Catheter-Based Ultrasound For 3D Control of Hyperthermia & Thermal Ablation with Image Guidance

Catheter-Cooled Configuration

Thermal Therapy Mediated Effects

- **Non-Lethal Moderate Temperature Exposure (40.45 °C [104-113°F])**
  - ↑ metabolism, inactivation of enzymes, rupture cell membranes, hyperemia, ↑ oxygenation, ↑ blood vessel permeability, heat shock-stress response
  - Gene therapy, drug delivery and activation, adjunct to RT/CT

- **Lethal Moderate Temperature Exposure (41-45 °C, long duration)**
  - Cellular repair mechanisms lose function or can’t keep up with accumulating damage
  - → Cell death & necrosis within 3-5 days

- **Lethal High Temperature (48-50 °C, short to long duration)**
  - Cellular and tissue structural changes
  - Thermal coagulation-irreversible protein denaturation
  - Thermal necrosis & immediate cell death

*Pearce and Thomsen 1995

Catheter-Based Ultrasound for Thermal Therapy 3D control of Hyperthermia & Ablation

- **Interstitial/Percutaneous Ultrasound Applicators**
  - Arrays of Tubular Radiators
  - Prostate, Brain, GYN, Liver, Soft Tissue Sites
  - Hyperthermia and targeted ablation

- **Transurethral/Intraluminal Ultrasound Applicators**
  - Arrays of Tubular, Planar, & Curvilinear Radiators
  - Prostate Ablation & Intrauterine Hyperthermia
  - GI/Digestive tumors

- **MR Temperature/Ablation Imaging**
  - Guidance, Treatment Control, & Assessment

→ Extrapolate to Other Site Specific Design & Treatment

Interstitial Ultrasound Applicators

- Arrays of miniature tubular PZT radiators
- 6-10 MHz, collimated beam output
- 360° or sectored for angle control (e.g., 90°, 180°, 270°)
- Catheter-Cooled Configuration
3D Control of Hyperthermia in HDR Implant
Treatment Planning for two prostate target volumes

- Selection of active length, sector, and aiming - a priori
- Tailor power control & conformal targeting

Applicators
4x10 mm Length
180° & 270° Sectors

HDR Plan
Peripheral Implant
UO+HME
Posterior Target

Technology Implemented for Clinical Hyperthermia
Enhanced spatial control & penetration

Prostate HDR+HT Implant Configuration
60 min HT, 1 Fraction
6-2x10 mm 13-g CC Applicators, ~ 7.3 MHz

USITT - Uterine Sarcoma
HDR+HT Implant Configuration

Hyperthermia 42-45°C for 45 min, 2 Fractions
Sequential HDR Brachytherapy, 4 Fractions

Directional Applicators
- avoid bone & stent
2x10 mm ~7MHz
220 and 360 deg. Applicators

Endocavity Ultrasound Applicator
Local HT + HDR Brachytherapy for Cervical Cancer

Endocavity HDR Ring Applicator

Endocavity US HT + HDR Applicator
Endocavity Ultrasound Hyperthermia
Treatment Simulation of cervix target treatment
Dual Sector Applicator

Dynamic Axial and Directional Control of Ablation
Biothermal Simulations of High-Intensity Ultrasound Devices

Dynamic Axial and Directional Control of Heating
Experiment – ex vivo and in vivo

Thermal Ablation of Uterine Fibroids
Shaped Thermal Coagulation – Ex Vivo Specimens

CTV

Clinical Target Volume

Radial Depth of Lesion (mm)

Axial Position (mm)

Axial Control
Multiple Transducer Segments
Independent Power Control

Angular Control
Secected Tubular Radiators
Pre-Selected Directioity

Concept
• Hysteroscopic or Laparoscopic
• Similar to RF, Laser, & Cryo
• Fast, Large Volume Ablation
• Selective Targeting, MRTI possible

Experiment
• Surgical Specimens
• 8 mm Ablations
• Ex Vivo Lesions
• TTC Stained
• ~ 4 cm OD x 5 cm long
Liver Ablation

Example of Tailored Lesions Ex Vivo

- 3x360° at 13 W, 10 min
  - 4.2 cm wide x 3.5 cm long
- 3x160° at 12 W, 10 min
  - 2.0 cm radial x 3.2 cm long
- 3x 360° Cluster Array
  - 7.5 cm x 4.2 cm long

Ultrasound Strain Imaging
- Terason Imaging probe
- External Compression
- RF data 15fps, <1 min comp time

MRTI for Device Evaluation & Control

- 0.5T GE Interventional MRT, 1.5T and 3.0T GE
- Applications for Prostate Ablation

MR Thermal Imaging (MRTI)
- Phase-difference mapping (PRF shift)
- SPGR (TE/TR=10-15 ms/120-190 ms, FA=60°)
- Endorectal receive coil maximizes SNR
- Resolution: 1.6 mm x 1.6 mm, 1.2 °C
- 3 planes simultaneously, 1-2 updates
- Integrated cooling on endorectal coil

Real-Time Monitoring Software
- Current Temperature
- Temperature Thresholds (52 °C)
- Thermal Dose (t > 120-240 min)

Interstitial Ultrasound

Directional And Longitudinal Control of Lesion

Experimental Setup:
- Applicator: 10 mm x 180 deg., 7.2 MHz
- Canine Prostate – In Vivo
- Ventral Placement, Direct Away from Urethra
- Chronic Study → Slow Controlled Heating
- 10-14 W Modulated for 15 min

MRTI Guided USITT - In Vivo Prostate, 0.5 T

- Dynamic Rotation of Interstitial Applicator w/MR Control

Temperature Distribution Mid-Gland
- 15-20 mm radial penetration in vivo
- Manual rotation/sweeping possible
- Conformal treatment

→ Conforming Therapy to Target Boundary
Multiple Applicator Implant
*In Vivo Prostate – “Posterior” 3-180° Applicators*

- **Maximum Temp**:
  - Urethral Cooling
  - Endorectal Cooling

- **Thermal Dose**:
  - 50 min
  - 240 min
  - 1000 min

- **Power Applied**: 5-17 W, 20 min

Nau et al., Medical Physics 2005

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Targeted Prostate Thermal Therapy w/ MRg
*Transurethral Catheter-Based Devices – BPH & Cancer*

- Design Schema and Strategies
  - Linear Transducer Array
  - Flexible Delivery Catheter
  - Urethral Cooling Balloon
  - Tubular, Planar, Curvilinear
  - Real-time MRTI monitoring/control

- Develop devices and evaluate approaches for delivering conformal therapy within *in vivo* canine prostate with MR temperature monitoring.

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**Multi-Sected Tubular Transurethral Applicator**
*Dynamic Angular & Length Control Without Movement*

- Tubular Array
  - 3.5 mm x 6 mm PZT
  - 3 x 120° sectors/tube

- Bladder Balloon

- Inflatable urethral cooling balloon

- Rotation & translation of assembly for initial position

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**Tri-Sected Tubular Transurethral Applicator**
*In Vivo Canine Prostate Evaluations (n=3) with MRTI*

- Case 1 – Dual-sector Control
- Case 2 – Translation w/ Coronal MRTI
- Case 3 – Tri-sector Control

- Fast selective treatment with dynamic angular control (10-15 min)
- Practical control with MRI feedback

Kiney et al. 2008
Curvilinear Transurethral Applicator
In Vivo Canine Prostate – Single Shots

- Lightly Focused Transducers, 6.5 MHz
- Multiple transducers (2-10mm x 3.5mm)
- 15-20 mm penetration, 1-2 minute shots
- Narrow lesions (~10-20°, 5 mm wide)
- Rotational sweeping w/ MRI compatible motor

Maximum Temp. Thermal Dose

Discrete Shots

Curvilinear Transurethral Applicator
In Vivo Canine Prostate – Conformal Targeting

- MRTI Control (Power, Position)
- ~52°C, t43 > 240 min at boundary
- 6.5 MHz, 10° sequential rotation

S-1

S-2

Catheter-Based Ultrasound Thermal Therapy
Summary

- Produce 3D conformable and effective heating patterns – penetration, dynamic axial and variable angular control
- Tailor heating for sequential hyperthermia within an HDR implant
- Transurethral and interstitial provide conformal & selective ablation
- Coupling MRTI with dynamic power control has potential for “precise” therapy targeting to prescribed boundary
- Dual mode devices – potential for delivery and guidance
- More complex but precise therapy possible
- Configurations adaptable for site and disease specific therapy

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MRTI Guided USITT
In Vivo Canine Brain Tumor

Setup:
- Implanted TVT Tumor
- Craniotomy 5 mm Burr Hole
- PRF: Interleaved gradient echo EPI
  (TR/TE=1000ms/40 ms, FA=60°)

ICDC Applicator:
- 2.2 mm OD x 10 mm, ~7.1 MHz, ~60°
- ~4-12 W for 10 min, 20 ml/min at 22 °C

Cooling T1 CE:
t1/2 = 50 min

Tumor: 1.7 cm OD