6_Therapy

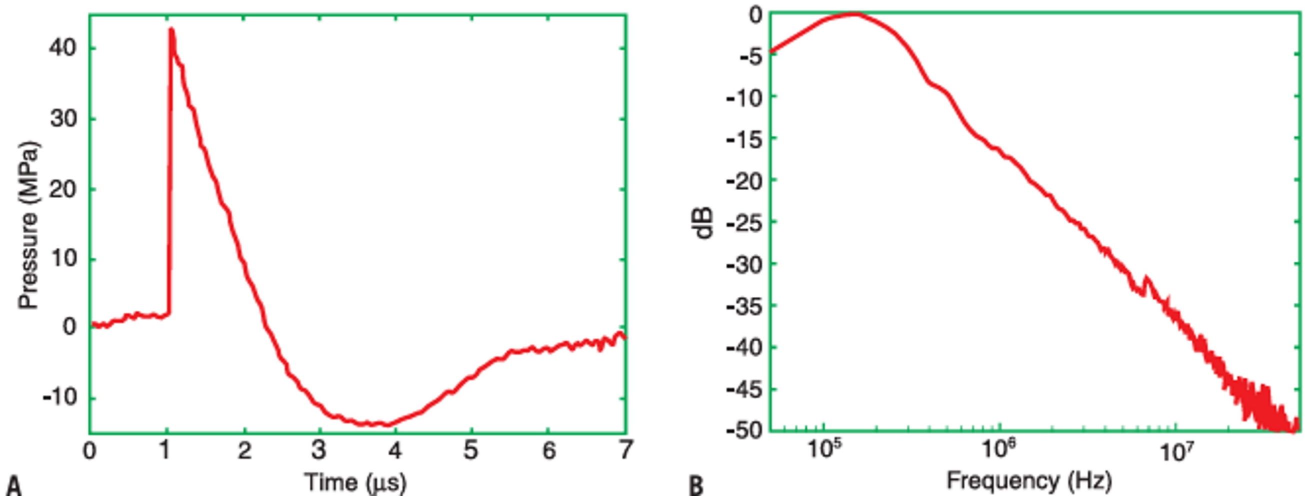
11 March 2025 14:27

Shock Wave Lithotripsy (SWL)

- **Introduction & Adoption:**
  - SWL was introduced in the 1980s as a treatment for urinary stones.
  - It quickly became the first-line treatment option.
  - In the U.S., approximately **70% of kidney stones** are treated using SWL.
- **Technological Advancements:**
  - SWL has seen several waves of technological improvements.
  - However, the **fundamentals of shock wave generation and delivery remain unchanged**.
  - Changes in lithotriptors have been significant from a **user perspective** but not in the **core pressure pulse mechanism**.
- **Mechanism of Action & Side Effects:**
  - Lithotriptors produce an **acoustic shock wave**, a characteristic pressure pulse.
  - This pulse is responsible for **breaking stones** but can also cause **collateral tissue damage**, sometimes significant.

Mechanisms of Shock Wave Lithotripsy (SWL) and Technological Developments

- **Mechanical Forces in SWL:**
  - Lithotriptors generate a **powerful acoustic field**, causing two primary mechanical forces:
    - **Direct stress** from the high-amplitude shock wave.
    - **Stresses and microjets** from the growth and collapse of **cavitation bubbles**.
  - Despite advancements in research, the **exact mechanisms of shock wave action** are not fully understood.
- **Challenges in Lithotriptor Development:**
  - No **completely safe yet effective** lithotriptor has been developed.
  - Recent trends in **high-amplitude, tightly focused shock waves** have increased **adverse effects and re-treatment rates**.
  - The goal within the field is to make SWL both **safer and more effective**.
- **Understanding Lithotriptor Function:**
  - Urologists must **optimize the use of available machines** by understanding how they function.
  - This chapter introduces **fundamental physical concepts** underlying SWL mechanisms.
- **Key Topics Covered in the Chapter:**
  - **Characteristics of lithotriptor shock waves**
  - **Acoustics of SWL** (including an **acoustics primer**)
  - **Acoustic cavitation** and its effects
  - **Physics of clinical lithotriptors**
  - **Shock generation and focusing**
  - **Coupling shock waves to the body**
  - **Focal zone of high acoustic pressure**
  - **Mechanisms of shock wave action**:
    - How **shock waves break stones**
    - How **shock waves cause tissue damage**
  - **Evolution of lithotriptor technology**
  - **Future directions in lithotripsy**

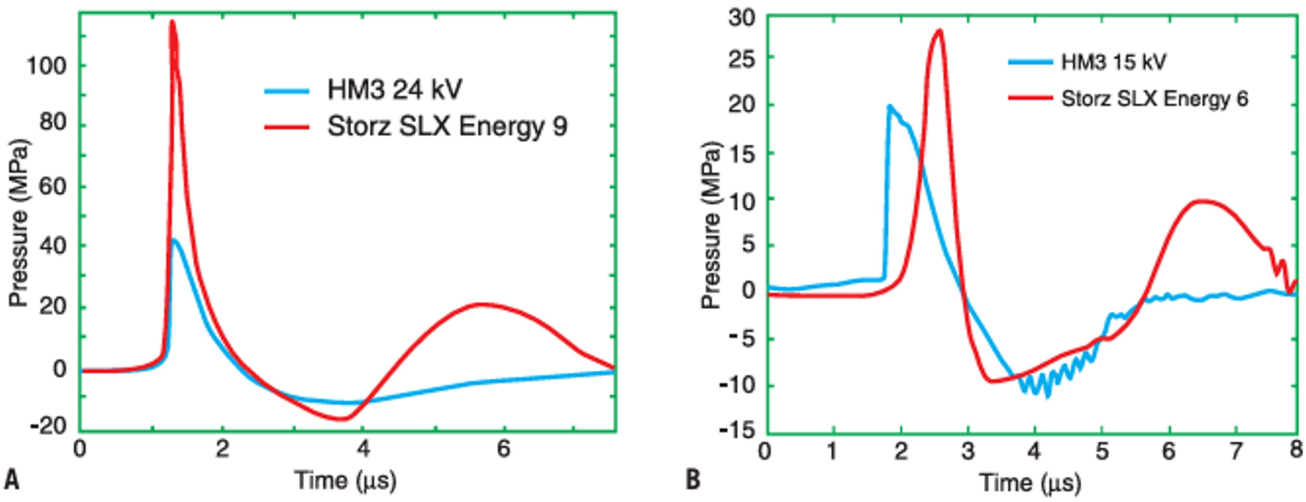


Characteristics of a Lithotriptor Shock Wave

- **Shock Wave Profile (Figure 38-1A):**
  - A typical shock wave at the focus of a lithotriptor is a **short pulse lasting ~5 µs**.
  - The wave starts with an **instantaneous jump** to a **peak positive pressure of ~40 MPa**.
  - This fast transition, referred to as a **"shock,"** is **faster than can be measured** (<5 ns).
  - The pressure drops to zero **after ~1 µs**, followed by a **negative pressure phase (~ 3 µs, -10 MPa peak)**.
  - Unlike the positive phase, the **negative phase lacks a sharp transition**.
  - The entire **5 µs pulse** is often called a **shock wave, shock pulse, or pressure pulse**, though **technically only the leading sharp transition is a shock**.
- **Frequency Spectrum (Figure 38-1B):**
  - The **amplitude spectrum** of the shock pulse reveals **no dominant frequency** or tone.
  - The energy is spread **over a wide frequency range** (100 kHz – 1 MHz), a key characteristic of a **short pulse**.
  - This suggests that lithotriptors **do not break kidney stones via resonance excitation**, unlike how an opera singer shatters a crystal glass.

Variations in Lithotriptor Shock Waves

- **General Characteristics of Lithotriptor Shock Waves:**
  - Most lithotriptors produce **a similarly shaped shock wave**, consisting of:
    - A **shock front**
    - A **compressive phase**
    - A **tensile tail**
  - Despite the similarity in waveform shape, **amplitude varies significantly** depending on the machine and settings.
  - **Peak positive pressure** typically ranges between **30 MPa and 110 MPa**, while **negative pressure** ranges between **-5 MPa and -15 MPa**.
- **Comparison of Shock Waveforms (Figures 38-2A & 38-2B):**



- **Figure 38-2A**:
  - Shows a comparison between **electrohydraulic** and **electromagnetic lithotriptor waveforms**.
  - The **main difference is amplitude**, while the basic waveform structure remains similar.
- **Figure 38-2B**:
  - Displays waveforms at **lower power settings** for both lithotriptors.
  - Again, the **shape is preserved**, but the **amplitudes differ**.

- **Impact of Shock Wave Amplitude & Focal Zone:**
  - Lithotriptor **shock waves have a unique form**, characterized by:
    - A **high-amplitude compressive phase** with an **extremely rapid transition** and **short duration**.
    - A **trailing tensile phase**.
  - While all lithotriptors share this basic waveform, there are **considerable differences in amplitude and spatial extent** of the acoustic output.
  - **Performance differences** among lithotriptors are likely influenced by **amplitude and focal zone size**.

What is an Acoustic Wave?

- **Definition & Formation:**
  - An **acoustic wave (sound wave)** is created whenever an **object moves within a fluid** (gas or liquid).
  - As the object moves, it **compresses** the surrounding fluid, forcing molecules closer together.
  - These compressed molecules push against **adjacent molecules**, transferring the compression forward.
  - This **chain reaction** results in a **traveling wave of compression**, known as an **acoustic wave**.
- **Wave Propagation & Medium Dependence:**
  - The **speed of an acoustic wave** (sound speed) is a **material property** of the medium.
  - **Key distinction: Molecules do not travel with the wave**—they only **jostle adjacent molecules** to pass energy forward.
  - **A medium is required** for acoustic waves to propagate.
- **Difference Between Acoustic and Electromagnetic Waves:**
  - **Acoustic Waves** (e.g., sound, seismic, water waves) require a **medium** (fluid or solid) to support **vibrations**.
  - **Electromagnetic Waves** (e.g., light, radio waves, X-rays) do **not** require a medium; they are carried by **photons** and can travel through a **vacuum**.
  - This explains why **sound cannot travel in space**, but **light can**.

Compressive and Tensile Phases of Sound Waves

- **Two Phases of an Acoustic Wave:**
  - A **compressive phase** occurs when molecules are **pushed together** due to the movement of an object within a fluid.
  - A **tensile phase (rarefaction)** occurs when an object moves away, creating a **partial vacuum**, causing neighboring molecules to move in and create a propagating **rarefactional disturbance**.
  - **Both compressive and tensile waves propagate at the same sound speed** in most cases.
- **Wave Generation and Form:**
  - **Typical acoustic sources** (e.g., audio speakers) **vibrate back and forth**, producing alternating **compression and rarefaction waves**.
  - This results in a **waveform** that is often **sinusoidal**, but **most acoustic waves, including lithotriptor pulses, are not sinusoidal**.
- **Wave Speed and Amplitude:**
  - For **small-amplitude waves (linear acoustics)**, every point of the waveform moves at the **same speed (c_0)**.
  - In **water and tissue, the sound speed is ~1,500 m/s**.
  - For **large-amplitude (nonlinear) waves**, such as **shock waves**, the **sound speed is slightly modified** by the wave's presence.
- **Measuring Acoustic Waves:**
  - Acoustic waves are typically measured as **pressure pulses over time at a fixed point in space** (e.g., via a microphone).
  - However, **waves also vary in space**, and it is useful to consider their **spatial extent** for analysis.

Reflection and Transmission of Sound Waves

- **Acoustic Wave Interaction with Different Media**
  - When an acoustic wave encounters a **medium with different impedance**, part of the wave is **transmitted** into the new medium, and part is **reflected** back.
  - At **normal incidence** (wave perpendicular to the surface), the amplitudes of the transmitted and reflected waves depend on the **impedance mismatch** between the two media.
- **Transmission Coefficient and Impedance Mismatch (Figure 38-4)**
  - The **intensity transmission coefficient** determines how much energy passes into a new medium.
  - **Water-to-tissue transmission**: Very efficient.
  - **Water-to-kidney stone transmission**: High, with **75–95% of energy transmitted**.
  - **Water-to-air transmission**: **Extremely low (<0.1%)**, meaning **99.9% of the energy is reflected**.
- **Implications for Lithotripsy**
  - **Shock wave generators are water-filled** to ensure efficient energy transfer.
  - **Immersion of the patient in water** provides the best coupling of shock waves to the body.
  - **Dry lithotriptors require careful air pocket elimination** between the shock head and the body.
  - **Shock waves do not effectively pass through air-filled organs** like the lungs or bowel segments.
  - **Optimal shock wave path**: The **flank of the patient** (defined by the **ribs, spine, and pelvic bone**) provides the best **pure tissue path to the kidney** for effective treatment.

Focusing and Diffraction of Sound

- **Purpose of Focusing in Lithotripsy**
  - **Shock waves are focused** to concentrate **acoustic energy** on the **kidney stone** while minimizing damage to surrounding tissue.

    - Lithotriptors achieve focusing through:
        - **Reflectors**
        - **Acoustic lenses**
        - **Spherically curved sources**
- **Wave Focusing Physics**
    - The **fundamental physics** of wave focusing is similar across different methods.
    - **Ideal focus**: All energy concentrated in an **infinitesimally small region** (theoretically impossible).
    - **Diffraction limitation**: Energy cannot be arbitrarily confined due to **wave propagation constraints**.
- **Focal Zone**
    - **Definition**: The finite region around the focus where **acoustic pressure remains high**.
    - **Theoretical lower bound**: If sound approaches from all angles, diffraction limits the **focal zone** to about **one wavelength**.
    - **Practical lithotripsy systems**: Since sound comes from a **single direction**, the **focal zone ranges from a few millimeters to tens of millimeters** in size.

Focal Zone

- **Definition and Terminology**
    - The **focal zone** of a lithotriptor is an **ellipsoidal** region where **high acoustic pressure** is concentrated.
    - Equivalent terms:
        - **Focal region**
        - **Hot spot**
        - **Focal spot**
        - **Focal volume**
        - **Zone of high pressure**
    - The **longest dimension** of the focal zone aligns with the **shock wave axis**.
- **Factors Determining Focal Zone Size**
    - The **length and diameter** of the focal zone depend on:
        - **Source diameter**
        - **Focal length** (distance from source to target)
        - **Frequency content** of the waveform
    - **Design features** of different lithotriptors affect their **focal zone size and acoustic pressure distribution**.
    - Some lithotriptors generate **extreme acoustic pressures in very narrow focal zones**.
- **Focal Zone Estimation**
    - **No explicit formula** for pulsed lithotripsy waveforms.
    - The **focal region of a lithotriptor** can be approximated using equations for the **focal region of a sine wave**.
- **Focal Zone Adjustments (Figures 38-6A & 38-6B)**
    - **Increasing source aperture diameter → Shorter and narrower focal zone**.
    - **Decreasing focal length (source-to-target distance) → Shorter and narrower focal zone**.
    - **Optimal design for a small focal zone**:
        - **Large aperture diameter**
        - **Short focal length**
    - **Limitations**:
        - The **size of the acoustic window in the flank** restricts extreme modifications.
        - The lithotriptor must still be able to **target stones deep in the body**.

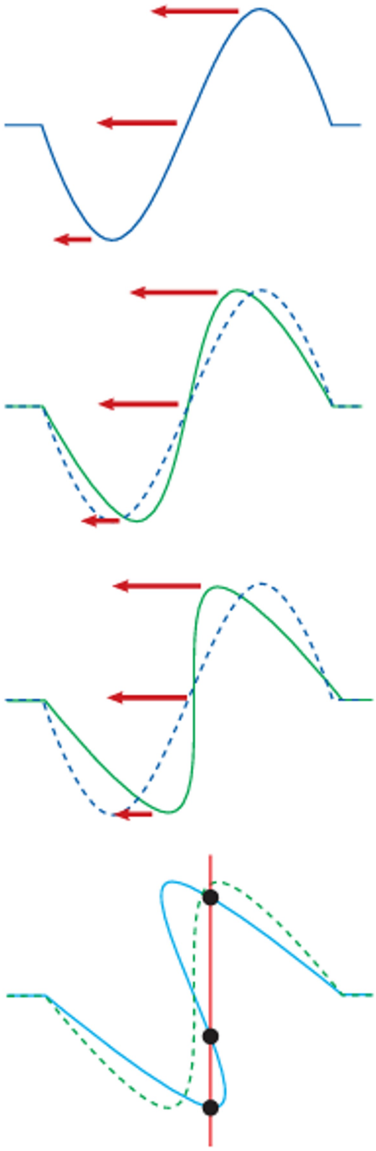
Sound Waves Are Not Just Pressure Waves

- **Multiple Effects of Sound Wave Propagation:**

- A propagating **sound wave** affects more than just **pressure**—it also influences:
  - **Density (ρ):**
    - **Increases** in compressed regions.
    - **Decreases** in rarefied (tensile) regions.
  - **Pressure:**
    - **Rises** during compression.
    - **Falls** during rarefaction.
  - **Particle velocity:**
    - Individual **fluid particles move** in response to the wave, but they **do not travel with it**.
- **Wave Behavior in a Fluid:**
  - Compression causes **higher local density**, while rarefaction leads to **lower local density**.
  - These variations contribute to the overall **wave propagation** in the medium.

Nonlinear Effects in High-Amplitude Acoustic Waves

- **Wave Speed Variation in High-Amplitude Waves:**
  - In **large-amplitude acoustic waves**, such as **lithotriptor shock waves**, the **wave speed is no longer constant**.
  - The speed of the wave **depends on the local compression** of the fluid.
- **Nonlinearity in Shock Waves:**
  - Even in **high-power lithotriptors**, water compression is **less than 5%**, yet nonlinearity still occurs.
  - Two physical effects contribute to this nonlinearity:
    - **Higher Pressure Increases Local Sound Speed:**
      - In regions of **high pressure**, the **local sound speed increases** beyond the normal value.
    - **Convective Effects in High-Pressure Regions:**
      - Molecules in **high-pressure regions** move with **higher particle velocity**, shifting forward in the **direction of wave propagation**.
  - In **tissue**, the **first effect (increased local sound speed) dominates** nonlinearity.
- **Wave Distortion and Nonlinear Propagation:**
  - **Nonlinear waves** differ from **linear waves** because **different parts of the wave travel at different speeds** (Equation 38-19).



- **Figure 38-7** illustrates how **a sinusoidal wave deforms** as it propagates under nonlinear conditions.
- Without **absorption**, the **wave can develop an infinite slope**, causing it to **fold over** and become **multivalued**.
- **This is similar to ocean waves fanning up a beach**, but in acoustics, such a waveform is **not physically possible**, as a **single point in space cannot have multiple pressure values simultaneously**.

Hydrophones Measure Shock Waves

- **Lithotriptor Acoustic Field Measurement**
  - The main physical property of a lithotriptor is its spatial and temporal acoustic pressure distribution.
  - The acoustic field is typically measured in water using a **hydrophone**, which converts pressure into an electrical signal.
- **Characteristics of Lithotripsy Shock Waves**
  - Lithotriptors generate **short, high-amplitude acoustic pulses** with a wide frequency band.
  - These pulses are focused on a **small volume in space**.
- **Hydrophone Requirements**
  - **Wide bandwidth**: 60 kHz to >20 MHz.
  - **Robustness**: Must withstand high pressures from shock waves.
  - **Small active area**: Approximately **0.5 mm**.
- **PVDF Hydrophones**

- First reliable lithotripsy shock wave measurements were done using **PVDF (polyvinylidene fluoride)**, a **piezoelectric plastic**.
- PVDF has:
  - **Very wide bandwidth**
  - **High amplitude acoustic pressure measurement capability**
  - **Manufacturable with a small active region**

- **Types of Hydrophones**
  - **Membrane hydrophones** and **needle hydrophones** have been used.
  - **Membrane hydrophones** provide the **best shock wave measurement**.
- **Limitations of PVDF Hydrophones**
  - **Weak water adhesion**: The tensile phase of the lithotripsy pulse can cause **cavitation** at the PVDF surface.
  - **Consequences of cavitation**:
    1. **Measurement issues**: The hydrophone cannot measure the **tensile phase** accurately. When a bubble forms, the **negative pressure is relieved**, causing the hydrophone to register close to zero.
    2. **Physical damage**: **Collapsing cavitation bubbles** can irreversibly damage the hydrophone.

Fiber Optic Probe Hydrophone (FOPH) for Lithotripsy Shock Waves

- **Introduction of FOPH**
  - A new hydrophone, the **fiber optic probe hydrophone (FOPH)**, has been developed.
  - It is now considered **state-of-the-art** for measuring lithotripsy shock waves.
  - **International measurement standards** recommend using the FOPH.
- **Working Principle**
  - The FOPH consists of a **laser** that injects light into one end of an **optical fiber**.
  - The other end is placed in the **lithotriptor field**.
  - It measures the **light reflected from the fiber's end**, which varies depending on the pressure in the fluid.
- **Advantages Over PVDF Hydrophones**
  - **Wide bandwidth** and **high-pressure measurement capability**, similar to PVDF.
  - **Smaller active area**: **100 µm** (compared to **500 µm** for PVDF hydrophones).
  - **Stronger water adhesion**:
    - Made of **silica**, which has high adhesion with water.
    - **Less cavitation**, allowing for **better measurement of the tensile phase**.
    - **More resistant to cavitation damage** than PVDF.
- **Limitations of FOPH**
  - **Weak signal** output.
  - **Not suitable for measuring low pressures** (≈2 MPa or less).

Measuring Shock Waves in the Body

- **Current Measurement Limitations**
  - **All published focal zone dimensions** come from **in vitro experiments**.
  - **Few studies** have attempted to measure **shock wave pressure in living animals**.
- **Effects of Tissue on Shock Wave Propagation**
  - **Tissue properties** (high attenuation and inhomogeneity) alter shock wave behavior as they travel through the body.
  - **Comparison of in vitro and in vivo waveforms (Figure 38-9)**:
    - Data from **Dornier HM3 lithotriptor** measured in **water** and in a **pig using a PVDF membrane hydrophone**.
    - **Basic waveform shape remains similar** between in vitro and in vivo conditions.
    - **Key differences in vivo**:
      - **30% decrease in peak positive pressure**.

        - **Significantly increased shock rise time** (**70 ns**).
    - **Both changes are consistent with the increased attenuation of tissue.**

Acoustic Cavitation

- **Definition and Mechanism**
    - **Acoustic cavitation** is a mechanical force generated by lithotriptor shock waves.
    - It occurs when the **tensile phase (negative pressure) of an acoustic wave** is strong enough to **create cavities (bubbles) in a fluid**.
    - In **lithotripsy**, the **tensile phase (~10 MPa)** induces **violent cavitation events**.
- **Role of Cavitation in Lithotripsy**
    - **Tissue damage** during **shock wave lithotripsy (SWL)** is partly caused by cavitation.
    - **Stone comminution** (fragmentation) is also **enhanced** by cavitation effects.
- **Bubble Formation and Growth**
    - Cavitation is typically **initiated** at:
        - **Micron-sized motes** in the fluid.
        - **Small gas pockets** trapped on rough surfaces.
    - Several **theories** describe how cavitation progresses once a bubble forms.
- **Bubble Dynamics (Figure 38-10)**
    - A **spherical bubble's radius** changes in response to a **lithotriptor shock wave**:
        1. **Compression phase**: The **positive pressure** of the shock wave **compresses the bubble**.
        2. **Expansion phase**: The **tensile phase** causes the bubble to grow from **1 µm to ~1 mm** over **150 µs**.
        3. **Inertial cavitation**:
            - The bubble continues to **expand after the shock wave passes** (~5 µs).
            - At this stage, bubble dynamics are **driven by fluid inertia** rather than acoustics.
            - **Gas and vapor diffusion** occurs inside the bubble.
        4. **Collapse phase**:
            - The **near-vacuum inside the bubble** and the surrounding **ambient pressure (~1 atm)** cause the bubble to collapse.
            - The collapse is **extremely violent**, generating **high heat and compression** that can even produce **light emission**.
        5. **Post-collapse effects**:
            - **Bubble rebounds** occur.
            - The **gas inside the bubble slowly diffuses back into the fluid**.
- **Acoustic Emissions from Cavitation**
    - **Lithotripsy-induced cavitation bubbles** generate **two acoustic emissions**:
        1. **Upon impact by the compressive shock wave**.
        2. **Upon collapse, hundreds of microseconds later**.
    - This **"double-bang" acoustic signature** can be used to **detect cavitation events**.
- **Cavitation Measurement Techniques**
    - Multiple methods exist to **measure cavitation**, utilizing the unique **acoustic emissions** it generates.

High-Speed Photography of Bubble Dynamics

- **Observing Cavitation with High-Speed Cameras**
    - High-speed photography can be used **in vitro** to observe **bubble behavior** from **formation to collapse**.
    - In **theory**, this method allows **tracking the entire bubble lifecycle**, but **practical limitations** exist.
- **Challenges in Capturing Full Bubble Dynamics**
    - **Growth Phase**:
        - Requires imaging at **millimeter scales** and **tens of microseconds** time resolution.

    - **Collapse Phase**:
        - Bubble shrinks to **less than 1 µm**.
        - Collapse dynamics occur at **nanosecond** timescales.
    - **Rebound and Dissolution Phase**:
        - **Remnant bubble (~10 µm)** dissolves slowly over **hundreds of milliseconds**.
    - **Wide range of spatial and temporal scales** makes it **impossible** to photograph the full process in a single recording.
- **Segmented Approach to Cavitation Study**
    - Due to these limitations, **cavitation is studied in separate phases** rather than as a whole.
- **Depth of Field Limitations**
    - **Cameras have a limited depth of field**, making it difficult to capture bubble behavior **throughout the entire cavitation field**.
    - This **prevents a complete record** of bubble dynamics in **large cavitation volumes**.

Laser Scattering of Single Bubbles

- **Principle of Laser Scattering for Bubble Measurement**
    - A **laser beam** is used to **illuminate** a cavitation bubble.
    - A **photodetector** collects the **scattered light**, which varies based on the **bubble's radius**.
    - For a **spherical bubble**, the amplitude of scattered light follows a **known pattern**, allowing **precise measurement of bubble dynamics**.
- **Advantages of Laser Scattering**
    - Captures **most spatial and temporal scales** of **lithotripsy-induced cavitation bubbles**.
    - Provides **high precision** for measuring **single bubble dynamics**.
- **Limitations of Laser Scattering**
    - **Small sample volume**: Can only measure a **tiny region** of the cavitation field.
    - **Requires unobstructed visual access** at **high magnification**.
    - **Assumes a single spherical bubble**:
        - Theory is **only accurate for isolated, perfectly spherical bubbles**.
        - **Cannot provide quantitative data** for **bubble clouds** or **non-spherical bubbles**, both of which are **common in lithotripsy-induced cavitation**.
        - Measurements in realistic **cavitation fields** are mostly **qualitative**.

Acoustic Detection Can Be Used In Vivo

- **Advantages of Acoustic Detection**
    - **Powerful tool** for characterizing **bubble dynamics in living subjects**.
    - Unlike imaging techniques, it can **monitor cavitation events in real-time**.
- **Modes of Acoustic Detection**

    Active Cavitation Detection (ACD)
        - Works similarly to **laser scattering** but uses **acoustic waves**.
        - **One transducer** sends an **acoustic wave** into the cavitation field.
        - **A second transducer** picks up **reflections from bubbles**.

    Passive Cavitation Detection (PCD)
        - **No external wave is transmitted**; instead, transducers **listen for natural emissions** from bubbles.
        - Cavitation bubbles produce a characteristic **"double-bang" acoustic signal**.
        - **Dual PCD**:
            - Uses **two receiving transducers**.
            - Enables **coincidence detection**, allowing sampling of a **small, discrete volume** of the cavitation field.
        - **Signal timing and amplitude** are influenced by factors like:
            - **Initial bubble size**.

            - **Lithotriptor pulse amplitude**.
- **Limitations of Acoustic Detection**
    - **Does not image bubbles** (cannot measure **bubble number or exact size**).
    - Instead, provides **valuable data** for:
        - **Characterizing lithotriptor acoustic output**.
        - **Assessing cavitation field dynamics**.

Other Cavitation Measurement Techniques (Figure 38-11)

- **Metal Foil Pitting Method**
    - Cavitation leads to **pitting on metal foils**.
    - **Number and depth of pits** can indicate the **violence of cavitation**.
- **Electromagnetic Probe**
    - Measures the **mechanical force** on a **steel ball** from:
        - The **incident shock wave**.
        - **Cavitation activity**.
- **Sonoluminescence and Sonochemistry**
    - **Extreme pressures and temperatures** inside cavitation bubbles can:
        - Produce **light emissions (sonoluminescence)**.
        - Enhance **chemical reaction rates (sonochemistry)**.
    - **Production of light and chemical byproducts** can be used to **quantify cavitation activity**.
    - **Interpretation is complex** as these are **secondary measurements** of the cavitation field.

Shock Generation and Focusing

Laser Scattering of Single Bubbles

- **Principle**:
    - A **laser beam** illuminates a **single cavitation bubble**, and a **photodetector** collects the **scattered light**.
    - The **amplitude of scattered light** varies predictably with **bubble radius**, allowing precise measurement.
- **Advantages**:
    - Captures **most spatial and temporal dynamics** of lithotripsy-induced cavitation bubbles.
- **Limitations**:
    - **Small sample volume** restricts large-scale measurement.
    - Requires **unrestricted visual access at high magnification**.
    - **Assumes a single spherical bubble**, making it **ineffective for bubble clouds or non-spherical bubbles**, which are common in lithotripsy.

Acoustic Detection Can Be Used In Vivo

- **Modes of Acoustic Detection**:
    - **Active Cavitation Detection (ACD)**
        - **One transducer** sends an **acoustic wave** into the cavitation field.
        - **A second transducer** detects **reflections from bubbles** (analogous to laser scattering).
    - **Passive Cavitation Detection (PCD)**
        - **No external wave transmission**—transducers **listen for natural emissions** from cavitation bubbles.
        - **Dual PCD**:
            - Uses **two receiving transducers**.
            - Allows **coincidence detection**, sampling a **small, discrete cavitation volume**.
- **Benefits of Acoustic Detection**:
    - Provides **valuable data** for **shock wave characterization** and **cavitation field dynamics**.
    - Can be used **in vivo**, unlike optical methods.
- **Limitations**:

    - Cannot **image bubbles** (does not provide bubble count or exact size).

Electrohydraulic Lithotriptors (EHL)

- **Shock Wave Generation**:
    - **Spark source** creates a **shock wave**.
    - The wave is **focused by an ellipsoidal reflector** (Figure 38-12).
    - Unlike other lithotriptor types, the **shock wave remains a shock wave throughout propagation**.
- **Focusing Mechanics**:
    - The **spark source must be precisely placed** at the **first focus of the ellipse**.
    - **Misalignment (even by a few mm)** causes:
        - **Loss of focusing efficiency**.
        - **Lengthening and broadening of the focal zone**.
    - **Electrode variability** causes **shot-to-shot variations**:
        - Shock wave amplitude can vary by **up to 50%**.
        - **Focal zone position may shift**.
- **Unique "Two-Pulse" Feature**:
    - EHL insonifies the target with **two waves**:
        Direct wave:
            - Travels **directly from the spark** to the target.
            - Arrives **~30 μs before the main wave**.
            - Has **low amplitude due to spherical spreading**.
            - Can **influence cavitation** caused by the main focused wave.
        Main focused wave:
            - Reflected and **concentrated at the focal point**.
- **Electrode Wear and Maintenance**:
    - **Electrodes degrade over time** and require replacement.
    - Some manufacturers **extend electrode life** by:
        - **Encapsulation**.
        - **Filling the casing with electrolyte**.
    - **Electrode wear affects acoustic output**, leading to inconsistencies in shock wave generation.

Electromagnetic Lithotriptors (EML)

- **Shock Wave Generation Mechanism**
    - Uses an **electrical coil** near a **metal plate** as the **acoustic source**.
    - When **electrical current pulses through the coil**, the **plate experiences a repulsive force**, generating an **acoustic wave**.
- **Types of Wave Generation (Figure 38-13)**
    - **Flat metal plate** → Generates a **plane wave**, focused by an **acoustic lens** (Figure 38-13A).
    - **Tube-shaped plate** → Generates a **cylindrical wave**, focused by a **parabolic reflector** (Figure 38-13B).
- **Advantages Over Electrohydraulic Lithotriptors (EHL)**
    - **More consistent focusing**:
        - Variation in **measured pressure waves is <10%**.
        - **Less shot-to-shot variation** compared to EHL.
    - **No electrodes to replace**, reducing maintenance needs.
- **Acoustic Differences Between EML and EHL**
    Initial Waveform Shape:
        - **EHL**: The wave **starts as a shock wave**.
        - **EML**: The wave starts as a **high-intensity ultrasonic wave** (smooth waveform, no discontinuities).
        - **EML shock formation**: The ultrasonic wave **undergoes nonlinear distortion** during propagation, **becoming a shock wave** before reaching the focus.

Trailing Positive Pressure Difference:
    - **EML waveforms have a smaller trailing positive pressure** after the **negative phase**.
    - This **likely does not impact stone stress** but **may influence cavitation dynamics**.

Piezoelectric Lithotriptor (PEL)

- **Shock Wave Generation Mechanism**
    - Uses **piezoelectric crystals** to generate **ultrasonic waves**.
    - When **voltage is applied**, the **crystals deform**, producing an **acoustic wave**.
    - **Crystals are arranged on the inside of a spherical cap**, focusing the acoustic wave at the **center of the sphere's curvature** (Figure 38-14A).
- **Advantages of PEL**
    - **Highly reproducible focus** with **minimal variation in focal waveforms**.
    - **Consistent shock wave formation**, similar to **electromagnetic lithotriptors (EML)**.
- **Waveform Characteristics**
    - **Starts as an acoustic pulse**, similar to EML.
    - A **shock wave forms before reaching the focus** due to **nonlinear propagation distortion** (Figure 38-14B).
    - **Presence of a trailing coda (ringing effect)**:
        - **Piezoelectric crystals continue vibrating for a few cycles** after excitation.
        - This **ringing effect** is **not present in EHL or EML**.
        - The **coda does not impact stone stress**, but it **may influence cavitation dynamics**.

Coupling of the Shock Source to the Body

- **Importance of Acoustic Impedance Matching**
    - Efficient **acoustic energy transfer** occurs when **acoustic impedances of two media are similar**.
    - **Water/tissue interface** provides **excellent coupling**, theoretically allowing **>99% energy transfer** into the body.
- **Impact of Air Pockets on Energy Transfer**
    - Even a **small air pocket** at the skin surface **drastically reduces energy transfer**.
    - **Air acts as a strong reflector**, preventing shock waves from penetrating the body effectively (**Figure 38-4**).
- **Significance of Proper Coupling**
    - Ensuring **good contact between the shock wave source and the patient** is **critical** for effective lithotripsy.

Water-Bath and Dry Lithotriptors

Water-Bath Lithotriptors (First-Generation, e.g., Dornier HM3)

- **Design and Coupling**:
    - **Patient is fully immersed in an open water bath**.
    - **Nothing but water** between the **shock source** and the **patient**, ensuring **ideal acoustic coupling**.
- **Challenges**:
    - **Bubbles from the spark gap** and **cavitation bubbles** can accumulate **against the patient's skin**, interfering with **subsequent shock waves**.
    - To prevent this:
        - The **ellipsoidal reflector** in the **Dornier HM3** is **tilted 14 degrees off vertical**.
        - **Continuous degassing** of the water is performed to **remove bubbles**.

Dry Lithotriptors (Modern Lithotriptors)

- **Design and Coupling**:
    - The **shock wave source** is mounted in a **“therapy head”** filled with **water**.

  - A **thin rubber membrane caps the therapy head** and is pressed **against the patient**.
  - A **coupling agent** (gel or oil) is applied between the **rubber membrane** and the **skin** to **reduce air pockets**.
  - **Water inside the therapy head is continuously recirculated and degassed** to prevent bubbles from interfering with **shock wave propagation**.
- **Limitations Compared to Water-Bath Lithotriptors**:
  - **Less effective coupling**:
    - The **rubber membrane** introduces an additional **reflecting interface**.
    - Even with couplants, **tiny air bubbles** between the **skin and membrane** are difficult to eliminate.
  - **In vitro studies show that different couplants significantly affect stone breakage**.
- **Clinical Trade-off**:
  - Despite **reduced performance**, dry therapy heads are **more convenient** for clinical use, making them the **preferred choice in modern lithotriptors**.

The Focal Zone of the Lithotriptor

- **Definition and Importance**
  - In lithotripsy, **acoustic energy is focused** to a **small zone** around the **focal point**.
  - The **focal point** is a **geometric location** where the shock waves converge, usually **aligned with the kidney stone for treatment**.
  - In **electrohydraulic lithotriptors (EHLs)**, the **focal point (F2)** is the **second focus of the ellipsoidal reflector**.
  - The **dimensions and pressure characteristics of the focal zone** are key factors **distinguishing different lithotriptors**.
- **IEC Standard Definition of the Focal Zone**
  - Defined as the **volume where peak acoustic pressure is at least half** of the **maximum peak positive pressure (p^+)**.
  - **Peak positive pressure (p^+)**: The **highest positive pressure** in the waveform (see **Figure 38-1**).
  - **Maximum peak pressure**: The **highest value of p^+ in the lithotriptor field**.
  - **Focus location**: Defined as the **point where maximum peak pressure occurs**.
  - The **focal zone shape** is typically an **elongated, elliptical ("cigar-shaped") volume**.
  - **Important considerations**:
    - The **maximum peak pressure does not always align** with the **stone placement location** recommended by the manufacturer.
    - **Focal zone dimensions change with power settings**.
- **Focal Zone Characteristics in Different Lithotriptors (Figure 38-15)**
  - **Dornier HM3 (Electrohydraulic Lithotriptor)**:
    - **Maximum peak pressure**: **40 MPa at 20 kV**.
    - **Focal zone dimensions**: **~60 mm long, 12 mm diameter**.
  - **Storz Modulith (Electromagnetic Lithotriptor)**:
    - **Maximum peak pressure**: **~100 MPa at energy level 8**.
    - **Focal zone dimensions**: **~35 mm long, 4 mm diameter**.
  - **Piezoelectric Lithotriptor**:
    - **Maximum peak pressure**: **~80 MPa**.
    - **Focal zone dimensions**: **~20 mm long, 3 mm diameter**.
- **Key Observations**
  - **Significant variation in focal zone dimensions across lithotriptors**.
  - **Lithotriptors with narrower focal zones tend to generate higher peak pressures**.

The Half-Maximum (–6 dB) Focal Zone and Alternative Definitions

- **Standard Definition (IEC Recommendation)**
  - The **half-maximum focal zone** (also called the **–6 dB focal zone**) refers to the **contour where the pressure is 6 decibels lower than the peak pressure**.
  - Example comparisons:
    - **Storz lithotriptor (peak pressure = 110 MPa at energy level 9)** → Focal zone defined at **55 MPa**.
    - **Dornier HM3 (peak pressure = 40 MPa)** → Focal zone defined at **20 MPa**.
  - **Problem with this definition**:
    - **Absolute pressure levels differ significantly** between machines.
    - If **55 MPa** were used as the threshold for the Dornier HM3, its **focal zone would be nonexistent**.
- **Alternative Focal Zone Definitions**
  - Various alternative definitions have been proposed:

    Half the peak negative pressure.
    Half the energy density.
    The surface where peak pressure is 5 MPa.
    Energy passing through a 10 mm diameter volume (approximate size of a kidney stone).
  - **No universal standard** has been agreed upon due to the **complexity of shock wave fragmentation mechanics**.

Effectiveness of Lithotriptors with Small, Tight Focal Zones

- **Theoretical Advantage**
  - **Electromagnetic (EML) and piezoelectric (PEL) lithotriptors** have **smaller focal spots**, leading to:
    - **More precise targeting** on the stone.
    - **Reduced damage to surrounding tissue**.
- **Experimental and Clinical Findings**
  - **In vitro studies** (with stationary stones) show that:
    - **High-pressure electromagnetic and piezoelectric lithotriptors do not** outperform electrohydraulic lithotriptors (EHLs) in breaking stones.
    - **High peak positive pressure alone does not correlate with better stone fragmentation in clinical settings**.
- **Clinical Issues with Small Focal Zones**
  - **Respiratory-induced stone motion** causes:
    - **Fewer shock waves hitting the stone**.
    - **More energy being deposited into surrounding tissue**.
  - **Lithotriptors with very high peak pressures (>100 MPa)** expose tissue to **excessive acoustic energy**, increasing the risk of **adverse effects** such as:
    - **Subcapsular hematomas**.

Device Equivalency and Equating Lithotriptor Performance

- **Lack of Standardized Metrics for Comparison**
  - Currently, **no agreed-upon metrics** exist for comparing the **acoustic output** of different lithotriptors.
  - **No straightforward method** to adjust a lithotriptor's settings to **match the performance of another device**.
- **Variability in Lithotriptor Characteristics**
  - Although all lithotriptors produce **shock waves with similar waveforms**, key differences include:
    - **Amplitude** (peak positive pressure).
    - **Focal zone size and shape**.
    - **Energy distribution**.
  - **Acoustic field measurements** can yield **very different values** between devices.
- **Example Comparison (Table 38-1)**
  - Comparison of an **electrohydraulic (EHL) vs. electromagnetic (EML) lithotriptor**:

        - **Energy incident on a 6.5 mm stone**: Similar (~0.484 mJ vs. 0.528 mJ).
        - **Peak positive pressure**: **Three times higher** in the **electromagnetic lithotriptor**.
    - **Key takeaway**: Even if **one parameter is matched**, **other properties remain significantly different**.
- **Effects of Adjusting Power Settings**
    - Reducing **power** on an **electromagnetic lithotriptor** to match the **pressure** of an electrohydraulic lithotriptor would cause:
        - **Energy output to drop nearly 10-fold**.
        - **Significant loss in fragmentation efficiency**.
- **Additional Factors Affecting Equivalency**
    - **Number of shock waves**:
        - **Electrohydraulic lithotriptors typically require fewer shock waves** to break stones than electromagnetic lithotriptors.
    - **Shock wave delivery rate**:
        - The **rate of shock wave application** has been reported to **impact fragmentation efficiency**.
- **Conclusion**
    - At present, **no clear way** exists to **adjust power, number of shocks, or delivery rate** to ensure **equivalency between different lithotriptors**.

Waves in Stones

- **Types of Waves in Kidney Stones**
    - Kidney stones are **elastic solids** that support **two types of waves**:
        - **Longitudinal (Compression) Waves**
            - Similar to **acoustic waves**.
            - **Molecules oscillate along the direction of propagation** (compression and rarefaction).
            - Travel at **speed cLc_L**(always faster than transverse waves).
        - **Transverse (Shear) Waves**
            - **Oscillations are perpendicular to propagation direction** (similar to a wave on a rope).
            - Unlike longitudinal waves, **do not cause compression and rarefaction**.
            - Travel at **speed cTc_T(slower than longitudinal waves)**.
- **Energy Division at the Stone Boundary**
    - When a **shock wave passes from urine/tissue into a stone**, its energy splits into **longitudinal and transverse waves** inside the stone.
    - **Energy partition depends on**:
        - **Material properties of the stone**.
        - **Angle of incidence** of the wave.
    - **Normal incidence** (perpendicular wave entry):
        - **All energy converts to longitudinal waves**.
        - **No transverse waves generated**.
    - **Oblique incidence (angled entry)**:
        - **Less energy enters as longitudinal waves**.
        - **More energy is converted into transverse waves**.
    - **Complex stone shapes** cause a **non-trivial energy distribution** between wave types.
- **Computer Simulation of Shock Wave Interaction (Figure 38-16)**
    - **Simulation models particle motion in an elastic solid**.
    - **Snapshots illustrate stress distribution** inside a cylindrical-shaped stone over time:
        - **Initial Frames**:
            - Shock wave enters the stone as **compression waves**.
        - **Mid Frames**:

        - **Longitudinal waves travel inside the stone**.
        - **Acoustic waves outside the stone generate shear waves** at the **lateral walls**.
        - **Shock wave reflects from the rear wall**.
    Wave Reflection Effects:
        - Since the **fluid impedance is lower than that of the stone**, the **reflected pressure wave inverts**.
        - The **leading compressive wave reflects as a tensile wave** (**negative pressure reflection coefficient RPR_P**due to Z2<Z1Z_2 < Z_1).
    Final Frames:
        - **Shear and longitudinal waves interact**, producing **high tensile stresses inside the stone**.
        - These **high tensile stresses contribute to stone fragmentation**.

Acoustic Properties of Stones and Shock Wave Fragmentation Mechanisms

Acoustic Properties of Kidney Stones

- The key **wave propagation properties** of kidney stones include:
    Density (ρ0\rho_0)
    Longitudinal sound speed (cLc_L)
    Transverse wave velocity (cTc_T)
- **Variability in Stone Properties** (Figure 38-17):
    - Different stone types (e.g., **uric acid, calcium oxalate monohydrate, cystine stones**) have **widely varying acoustic properties**.
    - Example: **Calcium oxalate monohydrate sound speed** ranges from **3,000 m/s to 4,500 m/s**.
    - Variations may be due to:
        - **Natural differences in stone composition**.
        - **Preparation factors** (e.g., **hydration levels**).

How Shock Waves Break Stones (Figure 38-18)

- **Several mechanisms** have been proposed to explain **stone fragmentation by shock waves**.
- Below are some of the **most likely mechanisms**:

Spall Fracture

- **Process**:
    Shock wave enters the stone and **reflects from the rear wall** (Figure 38-16).
    At the **stone/urine interface**, the **positive pressure pulse inverts**.
    This results in a **large tensile stress** near the **back wall** of the stone.
    The **incoming negative pressure tail** further **amplifies the tensile stress**.
    Since **most solids are weaker in tension than compression**, this **tensile stress causes material failure**, leading to **fracture**.

Shear Stress Fracture

- **Formation of Shear Stresses**:
    - **Shear waves** and **compressive waves** interact as the **shock wave propagates through the stone** (Figure 38-19).
    - Many materials, **especially layered kidney stones**, are **weak in shear**.
    - **Layered structures fracture easily** because:
        - The **bonding strength between layers** has **low ultimate shear stress**.
        - The **organic binder** in kidney stones is **softer than the crystalline phase**, making it vulnerable to **shear forces**.

Shear Stress and Superfocusing in Stone Fragmentation

Shear Stress Fracture

- **Generation of Shear Stresses**:
    - **Shear waves and compressive waves** develop as the **shock wave propagates through the stone** (**Figure 38-19**).
    - **Layered kidney stones** are particularly **weak in shear** because:

        - The **bonding strength between layers** has **low ultimate shear stress**.
        - The **organic binder** in kidney stones is **softer than the crystalline phase**.
    - As the **shock front moves through the stone**, it induces **high shear stresses at binder/crystal interfaces**, leading to **fracture**.
- **Impact of Shear Waves on Stone Fragmentation**:
    - **Shear waves in the stone can induce tensile stresses** greater than those caused by **spallation**.
    - **Figure 38-16** demonstrates that **shear waves interfere with reflected longitudinal waves**, producing the **largest tensile stresses in cylindrical stones**.

Superfocusing and Stress Amplification

- **What is Superfocusing?**
    - **Superfocusing** occurs when **stress amplification** happens inside the stone due to its **geometry**.
    - The **shock wave reflecting from the distal stone surface** can be focused through:
        - **Refraction**:
            - Affected by the **high sound speed and geometry of the stone**.
        - **Diffraction**:
            - Occurs at the **stone's corners**, redirecting energy into specific regions.
- **Effects of Superfocusing on Stone Failure**:
    - Reflected waves can **concentrate at caustics** (regions of **high stress** inside the stone).
    - **These high-stress regions lead to material failure**.
    - The **location and intensity of these stresses** depend on the **stone's shape and elastic properties**, such as:
        - **Density** (ρ\rho)
        - **Longitudinal wave speed** (cLc_L)
        - **Shear wave speed** (cTc_T)
- **Conclusion**:
    - **Shear stresses and superfocusing contribute significantly to kidney stone fragmentation**.
    - **Understanding the stone's geometry and wave propagation properties is key to predicting failure locations**.

Squeezing and Cavitation in Stone Fragmentation

Squeezing (Splitting Mechanism)

- **Cause**:
    - Due to the **difference in sound speed** between:
        - **Stone (>2,500> 2,500m/s)**
        - **Surrounding fluid (urine) (≈1,500\approx 1,500m/s)**
    - This causes the **shock wave inside the stone** to **travel faster** than the shock wave in the surrounding fluid.
- **Effect on the Stone**:
    - The **fluid shock wave exerts a circumferential force** on the stone (**hoop stress**).
    - This results in **maximum tensile stress** at the **proximal and distal ends** of the stone.
    - Leads to **axial splitting failure** of the stone.
- **Enhancing Squeezing Effect**:
    - The **splitting effect is enhanced** when the **entire stone is within the focal zone**.
    - A **new lithotriptor design** has been developed based on this principle and **documented in recent literature**.

Cavitation in Lithotripsy

- **What is Cavitation?**
    - Formation of **small bubbles (cavities) in the urine** surrounding the stone due to the **large negative pressure tail of the acoustic pulse**.
- **Microjet Formation and Impact**:
    - When a **cavitation bubble collapses near a solid surface** (e.g., kidney stone):

        - A **microjet of fluid pierces the bubble** and **impacts the stone surface at speeds >100 m/s** (**Figure 38-20**).
        - This **microjet contributes to stone surface damage**.
- **Secondary Shock Wave Emissions**:
    - **Bubble collapse** also generates **secondary shock waves**.
    - These waves have **amplitudes comparable to the primary shock wave**, enhancing fragmentation.
- **Evidence from Experiments**:
    - **In vitro studies where cavitation is suppressed** show a **significant reduction in stone fragmentation**.
    - **Cavitation is mainly a surface-acting mechanism**, primarily affecting:
        - **The proximal (shock wave incident) surface of the stone**.
- **Cavitation and Spall Fracture**:
    - Cavitation-induced stresses may **act via a spallation mechanism**.
- **Cluster Cavitation Theory**:
    - **Recent research** suggests lithotripsy **does not produce isolated cavitation bubbles**.
    - Instead, it creates **bubble clusters** (**Figure 38-21**).
    - The **coherent collapse of these clusters enhances cavitation's destructive power**.

Fatigue as a Mechanism of Stone Fragmentation

Fatigue Process in Kidney Stones

- **Definition**:
    - **Fatigue** occurs when **progressive crack development** leads to **stone failure** over time.
    - **Cracks originate at small imperfections** (nucleation sites), which are present in **all kidney stones**.
- **Formation of Cracks Under Shock Waves**:

    Initial imperfections act as **stress concentration sites**.

    Shock waves induce localized stresses far exceeding the average stress.

    Repetitive shock waves cause:
        - **Imperfections to grow into microcracks**.
        - **Microcracks to expand into macrocracks**.

    Tensile or shear stresses eventually **enlarge the cracks**, leading to **failure**.

    Fatigue is enhanced in regions of high stress coinciding with **weaker areas in the stone**.
- **Possible Synergistic Effects**:
    - Fatigue may **work alongside other mechanisms**, such as:
        - **Spallation** (high tensile stress near the back wall).
        - **Shear stress** (from longitudinal and transverse wave interactions).
        - **Cavitation** (localized high-stress regions from bubble collapse).

Evidence Supporting Fatigue as the Main Fragmentation Process

Stone Internal Structure Affects Fragmentation
- Studies show that **stone composition and internal microstructure influence** how stones break in lithotripsy.

Large Number of Shock Waves Required
- **Typically, >1,000 shock waves** are needed to break stones into small fragments.
- **Progressive fracture due to multiple stress cycles** is a classic hallmark of **fatigue failure**.

Uncertainty in the Dominant Fatigue Mechanism

- **Two most commonly cited drivers of fatigue**:

    Direct stress mechanisms (spall and shear forces).

    Cavitation-induced damage.

    Potential combination of both effects.
- **Challenges in Determining the Dominant Mechanism**:
    - **Limited material strength data for kidney stones**:

        - **Compression strength**
        - **Fracture toughness**
        - **Knoop hardness**
        - **Vickers microhardness**
    - **Lack of tensile and shear strength data**:
        - Measuring **brittle material properties** is **technically difficult**.
    - **Current mechanical tests are quasi-static** (minutes-long stress applications), whereas **shock waves act in microseconds**.

Conclusion

- **Stone failure in lithotripsy follows a fatigue process**, but the **dominant mechanism remains unclear**.
- **More data on stone material properties under rapid stress conditions** is needed to **fully describe the fracture process**.

Mechanisms of Tissue Damage in Shock Wave Lithotripsy (SWL)

Tissue Trauma in Lithotripsy

- **Shock wave lithotripsy (SWL) is known to cause kidney trauma**, and in some cases, the injury can be **severe**.
- **Clinical implications of SWL-induced damage** are still being investigated (**see Chapter 41, "Complications"**).
- **Myth: Shock Waves Pass Harmlessly Through the Body**
    - This assumption is **incorrect**.
    - **Most patients receiving at least 2,000 shock waves at midrange power or higher** experience **some form of tissue trauma**.
    - While **SWL has been highly beneficial**, some patients have suffered **severe or even catastrophic adverse effects**.

Physics of Tissue Damage

- **Acoustic Pulse and Focal Zone Effects**
    - **Lithotriptors generate focused acoustic pulses**.
    - The **acoustic field is broad at the source and narrows at the focus**.
    - The **focal zone** has **high acoustic pressure** and is **elongated (~50 mm in length, see Figure 38-15)**.
    - Because **kidneys are approximately 50 mm thick**, the **entire kidney is exposed to high-amplitude shock waves**.
    - **Patient motion (respiration, discomfort) can cause the stone to move out of the focal zone**, resulting in **shock waves impacting tissue instead of the stone**.

Tissue's Resistance to Damage vs. Kidney Stones

- **Advantages of Tissue Properties**
    - **Acoustic impedance of tissue is similar to water**, reducing **shock wave reflection** at tissue-water interfaces.
    - **Tissue does not experience spallation**, as it lacks the **extreme tensile forces** that cause stones to fracture.
    - **Tissue sound speed is nearly constant**, preventing **differential squeezing stresses** that could lead to splitting (unlike stones).
- **Vulnerabilities of Tissue**

    Shear Stress
        - **Shock wave pressure waves** induce **shear forces** in tissue.
        - Tissue is **not as resistant to shear as compression**, making it susceptible to **mechanical stress-induced injury**.

    Cavitation Damage
        - The **tensile phase of the shock wave** creates **cavitation bubbles** in tissue.
        - **Bubble collapse generates microjets and secondary shock waves**, which can **cause localized tissue damage**.

Conclusion

- **Tissue is not as vulnerable as kidney stones to certain failure mechanisms (spallation, splitting)**.
- **However, it remains susceptible to shear stress and cavitation**, both of which can

contribute to **SWL-induced tissue injury**.

Mechanical Stress and Cavitation as Mechanisms of Tissue Damage in Lithotripsy

Mechanical Stress in Tissue

- **Compression Due to Positive Pressure**
  - The **positive pressure of a lithotriptor pulse** compresses tissue.
  - **Tissue is generally resistant to isotropic compression**, but:
    - The **shock front rise time is ~70 ns** in tissue.
    - This corresponds to a **spatial scale of ~100 µm**.
    - Tissue structures between **10 µm to 1 mm** experience **large stress variations** as the shock wave passes.
- **Shear Forces from Shock Waves**
  - The **short rise time of the shock wave** results in **non-uniform tissue straining**, leading to **shear forces**.
  - **Tissue structures are highly sensitive to shear stress**.
  - **Shock wave-induced tissue distortion** could produce **enough shear to cause mechanical damage**.

Shear Stress Due to Tissue Inhomogeneities

- **Tissue is an inhomogeneous medium** with varying sound speeds at different length scales.
- **Sound speed variations (~mm scale) affect wave focusing**:
  - **Parts of the shock wave traveling through higher sound-speed regions** arrive **sooner**.
  - **Parts traveling through lower sound-speed regions** lag behind.
  - This **distortion of the wavefront** leads to **localized shear stresses in tissue**.
  - **Shear stress could be strong enough to cause mechanical damage**.

Cavitation as a Dominant Cause of Tissue Damage

- **Cavitation in Tissue During Lithotripsy**
  - **Cavitation bubbles form in tissue due to the tensile phase of the shock wave**.
  - **Passive cavitation detection (PCD) studies in humans and pigs** have identified **cavitation signatures in**:
    - **Perirenal fat**.
    - **The collecting system**.
    - **Renal parenchyma**.
    - **Subcapsular hematomas**.
- **Cavitation's Biological Effects**
  - Cavitation has been well-documented to cause **biological damage in vitro** (see **Carstensen EL, Miller DL, Dalecki D, Delius M, Williams JC**).
  - **Experimental evidence**:
    - **Reducing cavitation significantly reduces tissue damage** in both **in vitro cells and in vivo tissue**.
- **Cavitation in Blood Vessels vs. Tissue**
  - **Cavitation is more damaging in blood vessels than in surrounding tissue**:
    - **Tissue-constrained bubbles** cannot expand or collapse violently.
    - **Bubbles in blood vessels** experience **unrestricted growth and collapse**, making them **more destructive**.
  - This suggests that **vascular injury is a key concern in lithotripsy-induced tissue damage**.

Cavitation-Induced Tissue Damage Mechanisms

1. Collapsing Bubbles and Microjets

- **Mechanism**:
  - **Asymmetrical bubble collapse** generates **high-velocity microjets** of fluid.
  - These microjets are **strong enough to pit foils or etch metal**.
  - **Blood vessels, particularly capillaries, could be punctured** by these jets.

- **Weakness of the Theory**:
  - **Most injured blood vessels during lithotripsy are too small** to allow for **full bubble expansion and collapse**.
  - This suggests that **collapse-induced damage may not fully explain the vascular injuries seen in SWL**.

2. Bubble Expansion and Vessel Rupture

- **Mechanism**:
  - As the **shock wave's negative pressure phase passes through a blood vessel**, bubbles experience **rapid expansion** (see **Figure 38-10**).
  - **Explosive bubble growth exerts outward pressure**, potentially **rupturing vessel walls**.
- **Supporting Evidence**:
  - **Capillary rupture is often observed first**, indicating **small vessels experience the greatest stress**.
  - **In vitro experiments using capillary phantoms** support the **explosive bubble hypothesis**.
- **Potential for Additional Tissue Damage**:
  - If **bubble expansion can rupture blood vessels**, it may also **tear apart other soft tissue structures** nearby.

3. Hematoma Formation and Persistent Cavitation

- **Once blood vessels rupture**, **blood pools** in areas like hematomas, creating:
  - **Larger fluid-filled spaces** for cavitation bubbles to form.
  - **Pre-existing bubbles** in these pools that **act as nuclei for further cavitation events**.
  - **Reduced blood flow**, preventing cavitation bubbles from being **swept away**, prolonging their effects.
- **Observed Effects in SWL**:
  - **Intense passive cavitation detection (PCD) signals** recorded from hematomas.
  - **B-scan ultrasound shows increased echogenicity**, indicating **cavitation activity within hematomas**.
  - Violent **cavitation in pooled blood may lead to additional cell disruption** in the affected region.

Current Research and Unresolved Questions

- **Understanding tissue response to shock waves is still incomplete**:
  - Tissue **mechanical properties at high strain rates** (relevant to SWL) are **poorly understood**.
  - **Damage criteria are not well-defined**, making it **difficult to quantify tissue injury risk**.
- **Few experimental models exist** to **validate different hypotheses** about cavitation-induced damage.
- **General consensus**:
  - **Cavitation is likely the primary mechanism of tissue injury in SWL**.
  - **Further research is needed** to confirm the dominant physical processes involved.

The Evolution of the Lithotriptor

How Lithotriptors Have Changed Over the Years

- **Lithotripsy has been in clinical practice for over 25 years**, with **several design improvements**, but **no fundamental changes in acoustics**.
- **Key advancements in modern lithotriptors**:
  - **Compact and modular designs**.
  - **Dry shock heads** instead of water-bath immersion.
  - **Improved imaging for stone targeting**.
- **Despite these changes, the acoustic signature of lithotriptors remains largely the same**.
  - The **focal waveform of the Dornier HM3 is nearly identical** to that of modern lithotriptors.

Trade-Offs in Modern Lithotripsy

- **Success rates in lithotripsy have declined** with the introduction of newer devices.
- **Machines with tight focal zones and extreme peak positive pressures** have:
  - **Reduced stone fragmentation efficiency**.
  - **Increased collateral tissue damage**.
- **Progress has been made in convenience, but at a cost to treatment effectiveness**.

Early Lithotriptors: Electrohydraulic Devices

- The **first-generation lithotriptors** used **electrohydraulic shock wave generation**:
  - **Shock waves were produced by an underwater spark discharge**.
  - **Patients were fully immersed in a water bath** for optimal shock wave coupling.

The Dornier HM3: A Landmark Lithotriptor

- The **Dornier HM3** was one of the most successful **first-generation** lithotriptors.
- **Key characteristics of the HM3**:
  - **Moderate peak positive pressures (~40 MPa)**.
  - **Generous focal zone (~15 mm by 60 mm)**.
- **Impact of the Dornier HM3**:
  - **Widely adopted and highly successful**.
  - **Played a crucial role in the early success and widespread acceptance of lithotripsy**.
  - Some **centers still use the HM3 today** due to its **proven effectiveness**.

Challenges and Advancements in Lithotriptor Design

Perceived Drawbacks of the Dornier HM3

- Despite its effectiveness, the **Dornier HM3 had several limitations**:

  Open water bath was required for shock wave coupling.
  Treatment was painful, requiring **sedation or anesthesia**.
  Large, stationary equipment required a **dedicated water treatment facility**.
- **Physicians and Patients Desired Improvements**:
  - A **painless, convenient, walk-in/walk-out therapy** with **minimal or no anesthesia**.
  - Lithotriptor manufacturers **modified designs to address these concerns**.

Modifications and Improvements in Modern Lithotriptors

Elimination of the Open Water Bath

- **Shock head enclosed with a rubber membrane** for body coupling.
- **Advantages**:
  - **Easier access to patients** for medical staff.
  - **Lithotriptors no longer required a dedicated facility**.
  - **Enabled modular, portable lithotriptor designs** (used in mobile lithotripsy units).
- **Disadvantages**:
  - **Acoustic coupling with a water-tissue interface is superior**.
  - **Membrane coupling is less effective**, leading to **energy loss**.

Replacement of Electrohydraulic Electrodes

- **Electrohydraulic lithotriptors required frequent electrode replacements**, increasing cost and treatment time.
- **Electromagnetic and piezoelectric lithotriptors do not use electrodes**, reducing maintenance.
- **Issues with electrohydraulic electrode wear**:
  - **Spark gap widens with use**, leading to **greater variability in arc discharge paths**.
  - **Manufacturers improved electrode lifespan** using **electrolyte-filled encapsulated electrodes**.

The Challenge of Anesthesia-Free Lithotripsy

Discomfort from Shock Wave Treatment

- **Main cause of pain**: **Cutaneous pain at the shock wave entry point**.
- **Attempts to reduce pain** included **widening the shock source aperture** to **spread energy over a broader area**.

Trade-Offs of a Wider Aperture

- **Broader acoustic field along the shock wave axis**.
- **Narrower focal zone (~5 mm or less)**.
- **Some modern lithotriptors generate extreme peak positive pressures (>100 MPa)**.
- **Problems with a tight focal zone**:
  - **Difficult to keep perfectly aligned with the stone due to respiratory motion**.
  - **More challenging to hit the stone compared to a broad focal zone**.

Current Reality of Lithotripsy Comfort

- Regardless of design improvements, **lithotripsy remains uncomfortable**.
- If the patient is **not sedated**, they will **move during treatment**, reducing effectiveness.
- **Attempts to create a completely anesthesia-free lithotriptor have not yet been successful**.

Future Directions in Lithotriptor Design

1. Wide-Focus, Low-Pressure Lithotriptors

- **New approach in response to high-pressure, tight-focal-zone machines**.
- **Xi Xin-Eisenmenger Lithotriptor**:
  - **Largest focal zone in clinical use (18 × 180 mm)**.
  - **Low acoustic pressure (10–25 MPa)**.
  - Designed to test the **circumferential squeezing hypothesis** for enhanced stone breakage.
  - **Early trial results**:
    - **High stone-free rate (86%)**.
    - **Can be used without anesthesia**.

2. Cavitation Control Strategies

- **Manipulating cavitation bubbles with a second pulse**:
  - **Cavitation bubble cycle lasts ~300 µs in free field, ~600 µs at a stone surface**.
  - **Effect of timing on bubble collapse**:
    - **Early second pulse**: Stops further expansion → **minimal damage**.
    - **Late second pulse**: Accelerates collapse → **enhanced damage**.
- **Dual Pulse Lithotripsy**:
  - **Developed by Bailey** using **twin shock sources facing each other**.
  - Other researchers have refined this by:
    - **Firing multiple pulses along the same axis**.
    - **Using dual treatment heads at an angle** to accommodate patient anatomy.
  - **Potential benefits**:
    - **Tailored acoustic forces** for improved stone breakage.
    - **Reduced collateral tissue damage**.
  - **Still under development and testing**—no definitive efficacy and safety data yet.

3. Real-Time Stone Tracking for Targeted Shock Wave Delivery

- **Goal**: **Reduce unnecessary shock wave impact on tissue**.
- **Proposed tracking methods**:
  - **Monitor stone location and fire only when the stone is at the focus**.
  - **Acoustic time-reversal technology**:
    - Dynamically adjusts lithotriptor focus to track the stone as it moves.
- **Potential impact**:
  - **Fewer shock waves needed** to break stones.
  - **Lower risk of tissue injury**.
- **Current limitation**:
  - **No clinical devices yet employ real-time tracking**.

Final Thoughts

- **Lithotripsy technology is evolving** toward **improving efficiency and reducing tissue damage**.

- **Wide-focus, low-pressure lithotriptors, dual-pulse strategies, and real-time tracking** hold promise.
- **Further research and clinical validation are needed** before these innovations become standard practice.