Medical Applications of Shock Waves

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Ultrasonic Industry Association Meeting

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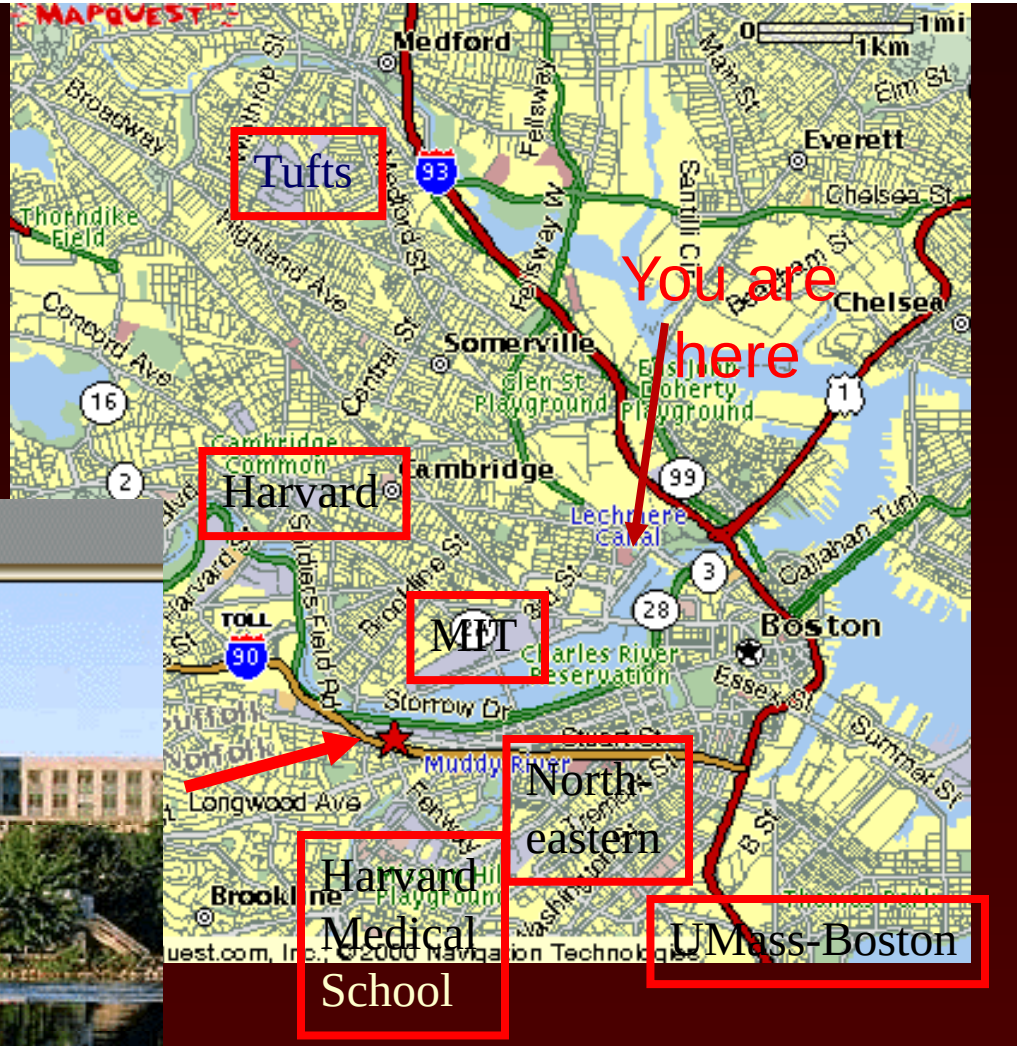
Boston

~3 million people
~70 colleges
~300 000 students

BU 30 000 students

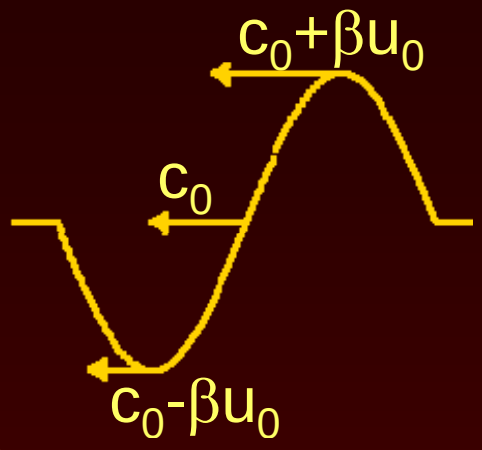


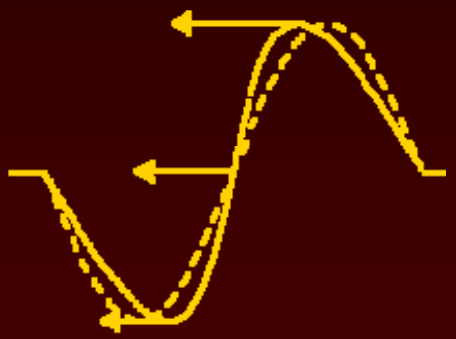
Outline

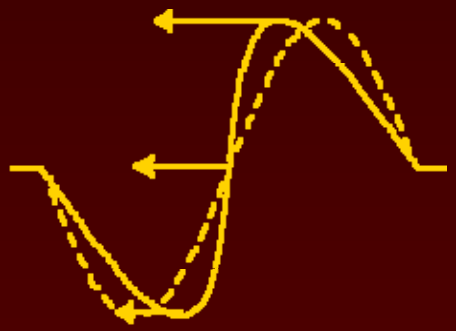
- Nonlinear Acoustics
- Shock Wave Lithotripsy (SWL)
- Orthopaedic Devices
- High Intensity Focused Ultrasound for Surgery
- Tissue Harmonic (Nonlinear) Imaging

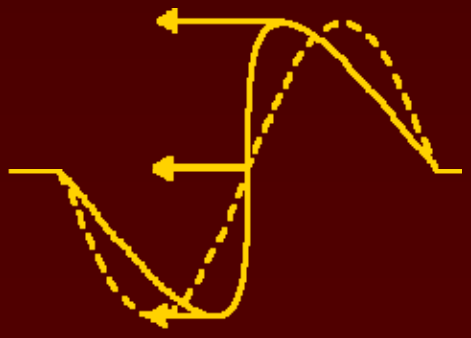
Nonlinear Distortion

ß Coefficient of nonlinearity
1.2 in air
3.5 in water
5-10 in tissue

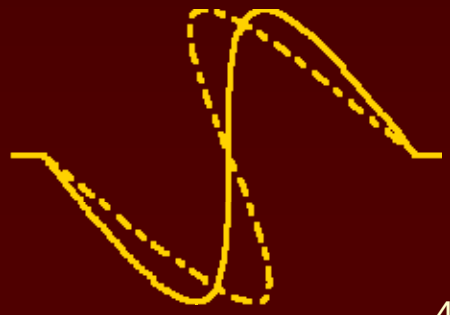




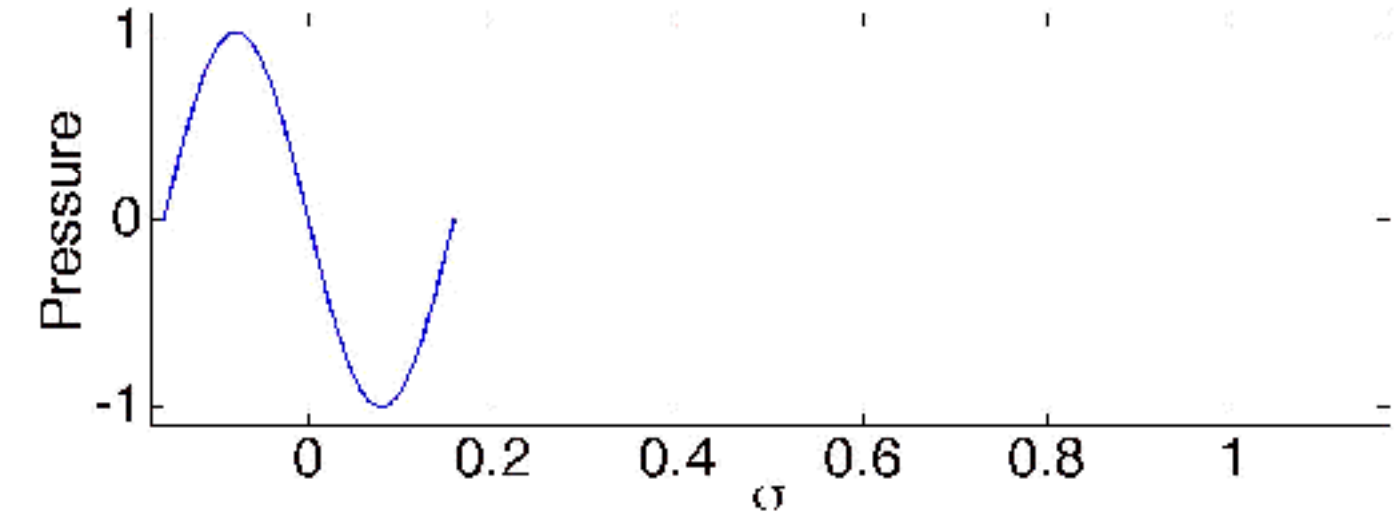


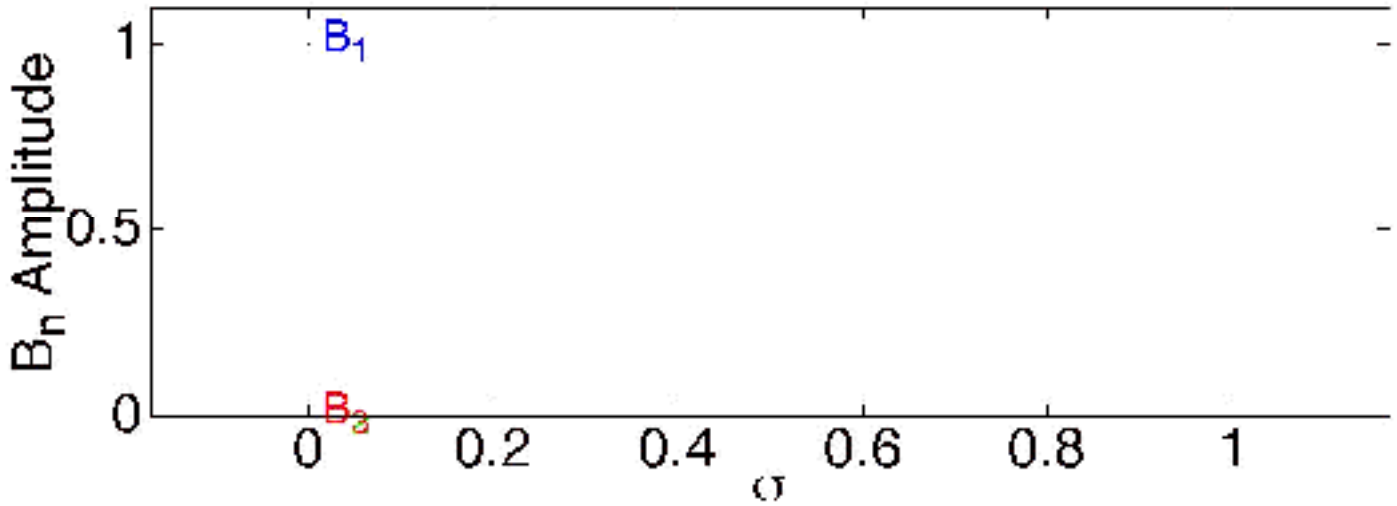


Beyond shock formation
wave is multivalued



Harmonic Production





Harmonic Generation

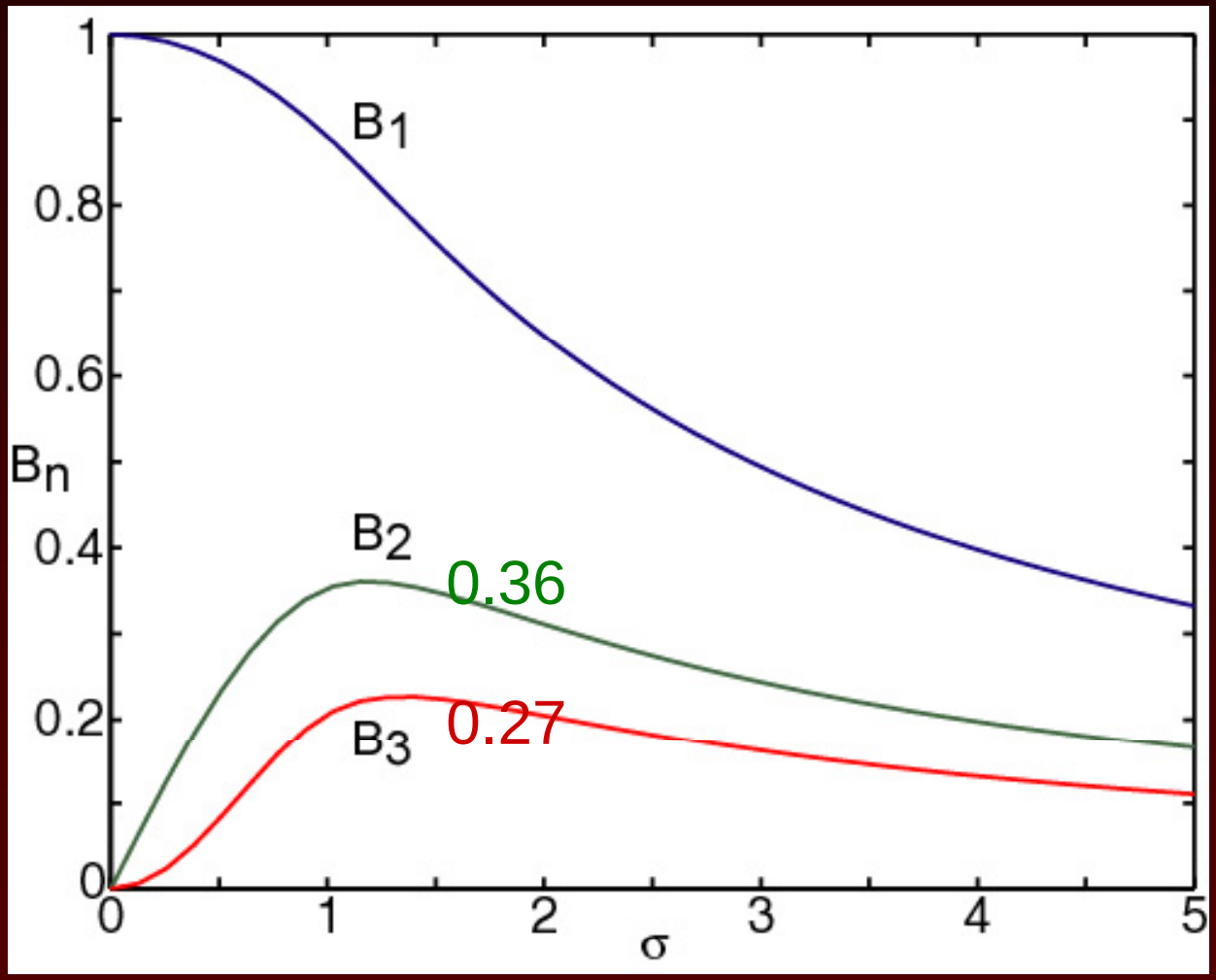
Plane Wave Shock Formation in Tissue

$$\bar{x} = \frac{100}{p_0 f_0} \text{ mm}$$

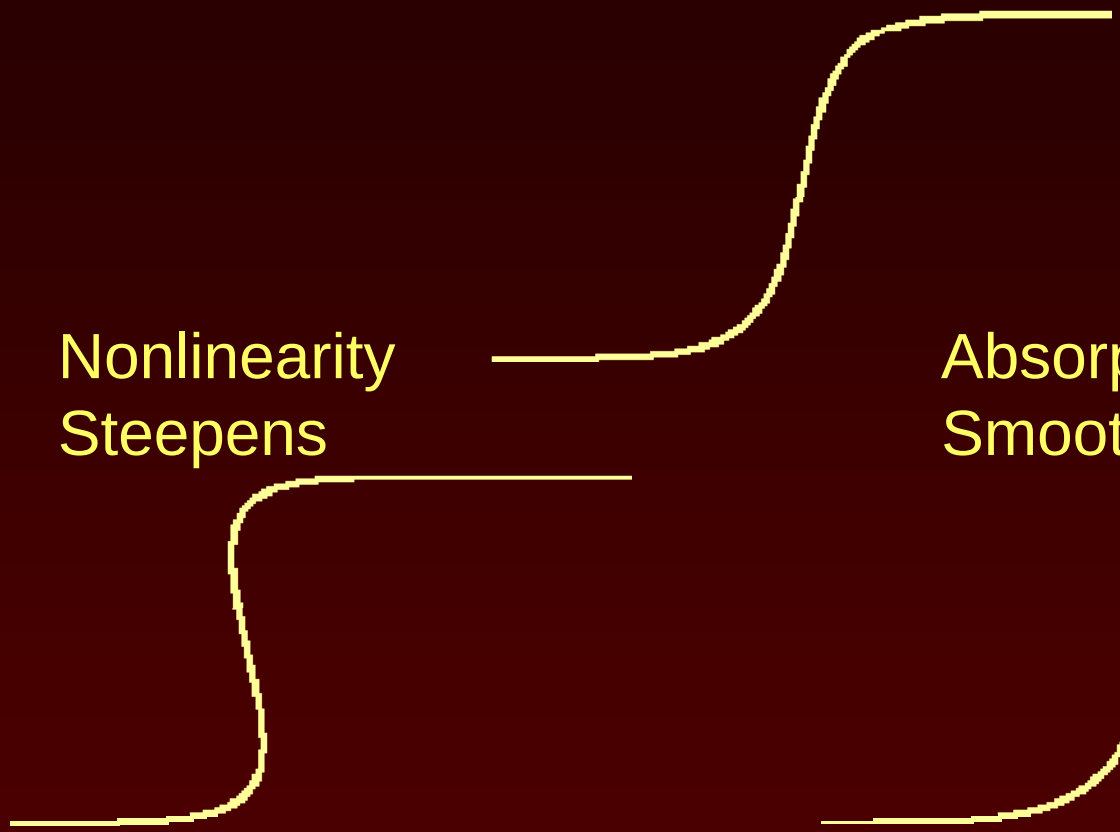
MPa MHz

Shock Parameter

$$\sigma = \frac{x}{\bar{x}}$$



Nonlinearity vs. Absorption



Nonlinearity
Steepens

Absorption
Smooths

$$\rho T \frac{\partial s}{\partial t} = \kappa \nabla^2 T$$

Thermal conduction
Viscosity, …

Length Scales

Nonlinearity

Plane wave shock formation distance in tissue

$$\bar{x} \approx \frac{100}{p_0 f}\ \text{mm} \cdot \text{MPa} \cdot \text{MHz}$$

At 3.5 MHz and 1 MPa length scale 30 mm

Absorption

Soft tissue 0.3 dB/cm/MHz

At 3.5 MHz length scale 10 mm

Diffraction

Focal lengths 10-150 mm

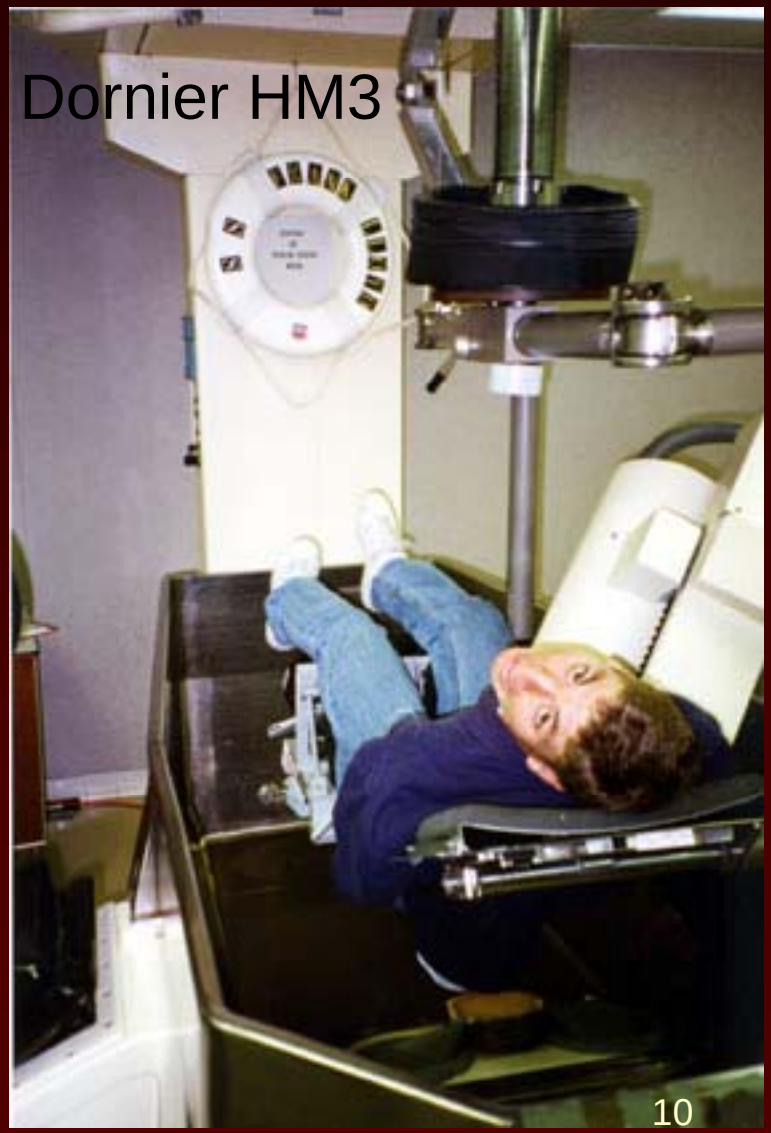
Kidney Stones

- Stones form in collecting system of kidney
- Stones have layered structure;
  100 μm crystalline (calcium oxylate) and 15 μm glue
- 1995: 10% of males and 4% of female have one episode by 70 years
- 2005: 13% of males and 7% of female have one episode by 70 years

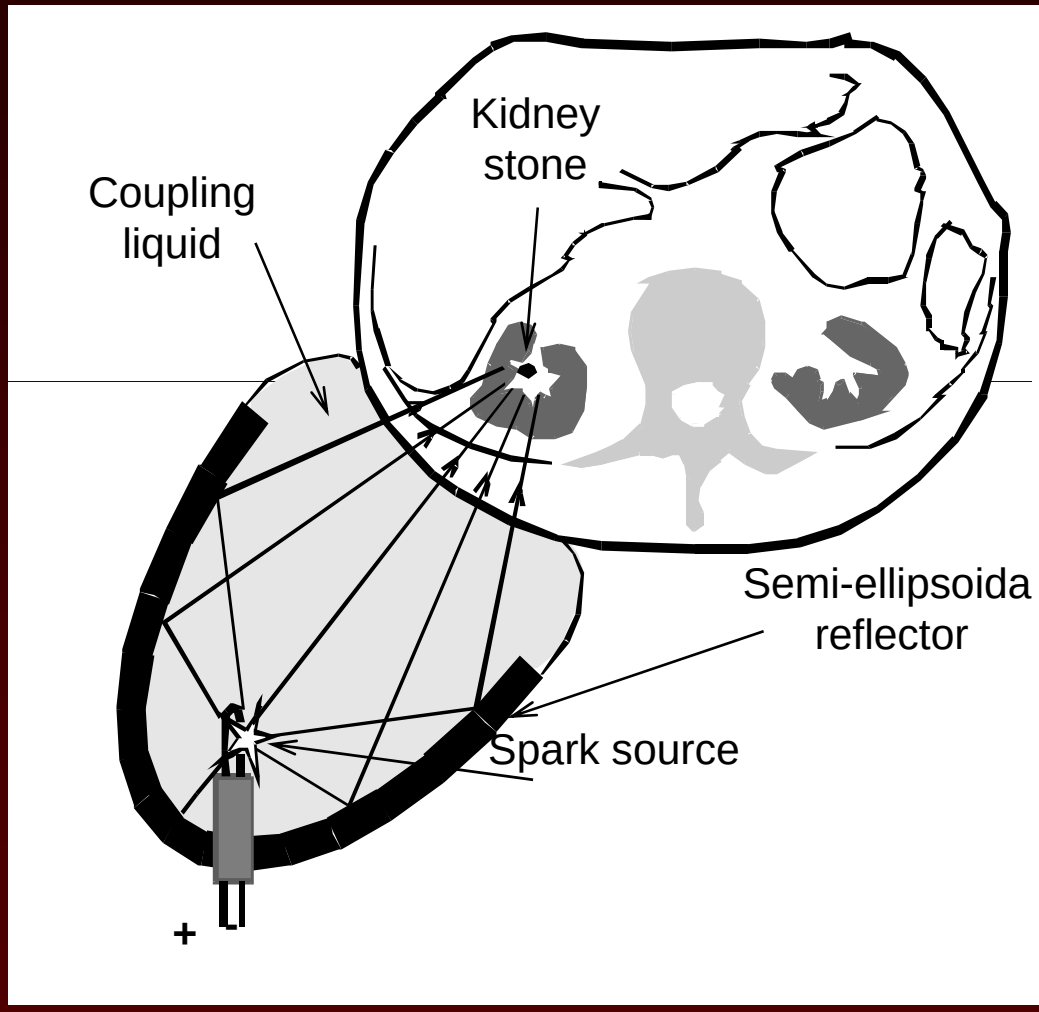
Extracorporeal Shock Wave Lithotripsy (ESWL)

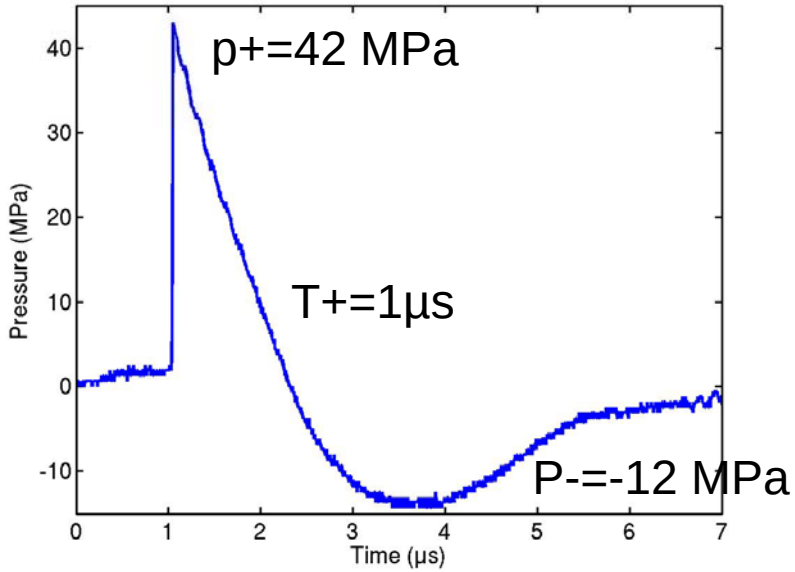
- Introduced 1980
- Shock waves generated outside the body are used to fragment stones

- Day surgery
- Typically with mild sedation
- 1000-4000 SWs at 1-2 Hz (30-90 mn)
- Some discomfort - pain in 10% of patients
- Some soreness at shock wave entry site
- Hematuria for 1-2 days

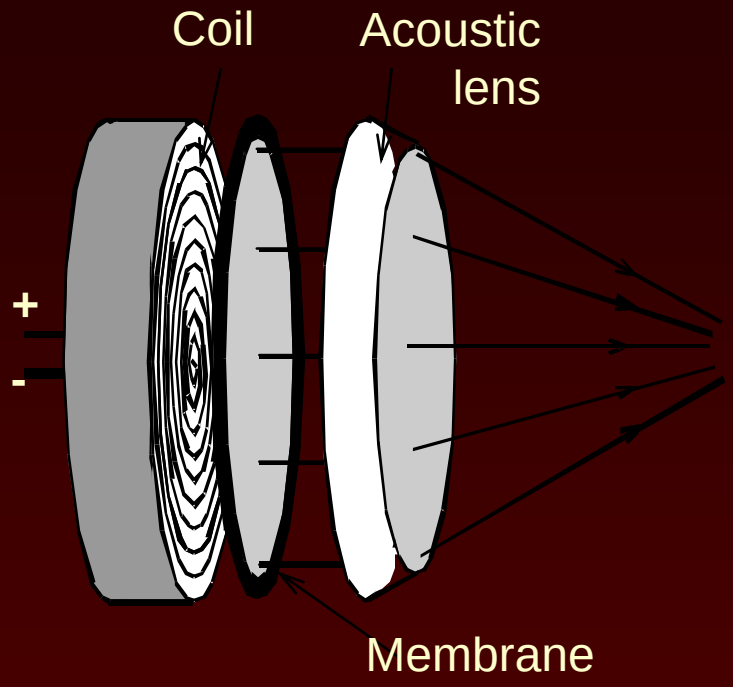


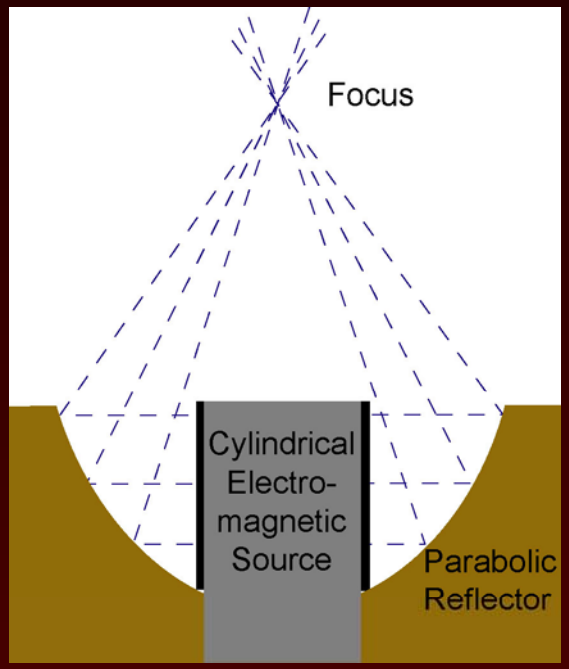
Electrohydraulic Shock Wave Lithotripsy

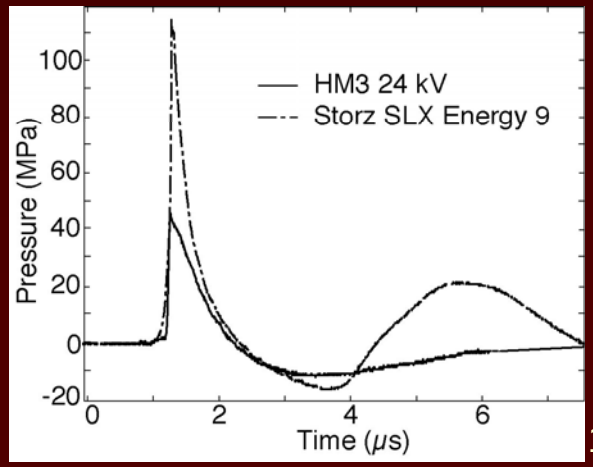




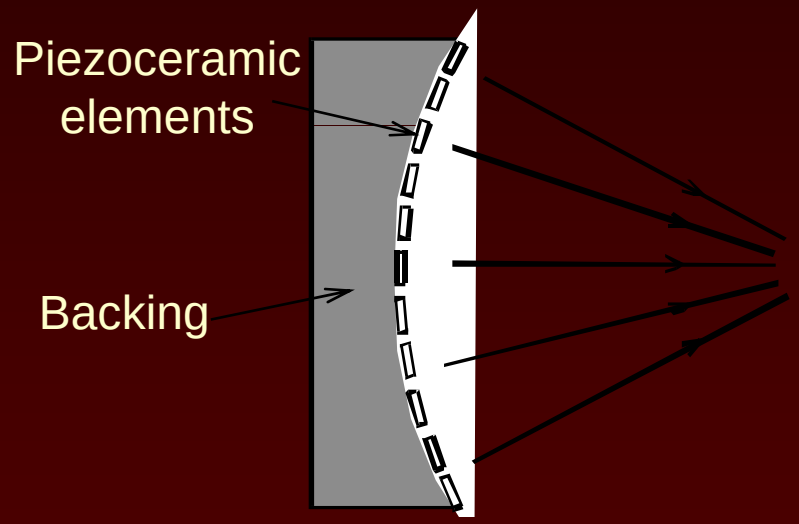
Electromagnetic Lithotripter

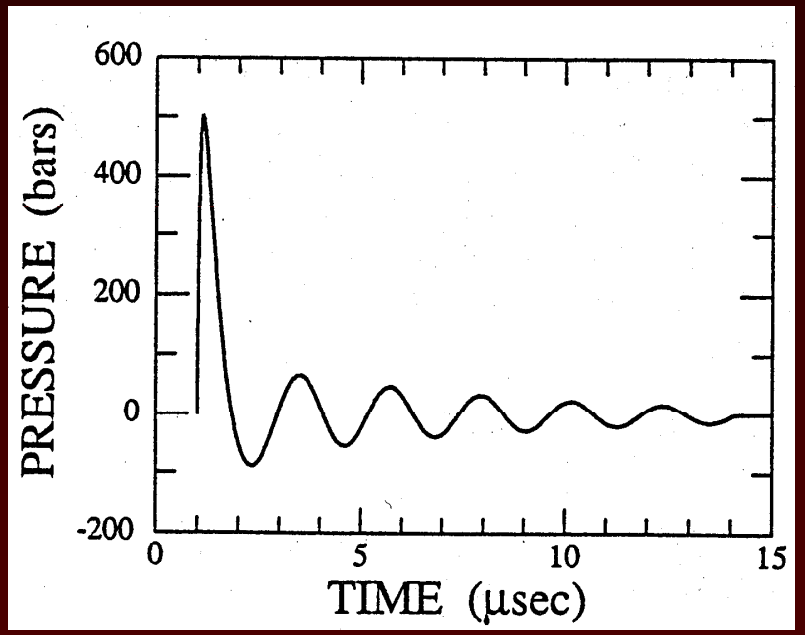






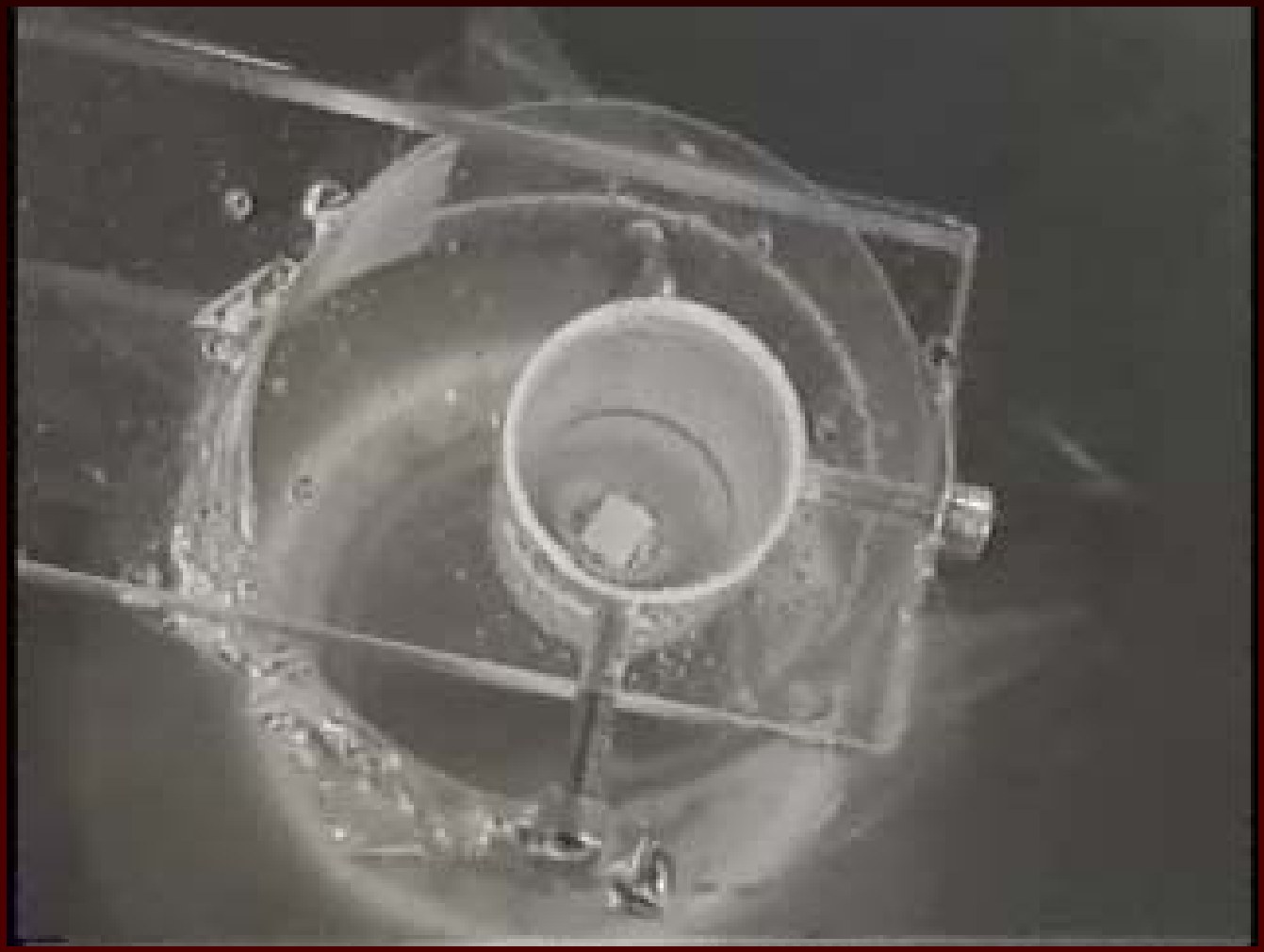
Piezoelectric Lithotripter





Storz Modulith SLX Electromagnetic Lithotripter

Ultracal 30 Disintegration



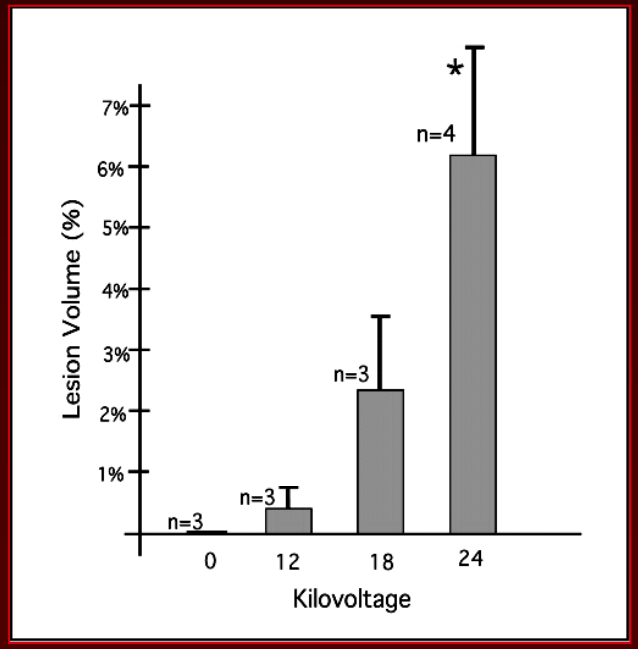
SWL Induces Injury

- Haematuria
- Subcapsular haemotomas
- Kidney failure

- Onset hypertension
- Affect growth of kidney in paediatric patients
- Possible association with diabetes (Krambeck et al J. Urol 2006) although contested (Sayo et al, Urol 2008, Makhlouf et al, Urol. 2009).

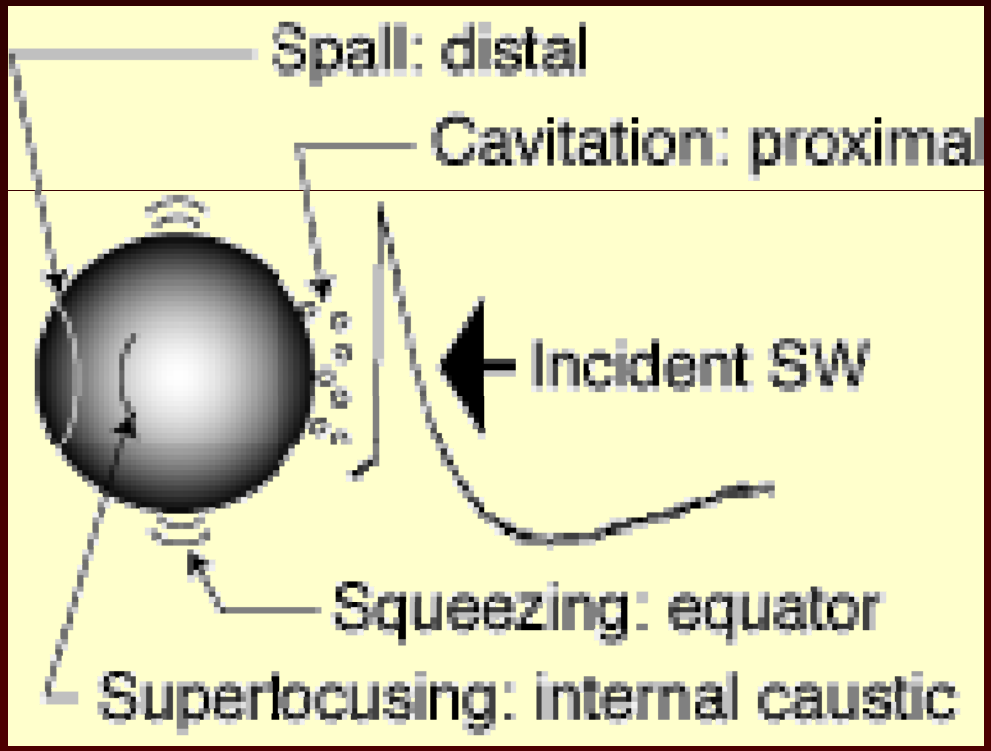
SWL-Induced Injury (EHL-Dornier HM3)

Lesion Size increases with SW amplitude

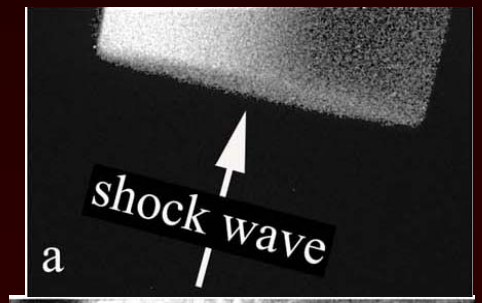


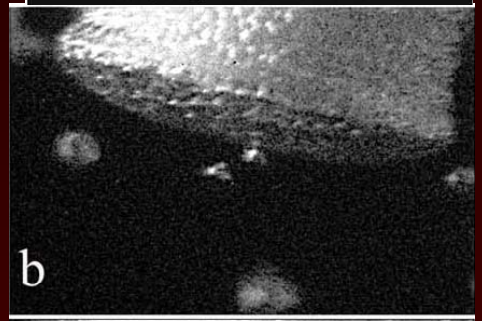
Mechanisms of Stone Comminution

- Compressive stress
- Tensile stress - spall
- Shear forces
- Cavitation
- Fatigue
- Squeezing/splitting

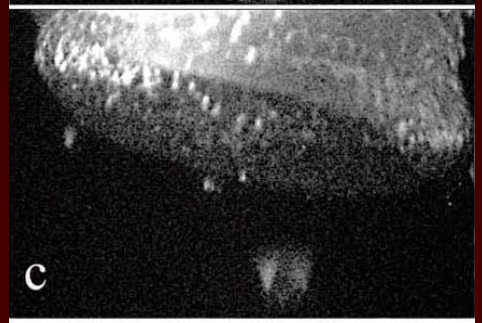


Cavitation Bubbles

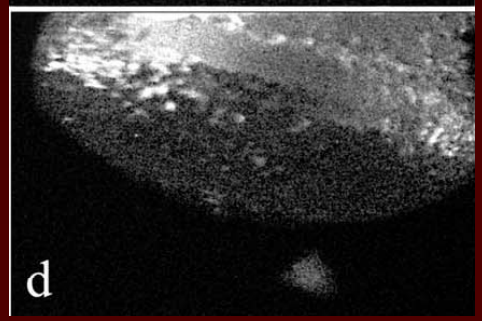




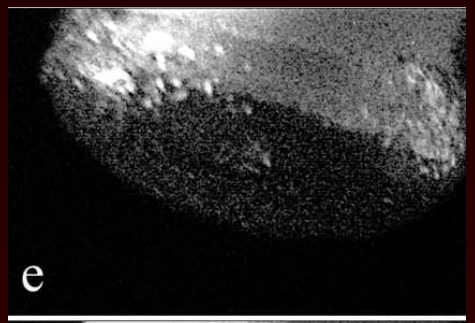
100 µs



200 µs

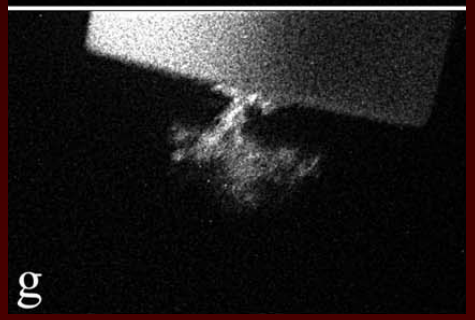


300 µs

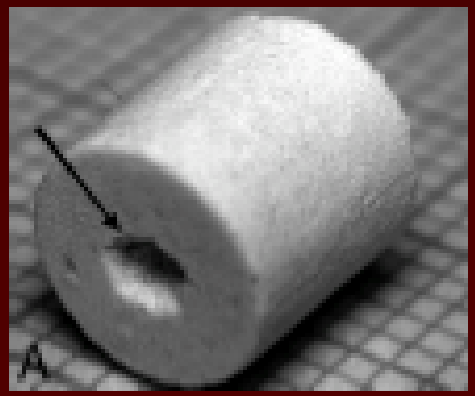


400 µs

500 µs



600 µs



Elastic Wave Simulations

Haibiao Luo, PhD Student

$$\rho \frac{\partial v_i}{\partial t} = \frac{\partial \tau_{ij}}{\partial x_j}$$

$$\frac{\partial \tau_{ij}}{\partial t} = \lambda \frac{\partial v_k}{\partial x_k} \delta_{ij} + \mu \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right)$$

$\mathbf{v}_i$	velocity vector	ρ	density
τ_{ij}	stress tensor	λ,μ	Lamé coefficient

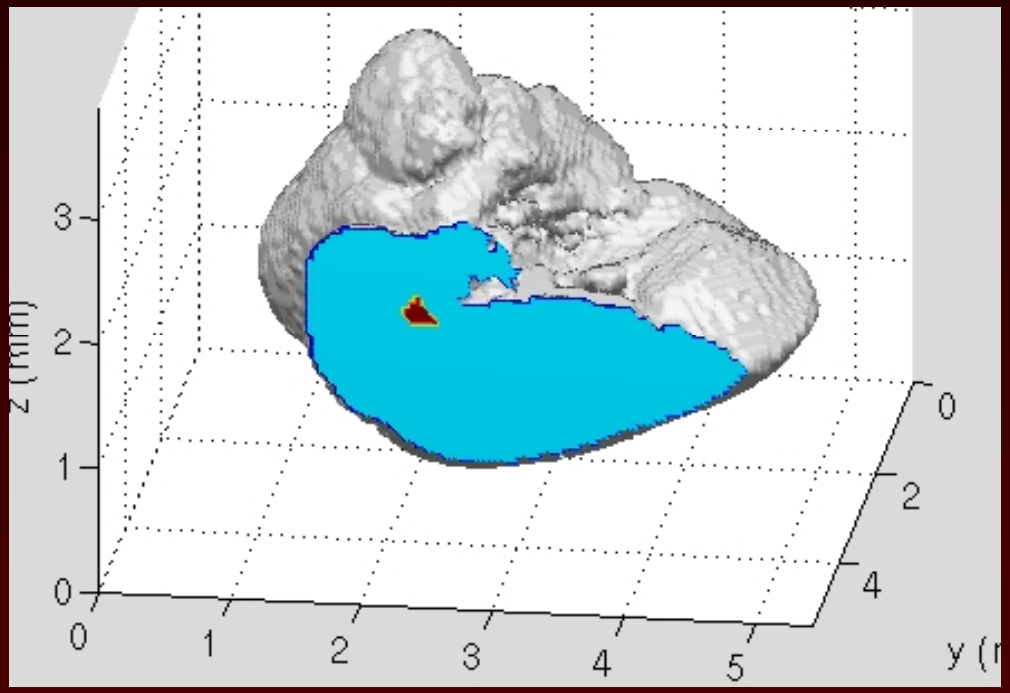
- Finite-difference time-domain code in two dimensions
- Grid staggered in both space and time (Virieux scheme or Yee cell).
- Unknowns: $\mathbf{v}_i$, τ_{ij}

Stress Waves in Natural Stones

- **Shock Waves incident on a kidney stone results in two waves in the stone:**
  - **Compression Waves**
  - **Shear Waves**

- **Waves generate tension and shear in the stone.**

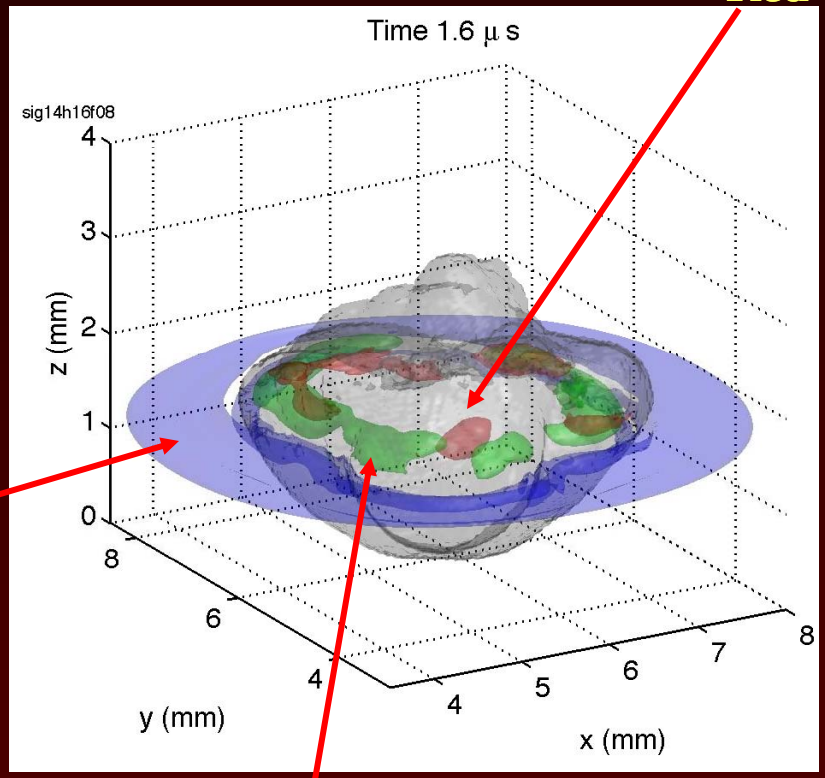
- **Solve dynamics equations for an elastic solid using a natural stone for the geometry.**



MicroCT Image of Natural Stone
COM=Blue
AP = Red
JC Williams, IU Med School

Display Isobars of Stress

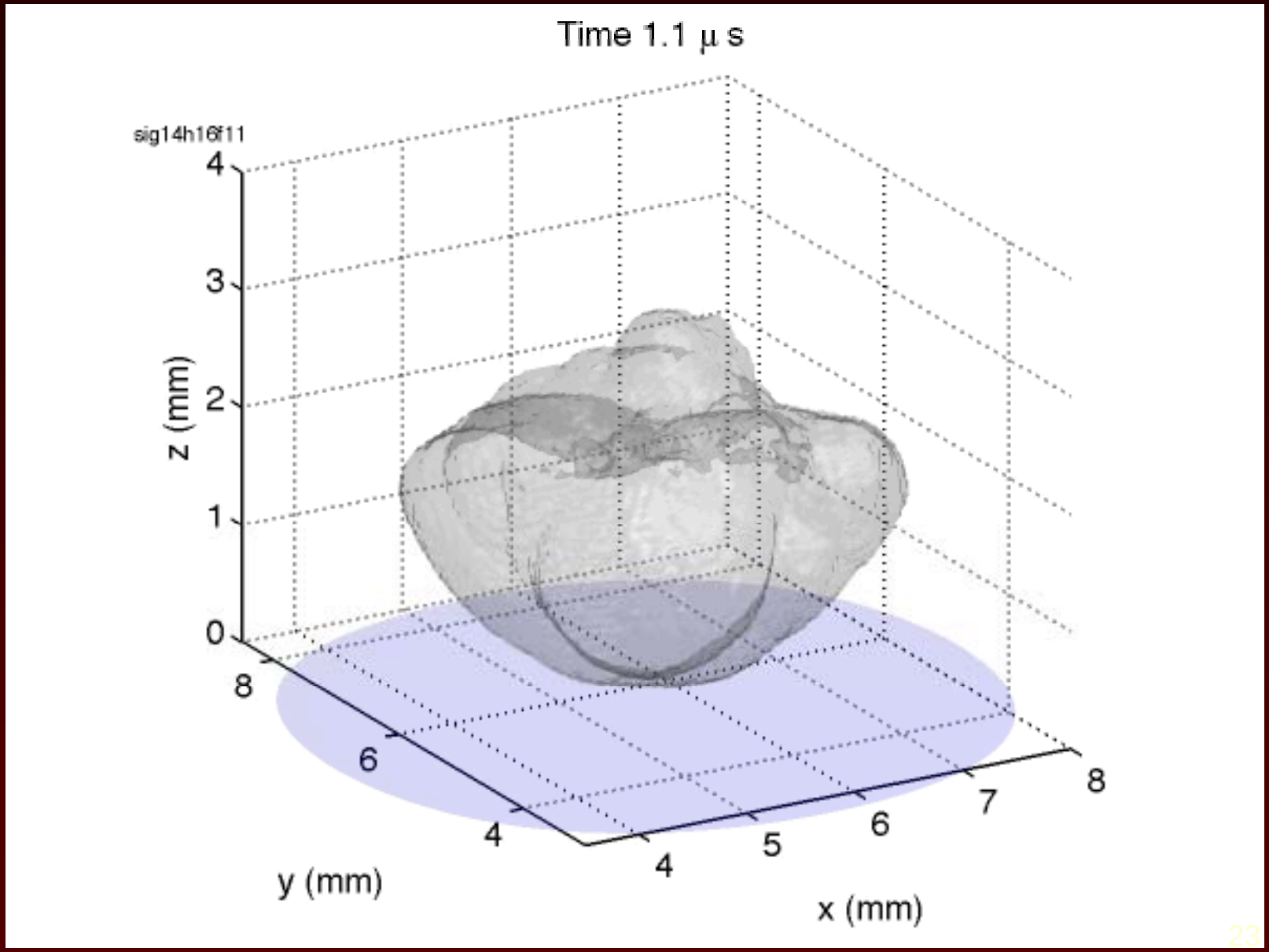
Red = Tension 60 MPa



Blue = Compression 20 MPa

Green = Maximum Shear at 40 MPa

Simulation 8 mm Focal Width

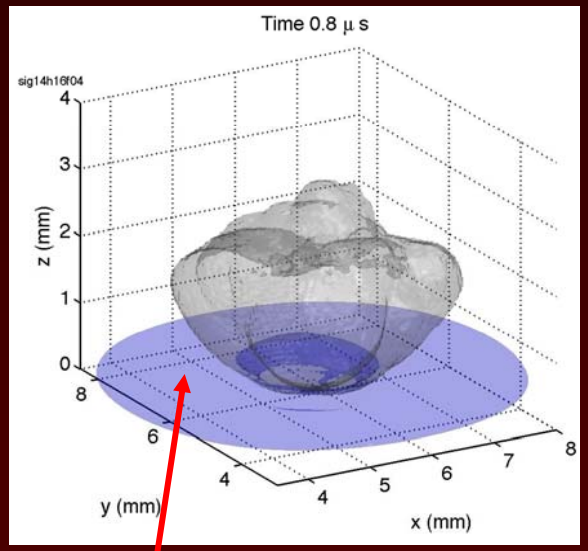


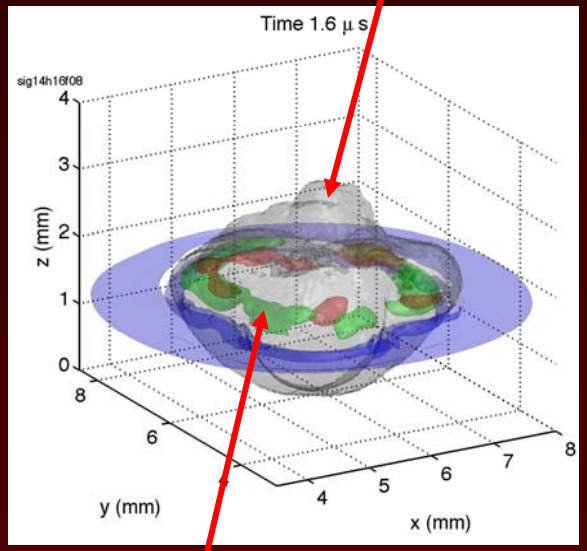
Shapshots of Stress Waves

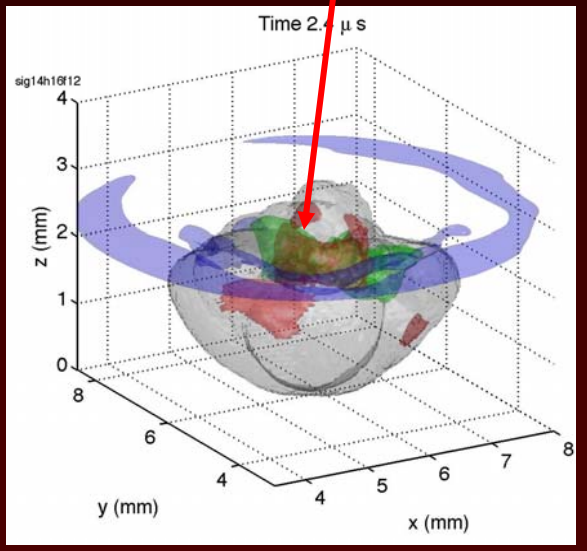
Blue = Compression
Red = Tension
Green = Shear

Absence of tension rules out contribution from spall

Shear waves responsible for tension







Incident Shock Wave

Shear wave generation at edge of stone

Evolution of Lithotripsy

- Introduced in 1980
- By 1990 about 85% of kidney stones in the US and Europe were treated with SWL
- Competing technology has advanced
  - Ureteroscopy
  - Percutaneuous nephrolithotomy
- 2005 Urologic Diseases in America report: 50% of stones are treated with SWL
- Mass General Hospital 2008
  - Ureteroscopy 386 (84%)
  - ESWL 62 (16%)

What has changed?

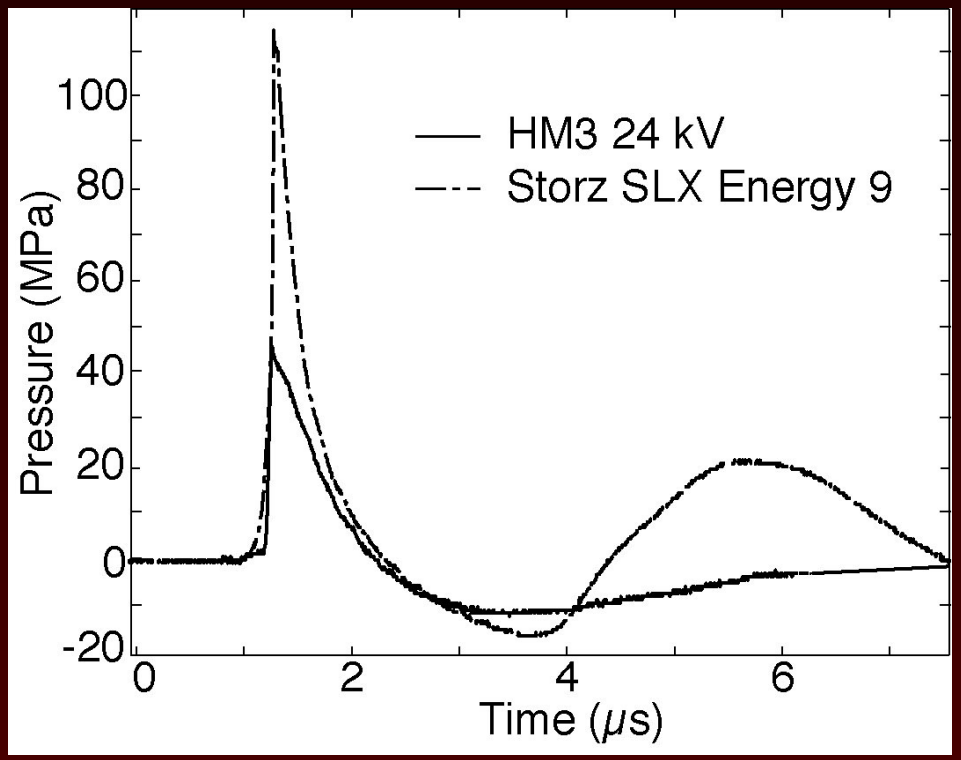
Dornier HM3

- Diameter of focal zone ~ 12 mm
- Water bath for coupling
- Slow rate - triggered by ECG < 1 Hz

Third Generation Lithotripters

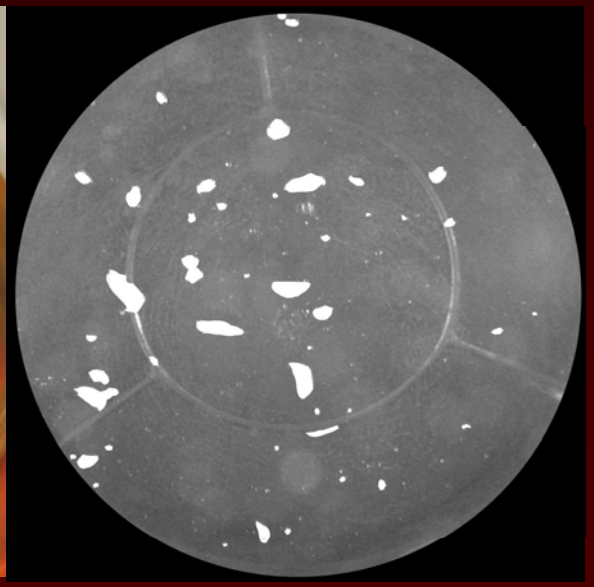
- Diameter of focal zone reduced to <8 mm
- SW source coupling through gel
- Rates increased to 2 Hz

Wide vs Narrow Focus

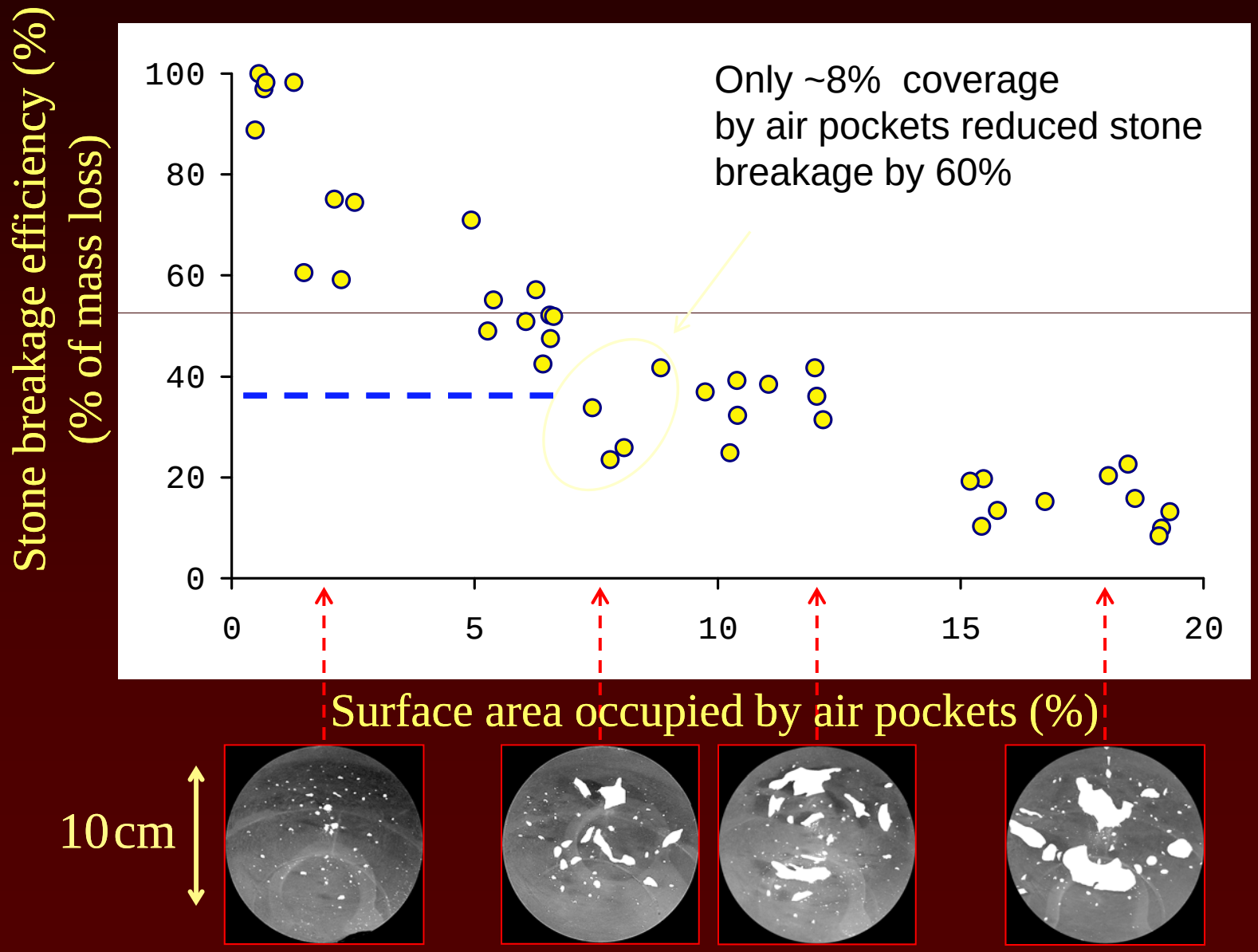


	Focal spot size (p+/2)	Retreatment	Haematoma
Modulith	4 mm × 35 mm	22.4% & 49.2%	3%
HM3	12 mm × 85 mm	4.1% - 7% Kerbl et al J. Endourol. 2002	0.8% Manufacturer

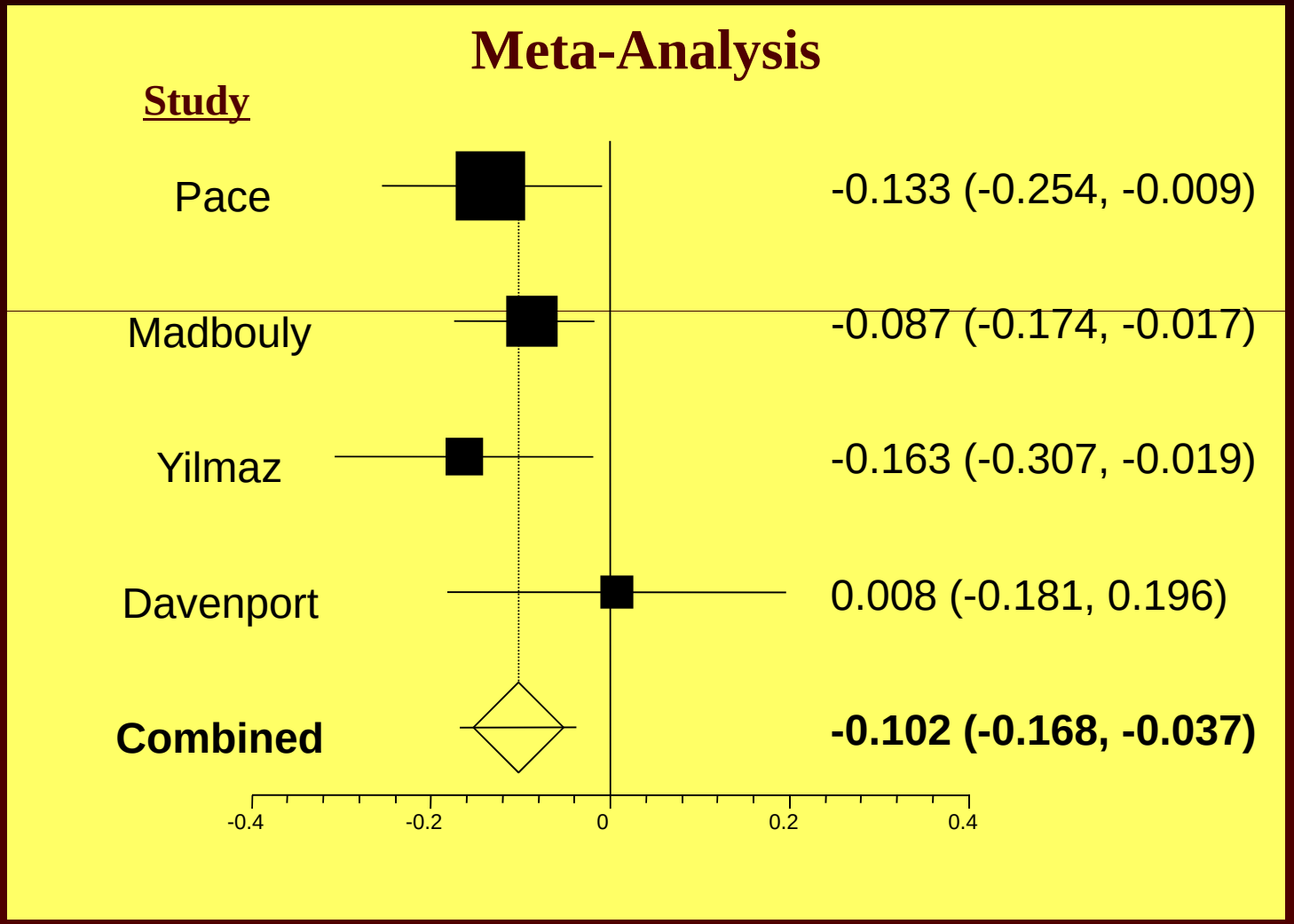
Coupling: Gel Results in Air Pockets



Fragmenation vs Air Pockets



The Effect of Shock Wave Rate



Shock Waves in Orthopaedics

Chronic soft tissue pains near the skeletal system

- Plantar fascitis (devices approved by FDA)
- Heel spurs
- Tennis elbow (epichondilitis)
- Shoulder rotator cuff calcifications

Soft Tissue Repair

- Revasuclarisation of the myocardium
- Wound/Burn Healing
- “micro-trauma” accelerates natural repair processes
- Neovascularisation
- Analgesic

Bone

- Fractures/Non-unions
- Bone growth
- Osteogenesis by bone tissue disruption

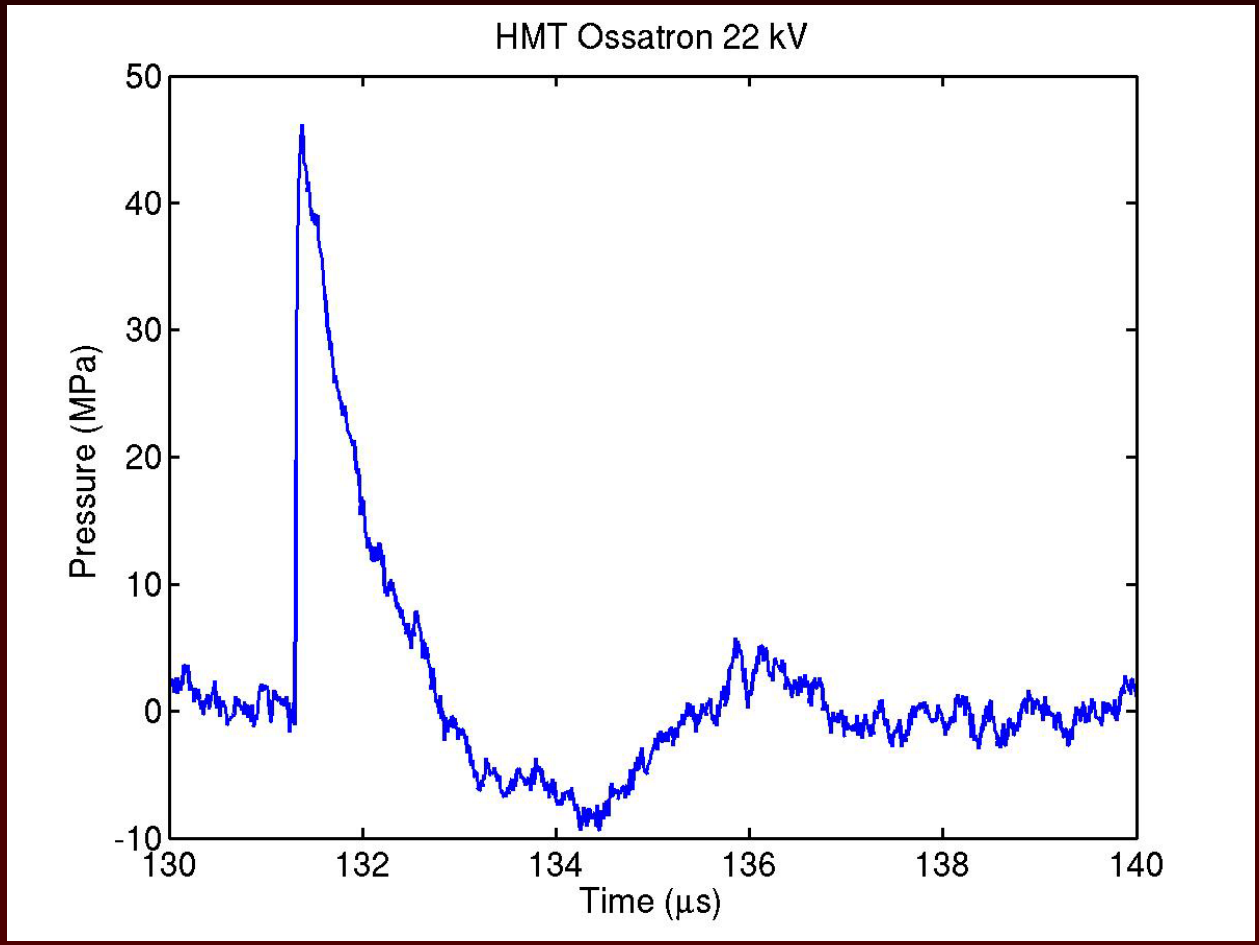
HMT Ossatron

FDA approval:

chronic lateral epicondylitis (tennis elbow)

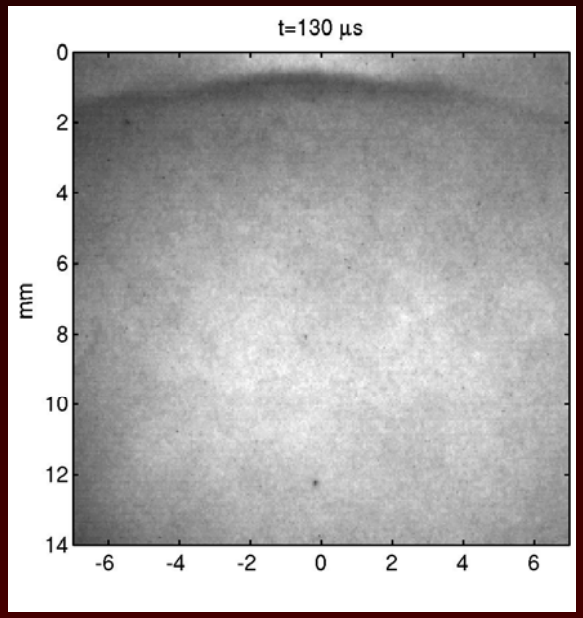
chronic plantar fasciitis (heel pain or heel spurs)

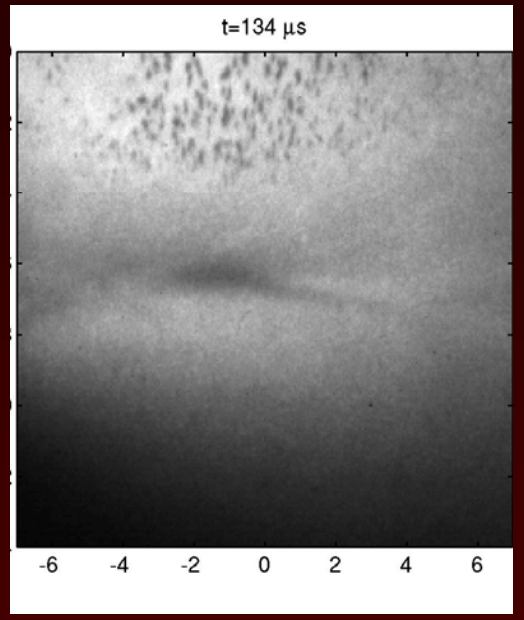
Ossatron - Focal Waveform

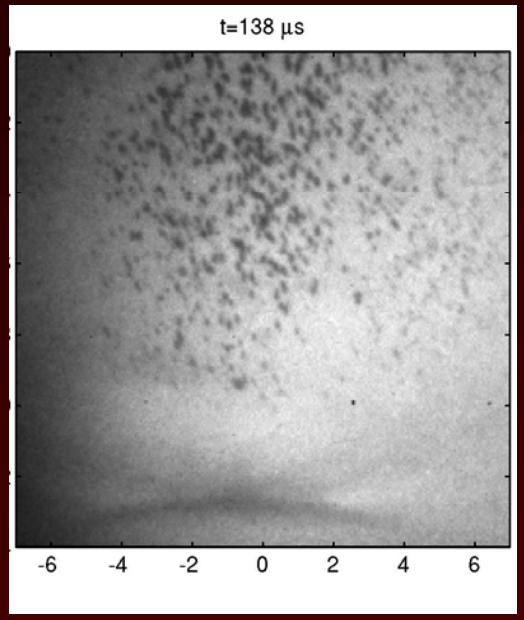


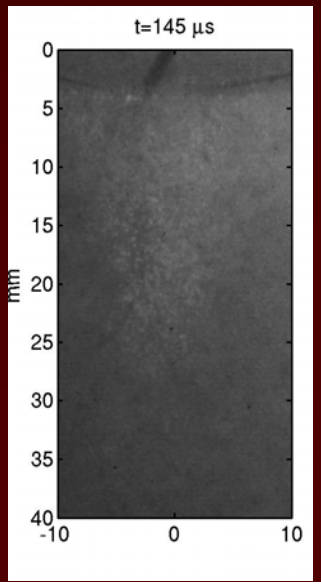
What is the stress distribution in the presence of bone?

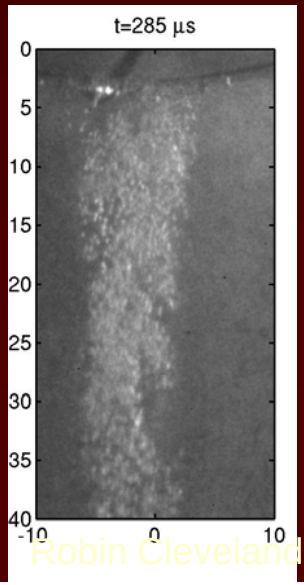
Ossatron - High Speed Camera

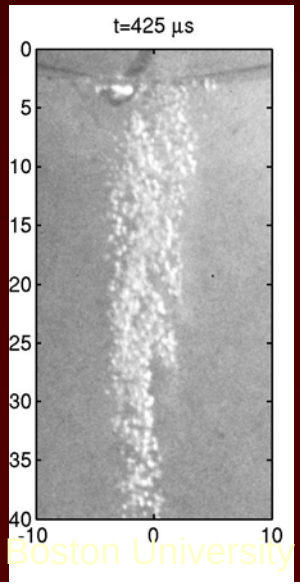


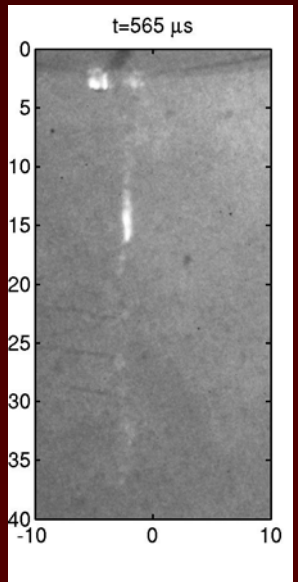












HMT Evotron/Equitron

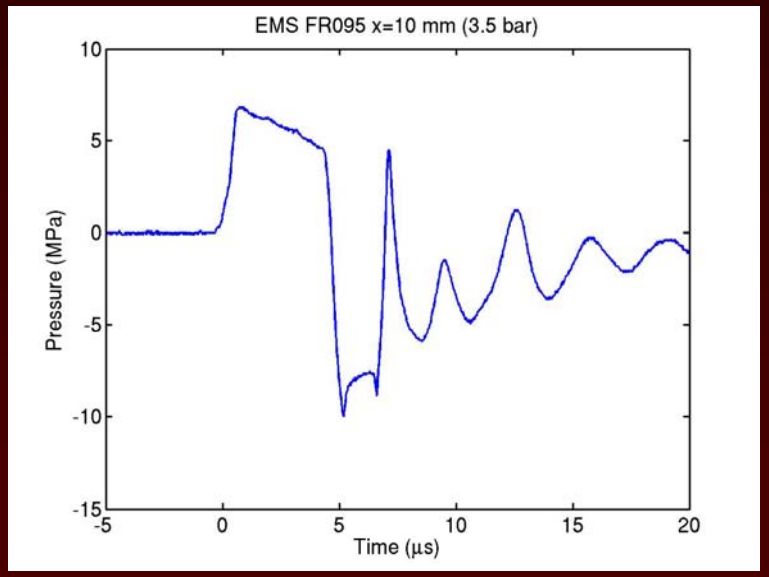
Electrohydraulic source

Ellipsoidal reflector with 35 mm focus

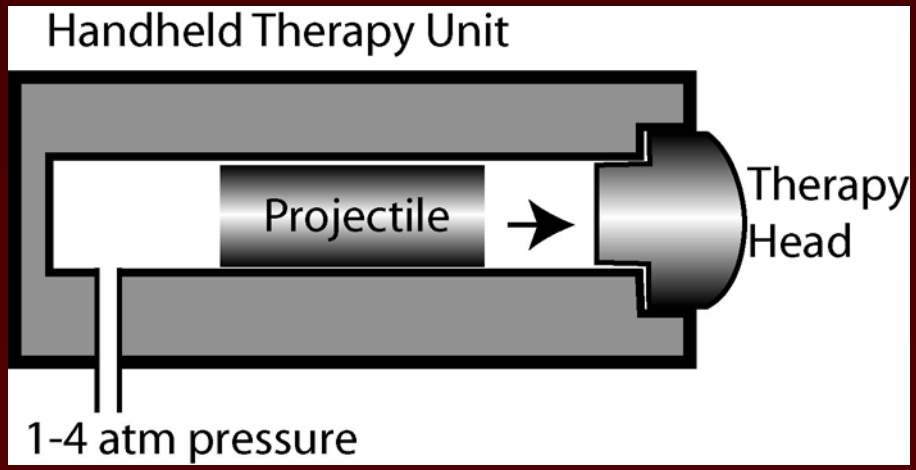
Equitron: Veterinarian version of a clinical device:

EMS Swiss Dolorclast

"Radial shock wave"



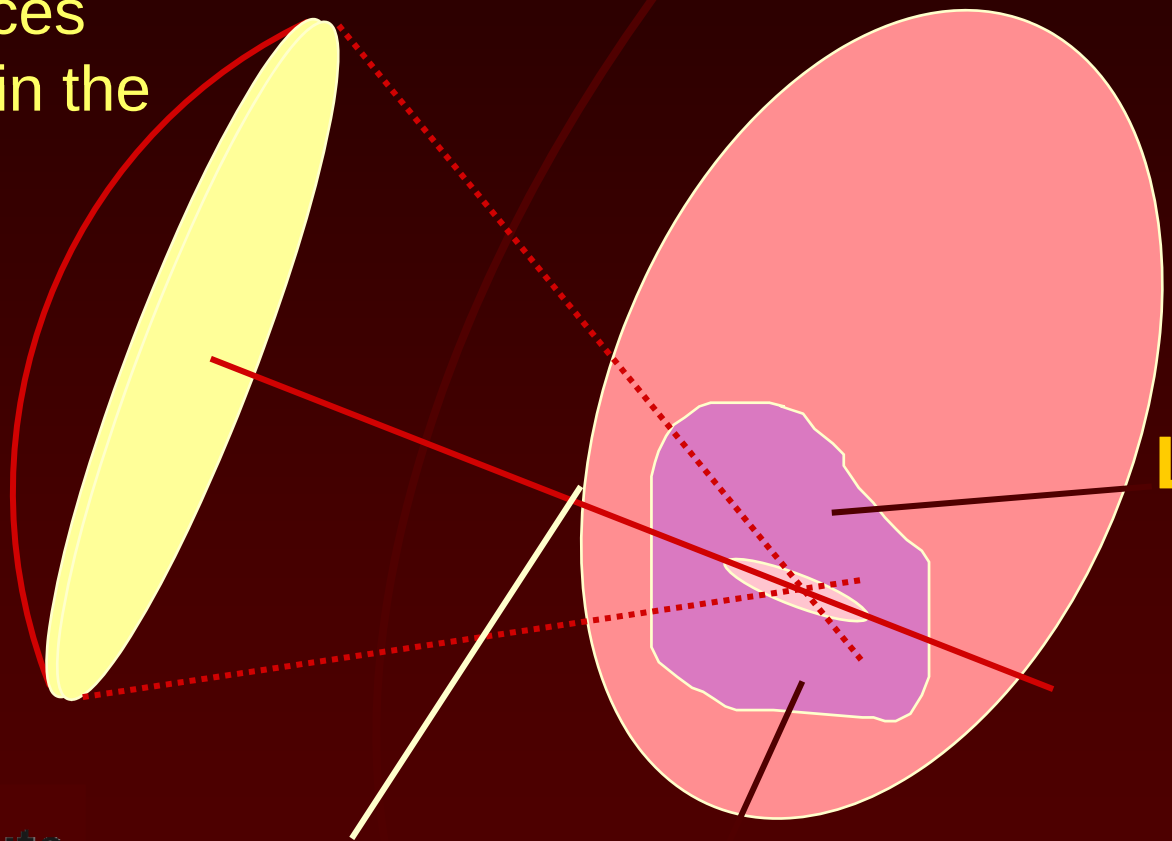
Ballistic source



High Intensity Focused Ultrasound
Focused Ultrasound Surgey

Absorption produces localised heating in the focal region:

- Cell lysis
- Haemostasis



The Institute of Cancer Research

US beam direction

Lesion

The Institute of Cancer Research

Robin Cleveland, Boston University

Applications of HIFU

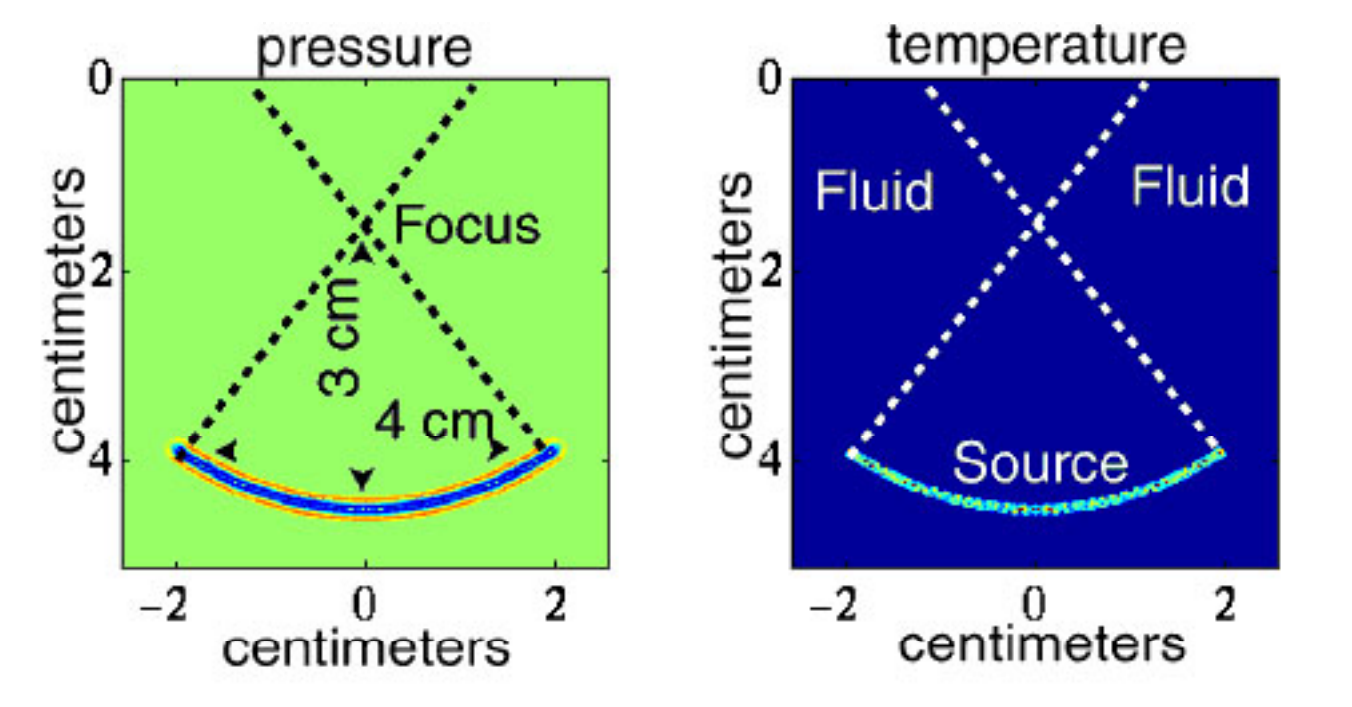
- Opthamology
  - FDA approval 1985
- Cancer
  - Liver, kidney, prostate, breast, brain, skin…
- Non Cancer
  - Uterine fibroids, epilepsy, liver surgery, BPH, opthalmology…
- Trauma Care
  - Acoustic hemostasis through vessel occlusion
    - Transcutaneous
    - Intraoperative
- Clinical Trials
  - Columbia University
  - University of Washington
  - Brigham and Women's Hospital

HAIFU 'JC-Tumor Therapy System

Therapeutic Ultrasound/HIFU Simulations with Heating

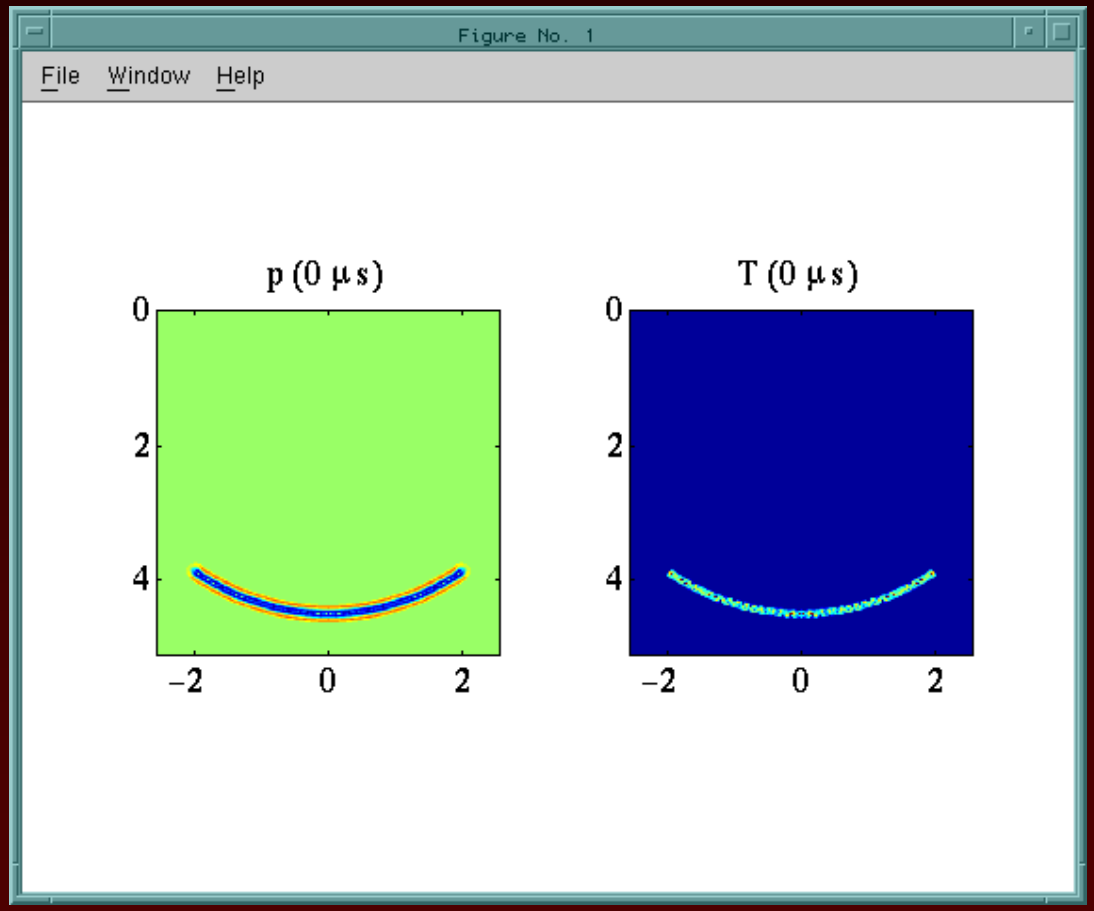
Solve nonlinear acoustics equations
Couple to the bioheat equation.

1 MHz source with 1 MPa source pressure



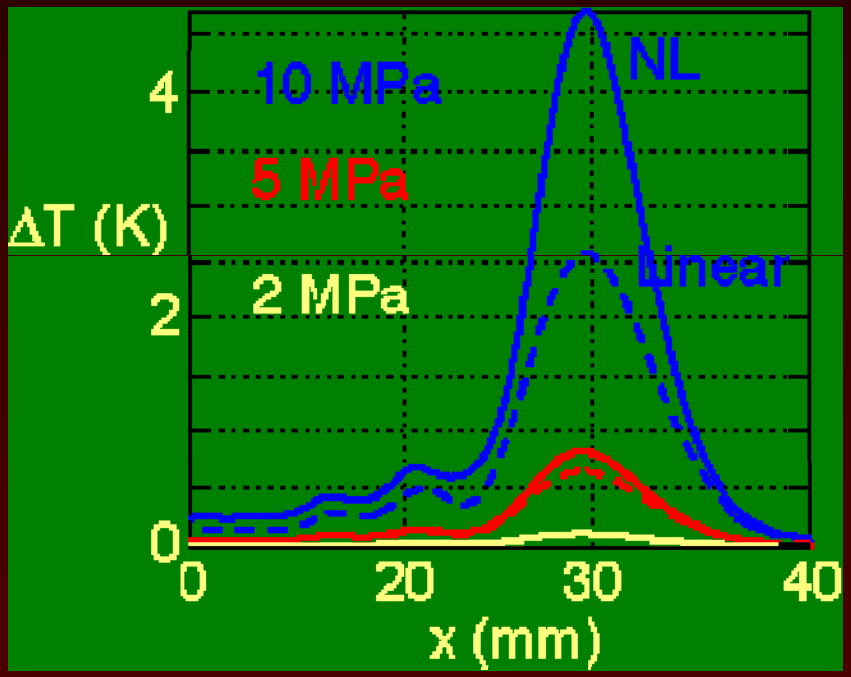
Hallaj and Cleveland, ARLO, 1999.

Simulations of Lesion Formation



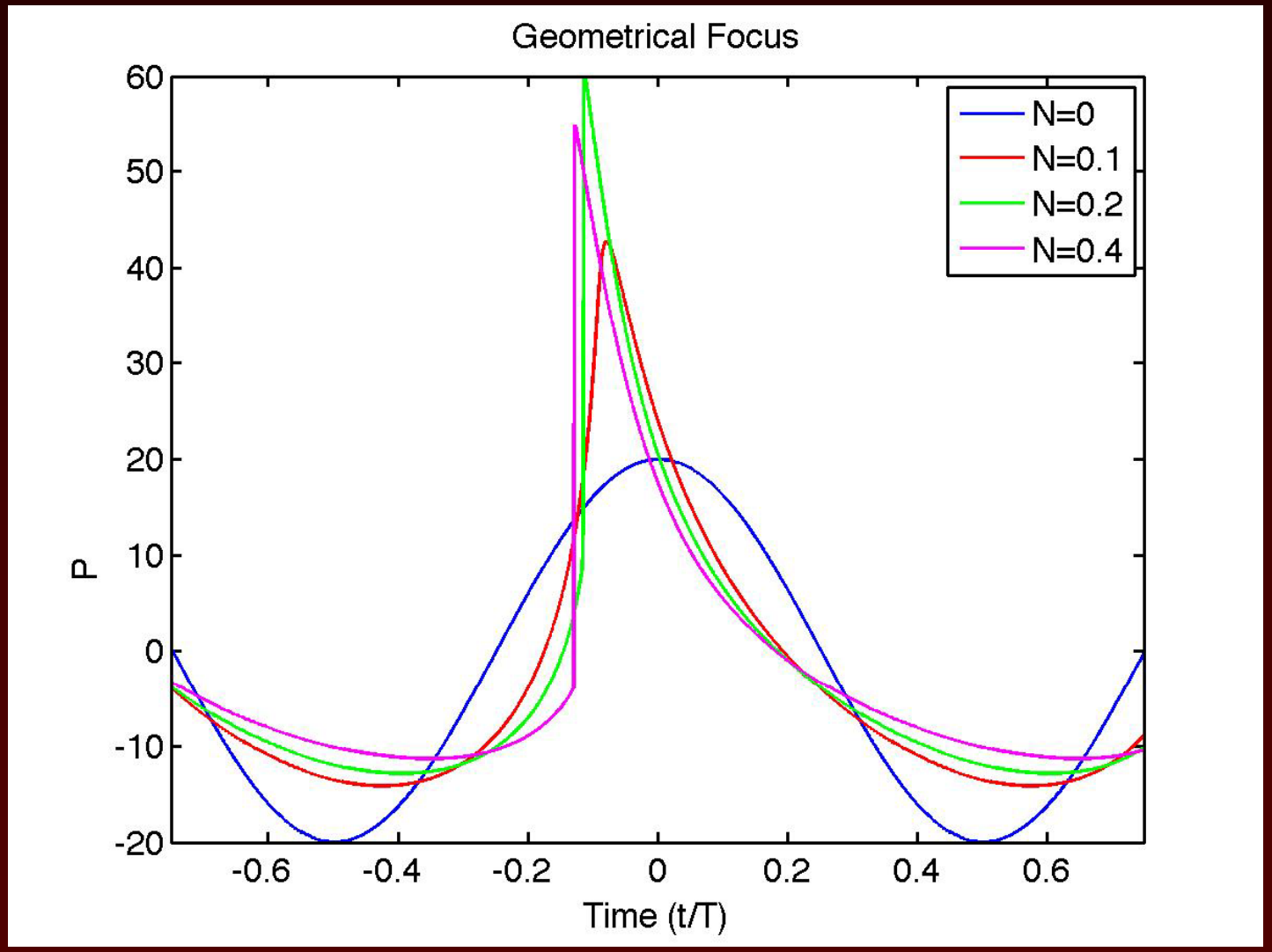
Nonlinear Enhancement of Heating

6 ms (6000 cycles) burst of 1 MHz ultrasound

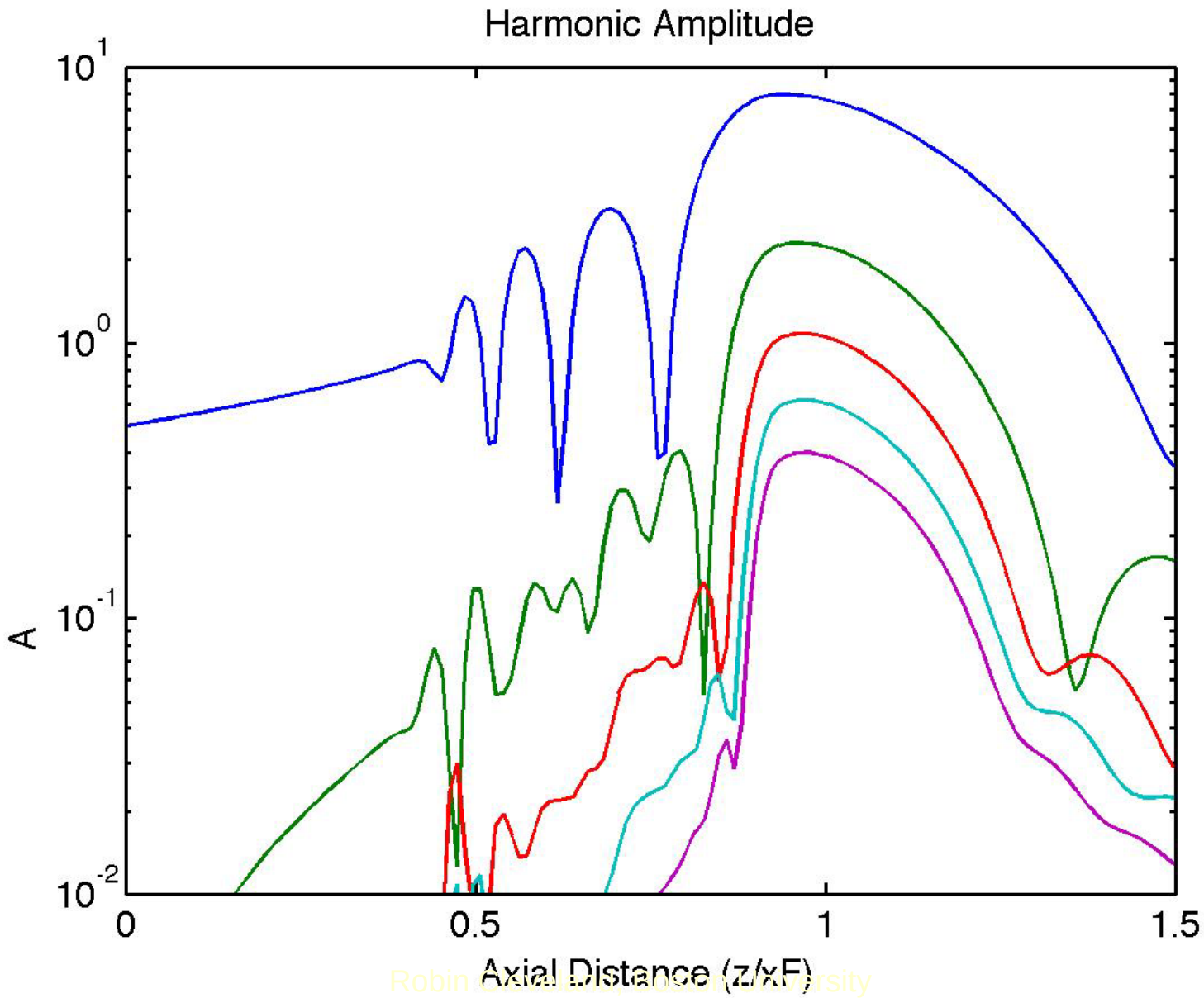


Nonlinear distortion converts energy to higher frequencies which are more readily absorbed

Focal Waveforms

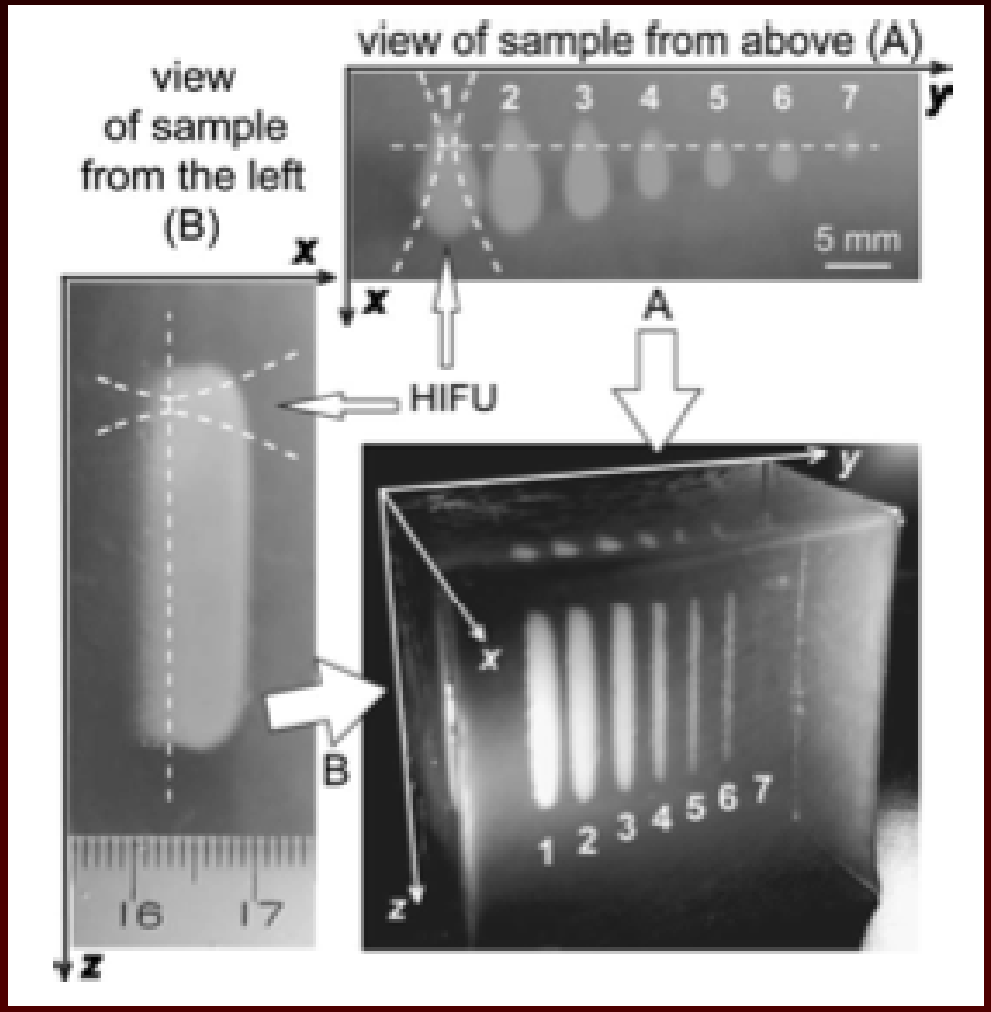


Harmonic Growth



Nonlinearity and Lesions

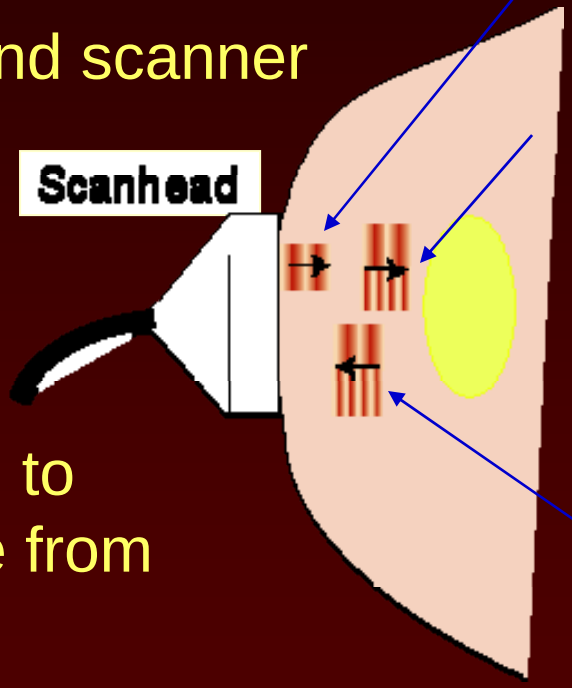
Transducer moved
Power 15 W average
Duty cycle
1: 6.25% (240 W pk)
7: 100% (15W)



Khohklova et al, Effects of nonlinear propagation, cavitation, and boiling in lesion formation by high intensity focused ultrasound in a gel phantom, JASA 119: 1834 (2006).

Tissue Harmonic Imaging

Diagnostic ultrasound scanner



Transmit at f_0

Nonlinear generation of $2f_0$

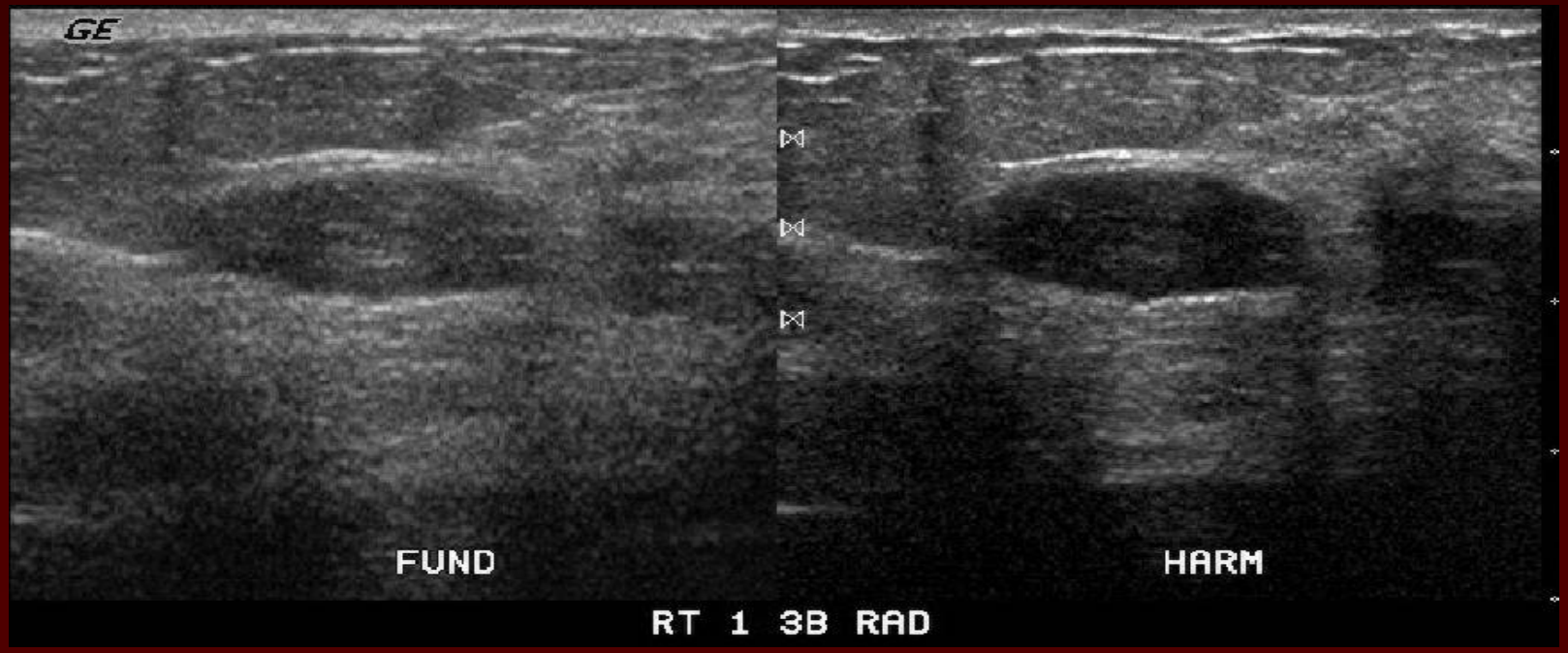
Processing to form image from $2f_0$ only

Reflection of both harmonics

Reduced clutter and enhanced boundary definition

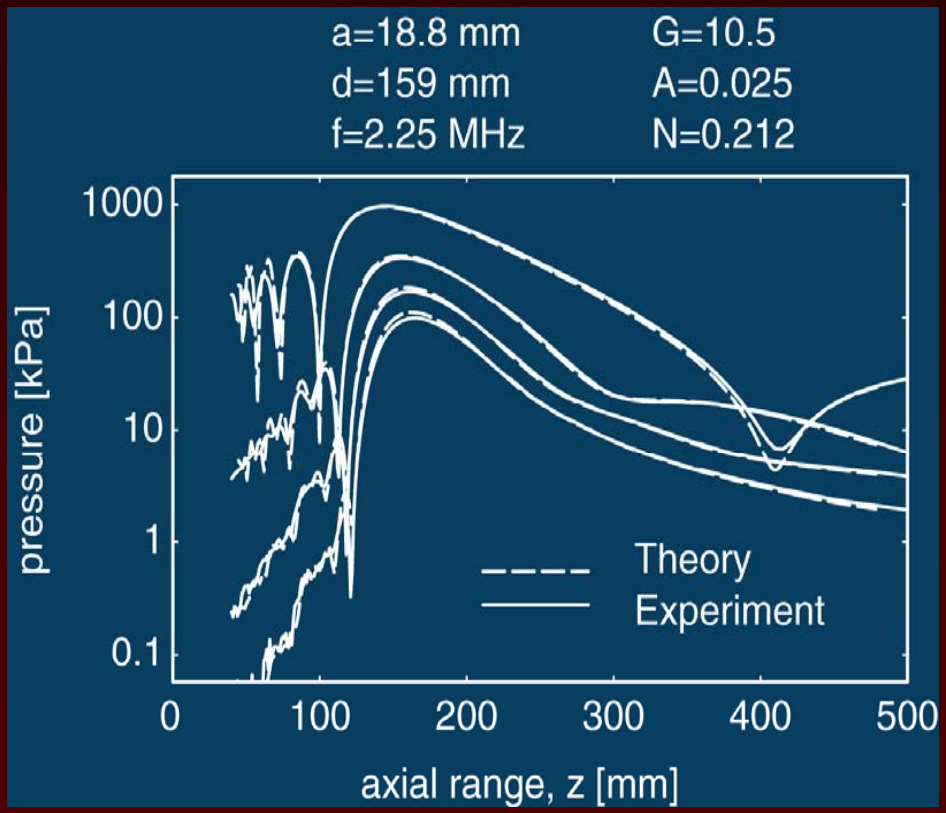
Harmonic Imaging of the Breast

- reduces clutter in cysts
- improves contrast
- improves border delineation



Nonlinear propagation in water

KZK and experiment



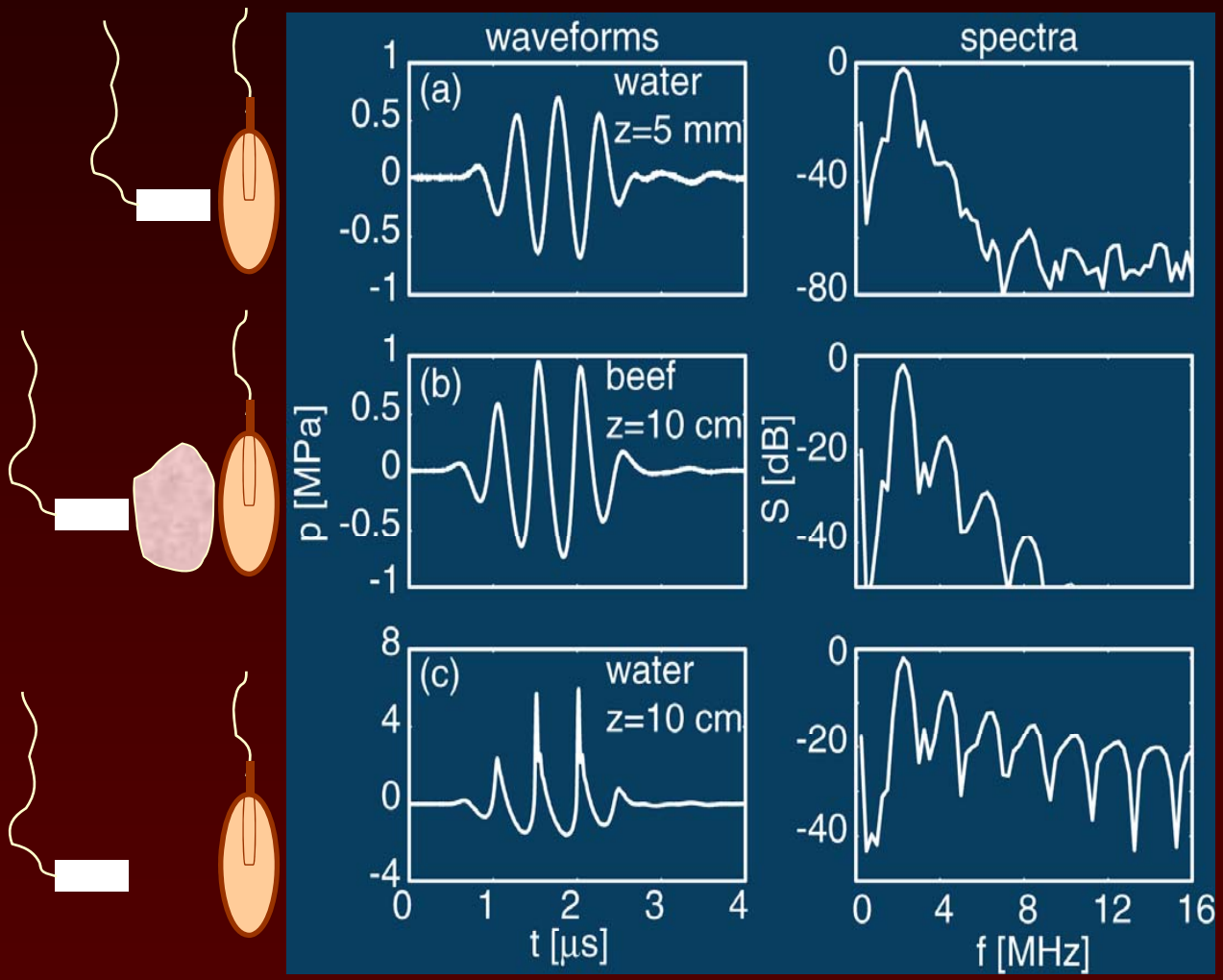
Circular x-ducer
Focused , CW

Axial pressure for 4 harmonic components

Fund
2nd hrm
3rd hrm
4th hrm

Averkiou and Hamilton, JASA 1995

Measurements in beef tissue



P3-2 Phased Array
MI=0.5
focus=8 cm

IEEE Ultrasonics 1997

Summary

- Physics of shock waves described by nonlinear acoustics
  - Waves distort and produce higher harmonics
- SWL revolutionised treatment of kidney stones
  - Risks associated with treatment
  - Mechanisms of stone comminution
- Shock waves for orthopaedic indications
- Nonlinearity enhances therapeutic heating
- Nonlinearity enhances diagnostic imaging

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ME 520 Acoustics 1

- Graduate level introductory acoustics
- Distance learning course Fall 2010
- Monday and Wednesday 4pm-6pm

http://www.bu.edu/me/me520-acoustics-i/

http://people.bu.edu/robinc/me520

Google search: bu me520

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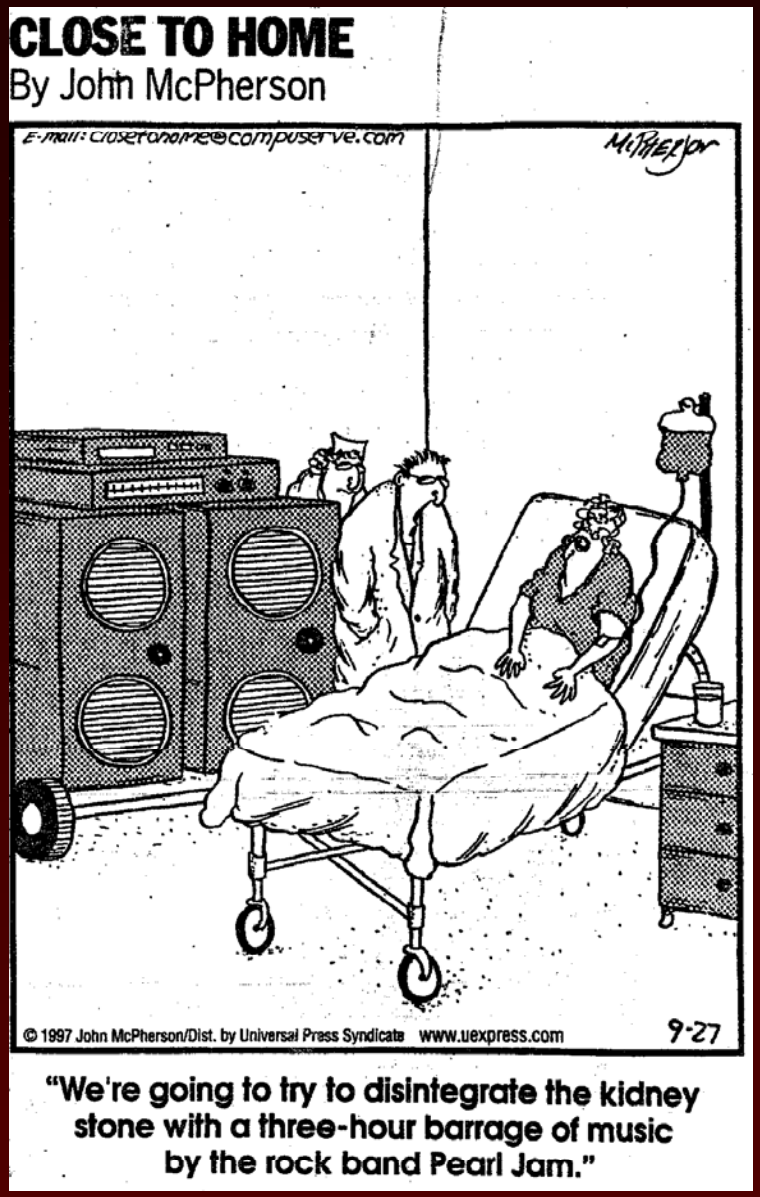

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