Medical Applications of Shock Waves

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Boston University

Ultrasonic Industry Association Meeting
14 April 2010
Boston
~3 million people
~70 colleges
~300,000 students

BU 30,000 students

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Outline

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

$\beta$ Coefficient of nonlinearity
1.2 in air
3.5 in water
5-10 in tissue

Beyond shock formation wave is multivalued

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Harmonic Production

![Graph showing the relationship between pressure and $B_n$ amplitude against frequency $\omega$.](image)
Harmonic Generation

Plane Wave Shock Formation in Tissue

\[ x = \frac{100}{\frac{p_0 f_0}{x}} \text{ mm} \]

MPa MHz

Shock Parameter

\[ \sigma = \frac{x}{x} \]

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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

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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

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Electromagnetic Lithotriptor

Coil

Acoustic lens

Membrane

Focus

Cylindrical Electromagnetic Source

Parabolic Reflector

Pressure (MPa)

HM3 24 kV

Storz SLX Energy 9

Time (µs)
Piezoelectric Lithotripter

Piezoceramic elements

Back ing

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Storz Modulith SLX
Electromagnetic Lithotripter

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Ultracal 30 Disintegration
SWL Induces Injury

- Haematuria
- Subcapsular haemotomas
- Kidney failure

- Onset hypertension
- Affect growth of kidney in paediatric patients
SWL-Induced Injury (EHL-Dornier HM3)

Lesion Size increases with SW amplitude

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Mechanisms of Stone Comminution

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

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Cavitation Bubbles

- **a**: Shock wave
- **b**: 100 µs
- **c**: 200 µs
- **d**: 300 µs
- **e**: 400 µs
- **f**: 500 µs
- **g**: 600 µs

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Elastic Wave Simulations
Haibiao Luo, PhD Student

\[
\rho \frac{\partial \mathbf{v}_i}{\partial t} = \frac{\partial \tau_{ij}}{\partial x_j}
\]

\[
\frac{\partial \tau_{ij}}{\partial t} = \lambda \frac{\partial \mathbf{v}_k}{\partial x_k} \delta_{ij} + \mu \left( \frac{\partial \mathbf{v}_i}{\partial x_j} + \frac{\partial \mathbf{v}_j}{\partial x_i} \right)
\]

- \( \mathbf{v}_i \): velocity vector
- \( \rho \): density
- \( \tau_{ij} \): stress tensor
- \( \lambda, \mu \): Lamé coefficients

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

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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

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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
  • Percutaneous 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

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Wide vs Narrow Focus

Focal spot size (p+/2)  Retreatment  Haematoma

Modulith
- 4 mm
- 35 mm

HM3
- 12 mm
- 85 mm

- 22.4% & 49.2%
- 3%

- 4.1% - 7%
- 0.8%

Kerbl et al
J. Endourol. 2002

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Manufacturer

- HM3 24 kV
- Storz SLX Energy 9
Coupling: Gel Results in Air Pockets
Fragmenation vs Air Pockets

Only ~8% coverage by air pockets reduced stone breakage by 60%
### The Effect of Shock Wave Rate

#### Meta-Analysis

<table>
<thead>
<tr>
<th>Study</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pace</td>
<td>-0.133 (-0.254, -0.009)</td>
</tr>
<tr>
<td>Madbouly</td>
<td>-0.087 (-0.174, -0.017)</td>
</tr>
<tr>
<td>Yilmaz</td>
<td>-0.163 (-0.307, -0.019)</td>
</tr>
<tr>
<td>Davenport</td>
<td>0.008 (-0.181, 0.196)</td>
</tr>
<tr>
<td>Combined</td>
<td>-0.102 (-0.168, -0.037)</td>
</tr>
</tbody>
</table>

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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

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HMT Ossatron

FDA approval:
chronic lateral epicondylitis (tennis elbow)
chronic plantar fasciitis (heel pain or heel spurs)
What is the stress distribution in the presence of bone?
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

Handheld Therapy Unit

1-4 atm pressure

Projectile → Therapy Head

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High Intensity Focused Ultrasound
Focused Ultrasound Surgery

Absorption produces localised heating in the focal region:
- Cell lysis
- Haemostasis
US beam direction

Lesion

Beef Liver

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Applications of HIFU

• Ophthalmology
  – FDA approval 1985

• Cancer
  – Liver, kidney, prostate, breast, brain, skin…

• Non Cancer
  – Uterine fibroids, epilepsy, liver surgery, BPH, ophthalmology…

• Trauma Care
  – Acoustic hemostasis through vessel occlusion
    • Transcutaneous
    • Intraoperative

• Clinical Trials
  – Columbia University
  – University of Washington
  – Brigham and Women’s Hospital
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
Robin Cléveland, Boston University
Simulations of Lesion Formation

Figure No. 1

- $p(0 \, \mu s)$
- $T(0 \, \mu s)$
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

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Harmonic Growth
Nonlinearity and Lesions

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


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Tissue Harmonic Imaging

Diagnostic ultrasound scanner

Transmit at $f_0$

Nonlinear generation of $2f_0$

Reflection of both harmonics

Processing to form image from $2f_0$ only

Reduced clutter and enhanced boundary definition

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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
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Measurements in beef tissue

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

IEEE Ultrasonics 1997

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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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