAR)

high point (device)

artifact

$T > 43\, ^\circ\text{C}$

$T \geq 90\, ^\circ\text{C}$

$\Omega \geq 1$
Planning (3D T1W Sub)

Verification (3D T1W Sub)

Targeting (3D T1W)

Monitoring (Thermal Dose)

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!

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