High Intensity Therapeutic Ultrasound Ablation of Tendons *Ex Vivo*

Robert Muratore, Ph.D.
Frederic L. Lizzi Center for Biomedical Engineering
Riverside Research Institute, New York NY USA

Tal Akabas
Cornell University, Ithaca NY USA

Isabella B. Muratore
Portledge School, Locust Valley NY USA

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Background

Clinical presentation

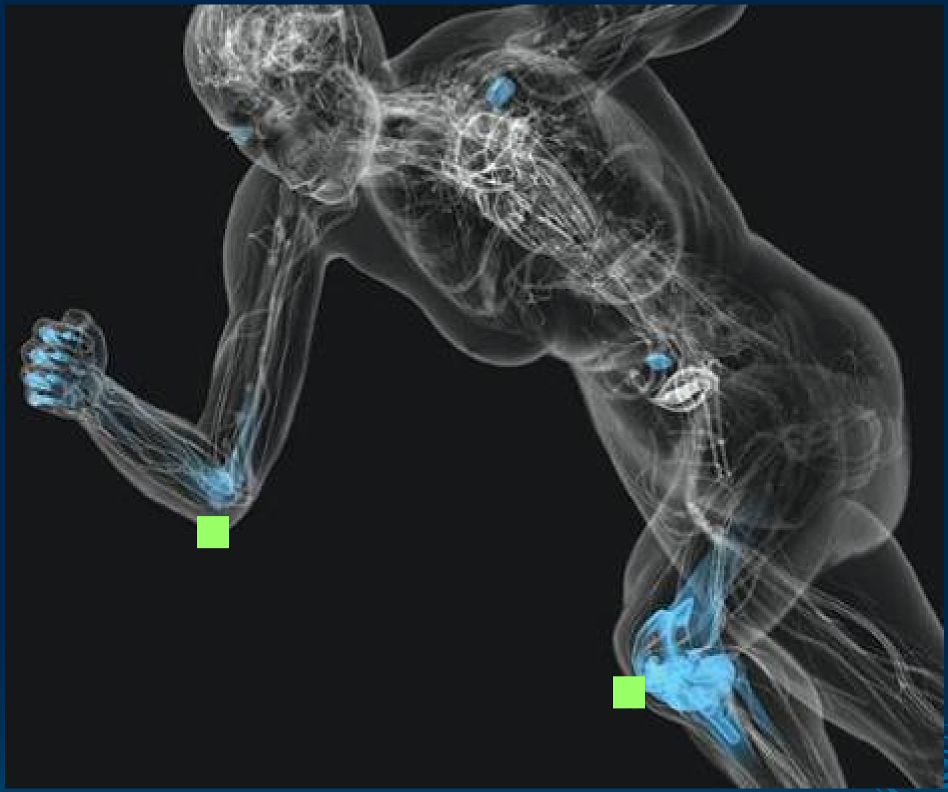
strenuous,
repetitive motion
(e.g., athletics)

↓ *Stenlund 1993*
Kettunen 2006

tendinopathy

↓ *Warden 2007*

tendinosis



Wired 2007

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Structural causes

collagen fibril length & cross-linking

↓ *Silver 2003*
Vanderby 2003

tensile tendon strength

regrowth is disordered

↓ *McShane 2006*

disordered collagen is weaker

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Current treatments

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

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

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

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

- Extracorporeal shock wave therapy *Seil 2006*
  - Limited effectiveness for non-calcific disease *Harniman 2004*
  - Broad (82 mm x 20 mm) focal region, difficult to aim *Cleveland 1998*

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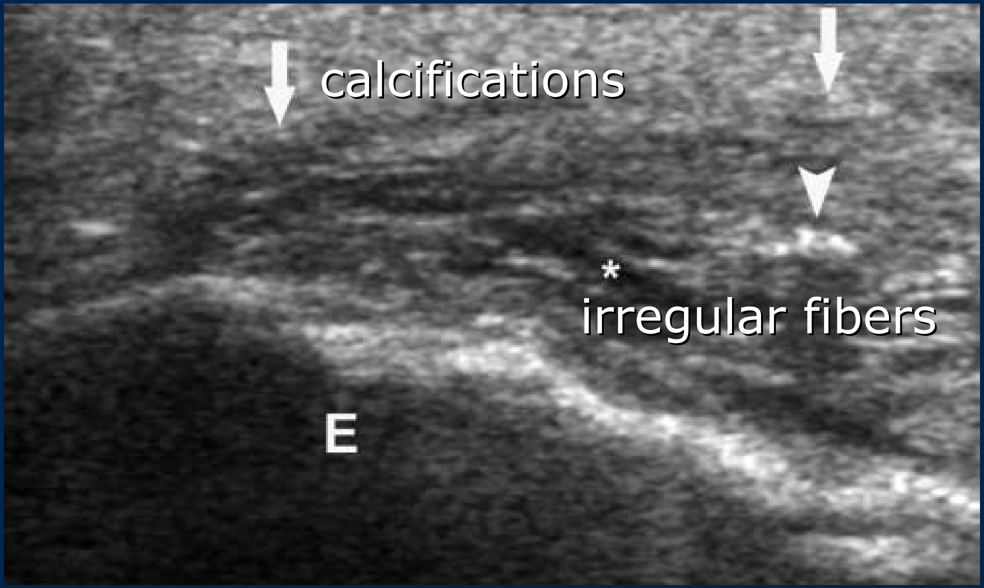
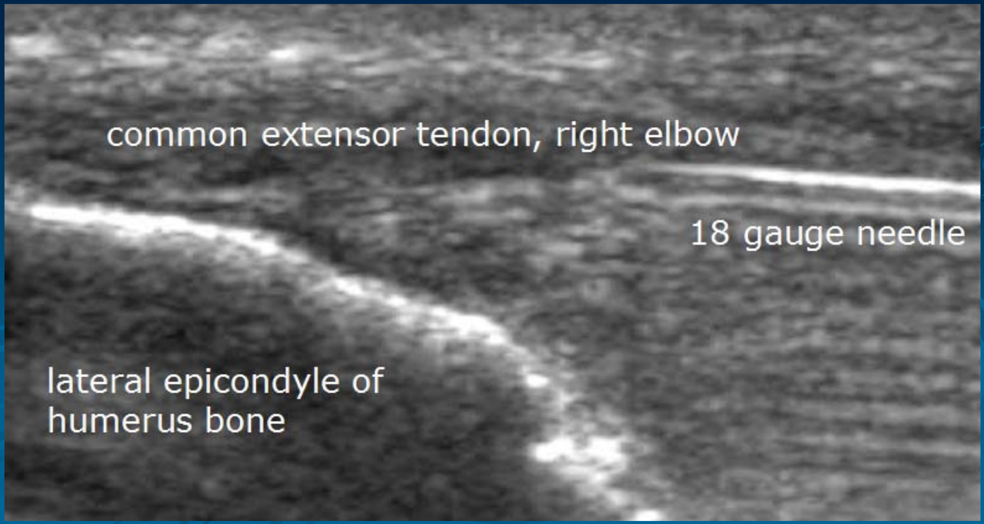
Ultrasound-guided therapy

preliminary
ultrasound
findings



from McShane 2006

needle tenotomy

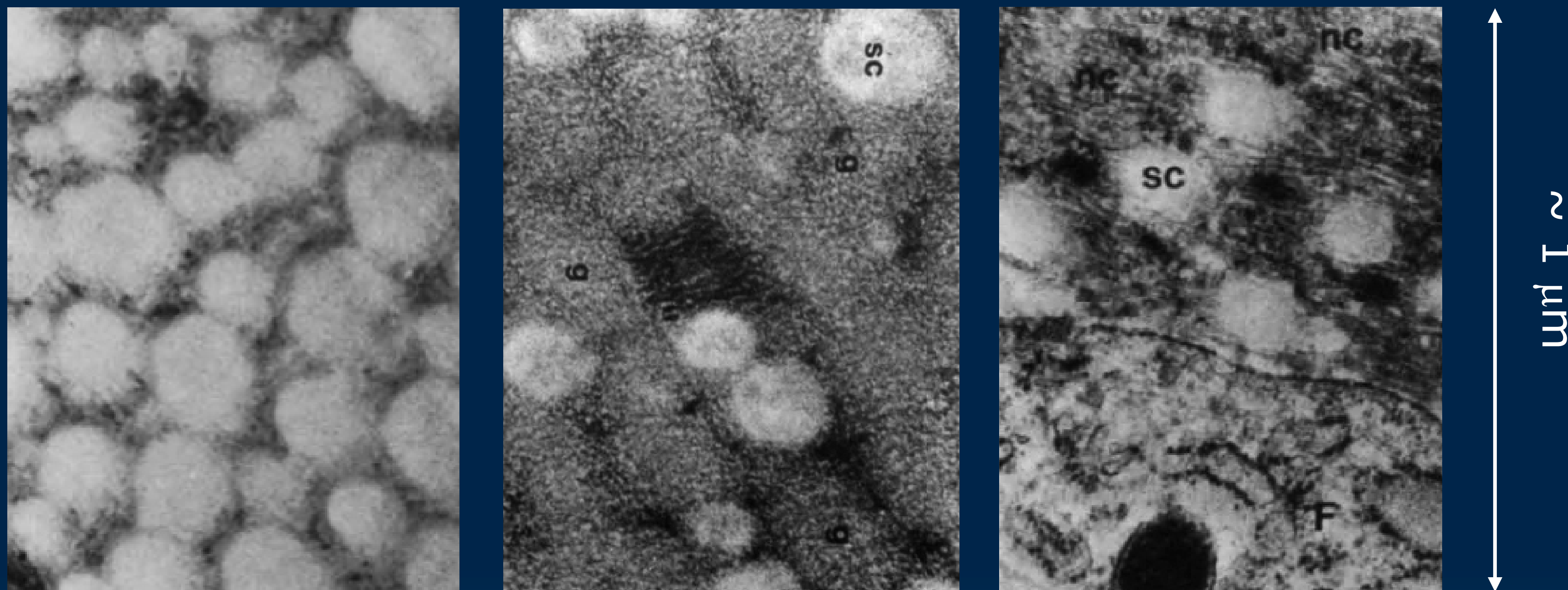


HITU & collagen

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

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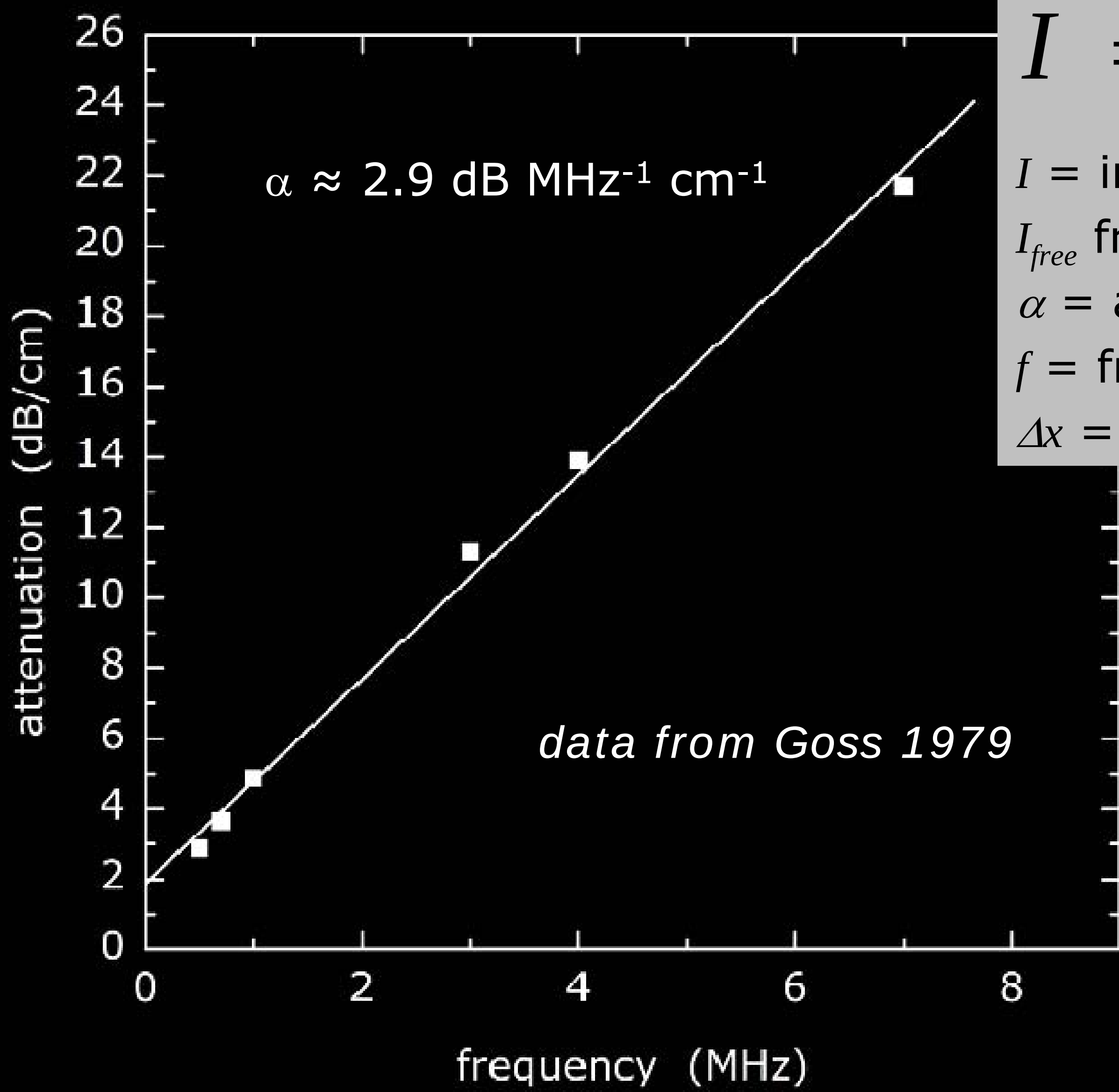
Attenuation in collagen



$$I = I_{free}\, e^{-2\alpha f \Delta x}$$

I = intensity

I_{free} from Rayleigh-Sommerfeld

α = attenuation coefficient

f = frequency

Δx = path length

Can HIFU penetrate and ablate thick tendon?

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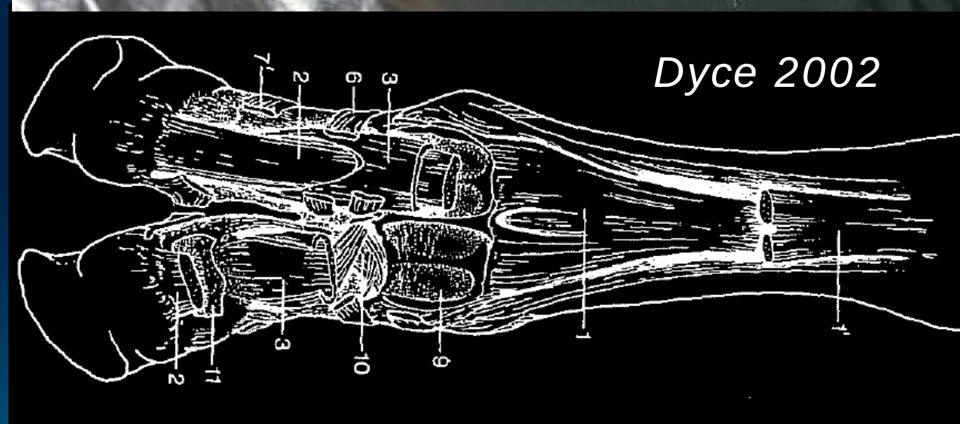
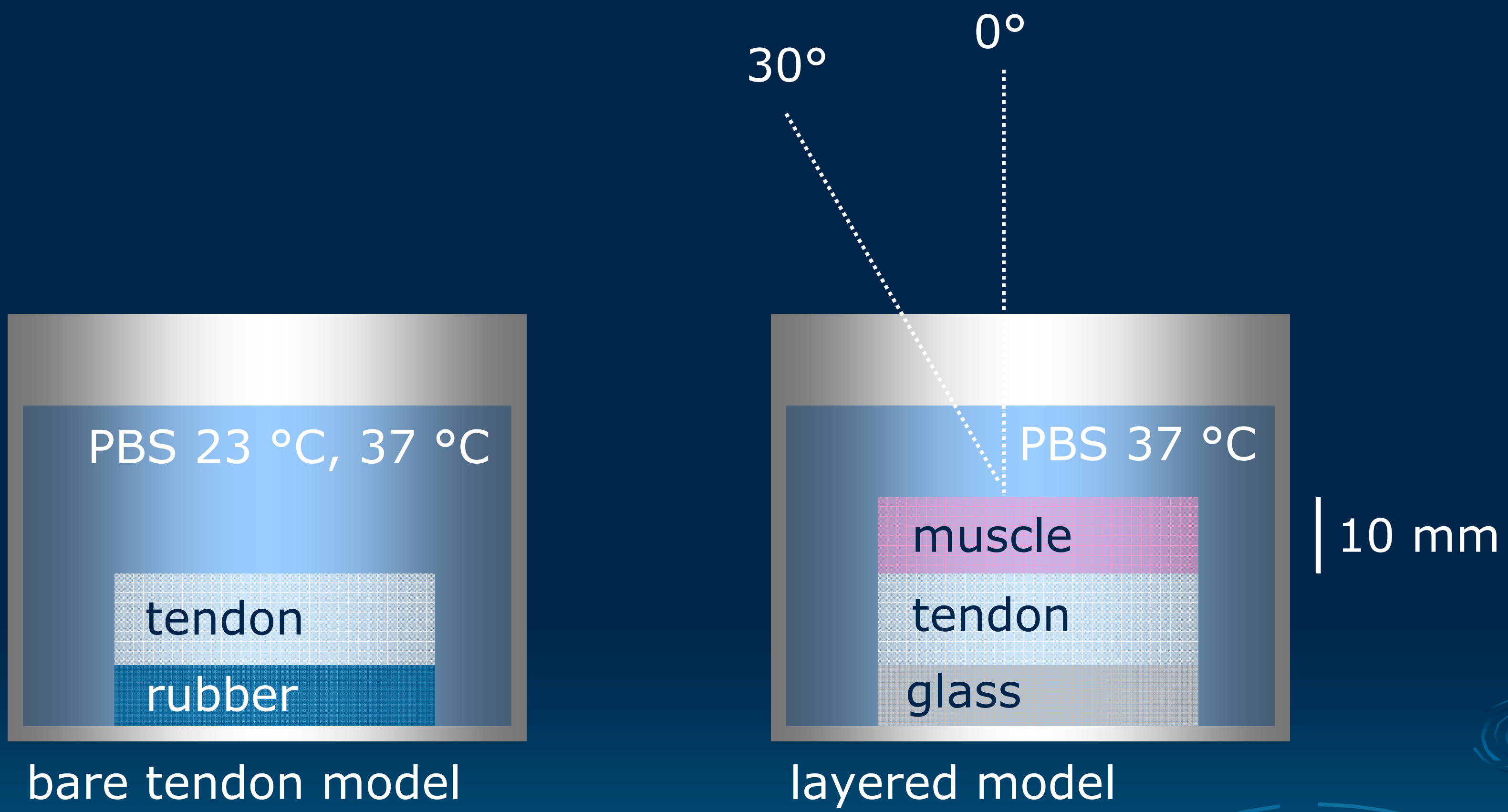
Methods

Achilles tendon

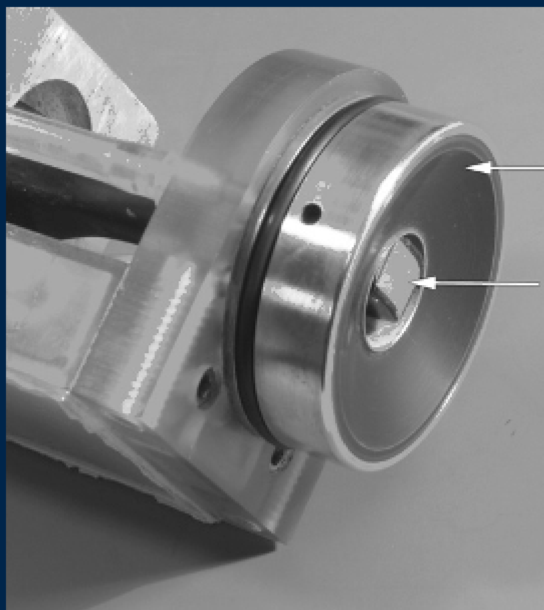


bovine deep digital flexor

Models

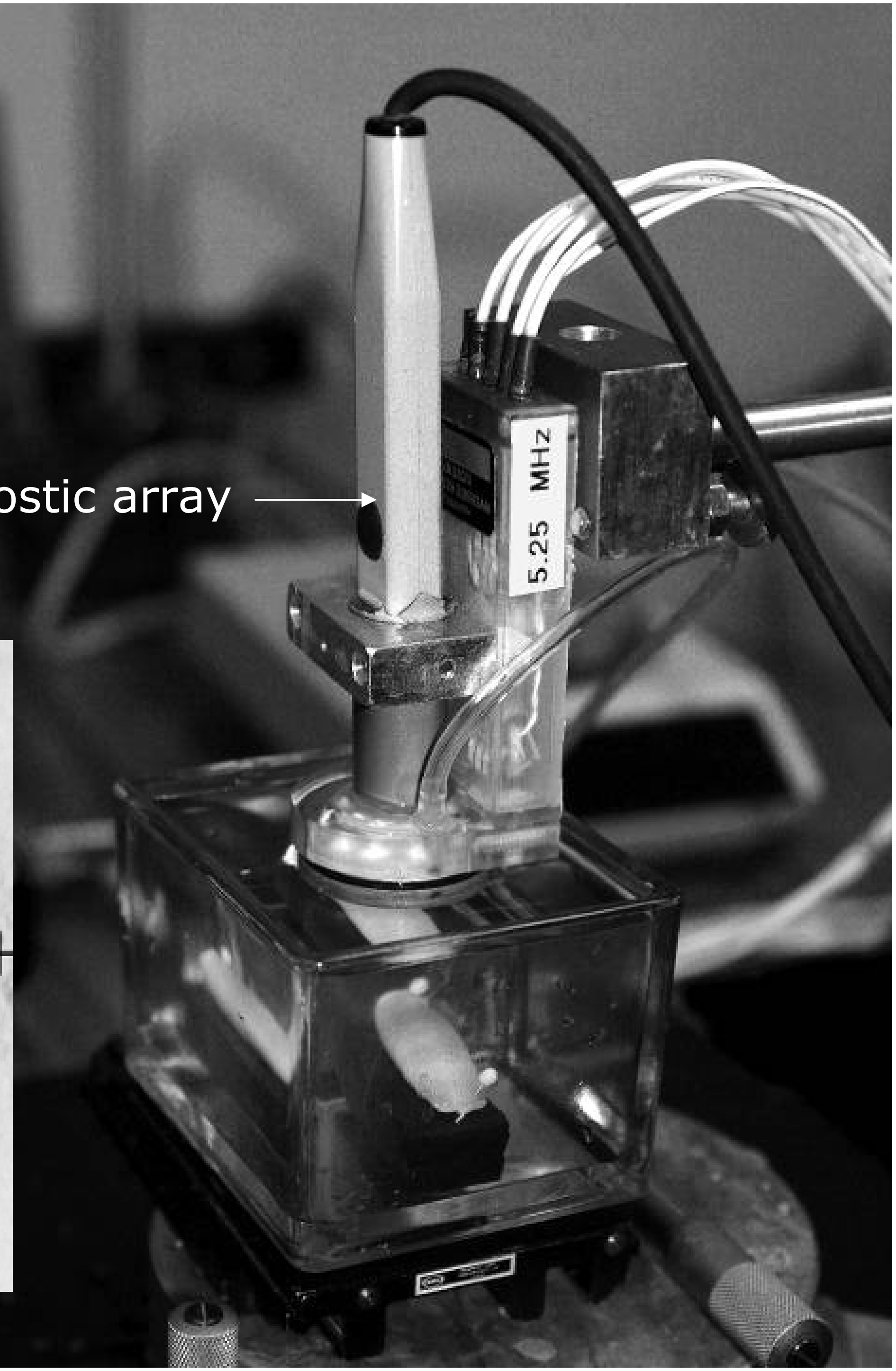

30°
0°
PBS 23 °C, 37 °C
tendon
rubber
PBS 37 °C
muscle
tendon
glass
10 mm
bare tendon model
layered model

Transducer



5 annuli

central diagnostic array



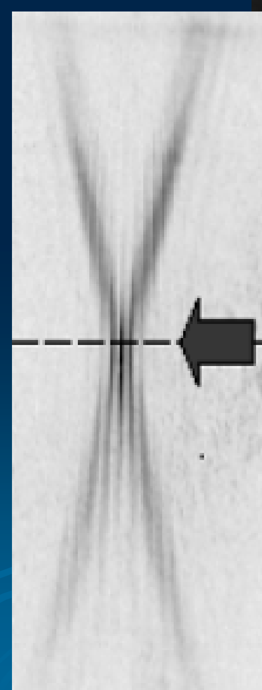
Sonic Concepts therapy

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

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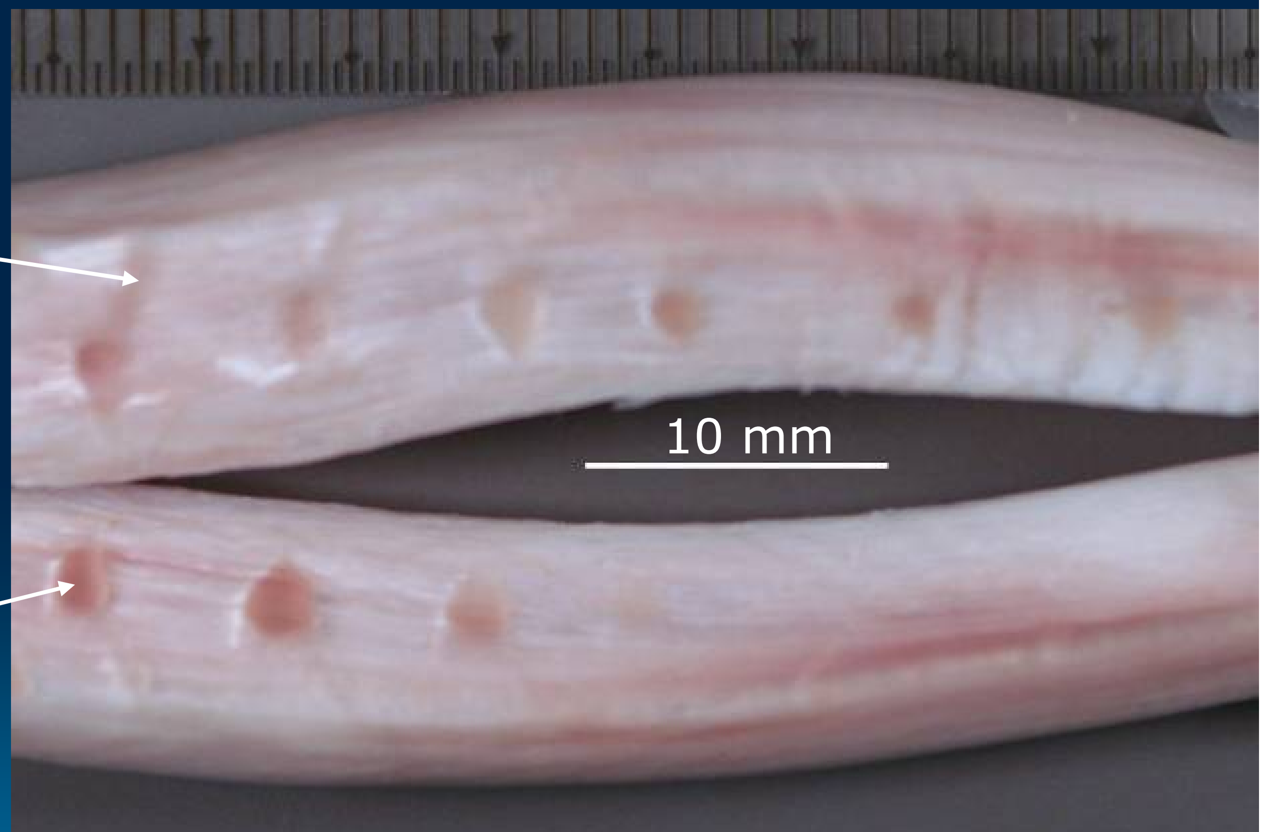
Bare tendon ablation

5.25 MHz
$0.55\ kW/cm^2$
5 s
6 mm deep
23 °C

beam

beam "legs"



tendon split post-ablation

ablation in focal regions

Lesion sizes are consistent: 23 °C

model	temperature °C	intensity* kW/cm^2	time s	depth mm	angle °	length mm	width mm	
bare tendon	23	0.55	5	6	0	3.60	1.92	
bare tendon	23	0.55	5	6	0	3.60	2.52	
bare tendon	23	0.55	5	6	0	2.88	1.80	
bare tendon	23	0.55	5	6	0	2.76	1.68	
bare tendon	23	0.55	5	6	0	2.28	1.20	
bare tendon	23	0.55	5	6	0	2.76	2.04	
						2.980	1.860	**mean**
						0.523	0.434	**st dev**

$$I = I_{free} e^{-2\alpha f \Delta x}$$

* *in-situ* intensity estimate

α = 2.9 dB MHz^{-1} cm^{-1}, f = 5.25 MHz, Δx = depth

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Lesion sizes are consistent: 37 °C

model	temperature °C	intensity* kW/cm²	time s	depth mm	angle °	length mm	width mm	
bare tendon	37	0.90	2	5	0	3.56	1.64	
bare tendon	37	0.90	2	5	0	4.39	1.79	
bare tendon	37	0.90	2	5	0	4.03	1.51	
bare tendon	37	0.90	2	5	0	3.20	2.10	
bare tendon	37	0.90	2	5	0	3.72	1.67	
bare tendon	37	0.90	2	5	0	3.10	2.29	
						3.667	1.833	**mean**
						0.492	0.300	**st dev**

$$I = I_{free}\, e^{-2\alpha f \Delta x}$$

* *in-situ* intensity estimate

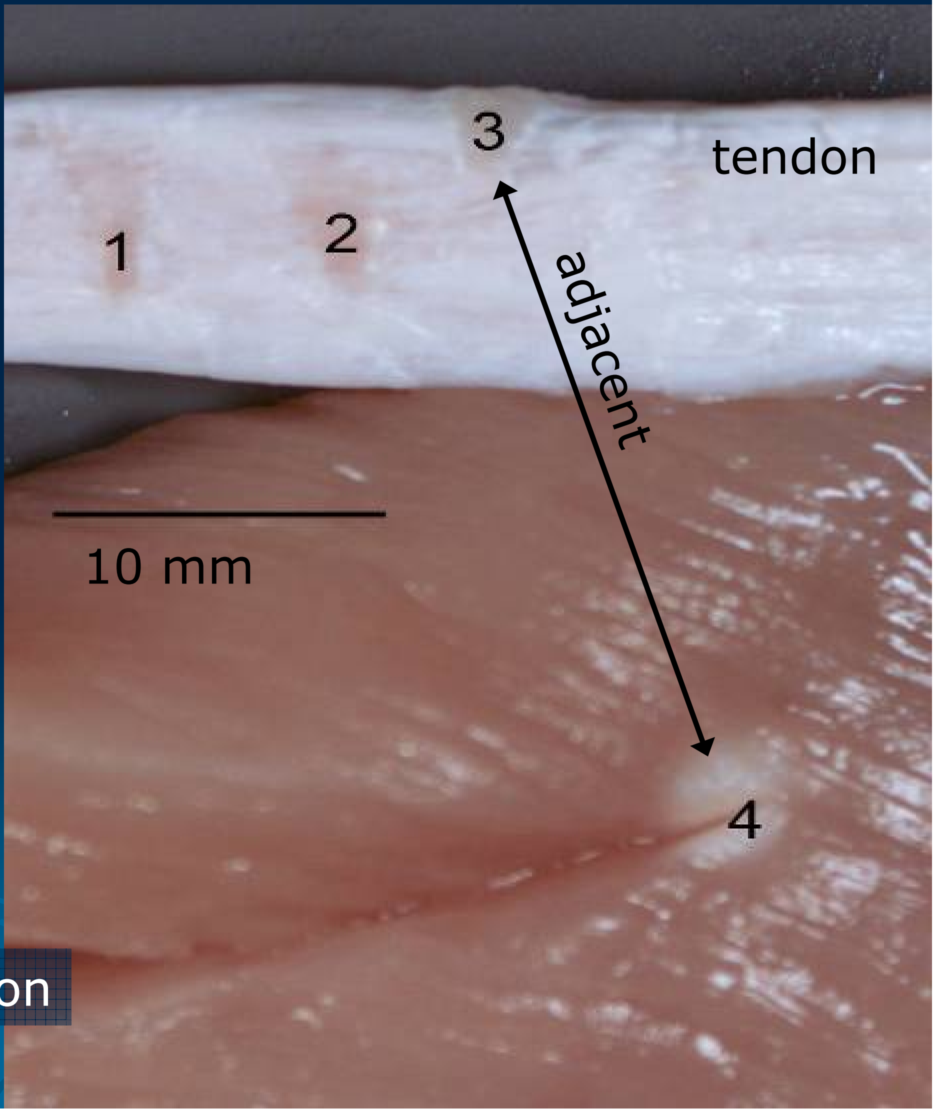
α = 2.9 dB MHz^{-1} cm^{-1}, f = 5.25 MHz, Δx = depth

Layered model ablation - 1

1 & 2: intramural lesions with no damage to overlying tissue

5.25 MHz
10 s

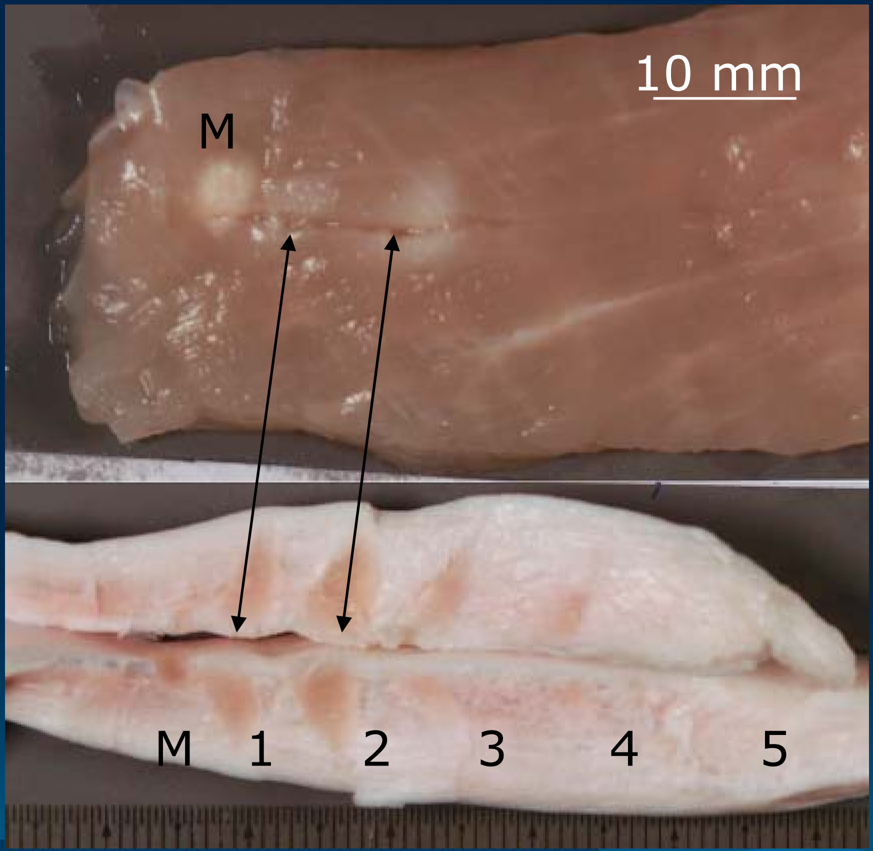
#	kW/cm^2	muscle	tendon
1	0.3	8.2 mm	6 mm
2	0.3	7.2 mm	6 mm
3	2.7	8.4 mm	0 mm



muscle folded back and split post-ablation

Layered model ablation - 2

muscle folded back post-ablation



tendon split post-ablation

5.25 MHz

#	kW/cm²	muscle	tendon	time
1	0.1	9 mm	7 mm	20 s
2	0.2	9 mm	7 mm	18 s
3	0.1	9 mm	7 mm	18 s
4	0.1	9 mm	7 mm	15 s
5	0.1	9 mm	7 mm	12 s

M “marker” lesion

Beam 20° incidence

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Angles & intensities, layered model

model	temperature °C	intensity* kW/cm^2	time s	depth mm	θ angle °	mean length mm	mean width mm	number
layered	37	0.23	10	7	15	3.97	2.76	4
layered	37	0.25	10	7	5	3.46	2.31	6
layered	37	0.25	10	7	0	5.92	2.19	6
layered	37	0.26	10	6	0	4.51	1.86	2
layered	37	0.32	10	6	0	4.07	2.06	1
layered	37	0.34	10	6	0	4.48	2.32	3

* *in-situ* intensity estimate

α_{muscle} = 0.5 dB MHz^{-1} cm^{-1}, f = 5.25 MHz, $\Delta x \approx$ 1 cm/cos θ

α_{tendon} = 2.9 dB MHz^{-1} cm^{-1}, f = 5.25 MHz, Δx = depth/cos θ

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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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