Cavitation Control in Burst Wave Lithotripsy of Kidney Stones: A Delicate Balance

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AAPM 2021

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DISCLOSURE

SonoMotion

- Equity
- Consultancy

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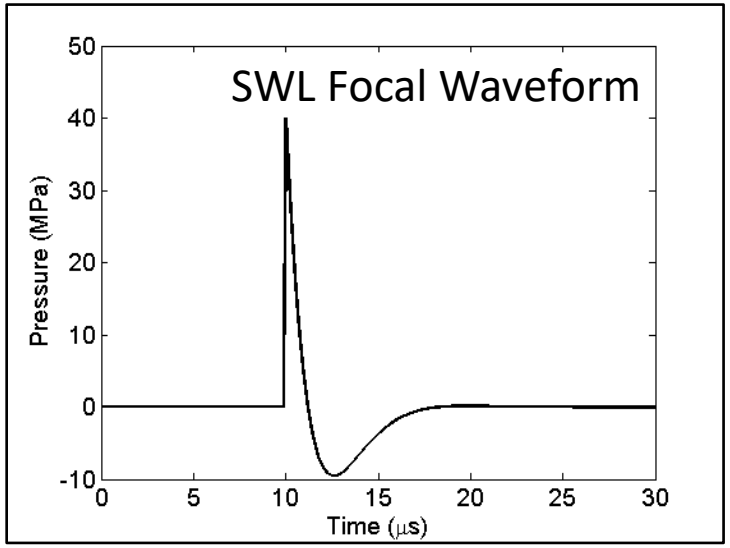
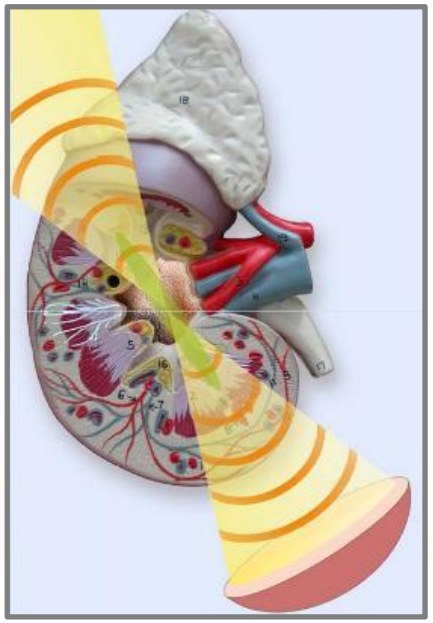
Shock Wave Lithotripsy (SWL)

- High-amplitude shock waves noninvasively fragment kidney stones into passable fragments.
- In a clinical setting, shock wave lithotripsy has moderate stone free rates (60-70%)
- SWL is no longer the most common procedure for stones – it has been overtaken by ureteroscopy

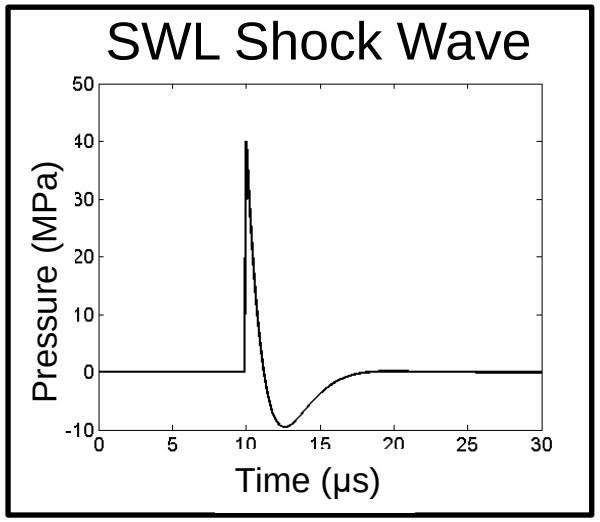


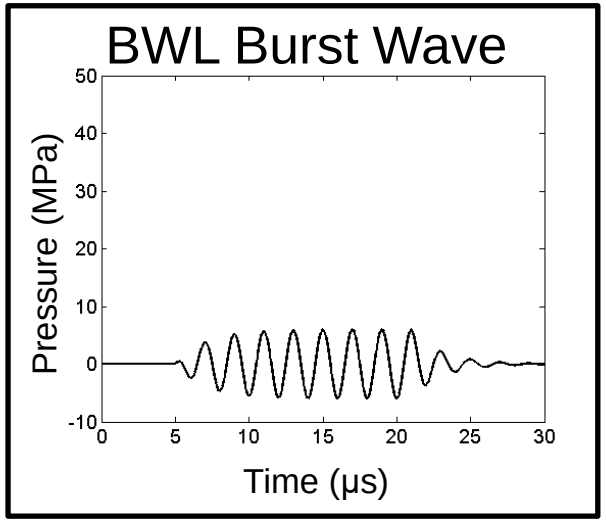


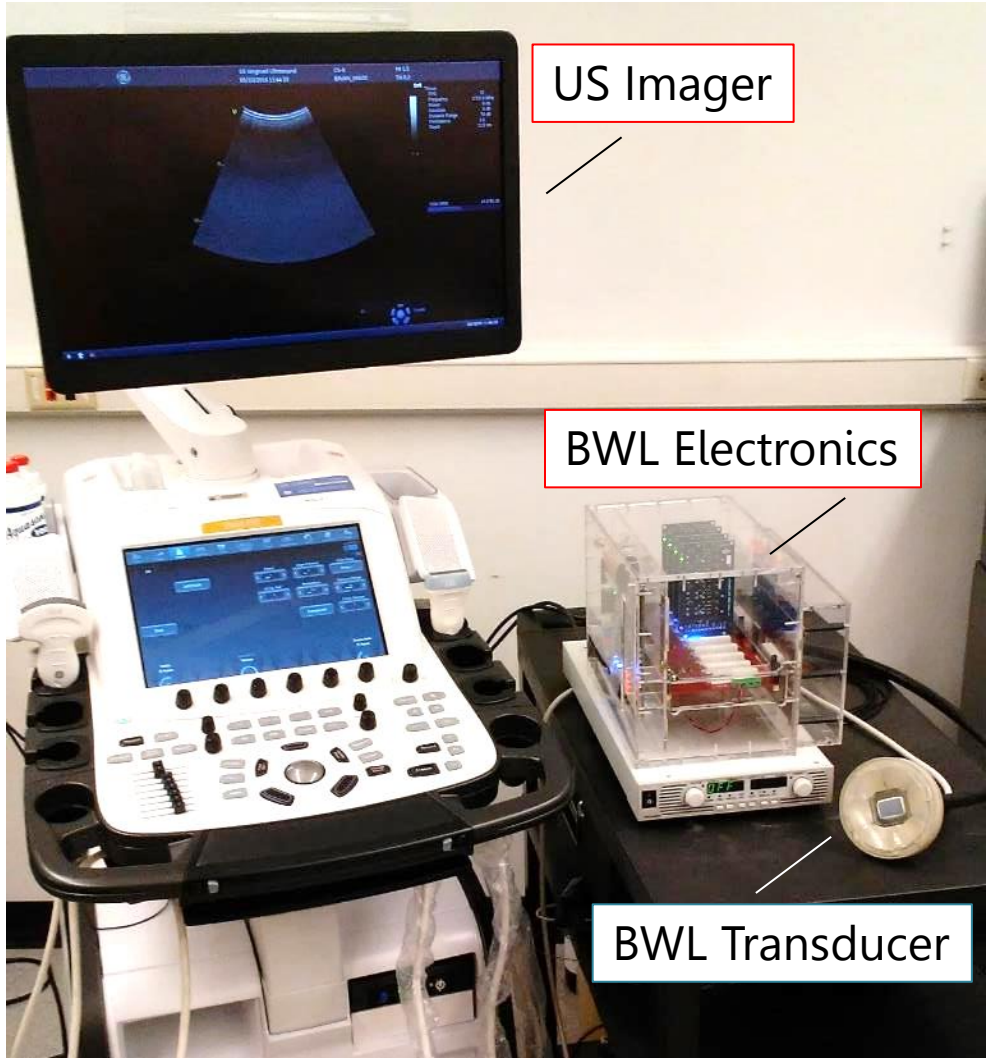
[1]Lingeman JE. J Urol 2004;**172**:1774.
[2]Matlaga, BR J Urol 2009;**181**:152-2156.

Burst Wave Lithotripsy (BWL)

Sinusoidal focused ultrasound pulses to achieve stone fragmentation

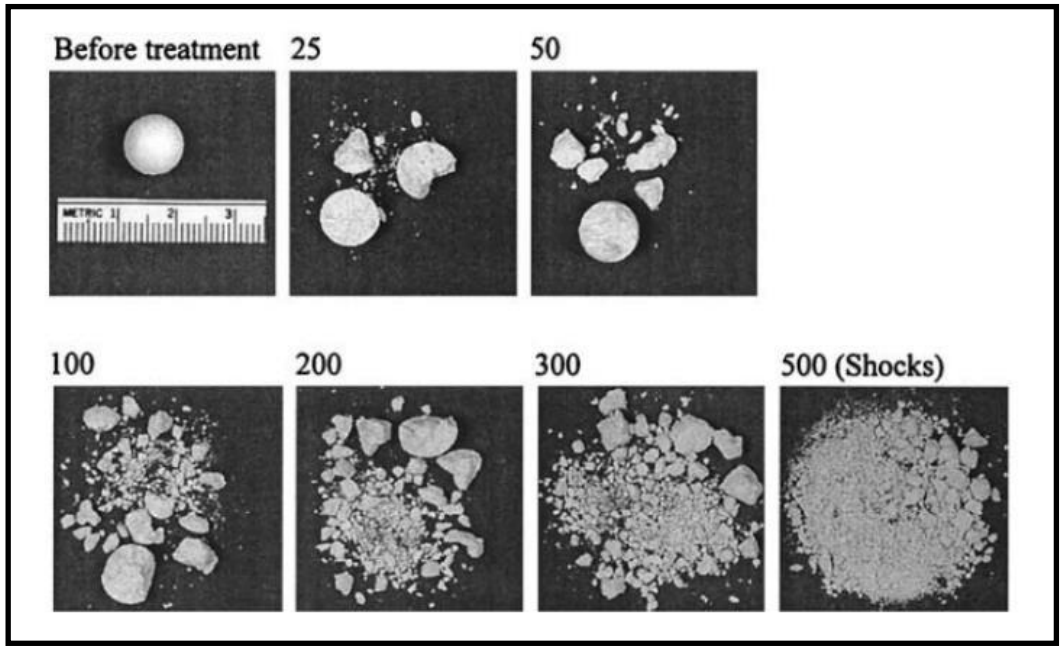






Burst Wave Lithotripsy

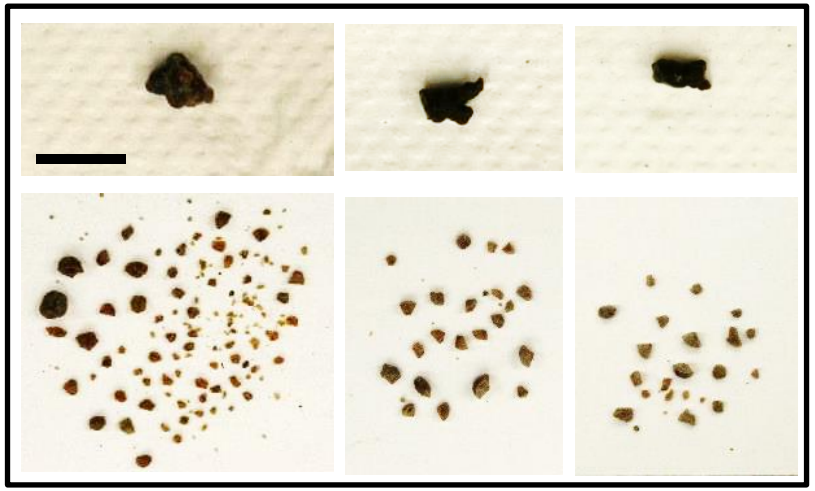
Zhu, Zhong et al, UMB 2002



Shock Wave Lithotripsy

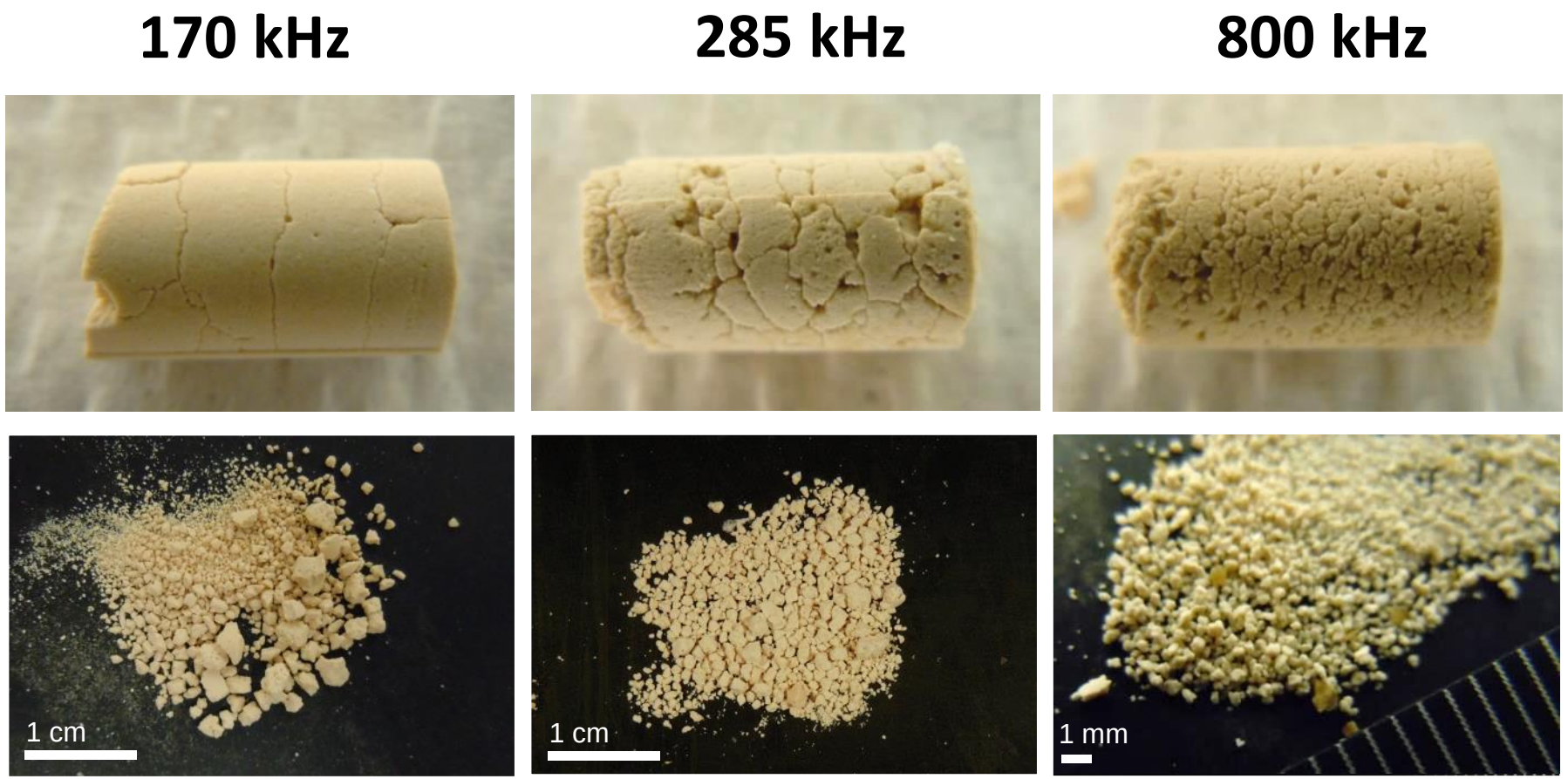
Treatment Progression

Burst Wave Lithotripsy



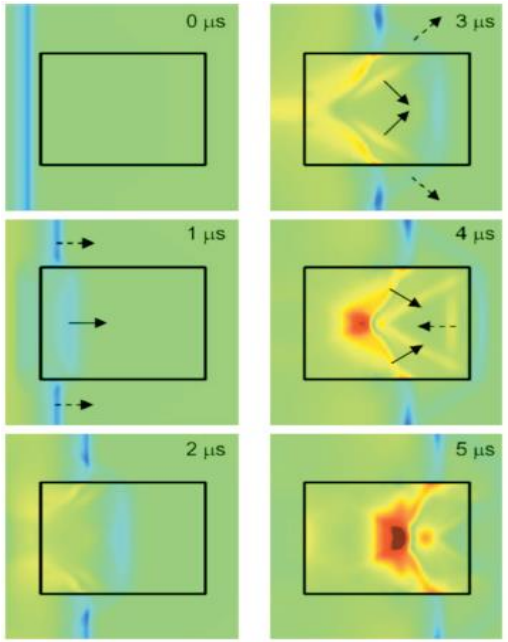
Maxwell et al, J Endourol 2019

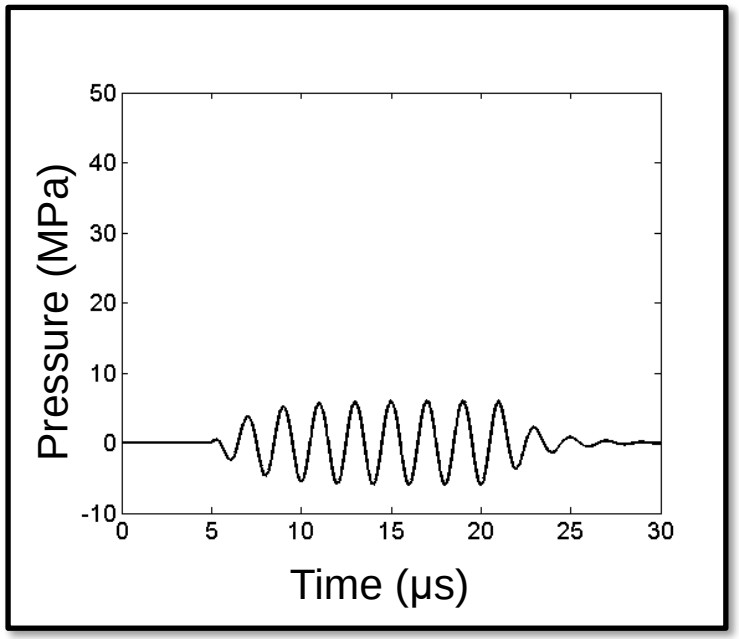
Burst Wave Lithotripsy



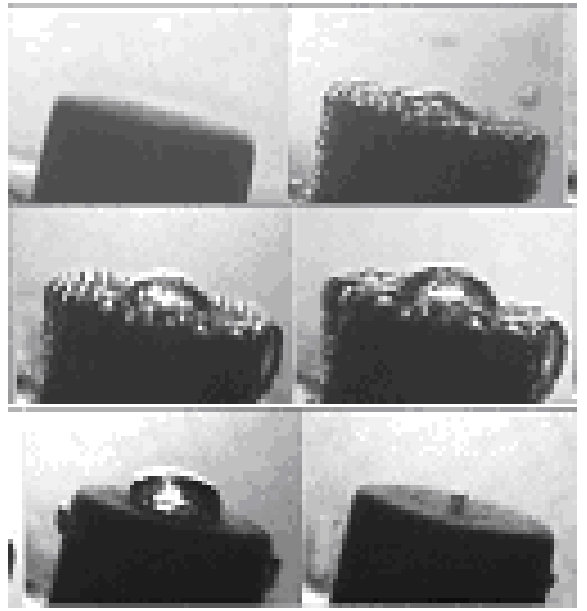
Stone fracture mechanisms

Elastic Waves





Cavitation



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Cavitation in burst wave lithotripsy

Cavitation in burst wave lithotripsy produces three dominant effects:

Cavitation in burst wave lithotripsy

Cavitation in burst wave lithotripsy produces three dominant effects:

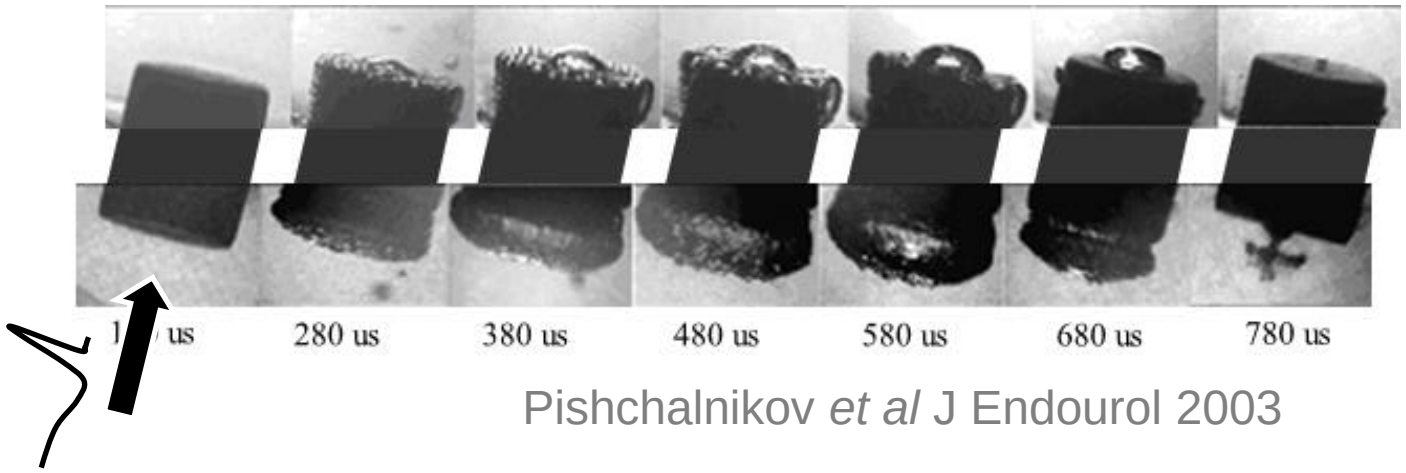
1. **Cavitation on the stone produces erosion of the stone.**

Acoustic cavitation

Inertial Cavitation

- Large bubble expansion
- Violent collapse
- Bubble microjetting
- Shock wave emission

Cavitation in SWL



Pishchalnikov *et al* J Endourol 2003

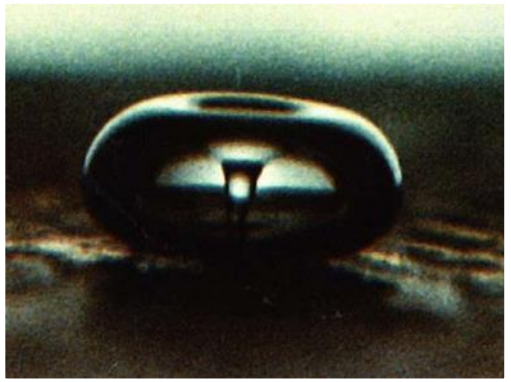


Photo by Larry Crum

Cavitation in stone fracture

Surrounding the stone by hydrogel instead of water reduces fragmentation

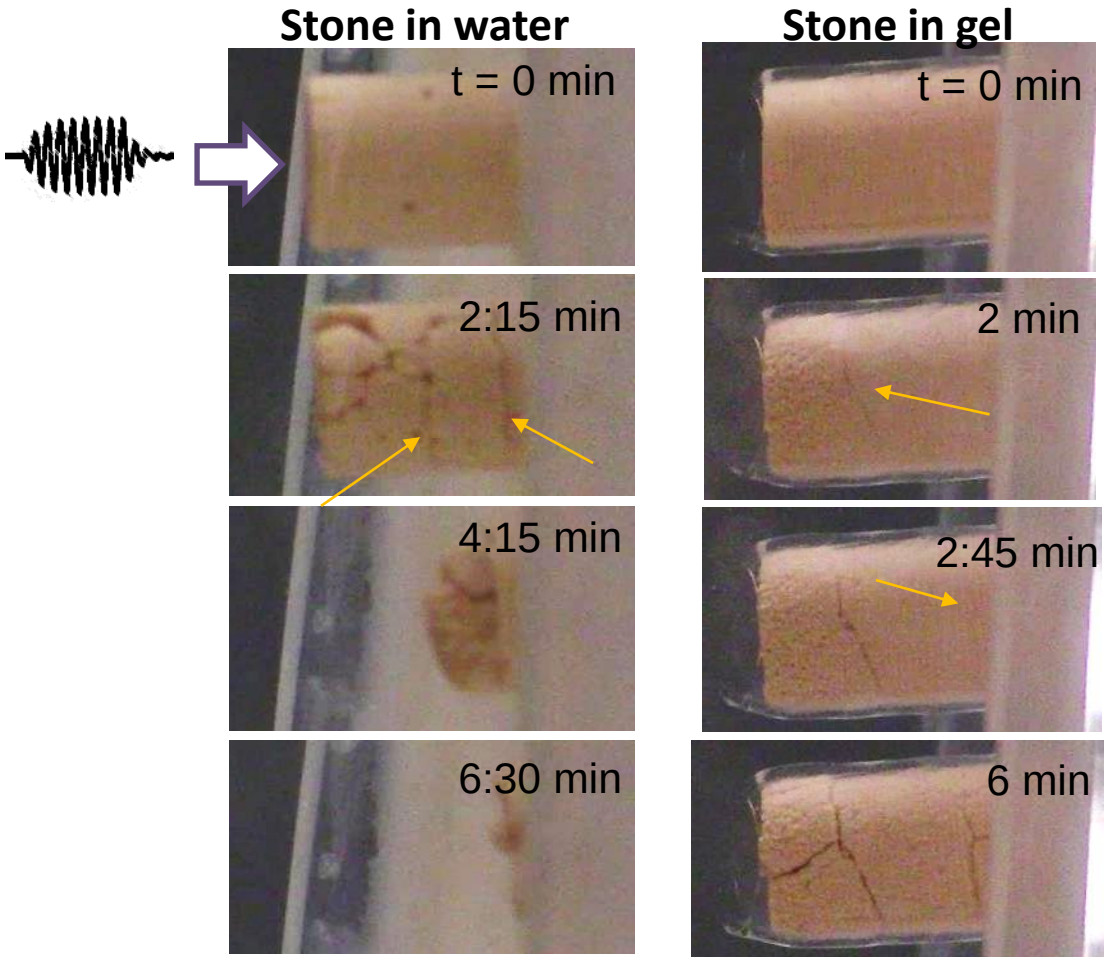
Parameters:

Frequency = 170 kHz

Pulse duration: 20 cycles

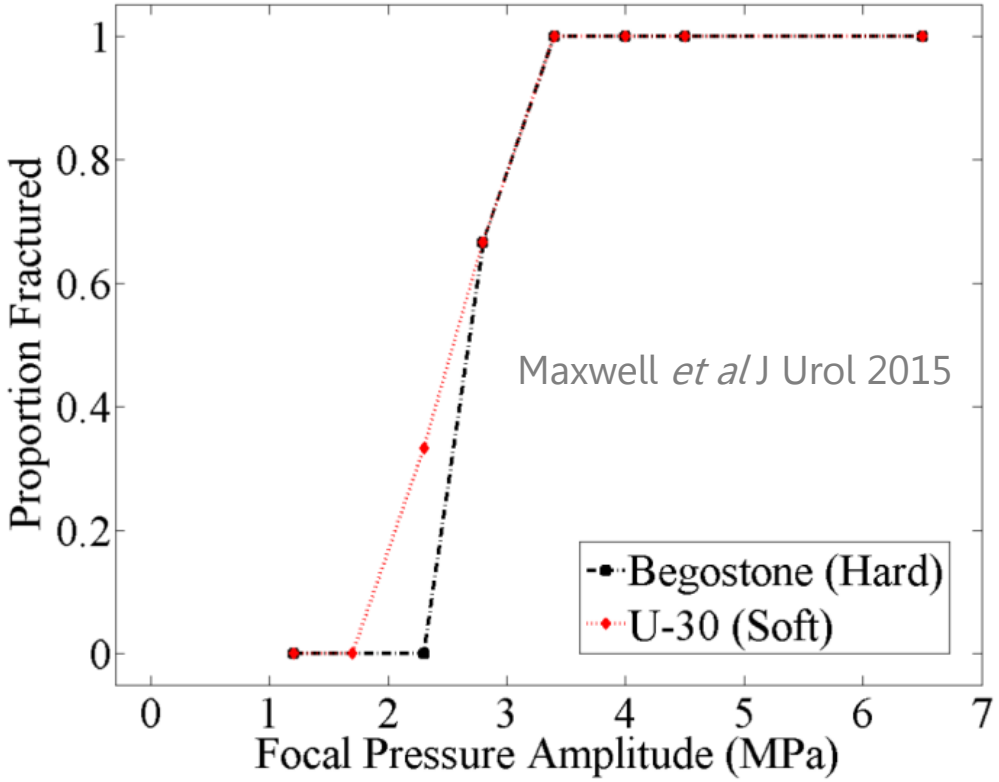
Pulse rate = 10 Hz

Focal Pressure: 7 MPa



Cavitation in stone fracture

Pressure threshold for fracture is independent of stone composition



Human kidney stone	*Artificial kidney stone composition*[a]	*Tensile strength (MPa)*	
		Human stones	*Artificial stones*
MAPH/CA	66 wt% BegoStone	0.6–1.3	1.2 ± 0.08
UA	72 wt% BegoStone	1.2–3.6	2.3 ± 0.16
Cystine	73 wt% BegoStone	1.3–3.7	2.5 ± 0.18
Oxalate	82 wt% BegoStone	3.1–5.2	4.2 ± 0.29
CHPD	81 wt% BegoStone	3.0–4.8	4.0 ± 0.28

Nyame et al J Endourol 2015

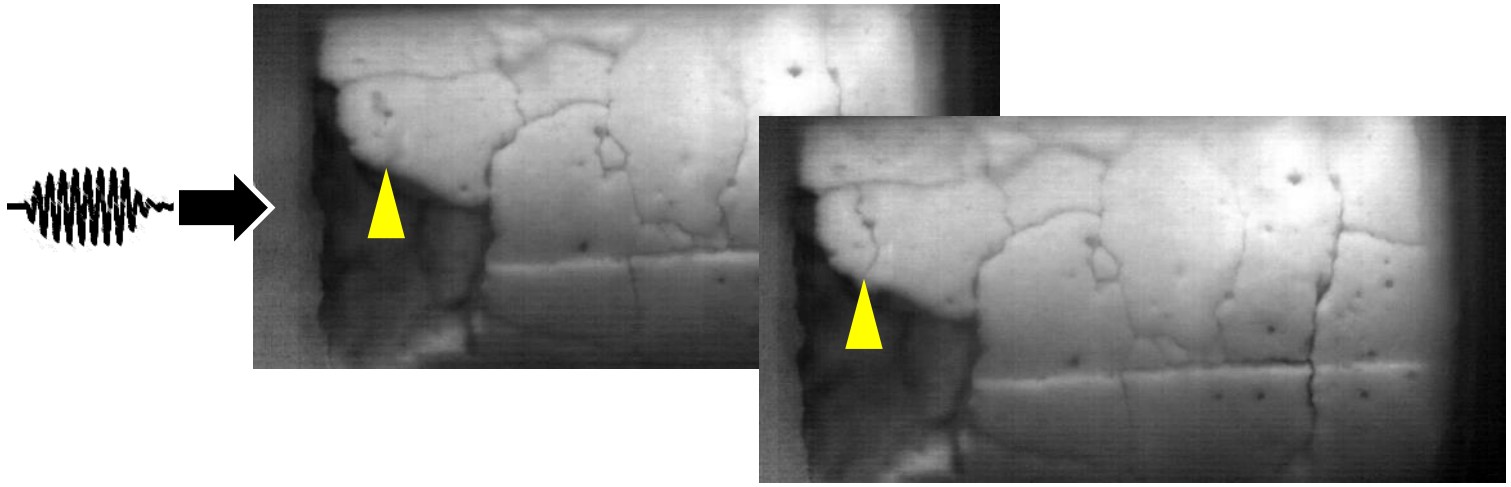
These data suggest cavitation threshold rather than tensile stress threshold limits onset of fracture.

Cavitation in stone fracture

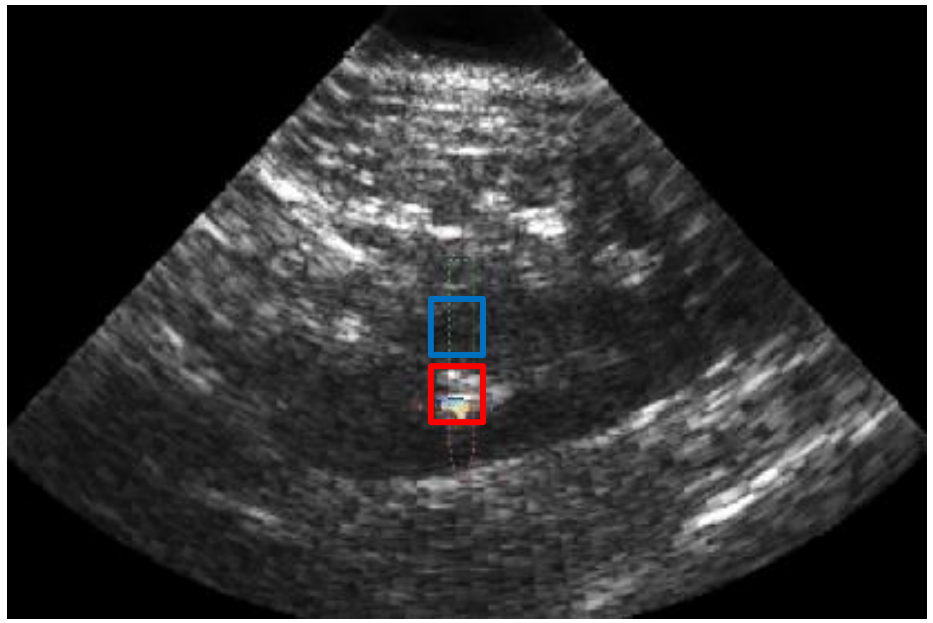
Direct observations of cavitation have been made

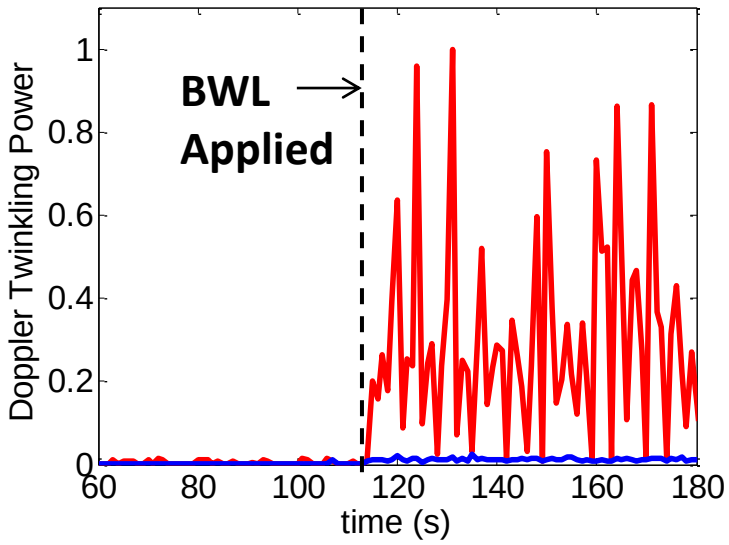
- High speed photography
- Ultrasound detection

High-speed photography



Doppler US imaging





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Cavitation in burst wave lithotripsy

Cavitation in burst wave lithotripsy produces three dominant effects:

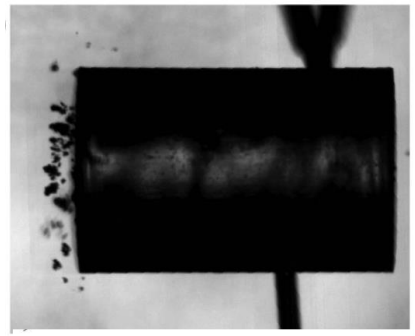
1. Cavitation on the stone produces erosion of the stone

2. **Cavitation blocks ultrasound waves and reduces stone fracture.**

Simulated cavitation and acoustic shielding

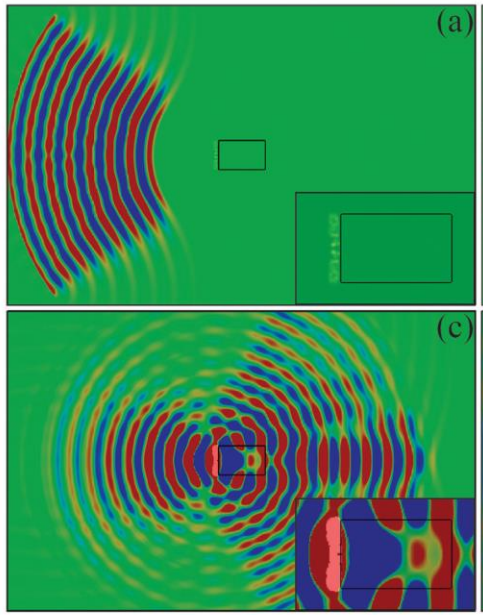
- Cavitation bubbles in urine/tissue cause shielding (scattering of acoustic wave)
- **Result:** up to 90% of the acoustic energy does not reach the stone

Observed Bubbles

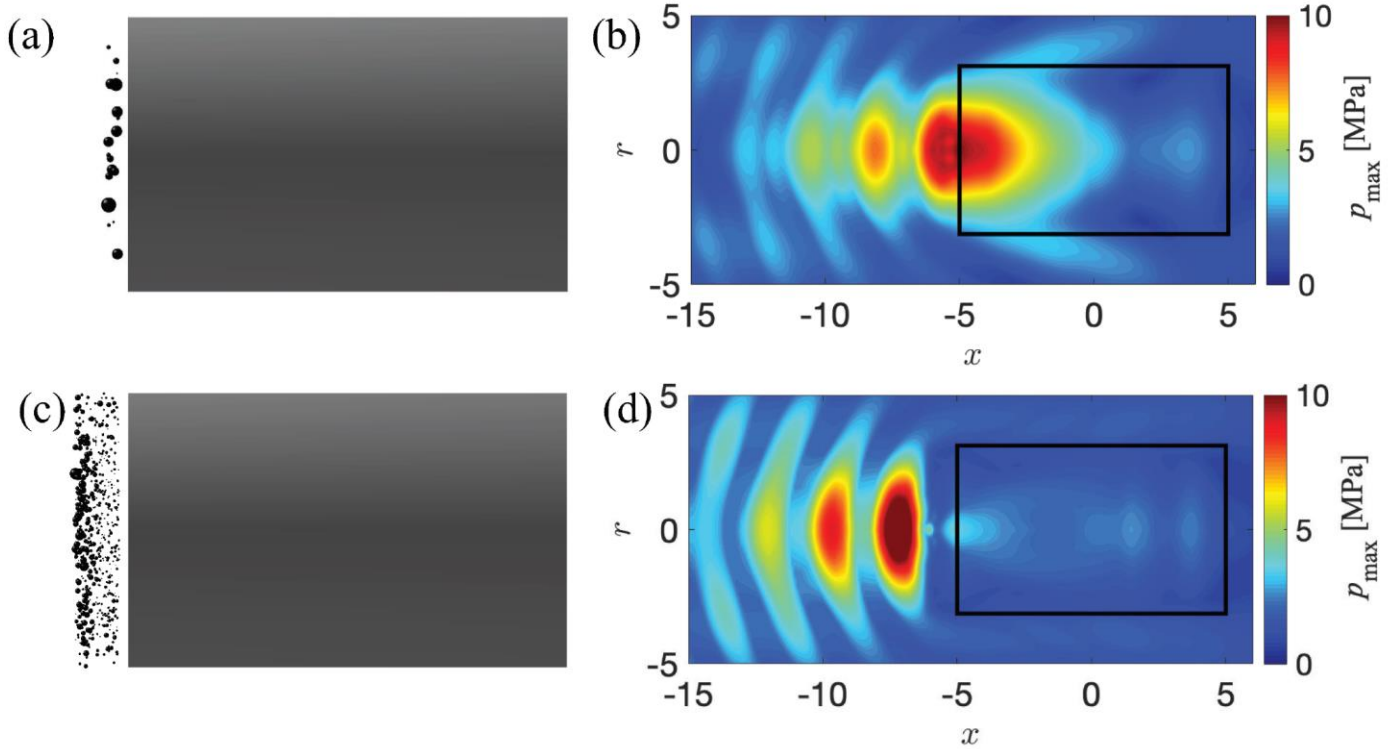


Simulated Bubbles

Simulated Scattering



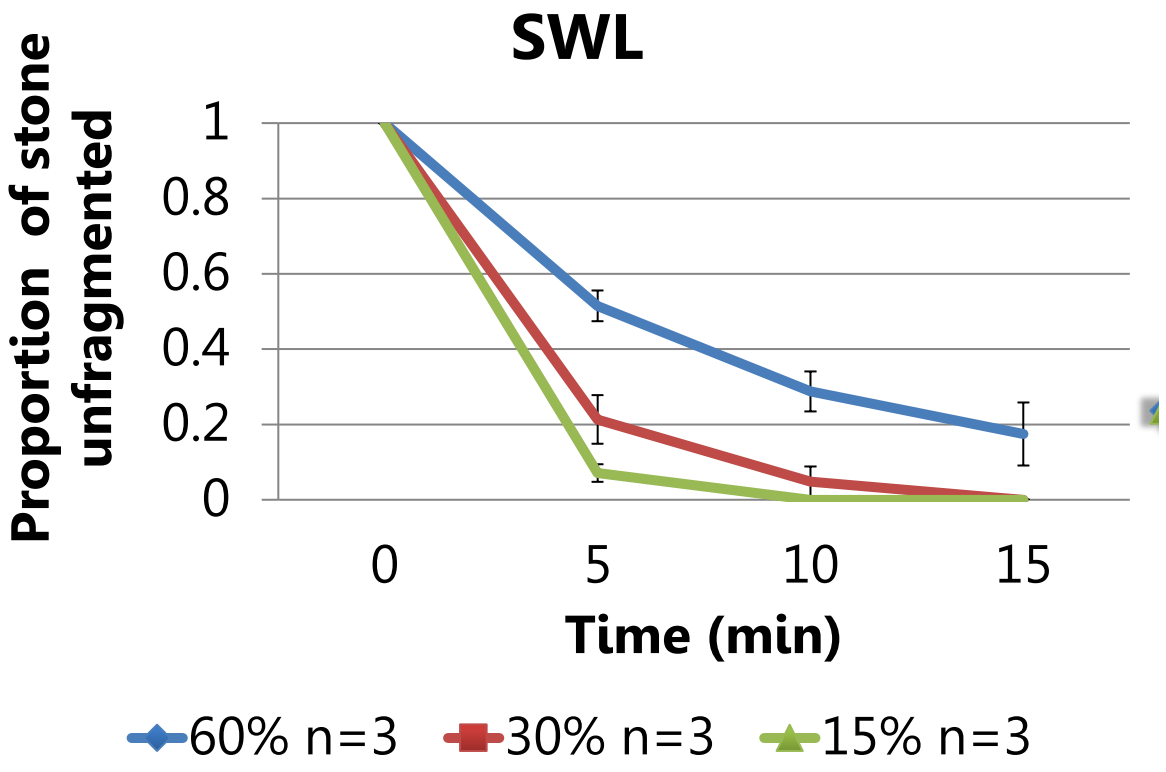
Acoustic Pressure

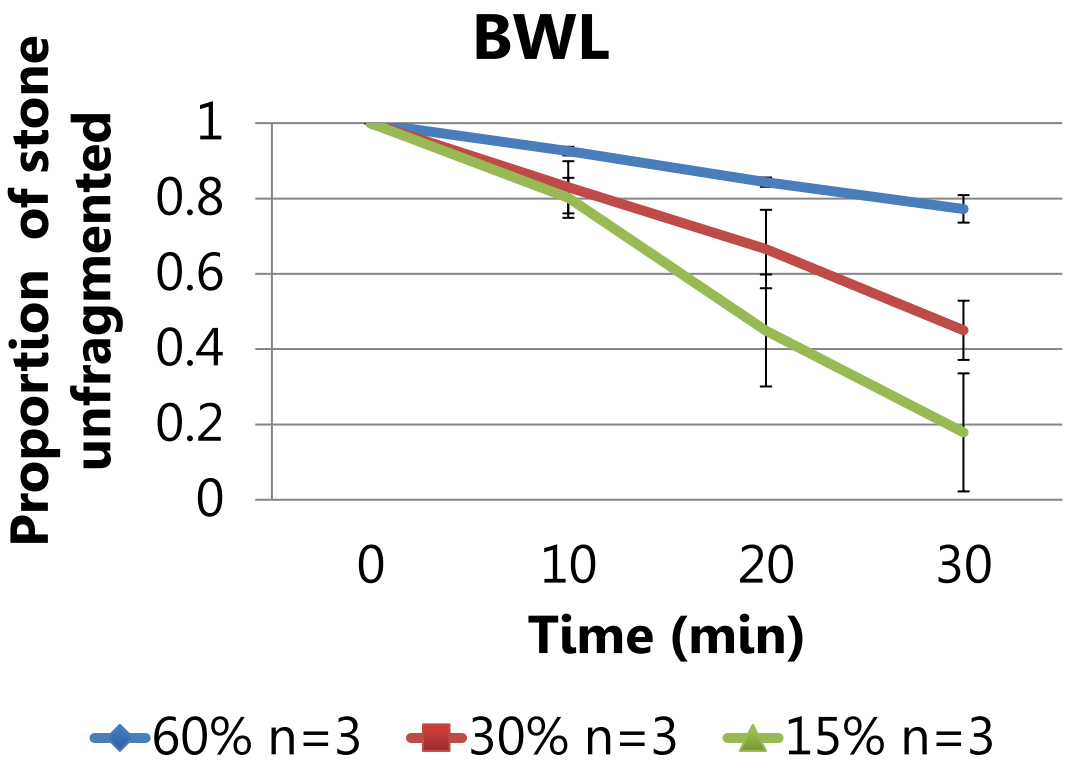


Maeda et al. JASA 2018; 144(5):2952-61.

Effect of water gas concentration on fragmentation

Water O_2 saturation: 15-60% (regulated by degassing system)





Randad et al J Endourol 2019;33(5):400-6.

Cavitation *in vitro*

- **Urine gas partial pressure[1]:**
  - P_0 = 537 mmHg ~ 71% saturation

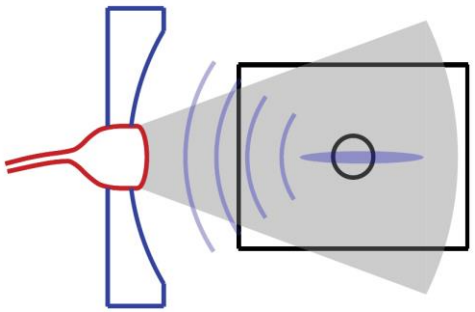
- **Gas composition in liquids** (by volume %)**:**
  - Water: trace CO_2, 68% N_2, 31% O_2
  - Blood: 70% CO_2, 2% N_2, 28% O_2
  - Urine: 70-80% CO_2, 10-20% N_2, <10% O_2

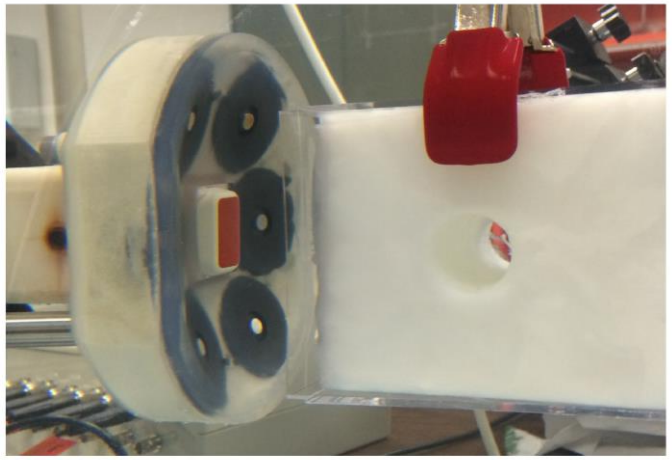
[1]Chaigneau and LeMoan. CR Acad Sci Ser D 1968

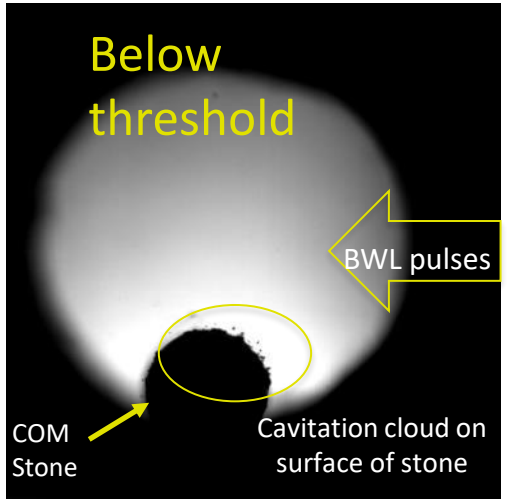
Matching cavitation *in vitro*

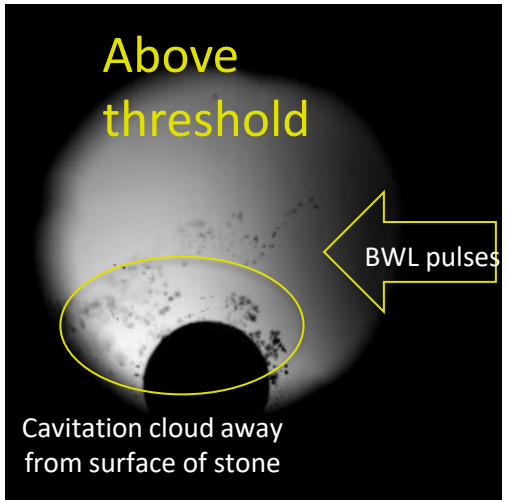
- Pressure threshold for cavitation clouds in BWL exposures

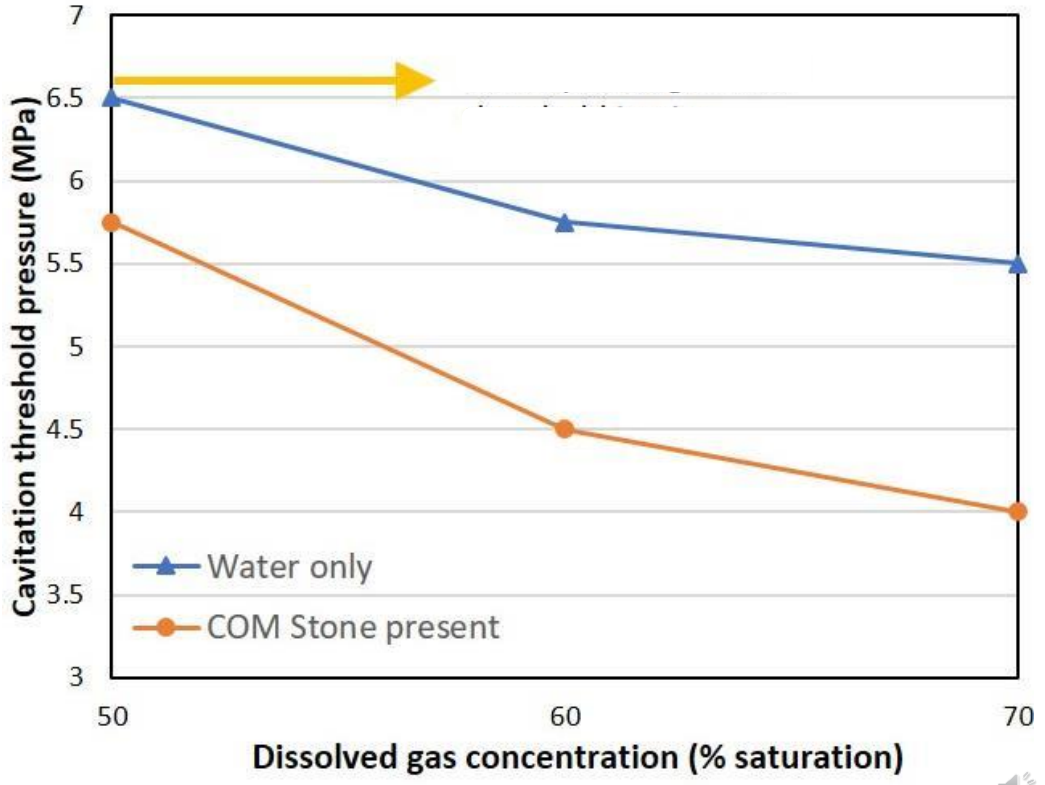
- Measured in fluid space of tissue phantom *in vitro* vs. gas concentration in deionized water











Hunter C. et al. 5th Joint Meeting ASA and ASJ. 2016

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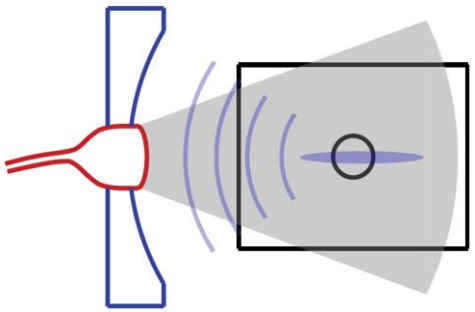
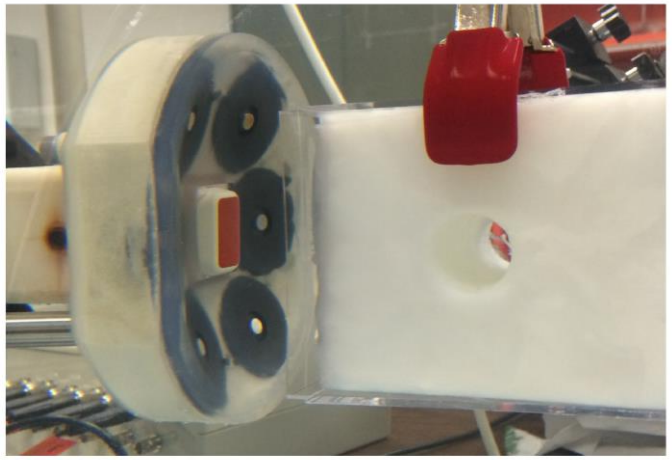
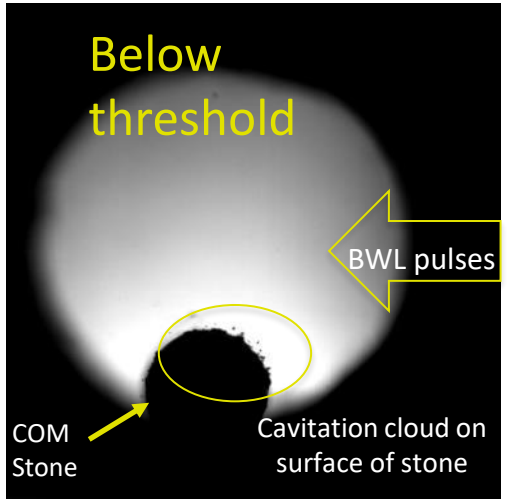
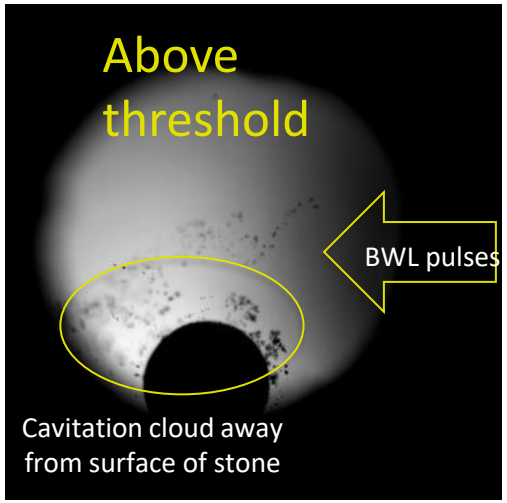
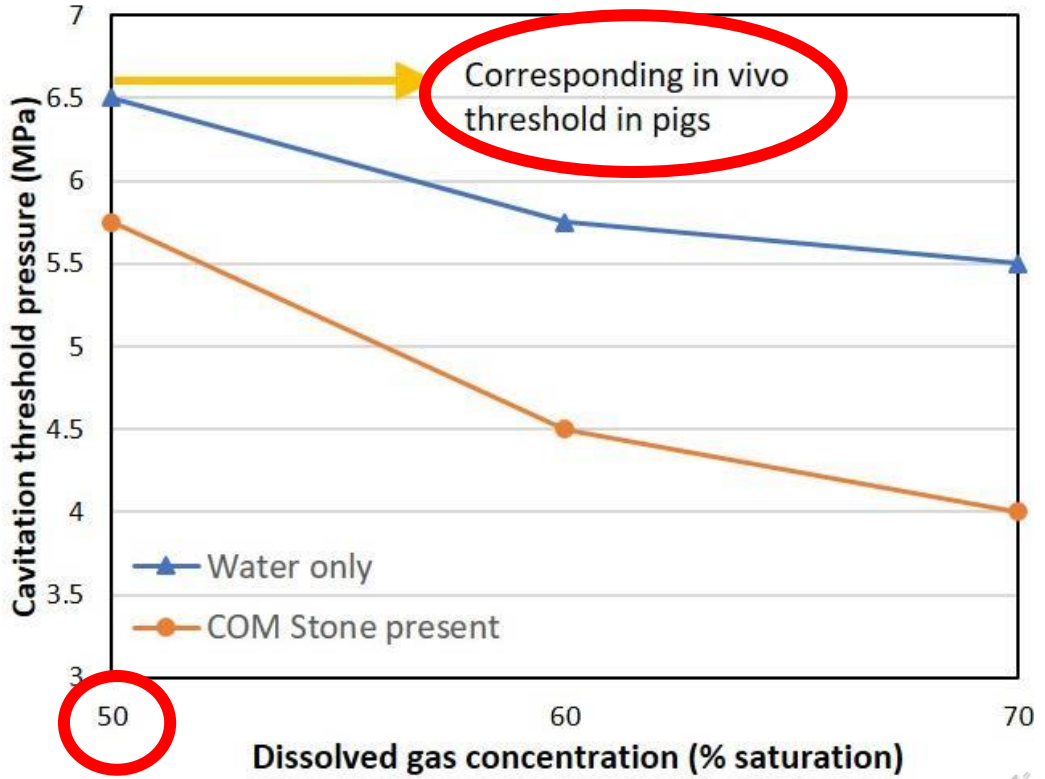






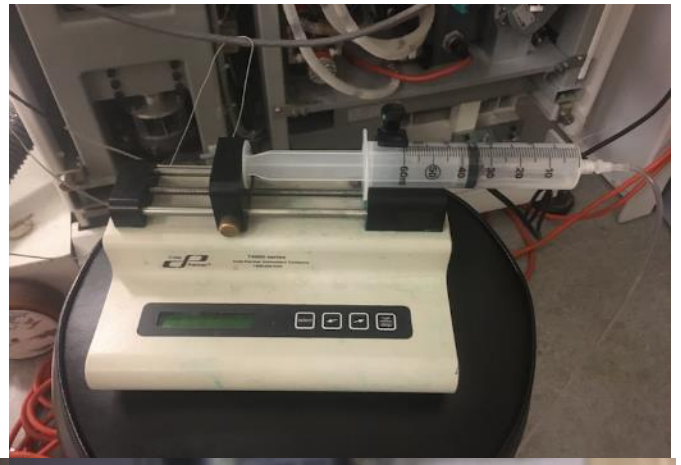


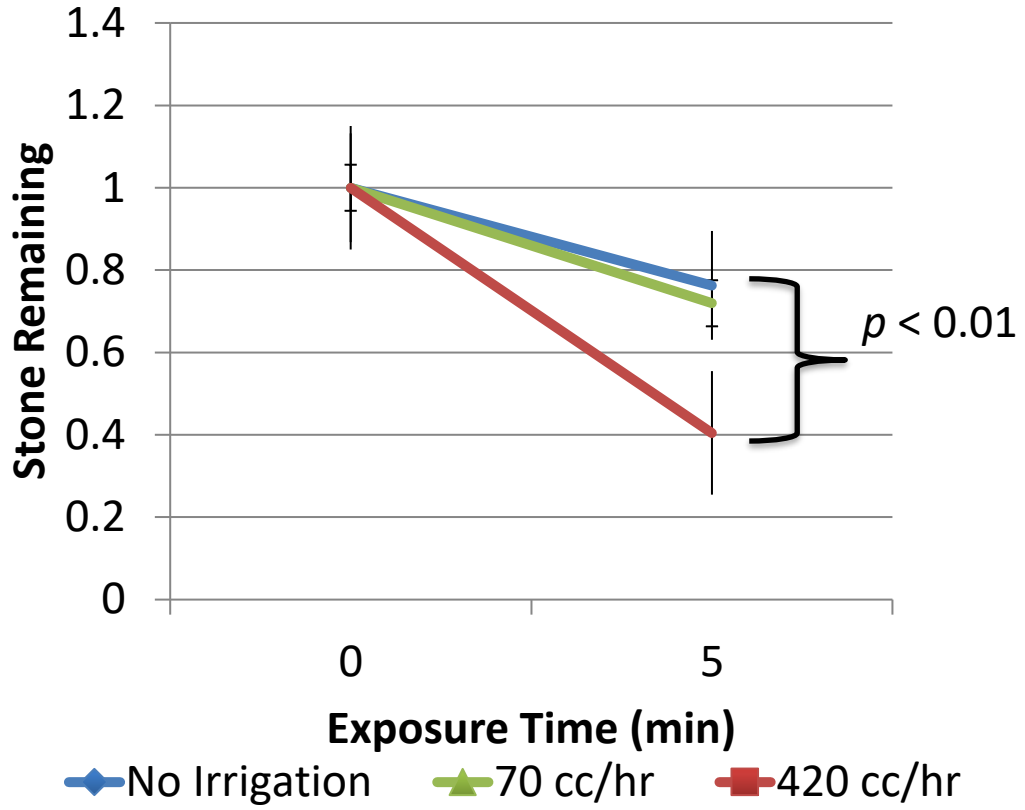


Hunter C. et al. 5th Joint Meeting ASA and ASJ. 2016

Irrigation Model

- Continuous Irrigation
- 0 - 420 cc/hr water
- 18 gauge needle
- Middle calyx puncture





Randad et al J Endourol 2019;33(5):400-6.

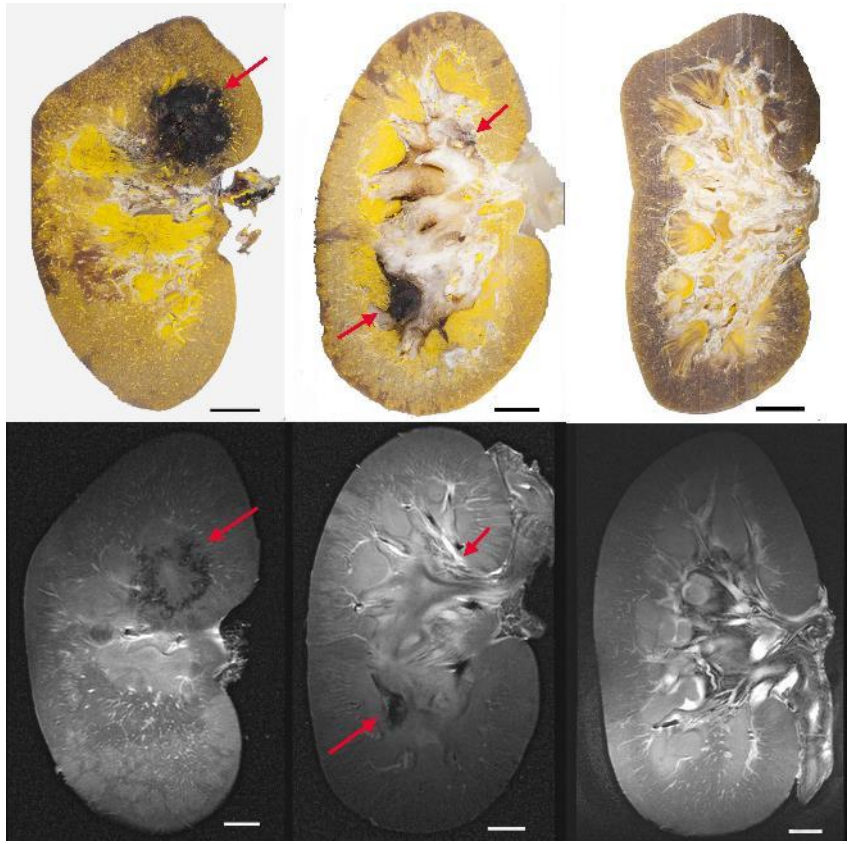
Cavitation in burst wave lithotripsy

Cavitation in burst wave lithotripsy produces three dominant effects:

1. Cavitation on the stone produces erosion of the stone.
2. Cavitation blocks ultrasound waves and reduces stone fracture.
3. **Cavitation in tissue produces injury to the tissue.**

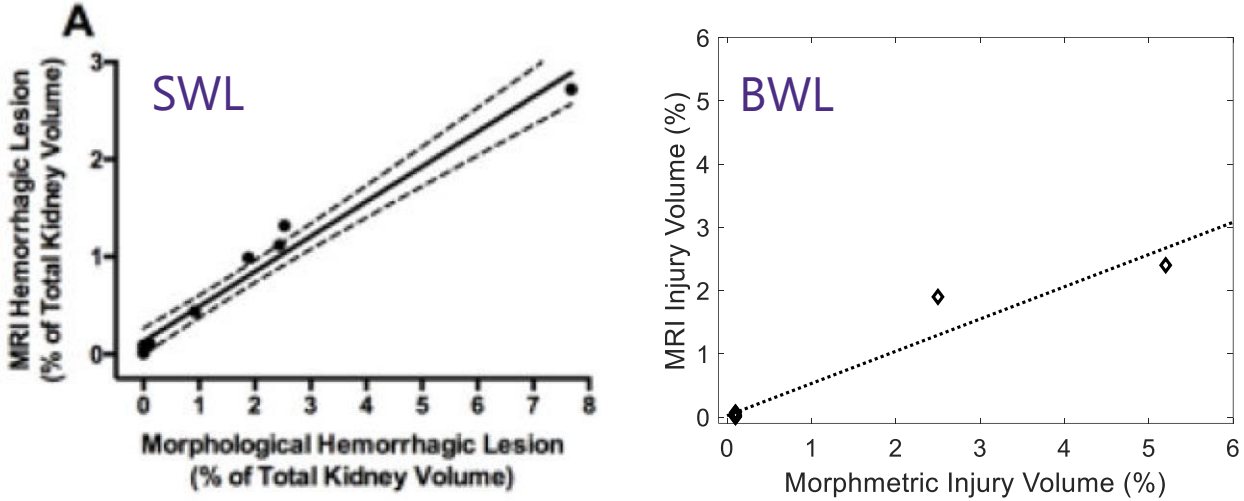
Detection of cavitation effects *in vivo* (BWL)

MRI used to quantify volume of lithotripsy injury

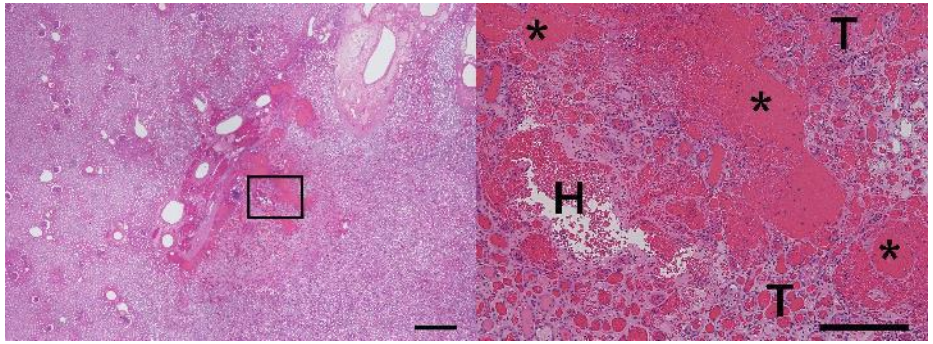


May *et al.* *J Endourol* 2017;31(8):786-92.

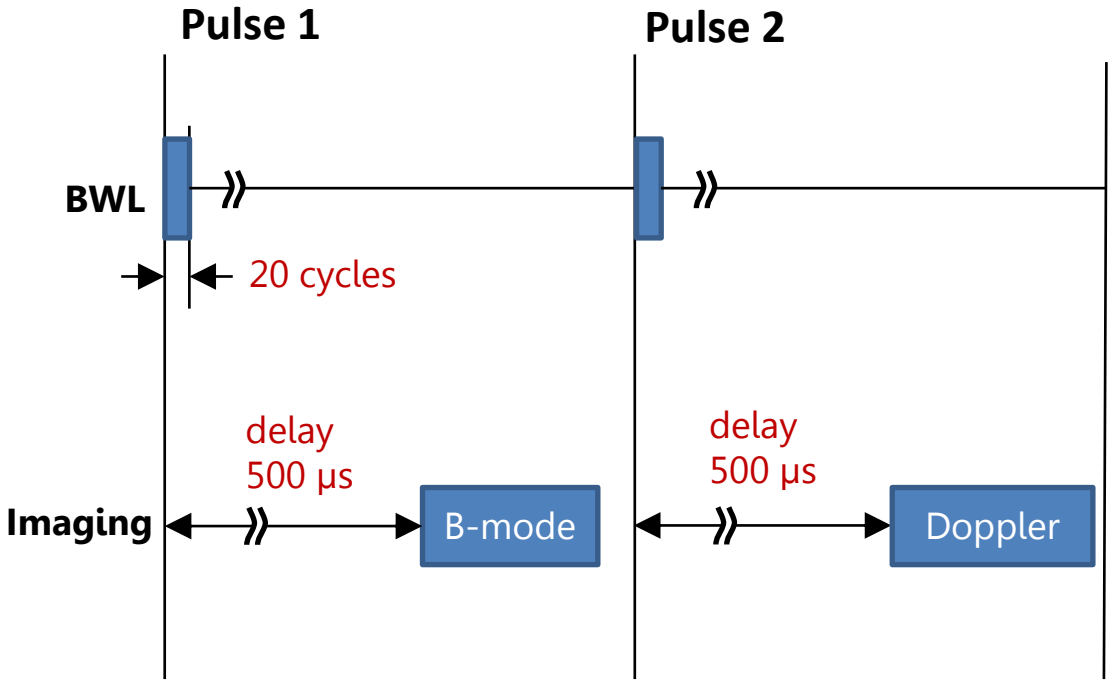
Histologic – MRI volumetric injury correlation

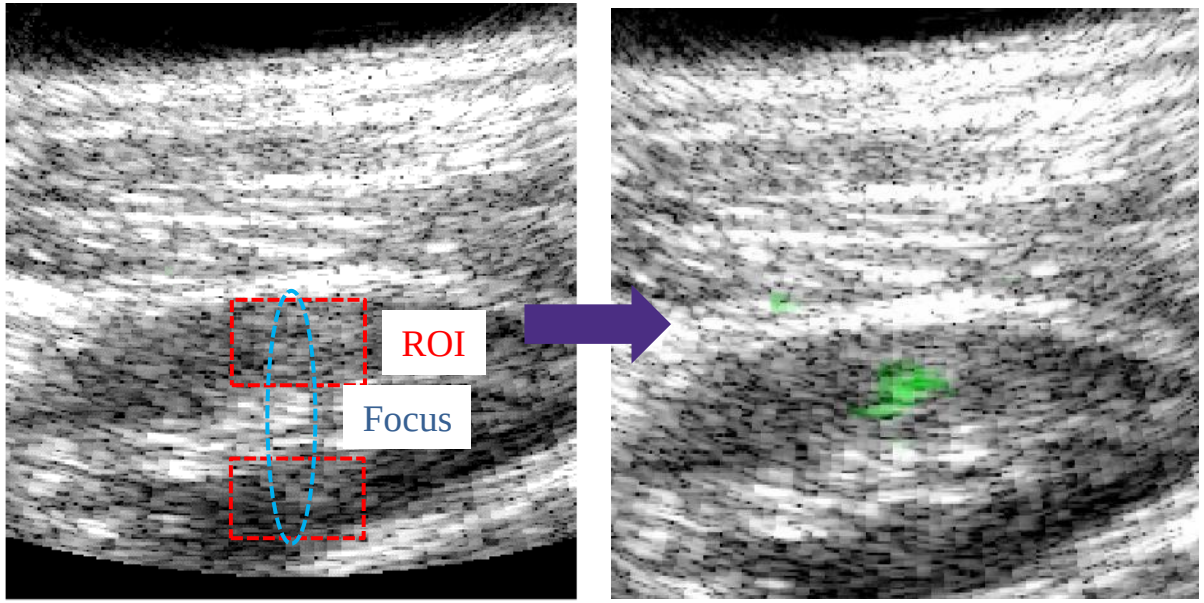


Handa *et al.* Urolithiasis 2017; 45:507-13.



Active bubble detection by power Doppler





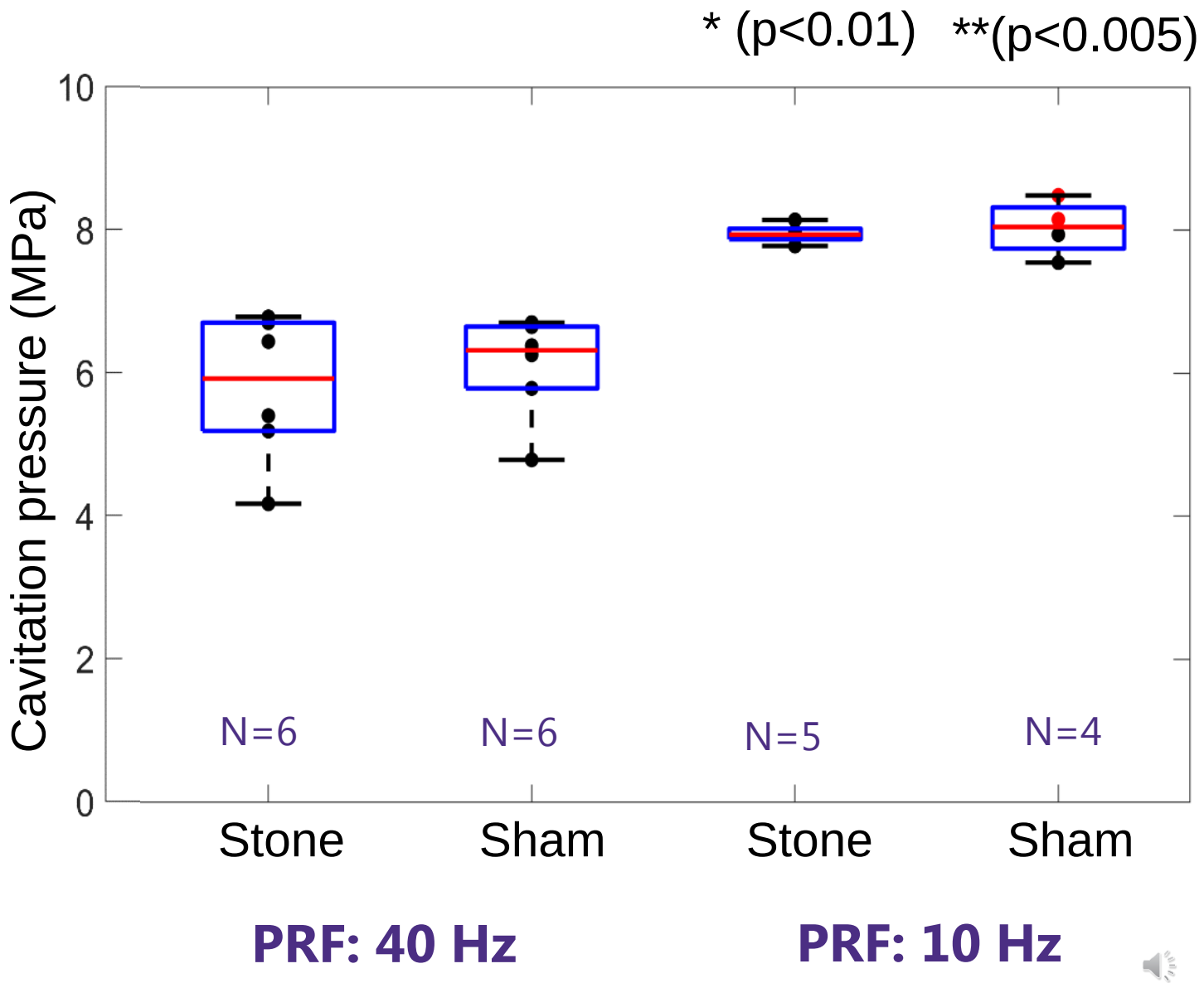
Peak Doppler power in ROI relative to average background power

- **With** cavitation observed: 28.6 dB (11.2 – 51 dB)
- **Without** cavitation observed: 6.4 dB (3.5-17.6 dB)

Maxwell et al Ultrasound Med Biol 2021 (In Press)

Pressure levels for cavitation in tissue

- Measurement of tissue cavitation thresholds in pigs with stones.
- Average pressure range for cavitation was 5.8 – 8.1 MPa
- Pressure significantly greater with PRF = 10 Hz vs 40 Hz



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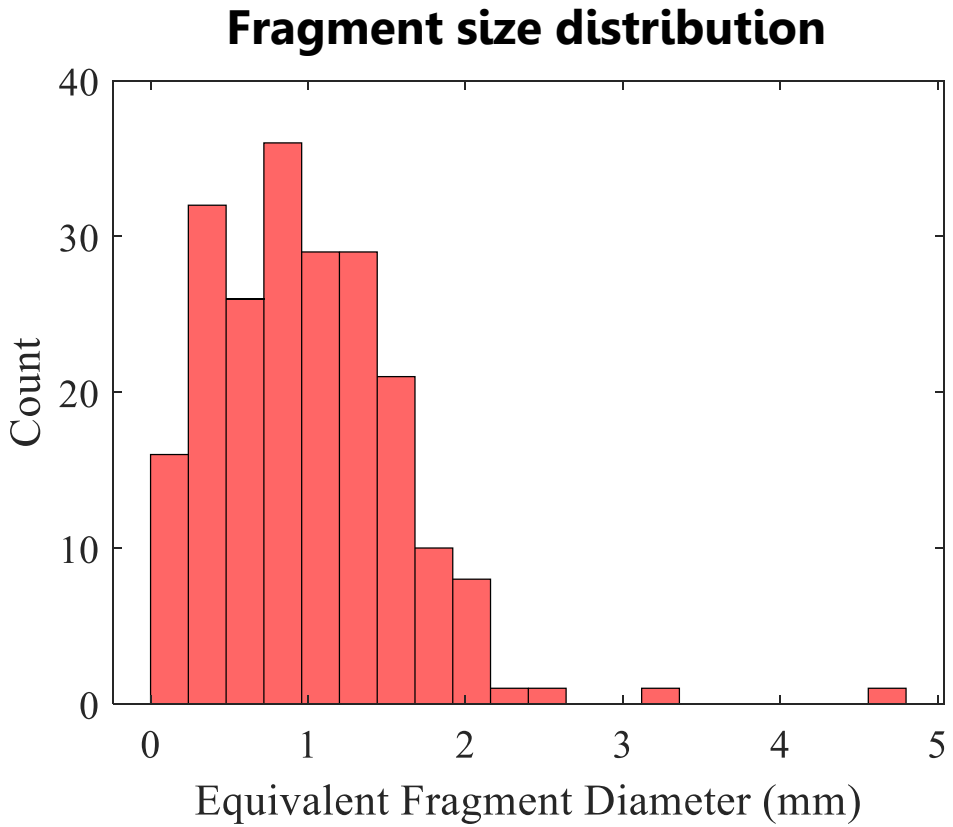
Methods to detect and confine cavitation to the stone can make BWL safer and more effective

Acute clinical simulation

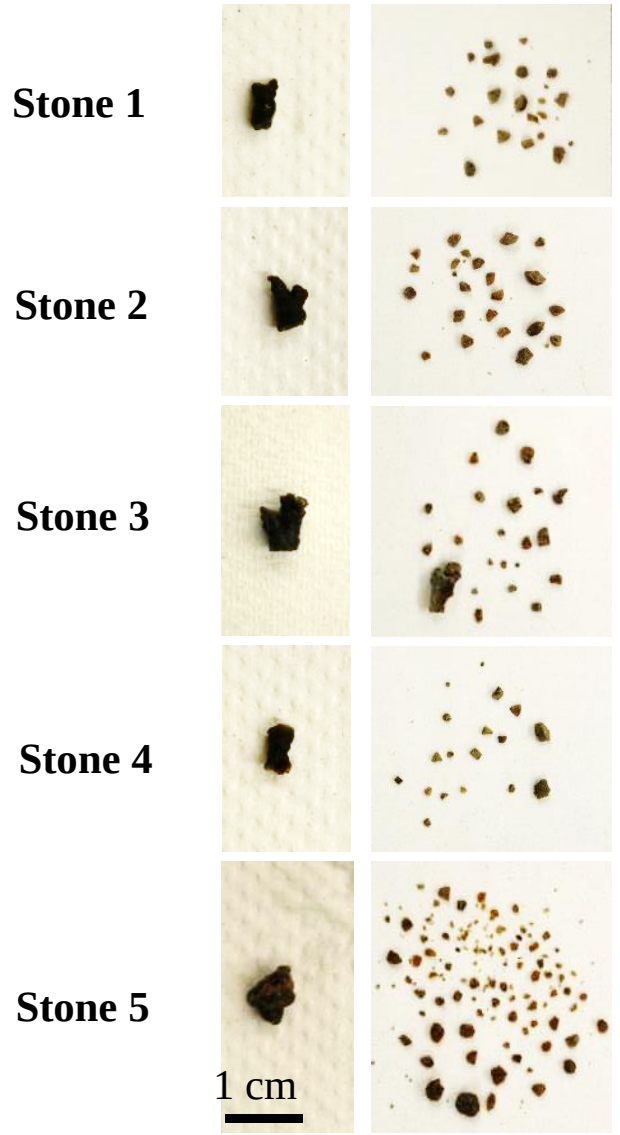
- Treatment of 6-7 mm COM stones in renal pelvis or calyx (n=5)
- Mean 87±17% of mass <2mm fragments

Coll DM AJR 2002; 178(1):101-3.

Stone Size	% Pass Naturally
≤ 4 mm	78%
5 – 7 mm	60%
> 7 mm	39%



Maxwell *et al* J Endourol 2019;33(10):787-92



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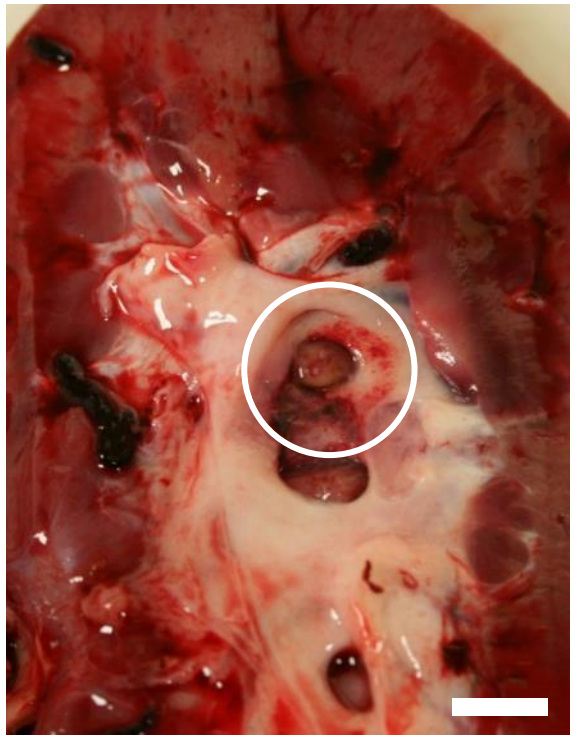
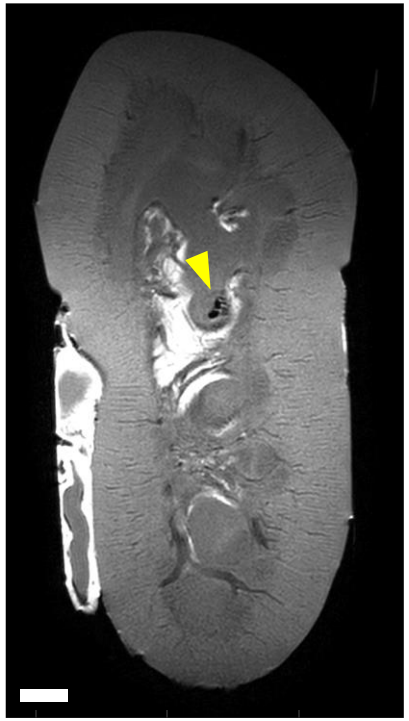
Acute Stone Model Pigs - Injury

- No parenchymal injury found in any kidney
- Minor petechial hemorrhage to mucosal wall

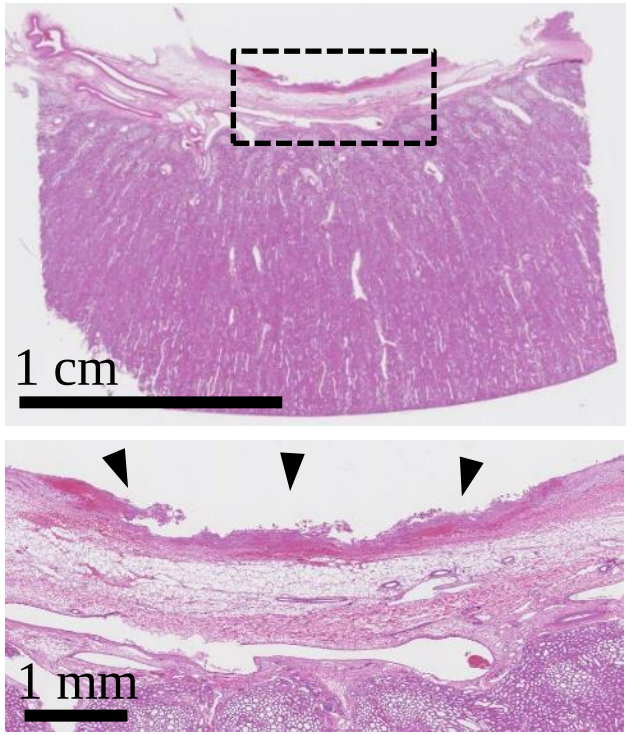
Gross Image



MRI



H&E Histology



Maxwell *et al* J Endourol 2019;33(10):787-92

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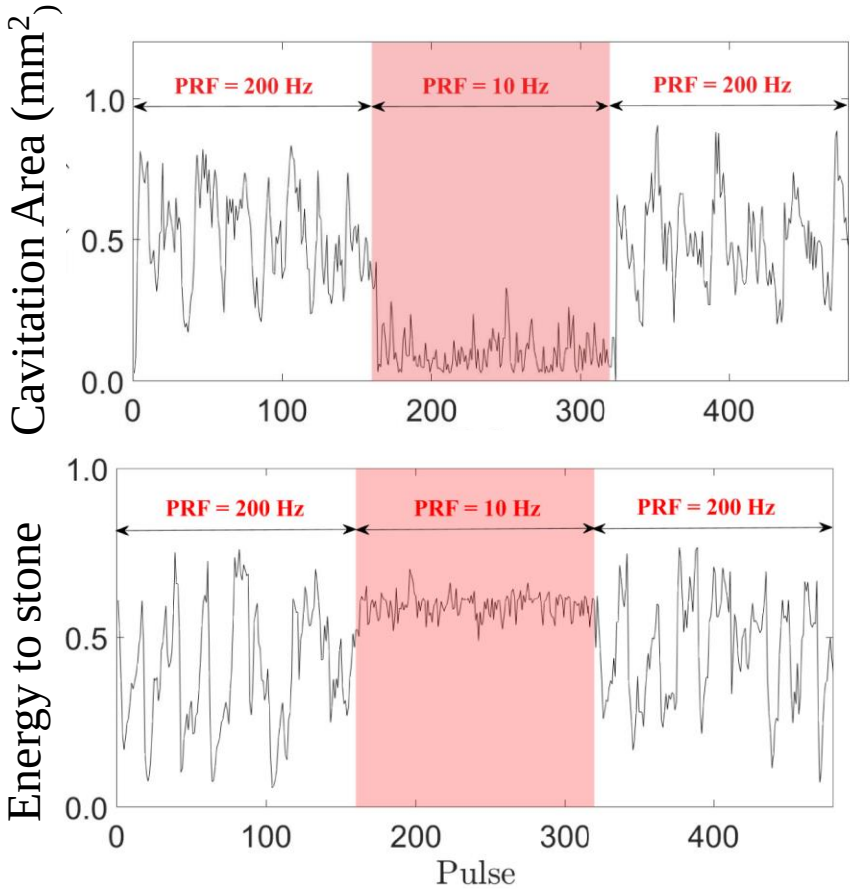
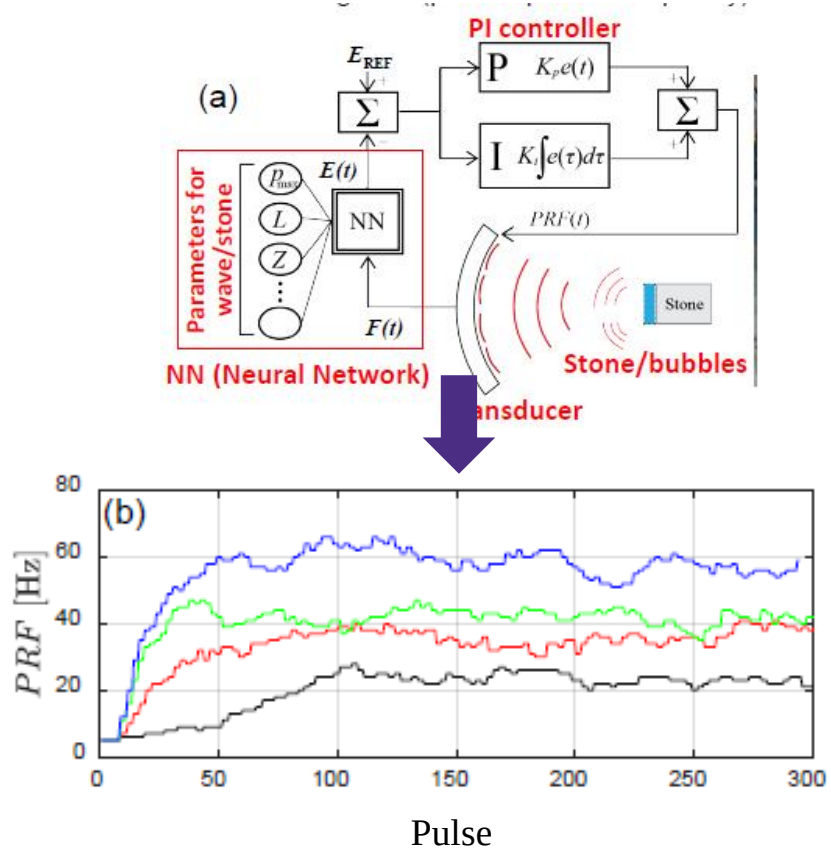
Mechanisms of SWL+BWL: Cavitation

- Modulation of acoustic parameters can control cavitation and maximize energy delivery





Maeda and Maxwell Phys Rev Appl 2021

Cavitation in burst wave lithotripsy

Cavitation in burst wave lithotripsy produces three dominant effects:

1. Cavitation on the stone produces erosion of the stone.
2. Cavitation blocks ultrasound waves and reduces stone fracture.
3. Cavitation in tissue produces injury to the tissue.

Methods to detect and confine cavitation to the stone can make BWL safer and more effective

Thank you

This work was supported by:

National Institute of Diabetes and Digestive and Kidney Diseases

K01 DK104854 and P01 DK043881