High Intensity Therapeutic Ultrasound Ablation of Tendons Ex Vivo

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Background
Clinical presentation

strenuous, repetitive motion (e.g., athletics)

- Stenlund 1993
- Kettunen 2006

tendinopathy

- Warden 2007

tendinosis

- Wired 2007
Structural causes

collagen fibril length & cross-linking

regrowth is disordered

Silver 2003
Vanderby 2003

McShane 2006

disordered collagen is weaker

tensile tendon strength
Current treatments

- Local injections of steroids and anesthetics  
  - Skin puncture, limited relief  
  *McShane 2006*

- Percutaneous tenotomy by blade  
  - Accessibility of blade, incision of overlying tissue  
  *Maffuli 1997*

- Percutaneous tenotomy by needle  
  - Skin puncture, patient resistance  
  *McShane 2006*

- Physical therapy  
  - Limited *per se*, patient commitment  
  *Christenson 2007*

- Extracorporeal shock wave therapy  
  - Limited effectiveness for non-calcific disease  
  *Harniman 2004*
  - Broad (82 mm x 20 mm) focal region, difficult to aim  
  *Cleveland 1998*
Ultrasound-guided therapy

preliminary ultrasound findings

needle tenotomy

from McShane 2006
HITU & collagen

rabbit scleral cross sections
HITU @ 4.6 MHz, 2 kW/cm², 5 s
from Coleman 1985

untreated
thick collagen fibrils

immediately post-HITU
many fibrils are dissociated

3 months post-HITU
new fibroblasts and new collagen fibrils

~ 1 μm
Attenuation in collagen

\[ \alpha \approx 2.9 \text{ dB MHz}^{-1} \text{ cm}^{-1} \]

Can HIFU penetrate and ablate thick tendon?

\[ I = I_{\text{free}} e^{-\frac{2}{\alpha} f \Delta x} \]

- \( I \): intensity
- \( I_{\text{free}} \): from Rayleigh-Sommerfeld
- \( \alpha \): attenuation coefficient
- \( f \): frequency
- \( \Delta x \): path length

Data from Goss 1979
Methods
Achilles tendon

bovine deep digital flexor

Dyce 2002
Models

PBS 23 °C, 37 °C

tendon
rubber

bare tendon model

PBS 37 °C

muscle
tendon
glass

layered model

30° 0°

10 mm
Transducer

5 annuli
central diagnostic array

Sonic Concepts therapy
33 mm diameter
7.0 W to 9.3 W
focal region
  35 mm axial position
  0.28 mm diameter
  2.5 mm length
Results
Bare tendon ablation

5.25 MHz
0.55 kW/cm²
5 s
6 mm deep
23 °C
Lesion sizes are consistent: 23 °C

<table>
<thead>
<tr>
<th>model</th>
<th>temperature °C</th>
<th>intensity kW/cm²</th>
<th>time s</th>
<th>depth mm</th>
<th>angle °</th>
<th>length mm</th>
<th>width mm</th>
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<tbody>
<tr>
<td>bare tendon</td>
<td>23</td>
<td>0.55</td>
<td>5</td>
<td>6</td>
<td>0</td>
<td>3.60</td>
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<td>0</td>
<td>2.76</td>
<td>2.04</td>
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</table>

\[
I = I_{\text{free}} e^{-2\alpha f \Delta x}
\]

*in-situ* intensity estimate

\[
\alpha = 2.9 \text{ dB MHz}^{-1} \text{ cm}^{-1}, \quad f = 5.25 \text{ MHz}, \quad \Delta x = \text{depth}
\]
Lesion sizes are consistent: 37 °C

<table>
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<th>model</th>
<th>temperature °C</th>
<th>intensity* kW/cm²</th>
<th>time s</th>
<th>depth mm</th>
<th>angle °</th>
<th>length mm</th>
<th>width mm</th>
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<tr>
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<td>37</td>
<td>0.90</td>
<td>2</td>
<td>5</td>
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<td>3.56</td>
<td>1.64</td>
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<td>4.03</td>
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\[ I = I_{\text{free}} e^{-2 \alpha f \Delta x} \]

* in-situ intensity estimate
\[ \alpha = 2.9 \, \text{dB MHz}^{-1} \, \text{cm}^{-1}, f = 5.25 \, \text{MHz}, \Delta x = \text{depth} \]
1 & 2: intramural lesions with no damage to overlying tissue

<table>
<thead>
<tr>
<th></th>
<th>kW/cm²</th>
<th>Muscle Damage (mm)</th>
<th>Tendon Damage (mm)</th>
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<tbody>
<tr>
<td>1</td>
<td>0.3</td>
<td>8.2</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>0.3</td>
<td>7.2</td>
<td>6</td>
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<tr>
<td>3</td>
<td>2.7</td>
<td>8.4</td>
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5.25 MHz
10 s

Muscle folded back and split post-ablation
Layered model ablation - 2

- Muscle folded back post-ablation
- Tendon split post-ablation

<table>
<thead>
<tr>
<th>#</th>
<th>kW/cm²</th>
<th>Muscle</th>
<th>Tendon</th>
<th>Time</th>
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<tbody>
<tr>
<td>1</td>
<td>0.1</td>
<td>9 mm</td>
<td>7 mm</td>
<td>20 s</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>9 mm</td>
<td>7 mm</td>
<td>18 s</td>
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<tr>
<td>3</td>
<td>0.1</td>
<td>9 mm</td>
<td>7 mm</td>
<td>18 s</td>
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<tr>
<td>4</td>
<td>0.1</td>
<td>9 mm</td>
<td>7 mm</td>
<td>15 s</td>
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<tr>
<td>5</td>
<td>0.1</td>
<td>9 mm</td>
<td>7 mm</td>
<td>12 s</td>
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M "marker" lesion

Beam 20° incidence

5.25 MHz
### Angles & intensities, layered model

<table>
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<th>model</th>
<th>temperature °C</th>
<th>intensity * kW/cm²</th>
<th>times</th>
<th>depth mm</th>
<th>θ angle °</th>
<th>mean length mm</th>
<th>mean width mm</th>
<th>number</th>
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<td>6</td>
<td>0</td>
<td>4.48</td>
<td>2.32</td>
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</table>

* *in-situ* intensity estimate

\[
\alpha_{\text{muscle}} = 0.5 \ \text{dB MHz}^{-1} \ \text{cm}^{-1}, \ f = 5.25 \ \text{MHz}, \ \Delta x \approx 1 \ \text{cm/cos} \ \theta
\]

\[
\alpha_{\text{tendon}} = 2.9 \ \text{dB MHz}^{-1} \ \text{cm}^{-1}, \ f = 5.25 \ \text{MHz}, \ \Delta x = \text{depth/cos} \ \theta
\]
Conclusions

- HITU can ablate tendon *ex vivo*
- Lesions are consistent
- Subsurface ablation spares overlying soft tissue
- Frequency, intensity, and time
  - readily achievable
  - clinically convenient
- Relative insensitivity to 20° angle & 30% intensity variations

*Promising for future clinical tendinosis applications*
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Thomas Jefferson University

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Weill Medical College, Cornell University

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