Thermoacoustic Range Verification for Ion Therapy

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Thermoacoustic Range Verification

inverse source problem

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- rapid heating (stress confinement)
- pressure jump (ultrasound)
- time of flight (sonar)

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$1\ \mathrm{Pa} = 1\ \mathrm{N/m^2}$

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1 Pa = 1 J/kg kg/m^3

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1 Pa = 1 Gy ρ

$$\delta p = \Gamma\, \rho\, \mathrm{D}$$

dose in Gy

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$$\delta p = \Gamma\, \rho\, D$$ dose in Gy

$\Gamma \sim 0.1$ in soft tissue

ρ = 1000 kg/m^3

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Clinical margin: 1 mm + 3.5% target depth

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soft tissue $\delta p \sim 100\ \mathrm{D}$ dose in Gy

Clinical margin: 1 mm + 3.5% target depth 8 mm at 20 cm

Experimental Setup

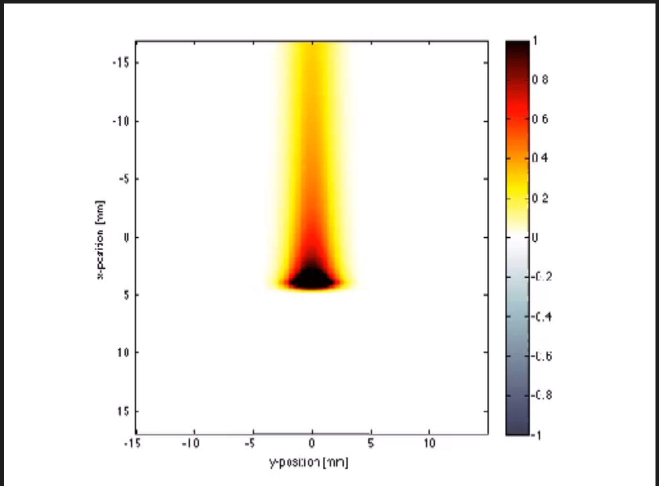
Accelerator: 88” cyclotron at LBNL
50 MeV protons, lost 1 MeV in ion chamber
2 μA for 2 μs on target
4.2 mm FWHM beam width
2 Gy/pulse in water target (SRIM)

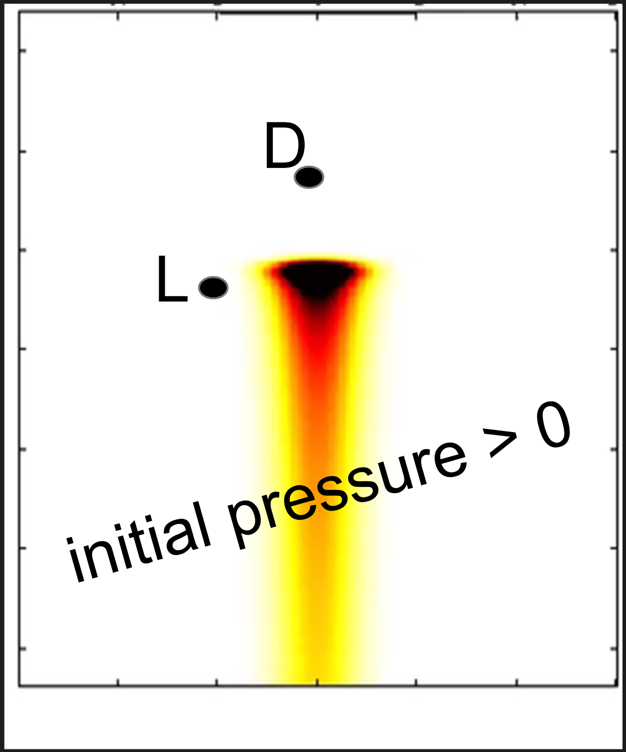
Targets: water in 112-qt LDPE container
gelatin phantom mimics muscle (ultrasound)

Ultrasound Hardware: clinical array with 96 channels, 300 µm pitch
1000 pulses averaged

Simulations

Positive (compressional) followed by weak negative (rarefactional)





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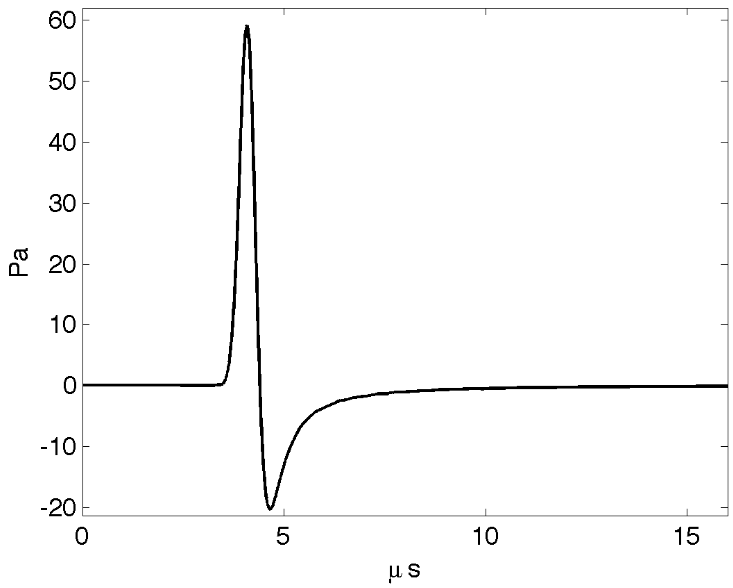
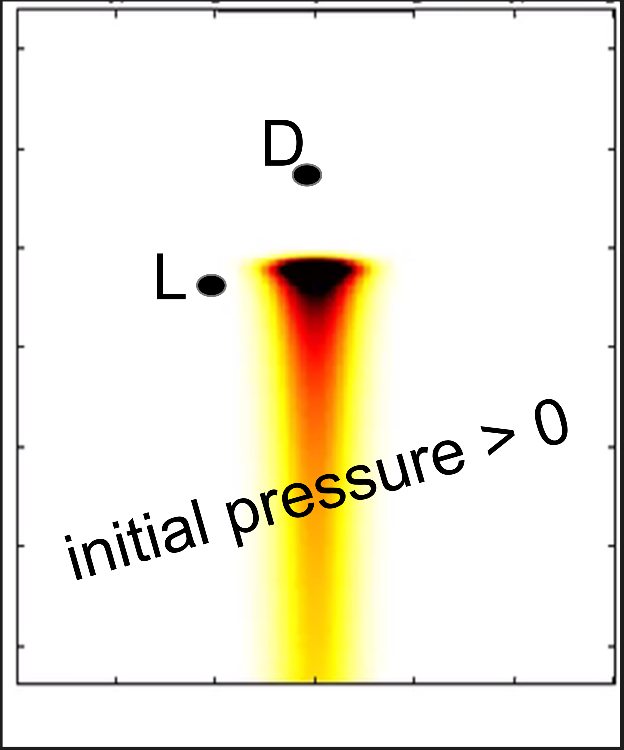
4 pC single-turn





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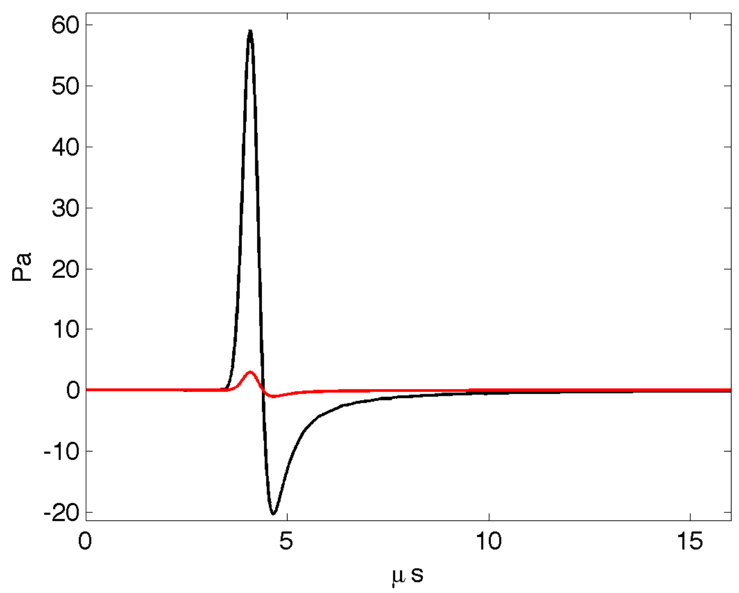
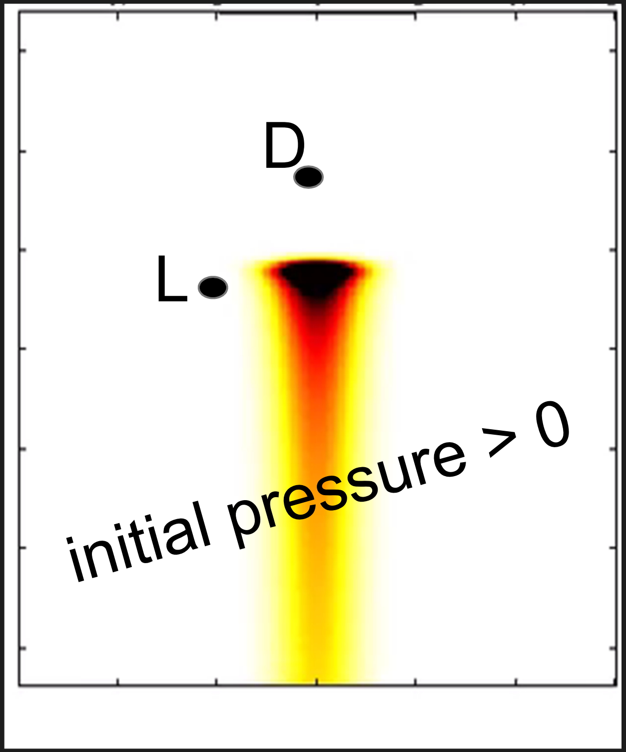
4 pC over 2 μs @ 10 MHz





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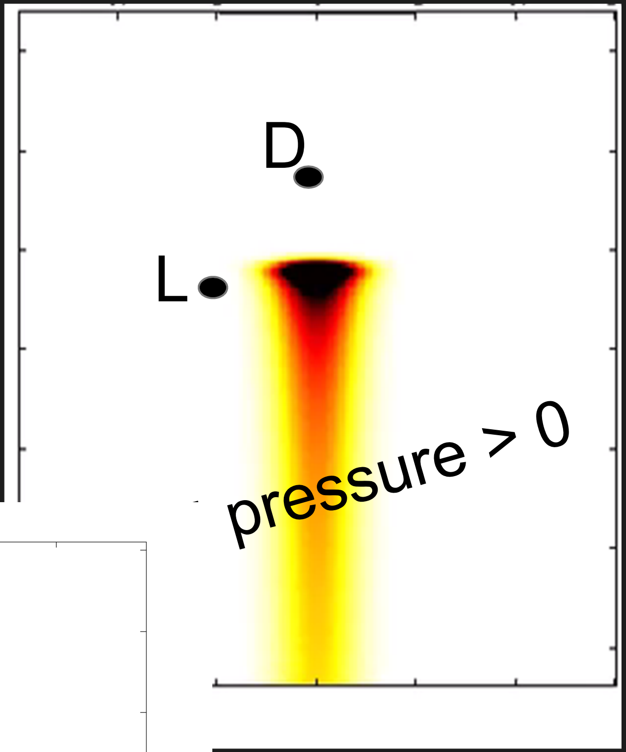

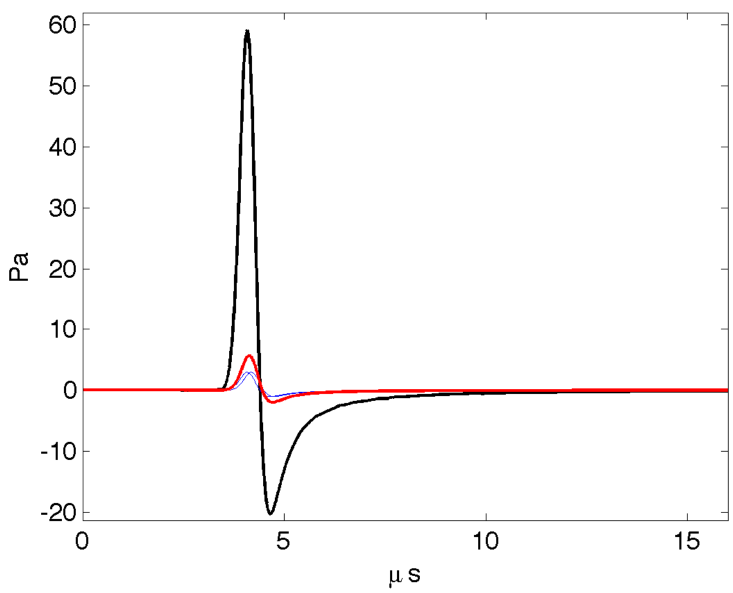

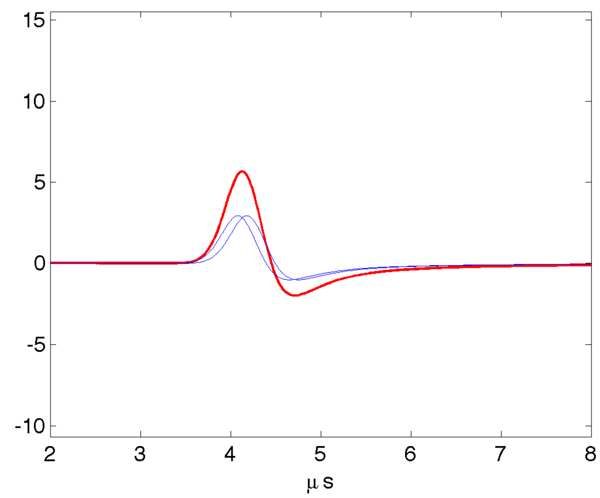

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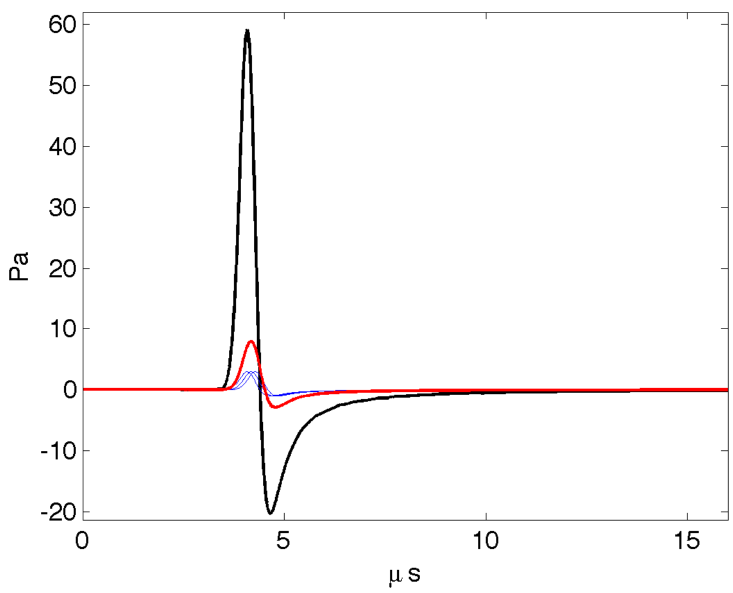

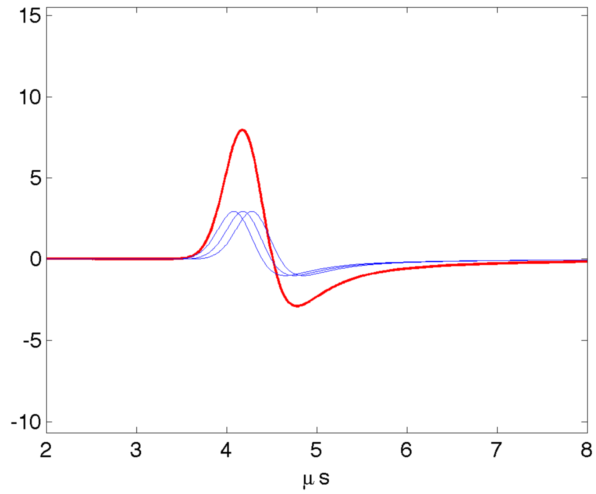

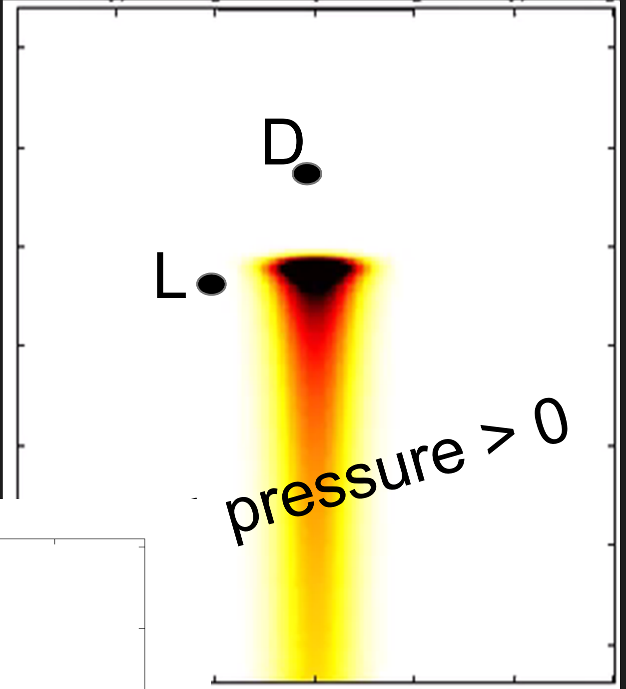

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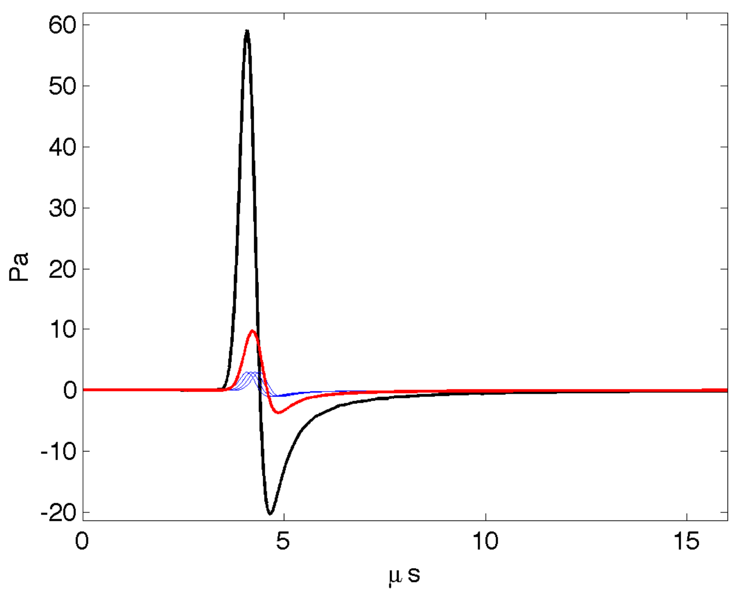

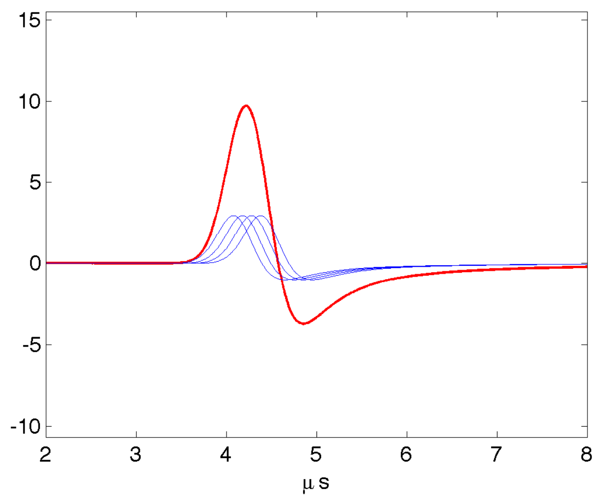

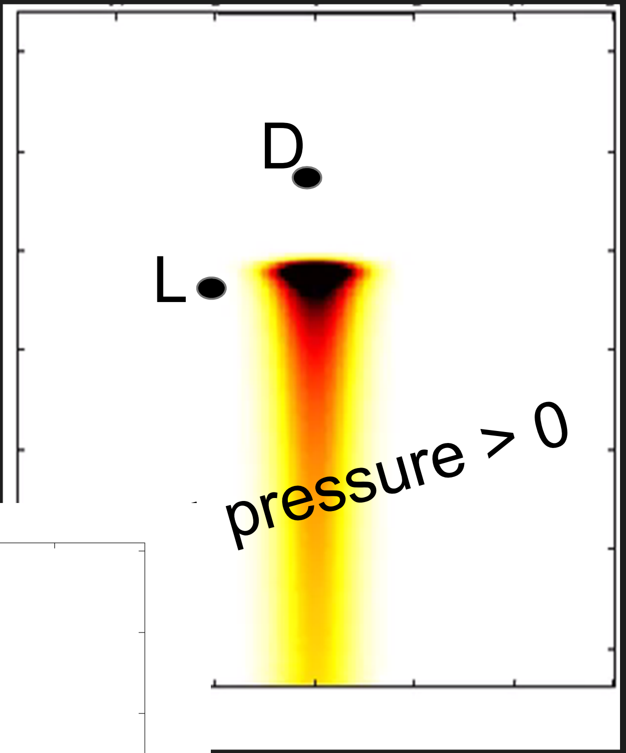

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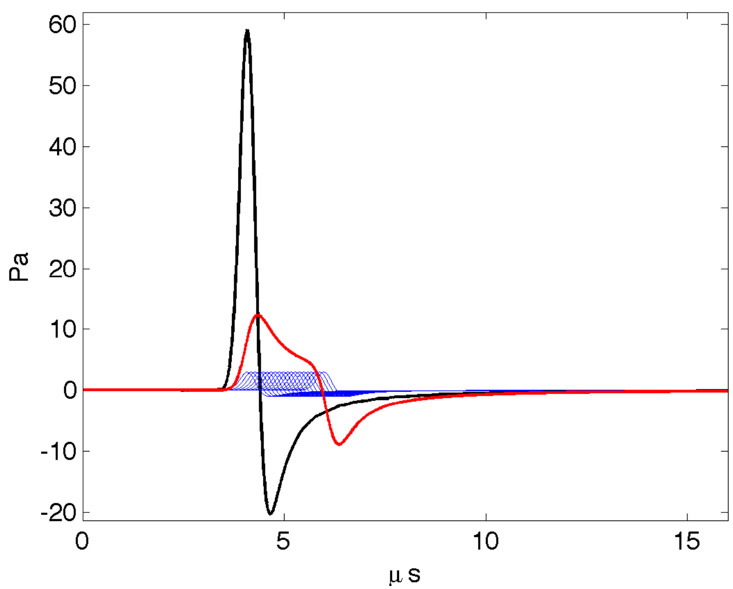

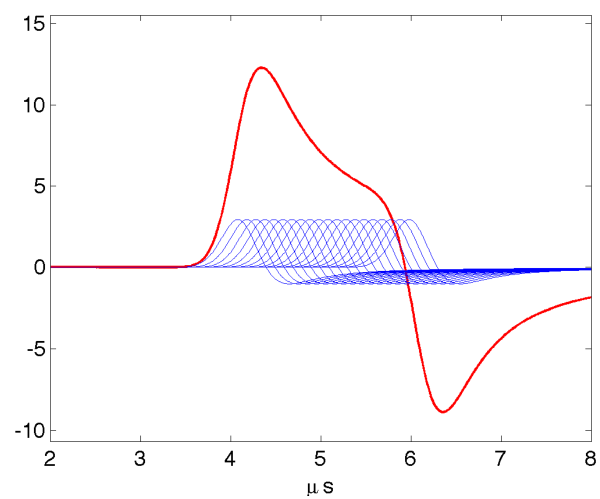

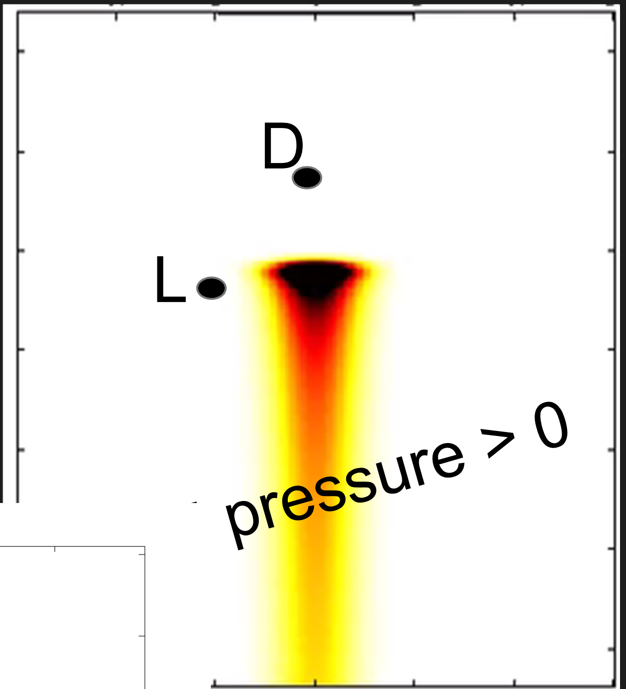

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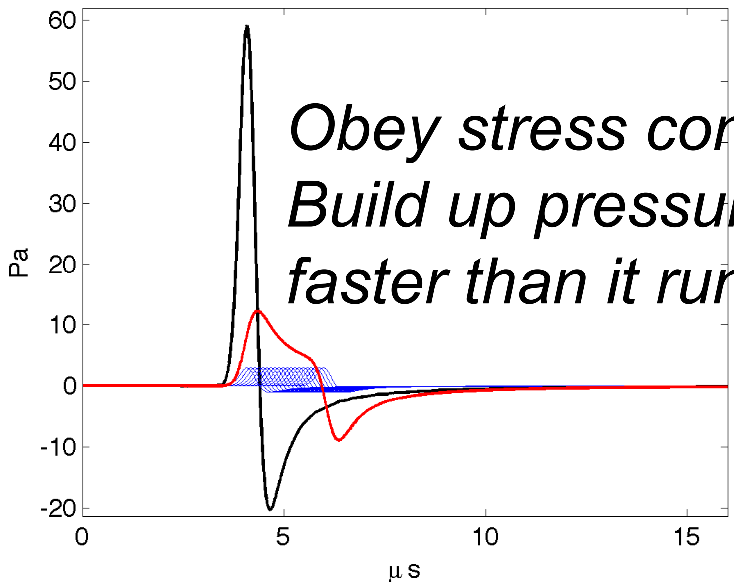
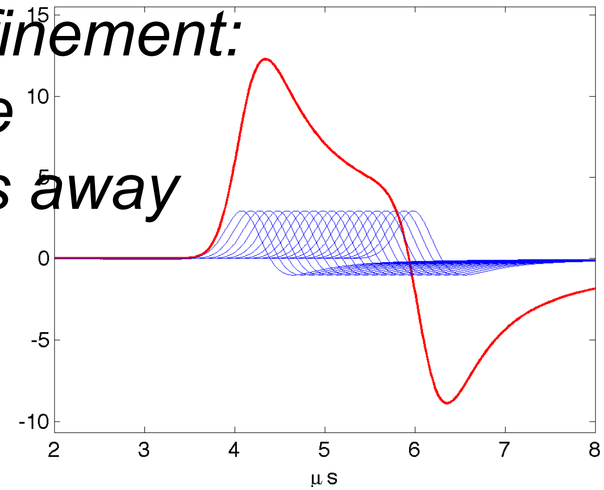
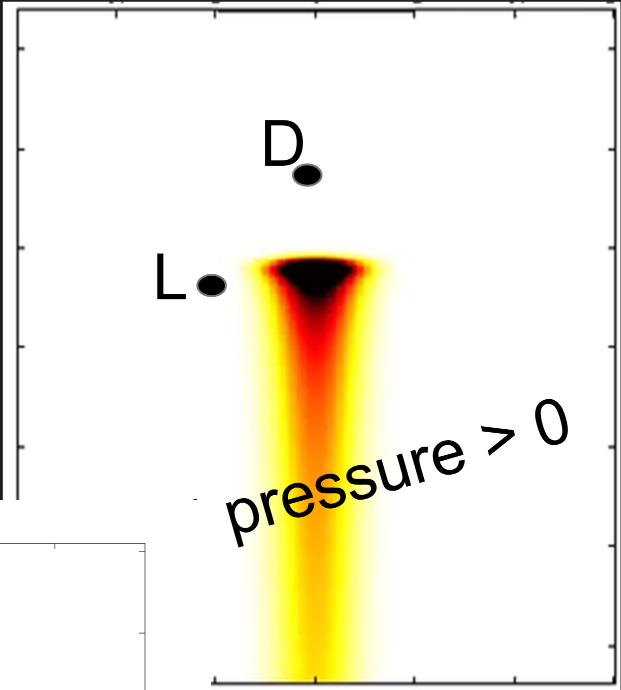


Obey stress confinement:
Build up pressure faster than it runs away





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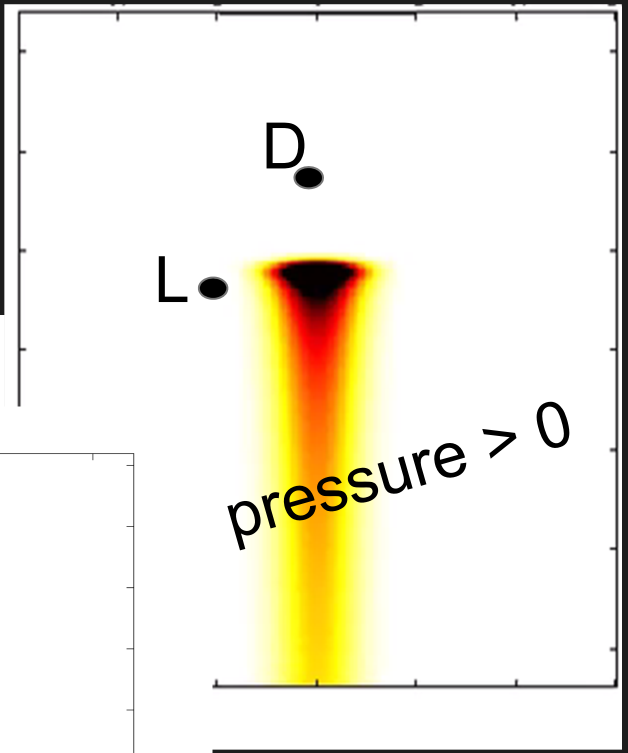
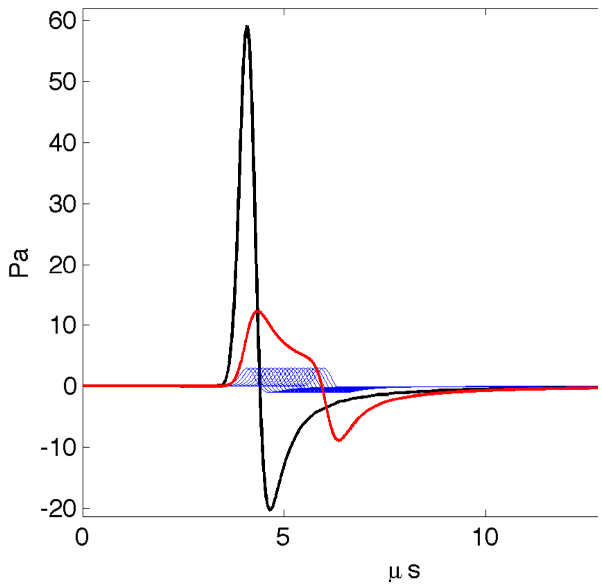
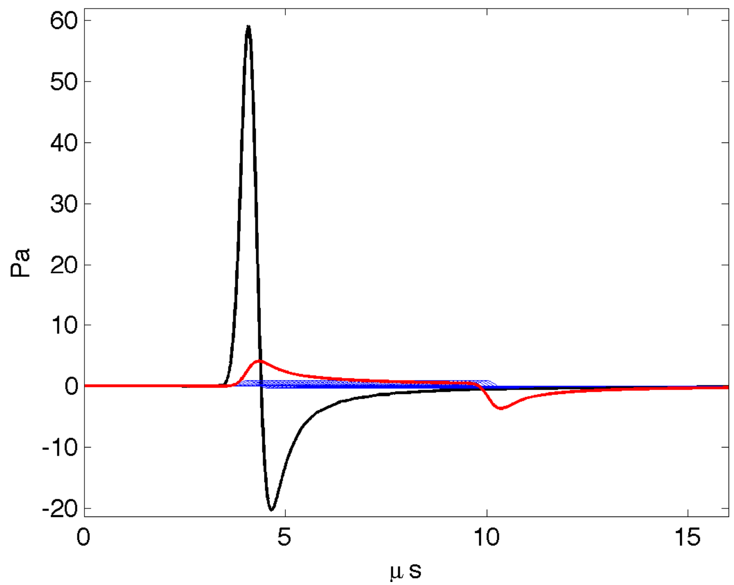


49 MeV: 4 pC in 2 μs



4 pC in 6 μs



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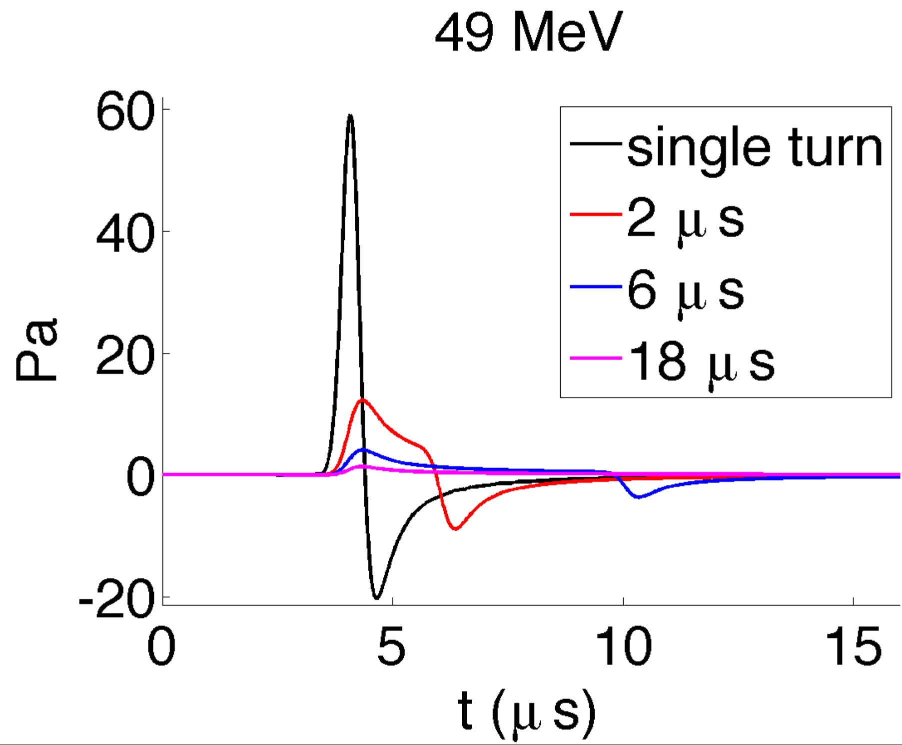
Positive (compressional) followed by negative (rarefactional)



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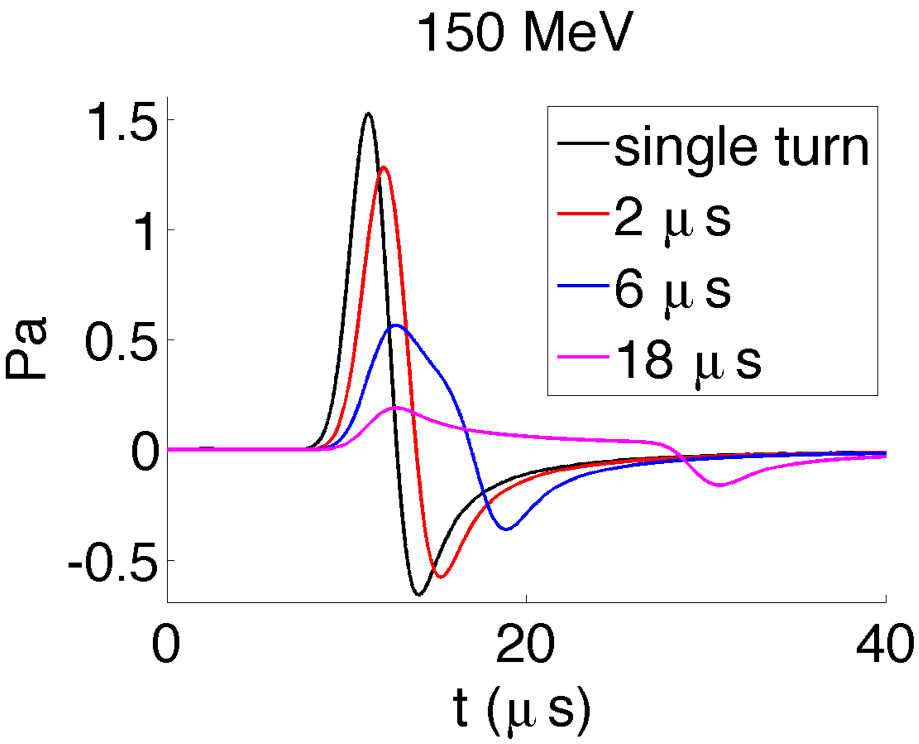

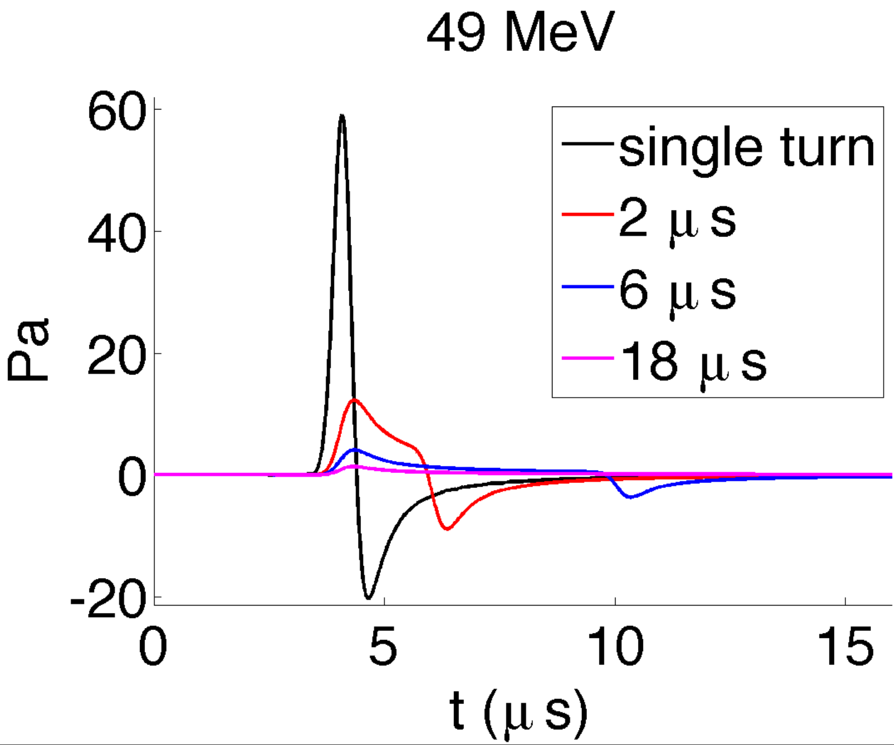

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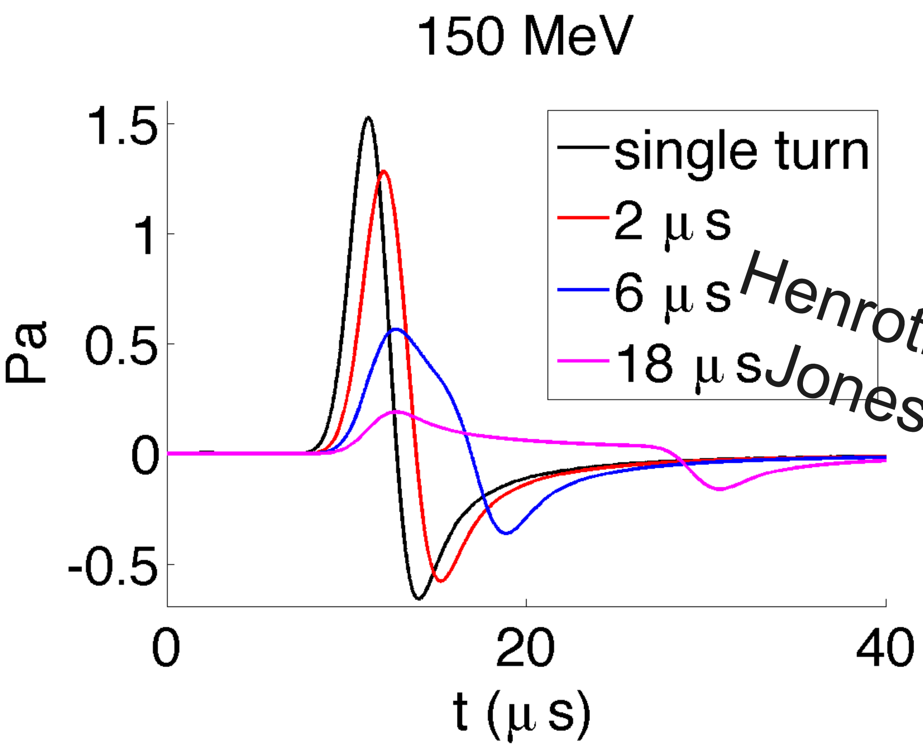
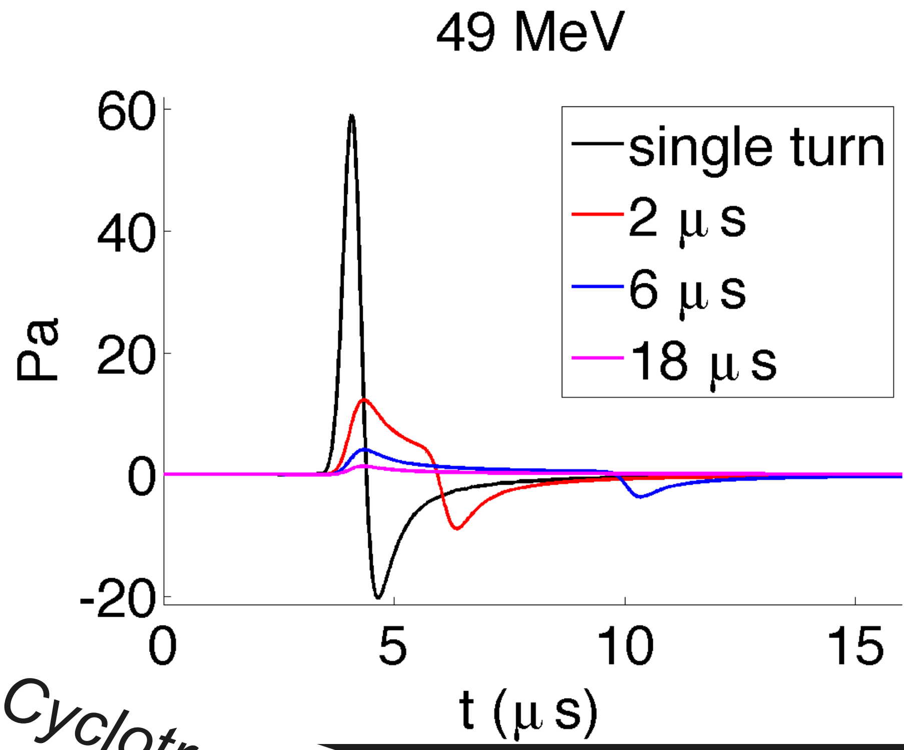


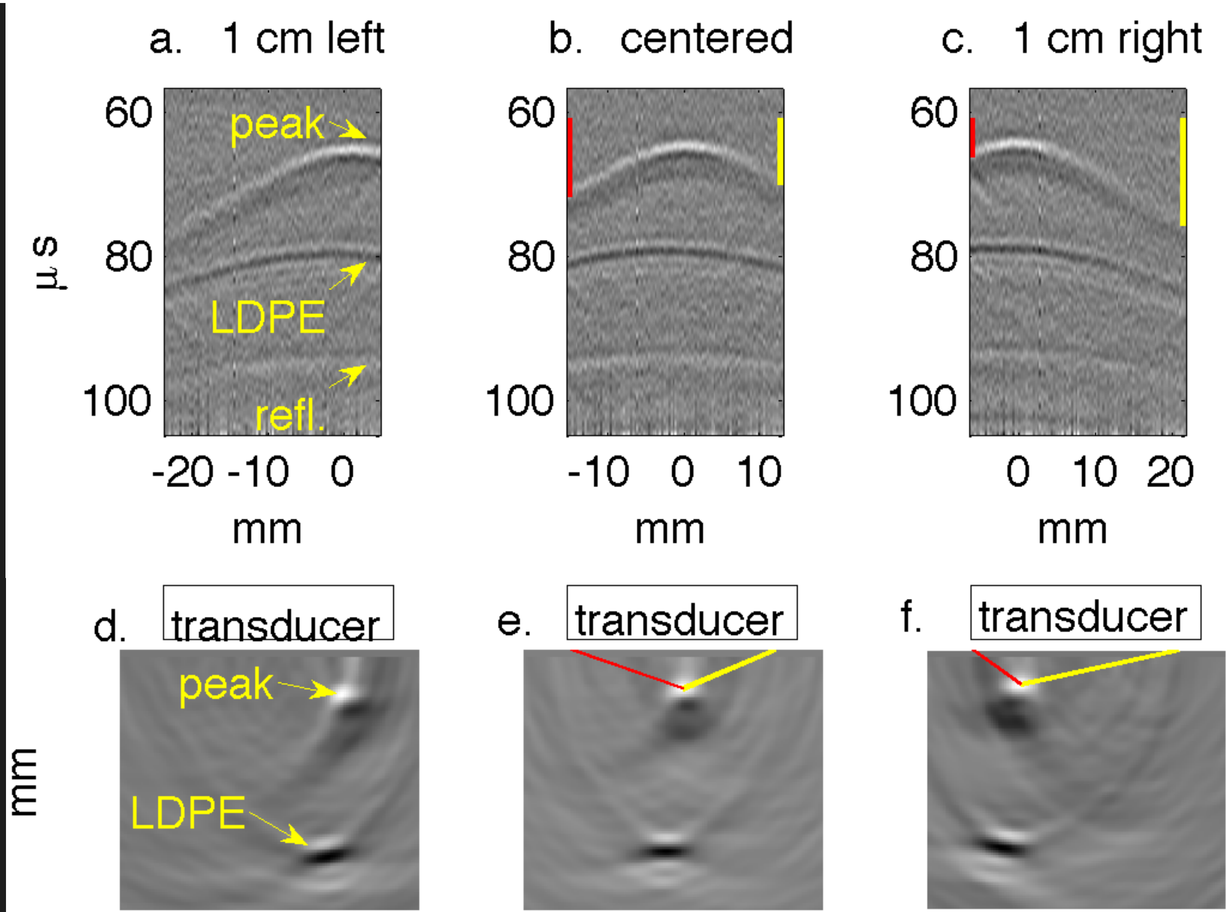


Henrotin, Cyclotrons 2016
Jones, Med Phys 2016

Waterbath Results

Expect 21.1 mm range

- within 1 mm
- consistently high
- 5 realizations



1 cm left	centered	1 cm right
21.7±0.2	21.9±0.0	22.0±0.02

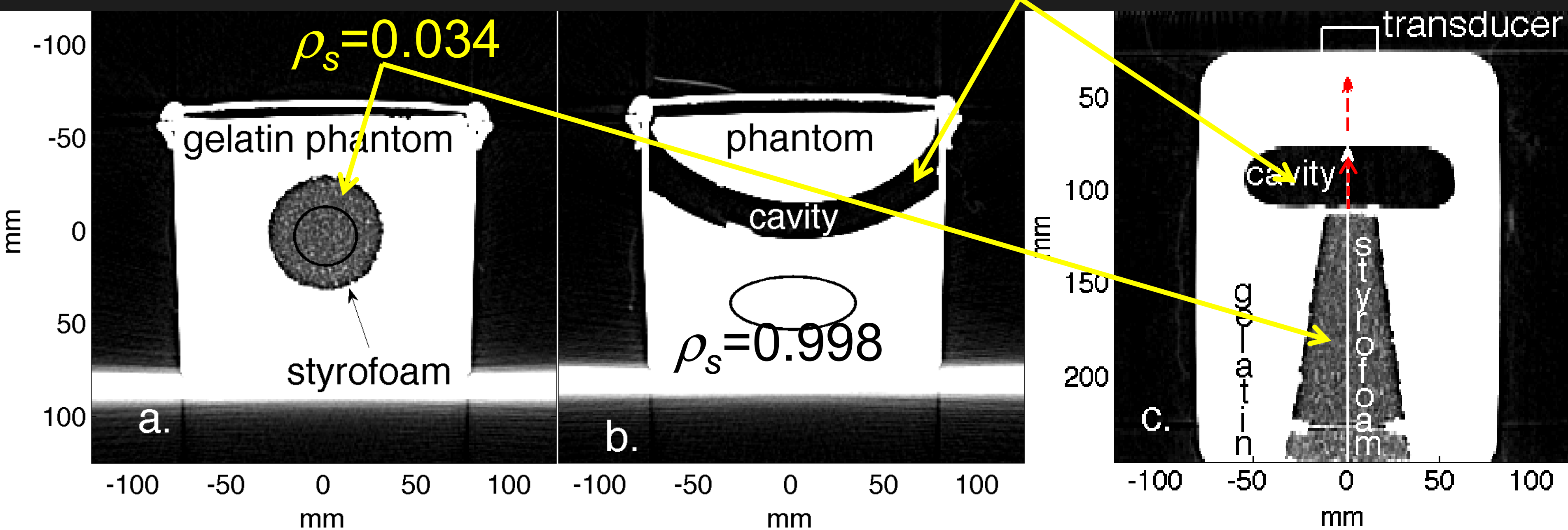
Patch, *et al PMB 2016*

Phantom Experiment

Gelatin phantom designed to
- mimic ultrasound properties of muscle
- detect error due to gas pocket

oil range should exceed gel range by ~10%

ρ_s = 0.911 olive oil



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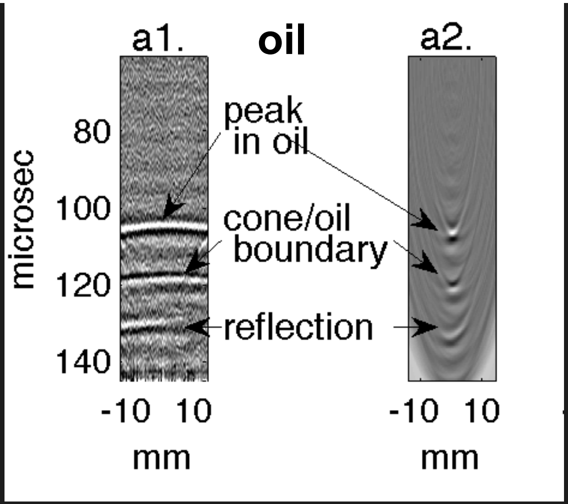
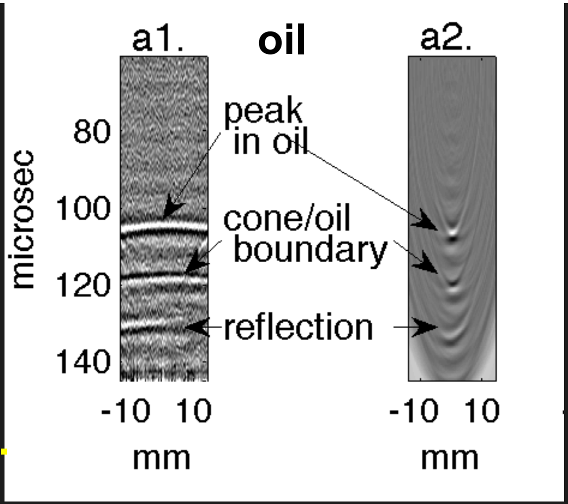
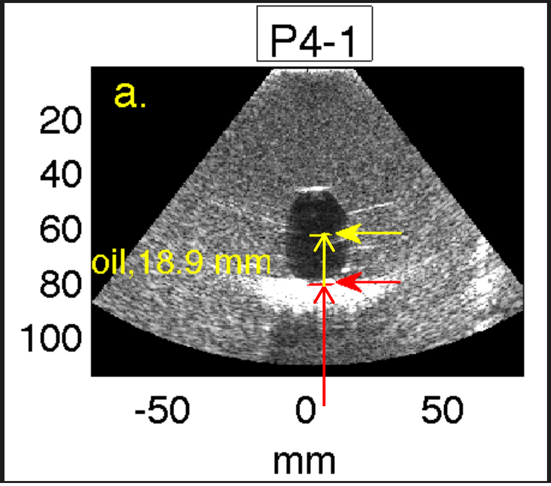


Phantom Results

Bragg Pk in yellow; entry point in red.
Same transducer ➔
automatic co-registration
of image & range estimate.



oil-filled cavity



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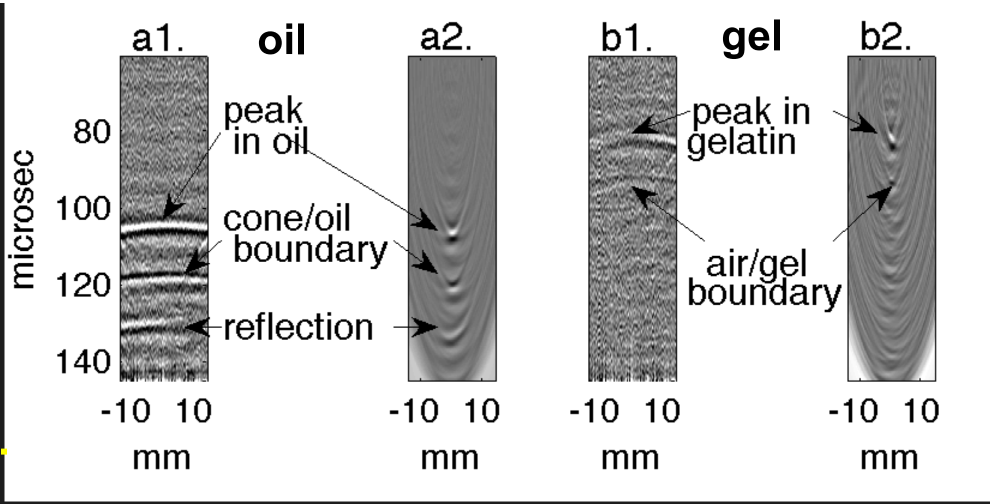

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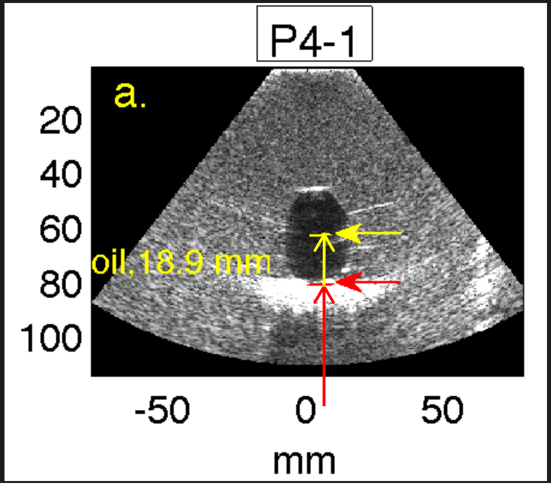

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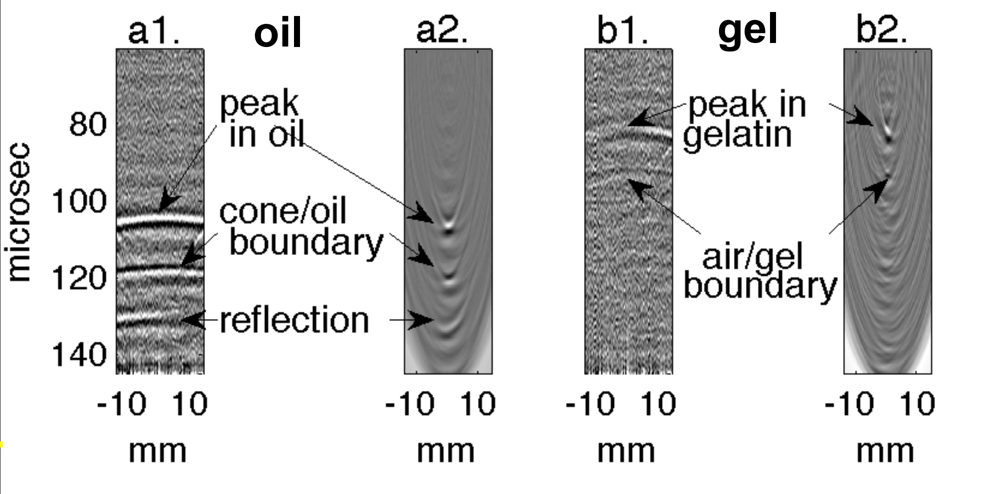

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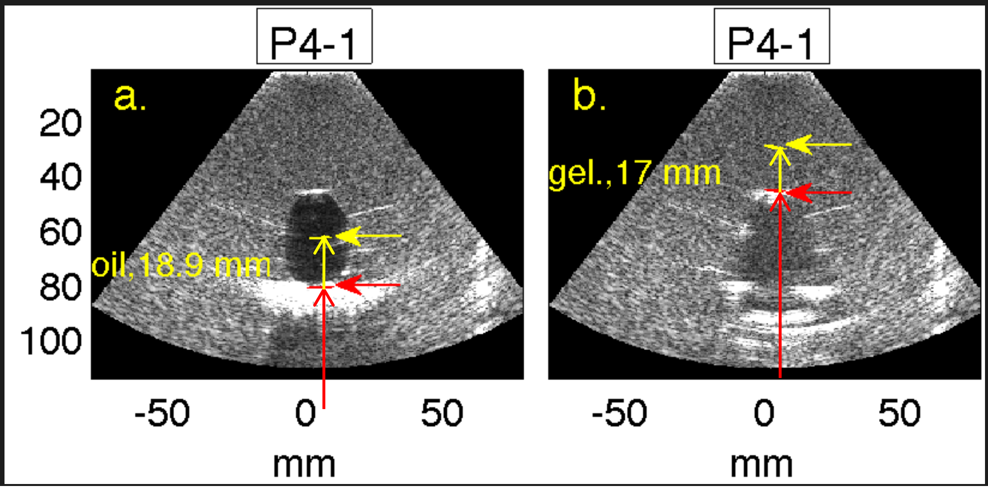

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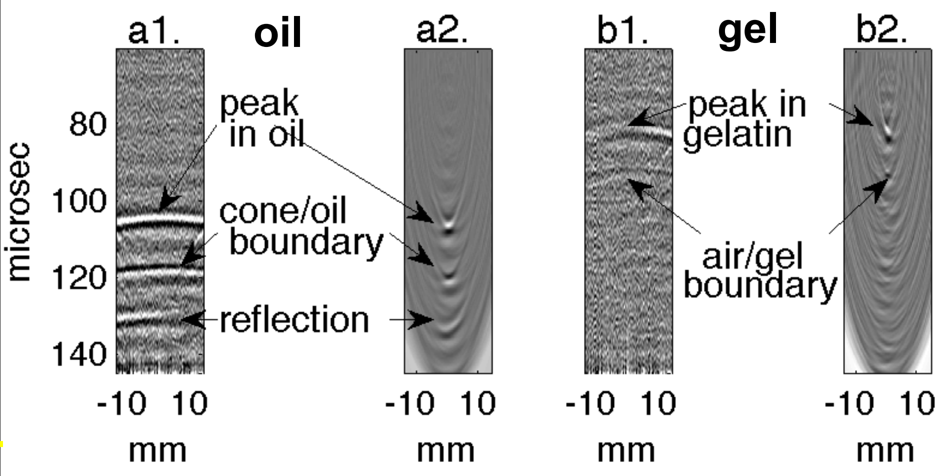

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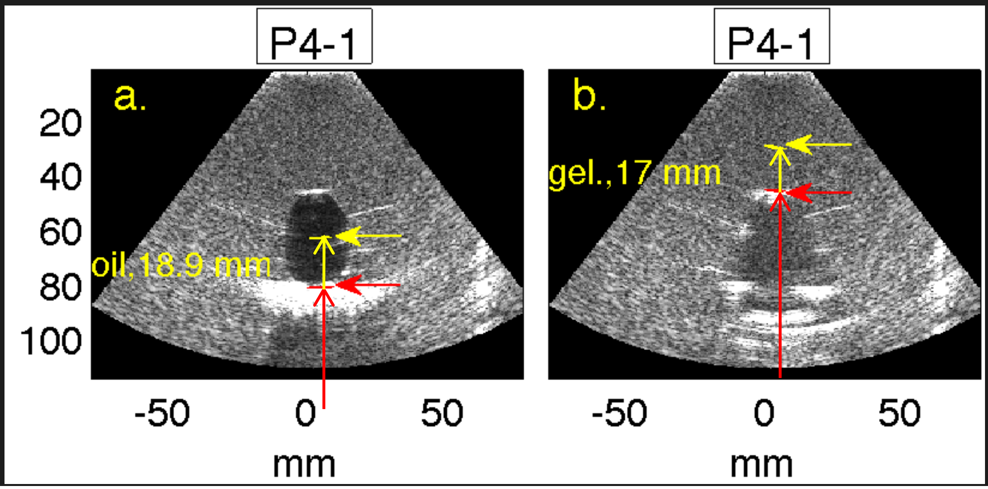

cavity status	distance distal (mm)	range μ ± σ (mm)	N
A w/oil	64.0	18.7 ± 0.1	27
B empty	29.3	16.9 ± 0.4	28

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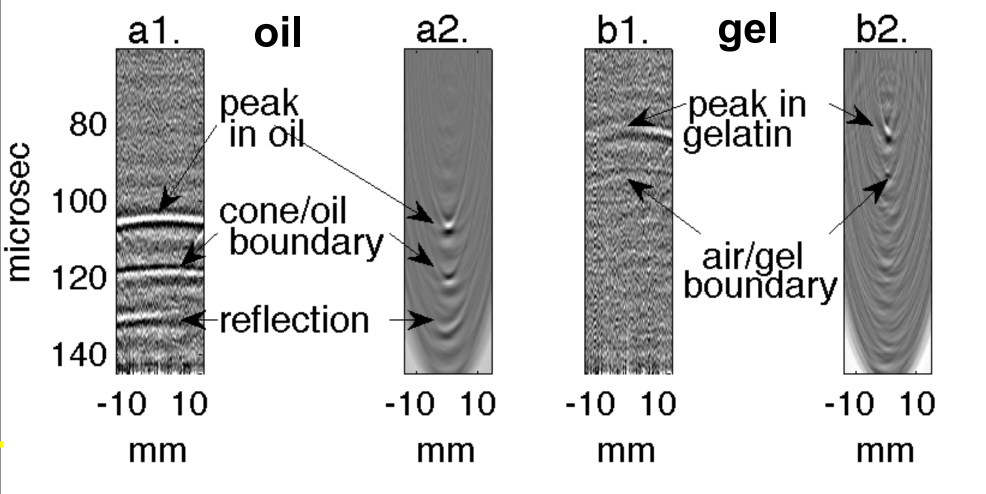

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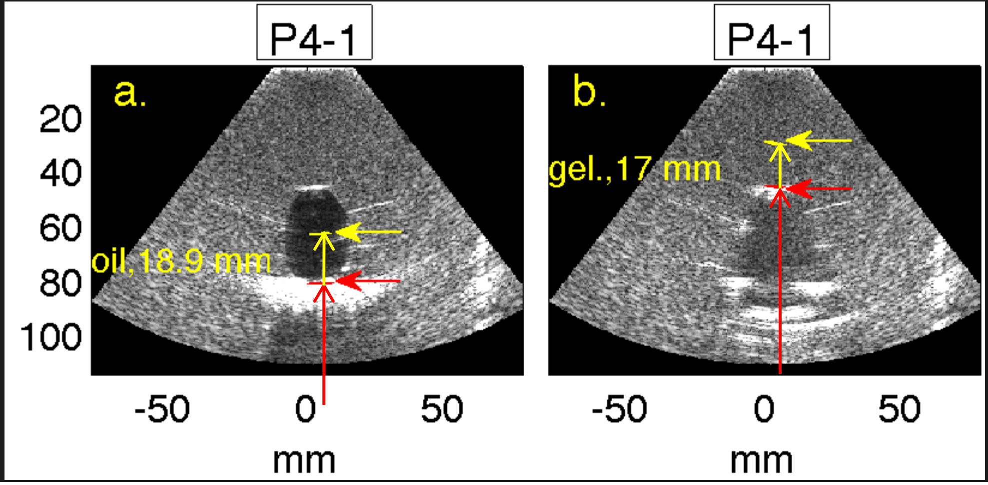

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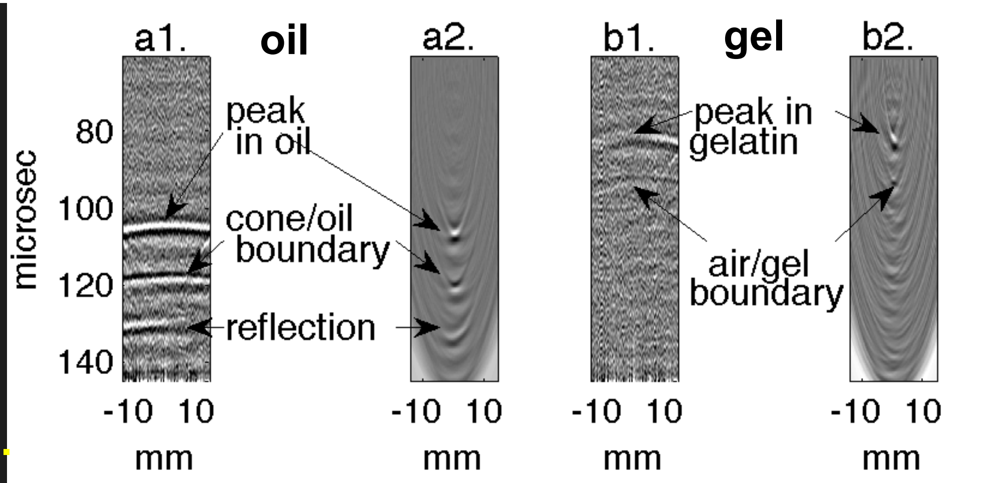

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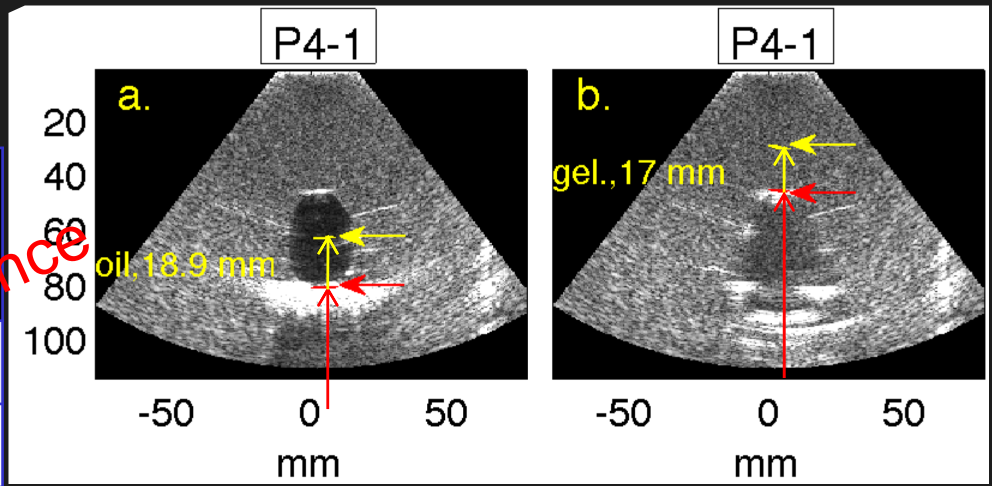
oil-filled cavity   empty cavity



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10x Kellnberger, SciRep 2016

~10% difference

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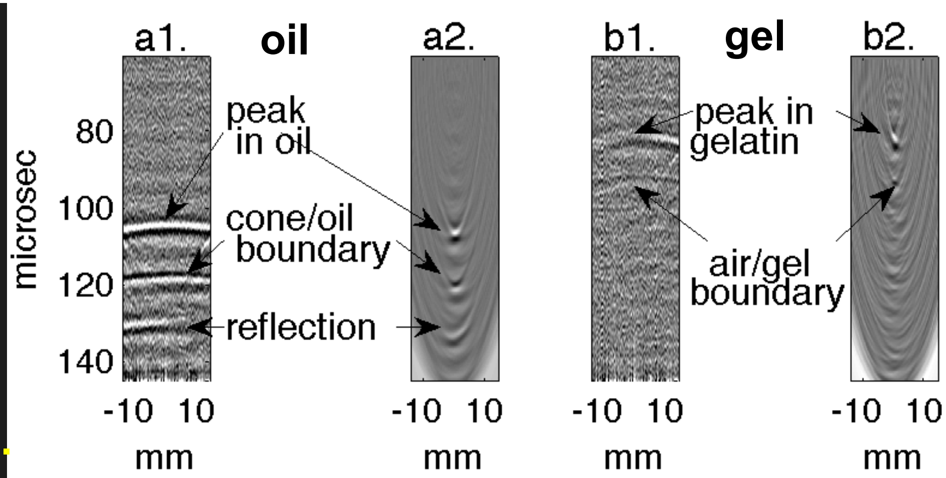

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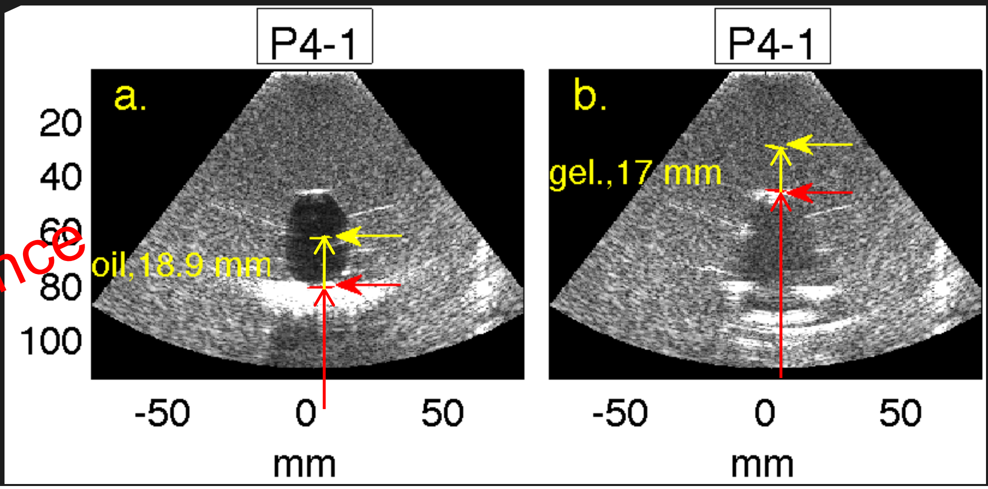

TA Range Ver. take-aways

- fast dose deposition increases TA signal strength and bandwidth
- off-the-shelf cardiac ultrasound array detected TA emissions from 2 Gy peak, but required overdosing the phantom
- custom ultrasound hardware sensitive to TA emissions required to detect within therapeutic dose limits

Acknowledgements

M Zolotorev & A Sessler, who coordinated first attempt @ LBNL in 2013
Dr. George Noid (MCW RadOnc) provided CT images of phantom
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Verasonics hardware: UWM Instrumentation Grant