Effect of Duty Cycle Variation on Acoustic Pressure Field Simulation in an Ultrasound Bioreactor

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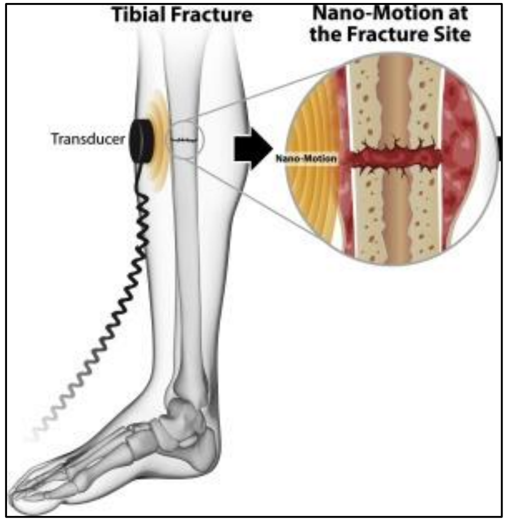
Introduction

➢Low intensity pulsed US treatment shows positive role in the bone fracture repair.

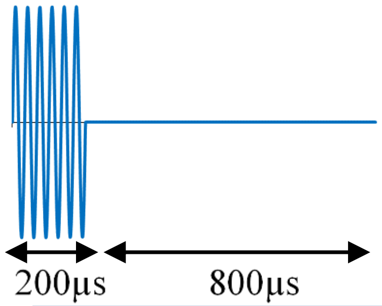
➢Transducer delivers ultrasound waves to fracture site.

- ❑ Promotes new bone formation
- ❑ Cost effective, no side effect
- ❑ LIPUS protocol: 200 µs burst of 1.5 MHz sine waves followed by 800 µs inactive period at 30 mW/cm^2 spatial average and temporal average (SATA) intensity.
- ❑ FDA in 2000 for bone fracture treatment.



Harrison *et al.*, Ultrasonics (2016)

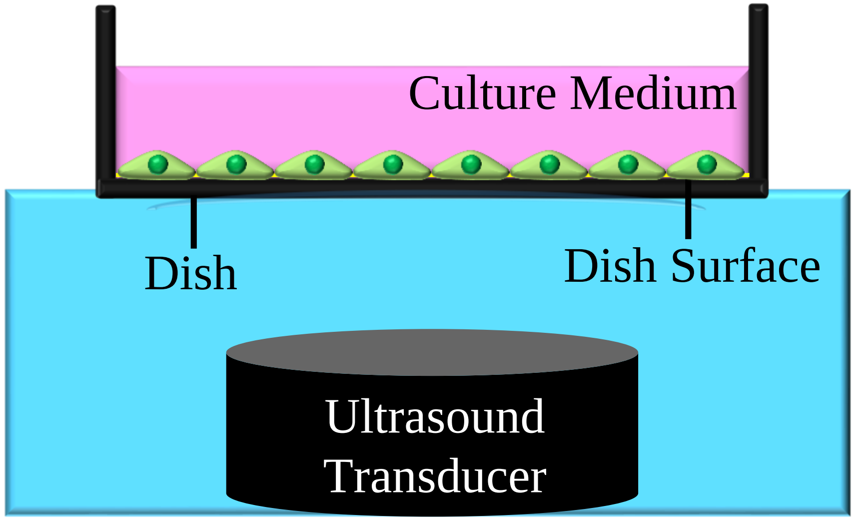
20% Duty Cycle



Introduction

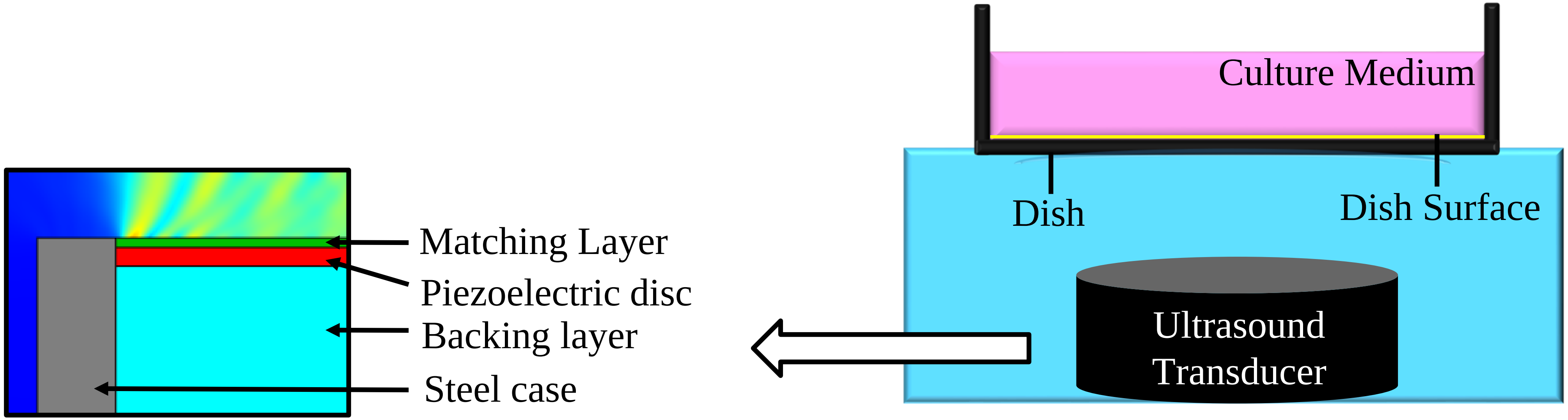
- US bioreactor as a tool to study bioeffects of therapeutic US *in vitro*

- Computational modeling is a valuable approach to study US wave propagation in the bioreactor.



Methods

- COMSOL Multiphysics software (V5.3)
- Piezoelectric Ultrasound Transducer



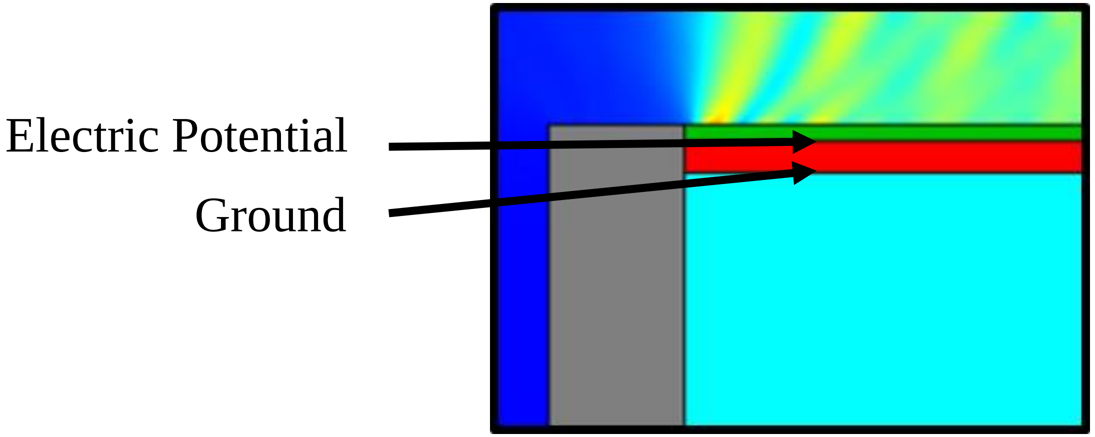
Methods

- Piezoelectric Properties: Lead Zirconate Titanate

c_E	Elastic Coefficients [Pa]
e^T	Transposed Coupling Matrix [C/m^2]
e	Coupling Matrix [C/m^2]
ε_s	Permittivity Matrix [F/m]

Stress Charge form

$$[T] = [c_E][S] - [e^T][E]$$
$$[D] = [e][S] - [\varepsilon_s][E]$$



Methods

- Three Physics were implemented:
  - Electrostatics interface

$$D = \varepsilon_0 E + P \quad \text{and} \quad E = -\nabla V$$

  - Solid

Time dependent simulation over one pulse is required to study pulsed US treatment.

  - Pressure Acoustics interface

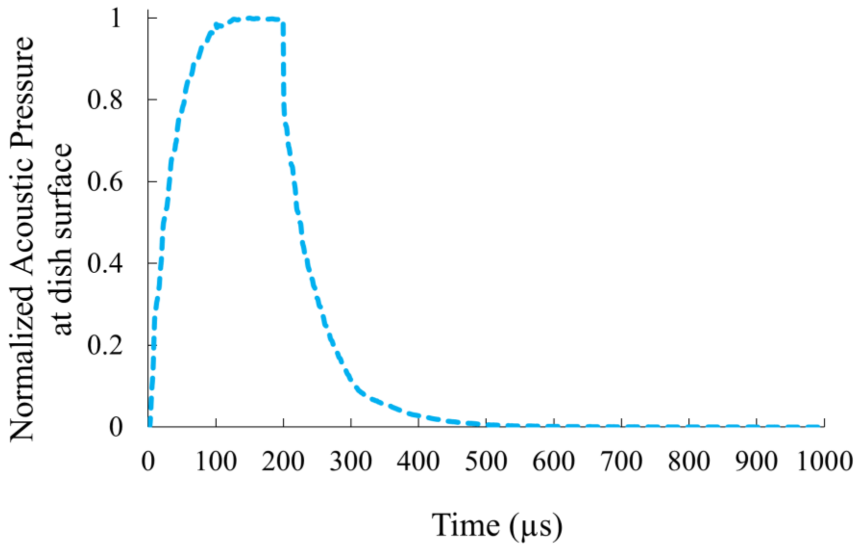
$$\nabla \cdot \left(-\frac{1}{\rho}\nabla p\right) - \frac{\omega^2 p}{\rho^2 c^2} = 0$$

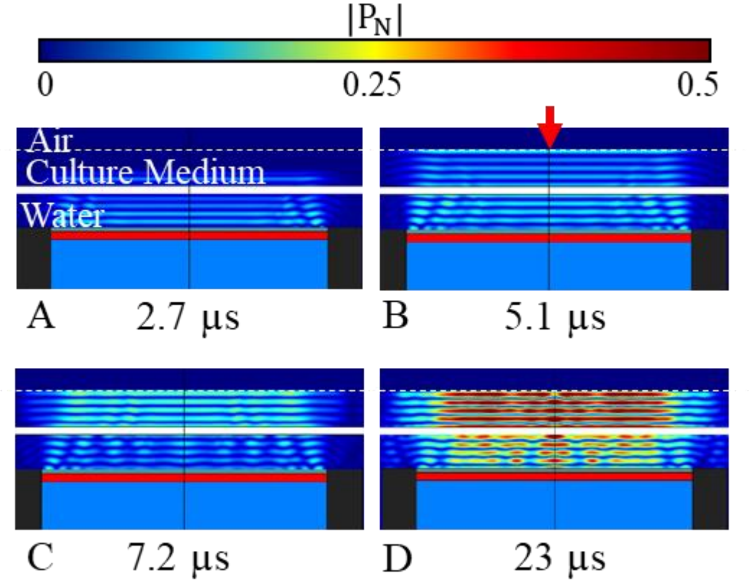
D	Displacement Field [C/m^2]
ε_0	Permittivity of Vacuum [F/m]
E	Electric Potential [V]
P	Polarization Vector [C/m^2]
∇V	Electric Potential Gradient [V]
T	Stress Tensor [Pa]
C	Elastic Coefficient [Pa]
S	Strain Tensor [m.m^{-1}]

ρ	Density [Kg/m^3]	ω	Angular Frequency (rad/s)
p	Acoustic Pressure [Pa]	c	Pressure Wave Speed [m/s]

Results

- Acoustic pressure pattern over 1 pulse (i.e. 1 ms) for 20% duty cycle
  - Time to reach maximum value: 125 µs



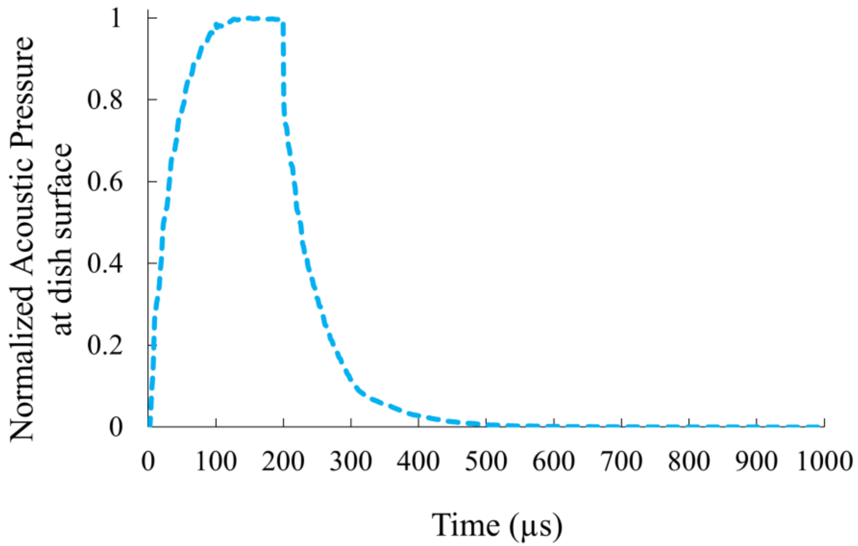


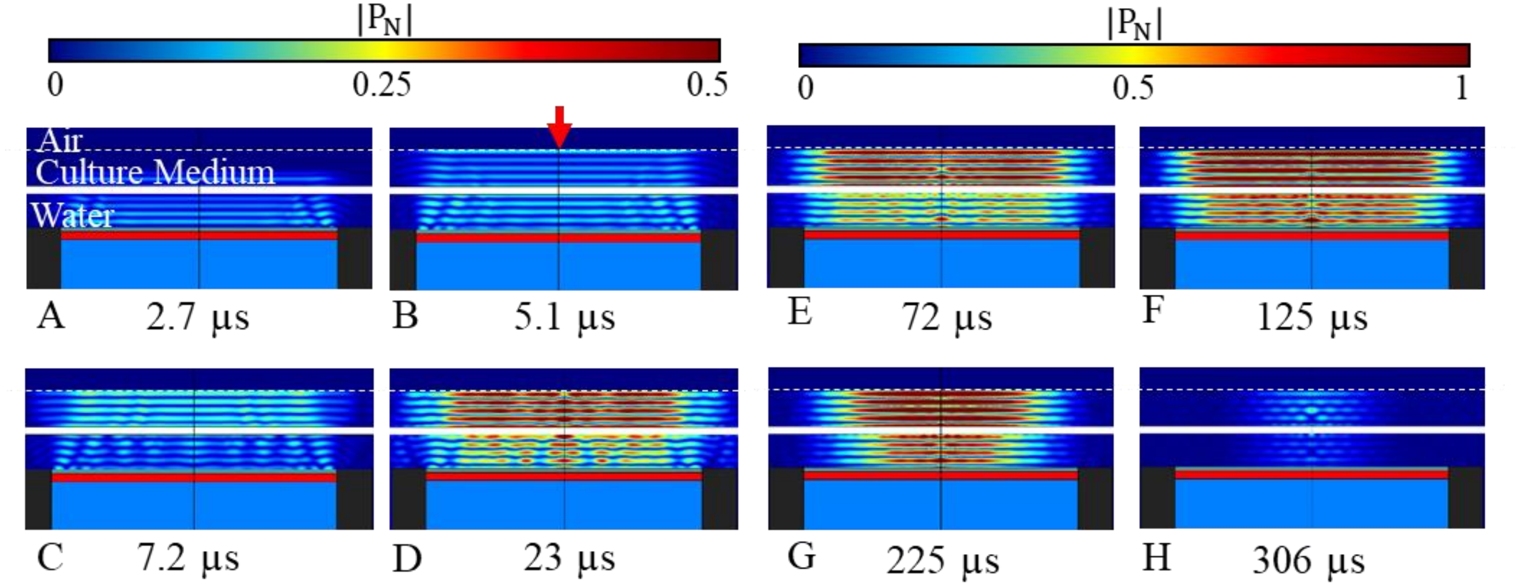
All graphs shows spatially average acoustic pressure at the dish surface.

t_{water}=3.1 mm, t_{medium}=3.4 mm

Results

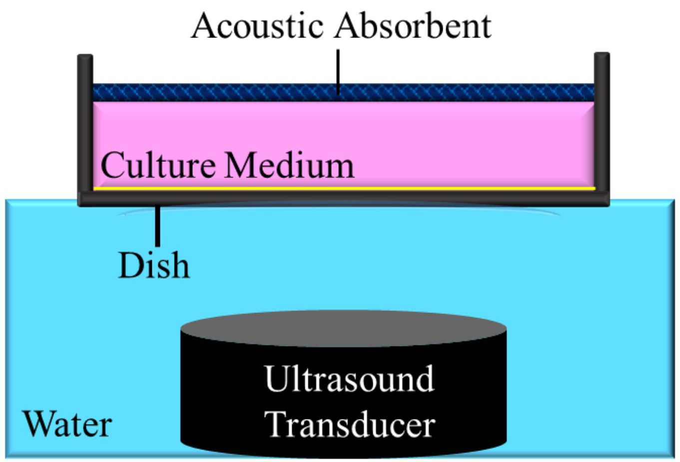
- Acoustic pressure pattern over 1 pulse (i.e. 1 ms)
  - Time to reach maximum value: 125 μs   add distance and culture medium height

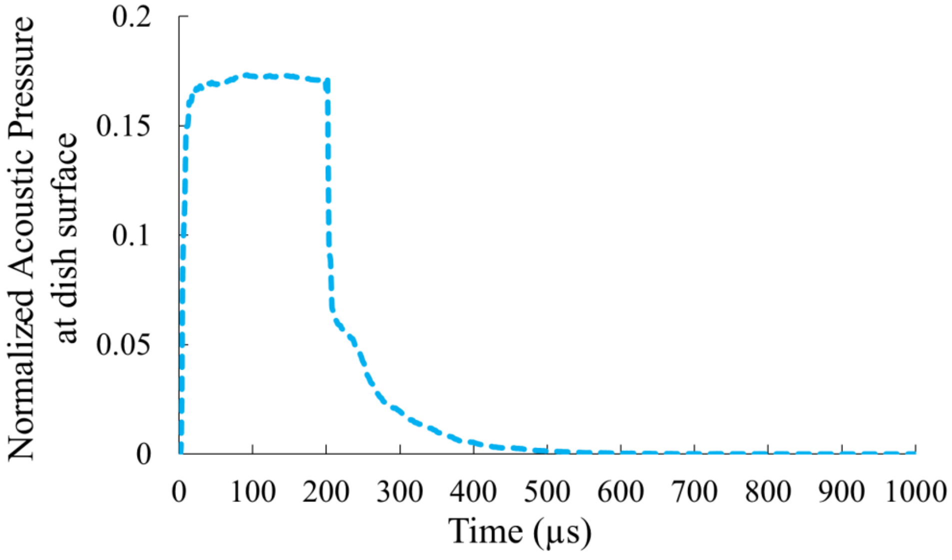


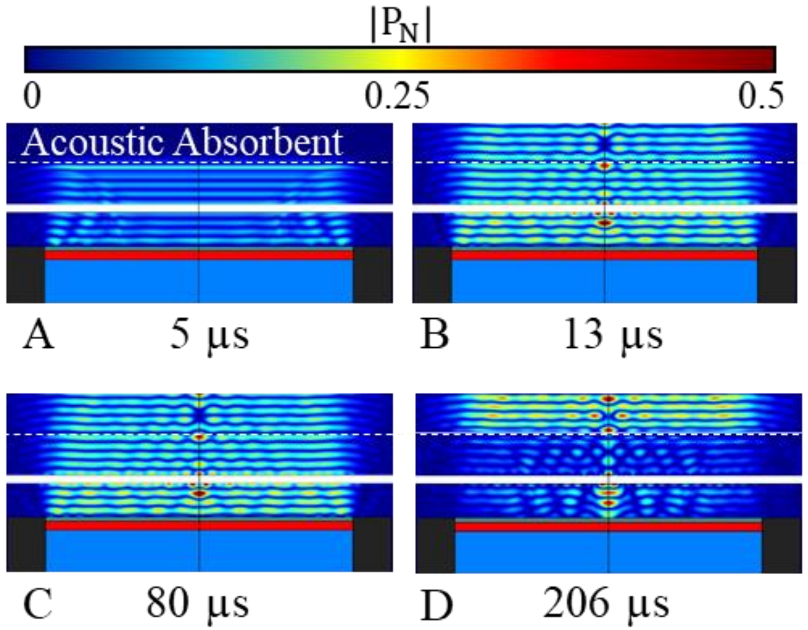


Results

- Evaluate the acoustic pressure field in the presence of the acoustic absorbent.
  - Perfectly Matched Layer was used to model the acoustic absorbent material.







t_{water}=2.8 mm, t_{medium}=3.4 mm

- Results are normalized to the maximum pressure in the original configuration

Results

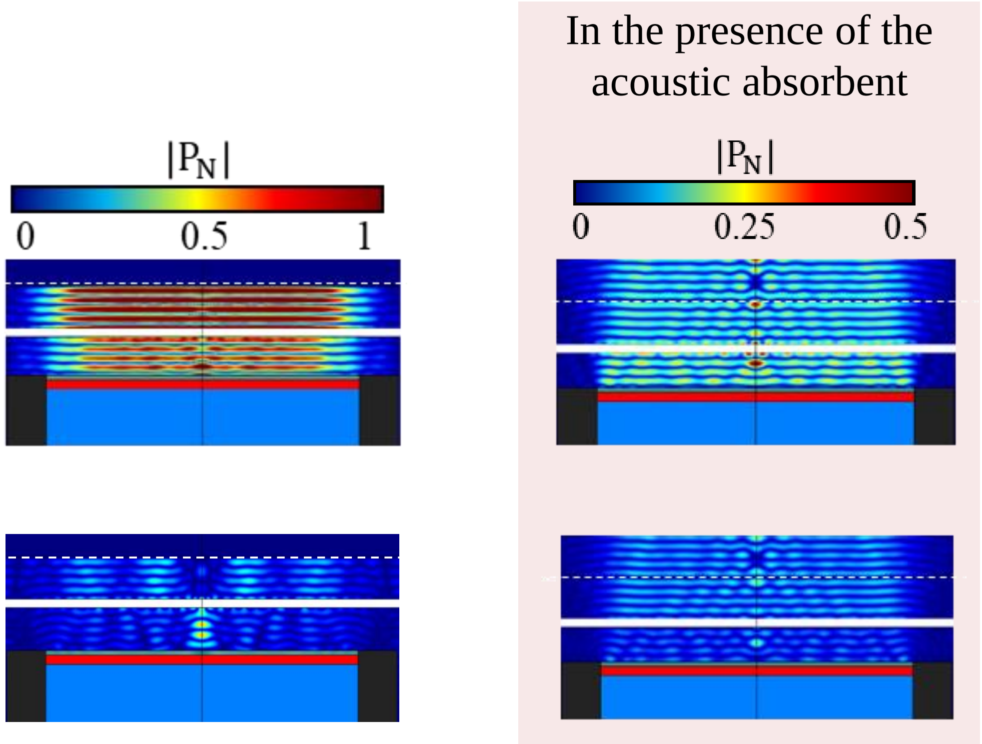
- 0.375 mm increase in the water layer thickness.

  Decrease in the acoustic pressure at the dish surface by

  - 5.2-fold in the original configuration
  - 1.8-fold in the modified configuration

Constructive Interference

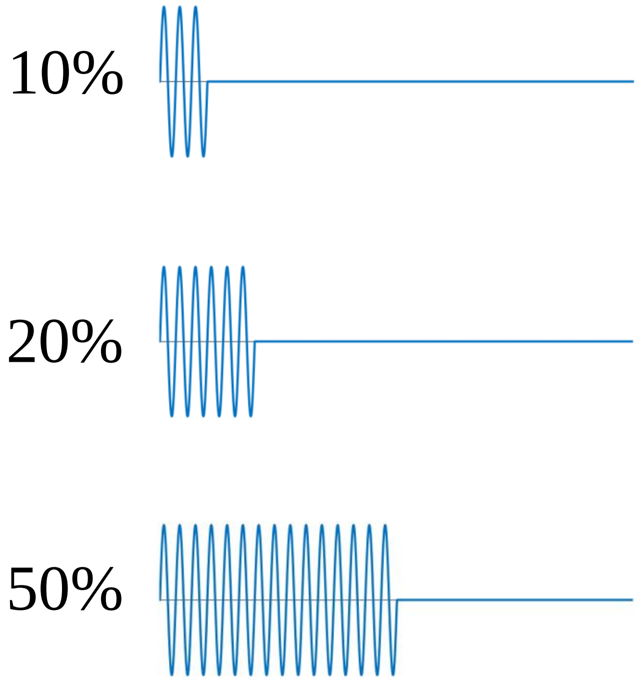
Destructive Interference

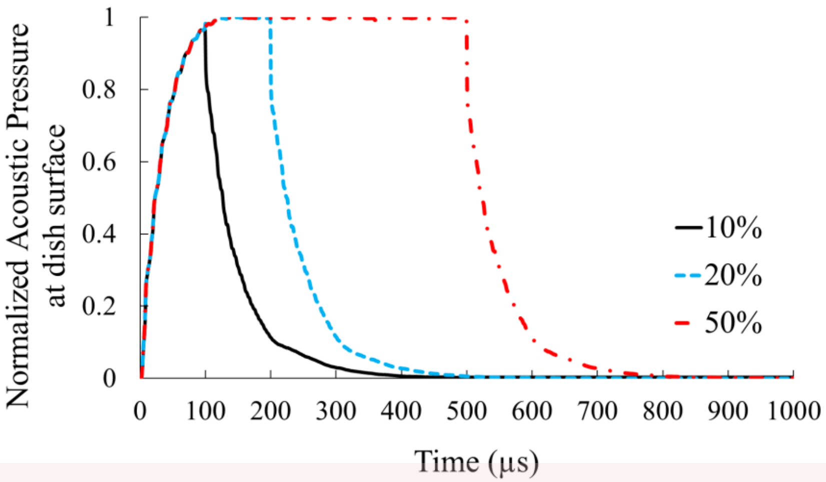


Results

- Effect of duty cycles variation using time-dependent simulation

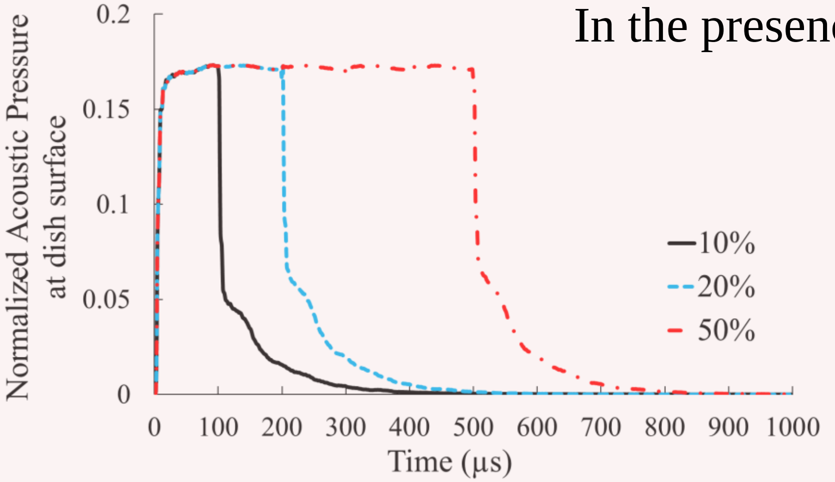
Duty Cycle





Summation of the total acoustic pressure	
20% / 10%	50% / 10%
1.6	3.7

In the presence of the acoustic absorbent



Summation of the total acoustic pressure	
20% / 10%	50% / 10%
1.9	4.3

Summary & Conclusion

- Using time-dependent simulation, contribution of the standing waves in the active and inactive period of the pulsed US signal was analyzed.

- Addition of the acoustic absorbent layer to eliminate reflection at the air interface resulted that the pressure pattern more closely followed the applied pulsed US signal.

- Increase in the duty cycle did not produce a similar increase in the total average acoustic pressure.

  The acoustic pressure did not reach the maximum pressure level at 10% duty cycle in the original configuration.

Future Studies

- Developing a model including cell monolayer.
- Analyzing US wave propagation in the 3D porous scaffolds

Acknowledgement

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Thank you